UNIVERSITY OF TECHNOLOGY SYDNEY

Faculty of Engineering & Information Technology

# Study on Vacuum Desalination of Seawater and Feasibility of Solar as the Energy Source

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For a Master of Engineering (Research) C03017

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# Abstract

This study covers the development of an energy efficient water desalination system that allows a reduction in the use of fossil fuel and meets the scarcity of drinking water. As part of planning to address shortfalls in fresh water supply for the world, several parallel investigations have been underway. Seawater can be a huge source of fresh water. Seawater is desalinated to provide drinking water at many locations throughout the world. Recent advancements in technology have reduced the costs and energy use of desalination. These technical advances and increasing shortages of freshwater have led to increasing numbers of large plants being constructed around the world. This trend is most evident in Australia, with the plant recently commissioned in Perth, a plant under construction on the Gold Coast and proposed new plants in Perth and in Sydney. Desalination is the process of removing salt and other minerals from salt water to produce usable water. A huge amount of energy is needed to do the desalination of seawater. So, a cost-effective and efficient way needs to be introduced to get the fresh water. A solar water heater can warm up the seawater (to a temperature above room temperature) easily during normal day-light condition. Then this warm water can be boiled at low temperature (well below the normal boiling point, 100°C) when surrounding pressure is reduced. The vapour from the boiling will then be condensed back into the liquid water at room temperature.

Experiments were conducted to reduce the surrounding pressure using a vacuum pump to allow water to evaporate at a temperature lower than the normal boiling temperature of 100°C. It also includes the review of literature and construction of the test rig and testing considering various parameters. The preliminary focus is on the evaporation of water at low temperature and pressure. The warm water of the similar temperature that we can achieve from a solar water heater was used to test the system. The ultimate goal of this research would be to establish a simple method to produce fresh water from seawater using a solar water heater, a vacuum pump that runs by solar electricity along with a condenser and pressure vessels.

# Acknowledgements

I would like to express the deepest appreciation to my supervisor Dr Phuoc Huynh for his tremendous support and advice through the learning process and thank him as he offered and gave me the opportunity to take up this research.

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Finally, Thanks for the support from my dear wife Dipannita Mushfiq and my beloved parents.

# Nomenclature

| **Symbol** | **Description** | **Unit** |
|---|---|---|
| $T$ | Temperature | °C |
| $Q$ | Flowrate | $m^3/s$ |
| $P$ | Power | W |
| $Pr$ | Pressure | kPa |
| $m$ | Mass | Kg |
| $v$ | Velocity | m/s |
| $t$ | Time | s |
| $F$ | Force | N |
| $E$ | Energy | J |
| $l$ | Length | m |
| $\omega$ | Angular velocity | rad/s |
| $V$ | Volume | $m^3$ |
| $d$ | Diameter | m |
| $r$ | Radius | m |
| $Re$ | Reynolds number | |
| $A$ | Area | $m^2$ |
| $\eta$ | Efficiency | % |
| %RH | Relative Humidity | % |
| $s$ | Specific heat of water | kJ/kg-K |
| $\Delta T$ | Temperature difference | K |
| LH | Latent heat | kJ/kg |
| $g$ | Gravity | $m/s^2$ |
| $N$ | Rotational speed | rpm |
| $\rho$ | Density | $kg/m^3$ |

# Nomenclature

# Abbreviations

| | |
|---|---|
| ASHRAE | American Society of Heating, Refrigerating and Air Conditioning Engineers |
| CAOW | Close Air Open Water |
| CFM | Cubic foot per minute |
| COP | Coefficient of Performance |
| CWOA | Close Water Open Air |
| ED | Electrodialysis |
| EDI | Electrodeionisation |
| EDR | Electrodialysis Reversal |
| EES | Engineering Equation Solver |
| FAO | Food and Agricultural Organization of United Nations |
| GDP | Gross Domestic Product |
| GDP | Gross Domestic Product |
| HD | Humidification Dehumidification |
| HFC | Heliostat Field Collector |
| HTF | Heat Transfer Fluid |
| HX | Heat Exchanger |
| IDA | International Desalination Association |
| IEA | International Energy Agency |
| IPCC | Intergovernmental Panel on Climate Change |
| MD | Membrane Distillation |
| MED | Multi Effect Distillation |
| MENA | Middle East and North Africa |
| MSF | Multi Stage Flash |
| NPV | Net Present Value |
| PDC | Parabolic Dish Collector |
| PEPD | Psychometric Energy Process Desalination |

Abbreviations

| | |
|---|---|
| PV | Photovoltaic |
| RES | Renewable Energy Sources |
| RO | Reverse Osmosis |
| SD | Solar Desalination |
| SEGS | Solar Energy Generating Systems |
| SNL | Sandia National Laboratory |
| TDS | Total Dissolved Solids |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |
| VC | Vapour Compression |
| VTC | V-Trough Collector |
| WRR | Water Recovery Rate |
| WHO | World Health Organization |

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# 1 Introduction

Water is an abundant natural resource, as approximately three-quarters of the earth's surface are covered by ocean water. However, 97.5% of this resource is comprised of saline water, leaving only 2.5% of fresh water (Verdier, Desalination Task 1, 2011). Moreover, almost two-thirds of this freshwater is inaccessible, since it's in the form of ice and snow in the Antarctic, artic islands and mountainous regions which results in less than 1% of the global water resource is being accessible freshwater.

Recognizing the importance of water for sustainable development, the United Nations declared 2005-2015 the "Water for Life" decade. In recent past, water crises ranked as third on the world's top ten risks, according to a report from the World Economic Forum based on concern, likelihood, impact and interconnections (Carlo Z. , 2014). Indeed, water is crucial for social and economic development. Yet evidence points to the fact that the current use of water is unsustainable. Growing demand for water resources due to population growth and evolving consumption patterns has increased water scarcity, amplifying the pressure on the natural resource and the ecosystem. The global population is expected to be 9.3 billion by 2050. This growth will increase the urban areas of the planet and the need for drinking water, health and sanitation, as well as energy, food and other goods and services that require water for their production and delivery. Agricultural water consumption, which is a significant cause of water scarcity, is expected to increase by 20% by 2050 (Nicholson, 2014). This increase in demand will occur particularly in countries undergoing accelerated economic growth and social development. Domestic and industrial water demands are also expected to increase. A Mckinsey & Company Report (2009) estimated a 40% disparity, by 2030, between the demand of water and a supply that is accessible, reliable and sustainable, if there are no efficiency gains until then. This water-scarce future represents a critical challenge to civilization.

Desalination of salt water and brackish water is a solution that can help reduce current and future water scarcity. Desalination is used to get the salt and mineral free water from sea water but for this process, a huge amount of energy resource is required. The general perception of "solar desalination" today comprises only small-scale technologies for decentralised water supply in remote places, which may be quite important for the development of rural areas but does not address the increasing water deficits of the quickly growing urban centres of demand (Houghton, 2011). However, desalination is an energy-intensive process. Diverse desalination technologies require different amounts of energy. Fossil fuels are currently utilized to supply most of the energy requirements. However, this leaves the desalination process vulnerable to global market prices and logistical supply issues. Furthermore, utilizing fossil fuels represents an unsustainable solution that increases environmental harm.

Conventional large-scale desalination is perceived as expensive, energy consuming and limited to rich countries like those of the Arabian Gulf, especially in view of the quickly escalating cost of fossil fuels like oil, natural gas and coal. The environmental impacts of large-scale desalination due to airborne emissions of pollutants from energy consumption and to the discharge of brine and chemical additives to the sea are increasingly considered as critical. For those reasons, most contemporary strategies against a "Global Water Crisis" consider seawater desalination only as a marginal element of supply. The focus of most recommendations lies on more efficient use of water, better accountability, re-use of wastewater, enhanced distribution and advanced irrigation systems. To this adds the recommendation to reduce agriculture and rather import food from other places. On the other hand, most sources that do recommend seawater desalination as part of a solution to the water crisis usually propose nuclear fission and fusion as an indispensable option. None of the presently discussed strategies includes solar power for seawater desalination within their portfolio of possible alternatives. However, quickly growing population and water demand and quickly depleting groundwater resources in the arid regions of the world require solutions that are affordable, secure and compatible with the environment in one word: sustainable (Stewart, 2007). Such solutions must also be able to cope with the magnitude of the demand and must be based on available or at least demonstrated the technology, as strategies bound to uncertain technical breakthroughs if not achieved in time would seriously endanger the whole region. Renewable energy sources have been accepted worldwide as sustainable sources of energy and are introduced to the energy sector with an annual growth rate of over 25% per year. From all available energy sources, solar energy is the one that correlates best with the demand for water, because it is obviously the main cause of water scarcity.

Using solar energy combined with vacuum technology desalination can be done saving energy as much as 95% which is desirable for the current fossil energy crisis and scarcity of fresh water (Carlo D. , 2002).

## 1.1 Background and Motivation

Water scarcity is an issue that currently affects every continent on the planet. Water scarcity occurs when, in a particular time period, water demand nears or exceeds water availability. As stated, water scarcity depends, among other factors, on the requirements of the local population. Yet demand varies widely depending on the area of the globe: the average individual from Europe or the United States requires between 200 and 600 litres while an individual from the African continent only uses 30 to 40 litres per day.

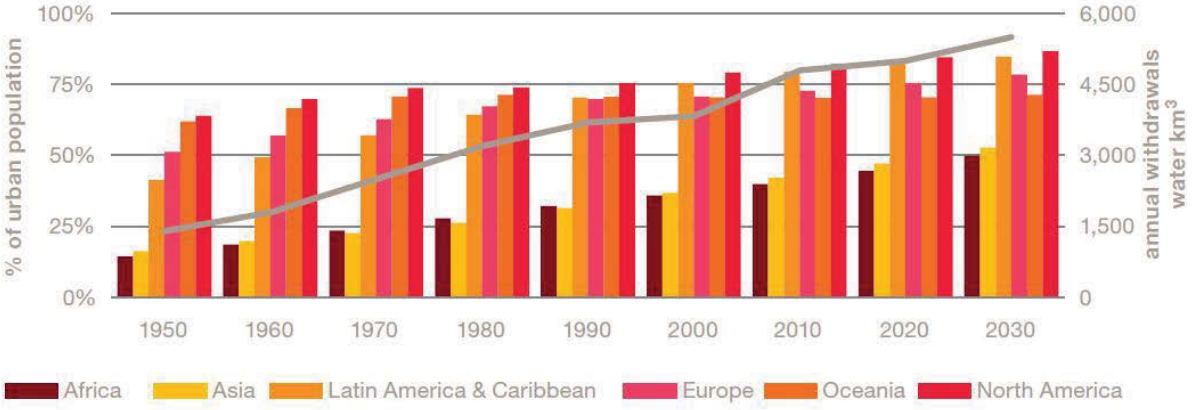


Figure 1 Trend in population density and water consumption *(Coopers, 2012)*

Data on water withdrawal and consumption is frequently based on estimates rather than actual measurements. Water withdrawal is the total amount of water taken from a lake, river or aquifer for any purpose. Water consumption is the fraction of withdrawn water that is lost in transmission, evaporation, absorption or chemical transformation, or otherwise made unavailable for other purposes as a result of human use. At present agriculture represents approximately 70% of total freshwater withdrawals globally, with the industrial sector representing 20% and the domestic sector 10%. Furthermore, the energy sector is responsible for 75% of the freshwater withdrawal in the industrial sector, More-developed countries tend to have a much larger proportion of freshwater withdrawals for industry, while in less-developed countries agriculture leads the consumption of water, more in the latter, agriculture can account for more than 90% of freshwater withdrawals. According to the Organisation for Economic Co-operation and Development (OECD), global water withdrawals are expected to increase by 55%, caused by increases in demand from manufacturing (400% growth), thermal electricity generation (140%) and domestic use (130%). This increase in demand will occur particularly in countries undergoing accelerated economic growth and social development such as Brazil, Russia, India, Indonesia, China and South Africa. Demand from the energy sector is expected to increase (as energy demand is expected to increase) with 90% of this demand again coming from countries outside the OECD. According to the same source, freshwater availability will be increasingly strained through 2050, if no new policies are introduced, with an increase of 2.3 billion people living in areas subjected to severe water stress, especially North and South Africa and South and Central Asia.

Safe and stable water supply is the major issue for sustainable development. There are more difficulties in securing adequate water supply now than in the past. The construction of reservoirs requires capital costs, the use of groundwater has to consider the treatment cost, and there are also significant costs in surface water treatment. On the contrary, the earth contains 97% of seawater with only 3% of fresh water available in which about 69% are icecaps and glaciers (Chambers, 2015). Therefore, the sea is the inexhaustible resource for drinking water supply. Due to advanced technologies, the cost of desalination may not be that high. The major commercial technology used in desalination can be divided into two categories, film and evaporation method. The evaporation method includes multi-effect distillation, multi-stage flash, and vapour compression. The membrane method includes reverse osmosis and electrodialysis. Currently, the most frequent applications of desalination technology in the world are reverse osmosis, followed by the method of multi-stage flash. Nevertheless, both of these two kinds of techniques use extensive energy. Although it seems to have no problem with the desalination technology, however, the process uses a huge amount of energy. This problem will be increasingly concerned about today's environment (Fath & Khaled, 2011). Therefore, we consider the use of renewable energy together with the evaporation method. This can reduce energy consumption. Meanwhile, the concept of sustainable energy use can be implemented through this process. In addition, the process of desalination will emit brine; its salinity is generally two times of seawater. As a result, it will result in mass mortality of aquatic organisms in receiving water. For the reason, it is expected that the designed system can reduce the negative effect on the environment.

In the conventional process, desalination is very similar to distillation where salt water is heated to its boiling point and then allows it to condensate. Heating the water to its boiling point requires a huge amount of heat energy which is ultimately produced by fossil energy. Thus, the process becomes so expensive raising the cost of fresh water. Underground water is a limited resource of water; rainwater is another resource but so much uncertain. Seawater is a huge resource for that if it can be achieved without huge energy investment. Using water's sensitivity to atmospheric pressure on its boiling point water can be evaporated at a very low temperature and condensed easily by the conventional method. The first aim to get a reliable desalination is to investigate distillation at low pressure. This property has been mainly investigated with the motivation of past studies in this field. Using a vacuum pump and solar heater water desalination must be a cost-effective and sustainable source of fresh water.

## 1.2 Research Contribution

The objective of this study is to develop a desalination system that would use solar energy to heat up the seawater slightly and a vacuum pump to evaporate the water followed by condensation at room temperature. The first thing is to ensure evaporation of water in low pressure as it is the most critical part of the experiment.

The target users of this study would be all countries with sea region like Australia, USA, South-Asia, UK, Middle-east and Africa and so on as most of the countries of the world are partly surrounded by sea. It is more applicable to the countries where fresh water demand is higher than the supply and in risk of lowering the underground water level to the danger line.

The overall objective of this research is to develop a very simple technology with a reasonable efficiency to provide clean and affordable freshwater most especially in developing countries where there are very low infrastructure and unskilled manpower, but with high abundance of solar energy. Such system would result in significantly reduced $CO_2$ emissions to the environment. And the anticipated cost of production is low since inexpensive materials could be used.

The main contributions of this project are summarised as follows:

- Study on different types of desalination and comparison between them. Review on solar aided vacuum desalination and develop a system to desalinate water using solar heat and vacuum pump.

- Evaluate the review to prepare an experimental setup which will mainly focus on evaporating water at low temperature and pressure followed by testing on experimental setup for credentials of the idea.

- Review experimental data and evaluate the industrial prospect of the setup considering the pros and cons of it. Evaluate energy savings and efficiency complete with health and safety.

- Extending the application of the reviewed and evaluated system towards water purification field.

- Theoretical and experimental investigation of the performance of the proposed plan.

- Establishing a prototype model which can be used in designing and manufacturing the devices of the industrial scale production system.

## 1.3 Research Benefit and its Impact

This research work has great benefit to the scientific community and researchers. This shows potential for the need of more specifically designed and optimized desalination plant for water desalination within the research field. This will lead to rapid commercialization of solar-powered desalination systems.

And in terms of new knowledge, a whole new concept of desalination is introduced which provides more efficient processes of desalination. The thermal energy required for evaporation is decreased significantly by reducing the pressure in the vessel and recycling the heat of condensation. The application of the research will lead to decrease the necessity of fossil energy and other maintenance cost required for water desalination.

A further benefit comes from making economic use of the waste brine stream, for example by co-locating with a chemical works needing a salt solution (e.g. for soaps and detergent, dyes, paper and glass production), or domestic salt production. In the case of some solar systems, there may be an opportunity for improved economics by using the shaded space below the solar collectors for horticulture. Solar greenhouses, with a focus on agricultural production in desert conditions, have been pursued with trials now underway. Alternatively, solar systems may be combined with forestry or date palms, making a convenient wind break reducing dust and sand.

Some key notes about why this research can be beneficiary to the world if the new methodology is successful are:

- Use only solar energy to desalinate seawater
- Energy conversion is minimised. Energy is used without changing its form as much as possible.
- Construction cost should be cheaper than any other conventional method
- Maintenance cost would be minimised
- Coastal installation of the plant would be easier and efficient
- No fossil fuel would be needed

- Use of underground water would be reduced
- A very simple working principle has been introduced
- Modification of plant can be achieved by controlling only a few things in diverse weather condition.

# 2 Literature Review

The literature associated with water desalination is presented here. An assessment of the global water crises was carried out base on the availability and consumption of water, water scarcity and possible solutions. Hence the review of desalination as one possible solution to the growing crises due to the scarcity of nature's most abundant resource. This includes a review of growing trend in adopting desalination for fresh water supply. Various technologies for water desalination are presented. The suitability of integrating renewable energy sources to desalination is explored. And finally, the cost of desalination and market opportunities are analysed.

## 2.1 The Global Water Resources

Water is the essence of life and a fundamental need for human existence. About 70% of the surface of the earth is covered with water. However, up to 97% of earth's water is salt water from the oceans with salinity up to 30,000 parts per million of total dissolved solids (ppm TDS). Only 3% of the earth's water is fresh water. A Freshwater body contains low concentrations of dissolved salts and other total dissolved solids.

Freshwater according to the World Health Organisation (WHO) can be defined as water with less than 500ppm TDS. Most of the fresh water comes from groundwater sources such as wells, or from surface waters such as rivers, lakes and reservoirs. The distribution of earth's water is shown in Figure 2. The ultimate source of fresh water is the precipitation of atmosphere in the form of rain and snow. This indicated as "other" in the figure below.

70% of earth covered with water

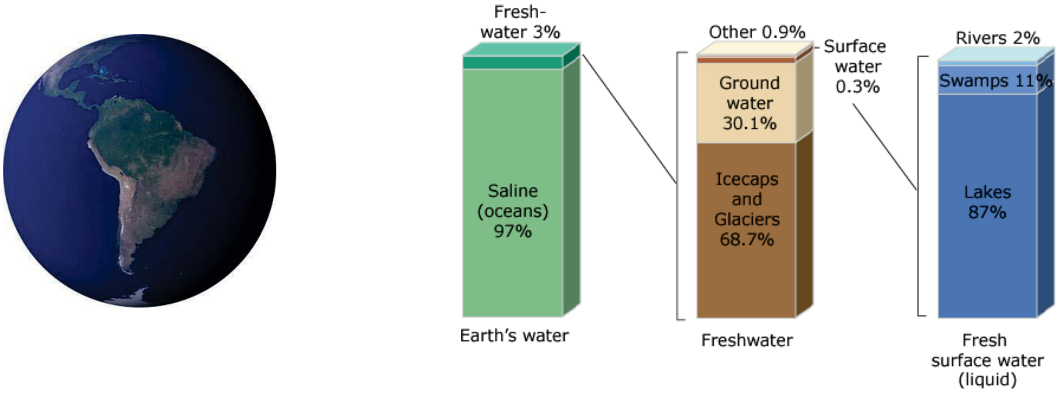


Figure 2 Distribution of earth's water (US Geological Survey) *(Watson, 2011)*

The current global water demand is above 4 x $10^{12}$ m³ per year. The annual global water withdrawal is expected to grow by about 10-12% every ten years to more than 5 x $10^{12}$m³ per year by 2050.

Figure *3* shows projected global and regional demand for fresh water.

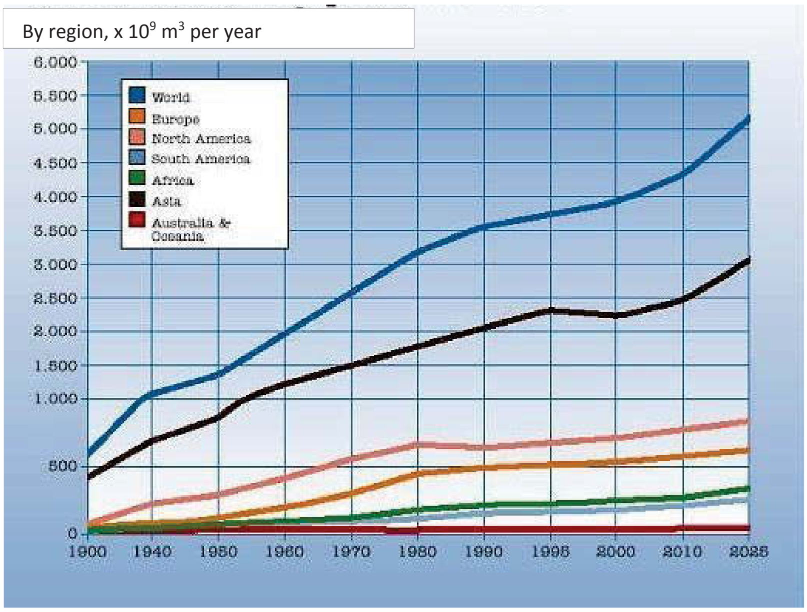


Figure 3 Projected freshwater demand by region *(Algoury, 2003)*

There have been various estimates of the global water resource base on different calculation methods. Shiklomanov in Gleick (1993) calculated the total volume of water in the world to be approximately 1.4 x $10^{18}$ $m^3$. Surface freshwater is 1.05 x$10^{14}$ $m^3$ or 0.3% of the world's freshwater (Tom, 2016). Niemczynowicz (2000) estimated more than 50% of the surface freshwater as non-renewable water. The amount of renewable water is therefore around 4.2 x $10^{13}$ $m^3$ per year which replenishes groundwater source or returns to the oceans by rivers. Most of it (around 3 x $10^{13}$ $m^3$ per year) is in flush flows that are not captured by man. It is assumed that the available renewable freshwater resource is between 9 x $10^{12}$ and 14 x $10^{12}$ $m^3$ per year. However around 70% of is required for the ecosystem and thus only 30% or 4.2 x $10^{12}$ $m^3$ per year is available for human consumption. The balance between availability of fresh water and demand has reached a critical level. If the world is to depend only on the freshwater source, soon any form of life will face extinction.

### 2.1.1 Water Scarcity

Despite huge water resources, many countries and regions do not have enough fresh water. Global water problems are attracting interesting attention. Water shortages are mainly as a result of rapid increase in world population. According to World Bank, about 80 countries now have water shortages that threaten health and economies while 40 percent of the world population mostly located in arid, remote areas and islands have no access to clean water (Krebs, 2009).

According to International Desalination Association (IDA), humans use as little as 0.02$m^3$ (20 litres) of water a day for domestic use in the developing countries to as high as 0.2$m^3$ (200 litres) in the developed countries. And although a lot of water is consumed by industry, the largest use of water is for producing the products we eat and wear. Consider these facts; it takes 0.245$m^3$ (245 litres) of water to produce 0.25kg of wheat. It takes 2.7$m^3$ (2700 litres) of water to produce an average size cotton shirt. Around 1.23$m^3$ (1230 litres) are required to produce 0.25kg of cheese. And 13$m^3$ (13000 litres) of water are needed to produce 1kg of beef. Agriculture uses up to 70 times more water to produce food than is used in drinking and other domestic purposes, including cooking, washing and bathing. Figure 4 shows the distribution of water consumption in three major sectors.

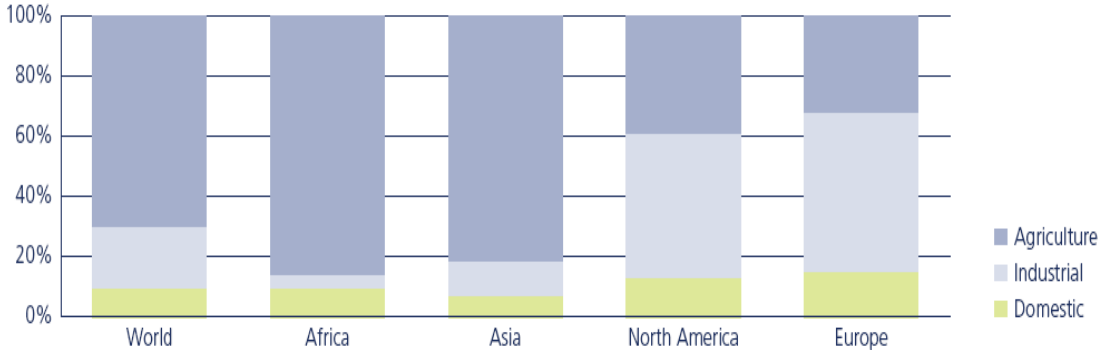


Figure 4 Distribution of water use by sector (source: fao-aquastat)

If the estimated 4 x $10^{12}$ $m^3$ per year available freshwater is divided by the current world population of 6.8 billion people, there will be only around 600 $m^3$ per person per year. Base on the world distribution in Figure 4 Distribution of water use by sector (source: fao-aquastat), there will be around 430$m^3$ (70%) per person per year for agriculture. There will be around 120$m^3$ (20%) and 60$m^3$ (10%) per person per year for industrial and domestic consumption respectively. The world population is projected to reach 9 billion by 2050 (see population projection in Appendix A). This will further reduce the available freshwater to around 450$m^3$ per person per year.

### 2.1.2 Water Resources and Availability

There are several methods of measuring water availability. The most widely used is Falkenmark's per capita index. This is the relationship between the available water resource and the population. Falkenmark projected about 0.1$m^3$ (100 litres) per person per day is the rough minimum required for domestic needs. And 5 to 20 times of the domestic need is required to meet the demands of the agricultural and industrial sectors (Gardner, 1997). Hence a benchmark which indicates water stress and water scarcity was established. A country is said to be water stressed when availability per capita is between 1000 to 1700$m^3$ per year. And anything below 1000$m^3$ per year per capita is regarded as water scarcity. The benchmark was further divided into four main categories by Schram (1999). It should be noted that the Falkenmark's concept does not account for other factors which include non-renewable water sources and virtual water. It only accounts for renewable water from rainfall or snow. Bearing in mind the world major rivers drying up, depletion of groundwater level and melting glaciers, it can be concluded that the approximation is generous. One advantage of the approximation is that data is widely available. And hence the concept is widely accepted by big organizations such as United Nations.

A detailed breakdown of annual renewable freshwater by country is attached in Appendix. Figure 5 shows the alarming extent of water scarcity across the world. The map shows the projected number of countries that will need to import 10% or more of their water by no later than 2025. It shows two key types of scarcity; water is said to be either physically scarce or economically scarce. Economic water scarcity occurs due to a lack of investment and is characterised by poor infrastructure and unequal distribution of water. Physical scarcity occurs when the water resources cannot meet the demands of the population. Arid regions are most associated with physical water scarcity.
However, there is an alarming trend in artificially created scarcity even in areas where water is apparently abundant.

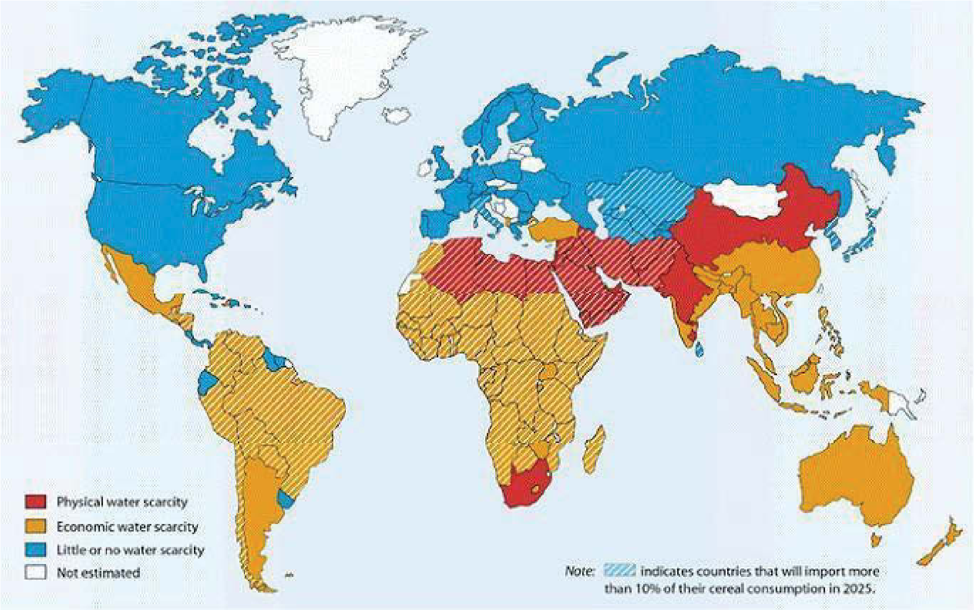


Figure 5 Distribution of water availability across the world *(Mckinsey, 2009)*

As the world's population is expected to grow every year as much as 40 to 50% over the next 50 years and with it, the demand for water will also rise. But there are other issues with our existing water sources from pollution to climate changes and water mismanagement that are literary drying out our resources.

Having seen the growing demand for water and very soon demand will be higher than supply. If the whole world were to depend on available freshwater sources only, it cannot meet the demand. Measures are taken for water recycling and proper management but are expensive. Even if it were possible to correct this problem with traditional methods such as dams, canals, reservoirs and deep wells, it would require an annual investment of approximately $180 billion on top of the $30 billion already spent each year.

And the fact that water withdrawal is higher than consumption, water management could play a vital role. However, it could be costlier than seeking out an alternative source of water. For example, in the UK alone, there is leakage of up to 3 billion litres of water per year. And to repair all the leakage will cost more than seeking the alternative source. And this is said to be the water has reached the economic leakage level. Reducing leakage level down to zero is virtually impossible and enormously expensive.

## 2.2 Desalination as a Solution to Water Scarcity

Water conservation is really a very crucial part of the overall water strategy. Every drop of water that is used is another drop in supply. It is very much encouraged to strengthen conservation efforts before turning to desalination. But in many communities, additional water supply is needed even after they have fully considered the conservation measures. There are in fact communities around the world that rely 100% on desalinated water for their supply (communities listed in Appendix). Hence desalination technique is the most promising solution to supply some remote regions with fresh water.

Desalination is the process of removing salt from water. Over the past decade, the number of desalination plants and their total capacity has almost doubled. As shown in Figure 6, the current production capacity exceeds 65 million m$^3$ per day and the number of plants has increased to more than 14,000 units (Kershner, 2008).

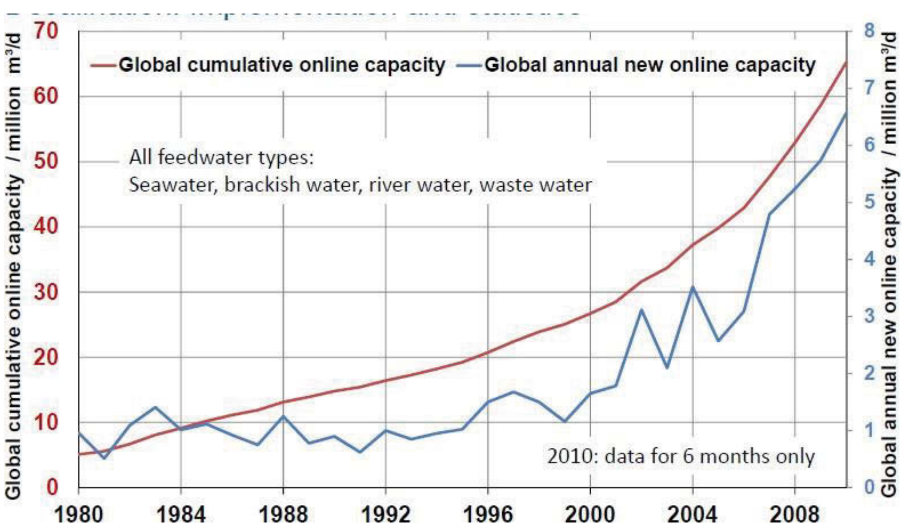


Figure 6 Global installed capacities of desalination (IDA Year Book 2010-2011)

The global installed capacity of desalination is shown in Figure 7 (see the complete list in Appendix). Saudi Arabia in the Middle East has the largest installed capacity, and then followed by Spain in Europe and then the USA in North America. All other top ten capacities are within the Middle East with Qatar and Kuwait depending 100% on desalination except Algeria and Libya in North Africa and then China in Asia (Quteishat, 2008).

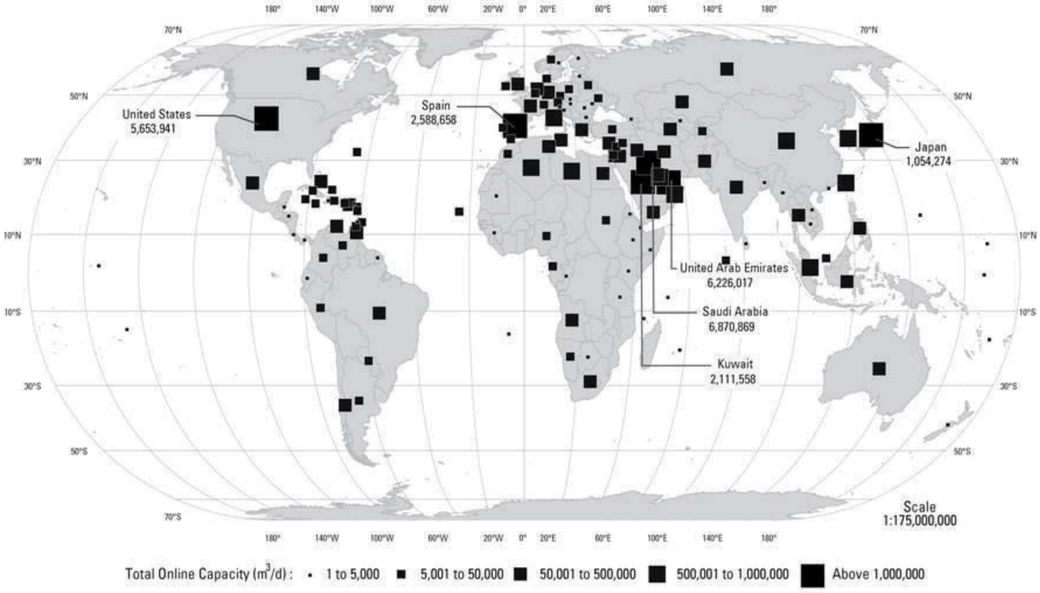


Figure 7 Total desalination capacity by country *(Zander, 2008)*

## 2.2.1 Present Desalination Technologies

There are several desalination processes and most of them are reliable and in commercial use. The most important processes are divided into two classes; the thermal and the membrane processes. The thermal process is based on natural processes of distillation and usually involves heat transfer. Main thermal technologies are the multi-effect distillation (MED) and multi-stage flash (MSF). The membrane process is based on filtration through a membrane and usually driven by electricity. Major membrane technologies are electrodialysis (ED) and reverse osmosis (RO). Thermal processes produce water around 20 ppm TDS and membrane processes are usually designed to produce water of 100-500 ppm TDS while 1000 ppm TDS is the maximum limit for drinking water. Other desalination technologies which are either not very common or are currently under research includes processes such as the membrane distillation, vapour compression and electrodeionization.

Membrane distillation (MD) (Figure 8) combines the use of both thermal distillation and membranes. The process was introduced commercially on a small scale in the 1980s. It primarily depends upon thermal evaporation and the use of membranes to pass vapour, which is then condensed to produce fresh water. In the process, saline water is warmed to enhance vapour production. This vapour is then exposed to a membrane that can pass water vapour but not liquid water. After the vapour passes through the membrane, it is condensed on a cooler surface to produce fresh water. In the liquid form, the fresh water cannot pass back through the membrane, so it is trapped and collected as the output of the plant (Papapetrou, 2010).

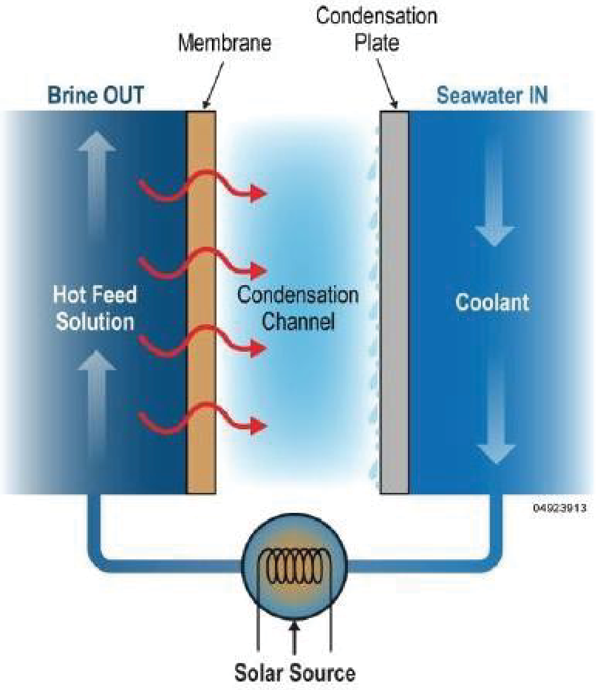


Figure 8 Principle of membrane distillation *(Schorr, 2011)*

MD has been used only in a few facilities since it requires more space, more pumping energy per unit of fresh water produced, and more money and other approaches. The main advantages of MD lie in its simplicity and the need for only small temperature differentials to operate. Commercially it is of little significance.

In Vapour Compression (VC) technique (Figure 9), the mechanism is similar to MED except that the heat for evaporating the water comes from the compression of vapour rather than the direct exchange of heat from vapour produced in a boiler. They are usually built in relatively small units ranging from a few litres up to 3000m$^3$ per day (Buros, 2000). It has high energy requirement and capital cost compared to other technologies.

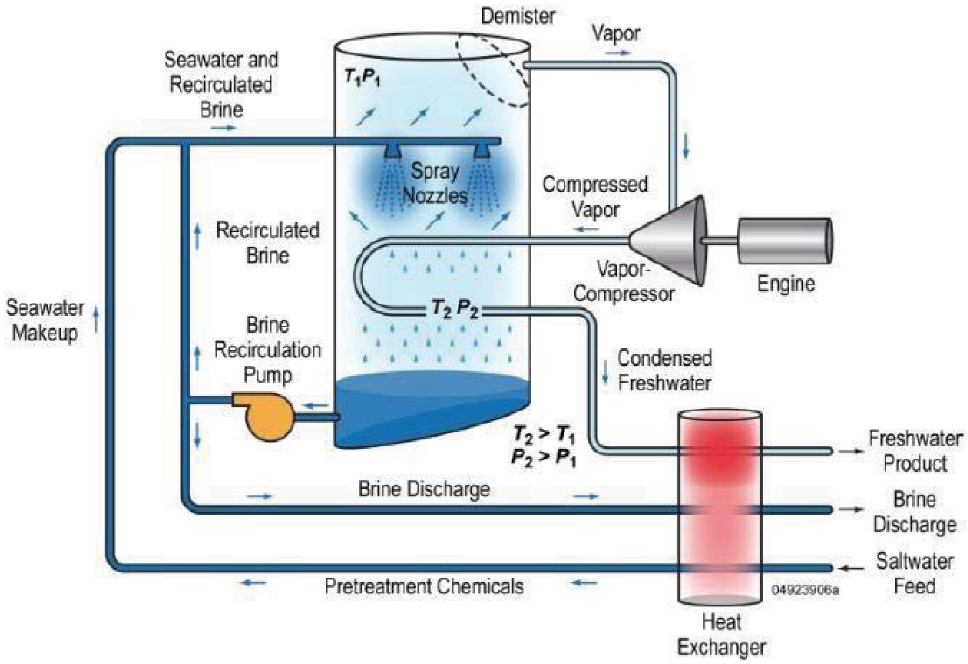


Figure 9 Vapour compression desalination system *(Schorr, 2011)*

Electrodeionisation (EDI) (Figure 10) is a modification of electrodialysis that combines ion exchange and membrane filtration. In this process, ions are removed using conventional ion exchange resin. However, an electric current allows the continuous regeneration of the resin eliminating the elution stage which induces addition of chemical reagents (Souilah, 2004). The main advantages of the EDI process include continuous operation, stable product quality, and the ability to produce high purity water without the need of chemical regeneration (Hernon, 1994). However, the principal application of EDI is limited to the further purification of water obtained from reverse osmosis.

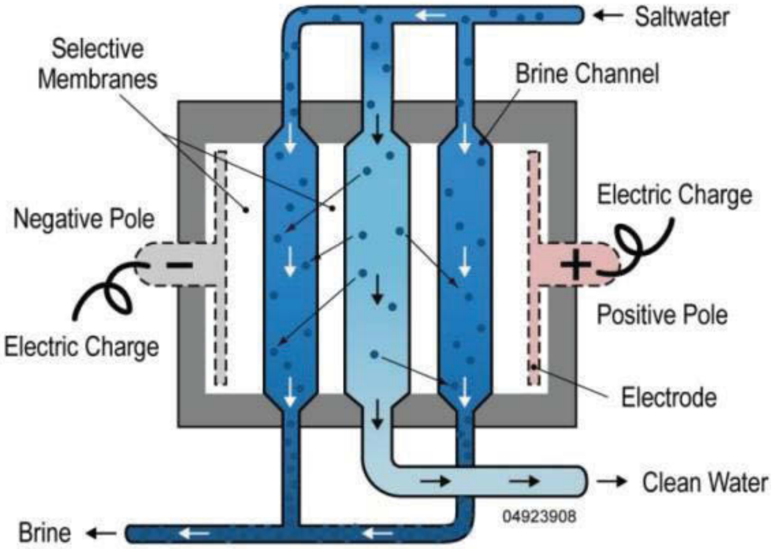


Figure 10 Principle of Electrodeionisation (Schorr, 2011)

Figure 11 shows the distribution of total worldwide installed capacity of desalination by technology. Each of the desalination technologies has its own unique advantage. However, all desalination technologies are known to be highly energy intensive. The investment and operation costs are also very high. And finally the discharge of a large amount of high concentration salt, known as brine can have effect on the environment.

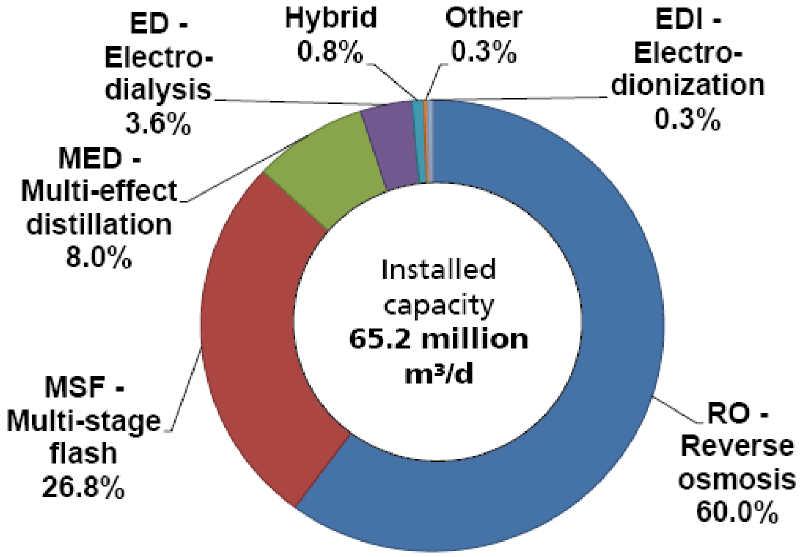


Figure 11 Total installed capacity by technology [IDA Year Book]

## 2.2.2 Reverse Osmosis (RO)

Membrane process represents the fastest growing process. In the reverse osmosis process, pressure is used for separation by forcing seawater to move through a membrane from a solution of salt water to obtain fresh water. A diagram of RO process is illustrated in Figure 12. In RO process, there is no need for heating or phase change. The major energy requirement is for pressurising the feed water. This pressure ranges from 10 to 25 bars for brackish water. Due to a higher concentration of seawater, it requires pressure from 50 to 80 bars. A turbine could be used to recover most of the energy consumed. Hence the RO process consumes 3kWh/m³ energy for brackish water and 5kWh/m³ consumption of seawater (El-Dessouky, 1998).

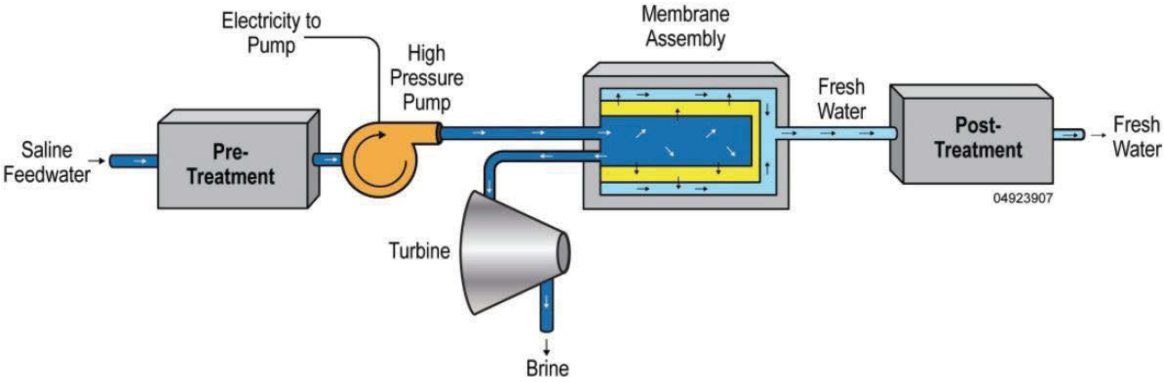


Figure 12 Principle of reverse osmosis process *(Schorr, 2011)*

RO plants have low capital cost and high maintenance and running cost due to the high cost of the membrane replacement and the cost of the energy used to drive the plant. The process also requires intensive pre/post-treatment. The RO system has a range from as little as 0.5m³ per day, the largest RO plant (Ashkelon Plant) is located in Israel with a capacity of 330,000m³ per day which contributes 5-6% water needs. The plant cost $212m with water cost $0.52/m³. It occupies 75,000m³ of land, and it consists of four 5.5MW high-pressure pump and 40,000 membrane modules.

## 2.2.3 Electrodialysis (ED)

Electrodialysis was commercially introduced in the early 1950s, about 10 years before RO. In the 1960s, Electrodialysis Reversal (EDR) was introduced, to avoid organic fouling problems. Electrodialysis uses an electrical potential to move salts selectively through a membrane and leaving the fresh water as product water. The amount of electricity required for ED and its costs increase with increasing salinity of feed water. The total energy consumption under ambient temperature conditions and assuming product water of 500 ppm TDS would be about 1.5 to 4 kWh/m³ for a feed water of 1500 to 3500 ppm TDS respectively (Loupasis, 2002). The ED process is illustrated in Figure 13. ED/EDR is not always a cost-effective option for seawater desalination and does not have a barrier effect against microbiological contamination. Hence it is more suitable for brackish water and used in conjunction with conventional water treatment plants.

Like RO, ED/EDR can have capacity from 1m³ per day. The largest EDR plant is located in Abrera with a capacity of treatment of 220.000 m³ per day (576 stacks in two stages, provided by GE Water & Process) and it is related with desalting brackish water to improve the quality of the produced drinking water. The cost of the plant is €61 million with operation and maintenance cost of $25 million over two years.

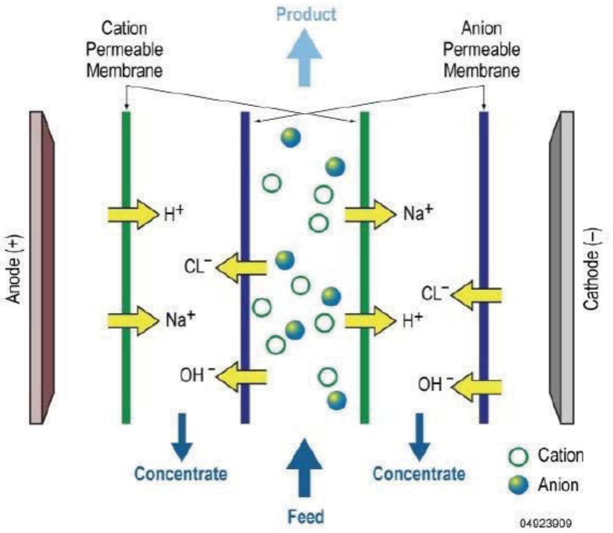


Figure 13 Ion exchange in electrodialysis process (Loupasis, 2002)

## 2.2.4 Multi-Stage Flash Distillation (MSF)

Multi-Stage flash is currently the most common technique used in thermally driven desalination. Seawater is heated and pressurised in the brine heater and then flows into chambers or stages. A fraction of it flashes into vapour due to lower pressure in the chamber and the brine passes from one stage to another and flashes repeatedly without adding more heat. The vapour produced by flashing is converted to fresh water by being condensed on tubes of heat exchangers that run through each stage. The feed water going to the heater cools the tubes and in turn, gets heated, so a reduced amount of thermal energy is required in the heater. A typical MSF unit is shown in Figure 14.

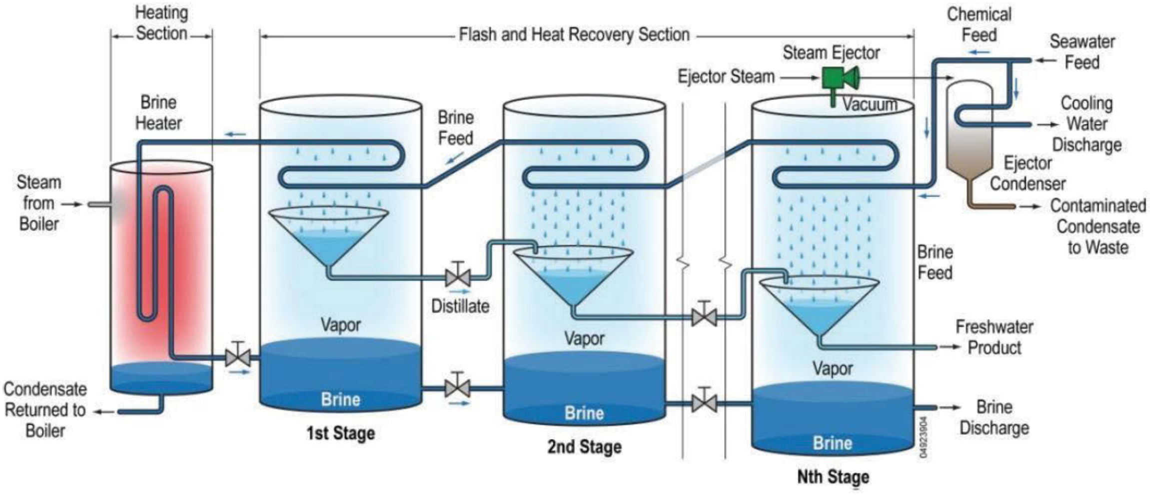


Figure 14 An illustration typical MSF plant *(Carlo D. , 2002)*

An MSF plant can contain from 4 to about 40 stages, and usually operate at temperatures of 100 - 110 °C to produce 6-11kg of distillate per kg of steam applied. Performance ratio can be as high as 12 and a 40-year lifespan. A plant with performance ration greater than 7 could consume the thermal energy of 290kJ/kg and the electricity used to drive auxiliary components is only 4 to 6 kWh/m$^3$. However, the overall capital and energy cost are very high. The largest MSF plant is Shoaiba Desalination Plant, Saudi Arabia. It was completed in 2003 with a total capacity of 450,000m$^3$ per day at an estimated total project cost of $1.06 billion.

## 2.2.5 Multiple Effect Distillation (MED)

The MED process uses the same principle of evaporation and condensation at various stages known as effects. Each effect has reduced pressure than the previous effect. Hence the seawater goes through multiple boiling without the need to supplying additional heat. Preheated steam from the boiler is fed into a series of tubes. It then heats the tube and acts as a heat exchanger to evaporate incoming seawater from another channel. The evaporated seawater becomes less salty and is fed into the next effects which are lower in pressure. The vapour condenses into fresh water. This is illustrated in

Figure 15. The MED has performance ratio up to 15 for 8 to 16 effects. It has the maximum operating temperature of 80°C and energy consumption of 290kJ/kg (thermal) and 2.5 to 3kWh/m³ (electrical). The largest MED plant is to be completed by 2012 with a capacity of 68,000m³ per day at the cost of $124 million in Yanbu Saudi Arabia.

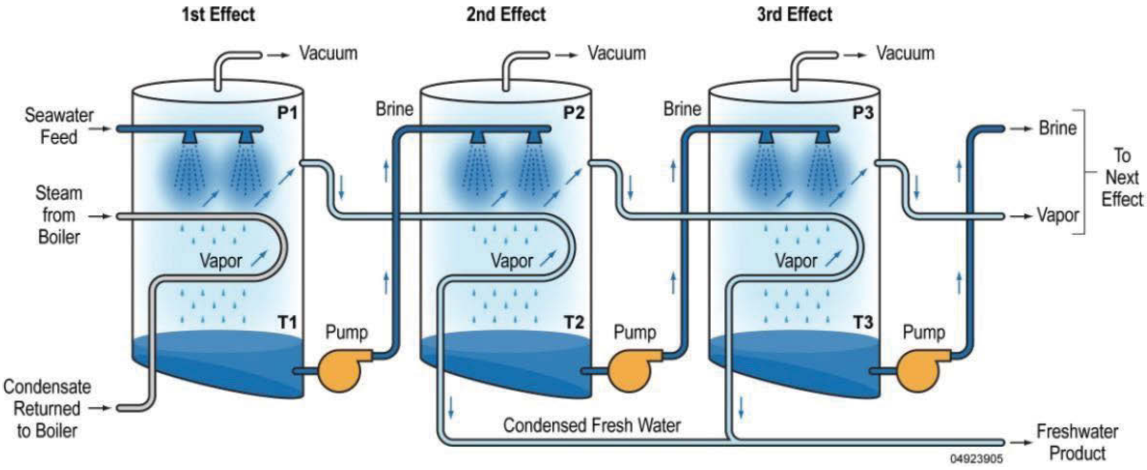


Figure 15 An illustration of MED plant *(El-Dessouky, 1998)*

## 2.3 Weather and Desalination

Climate change is caused by the emission of greenhouse gases. About 72% of the totally emitted greenhouse gases are carbon dioxide ($CO_2$), 18% Methane and 9% Nitrous oxide (NOx). Carbon dioxide emissions, therefore, are the most important cause of climate change. $CO_2$ is inevitably created by burning fuels like e.g. oil, natural gas, diesel, organic-diesel, petrol, organic-petrol, and ethanol. Energy is the major source of climate change. Over 80% of the world energy is from fossil fuel. The emissions of $CO_2$ have been dramatically increased within the last 50 years and are still increasing by almost 3% each year. The current emission is 29 billion t $CO_2$ and is projected to reach 58 billion t $CO_2$ by 2050 if action is not taken.

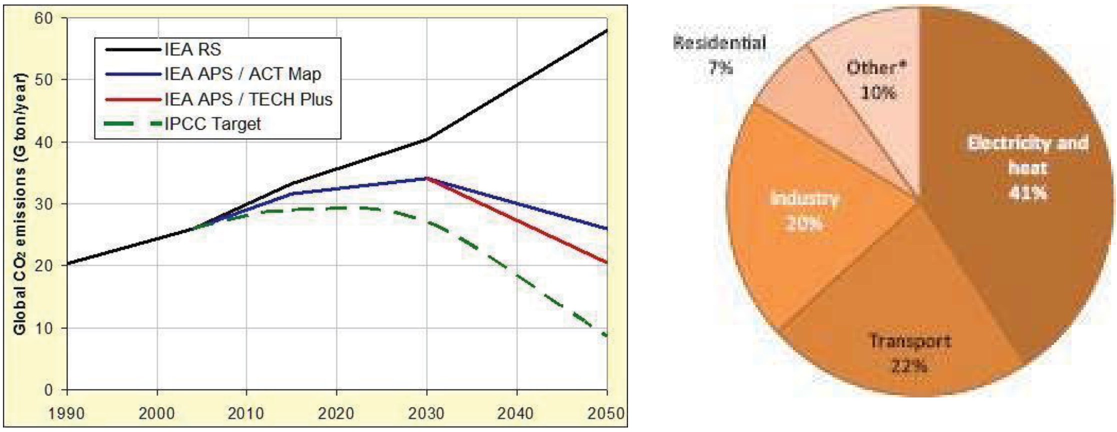


Figure 16 Projection of world $CO_2$ emissions and percentage by sector *(Pearsen, 2010)*

As shown in Figure 16, the electricity and heat generation sector account for major emission at 41%. Then followed by transport, industry and residential with 22%, 20% and 7% respectively. The other remaining 10% includes commercial/public service, agriculture/forestry, fishing, energy industries other than electricity generation, and other emissions not specified elsewhere.

The effect of climate change is posing threat to the whole world with global disasters, and most importantly drought which generally affects the availability of fresh water. Desalination which is seen as the best alternative to supply freshwater is very energy intensive. The use of desalination process will add to the already growing carbon emissions. And thus it can be seen that desalination alone without considering energy will not mitigate the growing water shortage but rather make it worse.

The global sources of freshwater are shown in Figure 17. Going by current estimate of water demand and the current installed capacity of desalination, it can be seen that desalination contributes to only 0.34% of global water supply. This contributes 0.7% of carbon emission to the electricity and heat generation sector and contributes 0.3% to the global carbon emission from all sectors. If by 2050 up 10% of global water supply is from desalination driven by fossil, water desalination will contribute 33% to emissions from electricity and heat generation, and 14% to global carbon emission. A detailed breakdown of the analysis can be found in Appendix D. Hence this makes it a paramount priority to drive water desalination using alternative renewable energy sources.

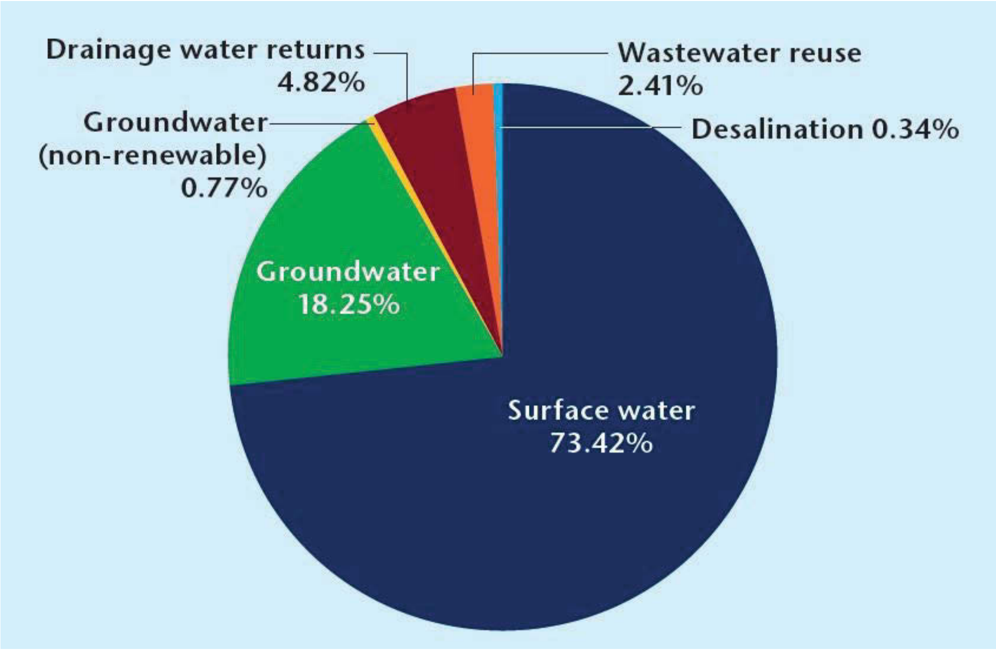


Figure 17 Global water withdrawal by source (Joachim, 2011)

## 2.4 Renewable Energy and Desalination

Due to the large energy consumption in the major commercial desalination processes, along with the growing concern about carbon emissions, there is a strong interest in desalination units driven by alternate sources of energy, and in particular, renewable energy sources (RES) such as solar, wind, geothermal and biomass energy. While the majority of desalination systems driven by RES are currently under research, the current installed capacity is more than 9,000m³ per day. The distribution of installed capacity of desalination by major RES is given in

Figure 18 World distribution of desalination capacity by major RES and the list of countries by capacity of desalination and renewable energy source is given in Appendix.

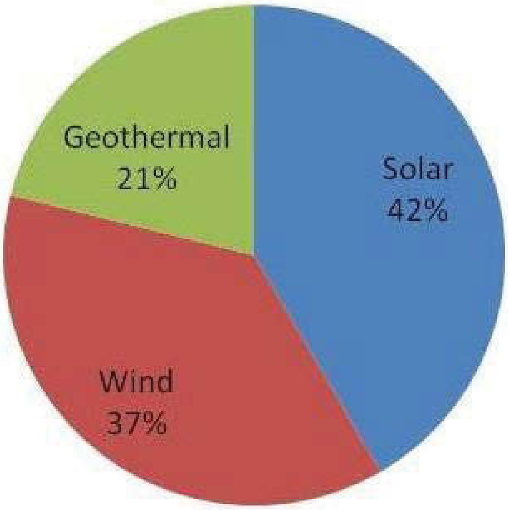
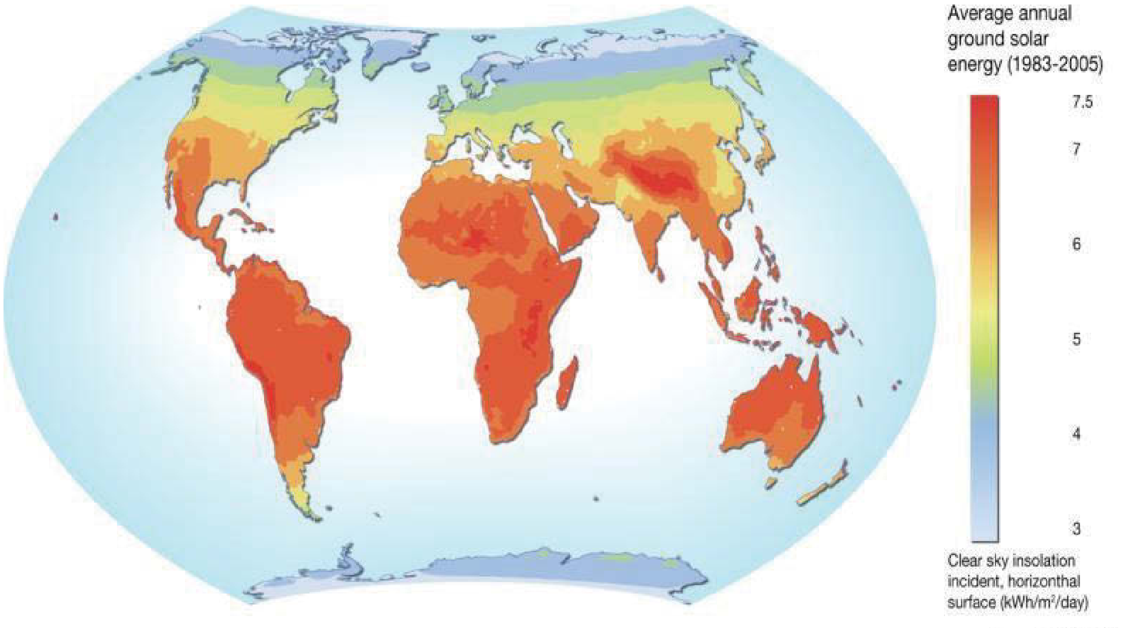


Figure 18 World distribution of desalination capacity by major RES *(Quteishat, 2008)*

It can be seen that solar energy dominates as a renewable energy source for desalination. Figure 19 shows the distribution of solar intensity around the world. It can be seen that regions with higher water scarcity have the most abundant solar energy. Hence the solar desalination process might be the answer for the optimum choice of water desalination. A 6kWh/m²/d of solar energy is equivalent to 0.6 litre/m²/d of oil.



Source: NASA 2008

Figure 19 Distribution of solar intensity around the world *(Joachim, 2011)*

Solar energy systems are now proven technologies and economically promising. There are two main types of solar energy systems. There is the photovoltaic (PV) system which converts solar radiation directly into electricity, and the solar thermal system which converts solar radiation into useful heat. The PV systems are characterised by high cost and lower efficiency when compared to the solar thermal systems. In solar thermal systems, solar collectors are used to harnessing the energy from the sun. The solar collector is a device that basically absorbs solar energy in form of heat through a heat transfer medium and converts it into useful energy. The useful heat/energy collected can then be used for various applications. It can be used for electric power generation using an expander or turbine, for hot water supply, for cooling, industrial process heat and most importantly for desalination.

Solar collectors are divided into two. They are the concentrating and non-concentrating solar collectors. The concentrating solar collector uses reflectors to focus and concentrate the solar radiation onto an absorber. While the non-concentrating solar collector does not focus the solar radiation but only uses flat surface absorbers to capture the solar energy.

The types of major concentrating solar collectors and their characteristics are given in Table 1.

Table 1 Major concentrating solar collectors *(Soteris, 2004)*

| Collector Type | Absorber Type | Concentration Ratio | Indicative Temperature Range (°C) |
|---|---|---|---|
| Linear Fresnel | Line | 10-40 | 60-250 |
| Parabolic trough | Line | 10-50 | 60-300 |
| Parabolic dish | Point | 100-1000 | 100-500 |
| Heliostat field | Point | 100-1500 | 150-2000 |

The non-concentrating collectors can provide the energy required for desalination. However, they are characterised by low efficiency. They are more suitable for domestic application as they are generally inexpensive and widely used for domestic hot water systems. A large area of non-concentrating solar collector is required for small to large scale community based desalination systems. And this generally increases cost and land footprint. Concentrating solar collectors coupled with desalination systems have more potential compared to non-concentrating solar collectors. They are more suitable for non-domestic application. The systems are complex and require large infrastructures. There are four major types of concentrating solar collectors which have been implemented with the primary aim of generating electricity. These systems can be adapted for desalination and most especially thermal desalination process. They are described as follows.

## 2.4.1 Parabolic Trough

Parabolic trough collector is a type of concentrating solar collector that uses the mirrored surface of a linear parabolic concentrator to concentrate direct solar radiation to an absorber tube running along the focal line of the parabola. The collector consists of long parallel rows of reflectors that are curved to form a parabolic trough with its receiver (absorber tube) placed at the focal point of the reflector. The receiver of a collector is linear. The absorber is often a metallic tube covered by a glass tube in order to reduce heat loss. The parabolic trough can collect up to 60% of the incident solar radiation and has achieved a peak electrical conversion efficiency of 20% (Enermodal, 1999).

The first parabolic power plant was built in Egypt by Frank Shuman (1912) with a total capacity of 55kW. The parabolic trough collector is already a rather matured technology due to many years of designing and operating experience. Parabolic trough collectors have been previously used mainly for large scale grid application. Commercial parabolic trough plants have been in operation for more than 15 years (Taillefer, 2006). Solar Energy Generating Systems (SEGS) is the largest solar energy generating facility in the world. It consists of nine plants with a total of 354 MW connected to the Californian electric grid. The plants have proven a maximum efficiency of 21 % for the conversion of direct solar radiation into grid electricity.

Another important application of this type of collector is the first commercial parabolic trough power plant in Europe known as the Andasol developed by Solar Millennium AG (Figure 20). The plant is located in Spain with a total capacity of 50 MW and operates with thermal storage. The collector has a surface area of over 510,000m2 which is equivalent to 70 soccer pitches. There are two more plants currently under construction. The Andasol 2 to be commissioned later this year and the Andasol 3 slated for 2011.

Figure 20 The Andasol Parabolic Trough Power Plant Spain (Source: Solar Millennium AG) *(Walker, 2011)*

## 2.4.2 Linear Fresnel

The linear Fresnel collector system consists of a set of parallel arrays of linear mirrors which concentrate light on to a fixed receiver mounted on a linear tower. The system operates base on principles of Fresnel. The system is similar to parabolic trough but instead, it is not parabolic in shape. It is also similar to the heliostat system, but the receiver is a linear tube mounted on a tower not very high above the collector. D. R. Mills et al (1997) recorded a maximum 38.5% thermal efficiency using compact linear Fresnel reflectors technology developed by Ausra Power. The plant is said to be operating with near perfect reflection and near zero thermal losses.

The first to apply this principle to a real system for solar collection was Francia (1968) who developed both linear and two-axis tracking Fresnel collectors systems. The system has been faced with several difficulties (Mills & Morrison, 1997). One difficulty with the linear Fresnel technology is that avoidance of shading and blocking between adjacent reflectors leads to increased spacing between reflectors. Blocking can be reduced by increasing the height of the absorber towers, but this increases cost. There is currently no commercial system of such that exist. However, Ausra Power has plans to commercialise such system after a demonstration of their 5 MW pilot plant Figure 21 located in California.

Figure 21 Linear Fresnel Collectors by Ausra Inc (Source: solarpaces.org) *(Mills & Morrison, 1997)*

### 2.4.3 Parabolic Dish

A parabolic dish collector is a point-focus collector that tracks the sun and concentrates its energy onto a receiver located at the focal point of the dish. The dish structure must track fully the sun to reflect the beam into the thermal receiver. The receiver absorbs the solar energy and converts it to thermal energy in a circulating fluid. A low molecular fluid is mostly preferred because of its good heat transfer characteristics of and low- pressure drop behaviour. Thus, hydrogen or helium is usually used as working fluids (Robert, 2008). Concentration ratios usually range from 100 to 1000, and they can achieve temperatures in excess of 500 °C. The main use of this type of concentrator is for parabolic dish- engines for electricity generation. The parabolic dish system does not have thermal storage capabilities; however, it can be hybridised to run on fossil fuel or other alternative renewable energy sources during periods without sunshine.

Several dish-engine prototypes have successfully operated over the last 10 years. The systems range from 10kW to the $400m^2$ 100kW of the Australian National University. They are particularly well suited for decentralised power supply and remote, stand-alone systems. The Stirling Energy Systems (SES) demonstrated the dish-engine system in a 150kW plant which has 6 units of the dish collectors each providing 25kW of electrical power Figure 22. A comprehensive report titled: A compendium of Solar Dish Stirling Technology, prepared by SNL gives details of different types of systems around the world.

Figure 22 The Parabolic Dish Collector *(Wissenz, 2008)*

### 2.4.4 Evacuated Tube Solar Collector

A new technology for solar collector is solar evacuated tube solar collector which includes four main components as below.

1. Evacuated Tube

Absorbs solar energy and converts it into usable heat. A vacuum between the two glass layers insulates against heat loss. The Heat Transfer Fin helps to transfer heat to the Heat Pipe. The silicon rubber caps at the end of the tube protect the tube and are UV resistant.

2. Heat Pipe

Copper vacuum pipe that transfers the heat from within the evacuated tube up to the manifold.

3. Manifold

Insulated box containing the copper header pipe. The header is a pair of contoured copper pipes with dry connects sockets that the heat pipes plug into. The manifold casing is made of a strong but lightweight aluminium alloy that is folded to form a strong protective enclosure. The casing is finished with matte black PVDF coating that is UV stabilised for long-term colour fastness. Glass wool insulation is "baked like a cake" to form a complete structural shell around the header pipe. This design minimises the amount of metal used in the casing, reducing embodied CO2, and making it very lightweight. The lightness of the manifold box is a feature that installers value when carrying onto the roof.

4. Mounting Frame

This part holds all other components and is used to mount it on the roof

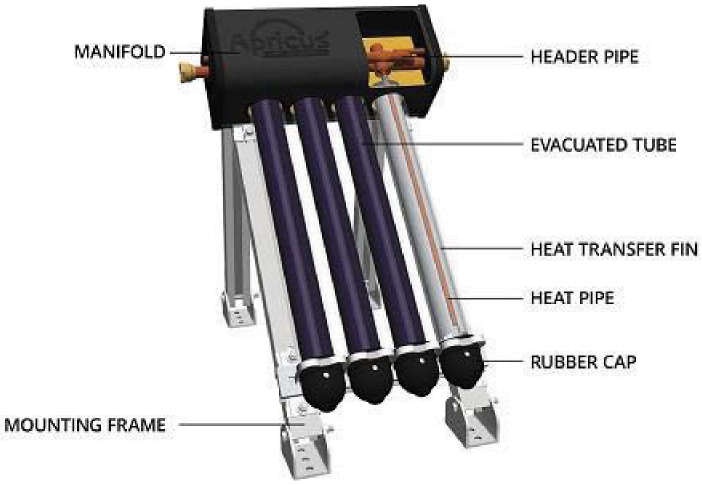


Figure 23 Evacuated tube solar collector *(Apricus, 2016)*

## 2.4.4 Industry Analysis with Respect to Desalination

The relatively high financial costs of desalination prevented the application and commercialisation of desalination technologies in most areas. However, desalination cost is changing with improved and less expensive technologies. Cost of desalination is already low enough to make desalination an attractive option for some communities when the benefits of desalination are considered, such as providing a drought-resistant supply and providing a means to diversify a large community's water supply portfolio. The cost of water desalination varies with the technology used. It depends mainly on size, location and environment conditions, quality of feed water, labour, operation and maintenance, and lifespan of the system. Although desalination plants have a longer life, it is recommended for a plant to have 20 years' lifespan. A breakdown cost of desalination system is adapted from Delyannis (1985) and given below.

COST OF CONSTRUCTION

- Construction of desalination unit
- Land and site preparation
- Auxiliaries include: Pipe and pumps of salt water and distillate Storage for saltwater and distillate
- Any other items of investment costs

COST OF PRODUCT WATER

- Energy and power for pumping, kg fuel or kWh
- Cost of raw water, if purchased or transported
- Cost of water treatment, if necessary
- Cost of maintenance and material replacement
- Labour for operation and maintenance
- Amortization of capital cost
- Taxes, insurance and subsidies, where applicable
- Annual operating charges should be computed per $m^3$ of product water.

# 2.5 Cost Comparison of Major Desalination Technologies

The cost of building a desalination unit and cost of fresh water produced is very crucial to designing a desalination system. The costs of energy and carbon emissions from a desalination plant are generally very high regardless of the type of technology used. Figure 24 shows percentage cost of major desalination systems and that driven by RES.

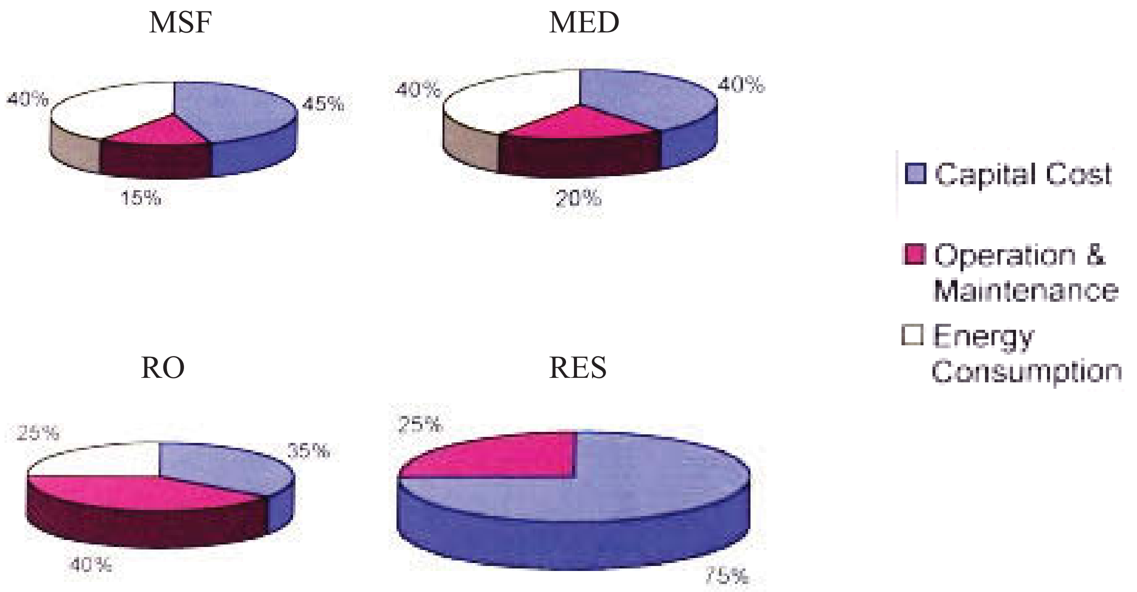


Figure 24 Major cost of desalination plants *(Bednarski & Morin, 2011)*

Not-with-standing the anticipated cost reduction offered by new emerging desalination technologies, the conventional desalination process remains expensive and unfeasible in many countries around the world. The limited means of financial resources of many countries are insufficient to meet the required process capital and operation expenses. Bednarski et al. (1997) compared the current water production cost of the MSF, RO, MED processes. Figure 25 shows a comparison of the major desalination technologies. For the MSF process, with a 27,000m$^3$ per day plant, the unit cost \$0.8/m$^3$.

This is almost equivalent to that of the RO process at an average of 0.93 per m$^3$. However, the value presented is not the real final value and mostly scientific and not based on a commercial plant. The actual value is highly dependent on the feed water source and the treatment cost of the feed water. So also with the MED, despite the fact that a lower unit cost is documented at \$0.45 per m³, this method has only been utilised commercially by the desalination industry on a very limited scale. Both the values from MSF and MED do not include the thermal energy cost of the systems. Assuming utilising solar energy to provide the thermal which can be considered free of charge, the cost of solar desalination SD will be \$1.03 per $m^3$. This indicates solar energy as very competitive when compared to fossil fuel driven desalination system.

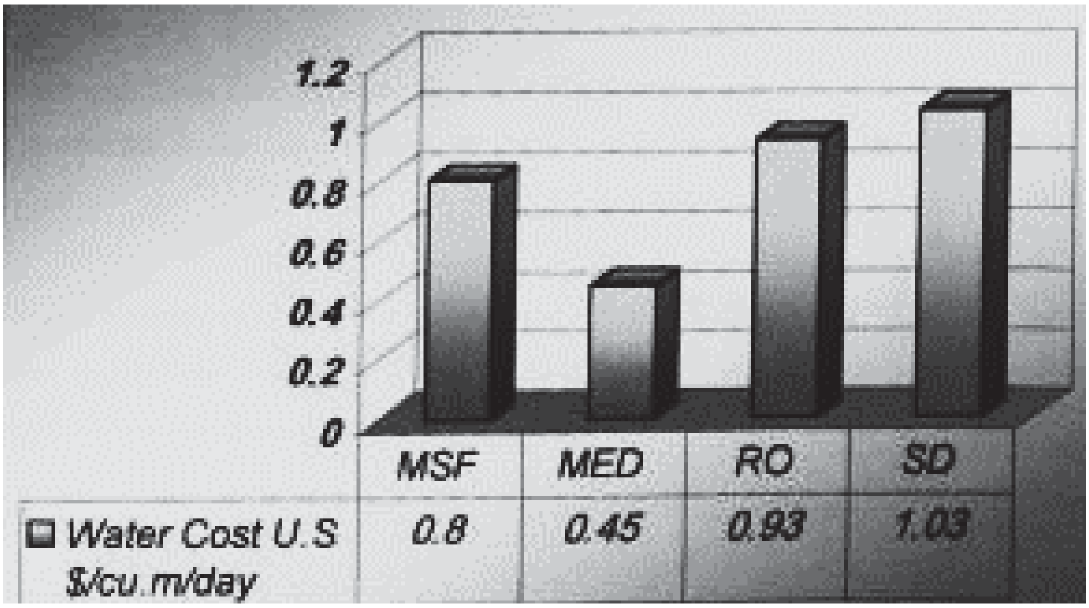


Figure 25 Unit water cost comparison of major desalination technologies *(Bednarski & Morin, 2011)*

## 2.5.1 Market Opportunities

Worldwide, less than 1% of drinking water is produced by desalination which is supplied by more than 14000 plants in more than 120 countries. Considering that almost one-quarter of the world's population lives less than 25 km from the coast, seawater could become one of the main sources of freshwater in the near future. The market volume has soared from \$2.5 billion in 2002 to \$3.8 billion in 2005 with a growth rate of over 15% per annum (estimated value is only for plant and equipment, and not considering the whole value chain). The market worldwide was estimated to reach nearly $30 billion with an installed capacity of more than 4.38 x $10^{10}$ per year (1.2 x $10^{8}$ $m^3$ per day) by 2015. A dramatic increase is expected in new technologies and small systems applications in Asia and in particular in India and China.

Current desalination plants are large installations. Their size and capital cost mean that only very large companies can engineer and install them. Their complexity means that local municipalities are often unable or unwilling to operate them. Modular size solar-driven systems can be the ultimate solution for these local municipalities. This also creates a huge new opportunity for those firms able to integrate the design, building and operation of these plants

In terms of the geographical breakdown of the market, the regions of the Middle East and North Africa (MENA) clearly dominate the demand (over 50% of the market share), followed by America, Europe, Asia Africa and Australia that share about 50% of the market respectively Figure 26. Although desalination is currently not a commonly used technology in Africa and the Caribbean where water supply is not only scarce and unreliable but often not potable even when accessible, governments and private organisations are strongly considering desalination as a way to meet the growing demand for potable and industry-quality water in these regions. In fact, in many of these countries, water distribution infrastructure is poorly developed and the few pipes that are laid often have leakages. This creates a whole new opportunity for decentralised non-large scale distributed water supply.

Urban end users that have the financial resources and require good quality water are turning to reverse osmosis RO desalination rather than rely on local water services. Industrial end users are also using RO to pre-treat municipal water before it is used as process water. Rural and remotely located end users such as tourist lodges and commercial farmers are also using desalination. The tourism industry in Southern and East Africa is booming and with island-based tourist lodges often having limited or no sources of fresh water, they, therefore, have to desalinate seawater. Desalinated brackish groundwater can be a good source of water for commercial farmers. Another key sector is the oil/gas sector and general energy sector which require a large amount of process water.

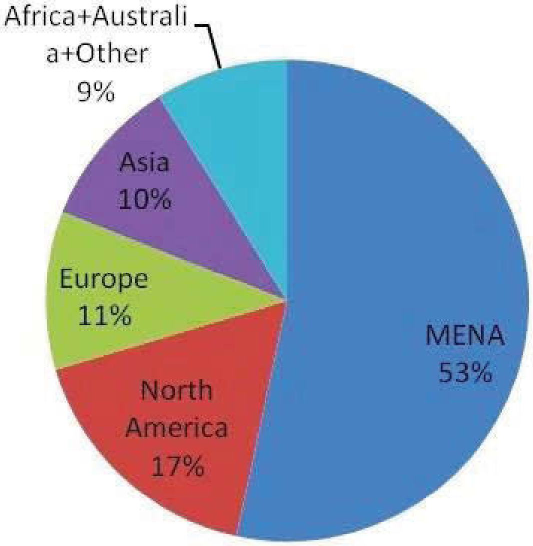


Figure 26 Desalination market share *(Quteishat, 2008)*

The most attractive markets for desalinated water are within the MENA region which constitutes over 50% market share. However, there are other potential regions where the price of public water is already comparatively high, and also a region where the climate is arid and regions where the population is rapidly growing. The future water demand in the MENA region was assessed by an analysis of Future Water, which included effects of climate change on the future availability of natural surface and groundwater resources. The analysis suggests that there will be a significant reduction of available surface and groundwater in the medium and long-term future, from 2.25 x $10^{11}$ $m^3$ per year (6.16 x $10^8$ $m^3$ per day) in the year 2000 to less than 1.9 x $10^{11}$ $m^3$ per year (5.2 x $10^8$ $m^3$ per day) in 2050. At the same time, water demand will grow from 2.55 x $10^{11}$ $m^3$ per year (7 x $10^8$ $m^3$ per day) in the year 2000 to 4.5 x $10^{11}$ $m^3$ per year (1.2 x $10^{10}$ $m^3$ per day) in 2050, opening a very dangerous gap of supply that will affect the whole region from now on (Verdier, Desalination Using Renewable Energy, 2011).

Taking into consideration the severity of the water gap projected in the MENA region the need for sustainable energy alternatives other than fossil fuel has never been more urgent. For being sun-rich and water-scarce region, the MENA region is one of the most suitable regions in the world to start implementing desalination plants sourced by solar thermal energy. According to scenarios generated within a study carried out by Fichtner (2011) for The World Bank, solar desalination is likely to become predominant starting from 2020 to 2030 when oil and gas sources are expected to be decreasing. The study identified huge solar desalination potential corresponding to 5.5 $10^{10}$ $m^3$ per year in 2030 and 9.8 x $10^{10}$ $m^3$ per year by 2050. Until then the key challenge is to take measures through research to bring solar desalination to its desired well-engineered level, achieving highest efficiency gains most especially using technologies such as membrane distillation and humidification dehumidification which are currently the most promising for solar thermal desalination. This potential transition from conventional desalination to solar desalination would further contribute to the climate protection. In the MENA region alone, there is potential to reduce the emissions of carbon dioxide from fossil fuel from 570 million t $CO_2$ in 2010 to 270 million t $CO_2$ in 2050. This can be achieved in spite of a significant growth of population and economy expected in the region that would lead to emissions of over 1.5 billion t $CO_2$ following a business as the usual strategy if no action is taken.

## 2.6 Thermo-physical Properties of Seawater

The density of surface seawater ranges from about 1020 to 1029 kg/$m^3$, depending on the temperature and salinity. At a temperature of 25 °C, the salinity of 35 g/kg and 1 atm pressure, the density of seawater is 1023.6 kg/$m^3$. Deep in the ocean, under high pressure, seawater can reach a density of 1050 kg/$m^3$ or higher (Yaniv, 2016). The density of seawater also changes with salinity. Brines generated by seawater desalination plants can have salinities up to 120 g/kg. The density of typical seawater brine of 120 g/kg salinity at 25 °C and atmospheric pressure is 1088 kg/$m^3$. Seawater pH is limited to the range 7.5 to 8.4. The speed of sound in seawater is about 1,500 m/s (whereas the speed of sound is usually around 330 m/s in the air at roughly 1000hPa pressure, 1 atmosphere), and varies with water temperature, salinity, and pressure. The thermal conductivity of seawater is 0.6 W/m-K at 25 °C and a salinity of 35 g/kg. The thermal conductivity decreases with increasing salinity and increases with increasing temperature.

## 2.6.1 Vapour Pressure of Water

Generally, water starts evaporating when it reaches its vapour pressure of that temperature (Bruce, 2013). The vapour pressure of water is the pressure at which water vapour is in thermodynamic equilibrium with its condensed state. At higher pressures, water would condense. The water vapour pressure is the partial pressure of water vapour in any gas mixture in equilibrium with solid or liquid water.

Table 2 Vapour pressure of water (0–100 °C) *(Bruce, 2013)*

| T, °C | T, °F | P, kPa | P, bar | P, Psia |
|---:|---:|---:|---:|---:|
| 0 | 32 | 0.611 | 0.006 | 0.089 |
| 5 | 41 | 0.873 | 0.009 | 0.127 |
| 10 | 50 | 1.228 | 0.012 | 0.178 |
| 15 | 59 | 1.706 | 0.017 | 0.247 |
| 20 | 68 | 2.339 | 0.023 | 0.339 |
| 25 | 77 | 3.169 | 0.032 | 0.46 |
| 30 | 86 | 4.246 | 0.042 | 0.616 |
| 35 | 95 | 5.627 | 0.056 | 0.816 |
| 40 | 104 | 7.381 | 0.074 | 1.07 |
| 45 | 113 | 9.59 | 0.096 | 1.391 |
| 50 | 122 | 12.344 | 0.123 | 1.79 |
| 55 | 131 | 15.752 | 0.158 | 2.284 |
| 60 | 140 | 19.932 | 0.199 | 2.89 |
| 65 | 149 | 25.022 | 0.25 | 3.628 |
| 70 | 158 | 31.176 | 0.312 | 4.521 |
| 75 | 167 | 38.563 | 0.386 | 5.592 |
| 80 | 176 | 47.373 | 0.474 | 6.869 |
| 85 | 185 | 57.815 | 0.578 | 8.383 |
| 90 | 194 | 70.117 | 0.701 | 10.167 |
| 95 | 203 | 84.529 | 0.845 | 12.257 |
| 100 | 212 | 101.32 | 1.013 | 14.691 |

## 2.6.2 Salt in Seawater

There are several salts in seawater, but the most abundant is ordinary table salt or sodium chloride (NaCl). Sodium chloride, like other salts, dissolves in water into its ions, so this is really a question about which ions are present in the greatest concentration. Sodium chloride dissociates into $Na^+$ and $Cl^-$ ions. The total amount of all types of salt in the sea averages about 35 parts per thousand (each litre of seawater contains about 35 grams of salt).

Sodium and chloride ions are present at much higher levels than components of any other salt. Sodium chloride is a white crystalline solid with a density of 2.16 g/mL, and a melting point of 801 °C which is way higher than the boiling point of water. It is also available as aqueous solutions of different concentrations, called saline solutions. The boiling point of Sodium chloride is 1,413 °C (Chambers, 2015).

## 2.7 Research Methodology

The boiling point is the temperature at which the vapour pressure of the liquid equals the pressure at the environment of liquid and the liquid changes to vapour. A liquid in a vacuum has a lower boiling point than when that liquid is at atmospheric pressure. In other words, the boiling point of a liquid varies depending upon the surrounding environmental pressure (Bruce, 2013). For a given pressure, different liquids boil at a different temperature. The heat of vaporization is the energy required to transform a given quantity of a substance from a liquid into a gas at a given pressure. Liquids may change to vapour at temperatures below their usual boiling point when surrounding pressure is changed. Evaporation is a surface phenomenon in which molecules of liquid escape into the surroundings as vapour. Even water will start boiling below 100°C when we reduce the pressure. And by a further decrease in pressure, it will start boiling at room temperature. The liquid uses its internal energy to change its phase.

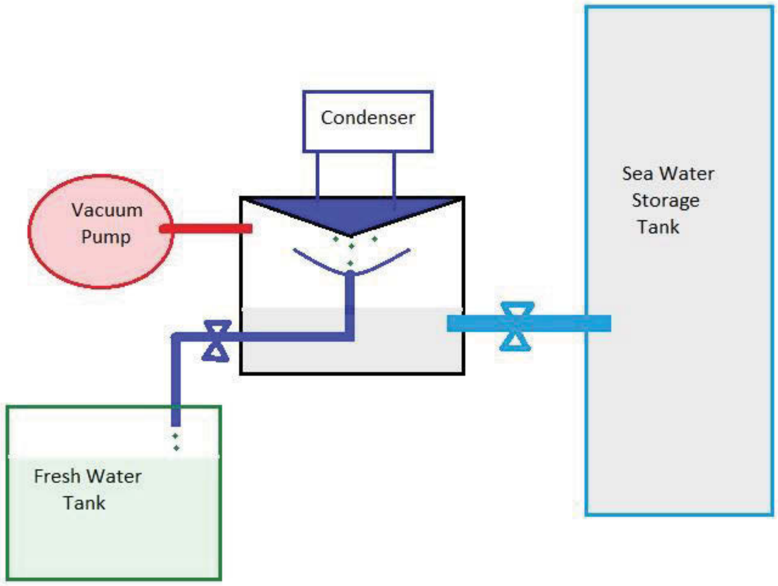


Figure 27 Schematic diagram of initially proposed Vacuum Desalination Plant

We can use solar evacuated tubes to raise the sea-water temperature 30°C above the room temperature. Then this heated water can be pushed into a sealed chamber and if we can create a pressure of around 12 kPa (abs) water will start to evaporate at 50°C. When this vapour gets in touch with chilled condenser it will turn into fresh water. This research can be done by proper planning and experiment. For desalination evaporation and condensation are the main parts. Solar energy can be used for evaporation and seawater from the deep sea can be used for condensation. Solar power plants are readily available in the market. These solar power plants can be used for the electricity requirement of the vacuum pump. Thus, the total system will be solar dependant and there will be no need for any other energy.

For our experiment, a 200 watt solar plant is enough to run the process for 24 hours. Generally, a 1580 x 808 x 35mm solar panel is enough to produce this amount of energy. As the vacuum pump will not be running continuously, constant electricity supply is not required. The vacuum pump will only be turned on when system pressure rises.

Figure 28 A typical 1580 x 808 x 35mm solar panel.

## 2.8 Former Research and Project Review

Many studies have been conducted using the vacuum technology for desalination previously. In this research former findings have been investigated and previous drawbacks have been taken into consideration.

### 2.8.1 Vacuum Desalination by Tower Method

The process of Vacuum Desalination takes advantage of the fact that water, when pulled upward by a vacuum, cannot rise more than 33 feet above the level of a surrounding body of water. So when a tube 50 feet tall (closed at the upper end) is inverted in a body of seawater, and a vacuum is applied, the seawater can only rise to 33 feet. The space above that water is at a very low pressure and can be almost fully evacuated. When the pressure above the water level reaches 0.5 psi, the seawater will vaporize (boil) at only about 29.4 degrees C, which is the ambient temperature in the tropics. Once vaporization has occurred, the water vapour in the evacuated space can condense on a cold surface within that space, and liquid fresh water is produced on that cold surface. From there, gravity can be employed to collect the fresh water, and pump it to its destination (Tomahawk, 2015)

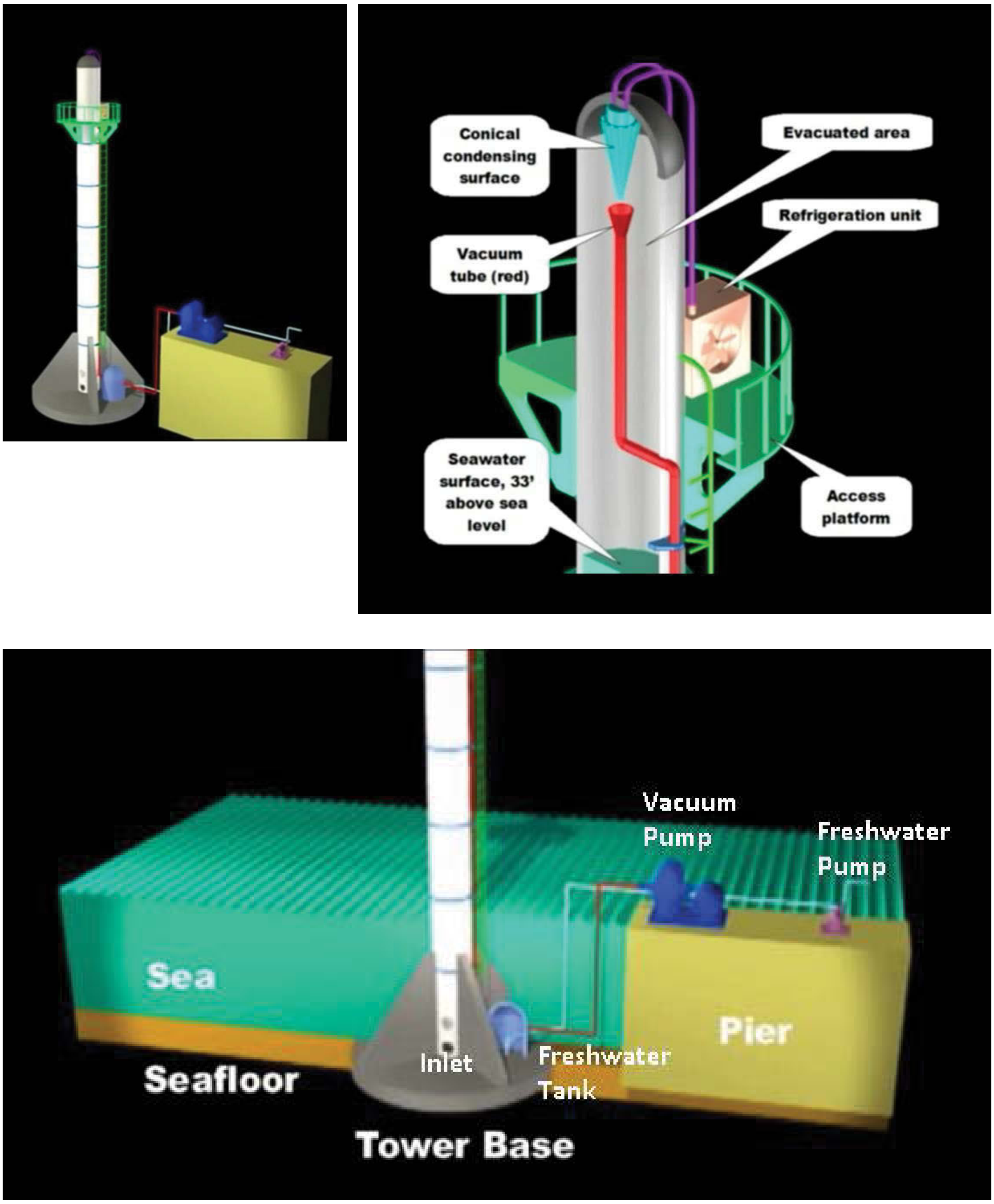


Figure 29 Vacuum Desalination by Tower Method *(Tomahawk, 2015)*

Though the basic idea is similar to our study, we will work on eliminating the following drawbacks of this process.

- This process requires near shore installation where the sea depth is 15-20 feet which is sometimes not feasible for diverse weather condition.
- The base of the tower needs to be buried in the sea. This might be disturbed by the sea creature and corrosion
- A minimum construction of 50 feet tall tower is required. Which is also not feasible sometimes near shore for high velocity of wind and diverse weather condition.
- A platformer is required on the top edge of the tower for maintenance. This could require skilled professional and risk is high.
- The process requires external refrigeration source for condensation. By using the solar collector, if we can raise the temperature of feed water, seawater of ambient temperature can also be used for condensation.
- The pumps used here require electric energy. We can replace it with solar energy.

## 2.8.2 Deep Seawater as Refrigerant

We can use deep seawater as the refrigerant for our condenser as its temperature is very low. The top part of the ocean is called the surface layer. Then there is a boundary layer called the thermocline. The thermocline separates the surface layers and the deep water of the ocean. The deep ocean is the third part of the ocean. The Sun hits the surface layer of the ocean, heating the water up. Wind and waves mix this layer up from top to bottom, so the heat gets mixed downward too. The temperature of the surface waters varies mainly with latitude. The polar seas (high latitude) can be as cold as -2 degrees Celsius (28.4 degrees Fahrenheit) while the Persian Gulf (low latitude) can be as warm as 36 degrees Celsius (96.8 degrees Fahrenheit). Ocean water, with an average salinity, freezes at -1.94 degrees Celsius (28.5 degrees Fahrenheit). That means at high latitudes sea ice can form. The average temperature of the ocean surface waters is about 17 degrees Celsius (62.6 degrees Fahrenheit). 90 % of the total volume of ocean is found below the thermocline in the deep ocean. The deep ocean is not well mixed. The deep ocean is made up of horizontal layers of equal density. Much of this deep ocean water is between 0-3 degrees Celsius (32-37.5 degrees Fahrenheit) which is almost the freezing point of water (Gary, 2016).

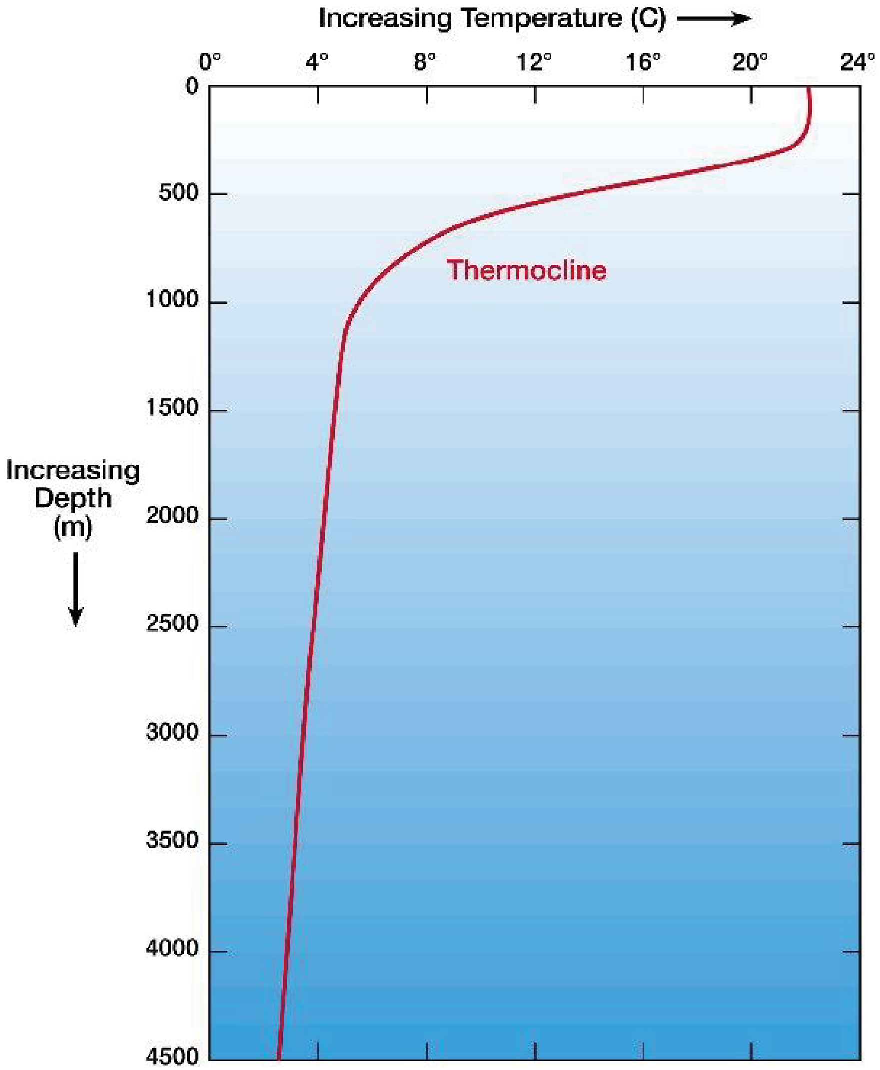


Figure 30 A simple temperature-depth ocean water profile (Gary, 2016)

## 2.8.3 Solar-Assisted Reverse Osmosis Desalination

In past decades, Reverse Osmosis (RO) has become the most used method for seawater desalination. Almost two third of desalination plants around the world are using reverse osmosis as the main method. Although reverse osmosis requires a relatively low amount of energy, it is still not feasible in some places with serious shortage of energy. Reverse osmosis and its related issues are not only limited to production of big scales of fresh water. Small RO devices are playing an important role as well. In past few years, small RO water desalination devices were of the most used devices all around the world, for providing households with fresh water wherever needed. They can desalinate saline water of different salt concentrations and produce enough drinkable water for small applications. The quality of produced water –which is the most and somehow the only important parameter- is always kept in an acceptable range. While the desalination device is designed to deliver high-quality water, the energy consumption and other environmental aspects of the device are usually neglected. Today, a small commercial RO device for seawater desalination, which is available in the market, consumes up to 10 kWh of electrical energy to produce.

During past decades, many attempts have been made in order to reduce the energy consumption of reverse osmosis desalination process. These attempts include modifying the characteristics of the process, developing membrane materials with higher efficiencies or introducing chemical reactions to ease the passage of water through the membrane or the separation of salt from it. Renewable energy also has a trending role in making reverse osmosis more feasible. Most of the methods which are based on renewable energy are aiming to provide green electricity in order to provide the RO plant with its whole or partial electricity needs. Solar photovoltaic (PV) panels and wind turbines are of those to achieve this goal. However, renewable energy can be used in other forms as well, to solve the cost related and energy-related issues of reverse osmosis process. The aim of this chapter is to investigate the feasibility of using solar energy, in the form of thermal energy, to reduce the energy consumption of RO desalination process. Solar energy has been used to increase the saline feed water's temperature before the desalination process. This is believed to have a considerable effect on the required energy to produce fresh water and also the recovery ratio and freshwater flow rate. This chapter shows the proposed method and discussed the results and other aspects of its application.

Solar PV Panels can be used to run the RO device off the grid and totally independent. PV panels, as shown in Figure 31 charge a battery and then the battery directly runs the RO device. Using a battery between the PV Panels and the RO device provides the opportunity to have a regulated and constant power source, even when the sun radiation is fluctuating, or during night time. However, this was not the major concern of this research. Proposed method aims to conduct a process of RO desalination with less electricity. For this purpose, solar energy has been used to heat up the saline feed water.

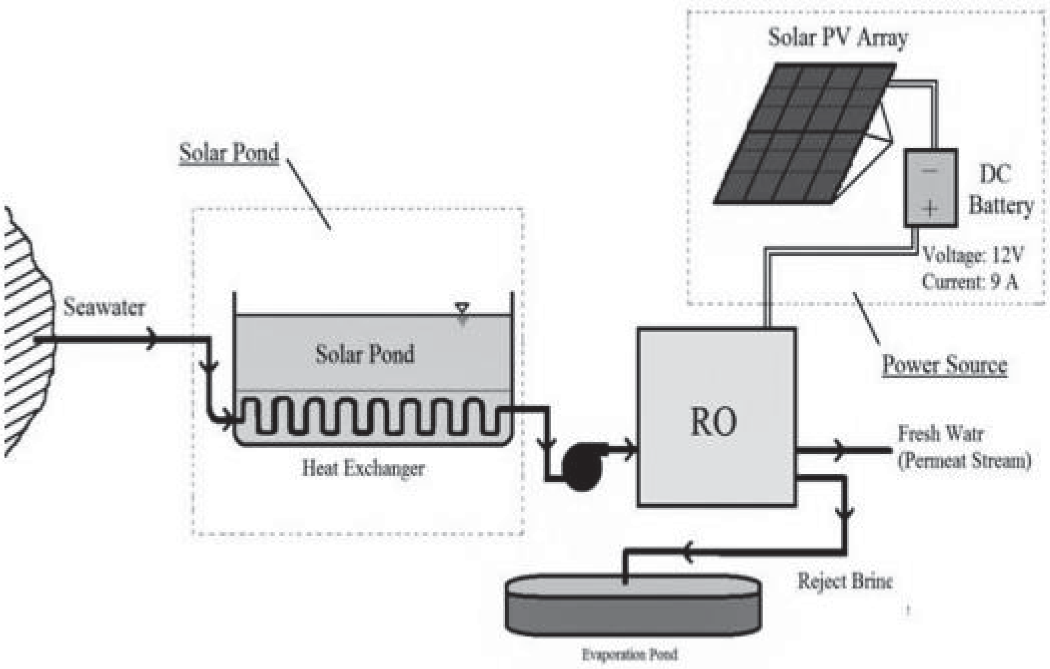


Figure 31 Solar-Assisted Reverse Osmosis Desalination (Moridpour, 2014)

The temperature of the feed stream has a considerable effect on the performance of a cross-membrane process. The effect of feed water temperature on the RO process has previously been studied and is well known. This research's main goal is to use a renewable source of energy to preheat the feed water and investigate its results and feasibilities. For this purpose, the solar pond was chosen as the renewable source of energy. Solar pond is able to harvest the solar energy in the form of thermal energy which is of great interest to achieve the aims of this research. It is simultaneously a solar collector and a heat storage mechanism with a relatively high thermal capacity. High thermal capacity allows the pre-heating to continue over longer periods of times with a continuous performance. Another important feature of solar pond is its compatibility with a desalination process. Solar pond, by its nature, needs salt for storing the solar heat. The required salt for the solar pond can be provided by the desalination plant. Some desalination plants and salt production plants have successfully been coupled with solar pond. As shown in Figure 31, the saline water is pumped through the internal heat exchanger in the solar pond and is heated up. By controlling the characteristics of the solar pond, the final temperature of the feed stream can be determined. The warm water then goes to the conventional process of reverse osmosis. This preheating improves the efficiency of the reverse osmosis desalination process and reduces its energy consumption.

### 2.8.4 Solar thermal desalination systems

Solar energy can be used in two forms. Either as thermal energy by heating a fluid or by converting it into electricity using photovoltaic arrays (PV). Solar energy is a relatively diffuse source of energy. It is also available almost everywhere, unlike wind, geothermal or even conventional fuels. Depending on the energy demand of the application, it may require large areas. Yet, most solar energy conversion systems are modular and can be installed almost everywhere (e.g. house roofs) which relieves the space availability problem. Cost-effectiveness is strongly influenced by the amount of solar radiation available at the site (Mohamed, 2010).

The basic principles of solar water distillation are so simple, as distillation replicates the way nature makes rain. The sun's energy heats water to the point of evaporation. As the water evaporates, water vapour rises, condensing on the glass surface for collection. This process removes impurities such as salts and heavy metals as well as eliminates microbiological organisms. The end result is water cleaner than the purest rainwater. Two types of systems could be included in this category: (1) Simple solar operated devices such as solar stills; (2) solar assisted distillation systems such as multi-effect humidification systems. These devices have low efficiency and low water productivity due to the ineffectiveness of solar collectors to convert most of the energy they capture, and to the intermittent availability of solar radiation. For this reason, solar thermal desalination has so far been limited to small-capacity units, which are appropriate in serving small communities in remote areas, exposed to water scarcity and at the same time, are characterized by high levels of solar radiation.

Solar-still designs can generally be grouped into four categories: (1) basin still, (2) tilted wick solar still, (3) multiple-tray tilted still, and (4) concentrating mirror still. The basin still consists of a basin, support structure, transparent glazing, and distillate trough. Thermal insulation is usually provided underneath the basin to minimize heat loss. Other ancillary components include sealants, piping and valves, storage, external cover, and a reflector (mirror) to concentrate light. Single basin stills have low efficiency, generally below 45%, due to high top losses. Double glazing can potentially reduce heat losses, but it also reduces the transmitted portion of the solar radiation. A tilted-wick solar still uses the capillary action of fibres to distribute feed water over the entire surface of the wick in a thin layer. This allows a higher temperature to form on this thin layer. Insulation in the back of wick is essential. A cloth wick needs frequent cleaning to remove sediment built-up and regular replacement of wick material due to weathering and ultraviolet degradation. Uneven wetting of the wick can result in dry spots that reduce efficiency. In a multiple-tray tilted still, a series of shallow horizontal black trays are enclosed in an insulated container with a transparent glazing on top. The feed-water supply tank is located above the still, and the vapour condenses and flows down to the collection channel and finally to the storage. The construction of this still is fairly complicated and involves many components that are more expensive than simple basin stills. Therefore, the slightly better efficiency it delivers may not justify its adoption. The concentrating mirror solar still uses a parabolic mirror for focusing sunlight onto an evaporator vessel. The water is evaporated in this vessel exposed to extremely high temperature. This type of still entails high construction and maintenance costs. Solar stills are characterized by low production rates of about 4–6 L/ ($m^2$ per day). Three types of solar stills are shown in Figure 32.

The use of nanotechnologies in Water could be in monitoring, desalinization, purification and wastewater treatment. This, in theory, plays a large role in averting future water shortages. But hoping that the 'magic' of nanotechnology will solve all water problems is still far away to be true, because of the basic problems of accessibility to technologies, affordability, and nanotechnology-based applications are still in R&D stage. None of them has been scaled up to industrial levels yet. Nanomaterials have a number of key physicochemical properties that make them particularly attractive as separation media for water purification. On a mass basis, they have much large surface areas than bulk particles. Nanomaterials can also be functionalized with various chemical groups to increase their affinity toward a given compound. They can also serve as high capacity/selectivity and recyclable ligands for toxic metal ions, radionuclides, organic and inorganic solutes/anions in aqueous solutions. Nanomaterials also provide unprecedented opportunities to develop more efficient water-purification catalysts and redox active media due to their large surface areas and their size and shape-dependent optical, electronic and catalytic properties. Nanomaterials are also being used to develop chlorine-free biocides through functionalization with chemical groups that selectively target key biochemical constituents of waterborne bacteria and viruses.

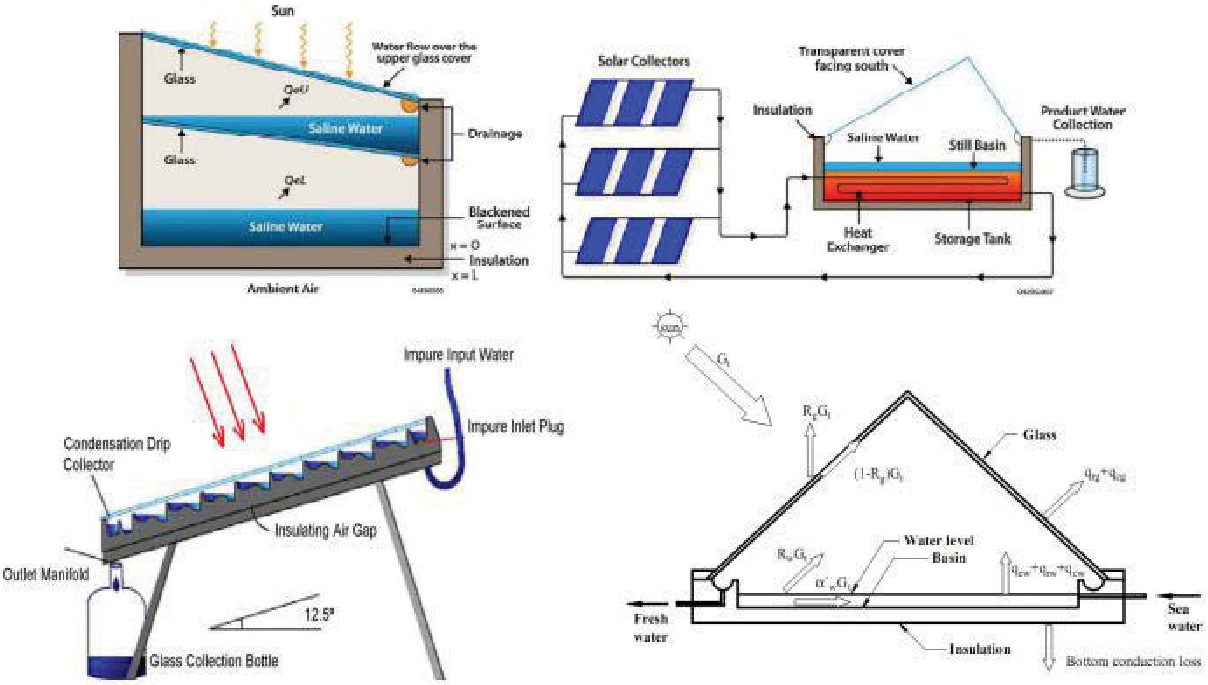


Figure 32 Schematic diagrams of a simple solar still

## 2.8.5 Solar Vacuum Tube Integrated Seawater Distillation

In this experimental study, a pond setup is constructed with 0.24 $m^2$ water surface area and 0.015$m^3$ water capacity. The constructed pond is equipped with a 0.15 m solar vacuum tube. Water circulation in the solar vacuum tubes occurs naturally and so it does not require any external circulation energy input into the system (Selimli & Recebli, 2016). The vacuum tube is inclined at an angle of $30^o$ for optimal solar light absorption. The solar pond internal surfaces are painted with black dye because of its high absorption coefficient (about 0.96). The solar pond is filled with seawater up to the level of about 0.05m. The feed water tank is attached to the pond with a ballcock to maintain constant water level in the pond. Firstly, the water heated by solar energy evaporates; a high-temperature steam meets low-temperature condensation glass and condenses. Condensed water droplets on the condensation glass come together and drip to the freshwater separation channel. Distilled water in the channel flows in a pipeline and collects in the fresh water storage tank. Water and condensation glass temperature is measured by T-type thermocouple. Potential difference between thermocouple ends is read by Voltcraft M3850 model multimeter. Solar radiation is measured by Cem DT-1307 model solarimeter. The experimental setup is illustrated in Figure 33.

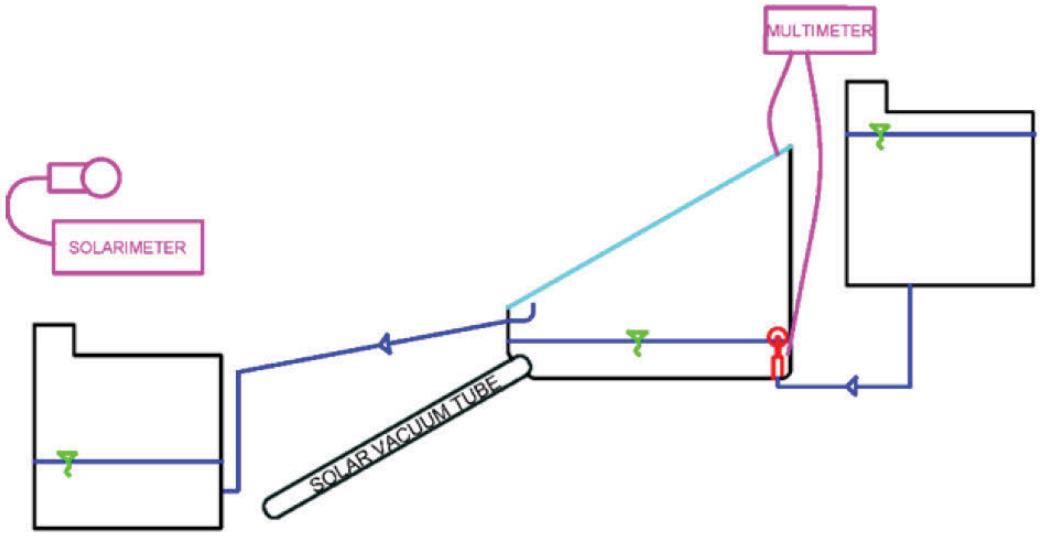


Figure 33 Solar vacuum tube integrated seawater distillation

Distillation performance is investigated for three different setup configurations. Firstly, the solar vacuum tube is isolated and the water is exposed to solar radiation from the condensation glass. Secondly, the solar vacuum tube is uncovered and the solar penetration to the water is allowed from the tube and condensation glass. Lastly, the condensation glass is isolated and solar radiation allowed only from the solar vacuum tube. Except for the aforementioned surfaces, all other surfaces of the setup are isolated to avoid heat losses. Each configuration is studied in three consecutive cloudless spring days. Measurements were taken every 15 minutes between 10:00 am to 4:30 pm and recorded.

## 2.9 Specific Heat and Latent Heat

The specific heat is the amount of heat per unit mass required to raise the temperature by one degree Celsius. The relationship between heat and temperature change is usually expressed in the form shown below where S is the specific heat. The relationship does not apply if a phase change is encountered, because the heat added or removed during a phase change does not change the temperature.

Energy required to heat up water, $Q = ms\Delta T$
S = Specific heat of water 4.18 kJ/kg-K
m = Mass of water in kg
$\Delta T$ = Temperature difference

The heat required to convert a solid into a liquid or vapour, or a liquid into a vapour, without change of temperature is called Latent Heat.

Energy required to convert $100^{0}$C 'm' kg water into $100^{0}$C 'm' kg vapour

= m x latent heat
= m kg x 2260 kJ/kg

# 3 New Vacuum Desalination Plant Design

As per the new idea and methodology, the next step was to verify this with some experimental setup. We did that in several stages to determine whether the idea was really workable or not. In this chapter, those several stages have been illustrated. The main process to check was distillation in vacuum pressure as it would determine whether we can establish vacuum desalination in this way or not. Available and easy accessible instruments have been used to conduct the preliminary tests and then a prototype setup has been established to test the process.

## 3.1 Prelim

The Idea of desalinating the water in a closed chamber was initially clarified by a very simple test. A typical medical syringe was used to create vacuum pressure over a certain amount of water inside the syringe which is a medical device that is used to inject fluid into or withdraw fluid from, the body. A medical syringe consists of a needle attached to a hollow cylinder that is fitted with a sliding plunger. The downward movement of the plunger injects fluid; upward movement withdraws fluid. Medical syringes were once made of metal or glass and required cleaning and sterilization before they could be used again. Now, most syringes used in medicine are plastic and disposable. The syringe we used was about 15 mm in diameter. We kept the syringe in the fridge for few minutes so that the surface inside gets cold. After that, we plunged some air in. The reason for plunging some air in was to give the upper surface of the water some room and preventing the water from contacting the piston. When there would be any change in the volume of air keeping the same mass the air pressure of the upper surface of water will drop following the Boyle's law or the pressure-volume law which states that the volume of a given amount of gas held at constant temperature varies inversely with the applied pressure when the temperature and mass are constant.

$$V \propto \frac{1}{P}$$

Another way of describing it is saying that their products are constant.
PV = C

When pressure goes up, volume goes down and when volume goes up, pressure goes down.

From the equation above, this can be derived:
$P_1V_1 = P_2V_2 = P_3V_3 = PnVn$……………………………………. (i)

So when the rubber piston is pulled out sealing the inlet the volume of air increases but the mass doesn't. So the pressure inside the syringe drops.
After plunging in some air inside the syringe we plunged some warm water into it. The water temperature was around $60^o$ C.

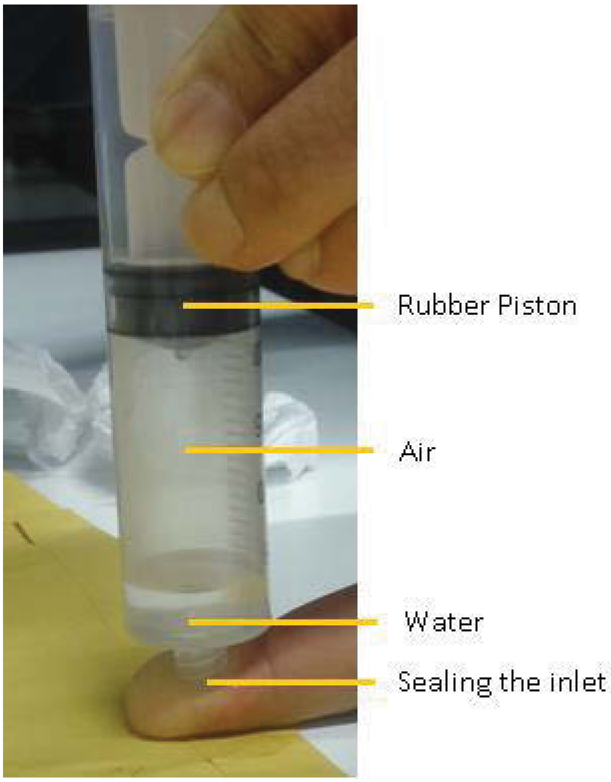


Figure 34 Preliminary test with a medical syringe

Then we sealed the inlet of the syringe with a finger and pulled out the piston. We could able to increase the volume into five times of the initial and left it for few seconds. We were able to visualise water mist- in fact, water vapour from the top surface of the warm water.

As the piston temperature was slightly lower than the warm water some condensation also took place. To be exact the air pressure inside was around 20 kPa at which water evaporates at around 61° C.

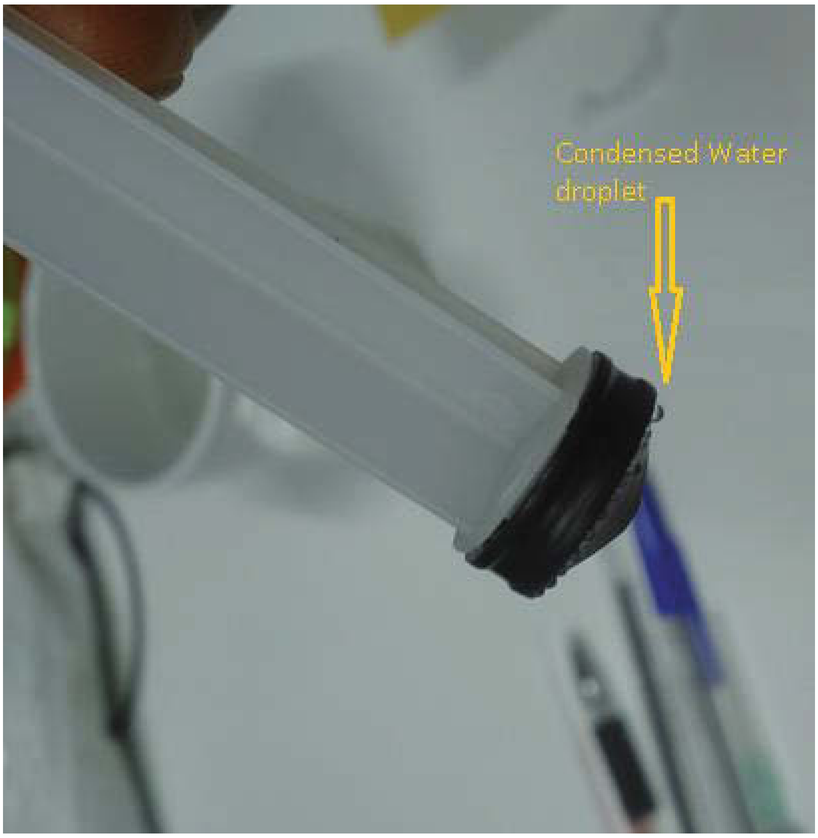


Figure 35 Condensed water droplets on cold piston

Air pressure inside the syringe dropped that enhanced the warm water to get evaporated little bit ended with some droplet of condensed water on the rubber piston as it was cold. By this simple experiment, it has been proven that we can desalinate or distil water by vacuum pressure inside closed chamber.

## 3.2 Prototype Modelling

As the idea was initially clarified by the syringe experiment, a model for experimental setup to apply this idea had been developed in AutoCAD. The initial model was based on a single cylinder, condenser comprising of cooling plates, freshwater receiver and a vacuum pump. The basic idea was to put some warm seawater around $50^0$C inside the cylinder and then close all the valves, start the vacuum pump and raise the vacuum pressure to the required level. The Freshwater receiver should collect the condensed water from the condenser and then stop the process and drain the fresh water and brine. The inner dia of the cylinder was 400 mm. It had one seawater inlet, one specially designed condenser attached to the vacuum pump and a cone-shaped water catcher to catch the freshwater condensed from the surface of the condenser.

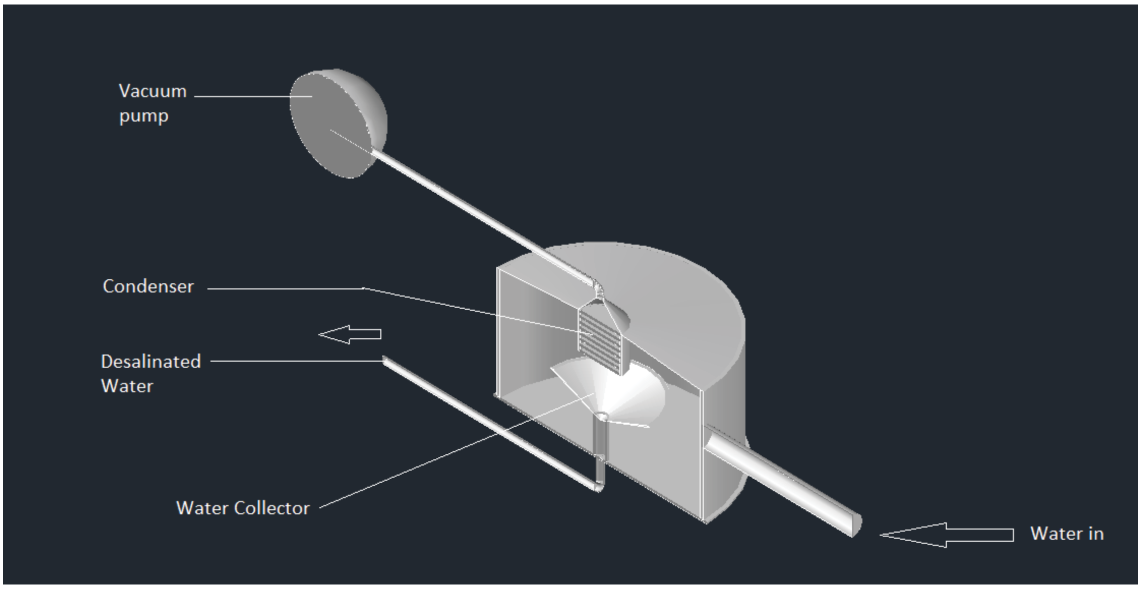


Figure 36 Cross-sectional view of initial prototype model in AutoCAD

The critical point of the model was its condenser. A plate based condenser was developed to give more exposed area to the evaporated water. Condensation rate would play a vital role in the success of this study so modelling the proper condenser is very important. In the designed condenser there are a bunch of aluminium or copper plates having a small hole to pass the water and vapour. The plates are arranged in a manner that the hole of the upper plate is in the maximum distance from the lower to ensure the condensation of vapour. Also, the plates are slightly inclined to the side of its hole so that condensed water will not get stuck between the plates, due to gravity condensed water should come down through this arrangement (Figure 37).

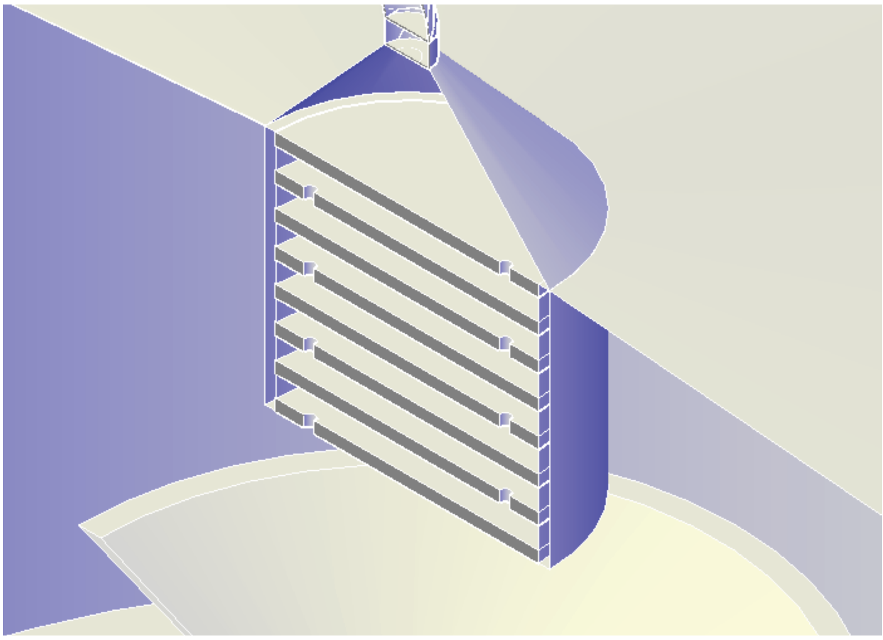


Figure 37 Cross-sectional view of plate-based Condenser in AutoCAD

Though the design for proto type model has been changed from its actual AutoCAD model, the fundamental and the basic working principle remained same. All of them had the same schematic diagram as below having difference in physical appearance.

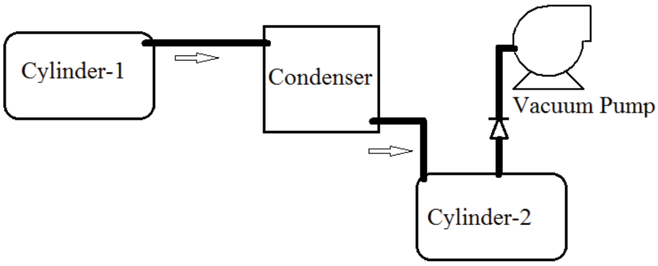


Figure 38 Schematic diagram of test rig.

## 3.3 Available Resources

For building up the experimental setup available resources of the university have been utilised. Following are the resources which have been utilised throughout the research. For some limitation and to keep the expenses minimum, the initial design has been modified time to time.

### 3.3.1 UTS Metrology Laboratory

The setting up part of the research has been done in Metrology laboratory under the supervision of Mr Vahik Avakian, Mechanical Engineer. This lab is Equipped with a wide range of measurement devices to measure almost any dimension. The Metrology Laboratory includes a touch-trigger co-ordinate measuring machine capable of measuring objects up to 508x406x203mm; a Hamar L-732 dual-axis laser coupled with Plane 5 software capable of measuring flatness, squareness, parallelism, levelness and straightness; and a Surtronic 3+ surface roughness meter. The laboratory is available for teaching, demonstration or consultation. Creating a list of the required components was done in this lab. Also, this lab has a wide range of fittings and equipment which have been utilised for this experiment. Some AutoCAD drawings have also been modified with the facility of metrology lab. The total assembly part of the diverse components has also been completed here.

### 3.3.2 UTS Workshop

Some components have been fabricated in UTS workshop under the supervision of Mr Laurence Stonard, Workshop Manager. They have a ready stock of various sheet metal, metal bars, fittings, tools, etc. The workshop is equipped with modern CNC's, hand tools, air tools, alignment tools, work tables with vices, hand and portable power tools, shaper machine, various welders, drillers, cutters, etc. This workshop follows all Australian standards for manufacturing and has adequate skilled personnel.

### 3.3.3 Vacuum Pump

The vacuum pump is another key part of this experiment. A readily available vacuum pump of DVP brand from metrology lab has been used in this experiment. This vacuum pump is compact in size, easy to move. The vacuum pump has an ultimate pressure of 0.1 kPa (absolute).

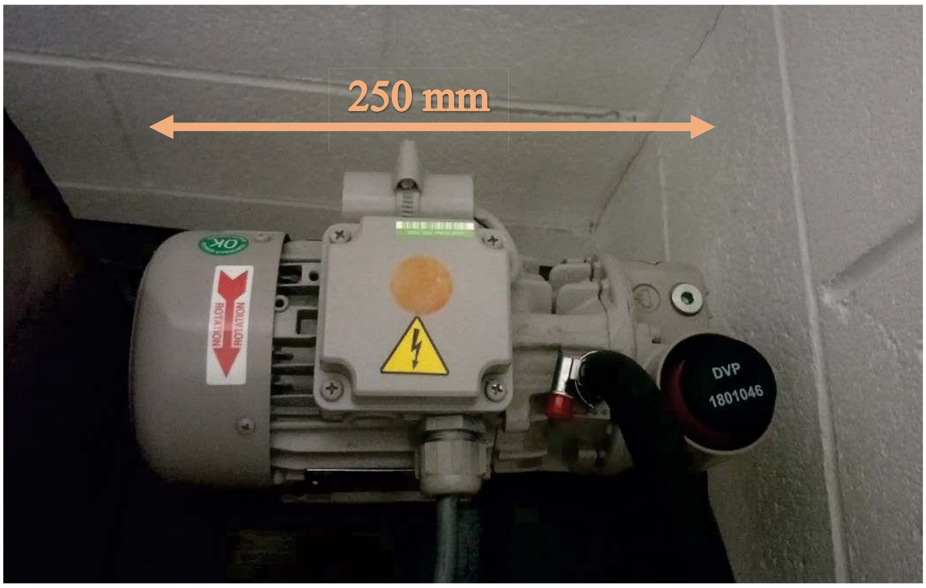


Figure 39 DVP LB.4 Vacuum Pump

Some key info about vacuum pump are:
Model: DVP LB.4
Max Flowrate: 1.1 L/s
Ultimate Pressure: 0.2 kPa (abs)
Motor Power: 0.12 kW
R.P.M: 2800
Weight: 5.4 kg
Pump intake size (Dia): 9mm

The pump is Oil lubricated vane vacuum pumps having Compact size combined with low ultimate pressure (abs.). Following are the main features of this unit.

- An effective damping and recovery system integrated into the oil box eliminates oil vapours at the exhaust and keeps noise level very low.

- The Monoblock design and the use of light alloys, these pumps have very limited overall dimensions and weight, which makes them ideal for applications in small spaces, where ventilation is adequate or on mobile equipment.

- Pump cooling is ensured by the motor fan. This series is suitable for evacuation of small closed systems and for a continuous operation within a pressure range from 500 to 20 mbar (abs.).

(More pump data can be found in Appendix.)

### 3.3.4 Copper Tube

We had to modify our condenser as fabricating the designed condenser was harder. We had plenty of copper tube in our stock and thought it would be easier and effective to bend the copper tube and make a spiral condenser. The copper tube we used has the following specifications.
Model Name: Copper Annealed Coil 12.70OD x 0.91Wt
Material: Copper
Product Dimensions (mm): W: 12.7 x H: 12.7, Thickness: 0.91
Actual inside diameter (mm): 10.88
Actual outside diameter (mm):12.70
Coiled: Yes

Maximum working pressure (kPa): 5290
Maximum working temperature: 200$^{o}$ C
Minimum working temperature: 0$^{o}$ C

Recommended Use: Use in plumbing, gas fitting and drainage applications.
Certified: WaterMark Certified to AS 1432

## 3.3.5 Sheet Metal

Instead of outsourcing our required customised cylinder, we decided to use sheet metal which was in stock to fabricate the chamber. Because of pressure requirement, sheet metal of certain thickness was required for fabrication. We used 2 mm thick Grade 304 stainless steel which is the standard "18/8" austenitic stainless; it is the most versatile and most widely used stainless steel, available in the widest range of products, forms and finishes. It has excellent forming and welding characteristics. Its corrosion resistance is very good in a wide range of atmospheric environments and many corrosive media. However, it is Subjected to pitting and crevice corrosion in warm chloride environments and to stress corrosion cracking above about 60°C. It is considered to be resistant to pitting corrosion in potable water with up to about 200mg/L chlorides at ambient temperature and reduces to about 150mg/L at 60°C. It is also good oxidation resistant in intermittent service to 870°C and in continuous service to 925°C. Continuous use of 304 in the 425- 860°C range is not recommended if subsequent aqueous corrosion resistance is important. Grade 304L is resistant to carbide precipitation and can be heated into this temperature range. It has a maximum tensile strength of 515 MPa.

## 3.3.6 Piping

As vacuum pressure was intended to apply throughout the setup flexible connection between the components needed proper attention. The ordinary pipe could deform and collapse when vacuum pressure would be applied. So, to connect the components e.g. vacuum pump, cylinders special flexible pipes were required. We have outsourced this special type of flexible pipes which can withstand vacuum pressure without collapsing.

These pipes are non-hazardous and have no reaction to brine water. Also, it can withstand -101.325 kPa inside.

### 3.3.7 Digital Thermometer

We have used a Benchtop Digital Thermometer (MDS41-TC) having 10 channels incorporated with rugged pipe plug thermocouple probe. The MDS41-TC is a high-precision digital benchtop meter that accepts thermocouple inputs. The large, easy-to-read 13 mm (0.5") display features 6 digits with 0.01° resolution. The thermocouple input model has 9 thermocouple types in memory, any one of which can be selected through the front panel. The unit is switchable to °C/°F/K. The single-channel unit includes a universal rear connector which accepts either the miniature or standard quick disconnect connector. The 10-channel MDSS uses screw terminals for temperature input. Optional scalable analogue output is available and can be ordered as a 0 to 10 Volt (DC) or 4 to 20 mA. The analogue output provides a retransmission of the measured temperature for recorders or data loggers. The rugged pipe plug thermocouple probe has a temperature range to 650°C [1200°F]. These high-pressure thermocouples plug sensors are ideal for vessel applications, pressurized containers and applications requiring mounted NPT security. The thermocouple-grade lead wires are stranded 20 AWG, fibreglass insulated, and stainless steel over braided with stripped leads. Exposed junctions are available for air or gas temperature measurements at ambient pressures.

### 3.3.8 Pressure Gauge and Fittings

We have used a couple of vacuum gauges. These gauges have good accuracy within Australian standard. Specification of this is given below.

Type: Back side thread
Fluid: Air

Indication precision: ±3%
Pressure Range: -100 kPa to 0 kPa

We have also used various fittings such as hose fittings, above fittings, clamps, ball valves, etc.

## 3.4 Primary Experimental Setup

Primary experimental setup was established using the available resources mentioned above. A very simple and cost-effective method was applied to build the setup.

### 3.4.1 Two Square Tanks

Two square tanks were made of 2 mm thick Grade 304 stainless steel. These tanks have inner dimensions of 400 mm x 400 mm x 400 mm. Both the tanks have a detachable lid on top. Tanks have been made by welding square sheet metals in all the sides. A weld thickness of 4mm has been maintained as the tank will be pressurised. Stainless steel confirms no reaction to water or saltwater. Each tank is equipped with a pressure gauge, temperature sensor, inlet valve and outlet valve. Brass fittings have been welded into the surface of the tanks for the connections.

### 3.4.2 Condenser

Annealed copper of dimensions (mm): W: 12.7 x H: 12.7, Thickness: 0.91 was used to make a coil. The coil was made by hand having 12 (twelve) turns. This coil was then welded into a square-shaped tank with inlet and outlet opening. The coil diameter is approximately 200 mm. This condenser tank has the similar dimension of the previous tank (400 mm x 400 mm x 400 mm) but the top side of the tank is open. The condenser has the similar properties of a shell and tube heat exchanger. There was also an arrangement to fill the condenser water with cold water and drain it continuously using syphon method. Figure 40 shows the details of the condenser fabricated. Hot water vapour would be circulated through inside of the copper coil and the outside of the coil would be submerged into cooling water. Condensed fresh water should come out from the outlet of the coil.

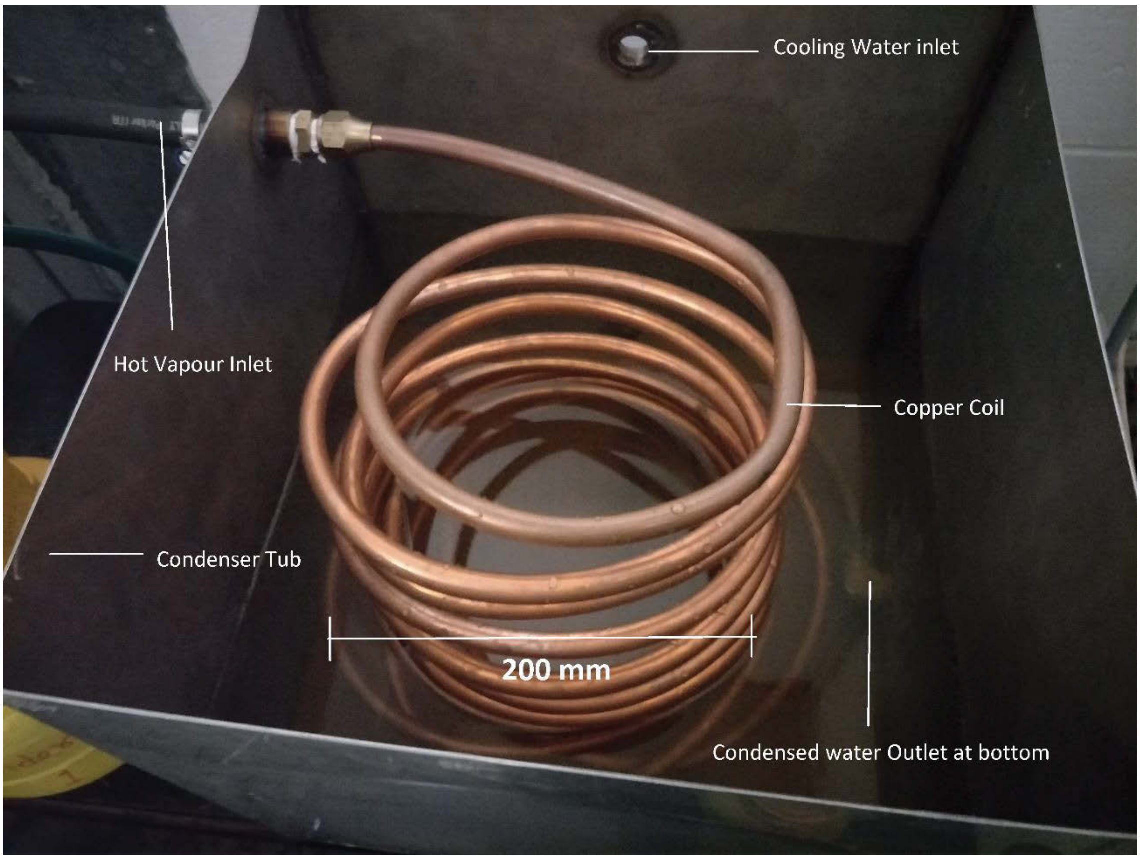


Figure 40 Condenser (Coil and Tank)

### 3.4.3 Assembly of Primary Experimental Setup

After fabrication of all the components, a test rig was assembled in metrology lab. According to the schematic diagram showed in Figure 41, the test rig was established. Condenser tank was attached above one of the tank (indicated as Tank-2) mentioned before. The joints were sealed by silicone gel. Condenser coil was connected to another tank indicated as Tank-1.

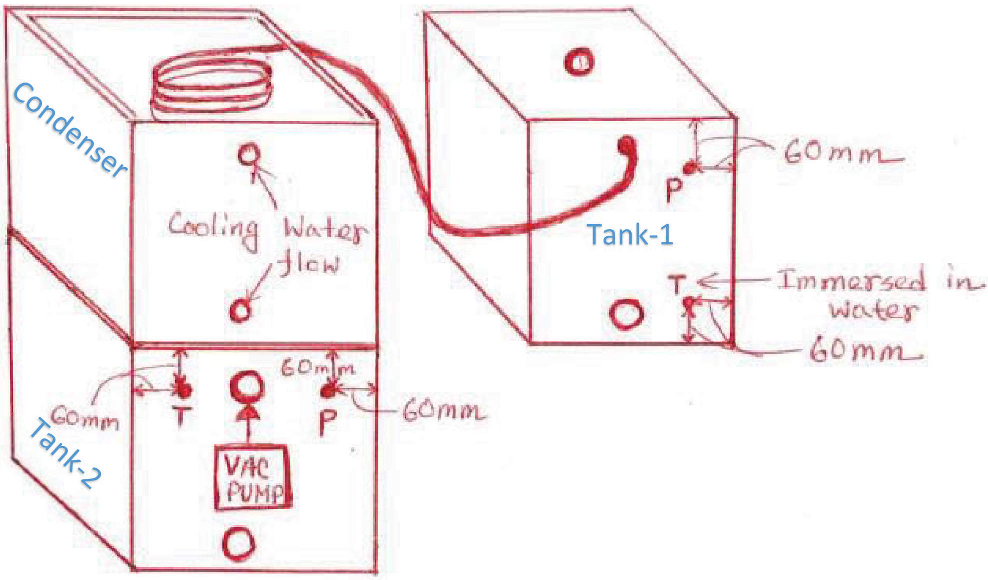


Figure 41 Schematic of primary experimental setup (T- Temperature sensor, P- Gauge)

Tank-1 is designated for putting the saltwater or feed water. This tank is then connected to condenser coil which exits towards Tank-2. Tank-2 is connected to the vacuum pump. Tank-2 is the fresh water tank. The total system is air-tight having no leakage. When vacuum pump is turned on air pressure inside Tank-2, Tank-1, and condenser coil starts decreasing. Vapour created from Tank-1 water has to pass through the condenser so that it would get condensed and fresh water droplet would drop into Tank-2.

## 3.4.4 Pressure Test

Before we do any experiment, we intended to do a pressure test to be confirmed that the test rig will withstand the vacuum pressure we desire. After proper curing of the silicone

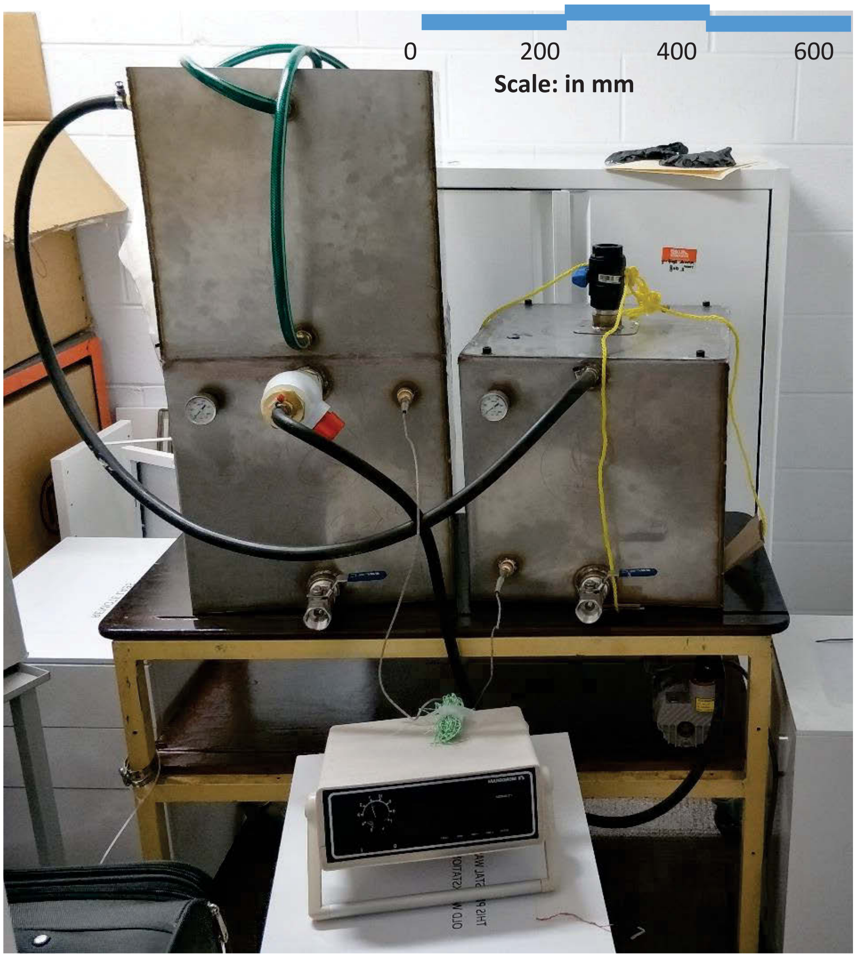


Figure 42 Primary Experimental Setup (Tank dimension: 400 x 400 x 400 mm )

sealant, we did a pressure test on the test rig. We closed all the valves without any water inside. Then turned on the vacuum pump. After few seconds, we were able to see the deflection in gauges. But there were some buckling noises coming from the tanks and the tank walls were bending inside slightly. We reached a gauge pressure of -70 kPa and then stopped the process. We came to a decision that the tank walls need supports internally to prevent collapsing inward. So put three round bars inside each of the tanks to support the walls. After that, we did the pressure test again and everything was fine. We turned the pressure until -75 kPa and there was no sign of deformation like earlier.

## 3.4.5 First Test Run

After the pressure test and completing all safety requirements and documentation, we opt for our first test run. Water preheated by supply water boiler was taken as feed water in Tank-1. The temperature of the water was around $70^{o}$ C. Then we closed all the valves and recorded the temperature of both the tanks, condenser. Condenser and Tank-2 were at room temperature around $22^{o}$ C. Condenser water tank was filled with cold water of room temperature. We used a weighing scale to measure the mass of empty tanks and then Tank-1 with feed water. The reason for scaling is to determine how much water has been distilled through the process. When water evaporates from Tank-1 and travel through the condenser to Tank-2, mass of water initially taken should reduce and the mass of Tank-2 should increase as it will have additional condensed water in it by the process. After measuring the mass, we turned on the vacuum pump. We allowed the vacuum pump for a long time and the maximum gauge reading we got was -65 kPa. We stopped the process and the pressure raised to normal which indicated there was leakage in the system. We were unable to reach the gauge pressure -75 kPa. Water of $70^{0}$C was taken as feed water which required -70.15 kPa gauge pressure to get evaporated.

### 3.4.5.1 Outcome of First Test Run

The findings of the first test run on primary test rig are as follows.

- We achieved -75kPa Gauge Pressure inside the tanks without water but only -65 kPa (gauge) was achievable with water. -60kPa (Gauge) should be the suitable working pressure for this test rig though it requires vacuum pump to be on continuously.

- The Gauges weren't properly calibrated. Gauge in tank 1 shows -2kPa in ambient pressure. We took consideration of Tank-1's gauge reading adding a correction factor (+2kPa).

- The vacuum pump seeped back air into the system when turned off, so the achieved negative pressure recovered to normal when it was turned off. We had to keep the vacuum pump turned on to prevent this.

- A weighing scale was used to find out the evaporation rate by measuring the mass of the tanks before and after the process begins.

- Sealant in tank 1 was damaged some places when the pressure got back to normal as it was compressed during operation. Lack of curing is one of the reason while tank 2 seemed to be alright.

- There was no difference between the mass of Tank-1 before and after the process, so on Tank-2 as well. Methodically there was no evaporation and condensation.

#### 3.4.5.2 Investigating Tank-2

As we couldn't find any significant result from first test run, we decided to dismantle Tank-2 and investigate it inside. Tank-2 is the freshwater receiver tank. Our intention was to check if there was any sign of water inside it or not. As this tank had never been poured with water nor had been processed with water, it should be dry totally. So, the lid of the tank-2 was opened and investigated. Despite the drawbacks, there were some positive findings as well. After opening up the lid of the tank, the existence of water was visible that indicated some water was evaporated and condensed during the process. As tank-2 was totally dry before the experiment, the existence of water in tank-2 after the test indicates there should be some evaporation and condensation during the process. It can also be for the presence of moisture in the air inside the tanks.
Figure *43* illustrates presence of water droplets inside Tank-2 after first test run.

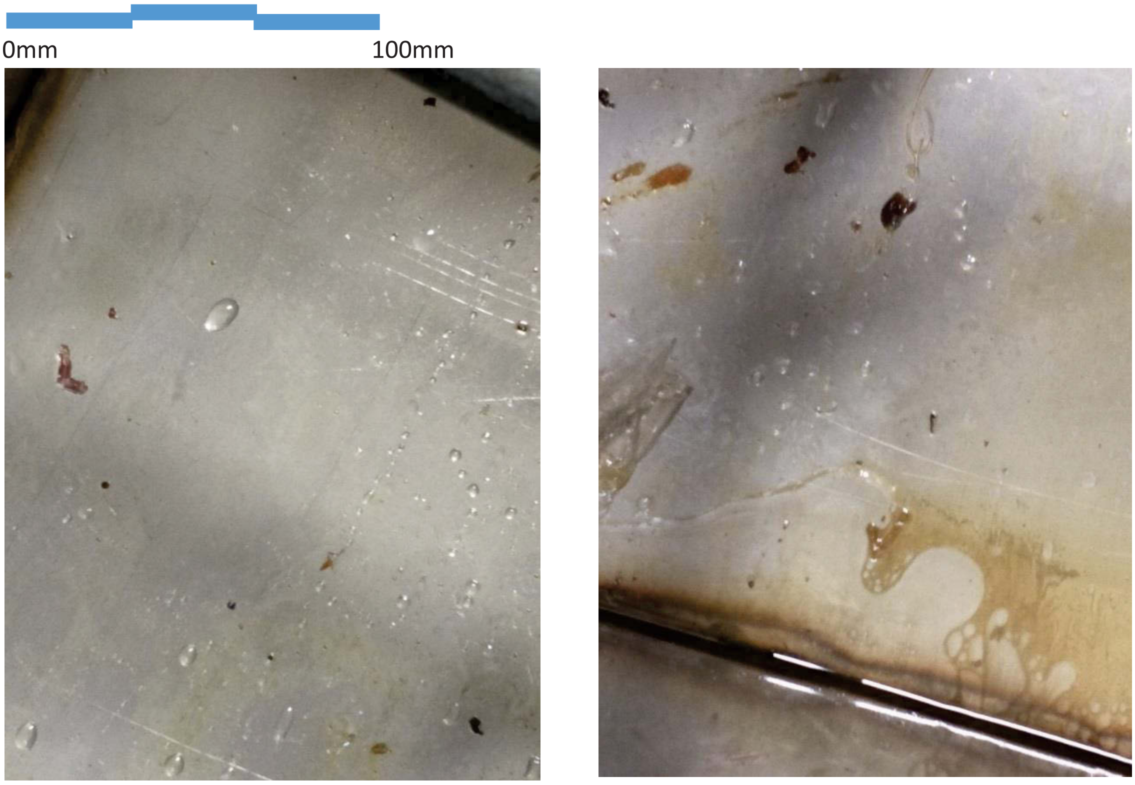


Figure 43 Water droplets inside Tank-2 (Freshwater receiver tank)

## 3.4.6 Recommendation and Decision from Primary Experimental Setup

Followings are the decision and recommendations after evaluating the outcome of primary experimental setup.

- It would not be possible to work with this experimental setup as this is not capable of withstanding a gauge pressure of -90 kPa.
- The condenser coil is fine to withstand the desired vacuum pressure.
- Two water tanks, Tank-1 and Tank-2 should be replaced with two pressure vessels which can withstand the desired vacuum pressure.
- To prevent vacuum pump from seeping back the air into the system, a non-return valve can be used in the pathway between the system and vacuum pump.

- Using the weighing scale to find out the evaporation rate is not the great way to do it. But still, it works well.
- To reduce the probability of leaking, pressure vessels should have very fewer joints and sealing. Gas cylinders could be an option.
- Piping and fittings looked alright to withstand the required pressure.

## 3.5 Revised Experimental Setup

Based on the findings from primary experimental setup, modification has been made to establish a more reliable test rig. Followings are the description of the changes.

### 3.5.1 Gas Cylinders instead of Square Tanks

The square-shaped tanks had been replaced by two pressure cylinders sourced from Bunnings Warehouse. These cylinders are safe and certified by Australian Standards. Previous gauge, temperature sensor and other fittings were installed on the cylinders accordingly. Cylinder specifications are as below:
Model Name: 2kg Gasmate Gas Cylinder
Model Number: 020CG
Material: Steel
Product Dimensions (mm): Dia: 200 x H: 305
Weight: 4.0kg
Volume inside (Litre): 4.7
Outlet Size (mm): 3'8" BSP-LH
Maximum allowable pressure: 3.3 MPa

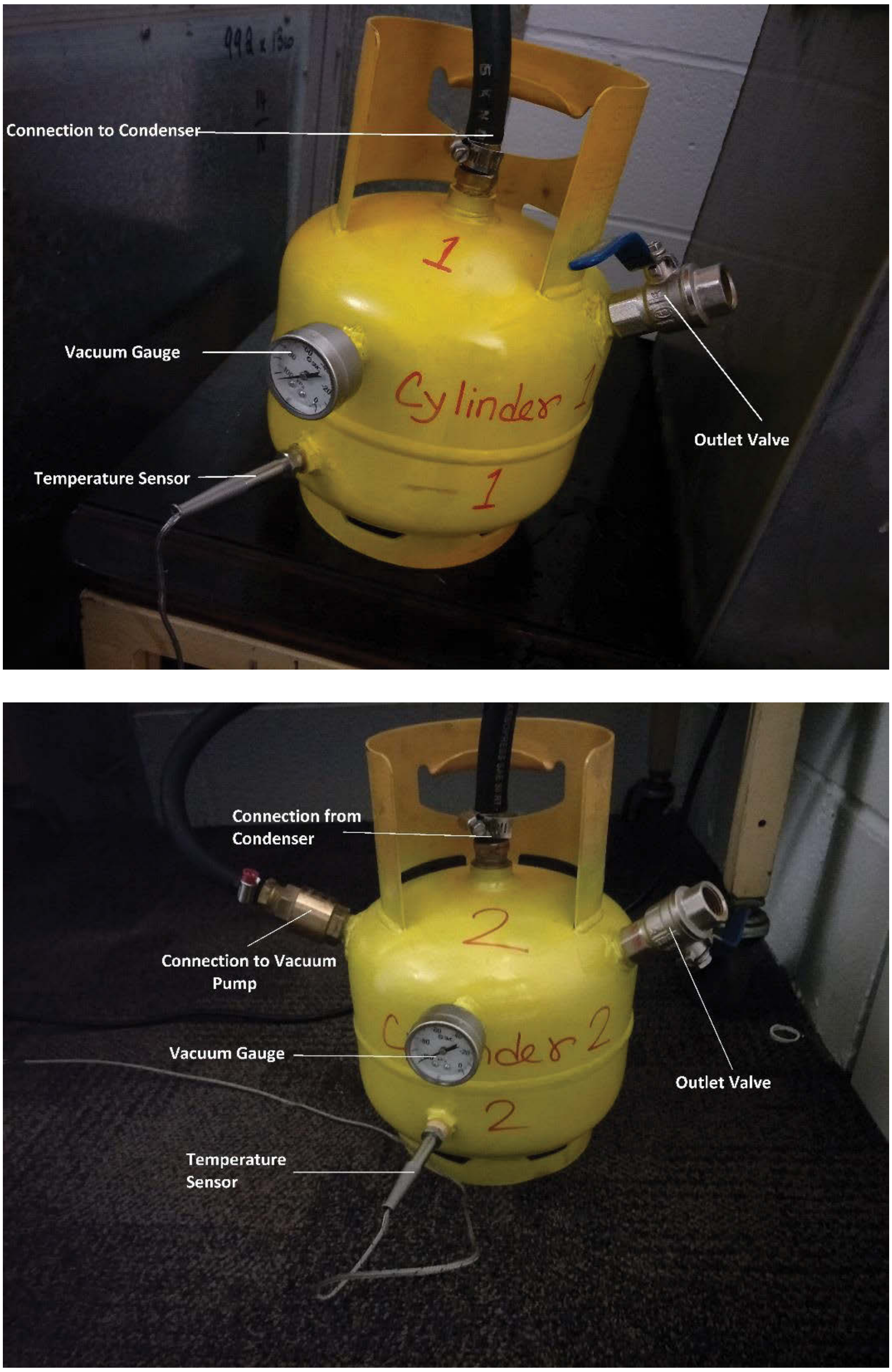


Figure 44 Two gas cylinders modified for testing (Cylinder diameter: 200 mm)

Figure 44 shows the two cylinders that were modified to construct the test rig. These cylinders have no silicon joining. All the fittings have been welded and threaded into it. They are highly rigid and ultimate strength is way above our requirement.

## 3.5.2 Non-return Valve

To prevent vacuum pump from seeping back the air into the system a non-return valve has been used between the vacuum pump and cylinder 2. This non-return valve only allows air to flow from the system towards vacuum pump. Air from vacuum pump to the system can't be pushed in. Details of the non-return valve are as below.

Connection: 1/2 in BSPP
Body Material: Brass
Maximum Working Pressure: 12 bar
Thread Size: 1/2in
Thread Standard: BSPP
Operating Temperature: -20˚ C / +100˚ C
Stem: Nylon
NBR 65 SH/PS seal on nylon holder
Stainless steel spring

Figure 45 Non-Return Valve

### 3.5.3 Assembly of Revised Experimental Setup & Trial run

After gaining all the required components the test rig has been re-assembled. Tank-1 has been replaced by Cylinder-1 and Tank-2 has been replaced by Cylinder-2. Cylinder-1 is connected with the inlet of condenser coil. Then the outlet of condenser coil is connected to Cylinder-2 via special hose. Cylinder-2 is also connected with the vacuum pump. The non-return valve is situated in between Cylinder-2 and vacuum pump.

Finishing the assembly of revised test rig, a leak test was done. Closing all the valves vacuum pump was being run until a gauge pressure -100 kPa was achieved in both the cylinders. After that, the vacuum pump was turned off and the non-return valve worked properly. We left the test rig for an hour in that stage and there was no deflection in the gauges. This indicated that there was no leakage in the system.

We filled up the condenser tank with cold water and filled the Cylinder-1 through the outlet valve with warm water of different temperatures each time to see the variation. Using the weighing scale, the mass of the water inside Cylinder-1 and Cylinder-2 has been measured.

Figure 46 illustrates the revised experimental setup which has been used as test rig of this study.

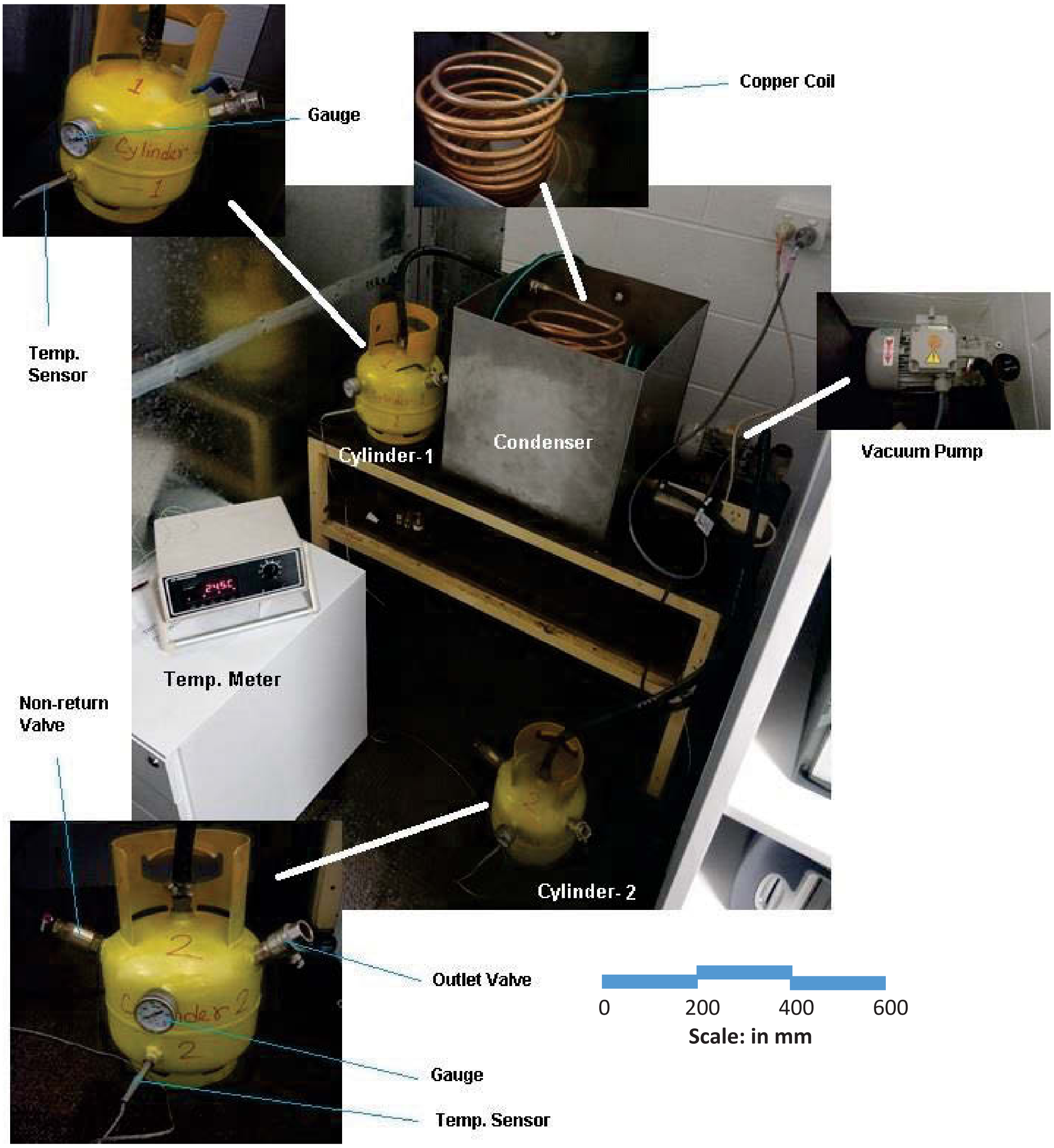


Figure 46 Revised experimental setup (Cylinder 1 & 2 Diameter: 200 mm, Condenser tank Dimension: 400 x 400 x 400 mm)

# 4 Experiments

Several testing has been done with the revised test rig varying the parameters. In this chapter collected data and calculation have been illustrated. We changed the temperature of feed water, pressure inside the cylinders and arrangements of the cylinders to analyse the process. We can divide our tests into several categories: Test- 1, 3, 4 and 14 have been done where cylinder-1 and condenser were on the same level and cylinder-2 at a lower level having higher initial feed water temperature and mass. Test- 2 and 12 have been done where cylinder-1 and condenser were on the same level and cylinder-2 at a lower level having lower initial feed water temperature and mass. Test- 5, 7 and 13 have been done where cylinder-1 and condenser were on the same level and cylinder-2 at a lower level having higher initial feed water mass and lower initial temperature. Test- 6 has been done where cylinder-1 and condenser were on the same level and cylinder-2 at a lower level having higher initial feed water temperature and lower initial mass. Followings are the recorded data and calculation for various test attempts. Test- 8 and 9 have been done where cylinder-1 and condenser were on the same level and cylinder-2 at a lower level having higher initial feed water temperature and mass and it was done immediately after one test. Test- 10 and 11 have been done where cylinder-1 was on upper level than condenser and cylinder-2 at a lower level than condenser having higher initial feed water temperature and mass and it was done immediately after one test. We have listed Test – 1, 2, 5, 6, 8 and 10 below and the other tests have been listed in Appendix. Operating conditions for all the tests can be categorized as below.

| Category | Operating Condition |
|---|---|
| **A** | Cylinder-1 and condenser on same level, Cylinder-2 at lower level |
| **B** | Cylinder-1 and condenser on same level, Cylinder-2 at lower level, done consecutively after one process |
| **C** | Cylinder-1 on upper level than condenser, Cylinder-2 at lower level, done consecutively after one process |

# 4.1 Test 1 (Operating Condition A)

In the first set of experimental data (Table 3), 1.95 kg water of around $73^0$C was taken in Cylinder-1 and after the process, we got 0.3 kg of condensed water in Cylinder-2 though around 0.4 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.95 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta T$= 80 K

Energy required to heat up $20^0$C water into $100^0$C water = ms$\Delta$T
= 652.1kJ

Energy required to convert $100^0$C 0.3 kg water into $100^0$C 0.3 kg vapour
= mass x latent heat
= 0.3 kg x 2260 kJ/kg
= 678 kJ

Total energy required for getting 0.3 kg of condensed water from 1.95 kg of water in conventional process is 1330.1 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 2min as we got the required pressure (-97 kPa gauge) by turning on the pump only for 2min = 120 Watt x 120s = 14.4 kJ

$$\% \text{ of distillation in our process} = \frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1} \text{ x } 100 = \frac{0.3}{1.95} \text{ x } 100$$

$$= 15.38\%$$

$$\text{Total Energy Savings} = \frac{(1330 - 14.4)\text{ kJ}}{1330\text{ kJ}} \text{ x } 100 = 98.9\%$$

*Table 3 Experimental Data: Test 1*

**Vacuum Desalination Experiment** **Data Set** **1**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 20 | R Humidity (%): | 65 | Weight of Feed (1) water (kg): | 1.95 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 20.7 | -2 | 4.45 | 20.5 | 0 | 19.5 |
| After Start (00min) Pump on | 6.4 | 73.9 | -2 | 4.45 | 20.5 | 0 | 19.5 |
| After Start (01min) | | 72.9 | -95 | | 20.5 | -97 | 20 |
| After Start (02min) Pump off | | 68 | -99 | | 21 | -97 | 21 |
| After Start (10min) | | 44 | -99 | | 24 | -97 | 22 |
| After Start (20min) | | 30 | -100 | | 23.9 | -98 | 23.3 |
| Finish (21min) | 6 | 29 | -2 | 4.75 | 23.9 | 0 | 23.3 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 1. In this table, if we take water of 73.9°C then 10 gram of water would be evaporated in the first attempt and the temperature of the rest of the water would become 71°C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.9 | 1.95 | 0.01 | 23.8 | 2.9 | 71.0 | 10.0 |
| 71.0 | 1.94 | 0.01 | 23.8 | 3.0 | 68.0 | 10.0 |
| 68.0 | 1.93 | 0.01 | 23.8 | 3.0 | 65.0 | 10.0 |
| 65.0 | 1.92 | 0.01 | 23.8 | 3.0 | 62.1 | 10.0 |
| 62.1 | 1.91 | 0.01 | 23.8 | 3.0 | 59.1 | 10.0 |
| 59.1 | 1.90 | 0.01 | 23.8 | 3.0 | 56.1 | 10.0 |
| 56.1 | 1.89 | 0.01 | 23.8 | 3.0 | 53.0 | 10.0 |
| 53.0 | 1.88 | 0.01 | 23.8 | 3.0 | 50.0 | 10.0 |
| 50.0 | 1.87 | 0.01 | 23.8 | 3.1 | 46.9 | 10.0 |
| 46.9 | 1.86 | 0.01 | 23.8 | 3.1 | 43.8 | 10.0 |
| 43.8 | 1.85 | 0.01 | 23.8 | 3.1 | 40.7 | 10.0 |
| 40.7 | 1.84 | 0.01 | 23.8 | 3.1 | 37.6 | 10.0 |
| 37.6 | 1.83 | 0.01 | 23.8 | 3.1 | 34.5 | 10.0 |
| 34.5 | 1.82 | 0.01 | 23.8 | 3.1 | 31.3 | 10.0 |
| 31.3 | 1.81 | 0.01 | 23.8 | 3.2 | 28.2 | 10.0 |
| 28.2 | 1.80 | 0.01 | 23.8 | 3.2 | 25.0 | 10.0 |
| 25.0 | 1.79 | 0.01 | 23.8 | 3.2 | 21.8 | 10.0 |
| 21.8 | 1.78 | 0.01 | 23.8 | 3.2 | 18.6 | 10.0 |
| 18.6 | 1.77 | 0.01 | 23.8 | 3.2 | 15.3 | 10.0 |
| 15.3 | 1.76 | 0.01 | 23.8 | 3.3 | 12.1 | 10.0 |
| 12.1 | 1.75 | 0.01 | 23.8 | 3.3 | 8.8 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became 24.58$^0$C and 0.18 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.18 kg of water in Cylinder-2. But from the experiment, we got 0.3 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

### Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 1. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 1.

| Initial Temp ($^{0}$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^{0}$C) | Final Temperature ($^{0}$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.9 | 1.95 | 0.0050 | 11.9 | 1.5 | 72.4 | 5.0 |
| 72.4 | 1.95 | 0.0050 | 11.9 | 1.5 | 71.0 | 5.0 |
| 71.0 | 1.94 | 0.0050 | 11.9 | 1.5 | 69.5 | 5.0 |
| 69.5 | 1.94 | 0.0050 | 11.9 | 1.5 | 68.0 | 5.0 |
| 68.0 | 1.93 | 0.0050 | 11.9 | 1.5 | 66.5 | 5.0 |
| 66.5 | 1.93 | 0.0050 | 11.9 | 1.5 | 65.1 | 5.0 |
| 65.1 | 1.92 | 0.0050 | 11.9 | 1.5 | 63.6 | 5.0 |
| 63.6 | 1.92 | 0.0050 | 11.9 | 1.5 | 62.1 | 5.0 |
| 62.1 | 1.91 | 0.0050 | 11.9 | 1.5 | 60.6 | 5.0 |
| 60.6 | 1.91 | 0.0050 | 11.9 | 1.5 | 59.1 | 5.0 |
| 59.1 | 1.90 | 0.0050 | 11.9 | 1.5 | 57.6 | 5.0 |
| 57.6 | 1.90 | 0.0050 | 11.9 | 1.5 | 56.1 | 5.0 |
| 56.1 | 1.89 | 0.0050 | 11.9 | 1.5 | 54.6 | 5.0 |
| 54.6 | 1.89 | 0.0050 | 11.9 | 1.5 | 53.0 | 5.0 |
| 53.0 | 1.88 | 0.0050 | 11.9 | 1.5 | 51.5 | 5.0 |
| 51.5 | 1.88 | 0.0050 | 11.9 | 1.5 | 50.0 | 5.0 |
| 50.0 | 1.87 | 0.0050 | 11.9 | 1.5 | 48.5 | 5.0 |
| 48.5 | 1.87 | 0.0050 | 11.9 | 1.5 | 46.9 | 5.0 |
| 46.9 | 1.86 | 0.0050 | 11.9 | 1.5 | 45.4 | 5.0 |
| 45.4 | 1.86 | 0.0050 | 11.9 | 1.5 | 43.9 | 5.0 |
| 43.9 | 1.85 | 0.0050 | 11.9 | 1.5 | 42.3 | 5.0 |
| 42.3 | 1.85 | 0.0050 | 11.9 | 1.5 | 40.8 | 5.0 |
| 40.8 | 1.84 | 0.0050 | 11.9 | 1.6 | 39.2 | 5.0 |
| 39.2 | 1.84 | 0.0050 | 11.9 | 1.6 | 37.7 | 5.0 |
| 37.7 | 1.83 | 0.0050 | 11.9 | 1.6 | 36.1 | 5.0 |
| 36.1 | 1.83 | 0.0050 | 11.9 | 1.6 | 34.5 | 5.0 |
| 34.5 | 1.82 | 0.0050 | 11.9 | 1.6 | 33.0 | 5.0 |
| 33.0 | 1.82 | 0.0050 | 11.9 | 1.6 | 31.4 | 5.0 |
| 31.4 | 1.81 | 0.0050 | 11.9 | 1.6 | 29.8 | 5.0 |
| 29.8 | 1.81 | 0.0050 | 11.9 | 1.6 | 28.2 | 5.0 |
| 28.2 | 1.80 | 0.0050 | 11.9 | 1.6 | 26.7 | 5.0 |
| 26.7 | 1.80 | 0.0050 | 11.9 | 1.6 | 25.1 | 5.0 |
| 25.1 | 1.79 | 0.0050 | 11.9 | 1.6 | 23.5 | 5.0 |
| 23.5 | 1.79 | 0.0050 | 11.9 | 1.6 | 21.9 | 5.0 |
| 21.9 | 1.78 | 0.0050 | 11.9 | 1.6 | 20.3 | 5.0 |
| 20.3 | 1.78 | 0.0050 | 11.9 | 1.6 | 18.7 | 5.0 |
| 18.7 | 1.77 | 0.0050 | 11.9 | 1.6 | 17.0 | 5.0 |
| 17.0 | 1.77 | 0.0050 | 11.9 | 1.6 | 15.4 | 5.0 |
| 15.4 | 1.76 | 0.0050 | 11.9 | 1.6 | 13.8 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 23.5$^0$C and 0.17 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.17 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 160 gram of water should be evaporated for 0-gram step from the graph below.

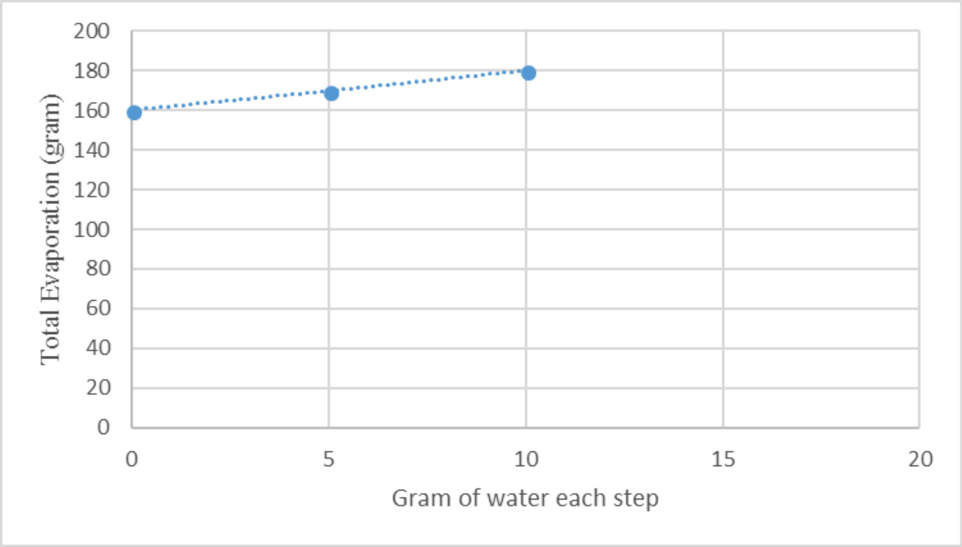


Figure 47Extrapolation for 0-gram step (Test 1)

# 4.2 Test 2 (Operating Condition A)

In this set of experimental data (Table 4), 1.5 kg water of around $45^0$C was taken in Cylinder-1 and after the process, we got 0.2 kg of condensed water in Cylinder-2 though around 0.3 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.5 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 80 K

Energy required to heat up $20^0$C water into $100^0$C water = ms$\Delta$T
= 501.6 kJ

Energy required to convert $100^0$C 0.2 kg water into $100^0$C 0.2 kg vapour
= mass x latent heat
= 0.2 kg x 2260 kJ/kg
= 452 kJ

Total energy required for getting 0.2 kg of condensed water from 1.5 kg of water in conventional process is 953.6 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 85 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 85 sec = 120 Watt x 85s = 10.2 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.2}{1.5}$ x 100
= 13.3%

Total Energy Savings = $\frac{(953.6 - 10.2)\text{ kJ}}{953.6\text{ kJ}}$ x 100 = 98.9%

*Table 4 Experimental Data: Test 2*

**Vacuum Desalination Experiment** **Data Set** **2**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 20.8 | R Humidity (%): | 70 | Weight of Feed (1) water (kg): | 1.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 20.9 | -2 | 4.45 | 21.3 | 0 | 20.1 |
| After Start (00min) Pump on | 5.95 | 45 | -2 | 4.45 | 21.3 | 0 | 20.1 |
| After Start (01min 25sec) Pump off | | 41 | -97 | | 22 | -98 | 21 |
| After Start (06min) | | 28.6 | -100 | | 22.5 | -98 | 22 |
| After Start (12min) | | 25.6 | -100 | | 22.5 | -98 | 23.6 |
| Finish (18min) | 5.65 | 24.7 | -2 | 4.65 | 22.3 | 0 | 22.9 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 2. In this table, if we take water of 45$^0$C then 10 gram of water would be evaporated in the first attempt and the temperature of the rest of the water would become 41.2$^0$C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 45.0 | 1.50 | 0.01 | 23.8 | 3.8 | 41.2 | 10.0 |
| 41.2 | 1.49 | 0.01 | 23.8 | 3.8 | 37.3 | 10.0 |
| 37.3 | 1.48 | 0.01 | 23.8 | 3.9 | 33.5 | 10.0 |
| 33.5 | 1.47 | 0.01 | 23.8 | 3.9 | 29.6 | 10.0 |
| 29.6 | 1.46 | 0.01 | 23.8 | 3.9 | 25.6 | 10.0 |
| 25.6 | 1.45 | 0.01 | 23.8 | 4.0 | 21.7 | 10.0 |
| 21.7 | 1.44 | 0.01 | 23.8 | 4.0 | 17.7 | 10.0 |
| 17.7 | 1.43 | 0.01 | 23.8 | 4.0 | 13.7 | 10.0 |
| 13.7 | 1.42 | 0.01 | 23.8 | 4.0 | 9.6 | 10.0 |
| 9.6 | 1.41 | 0.01 | 23.8 | 4.1 | 5.6 | 10.0 |
| 5.6 | 1.40 | 0.01 | 23.8 | 4.1 | 1.5 | 10.0 |
| 1.5 | 1.39 | 0.01 | 23.8 | 4.1 | -2.7 | 10.0 |
| -2.7 | 1.38 | 0.01 | 23.8 | 4.2 | -6.8 | 10.0 |
| -6.8 | 1.37 | 0.01 | 23.8 | 4.2 | -11.0 | 10.0 |
| -11.0 | 1.36 | 0.01 | 23.8 | 4.2 | -15.2 | 10.0 |
| -15.2 | 1.35 | 0.01 | 23.8 | 4.3 | -19.5 | 10.0 |
| -19.5 | 1.34 | 0.01 | 23.8 | 4.3 | -23.8 | 10.0 |
| -23.8 | 1.33 | 0.01 | 23.8 | 4.3 | -28.1 | 10.0 |
| -28.1 | 1.32 | 0.01 | 23.8 | 4.3 | -32.4 | 10.0 |
| -32.4 | 1.31 | 0.01 | 23.8 | 4.4 | -36.8 | 10.0 |
| -36.8 | 1.30 | 0.01 | 23.8 | 4.4 | -41.2 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became 21.7$^0$C and 0.07 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.07 kg of water in Cylinder-2. But from the experiment, we got 0.2 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 2. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 2.

| Initial Temp ($^{0}$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^{0}$C) | Final Temperature ($^{0}$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 45.0 | 1.50 | 0.0050 | 11.9 | 1.9 | 43.1 | 5.0 |
| 43.1 | 1.50 | 0.0050 | 11.9 | 1.9 | 41.2 | 5.0 |
| 41.2 | 1.49 | 0.0050 | 11.9 | 1.9 | 39.3 | 5.0 |
| 39.3 | 1.49 | 0.0050 | 11.9 | 1.9 | 37.3 | 5.0 |
| 37.3 | 1.48 | 0.0050 | 11.9 | 1.9 | 35.4 | 5.0 |
| 35.4 | 1.48 | 0.0050 | 11.9 | 1.9 | 33.5 | 5.0 |
| 33.5 | 1.47 | 0.0050 | 11.9 | 1.9 | 31.5 | 5.0 |
| 31.5 | 1.47 | 0.0050 | 11.9 | 2.0 | 29.6 | 5.0 |
| 29.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 27.6 | 5.0 |
| 27.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 25.7 | 5.0 |
| 25.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 23.7 | 5.0 |
| 23.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 21.7 | 5.0 |
| 21.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 19.7 | 5.0 |
| 19.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 17.7 | 5.0 |
| 17.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 15.7 | 5.0 |
| 15.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 13.7 | 5.0 |
| 13.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 11.7 | 5.0 |
| 11.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 9.7 | 5.0 |
| 9.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 7.7 | 5.0 |
| 7.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 5.6 | 5.0 |
| 5.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 3.6 | 5.0 |
| 3.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 1.5 | 5.0 |
| 1.5 | 1.39 | 0.0050 | 11.9 | 2.1 | -0.5 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 21.7$^{0}$C and 0.065 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.065 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 62 gram of water should be evaporated for 0-gram step from the graph below.

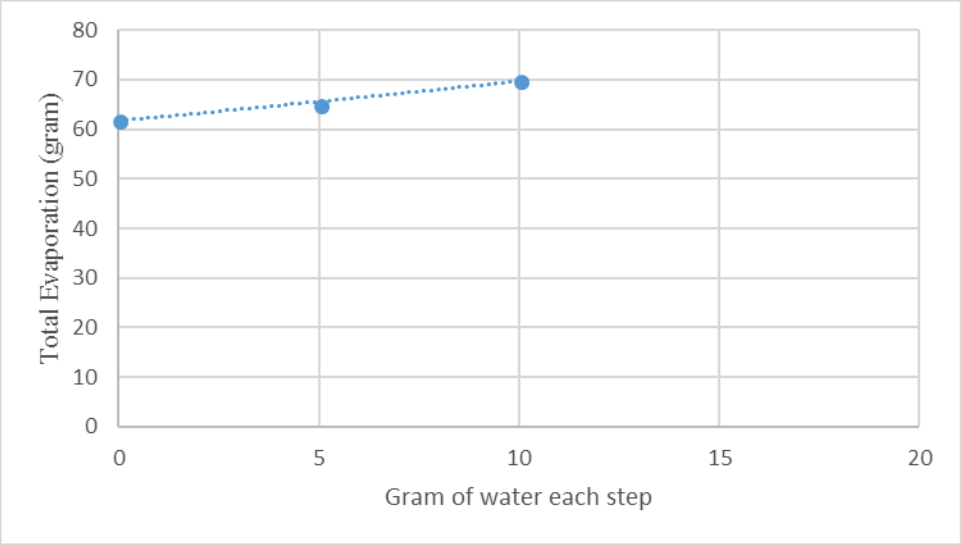


Figure 48 Extrapolation for 0-gram step (Test 2)

# 4.3 Test 5 (Operating Condition A)

In this set of experimental data (Table 5), 2.5 kg water of around $50^0$C was taken in Cylinder-1 and after the process, we got 0.2 kg of condensed water in Cylinder-2 though around 0.3 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2.5 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 79 K

Energy required to heat up $21^0$C water into $100^0$C water = ms$\Delta$T
= 825.6 kJ

Energy required to convert $100^0$C 0.2 kg water into $100^0$C 0.2 kg vapour
= mass x latent heat
= 0.2 kg x 2260 kJ/kg
= 452 kJ

Total energy required for getting 0.3 kg of condensed water from 2.5 kg of water in conventional process is 1277.6 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 135 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 135 sec = 120 Watt x 135s = 16.2 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.2}{2.5}$ x 100
= 14%

Total Energy Savings = $\frac{(1277.6 - 16.2)\ \text{kJ}}{1277.6\ \text{kJ}}$ x 100 = 98.7%

*Table 5 Experimental Data: Test 5*

**Vacuum Desalination Experiment** **Data Set** **5**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (º C) : | 21 | R Humidity (%): | 68 | Weight of Feed (1) water (kg): | 2.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | **Feed Water Vessel (Cylinder-1)** | | | **Desalinated Water Vessel (Cylinder-2)** | | | **Condenser** |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (º C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (º C) | Gauge Pressure 2 (kPa) | Temperature 3 (º C) |
| Before start (Empty) | 4.45 | 21 | -2 | 4.45 | 21 | 0 | 22 |
| After Start (00min)<br>Pump on | 6.95 | 50 | -2 | 4.45 | 21.5 | 0 | 22 |
| After Start (02min 15sec)<br>Pump off | | 39 | -99 | | 21.8 | -97 | 24 |
| After Start (10min) | | 30 | -100 | | 22.5 | -97 | 24 |
| After Start (15min) | | 26.5 | -100 | | 22.5 | -97 | 23.8 |
| Finish (16min) | 6.65 | 26 | -2 | 4.65 | 22.5 | 0 | 23.8 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 5. In this table, if we take water of $50^0$C then 10 gram of water would be evaporated in the first attempt and the temperature of the rest of the water would become $47.7^0$C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 2.50 | 0.01 | 23.8 | 2.3 | 47.7 | 10.0 |
| 47.7 | 2.49 | 0.01 | 23.8 | 2.3 | 45.4 | 10.0 |
| 45.4 | 2.48 | 0.01 | 23.8 | 2.3 | 43.1 | 10.0 |
| 43.1 | 2.47 | 0.01 | 23.8 | 2.3 | 40.8 | 10.0 |
| 40.8 | 2.46 | 0.01 | 23.8 | 2.3 | 38.5 | 10.0 |
| 38.5 | 2.45 | 0.01 | 23.8 | 2.3 | 36.1 | 10.0 |
| 36.1 | 2.44 | 0.01 | 23.8 | 2.3 | 33.8 | 10.0 |
| 33.8 | 2.43 | 0.01 | 23.8 | 2.4 | 31.4 | 10.0 |
| 31.4 | 2.42 | 0.01 | 23.8 | 2.4 | 29.1 | 10.0 |
| 29.1 | 2.41 | 0.01 | 23.8 | 2.4 | 26.7 | 10.0 |
| 26.7 | 2.40 | 0.01 | 23.8 | 2.4 | 24.3 | 10.0 |
| 24.3 | 2.39 | 0.01 | 23.8 | 2.4 | 21.9 | 10.0 |
| 21.9 | 2.38 | 0.01 | 23.8 | 2.4 | 19.5 | 10.0 |
| 19.5 | 2.37 | 0.01 | 23.8 | 2.4 | 17.1 | 10.0 |
| 17.1 | 2.36 | 0.01 | 23.8 | 2.4 | 14.7 | 10.0 |
| 14.7 | 2.35 | 0.01 | 23.8 | 2.4 | 12.2 | 10.0 |
| 12.2 | 2.34 | 0.01 | 23.8 | 2.4 | 9.8 | 10.0 |
| 9.8 | 2.33 | 0.01 | 23.8 | 2.5 | 7.3 | 10.0 |
| 7.3 | 2.32 | 0.01 | 23.8 | 2.5 | 4.9 | 10.0 |
| 4.9 | 2.31 | 0.01 | 23.8 | 2.5 | 2.4 | 10.0 |
| 2.4 | 2.30 | 0.01 | 23.8 | 2.5 | -0.1 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became $21.9^0$C and 0.13 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.13 kg of water in Cylinder-2. But from the experiment, we got 0.2 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 5. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 5.

| Initial Temp (${}^{0}$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest (${}^{0}$C) | Final Temperature (${}^{0}$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 2.50 | 0.0050 | 11.9 | 1.1 | 48.9 | 5.0 |
| 48.9 | 2.50 | 0.0050 | 11.9 | 1.1 | 47.7 | 5.0 |
| 47.7 | 2.49 | 0.0050 | 11.9 | 1.1 | 46.6 | 5.0 |
| 46.6 | 2.49 | 0.0050 | 11.9 | 1.1 | 45.4 | 5.0 |
| 45.4 | 2.48 | 0.0050 | 11.9 | 1.2 | 44.3 | 5.0 |
| 44.3 | 2.48 | 0.0050 | 11.9 | 1.2 | 43.1 | 5.0 |
| 43.1 | 2.47 | 0.0050 | 11.9 | 1.2 | 42.0 | 5.0 |
| 42.0 | 2.47 | 0.0050 | 11.9 | 1.2 | 40.8 | 5.0 |
| 40.8 | 2.46 | 0.0050 | 11.9 | 1.2 | 39.6 | 5.0 |
| 39.6 | 2.46 | 0.0050 | 11.9 | 1.2 | 38.5 | 5.0 |
| 38.5 | 2.45 | 0.0050 | 11.9 | 1.2 | 37.3 | 5.0 |
| 37.3 | 2.45 | 0.0050 | 11.9 | 1.2 | 36.1 | 5.0 |
| 36.1 | 2.44 | 0.0050 | 11.9 | 1.2 | 35.0 | 5.0 |
| 35.0 | 2.44 | 0.0050 | 11.9 | 1.2 | 33.8 | 5.0 |
| 33.8 | 2.43 | 0.0050 | 11.9 | 1.2 | 32.6 | 5.0 |
| 32.6 | 2.43 | 0.0050 | 11.9 | 1.2 | 31.5 | 5.0 |
| 31.5 | 2.42 | 0.0050 | 11.9 | 1.2 | 30.3 | 5.0 |
| 30.3 | 2.42 | 0.0050 | 11.9 | 1.2 | 29.1 | 5.0 |
| 29.1 | 2.41 | 0.0050 | 11.9 | 1.2 | 27.9 | 5.0 |
| 27.9 | 2.41 | 0.0050 | 11.9 | 1.2 | 26.7 | 5.0 |
| 26.7 | 2.40 | 0.0050 | 11.9 | 1.2 | 25.5 | 5.0 |
| 25.5 | 2.40 | 0.0050 | 11.9 | 1.2 | 24.3 | 5.0 |
| 24.3 | 2.39 | 0.0050 | 11.9 | 1.2 | 23.1 | 5.0 |
| 23.1 | 2.39 | 0.0050 | 11.9 | 1.2 | 22.0 | 5.0 |
| 22.0 | 2.38 | 0.0050 | 11.9 | 1.2 | 20.8 | 5.0 |
| 20.8 | 2.38 | 0.0050 | 11.9 | 1.2 | 19.6 | 5.0 |
| 19.6 | 2.37 | 0.0050 | 11.9 | 1.2 | 18.3 | 5.0 |
| 18.3 | 2.37 | 0.0050 | 11.9 | 1.2 | 17.1 | 5.0 |
| 17.1 | 2.36 | 0.0050 | 11.9 | 1.2 | 15.9 | 5.0 |
| 15.9 | 2.36 | 0.0050 | 11.9 | 1.2 | 14.7 | 5.0 |
| 14.7 | 2.35 | 0.0050 | 11.9 | 1.2 | 13.5 | 5.0 |
| 13.5 | 2.35 | 0.0050 | 11.9 | 1.2 | 12.3 | 5.0 |
| 12.3 | 2.34 | 0.0050 | 11.9 | 1.2 | 11.1 | 5.0 |
| 11.1 | 2.34 | 0.0050 | 11.9 | 1.2 | 9.8 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 22$^0$C and 0.125 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.125 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 120 gram of water should be evaporated for 0-gram step from the graph below.

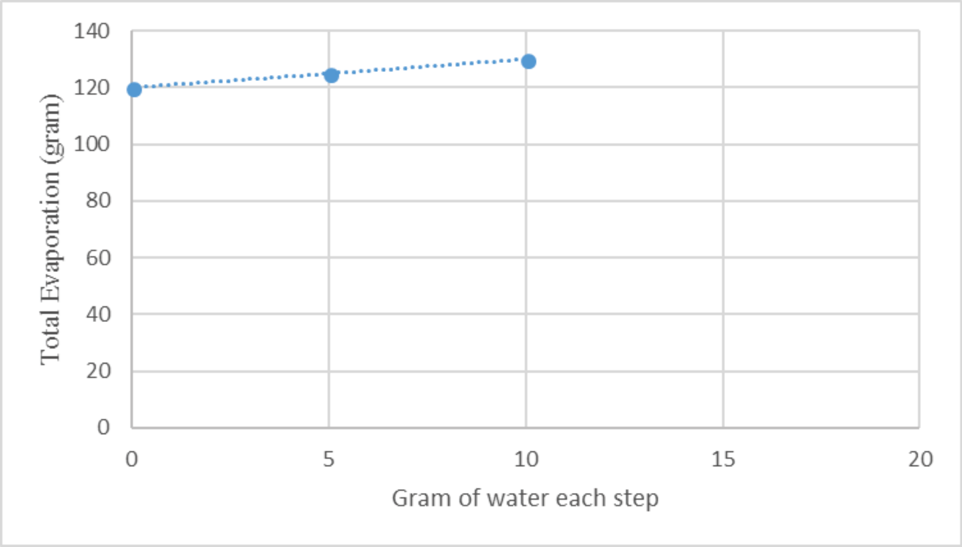


Figure 49 Extrapolation for 0-gram step (Test 5)

## 4.4 Test 6 (Operating Condition A)

In this set of experimental data (Table 6), 1.5 kg water of around 75$^0$C was taken in Cylinder-1 and after the process, we got 0.22 kg of condensed water in Cylinder-2 though around 0.3 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.5 kg
S= Specific heat of water 4.18 kJ/kg-K
ΔT= 79 K

Energy required to heat up 21$^0$C water into 100$^0$C water = msΔT
= 495.3 kJ

Energy required to convert 100$^0$C 0.22 kg water into 100$^0$C 0.22 kg vapour
= mass x latent heat
= 0.22 kg x 2260 kJ/kg
= 497.2 kJ

Total energy required for getting 0.22 kg of condensed water from 1.5 kg of water in conventional process is 992.5 kJ

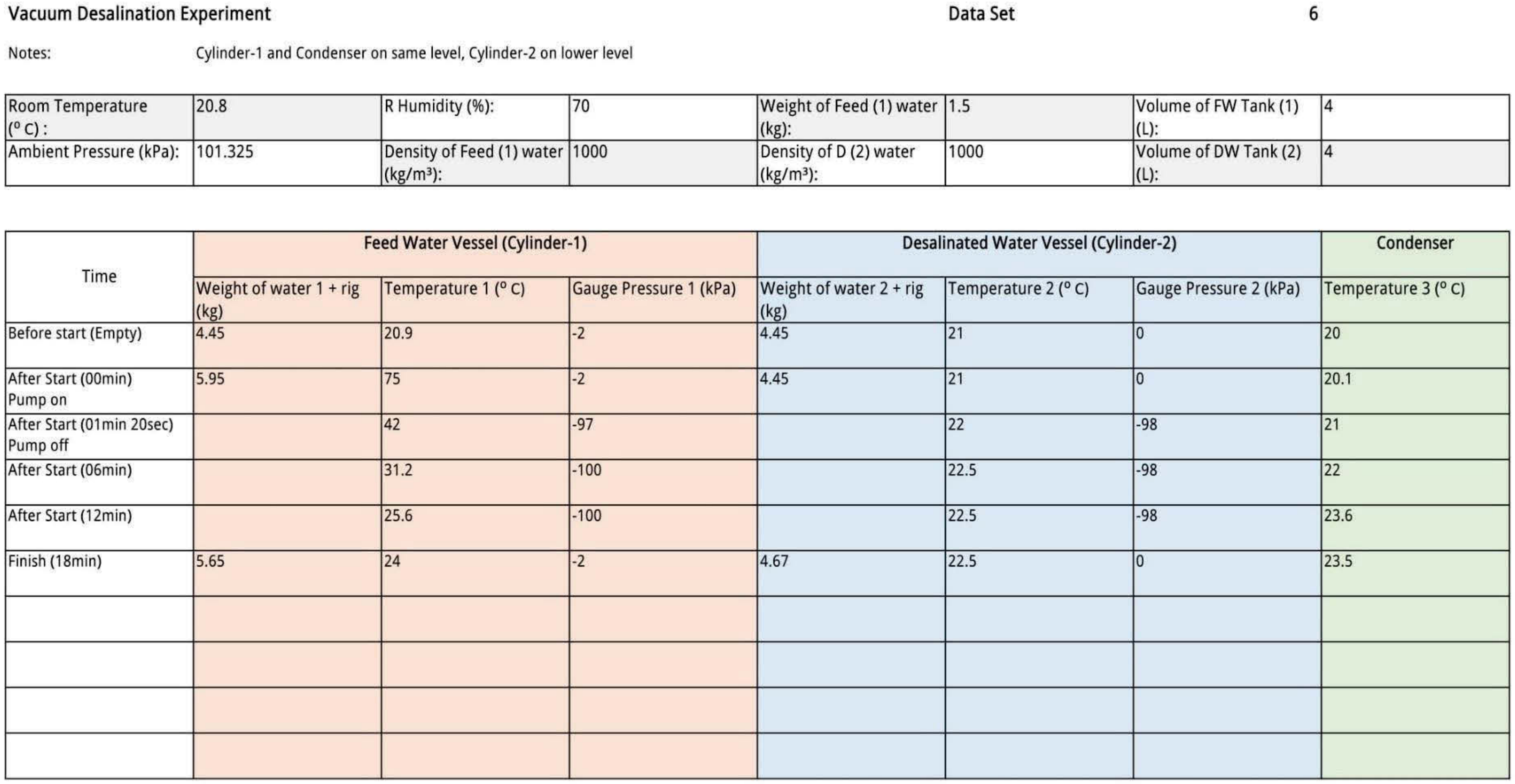
In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 80 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 80 sec = 120 Watt x 80s = 9.6 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.22}{1.5}$ x 100
= 14.7%

Total Energy Savings = $\frac{(992.5-9.6)\text{ kJ}}{992.5\text{ kJ}}$ x 100 = 99%

Table 6 Experimental Data: Test 6



**Vacuum Desalination Experiment** **Data Set** **6**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (º C) : | 20.8 | R Humidity (%): | 70 | Weight of Feed (1) water (kg): | 1.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (º C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (º C) | Gauge Pressure 2 (kPa) | Temperature 3 (º C) |
| Before start (Empty) | 4.45 | 20.9 | -2 | 4.45 | 21 | 0 | 20 |
| After Start (00min) Pump on | 5.95 | 75 | -2 | 4.45 | 21 | 0 | 20.1 |
| After Start (01min 20sec) Pump off | | 42 | -97 | | 22 | -98 | 21 |
| After Start (06min) | | 31.2 | -100 | | 22.5 | -98 | 22 |
| After Start (12min) | | 25.6 | -100 | | 22.5 | -98 | 23.6 |
| Finish (18min) | 5.65 | 24 | -2 | 4.67 | 22.5 | 0 | 23.5 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 6. In this table, if we take water of 75$^0$C then 10 gram of water would be evaporated in the first attempt and the temperature of the rest of the water would become 71.2$^0$C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 75.0 | 1.50 | 0.01 | 23.8 | 3.8 | 71.2 | 10.0 |
| 71.2 | 1.49 | 0.01 | 23.8 | 3.8 | 67.3 | 10.0 |
| 67.3 | 1.48 | 0.01 | 23.8 | 3.9 | 63.5 | 10.0 |
| 63.5 | 1.47 | 0.01 | 23.8 | 3.9 | 59.6 | 10.0 |
| 59.6 | 1.46 | 0.01 | 23.8 | 3.9 | 55.6 | 10.0 |
| 55.6 | 1.45 | 0.01 | 23.8 | 4.0 | 51.7 | 10.0 |
| 51.7 | 1.44 | 0.01 | 23.8 | 4.0 | 47.7 | 10.0 |
| 47.7 | 1.43 | 0.01 | 23.8 | 4.0 | 43.7 | 10.0 |
| 43.7 | 1.42 | 0.01 | 23.8 | 4.0 | 39.6 | 10.0 |
| 39.6 | 1.41 | 0.01 | 23.8 | 4.1 | 35.6 | 10.0 |
| 35.6 | 1.40 | 0.01 | 23.8 | 4.1 | 31.5 | 10.0 |
| 31.5 | 1.39 | 0.01 | 23.8 | 4.1 | 27.3 | 10.0 |
| 27.3 | 1.38 | 0.01 | 23.8 | 4.2 | 23.2 | 10.0 |
| 23.2 | 1.37 | 0.01 | 23.8 | 4.2 | 19.0 | 10.0 |
| 19.0 | 1.36 | 0.01 | 23.8 | 4.2 | 14.8 | 10.0 |
| 14.8 | 1.35 | 0.01 | 23.8 | 4.3 | 10.5 | 10.0 |
| 10.5 | 1.34 | 0.01 | 23.8 | 4.3 | 6.2 | 10.0 |
| 6.2 | 1.33 | 0.01 | 23.8 | 4.3 | 1.9 | 10.0 |
| 1.9 | 1.32 | 0.01 | 23.8 | 4.3 | -2.4 | 10.0 |
| -2.4 | 1.31 | 0.01 | 23.8 | 4.4 | -6.8 | 10.0 |
| -6.8 | 1.30 | 0.01 | 23.8 | 4.4 | -11.2 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became 23.2$^0$C and 0.14 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.14 kg of water in Cylinder-2. But from the experiment, we got 0.22 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

### Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 6. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 6.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 75.0 | 1.50 | 0.0050 | 11.9 | 1.9 | 73.1 | 5.0 |
| 73.1 | 1.50 | 0.0050 | 11.9 | 1.9 | 71.2 | 5.0 |
| 71.2 | 1.49 | 0.0050 | 11.9 | 1.9 | 69.3 | 5.0 |
| 69.3 | 1.49 | 0.0050 | 11.9 | 1.9 | 67.3 | 5.0 |
| 67.3 | 1.48 | 0.0050 | 11.9 | 1.9 | 65.4 | 5.0 |
| 65.4 | 1.48 | 0.0050 | 11.9 | 1.9 | 63.5 | 5.0 |
| 63.5 | 1.47 | 0.0050 | 11.9 | 1.9 | 61.5 | 5.0 |
| 61.5 | 1.47 | 0.0050 | 11.9 | 2.0 | 59.6 | 5.0 |
| 59.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 57.6 | 5.0 |
| 57.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 55.7 | 5.0 |
| 55.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 53.7 | 5.0 |
| 53.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 51.7 | 5.0 |
| 51.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 49.7 | 5.0 |
| 49.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 47.7 | 5.0 |
| 47.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 45.7 | 5.0 |
| 45.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 43.7 | 5.0 |
| 43.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 41.7 | 5.0 |
| 41.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 39.7 | 5.0 |
| 39.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 37.7 | 5.0 |
| 37.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 35.6 | 5.0 |
| 35.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 33.6 | 5.0 |
| 33.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 31.5 | 5.0 |
| 31.5 | 1.39 | 0.0050 | 11.9 | 2.1 | 29.5 | 5.0 |
| 29.5 | 1.39 | 0.0050 | 11.9 | 2.1 | 27.4 | 5.0 |
| 27.4 | 1.38 | 0.0050 | 11.9 | 2.1 | 25.4 | 5.0 |
| 25.4 | 1.38 | 0.0050 | 11.9 | 2.1 | 23.3 | 5.0 |
| 23.3 | 1.37 | 0.0050 | 11.9 | 2.1 | 21.2 | 5.0 |
| 21.2 | 1.37 | 0.0050 | 11.9 | 2.1 | 19.1 | 5.0 |
| 19.1 | 1.36 | 0.0050 | 11.9 | 2.1 | 17.0 | 5.0 |
| 17.0 | 1.36 | 0.0050 | 11.9 | 2.1 | 14.9 | 5.0 |
| 14.9 | 1.35 | 0.0050 | 11.9 | 2.1 | 12.8 | 5.0 |
| 12.8 | 1.35 | 0.0050 | 11.9 | 2.1 | 10.6 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 10.6 | 1.34 | 0.0050 | 11.9 | 2.1 | 8.5 | 5.0 |
| 8.5 | 1.34 | 0.0050 | 11.9 | 2.1 | 6.4 | 5.0 |
| 6.4 | 1.33 | 0.0050 | 11.9 | 2.1 | 4.2 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became $23.3^0$C and 0.135 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.135 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 130 gram of water should be evaporated for 0-gram step from the graph below.

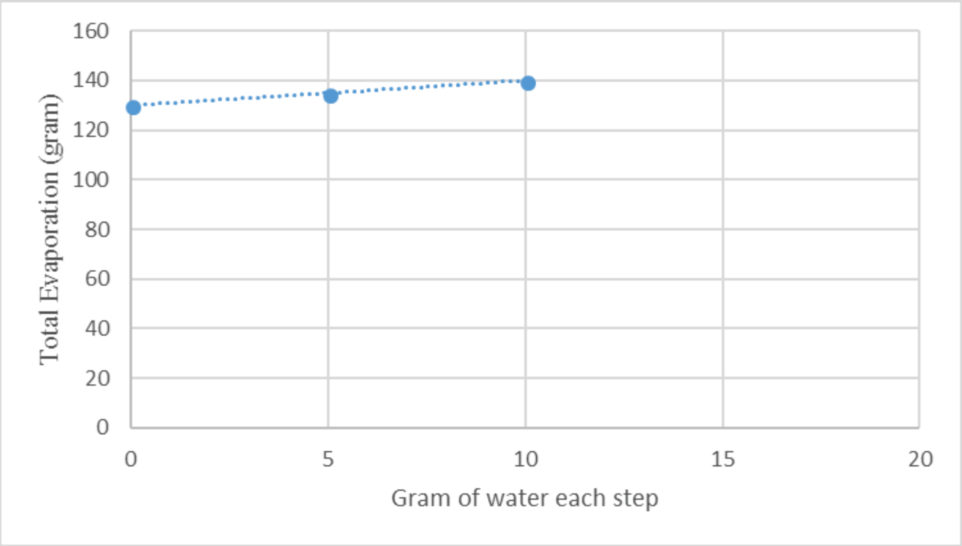


Figure 50 Extrapolation for 0-gram step (Test 6)

# 4.5 Test 8 (Operating Condition B)

In this set of experimental data (Table 7), 1.95 kg water of around 74$^0$C was taken in Cylinder-1 and after the process, we got 0.33 kg of condensed water in Cylinder-2 though around 0.4 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.95 kg
S= Specific heat of water 4.18 kJ/kg-K
ΔT= 80 K

Energy required to heat up 20$^0$C water into 100$^0$C water = msΔT
= 652.1 kJ

Energy required to convert 100$^0$C 0.33 kg water into 100$^0$C 0.33 kg vapour
= mass x latent heat
= 0.33 kg x 2260 kJ/kg
= 745.8 kJ

Total energy required for getting 0.33 kg of condensed water from 1.95 kg of water in conventional process is 1397.9 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 120 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 120 sec = 120 Watt x 120s = 14.4 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.33}{1.95}$ x 100
= 16.9%

Total Energy Savings = $\frac{(1397.9 - 14.4)\text{ kJ}}{1397.9\text{ kJ}}$ x 100 = 98.9%

*Table 7 Experimental Data: Test 8*

**Vacuum Desalination Experiment** **Data Set** **8**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 20 | R Humidity (%): | 65 | Weight of Feed (1) water (kg): | 1.95 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 20.7 | -2 | 4.45 | 20.5 | 0 | 23.3 |
| After Start (00min) Pump on | 6.4 | 74 | -2 | 4.45 | 20.5 | 0 | 24 |
| After Start (01min) | | 73 | -95 | | 20.5 | -97 | 24.3 |
| After Start (02min) Pump off | | 68.3 | -99 | | 21 | -97 | 24.4 |
| After Start (10min) | | 43 | -99 | | 24 | -97 | 24.8 |
| After Start (20min) | | 29 | -100 | | 24 | -98 | 25 |
| Finish (21min) | 6 | 26 | -2 | 4.78 | 24 | 0 | 25 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 8. In this table, if we take water of 74$^0$C then 10 gram of water would be evaporated in the first attempt and the temperature of the rest of the water would become 71.1$^0$C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 74.0 | 1.95 | 0.01 | 23.8 | 2.9 | 71.1 | 10.0 |
| 71.1 | 1.94 | 0.01 | 23.8 | 3.0 | 68.1 | 10.0 |
| 68.1 | 1.93 | 0.01 | 23.8 | 3.0 | 65.1 | 10.0 |
| 65.1 | 1.92 | 0.01 | 23.8 | 3.0 | 62.2 | 10.0 |
| 62.2 | 1.91 | 0.01 | 23.8 | 3.0 | 59.2 | 10.0 |
| 59.2 | 1.90 | 0.01 | 23.8 | 3.0 | 56.2 | 10.0 |
| 56.2 | 1.89 | 0.01 | 23.8 | 3.0 | 53.1 | 10.0 |
| 53.1 | 1.88 | 0.01 | 23.8 | 3.0 | 50.1 | 10.0 |
| 50.1 | 1.87 | 0.01 | 23.8 | 3.1 | 47.0 | 10.0 |
| 47.0 | 1.86 | 0.01 | 23.8 | 3.1 | 43.9 | 10.0 |
| 43.9 | 1.85 | 0.01 | 23.8 | 3.1 | 40.8 | 10.0 |
| 40.8 | 1.84 | 0.01 | 23.8 | 3.1 | 37.7 | 10.0 |
| 37.7 | 1.83 | 0.01 | 23.8 | 3.1 | 34.6 | 10.0 |
| 34.6 | 1.82 | 0.01 | 23.8 | 3.1 | 31.4 | 10.0 |
| 31.4 | 1.81 | 0.01 | 23.8 | 3.2 | 28.3 | 10.0 |
| 28.3 | 1.80 | 0.01 | 23.8 | 3.2 | 25.1 | 10.0 |
| 25.1 | 1.79 | 0.01 | 23.8 | 3.2 | 21.9 | 10.0 |
| 21.9 | 1.78 | 0.01 | 23.8 | 3.2 | 18.7 | 10.0 |
| 18.7 | 1.77 | 0.01 | 23.8 | 3.2 | 15.4 | 10.0 |
| 15.4 | 1.76 | 0.01 | 23.8 | 3.3 | 12.2 | 10.0 |
| 12.2 | 1.75 | 0.01 | 23.8 | 3.3 | 8.9 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became 21.9$^0$C and 0.18 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.18 kg of water in Cylinder-2. But from the experiment, we got 0.33 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

### Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 8. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 8.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 74.0 | 1.95 | 0.0050 | 11.9 | 1.5 | 72.5 | 5.0 |
| 72.5 | 1.95 | 0.0050 | 11.9 | 1.5 | 71.1 | 5.0 |
| 71.1 | 1.94 | 0.0050 | 11.9 | 1.5 | 69.6 | 5.0 |
| 69.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 68.1 | 5.0 |
| 68.1 | 1.93 | 0.0050 | 11.9 | 1.5 | 66.6 | 5.0 |
| 66.6 | 1.93 | 0.0050 | 11.9 | 1.5 | 65.2 | 5.0 |
| 65.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 63.7 | 5.0 |
| 63.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 62.2 | 5.0 |
| 62.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 60.7 | 5.0 |
| 60.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 59.2 | 5.0 |
| 59.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 57.7 | 5.0 |
| 57.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 56.2 | 5.0 |
| 56.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 54.7 | 5.0 |
| 54.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 53.1 | 5.0 |
| 53.1 | 1.88 | 0.0050 | 11.9 | 1.5 | 51.6 | 5.0 |
| 51.6 | 1.88 | 0.0050 | 11.9 | 1.5 | 50.1 | 5.0 |
| 50.1 | 1.87 | 0.0050 | 11.9 | 1.5 | 48.6 | 5.0 |
| 48.6 | 1.87 | 0.0050 | 11.9 | 1.5 | 47.0 | 5.0 |
| 47.0 | 1.86 | 0.0050 | 11.9 | 1.5 | 45.5 | 5.0 |
| 45.5 | 1.86 | 0.0050 | 11.9 | 1.5 | 44.0 | 5.0 |
| 44.0 | 1.85 | 0.0050 | 11.9 | 1.5 | 42.4 | 5.0 |
| 42.4 | 1.85 | 0.0050 | 11.9 | 1.5 | 40.9 | 5.0 |
| 40.9 | 1.84 | 0.0050 | 11.9 | 1.6 | 39.3 | 5.0 |
| 39.3 | 1.84 | 0.0050 | 11.9 | 1.6 | 37.8 | 5.0 |
| 37.8 | 1.83 | 0.0050 | 11.9 | 1.6 | 36.2 | 5.0 |
| 36.2 | 1.83 | 0.0050 | 11.9 | 1.6 | 34.6 | 5.0 |
| 34.6 | 1.82 | 0.0050 | 11.9 | 1.6 | 33.1 | 5.0 |
| 33.1 | 1.82 | 0.0050 | 11.9 | 1.6 | 31.5 | 5.0 |
| 31.5 | 1.81 | 0.0050 | 11.9 | 1.6 | 29.9 | 5.0 |
| 29.9 | 1.81 | 0.0050 | 11.9 | 1.6 | 28.3 | 5.0 |
| 28.3 | 1.80 | 0.0050 | 11.9 | 1.6 | 26.8 | 5.0 |
| 26.8 | 1.80 | 0.0050 | 11.9 | 1.6 | 25.2 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.2 | 1.79 | 0.0050 | 11.9 | 1.6 | 23.6 | 5.0 |
| 23.6 | 1.79 | 0.0050 | 11.9 | 1.6 | 22.0 | 5.0 |
| 22.0 | 1.78 | 0.0050 | 11.9 | 1.6 | 20.4 | 5.0 |
| 20.4 | 1.78 | 0.0050 | 11.9 | 1.6 | 18.8 | 5.0 |
| 18.8 | 1.77 | 0.0050 | 11.9 | 1.6 | 17.1 | 5.0 |
| 17.1 | 1.77 | 0.0050 | 11.9 | 1.6 | 15.5 | 5.0 |
| 15.5 | 1.76 | 0.0050 | 11.9 | 1.6 | 13.9 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became $22^0$C and 0.175 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.175 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 170 gram of water should be evaporated for 0-gram step from the graph below.

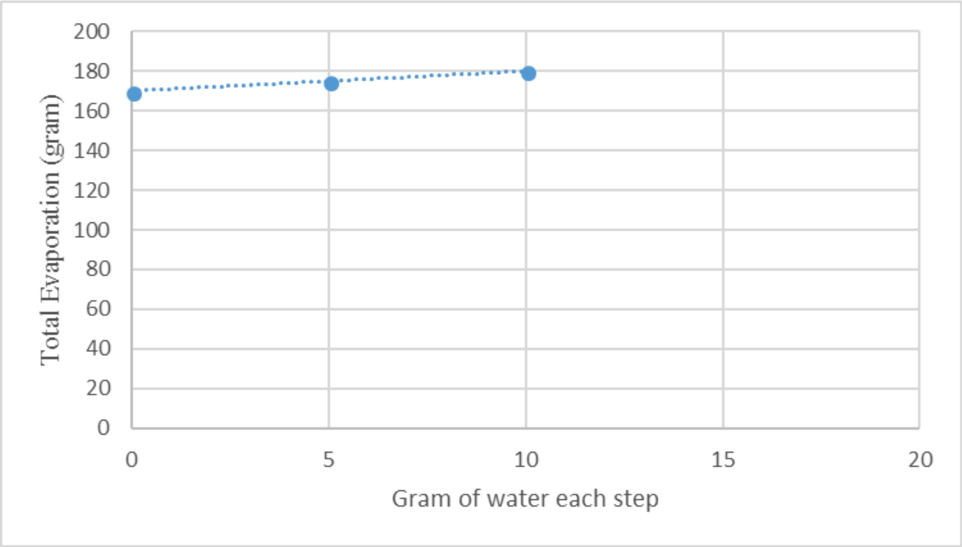


Figure 51 Extrapolation for 0-gram step (Test 8)

# 4.6 Test 10 (Operating Condition C)

In this set of experimental data (Table 8), 2.5 kg water of around 73$^0$C was taken in Cylinder-1 and after the process, we got 0.39 kg of condensed water in Cylinder-2 though around 0.45 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2.5 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 77 K

Energy required to heat up 23$^0$C water into 100$^0$C water = ms$\Delta$T
= 804.65 kJ

Energy required to convert 100$^0$C 0.39 kg water into 100$^0$C 0.39 kg vapour
= mass x latent heat
= 0.39 kg x 2260 kJ/kg
= 881.4 kJ

Total energy required for getting 0.39 kg of condensed water from 2.5 kg of water in conventional process is 1686.1 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 135 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 135 sec = 120 Watt x 135s = 16.2 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.39}{2.5}$ x 100
= 15.6%

Total Energy Savings = $\frac{(1686.1 - 16.2)\text{ kJ}}{1686.1\text{ kJ}}$ x 100 = 99.04%

*Table 8 Experimental Data: Test 10*

**Vacuum Desalination Experiment** **Data Set** **10**

Notes: Cylinder-1 on upper level than Condenser, Cylinder-2 on lower level than Condenser, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 23 | R Humidity (%): | 65 | Weight of Feed (1) water (kg): | 2.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 23 | -2 | 4.45 | 23 | 0 | 22 |
| After Start (00min) Pump on | 6.95 | 73 | -2 | 4.45 | 23.1 | 0 | 22 |
| After Start (02min 15sec) Pump off | | 48 | -99 | | 23.5 | -97 | 23 |
| After Start (10min) | | 31 | -100 | | 23.5 | -97 | 23.5 |
| After Start (15min) | | 28 | -100 | | 23.8 | -97 | 23.9 |
| Finish (16min) | 6.5 | 27.8 | -2 | 4.84 | 23.8 | 0 | 23.8 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 10. In this table, if we take water of 73⁰C then 10 gram water would be evaporated in the first attempt and the temperature of the rest of the water would become 70.7⁰C to supply the required latent heat of evaporated water and this would continue in step by step as calculated below.

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp (⁰C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest (⁰C) | Final Temperature (⁰C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.0 | 2.50 | 0.01 | 23.8 | 2.3 | 70.7 | 10.0 |
| 70.7 | 2.49 | 0.01 | 23.8 | 2.3 | 68.4 | 10.0 |
| 68.4 | 2.48 | 0.01 | 23.8 | 2.3 | 66.1 | 10.0 |
| 66.1 | 2.47 | 0.01 | 23.8 | 2.3 | 63.8 | 10.0 |
| 63.8 | 2.46 | 0.01 | 23.8 | 2.3 | 61.5 | 10.0 |
| 61.5 | 2.45 | 0.01 | 23.8 | 2.3 | 59.1 | 10.0 |
| 59.1 | 2.44 | 0.01 | 23.8 | 2.3 | 56.8 | 10.0 |
| 56.8 | 2.43 | 0.01 | 23.8 | 2.4 | 54.4 | 10.0 |
| 54.4 | 2.42 | 0.01 | 23.8 | 2.4 | 52.1 | 10.0 |
| 52.1 | 2.41 | 0.01 | 23.8 | 2.4 | 49.7 | 10.0 |
| 49.7 | 2.40 | 0.01 | 23.8 | 2.4 | 47.3 | 10.0 |
| 47.3 | 2.39 | 0.01 | 23.8 | 2.4 | 44.9 | 10.0 |
| 44.9 | 2.38 | 0.01 | 23.8 | 2.4 | 42.5 | 10.0 |
| 42.5 | 2.37 | 0.01 | 23.8 | 2.4 | 40.1 | 10.0 |
| 40.1 | 2.36 | 0.01 | 23.8 | 2.4 | 37.7 | 10.0 |
| 37.7 | 2.35 | 0.01 | 23.8 | 2.4 | 35.2 | 10.0 |
| 35.2 | 2.34 | 0.01 | 23.8 | 2.4 | 32.8 | 10.0 |
| 32.8 | 2.33 | 0.01 | 23.8 | 2.5 | 30.3 | 10.0 |
| 30.3 | 2.32 | 0.01 | 23.8 | 2.5 | 27.9 | 10.0 |
| 27.9 | 2.31 | 0.01 | 23.8 | 2.5 | 25.4 | 10.0 |
| 25.4 | 2.30 | 0.01 | 23.8 | 2.5 | 22.9 | 10.0 |
| 22.9 | 2.29 | 0.01 | 23.8 | 2.5 | 20.4 | 10.0 |

From the above calculation, we found that water was evaporated until the temperature became 22.9⁰C and 0.22 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.22 kg of water in Cylinder-2. But from the experiment, we got 0.39 kg of condensed water in Cylinder-2. This has been discussed in Test Results.

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for Test 10. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of Test 10.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated Water (gram) |
|---|---|---|---|---|---|---|
| 73.0 | 2.50 | 0.0050 | 11.9 | 1.1 | 71.9 | 5.0 |
| 71.9 | 2.50 | 0.0050 | 11.9 | 1.1 | 70.7 | 5.0 |
| 70.7 | 2.49 | 0.0050 | 11.9 | 1.1 | 69.6 | 5.0 |
| 69.6 | 2.49 | 0.0050 | 11.9 | 1.1 | 68.4 | 5.0 |
| 68.4 | 2.48 | 0.0050 | 11.9 | 1.2 | 67.3 | 5.0 |
| 67.3 | 2.48 | 0.0050 | 11.9 | 1.2 | 66.1 | 5.0 |
| 66.1 | 2.47 | 0.0050 | 11.9 | 1.2 | 65.0 | 5.0 |
| 65.0 | 2.47 | 0.0050 | 11.9 | 1.2 | 63.8 | 5.0 |
| 63.8 | 2.46 | 0.0050 | 11.9 | 1.2 | 62.6 | 5.0 |
| 62.6 | 2.46 | 0.0050 | 11.9 | 1.2 | 61.5 | 5.0 |
| 61.5 | 2.45 | 0.0050 | 11.9 | 1.2 | 60.3 | 5.0 |
| 60.3 | 2.45 | 0.0050 | 11.9 | 1.2 | 59.1 | 5.0 |
| 59.1 | 2.44 | 0.0050 | 11.9 | 1.2 | 58.0 | 5.0 |
| 58.0 | 2.44 | 0.0050 | 11.9 | 1.2 | 56.8 | 5.0 |
| 56.8 | 2.43 | 0.0050 | 11.9 | 1.2 | 55.6 | 5.0 |
| 55.6 | 2.43 | 0.0050 | 11.9 | 1.2 | 54.5 | 5.0 |
| 54.5 | 2.42 | 0.0050 | 11.9 | 1.2 | 53.3 | 5.0 |
| 53.3 | 2.42 | 0.0050 | 11.9 | 1.2 | 52.1 | 5.0 |
| 52.1 | 2.41 | 0.0050 | 11.9 | 1.2 | 50.9 | 5.0 |
| 50.9 | 2.41 | 0.0050 | 11.9 | 1.2 | 49.7 | 5.0 |
| 49.7 | 2.40 | 0.0050 | 11.9 | 1.2 | 48.5 | 5.0 |
| 48.5 | 2.40 | 0.0050 | 11.9 | 1.2 | 47.3 | 5.0 |
| 47.3 | 2.39 | 0.0050 | 11.9 | 1.2 | 46.1 | 5.0 |
| 46.1 | 2.39 | 0.0050 | 11.9 | 1.2 | 45.0 | 5.0 |
| 45.0 | 2.38 | 0.0050 | 11.9 | 1.2 | 43.8 | 5.0 |
| 43.8 | 2.38 | 0.0050 | 11.9 | 1.2 | 42.6 | 5.0 |
| 42.6 | 2.37 | 0.0050 | 11.9 | 1.2 | 41.3 | 5.0 |
| 41.3 | 2.37 | 0.0050 | 11.9 | 1.2 | 40.1 | 5.0 |
| 40.1 | 2.36 | 0.0050 | 11.9 | 1.2 | 38.9 | 5.0 |
| 38.9 | 2.36 | 0.0050 | 11.9 | 1.2 | 37.7 | 5.0 |
| 37.7 | 2.35 | 0.0050 | 11.9 | 1.2 | 36.5 | 5.0 |
| 36.5 | 2.35 | 0.0050 | 11.9 | 1.2 | 35.3 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 35.3 | 2.34 | 0.0050 | 11.9 | 1.2 | 34.1 | 5.0 |
| 34.1 | 2.34 | 0.0050 | 11.9 | 1.2 | 32.8 | 5.0 |
| 32.8 | 2.33 | 0.0050 | 11.9 | 1.2 | 31.6 | 5.0 |
| 31.6 | 2.33 | 0.0050 | 11.9 | 1.2 | 30.4 | 5.0 |
| 30.4 | 2.32 | 0.0050 | 11.9 | 1.2 | 29.2 | 5.0 |
| 29.2 | 2.32 | 0.0050 | 11.9 | 1.2 | 27.9 | 5.0 |
| 27.9 | 2.31 | 0.0050 | 11.9 | 1.2 | 26.7 | 5.0 |
| 26.7 | 2.31 | 0.0050 | 11.9 | 1.2 | 25.5 | 5.0 |
| 25.5 | 2.30 | 0.0050 | 11.9 | 1.2 | 24.2 | 5.0 |
| 24.2 | 2.30 | 0.0050 | 11.9 | 1.2 | 23.0 | 5.0 |
| 23.0 | 2.29 | 0.0050 | 11.9 | 1.2 | 21.7 | 5.0 |
| 21.7 | 2.29 | 0.0050 | 11.9 | 1.2 | 20.5 | 5.0 |
| 20.5 | 2.28 | 0.0050 | 11.9 | 1.3 | 19.2 | 5.0 |
| 19.2 | 2.28 | 0.0050 | 11.9 | 1.3 | 18.0 | 5.0 |
| 18.0 | 2.27 | 0.0050 | 11.9 | 1.3 | 16.7 | 5.0 |
| 16.7 | 2.27 | 0.0050 | 11.9 | 1.3 | 15.5 | 5.0 |
| 15.5 | 2.26 | 0.0050 | 11.9 | 1.3 | 14.2 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 23$^{0}$C and 0.215 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.215 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 210 gram of water should be evaporated for 0-gram step from the graph below.

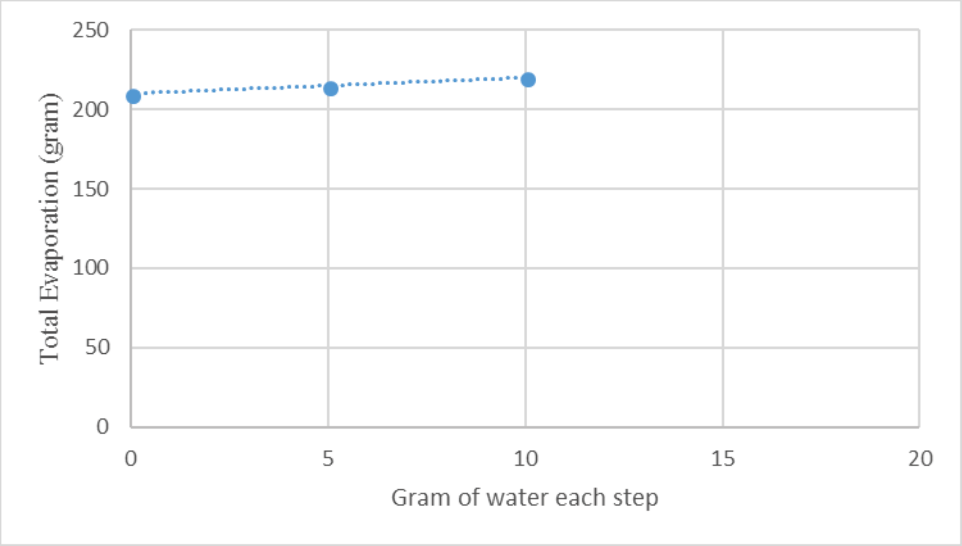
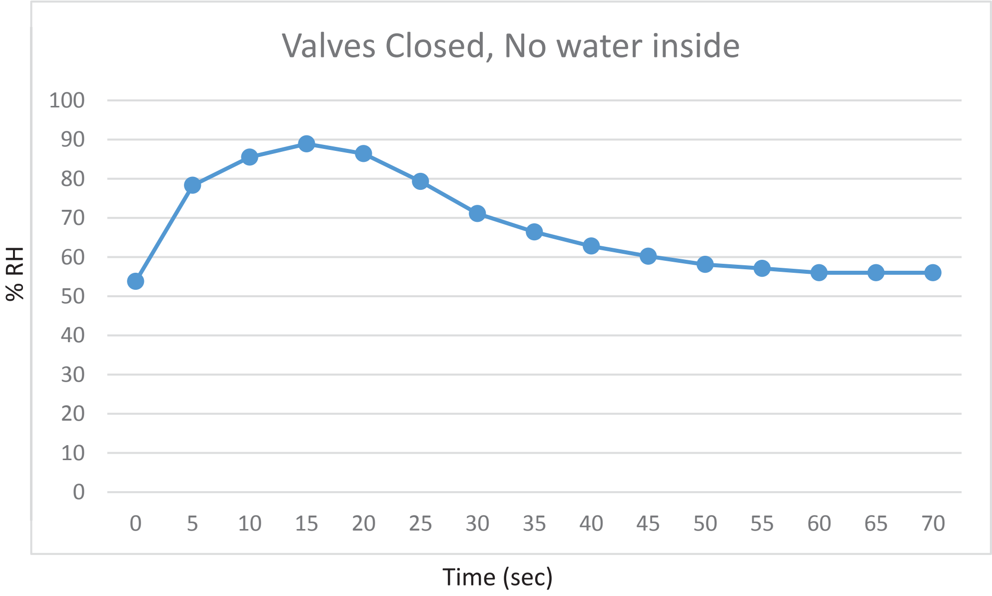
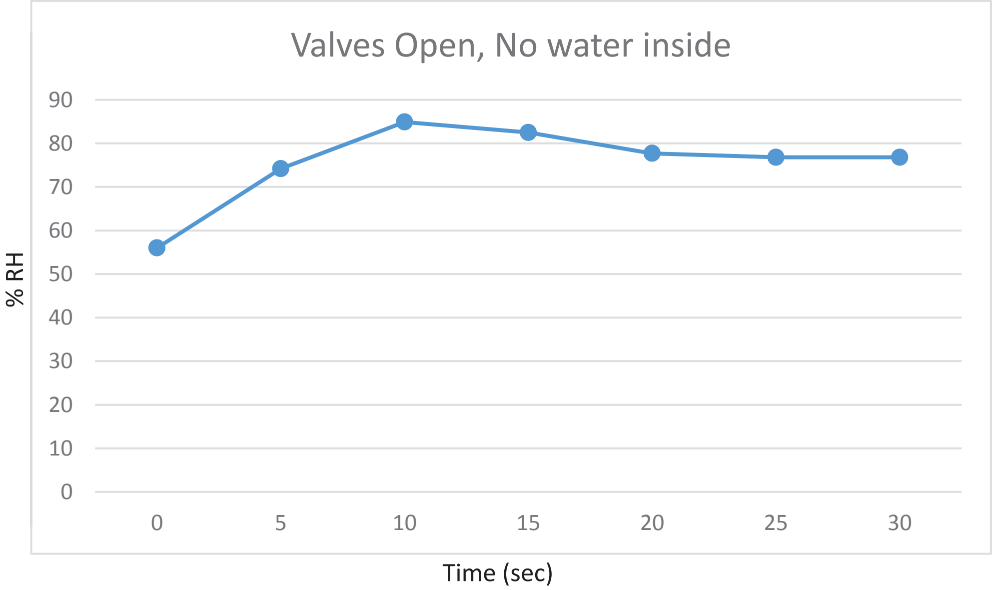


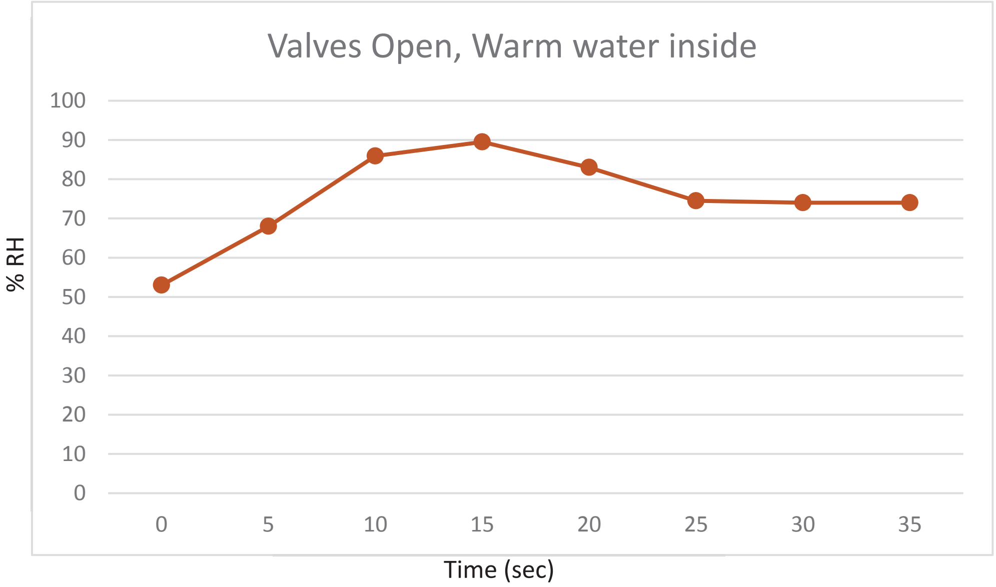
Figure 52 Extrapolation for 0-gram step (Test 10)

# 4.7 Investigation on Exhaust Air of Vacuum Pump

Several tests have been carried out on the exhaust air of the vacuum pump to find out whether it's emitting vapour from the tanks. The pump has been run in different circumstances and the exhaust air of the vacuum pump has been investigated to find out if there were any significant changes in the % of Relative Humidity. The results are as below.







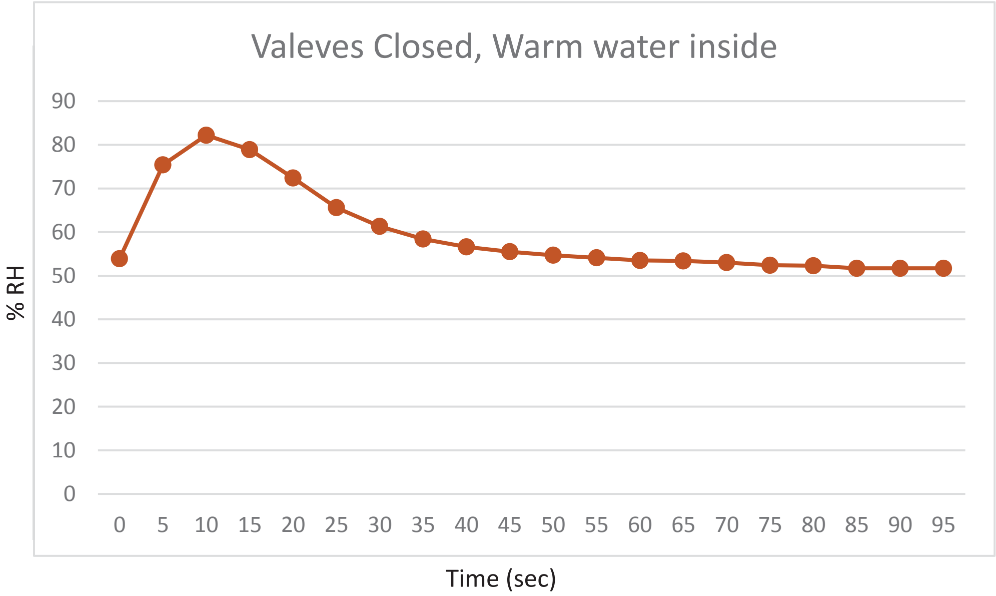


Figure 53 Time vs %RH of the exhaust air of vacuum pump at different circumstances

From the above curves, it is predictable that, the vapour content in the exhaust air doesn't have any significant change when the system is operated with warm water (at -98 kPa Gauge) than the normal conditions. This emphasises that the missing 0.1 kg of water has not been sucked out by the vacuum pump. There must be some other reason for that. One probable reason could be the uneven turns of coils in the condenser. Water can be stuck inside those uneven curves or turns of copper tube in the condenser. Further investigation would be carried out to solve this issue.

# 4.8 Test Results

Tests were run for various test rig orientation. The tests are labelled by the test number as listed above. The rate of distillation has been calculated for each test. The pressure and initial temperature of warm water have been varied test to test. Moreover, the position of cylinders and condenser has been changed several times to find the best result. The main principle of the test is to fill Cylinder-1 with warm water, close all the valves, record temperatures of cylinders and condenser water, then turn on the vacuum machine and keep it on until the desired vacuum pressure is achieved inside the cylinders. Once the desired vacuum pressure is achieved, we turned off the vacuum pump. The desired pressure is based on the room temperature. We selected a vacuum pressure at which water will evaporate slightly above our room temperature. Say, if our room temperature is 25°C, the desired vacuum pressure would be -97 kPa (gauge) at which water would evaporate at around 30°C.

We have investigated on the position of the cylinders. We have put Cylinder-1 and Condenser above the Cylinder-2 and got better results, to be exact we got around 15% more distillation when Cylinder- 2 was at a lower level.

## 4.8.1 Determine Test Base Result

For this research, a base set of results is required to compare all other test results for the different position of cylinders and also for different temperature and pressure.

All of the test results of this research were determined using the refurbished test rig where the position of cylinders can be modified and temperature and pressure can be controlled and monitored.

### 4.8.1.1 Cylinder- 1, 2 and Condenser on the same Level

Initially, we arranged our test rig in such a way that both the cylinders and the condenser remain on the same level. In this arrangement, the percentage of condensed water was so low. We got only 1% of distillation from this arrangement. We tried this for several runs but the results were not acceptable. No data has been listed for this orientation as it did not work according to our expectation. The reason for this should be the gravitational force. As the condenser and Cylinder- 2 were on the same level, in fact, the inlet of the Cylinder- 2 was slightly above the outlet of the condenser, condensed water intended to remain inside the condenser due to gravitational force. So, we changed the position of the cylinders.

### 4.8.1.2 Cylinder-1 and Condenser on the Same Level, Cylinder- 2 on Lower Level

We put the Cylinder- 2 on the lower level than the condenser. Due to the gravitational force, the water condensed inside the condenser should come through the Cylinder- 2. This idea worked when we started the test run. All the test run listed here have been done in this orientation of cylinders. From Test 1 to 7 we got similar results but when the initial temperature was taken higher the rate of water distillation was higher. Also, when we took more warm water the percentage of water distillation was better. This is because of the heat requirement of evaporation. The more heat water has the more amount of it would be evaporated. So, if we take more amount of warm water it would have more heat to enhance the evaporation. On an average 300 gram of water can be distilled in this process from 2 kg of water. But from the rate of evaporation calculation, we found that if it was possible to maintain a flow of water of constant temperature, more evaporation was possible. Also, there is a difference between the amount of water lost from Cylinder- 1 and the amount of water gained in Cylinder- 2. We lost more water than we gained. There could be two possible reasons:

- Water vapour being sucked out by the vacuum pump
- Leakage or immeasurability

We have investigated on both of these. We also had few tests where cylinder-1 was at an upper level than condenser and cylinder-2 was at lower level. But this didn't give us any significant difference in the percentage of distillation.

## 4.8.1.3 Investigating Moisture in Vacuum Pump Exhaust Air

To find out whether the vacuum pump is sucking out water vapour we did some investigation on its exhaust air. Using a humidity meter, we measured the % of Relative Humidity in the exhaust air of the vacuum in different circumstances (Listed in 4.15 Investigation on Exhaust Air of Vacuum Pump). From this investigation, we found out no water vapour has been sucked out by the pump during the process. That means the efficiency of the condenser is alright and all the water vapour has been condensed fully.

## 4.8.1.4 Investigating Condenser Coil

We did a visual investigation on the condenser coil as this is the only part we could not take the weight. We found that the turns of the coil were not evenly distributed and not all the turns have a downward slope. To check this more efficiently we ran one process immediately finishing another one. We found that in the first run the difference between the water we got from Cylinder-2 and the water we lost from Cylinder-1 was 100 gram but in the second run (immediately after previous) it was around 50 gram. That means water from the first run filled some of the uneven areas inside the coil for which we could get a better result from the second run. To overcome this the coil could be reformed by machining or a simple plate-based condenser coil can be used (see Appendix).

Figure 54 Condenser Coil (Coil OD: 200 mm)

# 5 Summary, Findings and Future Work

## 5.1 Research Summary

The main purpose of this research was to determine whether it is efficient to use vacuum pressure for water desalinating. To do this a test rig has been designed, fabricated and operated in the workshop and metrology laboratory of the University of Technology Sydney. AutoCAD has been used to design the test rig. Some preliminary simple tests have been done to predict the idea.

To analyse the efficiency of the new desalination idea, the prototype test rig has been used to investigate the evaporation and condensation of warm water in vacuum pressure. In the beginning, it was difficult to record any data from the test. This was due to the inability of the primary test rig to withstand vacuum pressure inside. To resolve this entire test rig was refurbished with new gas cylinders. These cylinders are Australian standard pressure vessels that can withstand high pressure and temperature.

Existing measuring sensors of metrology lab have been used in this experiment with proper calibration. The data has been recorded in different circumstances and orientations. Mathematical calculations have also been done based on the theories to determine and compare the data we got. Test location has been changed time to time to achieve data in different weather condition.

To comply with the safety standard of Australia, Safe Work Method Statement, Risk analysis have been done before starting the testing. This has been followed for every single location and test during the experiment. SOP, SWMS, General RA have been added in Appendix.

As our square shaped tanks were not able to withstand the required pressure and it started deforming when vacuum pressure raised inside, we added beams inside the tanks to give it extra support against collapsing. But this time the sealant broke up and the pressure inside the tanks became normal again. Once we found the shortcomings of the tanks we replaced both with two gas cylinders having all the requirements for pressure vessel according to the Australian standard. The revised experimental setup passed the leak test and it has been used as the test rig for the experiment.

In the first few tests the percentage of water we got from Cylinder-2 was low. So, we placed the Cylinder-2 on a lower level than the condenser and Cylinder-1. This arrangement worked well.

Moreover, there was a difference between the water we got from Cylinder-2 and the water we lost from Cylinder-1 which is not feasible as there was no leakage. So, we investigated the exhaust gas of the vacuum pump to confirm whether it was pulling away some part of evaporated water or not. But the investigation confirmed that there was no additional moisture in the exhaust air than normal. That also confirmed that the condenser is capable of condensing all the evaporated water passing through it. Finally, we found out that the turns of the condenser coil were not evenly distributed. Not all the turns were in downward condition in one side. So due to this some condensed water may stick inside the coil and wouldn't go through Cylinder-2 due to gravity. This was verified by couple of consequent tests.

## 5.2 Research Findings

The preliminary simple test indicated the feasibility of vacuum desalination of water. The primary experimental setup ended up with no data recorded as it was unable to withstand the required vacuum pressure to evaporate water at a low temperature. The findings from the primary setup helped to refurbish the setup accordingly.

Following are some graphic representations for all the experiments in general. (Data collected from Chapter 4).

Table 9 Overall outcome of all the tests.

| Test no. | Operational Condition | Initial mass of water (kg) | Initial Temperature of water (º C) | % of Energy Savings | % of Distillation from initial mass of water |
|---|---|---|---|---|---|
| 1 | A | 1.95 | 73 | 98.9 | 15.38 |
| 2 | A | 1.5 | 45 | 98.9 | 13.3 |
| 3 | A | 2.5 | 73 | 99 | 14 |
| 4 | A | 2 | 74 | 98.9 | 15 |
| 5 | A | 2.5 | 50 | 98.7 | 14 |
| 6 | A | 1.5 | 75 | 99 | 14.7 |
| 7 | A | 2 | 50 | 98.8 | 12.5 |
| 8 | B | 1.95 | 74 | 98.9 | 16.9 |
| 9 | B | 1.5 | 45 | 99 | 16.6 |
| 10 | C | 2.5 | 73 | 99.04 | 15.6 |
| 11 | C | 2 | 74 | 99 | 15 |
| 12 | C | 1.5 | 50 | 98.8 | 10 |
| 13 | B | 2 | 50 | 98.8 | 12.5 |
| 14 | A | 2 | 73 | 98.8 | 15 |

Operational Conditions:

A) Cylinder-1 and condenser on same level, Cylinder-2 at lower level

B) Cylinder-1 and condenser on same level, Cylinder-2 at lower level, done consecutively after one process.

C) Cylinder-1 on upper level than condenser, Cylinder-2 at lower level, done consecutively after one process.

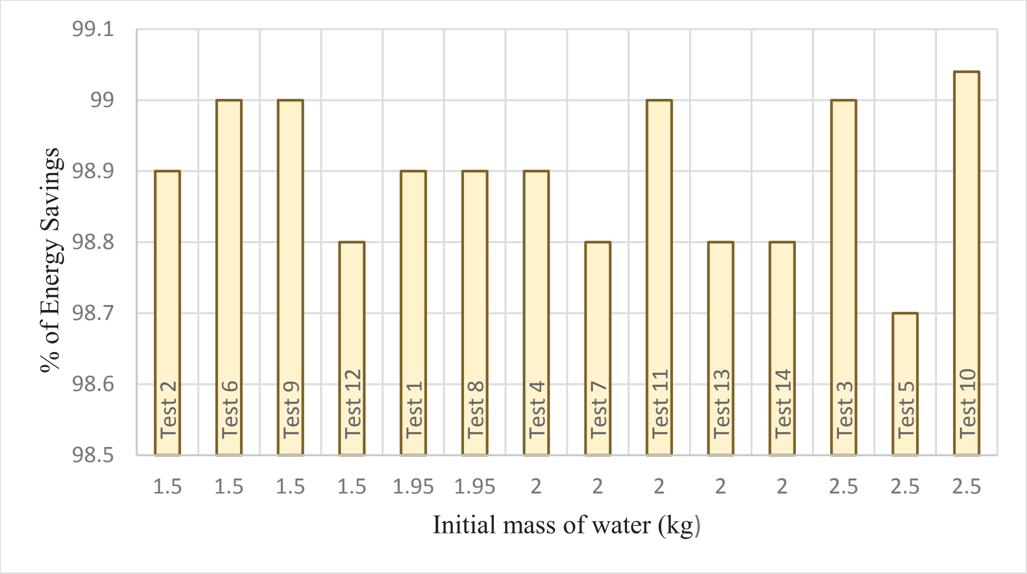


Figure 55 Initial mass of water vs % of Energy Savings for Test 1 – 14.

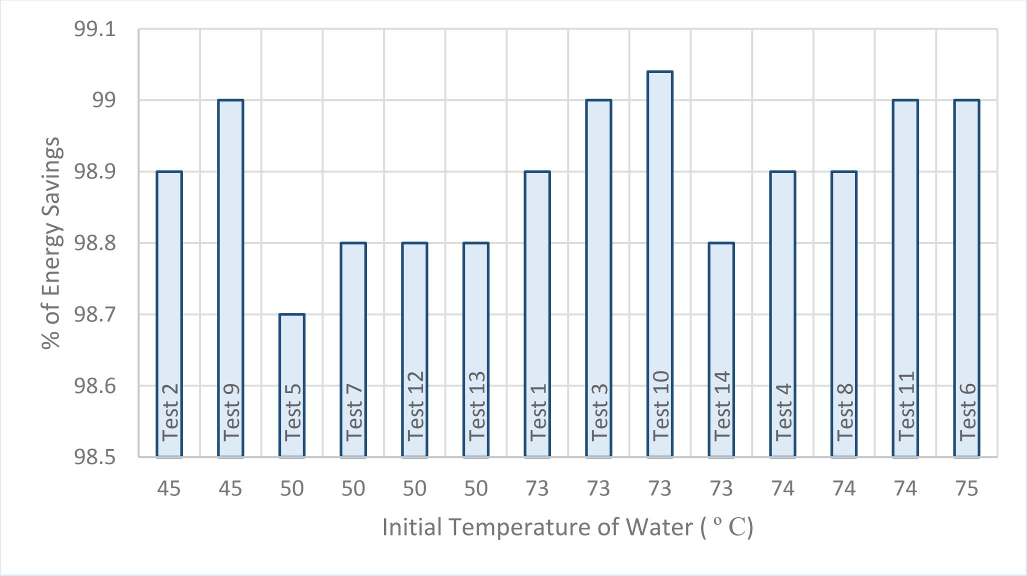


Figure 56 Initial Temperature of water vs % of Energy Savings for Test 1 – 14.

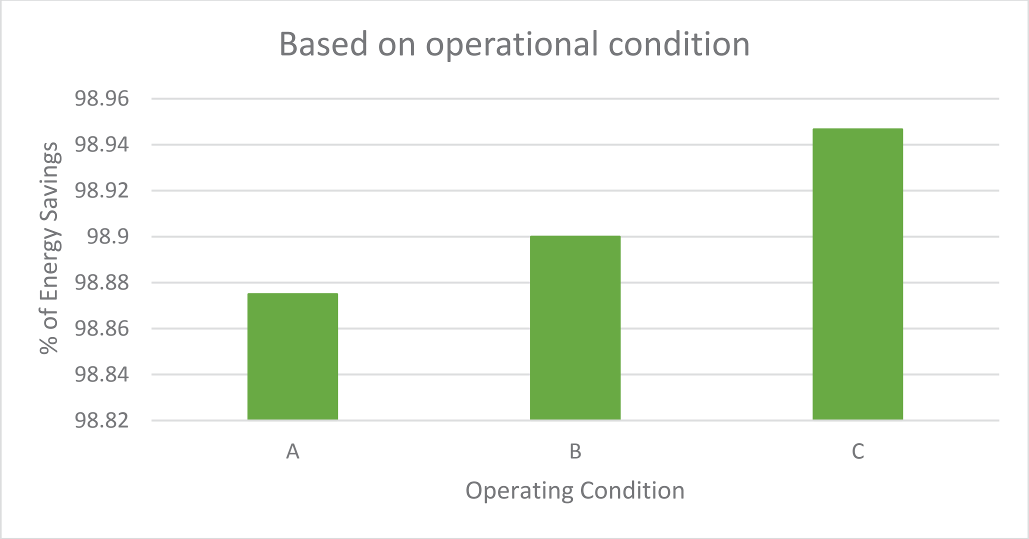


Figure 57 Average % of Energy Savings for each operational condition.

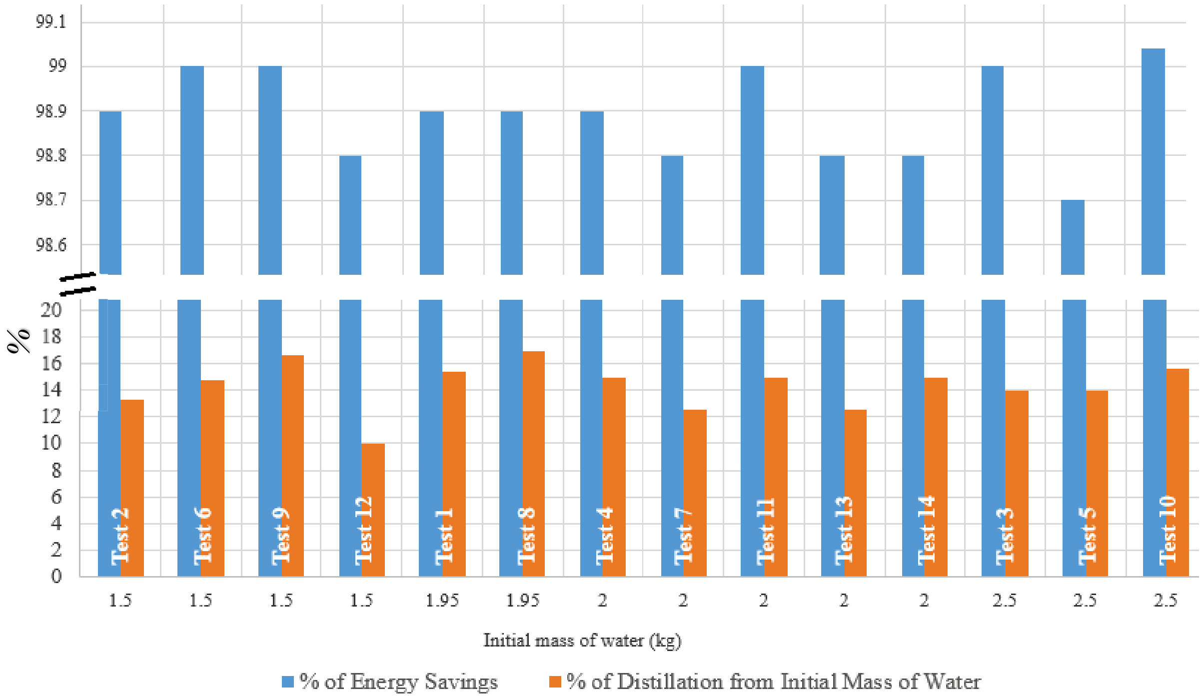


Figure 58 Comparison between % of Energy Savings and % of Distillation from Initial Mass of Water

From the above graphic representations, we can say percentage of evaporation from the initial water taken is a factor to determine the efficiency of this system. The efficiency of the system can be determined by its % of Energy Savings as calculated in all the tests (Chapter 4). As mentioned earlier, we can say, this arrangement works more efficiently with higher initial temperature and mass of water with consecutive operations.

## Important Note About Simultaneous Operation of the Process:

After several testing at different arrangements, this is obvious that water can be desalinated with vacuum pressure. Moreover, to run the process simultaneously a certain amount of heat flow to the feed water is also needed constantly as water will absorb heat from the surroundings when it changes its state from liquid to vapour. This is because of the latent heat requirement of the water to get evaporated. When water changes its state from liquid to vapour, latent heat needs to be supplied to it otherwise it will not be evaporated. For this, warm water of a certain temperature needs to be flown through the feed water tank. In addition, feed water tank (cylinder-1) needs to be at a higher level than the condenser and fresh water tank (cylinder-2) needs to be at a lower level than the condenser to get the help from gravity to flow the condensed fresh water into the fresh water tank. From the experiments, we can say, we need a constant flow of supply water of at least 5° C hotter than the ambient temperature to keep the process running. We also need to maintain the vacuum pressure inside the cylinders at which water will evaporate (at 5° C hotter than the ambient temperature). Solar energy will be used to retain the supply water temperature 5° C hotter than the ambient temperature during the process. When supply water temperature becomes the same as ambient temperature, though the vacuum pressure inside the cylinders is enough for water to evaporate, this process might not work as the evaporated water will be condensed again in the condenser. Condenser should have a lower or same temperature of the ambient temperature.

Above all following are the key points we can confirm from this study.

- Water can be desalinated in vacuum pressure below 100° C.

- The vacuum pump doesn’t need to be operated for the whole process. Once the vacuum pressure has been achieved inside the system it can be turned off and the process will run automatically if we can maintain a flow of warm water of certain temperature.
- The process requires very low energy consumption and solar energy can warm up the water to its desired temperature.
- To utilise gravitational force, condensed water catcher (Cylinder-2) can be placed at a lower level than the condenser.
- The vacuum pressure maintained inside the system should not be same or more than the pressure at which water can be evaporated at the temperature of the condenser. If so condensed water would start to evaporate again or no condensation may occur.
- We worked with normal water but the system should work well with seawater as the characteristics of seawater would not make any corrosive consequence to the experimental setup based on the properties of components which has been discussed earlier. Still, testing with seawater would be done in future work.

## 5.3 Proposed Setup

Based on the findings of our prototype experiment, we can establish a more practical prototype setup which would contain solar evacuated tubes for water heating, solar panel for power, water cylinders, and various sensors to control the operation. For a prototype setup containing the above features, we can use the following components.

>120 watt water pump (will only be needed to pump seawater into the feed tank)

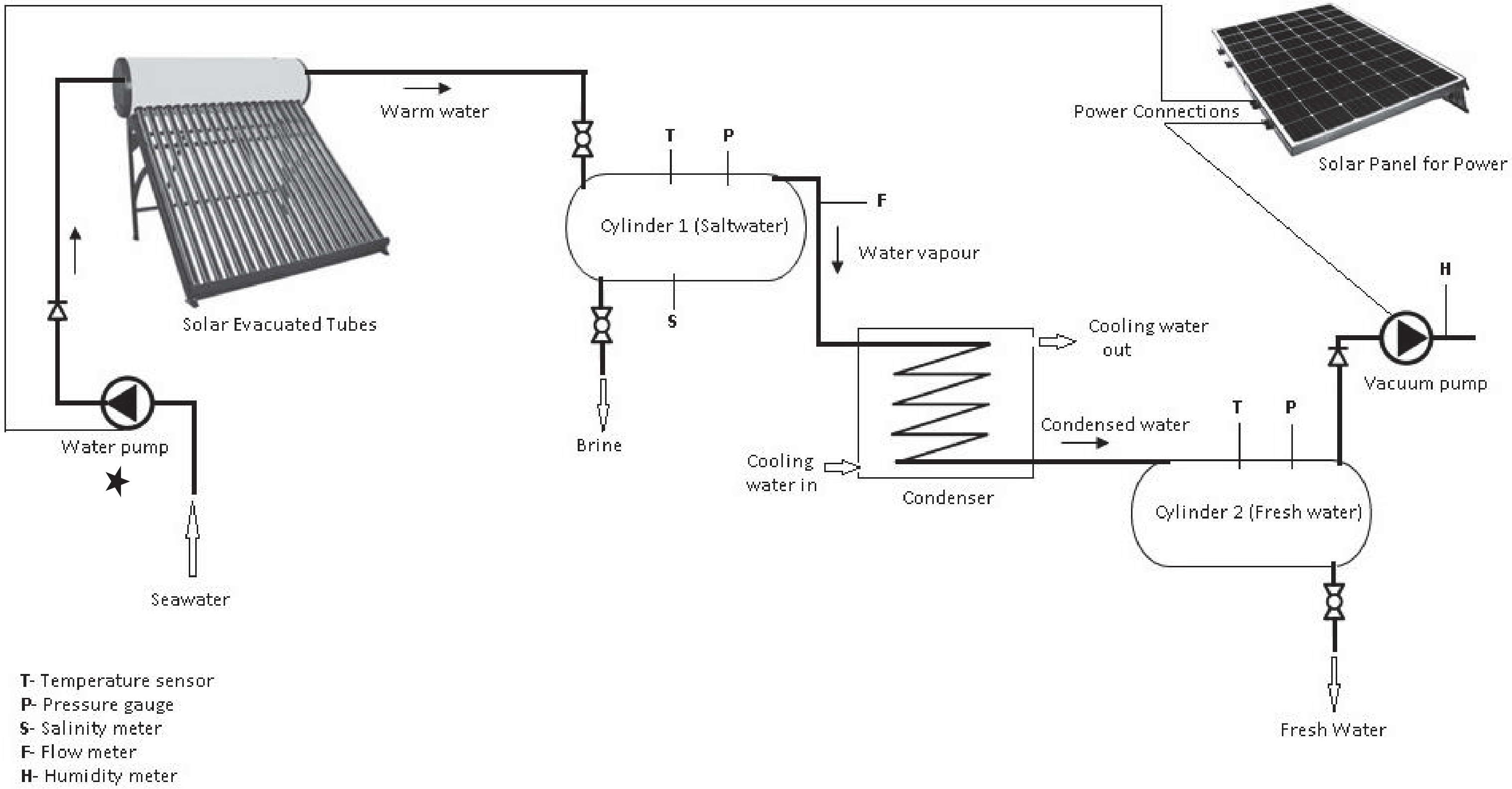
>120 watt vacuum pump

>10 evacuated tubes solar hot water system

>320 watt solar power plant

>Existing cylinders, condenser, temperature sensors, pressure gauges, humidity meter, flow meter, salinity meter

The figure below illustrates the proposed experimental setup. Based on the experimental data this setup could be capable of producing 2.5 litres of fresh water per hour during the daytime.



★ *Water pump is only required to keep the flow of seawater to solar heater from ground. Vacuum would be done by vacuum pump only.*

*Figure 59 Proposed Experimental Setup*

## 5.4 Advantages of Proposed Method over Various Methods of Desalination

**Reverse Osmosis Desalination**

Reverse osmosis systems, in general, are not entirely self-sustaining. Water must be pre-treated with chemicals, for instance, so nothing will clog the fine membrane. And the membrane itself is not entirely easy to deal with; it must be cleaned often and can trap bacteria. A concern unique to the desalination plants is that small fish or marine life can be sucked into the system; adjusting intake pressures and velocities can usually prevent harm. In our proposed system there is no need for other chemicals or expensive filters, moreover proposed system is sustainable and durable requiring low maintenance.

The biggest impediment to reverse osmosis filtration systems is the cost. For a developing nation, installing reverse osmosis systems is an impractical possibility.

As for individual use, reverse osmosis systems can produce frustratingly little yield. A typical system will only be able to reuse about 5 to 15 percent of the water that's being pumped in, thus leaving up to 85 percent wastewater. In contrast, solar aided vacuum plant will incur a one-off cost to establish it and would be more efficient.

**Multi-Stage Flash Distillation**

In Multi-Stage Flash Distillation, seawater is pumped into a brine heater where the water is heated. The heated water is then passed to another container that is significantly lower in pressure; this pressure change causes the seawater to instantaneously (flash) boil and converts to steam. Only a small percentage of the water is converted due to the pressure change, so the water often goes through several "stages" of pressure drops in order to extract the water. High maintenance cost, since it requires extensive training. It also requires a huge amount of thermal energy as compared in the calculation part. Moreover, disposing of the brine of high temperature is difficult. But in solar aided vacuum desalination operating temperature is low leaving a low risk operating condition.

**Electrodialysis**

Electrodialysis involves running a large amount of electric current through a container of seawater. This creates a salt-poor layer on one side and a salt-rich layer on the other side.

This method is very efficient because it does not require a change of state for the water however it does require massive amounts of electricity that can get very expensive. Electrodialysis requires massive amounts of electricity to produce the desired effect. It may not be financially feasible for many countries suffering from water shortages. Also, often this process produces acidic water.

### Tower Method for Vacuum Desalination

There is another method in vacuum desalination which involves a tube, 50 feet tall (closed at the upper end) is inverted in a body of seawater, and a vacuum is applied, the seawater can only rise to 33 feet. The space above that water is at a very low pressure and can be almost fully evacuated. When the pressure above the water level reaches 0.5 psi, the seawater will vaporize (boil) at only about 85 degrees F, which is the ambient temperature in the tropics. Once vaporization has occurred, the water vapour in the evacuated space can condense on a cold surface within that space, and liquid fresh water is produced on that cold surface. From there, gravity can be employed to collect the fresh water, and pump it to its destination. But achieving the height of the tower might not be feasible nearby sea in some areas due to diverse weather condition. It is also difficult to setup and repair when necessary. Moreover, the lower part of the system is buried in seafloor which also requires very skill works. It may cause harm to the water creatures. But vacuum desalination in the closed vessel is safe, easy to set up and efficient.

## 5.5 Conclusion and Future Work

A very simple distillation system has been demonstrated the ability of distillation using an electric heater and vacuum pump. The proof experiment with solar-heat is not performed as yet, but the principle is the same with the achieved experiment. Because of the cost of this scheme is very cheap, this scheme seems to be adaptable to the very rural area of the arid countries. The vacuum pump requires a very low energy which can easily be achieved by a small solar power plant. This method is applicable to making drinking water, and the water production for the agriculture with the drip irrigation. Since this method is similar to the distillation, this scheme is also useful for purifying drinking water in the contaminated well water area. In Asia or Africa where many wells are contaminated with Arsenic, and the measure to remove this contamination is urgently required. We strongly believe our method should be used in such cases. The amount of water production of this system is not large as conventional methods (MSF or RO), but this scheme requires almost no running cost for more than 30 years as the solar plants usually require no major refurbishment for about 30 years once installed and also other products are proposed to use for the plant need very less maintenance. Finally, we want to mention our system can be freely modified based on application.

Even though the results for this thesis have proven that the design theory and the laboratory testing were conclusive, some future work which could not be accomplished during this thesis would be recommended to further enhance the findings. Such as

- Add solar evacuated tube, solar power plant into the test rig as shown in proposed experimental setup and evaluate the findings of this experiment.
- Find out rate of corrosion related to salt and experimental setup made with different materials.
- Scale calculation for using the setup in industrial production.
- Investigate on solar evacuated tube practically and clarify its properties.
- Investigate on how to increase the percentage of fresh water production.

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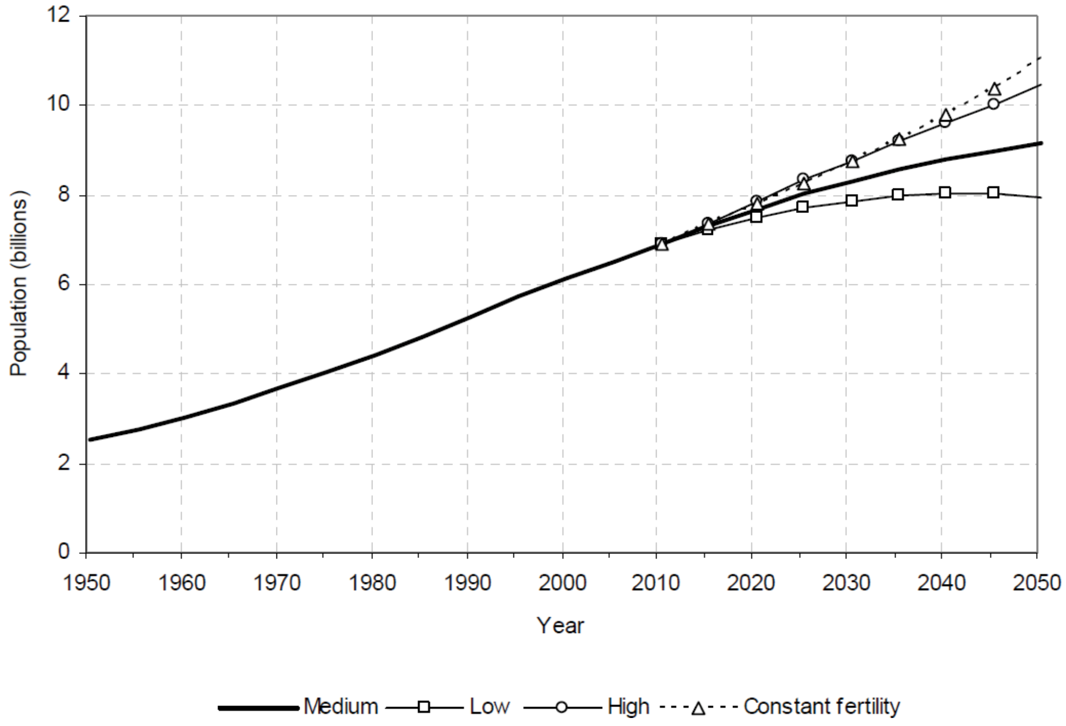
# Chapter 6 – Reference

# Appendix

A1. World population (1950-2050) based on different projections and variants (UN, 2009).



# Appendix

## A2. Population, Annual Renewable Freshwater Availability, 1950, 1995 and 2025 (PAI, 1997)

| Country | Total Annual Renewable Freshwater Available ($10^6$ $m^3$) | 1950 | | 1995 | | 2025 | |
|---|---|---|---|---|---|---|---|
| | | Population ($1x10^6$) | Per capita Water availability ($m^3$) | Population ($1x10^6$) | Per capita Water availability ($m^3$) | Population ($1x10^6$) | Per capita Water availability ($m^3$) |
| Afghanistan | 50 | 8.9 | 5,582 | 19.7 | 2,543 | 45.3 | 1,105 |
| Albania | 21.3 | 1.2 | 17,317 | 3.4 | 6,296 | 4.3 | 4,959 |
| Algeria | 14.8 | 8.8 | 1,691 | 28.1 | 527 | 47.3 | 313 |
| Angola | 184 | 4.1 | 44,541 | 10.8 | 17,012 | 25.5 | 7,202 |
| Argentina | 994 | 17.2 | 57,959 | 34.8 | 28,590 | 47.2 | 21,077 |
| Armenia | 13.3 | 1.4 | 9,801 | 3.6 | 3,654 | 4.2 | 3,171 |
| Australia | 343 | 8.2 | 41,733 | 17.9 | 19,198 | 23.9 | 14,333 |
| Austria | 90.3 | 6.9 | 13,021 | 8 | 11,224 | 8.3 | 10,873 |
| Azerbaijan | 33 | 2.9 | 11,388 | 7.5 | 4,379 | 9.7 | 3,395 |
| Bahrain | 0.09 | 0.12 | 776 | 0.56 | 162 | 0.86 | 104 |
| Bangladish | 2,357 | 41.8 | 56,411 | 118.2 | 19,936 | 179.9 | 13,096 |
| Barbados | 0.05 | 0.21 | 237 | 0.26 | 192 | 0.29 | 169 |
| Belarus | 74 | 7.7 | 9,529 | 10.4 | 7,129 | 9.6 | 7,655 |
| Belgium | 12 | 8.6 | 1,447 | 10.1 | 1,234 | 10.3 | 1,217 |
| Beliza | 16 | 0.07 | 231,884 | 0.21 | 75,117 | 0.38 | 42,667 |
| Benin | 25.8 | 2 | 12,610 | 5.4 | 4,770 | 12.3 | 2,102 |
| Bhutan | 95 | 0.73 | 129,428 | 1.8 | 53,672 | 3.6 | 26,056 |
| Bolivia | 300 | 2.7 | 110,538 | 7.4 | 40,464 | 13.1 | 22,847 |
| Botswana | 14.7 | 0.39 | 37,789 | 1.5 | 10,138 | 2.6 | 5,707 |
| Brazil | 6,950 | 53.9 | 128,763 | 159 | 43,707 | 216.6 | 32,089 |
| Bulgaria | 205 | 7.3 | 28,272 | 8.5 | 24,092 | 7.5 | 27,506 |
| Burkina Faso | 28 | 3.6 | 7,663 | 10.5 | 2,672 | 23.5 | 1,194 |
| Burundi | 3.6 | 2.5 | 1,466 | 6.1 | 594 | 12.3 | 292 |
| Cambodia | 498 | 4.3 | 114,611 | 10 | 49,691 | 16.9 | 29,317 |
| Cameroon | 268 | 4.5 | 60,009 | 13.2 | 20,315 | 28.5 | 9,397 |
| Canada | 2,901 | 13.7 | 211,181 | 29.4 | 98,667 | 36.4 | 79,731 |
| Cape verde | 0.3 | 0.15 | 2,055 | 0.39 | 777 | 0.68 | 442 |
| Cen. Africa | 141 | 1.3 | 107,306 | 2.9 | 48,139 | 6 | 23,477 |
| Chad | 43 | 2.7 | 16,178 | 6.3 | 6,788 | 12.6 | 3,400 |
| Chile | 468 | 6.1 | 76,948 | 14.2 | 32,935 | 19.6 | 23,941 |
| China | 2,800 | 554.8 | 5,047 | 1,220 | 2,295 | 1,480 | 1,891 |
| Colombia | 1,070 | 11.9 | 89,570 | 35.8 | 29,877 | 52.7 | 20,316 |
| Comoros | 1.02 | 0.17 | 5,896 | 0.61 | 1,667 | 1.3 | 760 |
| Congo | 832 | 0.81 | 1,029,703 | 2.6 | 320,864 | 5.7 | 144,771 |
| Costa Rica | 95 | 0.86 | 110,209 | 3.4 | 27,745 | 5.6 | 16,940 |
| Cote D'ivoire | 77.7 | 2.8 | 27,990 | 13.7 | 5,674 | 24.4 | 3,185 |

## A2 continued

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Croatia | 61.4 | 3.9 | 15,948 | 4.5 | 13,629 | 4.2 | 14,471 |
| Cuba | 34.5 | 5.9 | 5,897 | 10.9 | 3,147 | 11.8 | 2,924 |
| Cyprus | 0.9 | 0.49 | 1,822 | 0.75 | 1,208 | 0.95 | 947 |
| Czech Rep | 58.2 | 8.9 | 6,521 | 10.3 | 5,671 | 9.6 | 6,046 |
| Denmark | 13 | 4.3 | 3,044 | 5.2 | 2,489 | 5.3 | 2,442 |
| Djibouti | 2.3 | 0.06 | 37,097 | 0.6 | 3,827 | 1.1 | 2,028 |
| Dominican | 20 | 2.4 | 8,500 | 7.8 | 2,557 | 11.2 | 1,791 |
| Ecuador | 314 | 3.4 | 92,707 | 11.5 | 27,400 | 17.8 | 17,644 |
| Egypt | 58.1 | 21.8 | 2,661 | 62.1 | 936 | 95.8 | 607 |
| El Salvador | 18.95 | 1.9 | 9,713 | 5.7 | 3,347 | 9.2 | 2,055 |
| Equat. Guinea | 30 | 0.23 | 132,743 | 0.4 | 75,000 | 0.79 | 37,594 |
| Eritrea | 8.8 | 1.1 | 7,719 | 3.2 | 2,775 | 6.5 | 1,353 |
| Estonia | 17.6 | 1.1 | 15,985 | 1.5 | 11,828 | 1.3 | 14,013 |
| Ethiopia | 110 | 18.4 | 5,967 | 56.4 | 1,950 | 136.3 | 807 |
| Fiji | 28.6 | 0.29 | 98,789 | 0.78 | 36,416 | 1.2 | 24,402 |
| Finland | 113 | 4 | 28,187 | 5.1 | 22,126 | 5.3 | 21,345 |
| France | 198 | 41.8 | 4,734 | 58.1 | 3,408 | 60.4 | 3,279 |
| Gabon | 164 | 0.47 | 349,680 | 1 | 152,416 | 2.1 | 77,432 |
| Gambia | 8 | 0.29 | 27,211 | 1.1 | 7,201 | 1.9 | 4,032 |
| Germany | 171 | 68.4 | 2,501 | 81.6 | 2,096 | 80.9 | 2,114 |
| Ghana | 53.2 | 4.9 | 10,857 | 17.3 | 3,068 | 36.3 | 1,464 |
| Greece | 58.7 | 7.6 | 7,752 | 10.5 | 5,610 | 10.1 | 5,822 |
| Guatemala | 116 | 2.9 | 39,070 | 10.6 | 10,922 | 21.7 | 5,354 |
| Guinea | 226 | 2.6 | 88,627 | 7.3 | 30,752 | 15.3 | 14,785 |
| Guinea-Bissau | 27 | 0.5 | 53,465 | 1.1 | 25,257 | 1.9 | 14,055 |
| Guyana | 241 | 0.4 | 569,740 | 0.83 | 290,361 | 1.1 | 216,338 |
| Haiti | 11 | 3.3 | 3,373 | 7.1 | 1,544 | 12.5 | 879 |
| Honduras | 63.4 | 1.4 | 45,942 | 5.7 | 11,213 | 10.7 | 5,950 |
| Hungary | 120 | 9.3 | 12,851 | 10.1 | 11,874 | 8.7 | 13,846 |
| Iceland | 168 | 0.14 | 1,174,825 | 0.27 | 624,535 | 0.34 | 500,000 |
| India | 2,085 | 357.6 | 5,831 | 929 | 2,244 | 1,330 | 1,567 |
| Indonesia | 2,530 | 79.5 | 31,809 | 197.5 | 12,813 | 275 | 9,190 |
| Iran | 117.5 | 16.9 | 6,947 | 68.4 | 1,719 | 128.3 | 916 |
| Iraq | 109.2 | 5.2 | 21,171 | 20.1 | 5,434 | 41.6 | 2,625 |
| Ireland | 50 | 2.9 | 16,841 | 3.5 | 14,100 | 3.7 | 13,430 |
| Israel | 2.15 | 1.3 | 1,709 | 5.5 | 389 | 7.9 | 270 |
| Italy | 167 | 47.1 | 3,545 | 57.2 | 2,919 | 51.7 | 3,227 |
| Jamaica | 8.3 | 1.4 | 5,916 | 2.5 | 3,363 | 3.4 | 2,463 |
| Japan | 547 | 83.6 | 6,541 | 125.1 | 4,374 | 121.3 | 4,508 |
| Jordan | 1.71 | 1.2 | 1,382 | 5.4 | 318 | 11.9 | 144 |
| Kazakhstan | 169.4 | 6.7 | 25,272 | 16.8 | 10,073 | 20 | 8,450 |
| Kenya | 30.2 | 6.3 | 4,820 | 27.2 | 1,112 | 50.2 | 602 |

# Appendix

## A2 Continued

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Kuwait | 0.16 | 0.15 | 1,053 | 1.7 | 95 | 2.9 | 55 |
| Kyrgyzstan | 61.7 | 1.7 | 35,460 | 4.5 | 13,834 | 5.9 | 10,370 |
| Laos | 270 | 1.8 | 153,846 | 4.9 | 55,305 | 10.2 | 26,465 |
| Latvia | 34 | 1.9 | 17,445 | 2.5 | 13,407 | 2.1 | 16,129 |
| Lebanon | 5.58 | 1.4 | 3,867 | 3 | 1,854 | 4.4 | 1,261 |
| Lesotho | 5.2 | 0.73 | 7,084 | 2 | 2,565 | 4 | 1,290 |
| Liberia | 232 | 0.82 | 281,553 | 2.1 | 109,279 | 6.6 | 35,296 |
| Libya | 0.6 | 1 | 583 | 5.4 | 111 | 12.9 | 47 |
| Lithuania | 24.2 | 2.6 | 9,427 | 3.7 | 6,478 | 3.5 | 6,873 |
| Luxembourg | 5 | 0.29 | 16,892 | 0.41 | 12,285 | 0.47 | 10,730 |
| Madagascar | 337 | 4.2 | 79,688 | 14.9 | 22,657 | 34.5 | 9,775 |
| Malawi | 18.7 | 2.9 | 6,491 | 9.7 | 1,933 | 20.4 | 917 |
| Malaysia | 456 | 6.1 | 74,632 | 20.1 | 22,642 | 31.6 | 14,441 |
| Mali | 67 | 3.5 | 19,034 | 10.8 | 6,207 | 24.6 | 2,726 |
| Malta | 0.03 | 0.31 | 96 | 0.37 | 82 | 0.42 | 71 |
| Mauritania | 11.4 | 0.83 | 13,818 | 2.3 | 5,013 | 4.4 | 2,566 |
| Mauritius | 2.2 | 0.49 | 4,462 | 1.1 | 1,970 | 1.5 | 1,485 |
| Mexico | 357.4 | 27.7 | 12,885 | 91.1 | 3,921 | 130.2 | 2,745 |
| Moldova | 13.7 | 2.3 | 5,852 | 4.4 | 3,088 | 4.9 | 2,814 |
| Mongolia | 24.6 | 0.76 | 32,326 | 2.5 | 9,988 | 4.1 | 6,071 |
| Morocco | 30 | 8.9 | 3,351 | 26.5 | 1,131 | 39.9 | 751 |
| Mozambique | 208 | 6.2 | 33,559 | 17.3 | 12,051 | 35.4 | 5,868 |
| Myanmar | 1,082 | 17.8 | 60,677 | 45.1 | 23,988 | 67.6 | 15,996 |
| Namibia | 45.5 | 0.51 | 89,041 | 1.5 | 29,622 | 2.9 | 15,172 |
| Nepal | 170 | 7.9 | 21,623 | 21.5 | 7,923 | 40.6 | 4,192 |
| Netherlands | 90 | 10.1 | 8,899 | 15.5 | 5,813 | 16.1 | 5,576 |
| New Zealand | 327 | 1.9 | 171,384 | 3.6 | 91,828 | 4.9 | 67,036 |
| Nicaragua | 175 | 1.1 | 159,381 | 4.1 | 42,445 | 7.6 | 22,909 |
| Niger | 32.5 | 2.4 | 13,542 | 9.2 | 3,552 | 22.4 | 1,452 |
| Nigeria | 280 | 32.9 | 8,502 | 111.7 | 2,506 | 238.4 | 1,175 |
| North Korea | 67 | 9.5 | 7,062 | 22.1 | 3,032 | 30 | 2,230 |
| Norway | 392 | 3.3 | 120,061 | 4.3 | 90,489 | 4.7 | 84,084 |
| Oman | 1.93 | 0.46 | 4,232 | 2.2 | 874 | 6.5 | 295 |
| Pakistan | 468 | 39.5 | 11,844 | 136.3 | 3,435 | 268.9 | 1,740 |
| Panama | 144 | 0.86 | 167,442 | 2.6 | 54,732 | 3.8 | 38,105 |
| Papua New Guinea | 801 | 1.6 | 496,590 | 4.3 | 186,236 | 7.5 | 106,149 |
| Paraguay | 314 | 1.5 | 211,022 | 4.8 | 65,037 | 9.4 | 33,565 |
| Peru | 40 | 7.6 | 5,241 | 23.5 | 1,700 | 35.5 | 1,126 |
| Phillippines | 323 | 20.9 | 15,390 | 67.8 | 4,761 | 105.2 | 3,071 |
| Poland | 56.2 | 24.8 | 2,264 | 38.6 | 1,458 | 39.9 | 1,406 |
| Portugal | 69.6 | 8.4 | 8,281 | 9.8 | 7,091 | 9.4 | 7,374 |

# Appendix

## A2 Continued

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Qatar | 0.05 | 25 | 2,000 | 0.55 | 91 | 0.78 | 64 |
| Romania | 208 | 16.3 | 12,752 | 22.7 | 9,152 | 21.1 | 9,859 |
| Russia | 4,498 | 102.2 | 44,015 | 148.5 | 30,298 | 131.4 | 34,233 |
| Rwanda | 6.3 | 2.1 | 2,972 | 5.2 | 1,215 | 12.9 | 485 |
| Saudi Arabia | 4.55 | 3.2 | 1,421 | 18.3 | 249 | 42.4 | 107 |
| Senegal | 39.4 | 2.5 | 15,760 | 8.3 | 4,740 | 16.9 | 2,332 |
| Sierra Leone | 160 | 1.9 | 82,305 | 4.2 | 38,141 | 8.2 | 19,512 |
| Singapore | 0.06 | 1 | 587 | 3.3 | 180 | 4.2 | 142 |
| Slovak | 30.8 | 3.5 | 8,894 | 5.3 | 5,770 | 5.5 | 5,632 |
| Solomon | 44.7 | 0.1 | 496,667 | 0.38 | 118,254 | 0.84 | 52,962 |
| Somalia | 13.5 | 3.1 | 4,395 | 9.5 | 1,422 | 23.7 | 570 |
| South Africa | 50 | 13.7 | 3,654 | 41.5 | 1,206 | 71.6 | 698 |
| South Korea | 66.1 | 20.4 | 3,247 | 44.9 | 1,472 | 52.5 | 1,258 |
| Spain | 111.3 | 28 | 3,974 | 39.6 | 2,809 | 37.5 | 2,968 |
| Sri Lanka | 43.2 | 7.7 | 5,626 | 17.9 | 2,410 | 23.9 | 1,805 |
| Sudan | 154 | 9.2 | 16,757 | 26.7 | 5,766 | 46.9 | 3,287 |
| Suriname | 200 | 0.22 | 930,233 | 0.43 | 468,384 | 0.61 | 330,579 |
| Swaziland | 4.5 | 0.26 | 17,045 | 0.86 | 5,251 | 1.7 | 2,687 |
| Sweden | 180 | 7 | 25,663 | 8.8 | 20,482 | 9.5 | 18,925 |
| Switzerland | 50 | 4.7 | 10,652 | 7.2 | 6,977 | 7.6 | 6,595 |
| Syria | 53.69 | 3.5 | 15,362 | 14.2 | 3,780 | 26.3 | 2,041 |
| Tajikistan | 101.3 | 1.5 | 66,123 | 5.8 | 17,382 | 9.7 | 10,393 |
| Tanzania | 89 | 7.9 | 11,286 | 30 | 2,964 | 62.4 | 1,425 |
| Thailand | 179 | 20 | 8,946 | 58.2 | 3,073 | 69.1 | 2,591 |
| Togo | 12 | 1.3 | 9,029 | 4.1 | 2,938 | 8.8 | 1,370 |
| Trinidad & Tobago | 5.1 | 0.64 | 8,019 | 1.3 | 3,963 | 1.7 | 3,014 |
| Tunisia | 3.9 | 3.5 | 1,105 | 8.9 | 434 | 13.5 | 288 |
| Turkey | 193.1 | 20.8 | 9,280 | 60.8 | 3,174 | 85.5 | 2,251 |
| Turkmenistan | 72 | 1.2 | 59,455 | 4.1 | 17,669 | 6.5 | 11,128 |
| Uganda | 66 | 4.8 | 13,860 | 19.7 | 3,352 | 44.9 | 1,467 |
| Ukraine | 231 | 36.9 | 6,259 | 51.8 | 4,463 | 45.9 | 5,024 |
| UAE | 1.99 | 0.1 | 28,471 | 2.2 | 902 | 3.3 | 604 |
| UK | 71 | 50.6 | 1,403 | 58.1 | 1,222 | 59.5 | 1,193 |
| USA | 2,478 | 157.8 | 15,702 | 267.1 | 9,277 | 332.5 | 7,453 |
| Uruguay | 124 | 2.2 | 55,382 | 3.2 | 38,920 | 3.7 | 33,586 |
| Uzbekistan | 129.6 | 6.3 | 20,526 | 22.8 | 5,694 | 36.5 | 3,551 |
| Venezuela | 1,317 | 5.1 | 258,539 | 21.8 | 60,291 | 34.8 | 37,872 |
| Viet Nam | 376 | 29.9 | 12,553 | 73.8 | 5,095 | 110.1 | 3,415 |
| Yemen | 5.2 | 4.3 | 1,205 | 15 | 346 | 39.6 | 131 |
| Zaire | 1,019 | 12.2 | 83,634 | 45.5 | 22,419 | 105.9 | 9,620 |
| Zambia | 116 | 2.4 | 47,541 | 8.1 | 14,355 | 16.2 | 7,177 |
| Zimbabwe | 20 | 2.7 | 7,326 | 11.2 | 1,787 | 19.3 | 1,034 |

## A3. Installed desalination capacity by location as at 2004

| Countries | Capacity ($m^3$/d) | Countries | Capacity ($m^3$/d) | Countries | Capacity ($m^3$/d) |
|---|---|---|---|---|---|
| Algeria | 544,393 | Germany | 289,882 | Pakistan | 38,729 |
| Angola | 780 | Gibraltar | 30,140 | Palau Pacific | 180 |
| Antarctica | 754 | Greece | 76,673 | Palestine | 5,046 |
| Antigue | 39,072 | Grenada | 300 | Paraguary | 5,091 |
| Antilles | 13,899 | Guinea | 2,726 | Peru | 39,002 |
| Antilles | 288,233 | Honduras | 651 | Philippines | 38,032 |
| Argentina | 26,516 | Hungary | 815 | Poland | 30,212 |
| Ascension | 2,862 | India | 450,296 | Polynesia | 200 |
| Australia | 331,186 | Indonesia | 199,970 | Portugal | 13,500 |
| Austria | 26,153 | Iran | 643,711 | Qatar | 762,932 |
| Azerbaijan | 12,910 | Iraq | 397,753 | Romania | 120 |
| Bahamas | 71,971 | Ireland | 12,475 | Russia | 126,142 |
| Bahrain | 516,059 | Israel | 771,872 | Saudi Arabia | 6,569,172 |
| Barbados | 35,946 | Italy | 673,739 | Senegal | 132 |
| Belarus | 12,640 | Jamaica | 7,830 | Singapore | 328,726 |
| Belgium | 10,173 | Japan | 1,299,691 | Slovenia | 3,280 |
| Belize | 2,787 | Jordan | 328,507 | Somalia | 408 |
| Bermuda | 28,796 | Kazakhstan | 211,512 | South Africa | 102,524 |
| Botswana | 270 | Kenya | 400 | Spain | 2,418,974 |
| Brazil | 25,349 | Kiribati | 330 | Sudan | 21,876 |
| Bulgaria | 1,320 | Korea | 785,499 | Sweden | 4,592 |
| Cambodia | 240 | Kuwait | 2,181,026 | Switzerland | 13,393 |
| Canada | 70,906 | Laos | 9,600 | Syria | 8,183 |
| Cape Verde | 26,173 | Lebanon | 18,390 | Taiwan | 335,755 |
| Cayman islands | 26,957 | Liechtenstein | 151 | Thailand | 40,269 |
| Chile | 134,592 | Libya | 859,514 | Trinidad | 117,351 |
| Columbia | 12,800 | Malaysia | 37,318 | Tunisia | 81,209 |
| Comoros | 268 | Maldives | 15,332 | Turkey | 22,182 |
| Congo | 800 | Malta | 148,572 | Turkmenistan | 165,807 |
| Costa Rica | 1,363 | Marshalls | 2,650 | Turks & Caicos | 2,004 |
| Cuba | 25,117 | Mauritania | 4,654 | UAE | 5,532,777 |
| Cyprus | 106,850 | Mexico | 431,083 | Ukraine | 21,000 |
| Czech | 35,637 | Morocco | 56,856 | UK | 295,901 |
| Denmark | 26,052 | Mozambique | 189 | USA | 6,128,009 |
| Djibouti | 554 | Myanmar | 240 | Uzbekistan | 31,600 |
| Dominican | 2,294 | Namibia | 12,297 | Venezuela | 28,302 |
| Ecuador | 7,685 | Nauru pacific | 1,136 | Vietnam | 680 |
| Egypt | 303,915 | Nethrelands | 238,177 | Virgin Islands | 23,709 |

# Appendix

## A3 continued

| | | | | | |
|---|---|---|---|---|---|
| El Salvador | 378 | New Zealand | 220 | Yemen | 77,948 |
| Eritrea | 1,000 | Nicaragua | 2,400 | Yugoslawia | 2,204 |
| Fiji | 1,020 | Nigeria | 9,570 | Unknown | 70,518 |
| Finland | 1,521 | Norway | 1,884 | | |
| France | 219,257 | Oman | 334,879 | | |

## A4 Analysis of CO2 emission

| Tech | Use [%] | Capacity [m$^3$/d] | Energy [kWh/m$^3$] | Energy [kWh/d] | Energy [kWh/y] | Carbon Emission [kgCO2/y] |
|---|---|---|---|---|---|---|
| RO | 60 | 39,000,000 | 3 | 117,000,000 | 42,705,000,000 | 23,060,700,000 |
| MSF | 26.8 | 17,420,000 | 13.5 | 235,170,000 | 85,837,050,000 | 46,352,007,000 |
| MED | 8 | 5,200,000 | 6.5 | 33,800,000 | 12,337,000,000 | 6,661,980,000 |
| ED | 3.6 | 2,340,000 | 1.5 | 3,510,000 | 1,281,150,000 | 691,821,000 |
| Hybrid | 0.8 | 520,000 | 1.5 | 780,000 | 284,700,000 | 153,738,000 |
| EDI | 0.3 | 195,000 | 1.5 | 292,500 | 106,762,500 | 57,651,750 |
| Other | 0.3 | 195,000 | 1.5 | 292,500 | 106,762,500 | 57,651,750 |
| Total | 99.8 | 64,870,000 | 29 | 390845000 | 1.42658E+11 | 77,035,549,500 |

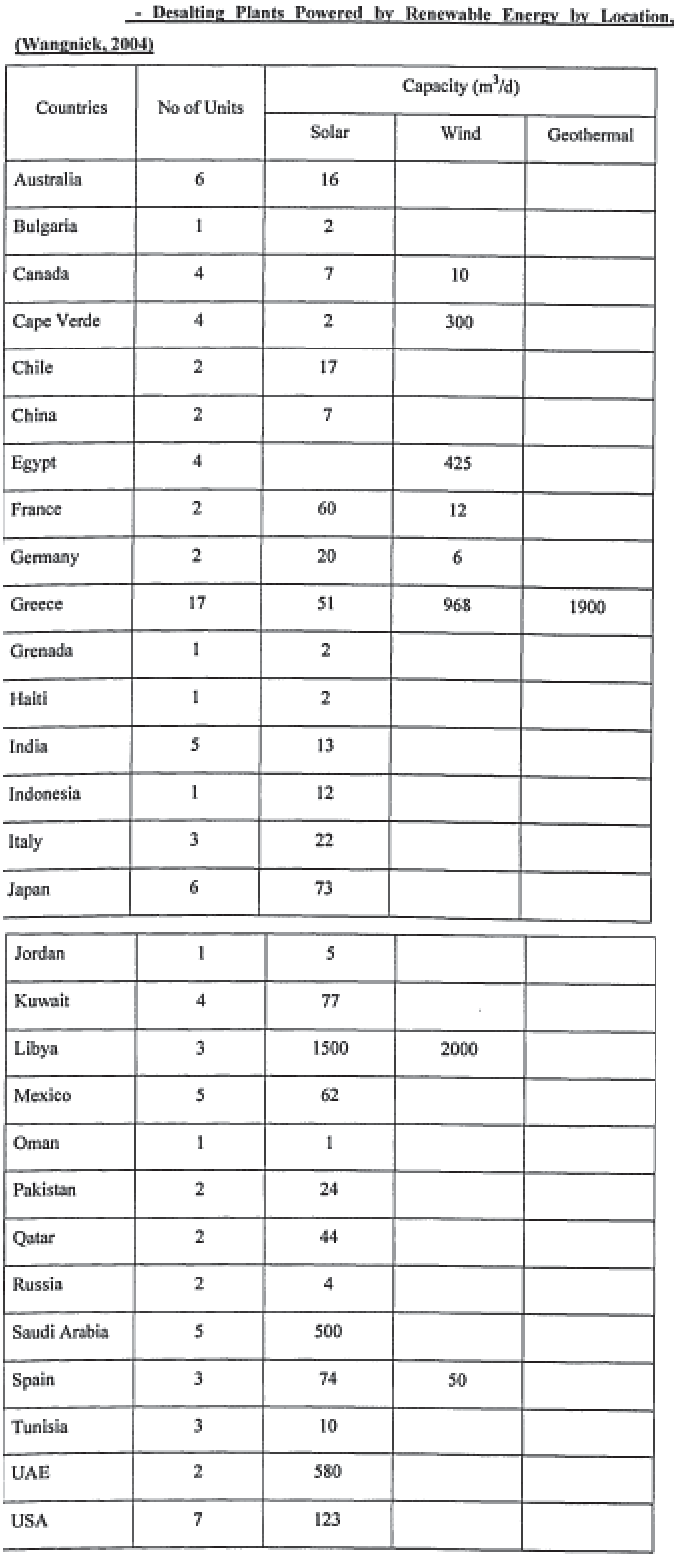
2010 Global CO2 Emission = 29 billion tonnes
2010 Desalination (@ current capacity) CO2 Emission = 77 million tonnes
2010 Power & Heat (@ 41% of global emission) CO2 Emission = 11 billion tonnes

| Supply by Desalination | Demand [m$^3$/y] | Total Energy [kWh/m$^3$] | Energy [kWh/y] | CO2 [kg/y] | CO2 [tonne/y] |
|---|---|---|---|---|---|
| 10% | 5.2E+11 | 29 | 1.508E+13 | 8.1432E+12 | 8143200000 |

2050 Global CO2 Emission = 58 billion tonnes
2050 Desalination (@ 10% of 2025 demand) CO2 Emission = 8 billion tonnes 2050 Power & Heat (@ 41% of global emission) CO2 Emission = 24 billion tonnes

# Appendix

## A4 continued

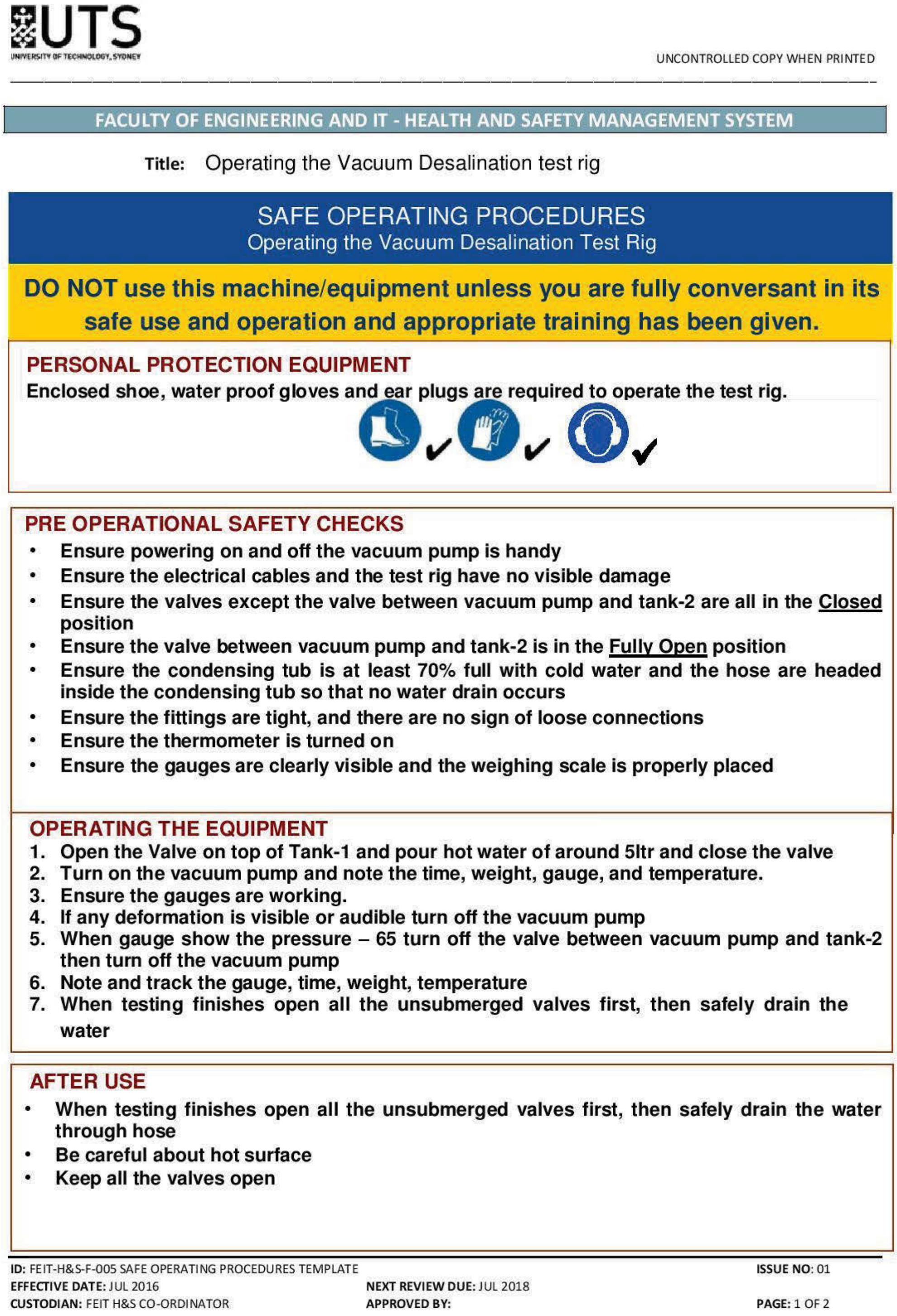


**- Desalting Plants Powered by Renewable Energy by Location, (Wangnick, 2004)**

| Countries | No of Units | Capacity (m$^3$/d) | | |
|---|---|---|---|---|
| | | Solar | Wind | Geothermal |
| Australia | 6 | 16 | | |
| Bulgaria | 1 | 2 | | |
| Canada | 4 | 7 | 10 | |
| Cape Verde | 4 | 2 | 300 | |
| Chile | 2 | 17 | | |
| China | 2 | 7 | | |
| Egypt | 4 | | 425 | |
| France | 2 | 60 | 12 | |
| Germany | 2 | 20 | 6 | |
| Greece | 17 | 51 | 968 | 1900 |
| Grenada | 1 | 2 | | |
| Haiti | 1 | 2 | | |
| India | 5 | 13 | | |
| Indonesia | 1 | 12 | | |
| Italy | 3 | 22 | | |
| Japan | 6 | 73 | | |
| Jordan | 1 | 5 | | |
| Kuwait | 4 | 77 | | |
| Libya | 3 | 1500 | 2000 | |
| Mexico | 5 | 62 | | |
| Oman | 1 | 1 | | |
| Pakistan | 2 | 24 | | |
| Qatar | 2 | 44 | | |
| Russia | 2 | 4 | | |
| Saudi Arabia | 5 | 500 | | |
| Spain | 3 | 74 | 50 | |
| Tunisia | 3 | 10 | | |
| UAE | 2 | 580 | | |
| USA | 7 | 123 | | |

# Appendix

## A5. SOP



**FACULTY OF ENGINEERING AND IT - HEALTH AND SAFETY MANAGEMENT SYSTEM**

**Title:** Operating the Vacuum Desalination test rig

### SAFE OPERATING PROCEDURES

Operating the Vacuum Desalination Test Rig

**DO NOT use this machine/equipment unless you are fully conversant in its safe use and operation and appropriate training has been given.**

**PERSONAL PROTECTION EQUIPMENT**

**Enclosed shoe, water proof gloves and ear plugs are required to operate the test rig.**

✓ ✓ ✓

**PRE OPERATIONAL SAFETY CHECKS**

- **Ensure powering on and off the vacuum pump is handy**
- **Ensure the electrical cables and the test rig have no visible damage**
- **Ensure the valves except the valve between vacuum pump and tank-2 are all in the Closed position**
- **Ensure the valve between vacuum pump and tank-2 is in the Fully Open position**
- **Ensure the condensing tub is at least 70% full with cold water and the hose are headed inside the condensing tub so that no water drain occurs**
- **Ensure the fittings are tight, and there are no sign of loose connections**
- **Ensure the thermometer is turned on**
- **Ensure the gauges are clearly visible and the weighing scale is properly placed**

**OPERATING THE EQUIPMENT**

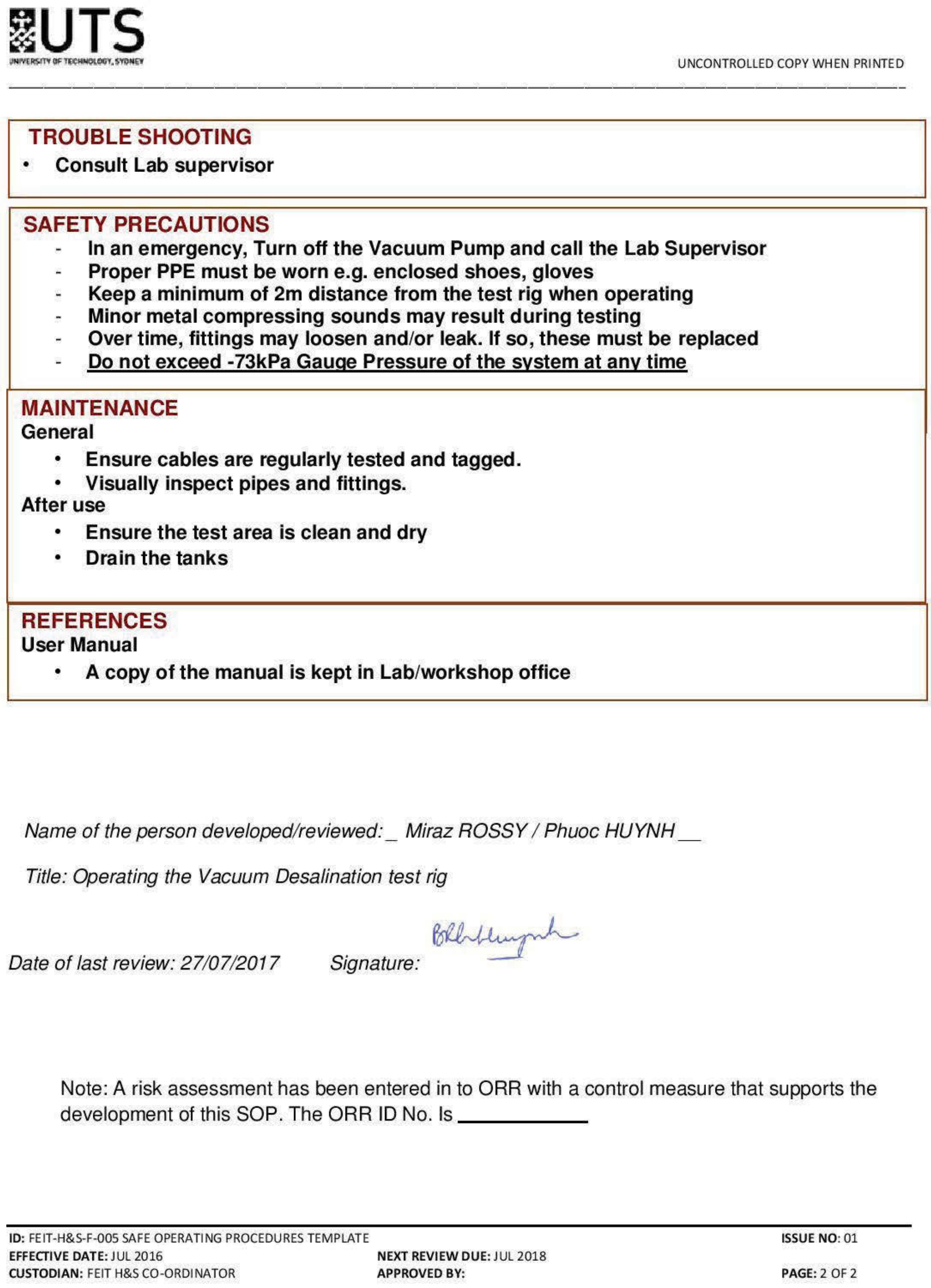
1. **Open the Valve on top of Tank-1 and pour hot water of around 5ltr and close the valve**
2. **Turn on the vacuum pump and note the time, weight, gauge, and temperature.**
3. **Ensure the gauges are working.**
4. **If any deformation is visible or audible turn off the vacuum pump**
5. **When gauge show the pressure – 65 turn off the valve between vacuum pump and tank-2 then turn off the vacuum pump**
6. **Note and track the gauge, time, weight, temperature**
7. **When testing finishes open all the unsubmerged valves first, then safely drain the water**

**AFTER USE**

- **When testing finishes open all the unsubmerged valves first, then safely drain the water through hose**
- **Be careful about hot surface**
- **Keep all the valves open**

**ID:** FEIT-H&S-F-005 SAFE OPERATING PROCEDURES TEMPLATE **ISSUE NO:** 01
**EFFECTIVE DATE:** JUL 2016 **NEXT REVIEW DUE:** JUL 2018
**CUSTODIAN:** FEIT H&S CO-ORDINATOR **APPROVED BY:** **PAGE:** 1 OF 2

## A5 continued



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**TROUBLE SHOOTING**

- **Consult Lab supervisor**

**SAFETY PRECAUTIONS**

- **In an emergency, Turn off the Vacuum Pump and call the Lab Supervisor**
- **Proper PPE must be worn e.g. enclosed shoes, gloves**
- **Keep a minimum of 2m distance from the test rig when operating**
- **Minor metal compressing sounds may result during testing**
- **Over time, fittings may loosen and/or leak. If so, these must be replaced**
- **Do not exceed -73kPa Gauge Pressure of the system at any time**

**MAINTENANCE**

**General**

- **Ensure cables are regularly tested and tagged.**
- **Visually inspect pipes and fittings.**

**After use**

- **Ensure the test area is clean and dry**
- **Drain the tanks**

**REFERENCES**

**User Manual**

- **A copy of the manual is kept in Lab/workshop office**

*Name of the person developed/reviewed:_ Miraz ROSSY / Phuoc HUYNH __*

*Title: Operating the Vacuum Desalination test rig*

*Date of last review: 27/07/2017* *Signature:*

Note: A risk assessment has been entered in to ORR with a control measure that supports the development of this SOP. The ORR ID No. Is ____________

**ID:** FEIT-H&S-F-005 SAFE OPERATING PROCEDURES TEMPLATE **ISSUE NO:** 01
**EFFECTIVE DATE:** JUL 2016 **NEXT REVIEW DUE:** JUL 2018
**CUSTODIAN:** FEIT H&S CO-ORDINATOR **APPROVED BY:** **PAGE:** 2 OF 2

# A6. General Risk Assessment

## GENERAL RISK ASSESSMENT TEMPLATE

UNIVERSITY OF TECHNOLOGY SYDNEY

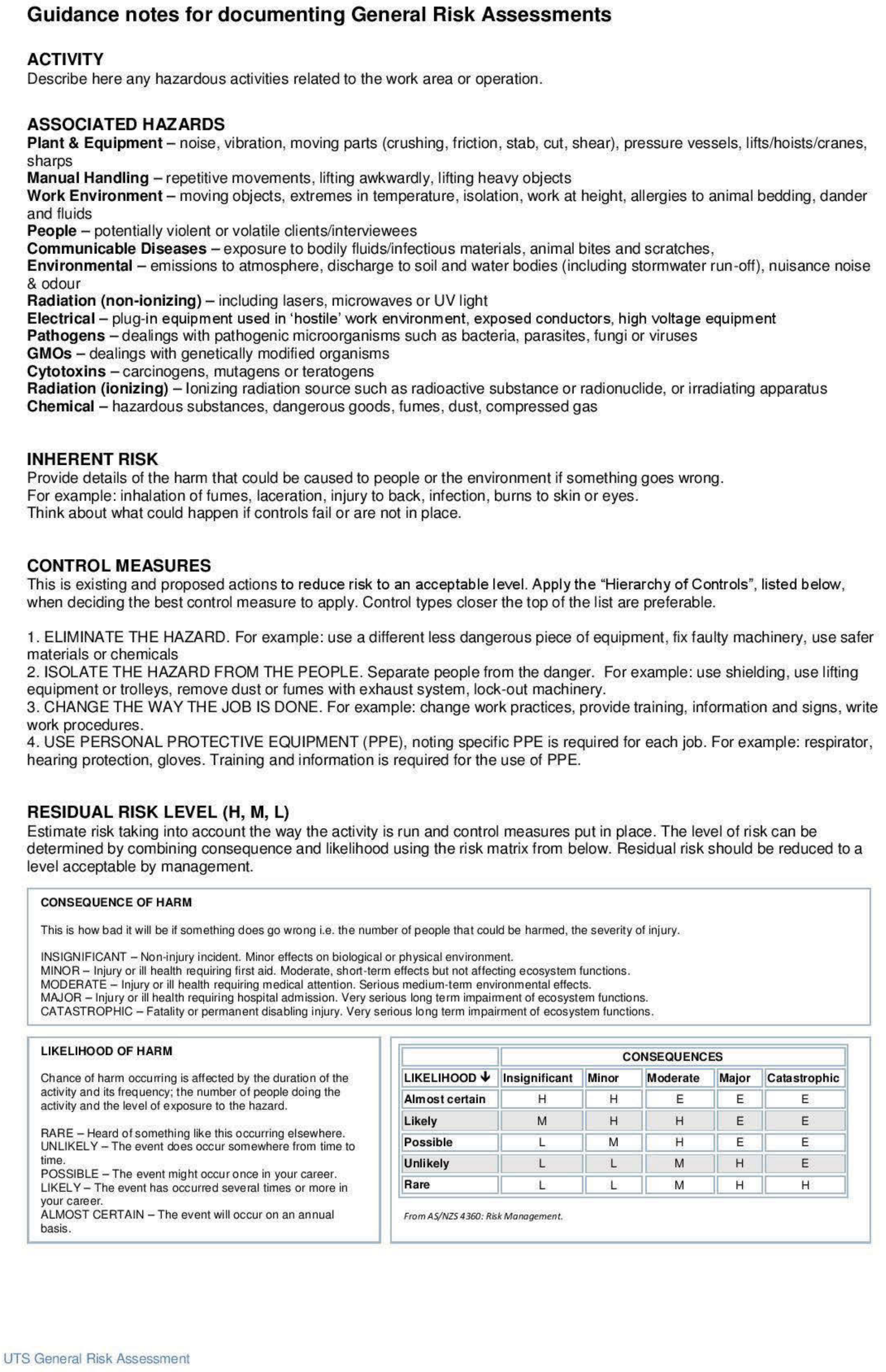
| | | | |
|---|---|---|---|
| **Work area / operation** | Vacuum Desalination Test Rig | **Assessors name** | |
| **Other persons consulted** | Dr. Phuoc Huynh, Vahik Avakian | **Date** | 28/07/2017 |

| **ACTIVITY** | **ASSOCIATED HAZARDS** | **INHERENT RISK** - Harm that could occur from these hazards if controls fail or are not in place. | **CONTROL MEASURES** - Existing and *proposed action* to minimise risk to an acceptable level.<br>*Note Proposed Actions in italics.* | **TARGET COMPLETION DATE** - To implement proposed controls | **RESIDUAL RISK LEVEL** (H,M,L) |
|---|---|---|---|---|---|
| Operating the Test rig | Vacuum Pressure Vessel | Collapsed tank | Do not exceed the vacuum gauge pressure -65kPa | | M |
| | Hot Surface | Burn of skin | Use PPE | | L |
| | Wet Floor | Slippage | Use PPE | | L |
| | Vibration | Minor physical injury | Keep 2m distance from test rig when operating | | L |
| | Noise | Harms ears | Use PPE | | L |
| | | | | | |

| | | | | | |
|---|---|---|---|---|---|
| **Supervisor approval of assessment** | I am satisfied that the residual risk with existing controls is acceptable ☐Yes ☐No<br>OR<br>I am satisfied that that the proposed controls will reduce risk to an acceptable level. √ Yes ☐No | | | | |
| Supervisors Name | Phuoc HUYNH | Signature | | Date | 04/08/2017 |

# Appendix

## A6 continued



### Guidance notes for documenting General Risk Assessments

**ACTIVITY**
Describe here any hazardous activities related to the work area or operation.

**ASSOCIATED HAZARDS**
**Plant & Equipment** – noise, vibration, moving parts (crushing, friction, stab, cut, shear), pressure vessels, lifts/hoists/cranes, sharps
**Manual Handling** – repetitive movements, lifting awkwardly, lifting heavy objects
**Work Environment** – moving objects, extremes in temperature, isolation, work at height, allergies to animal bedding, dander and fluids
**People** – potentially violent or volatile clients/interviewees
**Communicable Diseases** – exposure to bodily fluids/infectious materials, animal bites and scratches,
**Environmental** – emissions to atmosphere, discharge to soil and water bodies (including stormwater run-off), nuisance noise & odour
**Radiation (non-ionizing)** – including lasers, microwaves or UV light
**Electrical** – plug-in equipment used in 'hostile' work environment, exposed conductors, high voltage equipment
**Pathogens** – dealings with pathogenic microorganisms such as bacteria, parasites, fungi or viruses
**GMOs** – dealings with genetically modified organisms
**Cytotoxins** – carcinogens, mutagens or teratogens
**Radiation (ionizing)** – Ionizing radiation source such as radioactive substance or radionuclide, or irradiating apparatus
**Chemical** – hazardous substances, dangerous goods, fumes, dust, compressed gas

**INHERENT RISK**
Provide details of the harm that could be caused to people or the environment if something goes wrong.
For example: inhalation of fumes, laceration, injury to back, infection, burns to skin or eyes.
Think about what could happen if controls fail or are not in place.

**CONTROL MEASURES**
This is existing and proposed actions to reduce risk to an acceptable level. Apply the "Hierarchy of Controls", listed below, when deciding the best control measure to apply. Control types closer the top of the list are preferable.

1. ELIMINATE THE HAZARD. For example: use a different less dangerous piece of equipment, fix faulty machinery, use safer materials or chemicals
2. ISOLATE THE HAZARD FROM THE PEOPLE. Separate people from the danger. For example: use shielding, use lifting equipment or trolleys, remove dust or fumes with exhaust system, lock-out machinery.
3. CHANGE THE WAY THE JOB IS DONE. For example: change work practices, provide training, information and signs, write work procedures.
4. USE PERSONAL PROTECTIVE EQUIPMENT (PPE), noting specific PPE is required for each job. For example: respirator, hearing protection, gloves. Training and information is required for the use of PPE.

**RESIDUAL RISK LEVEL (H, M, L)**
Estimate risk taking into account the way the activity is run and control measures put in place. The level of risk can be determined by combining consequence and likelihood using the risk matrix from below. Residual risk should be reduced to a level acceptable by management.

**CONSEQUENCE OF HARM**

This is how bad it will be if something does go wrong i.e. the number of people that could be harmed, the severity of injury.

INSIGNIFICANT – Non-injury incident. Minor effects on biological or physical environment.
MINOR – Injury or ill health requiring first aid. Moderate, short-term effects but not affecting ecosystem functions.
MODERATE – Injury or ill health requiring medical attention. Serious medium-term environmental effects.
MAJOR – Injury or ill health requiring hospital admission. Very serious long term impairment of ecosystem functions.
CATASTROPHIC – Fatality or permanent disabling injury. Very serious long term impairment of ecosystem functions.

**LIKELIHOOD OF HARM**

Chance of harm occurring is affected by the duration of the activity and its frequency; the number of people doing the activity and the level of exposure to the hazard.

RARE – Heard of something like this occurring elsewhere.
UNLIKELY – The event does occur somewhere from time to time.
POSSIBLE – The event might occur once in your career.
LIKELY – The event has occurred several times or more in your career.
ALMOST CERTAIN – The event will occur on an annual basis.

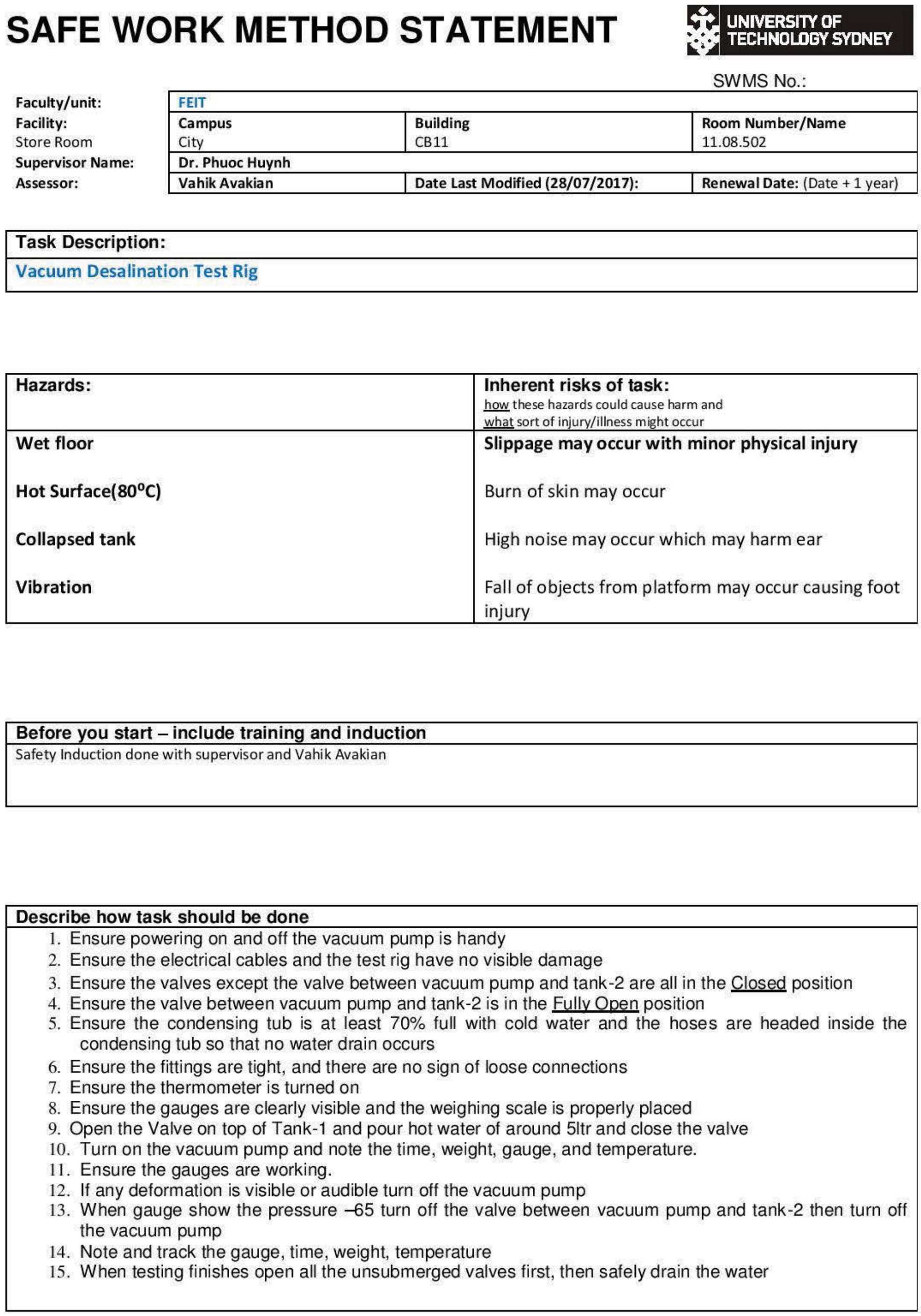
| | **CONSEQUENCES** | | | | |
|---|---|---|---|---|---|
| **LIKELIHOOD ↓** | **Insignificant** | **Minor** | **Moderate** | **Major** | **Catastrophic** |
| **Almost certain** | H | H | E | E | E |
| **Likely** | M | H | H | E | E |
| **Possible** | L | M | H | E | E |
| **Unlikely** | L | L | M | H | E |
| **Rare** | L | L | M | H | H |

*From AS/NZS 4360: Risk Management.*

UTS General Risk Assessment

Appendix

## A7. SWMS



# SAFE WORK METHOD STATEMENT

UNIVERSITY OF TECHNOLOGY SYDNEY

SWMS No.:

| | | | |
|---|---|---|---|
| **Faculty/unit:** | FEIT | | |
| **Facility:**<br>Store Room | **Campus**<br>City | **Building**<br>CB11 | **Room Number/Name**<br>11.08.502 |
| **Supervisor Name:** | **Dr. Phuoc Huynh** | | |
| **Assessor:** | **Vahik Avakian** | **Date Last Modified (28/07/2017):** | **Renewal Date:** (Date + 1 year) |

| **Task Description:** |
|---|
| Vacuum Desalination Test Rig |

| **Hazards:** | **Inherent risks of task:**<br>how these hazards could cause harm and<br>what sort of injury/illness might occur |
|---|---|
| **Wet floor** | **Slippage may occur with minor physical injury** |
| **Hot Surface(80$^{o}$C)** | Burn of skin may occur |
| **Collapsed tank** | High noise may occur which may harm ear |
| **Vibration** | Fall of objects from platform may occur causing foot injury |

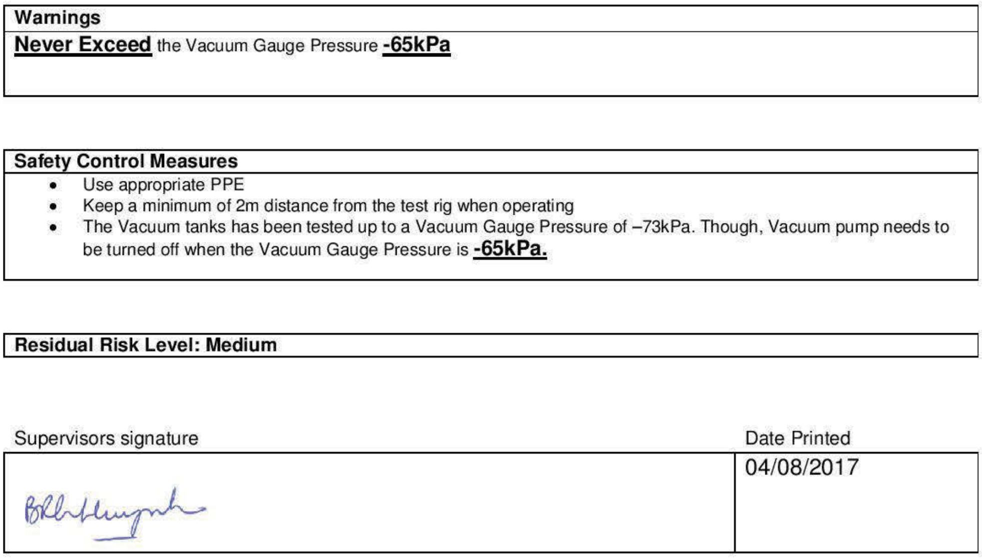
| **Before you start – include training and induction** |
|---|
| Safety Induction done with supervisor and Vahik Avakian |

**Describe how task should be done**

1. Ensure powering on and off the vacuum pump is handy
2. Ensure the electrical cables and the test rig have no visible damage
3. Ensure the valves except the valve between vacuum pump and tank-2 are all in the Closed position
4. Ensure the valve between vacuum pump and tank-2 is in the Fully Open position
5. Ensure the condensing tub is at least 70% full with cold water and the hoses are headed inside the condensing tub so that no water drain occurs
6. Ensure the fittings are tight, and there are no sign of loose connections
7. Ensure the thermometer is turned on
8. Ensure the gauges are clearly visible and the weighing scale is properly placed
9. Open the Valve on top of Tank-1 and pour hot water of around 5ltr and close the valve
10. Turn on the vacuum pump and note the time, weight, gauge, and temperature.
11. Ensure the gauges are working.
12. If any deformation is visible or audible turn off the vacuum pump
13. When gauge show the pressure –65 turn off the valve between vacuum pump and tank-2 then turn off the vacuum pump
14. Note and track the gauge, time, weight, temperature
15. When testing finishes open all the unsubmerged valves first, then safely drain the water

# Appendix

## A7 continued



**Warnings**

**<u>Never Exceed</u>** the Vacuum Gauge Pressure **<u>-65kPa</u>**

**Safety Control Measures**

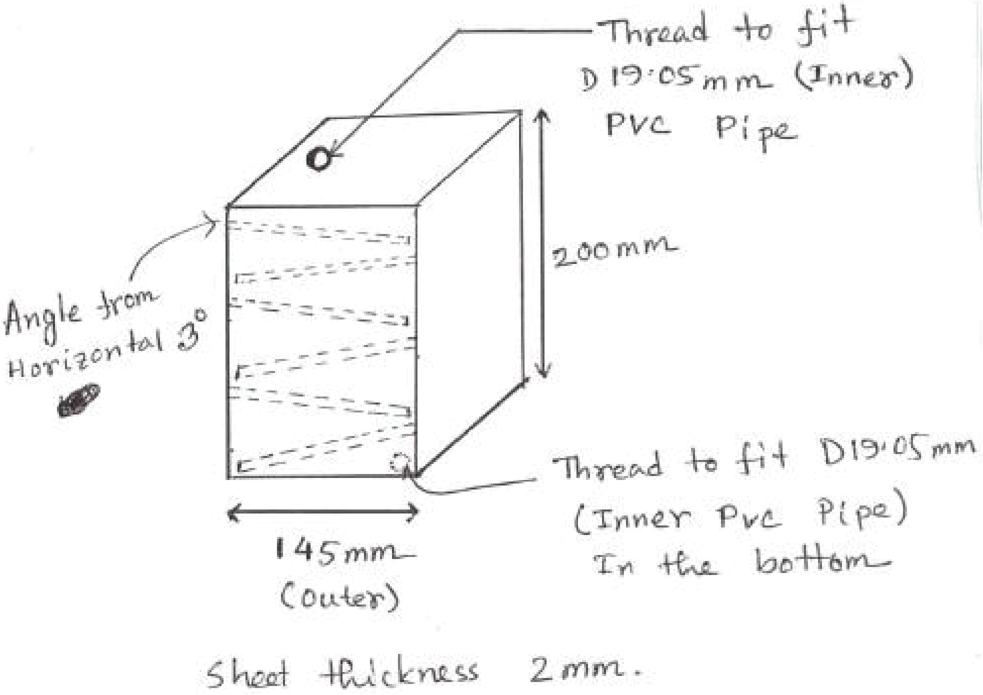
- Use appropriate PPE
- Keep a minimum of 2m distance from the test rig when operating
- The Vacuum tanks has been tested up to a Vacuum Gauge Pressure of –73kPa. Though, Vacuum pump needs to be turned off when the Vacuum Gauge Pressure is **<u>-65kPa.</u>**

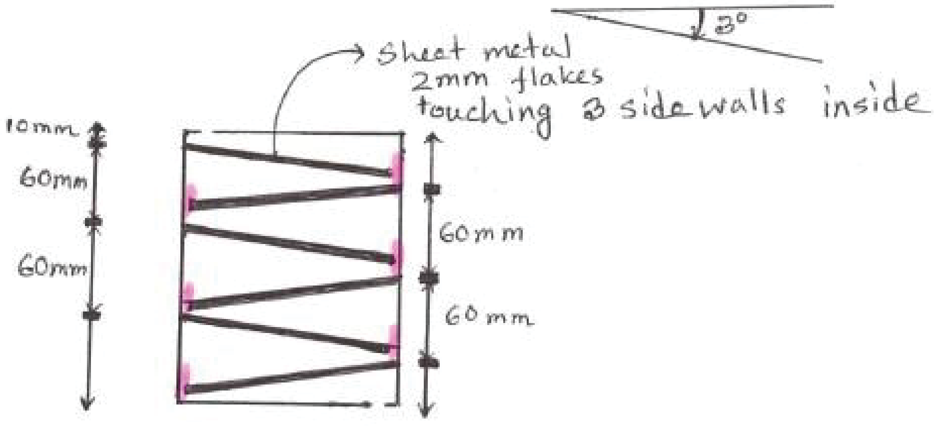
**Residual Risk Level: Medium**

| Supervisors signature | Date Printed |
|---|---|
|  | 04/08/2017 |

## Appendix

## A8. Simplified condenser model- Plate based



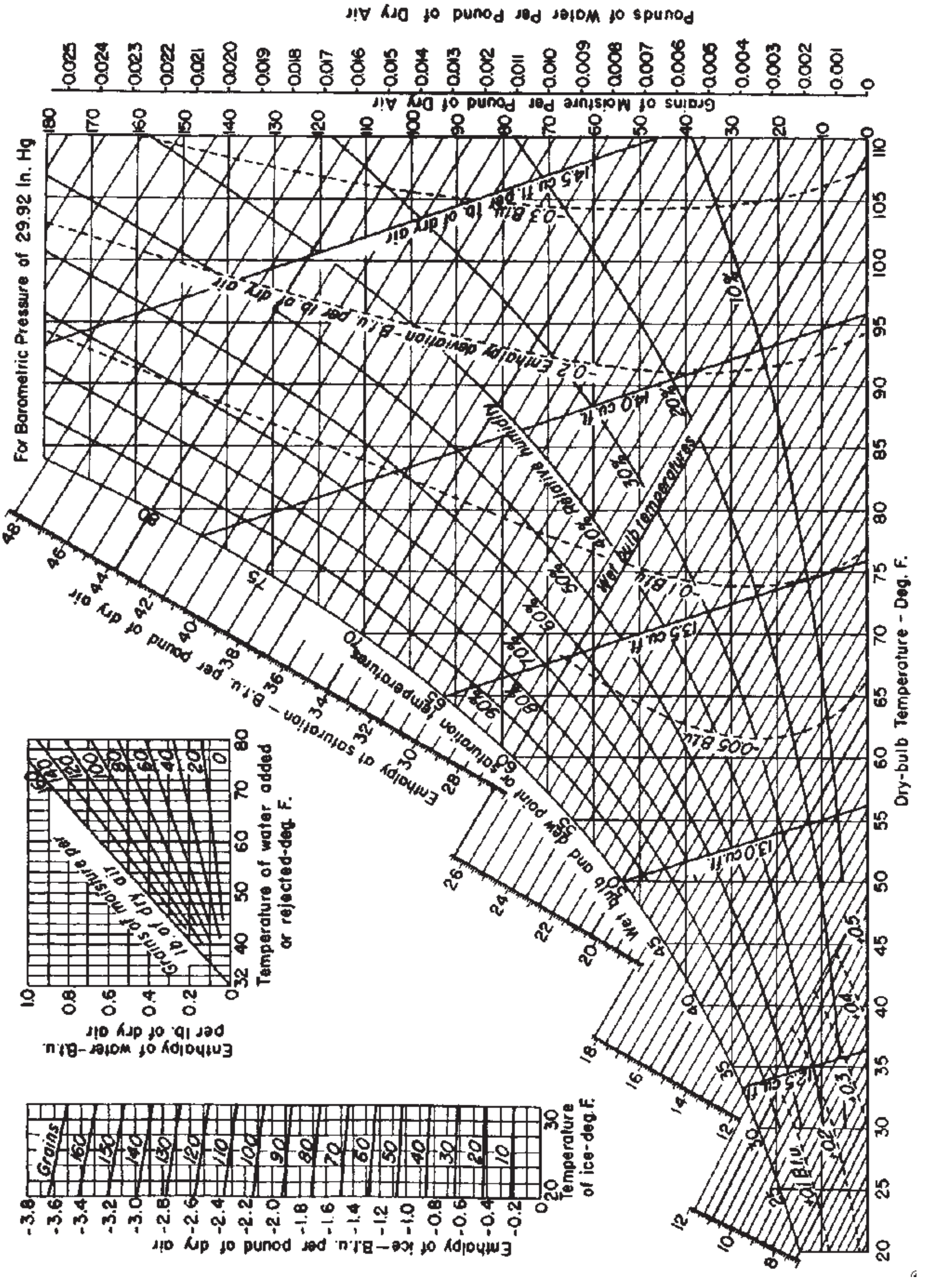


Cross sectional View

→▮← 10mm clearance from the side wall

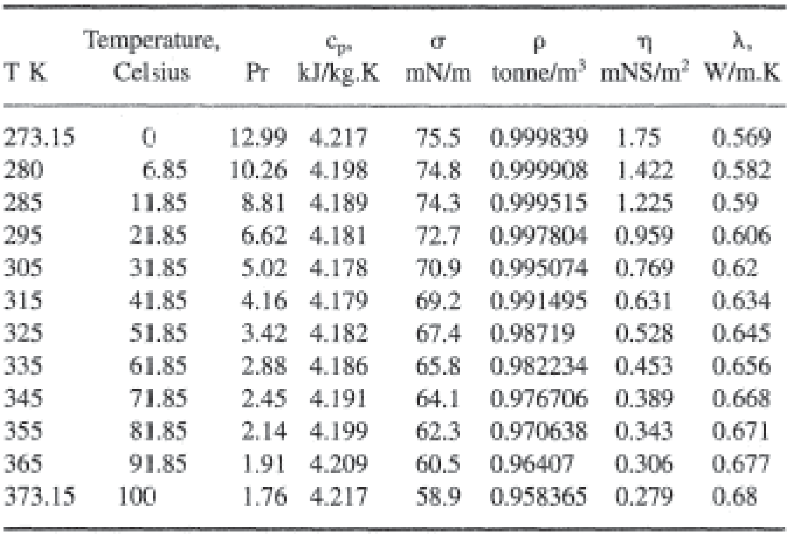
Appendix

## A9. Psychometric Chart

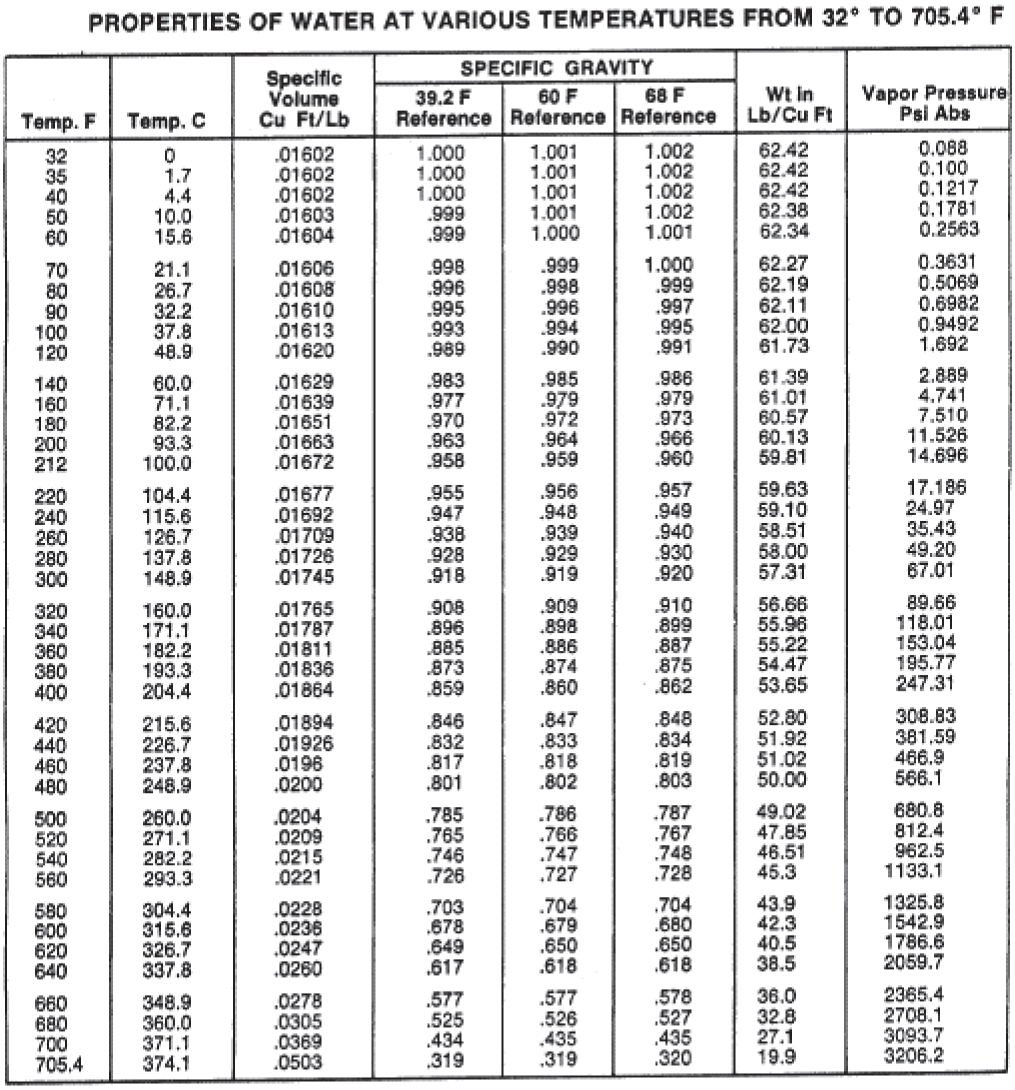


Appendix

## A10. Water properties



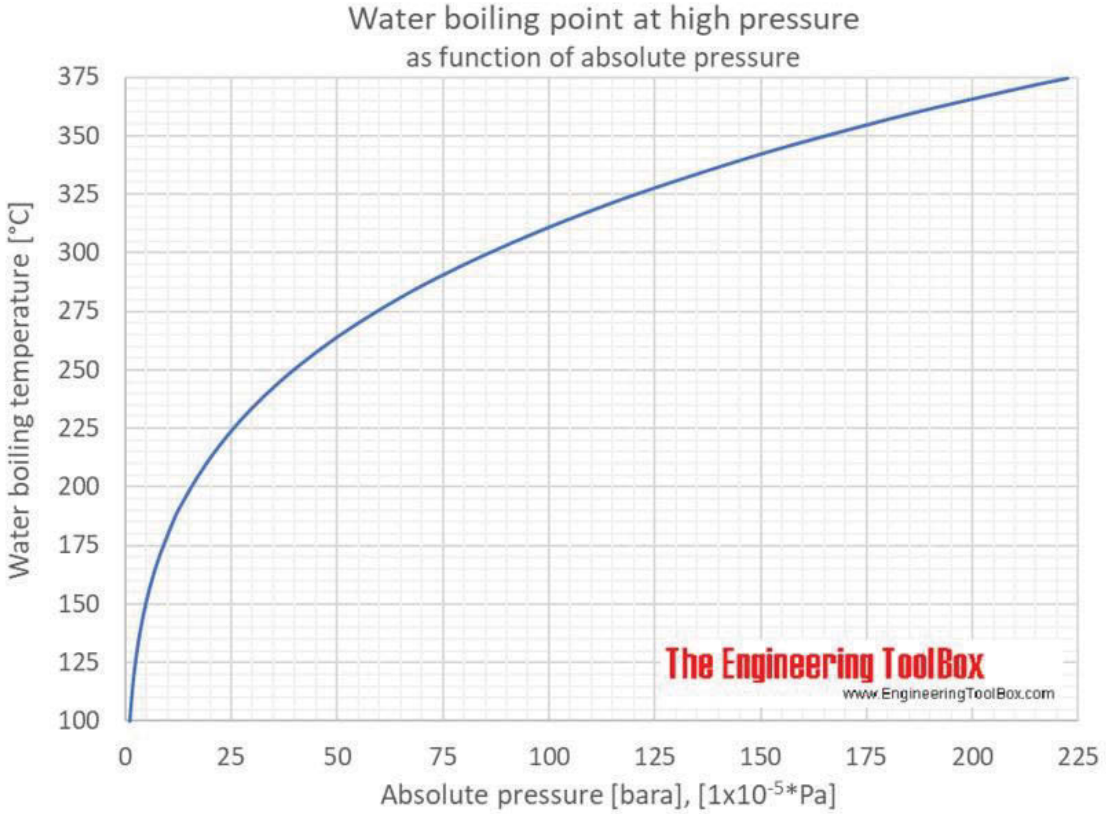
| T K | Temperature, Celsius | Pr | $c_p$, kJ/kg.K | $\sigma$ mN/m | $\rho$ tonne/m$^3$ | $\eta$ mNS/m$^2$ | $\lambda$, W/m.K |
|---|---|---|---|---|---|---|---|
| 273.15 | 0 | 12.99 | 4.217 | 75.5 | 0.999839 | 1.75 | 0.569 |
| 280 | 6.85 | 10.26 | 4.198 | 74.8 | 0.999908 | 1.422 | 0.582 |
| 285 | 11.85 | 8.81 | 4.189 | 74.3 | 0.999515 | 1.225 | 0.59 |
| 295 | 21.85 | 6.62 | 4.181 | 72.7 | 0.997804 | 0.959 | 0.606 |
| 305 | 31.85 | 5.02 | 4.178 | 70.9 | 0.995074 | 0.769 | 0.62 |
| 315 | 41.85 | 4.16 | 4.179 | 69.2 | 0.991495 | 0.631 | 0.634 |
| 325 | 51.85 | 3.42 | 4.182 | 67.4 | 0.98719 | 0.528 | 0.645 |
| 335 | 61.85 | 2.88 | 4.186 | 65.8 | 0.982234 | 0.453 | 0.656 |
| 345 | 71.85 | 2.45 | 4.191 | 64.1 | 0.976706 | 0.389 | 0.668 |
| 355 | 81.85 | 2.14 | 4.199 | 62.3 | 0.970638 | 0.343 | 0.671 |
| 365 | 91.85 | 1.91 | 4.209 | 60.5 | 0.96407 | 0.306 | 0.677 |
| 373.15 | 100 | 1.76 | 4.217 | 58.9 | 0.958365 | 0.279 | 0.68 |

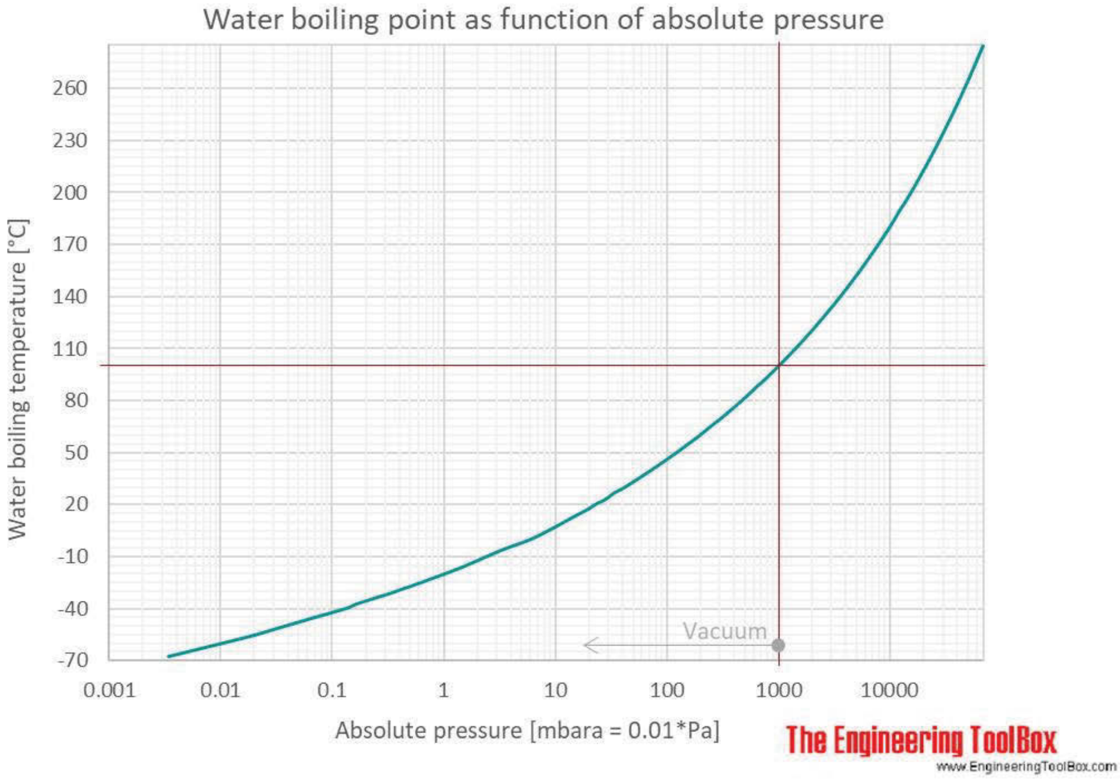


**PROPERTIES OF WATER AT VARIOUS TEMPERATURES FROM 32° TO 705.4° F**

| Temp. F | Temp. C | Specific Volume Cu Ft/Lb | SPECIFIC GRAVITY | | | Wt In Lb/Cu Ft | Vapor Pressure Psi Abs |
|---|---|---|---|---|---|---|---|
| | | | 39.2 F Reference | 60 F Reference | 68 F Reference | | |
| 32 | 0 | .01602 | 1.000 | 1.001 | 1.002 | 62.42 | 0.088 |
| 35 | 1.7 | .01602 | 1.000 | 1.001 | 1.002 | 62.42 | 0.100 |
| 40 | 4.4 | .01602 | 1.000 | 1.001 | 1.002 | 62.42 | 0.1217 |
| 50 | 10.0 | .01603 | .999 | 1.001 | 1.002 | 62.38 | 0.1781 |
| 60 | 15.6 | .01604 | .999 | 1.000 | 1.001 | 62.34 | 0.2563 |
| 70 | 21.1 | .01606 | .998 | .999 | 1.000 | 62.27 | 0.3631 |
| 80 | 26.7 | .01608 | .996 | .998 | .999 | 62.19 | 0.5069 |
| 90 | 32.2 | .01610 | .995 | .996 | .997 | 62.11 | 0.6982 |
| 100 | 37.8 | .01613 | .993 | .994 | .995 | 62.00 | 0.9492 |
| 120 | 48.9 | .01620 | .989 | .990 | .991 | 61.73 | 1.692 |
| 140 | 60.0 | .01629 | .983 | .985 | .986 | 61.39 | 2.889 |
| 160 | 71.1 | .01639 | .977 | .979 | .979 | 61.01 | 4.741 |
| 180 | 82.2 | .01651 | .970 | .972 | .973 | 60.57 | 7.510 |
| 200 | 93.3 | .01663 | .963 | .964 | .966 | 60.13 | 11.526 |
| 212 | 100.0 | .01672 | .958 | .959 | .960 | 59.81 | 14.696 |
| 220 | 104.4 | .01677 | .955 | .956 | .957 | 59.63 | 17.186 |
| 240 | 115.6 | .01692 | .947 | .948 | .949 | 59.10 | 24.97 |
| 260 | 126.7 | .01709 | .938 | .939 | .940 | 58.51 | 35.43 |
| 280 | 137.8 | .01726 | .928 | .929 | .930 | 58.00 | 49.20 |
| 300 | 148.9 | .01745 | .918 | .919 | .920 | 57.31 | 67.01 |
| 320 | 160.0 | .01765 | .908 | .909 | .910 | 56.66 | 89.66 |
| 340 | 171.1 | .01787 | .896 | .898 | .899 | 55.96 | 118.01 |
| 360 | 182.2 | .01811 | .885 | .886 | .887 | 55.22 | 153.04 |
| 380 | 193.3 | .01836 | .873 | .874 | .875 | 54.47 | 195.77 |
| 400 | 204.4 | .01864 | .859 | .860 | .862 | 53.65 | 247.31 |
| 420 | 215.6 | .01894 | .846 | .847 | .848 | 52.80 | 308.83 |
| 440 | 226.7 | .01926 | .832 | .833 | .834 | 51.92 | 381.59 |
| 460 | 237.8 | .0196 | .817 | .818 | .819 | 51.02 | 466.9 |
| 480 | 248.9 | .0200 | .801 | .802 | .803 | 50.00 | 566.1 |
| 500 | 260.0 | .0204 | .785 | .786 | .787 | 49.02 | 680.8 |
| 520 | 271.1 | .0209 | .765 | .766 | .767 | 47.85 | 812.4 |
| 540 | 282.2 | .0215 | .746 | .747 | .748 | 46.51 | 962.5 |
| 560 | 293.3 | .0221 | .726 | .727 | .728 | 45.3 | 1133.1 |
| 580 | 304.4 | .0228 | .703 | .704 | .704 | 43.9 | 1325.8 |
| 600 | 315.6 | .0236 | .678 | .679 | .680 | 42.3 | 1542.9 |
| 620 | 326.7 | .0247 | .649 | .650 | .650 | 40.5 | 1786.6 |
| 640 | 337.8 | .0260 | .617 | .618 | .618 | 38.5 | 2059.7 |
| 660 | 348.9 | .0278 | .577 | .577 | .578 | 36.0 | 2365.4 |
| 680 | 360.0 | .0305 | .525 | .526 | .527 | 32.8 | 2708.1 |
| 700 | 371.1 | .0369 | .434 | .435 | .435 | 27.1 | 3093.7 |
| 705.4 | 374.1 | .0503 | .319 | .319 | .320 | 19.9 | 3206.2 |

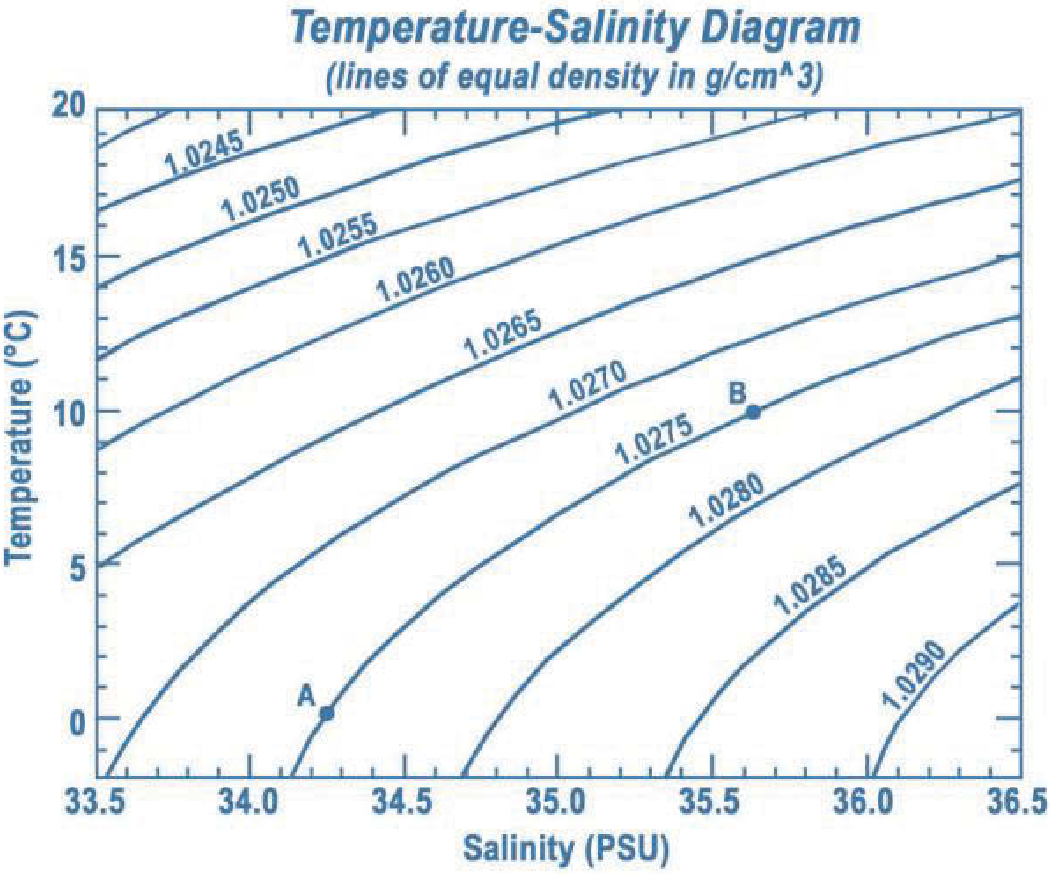
A10 continued

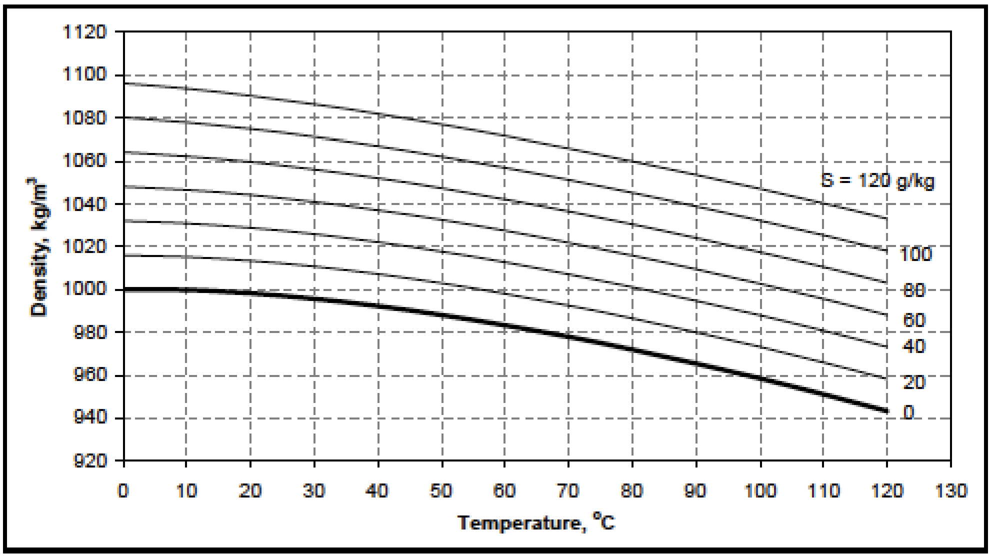




Appendix

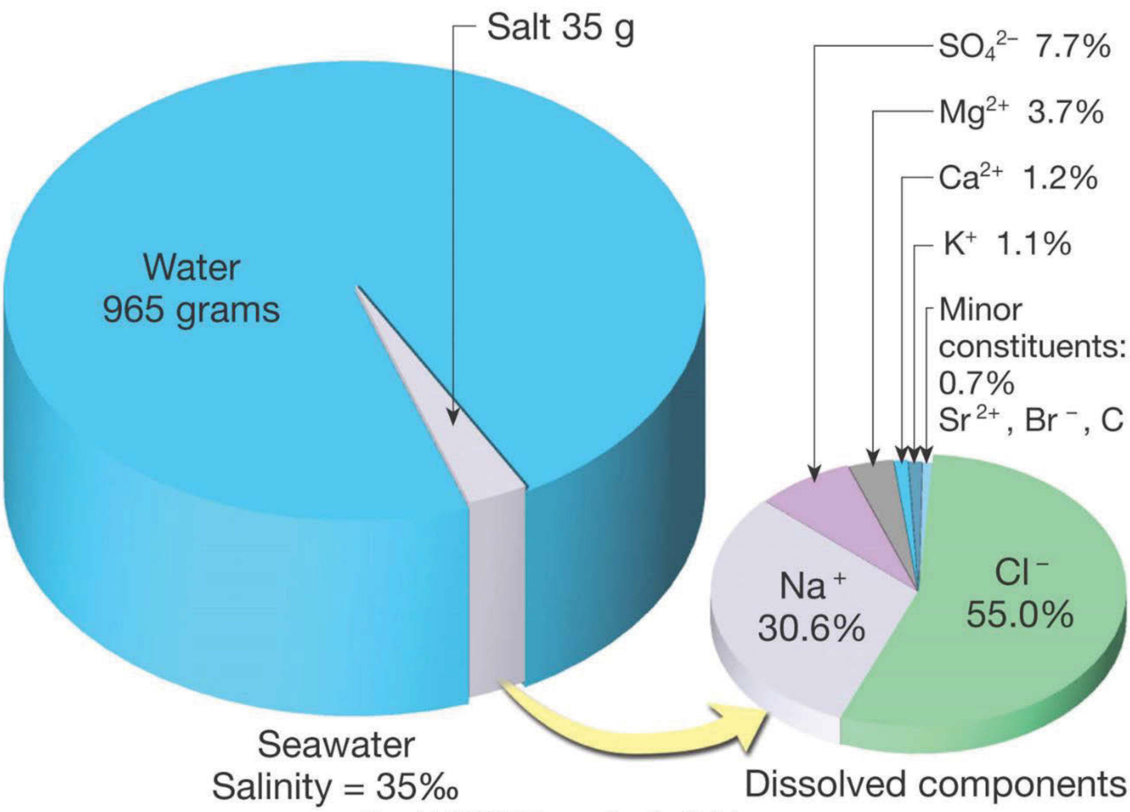
## A11. Properties of Seawater



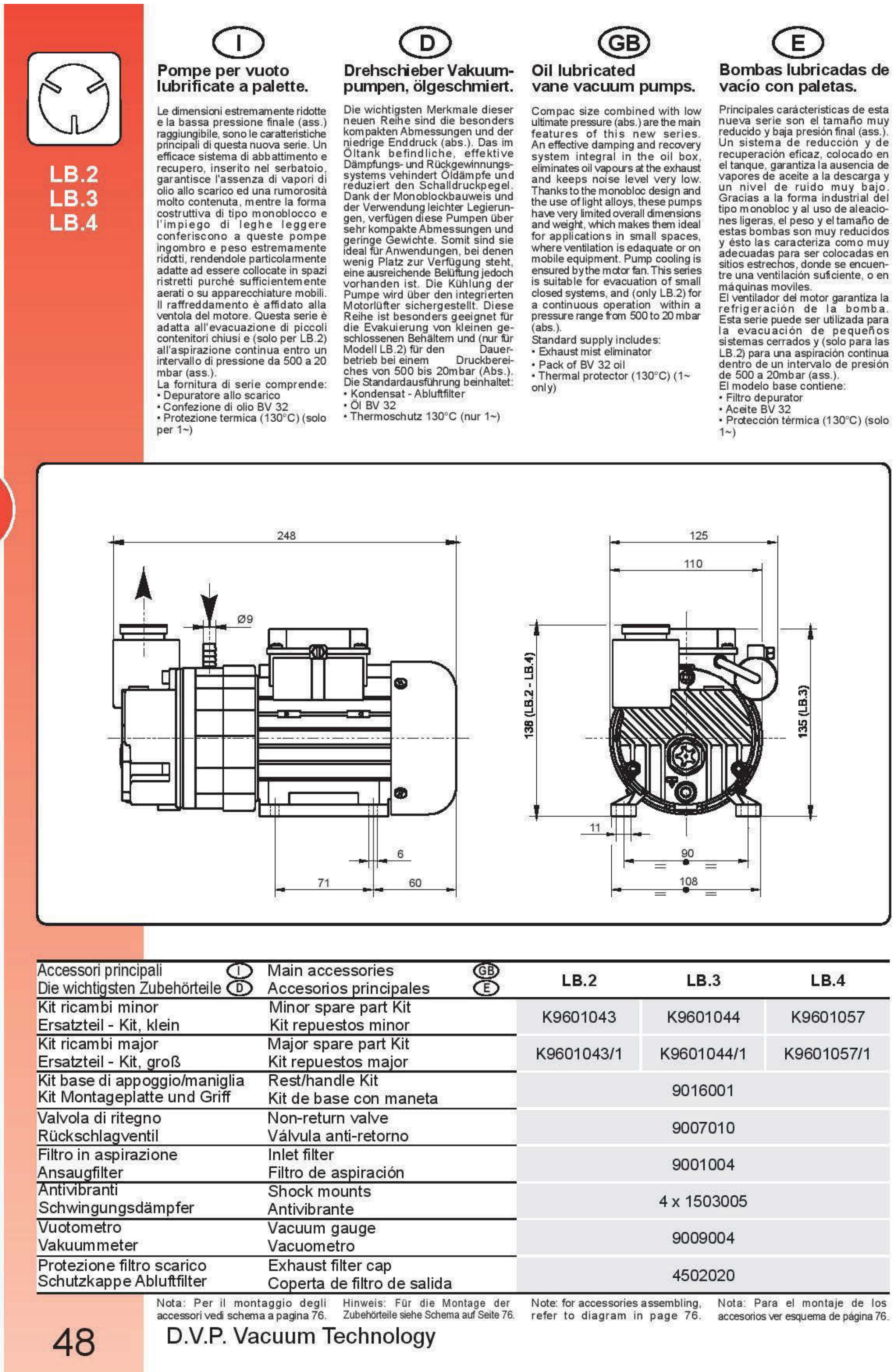


Appendix

A11 continued



## A12. Vacuum Pump Data



**LB.2**
**LB.3**
**LB.4**

(I)

### Pompe per vuoto lubrificate a palette.

Le dimensioni estremamente ridotte e la bassa pressione finale (ass.) raggiungibile, sono le caratteristiche principali di questa nuova serie. Un efficace sistema di abbattimento e recupero, inserito nel serbatoio, garantisce l'assenza di vapori di olio allo scarico ed una rumorosità molto contenuta, mentre la forma costruttiva di tipo monoblocco e l'impiego di leghe leggere conferiscono a queste pompe ingombro e peso estremamente ridotti, rendendole particolarmente adatte ad essere collocate in spazi ristretti purché sufficientemente aerati o su apparecchiature mobili. Il raffreddamento è affidato alla ventola del motore. Questa serie è adatta all'evacuazione di piccoli contenitori chiusi e (solo per LB.2) all'aspirazione continua entro un intervallo di pressione da 500 a 20 mbar (ass.).

La fornitura di serie comprende:
- Depuratore allo scarico
- Confezione di olio BV 32
- Protezione termica (130°C) (solo per 1~)

(D)

### Drehschieber Vakuumpumpen, ölgeschmiert.

Die wichtigsten Merkmale dieser neuen Reihe sind die besonders kompakten Abmessungen und der niedrige Enddruck (abs.). Das im Öltank befindliche, effektive Dämpfungs- und Rückgewinnungssystems vehindert Öldämpfe und reduziert den Schalldruckpegel. Dank der Monoblockbauweis und der Verwendung leichter Legierungen, verfügen diese Pumpen über sehr kompakte Abmessungen und geringe Gewichte. Somit sind sie ideal für Anwendungen, bei denen wenig Platz zur Verfügung steht, eine ausreichende Belüftung jedoch vorhanden ist. Die Kühlung der Pumpe wird über den integrierten Motorlüfter sichergestellt. Diese Reihe ist besonders geeignet für die Evakuierung von kleinen geschlossenen Behältern und (nur für Modell LB.2) für den Dauerbetrieb bei einem Druckbereiches von 500 bis 20mbar (Abs.).

Die Standardausführung beinhaltet:
- Kondensat - Abluftfilter
- Öl BV 32
- Thermoschutz 130°C (nur 1~)

(GB)

### Oil lubricated vane vacuum pumps.

Compac size combined with low ultimate pressure (abs.) are the main features of this new series. An effective damping and recovery system integral in the oil box, eliminates oil vapours at the exhaust and keeps noise level very low. Thanks to the monobloc design and the use of light alloys, these pumps have very limited overall dimensions and weight, which makes them ideal for applications in small spaces, where ventilation is edaquate or on mobile equipment. Pump cooling is ensured by the motor fan. This series is suitable for evacuation of small closed systems, and (only LB.2) for a continuous operation within a pressure range from 500 to 20 mbar (abs.).

Standard supply includes:
- Exhaust mist eliminator
- Pack of BV 32 oil
- Thermal protector (130°C) (1~ only)

(E)

### Bombas lubricadas de vacío con paletas.

Principales carácteristicas de esta nueva serie son el tamaño muy reducido y baja presión final (ass.). Un sistema de reducción y de recuperación eficaz, colocado en el tanque, garantiza la ausencia de vapores de aceite a la descarga y un nivel de ruido muy bajo. Gracias a la forma industrial del tipo monobloc y al uso de aleaciones ligeras, el peso y el tamaño de estas bombas son muy reducidos y ésto las caracteriza como muy adecuadas para ser colocadas en sitios estrechos, donde se encuentre una ventilación suficiente, o en máquinas moviles.
El ventilador del motor garantiza la refrigeración de la bomba. Esta serie puede ser utilizada para la evacuación de pequeños sistemas cerrados y (solo para las LB.2) para una aspiración continua dentro de un intervalo de presión de 500 a 20mbar (ass.).

El modelo base contiene:
- Filtro depurator
- Aceite BV 32
- Protección térmica (130°C) (solo 1~)

| Accessori principali (I)<br>Die wichtigsten Zubehörteile (D) | Main accessories (GB)<br>Accesorios principales (E) | LB.2 | LB.3 | LB.4 |
|---|---|---|---|---|
| Kit ricambi minor<br>Ersatzteil - Kit, klein | Minor spare part Kit<br>Kit repuestos minor | K9601043 | K9601044 | K9601057 |
| Kit ricambi major<br>Ersatzteil - Kit, groß | Major spare part Kit<br>Kit repuestos major | K9601043/1 | K9601044/1 | K9601057/1 |
| Kit base di appoggio/maniglia<br>Kit Montageplatte und Griff | Rest/handle Kit<br>Kit de base con maneta | 9016001 | | |
| Valvola di ritegno<br>Rückschlagventil | Non-return valve<br>Válvula anti-retorno | 9007010 | | |
| Filtro in aspirazione<br>Ansaugfilter | Inlet filter<br>Filtro de aspiración | 9001004 | | |
| Antivibranti<br>Schwingungsdämpfer | Shock mounts<br>Antivibrante | 4 x 1503005 | | |
| Vuotometro<br>Vakuummeter | Vacuum gauge<br>Vacuometro | 9009004 | | |
| Protezione filtro scarico<br>Schutzkappe Abluftfilter | Exhaust filter cap<br>Coperta de filtro de salida | 4502020 | | |

Nota: Per il montaggio degli accessori vedi schema a pagina 76.

Hinweis: Für die Montage der Zubehörteile siehe Schema auf Seite 76.

Note: for accessories assembling, refer to diagram in page 76.

Nota: Para el montaje de los accesorios ver esquema de página 76.

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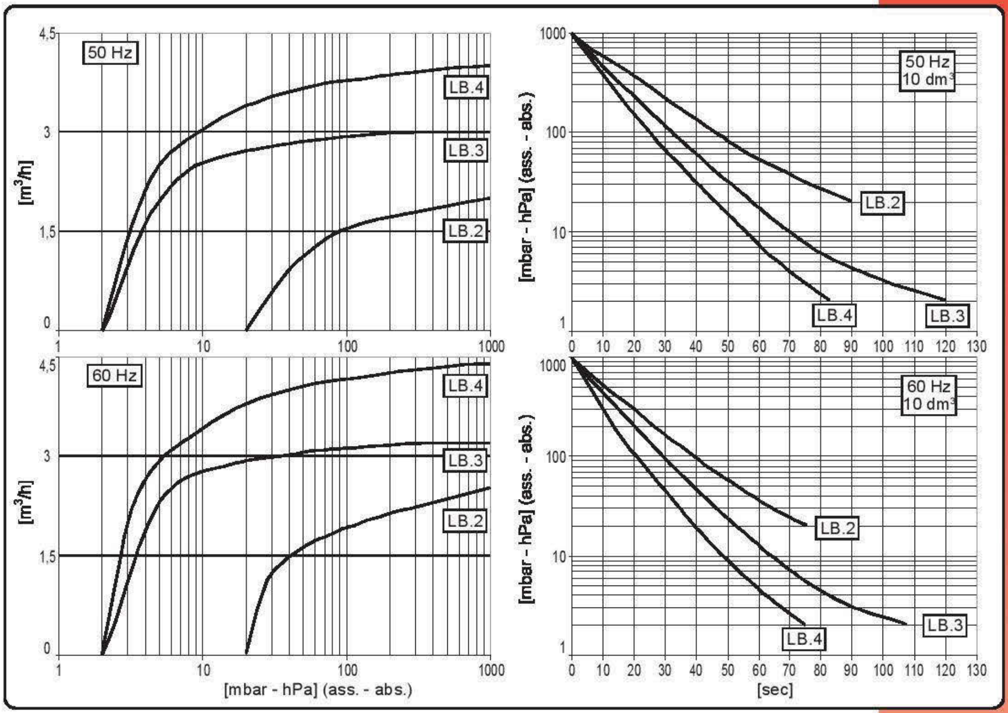
A12 continued



| Modello Ⓘ<br>Modell Ⓓ | Model (GB)<br>Modelo (E) | | LB.2 | | LB.3 | | LB.4 | |
|---|---|---|---|---|---|---|---|---|
| | | | 50Hz | 60Hz | 50Hz | 60Hz | 50Hz | 60Hz |
| Codice catalogo<br>Artikelnummer | Catalog code<br>Código catálogo | | 9601043 | | 9601044 | | 9601057 | |
| Portata<br>Saugvermögen | Inlet capacity<br>Caudal | m³/h | 2 | 2,5 | 3 | 3,2 | 4 | 4,4 |
| Pressione finale (ass.)<br>Enddruck (abs.) | Final pressure (abs.)<br>Presión final (abs.) | mbar<br>hPa | 20 | | 2 | | | |
| Max pressione di asp. per vapore d'acqua<br>Max. Eintrittsdruck für Wasserdampf | Max inlet pressure for water vapour<br>Presión máx. admisible del vapor de agua | mbar<br>hPa | - - | - - | - - | - - | - - | - - |
| Max q.tà vapore d'acqua<br>Max. Wasserdampfverträglichkeit | Max water vapour pumping rate<br>Cantidad máx. vapor de agua | kg/h | - - | - - | - - | - - | - - | - - |
| Potenza motore<br>Motorleistung | Motor power<br>Potencia motor | (1~) kW<br>(3~) kW | 0,12<br>0,12 | 0,15<br>0,14 | 0,12<br>0,12 | 0,15<br>0,14 | 0,12<br>0,12 | 0,15<br>0,14 |
| Numero di giri nominali<br>U/min | R.p.m.<br>Número de revoluciones | n/min | 2800 | 3300 | 2800 | 3300 | 2800 | 3300 |
| Rumorosità (UNI EN ISO 2151)<br>Schalldruckpegel (UNI EN ISO 2151) | Noise level (UNI EN ISO 2151)<br>Nivel sonoro (UNI EN ISO 2151) | dB(A) | 57 | 59 | 56 | 58 | 57 | 59 |
| Temperatura di funzionamento*<br>Betriebstemperatur* | Operating temperature*<br>Temperatura de funcionamiento* | °C | 60÷65 | 65÷70 | 60÷65 | 65÷70 | 60÷65 | 65÷70 |
| Tipo olio<br>Öltyp | Oil type<br>Tipo aceite | | BV32 (SW40) | | | | | |
| Carica olio<br>Ölmenge | Oil quantity<br>Carga aceite | dm³ | 0,06 | | | | | |
| Peso<br>Gewicht | Weight<br>Peso | (1~); (3~) kg [N] | 5,4 [52,9] | | | | | |
| Aspirazione pompa<br>Saugstutzen | Pump intake<br>Boca de aspiración | | Ø9 | | | | | |

(*) Temperatura ambiente 20°C (*) Umgebungstemperatur 20°C (*) Ambient Temperature 20°C (*) Temperatura ambiente 20°C

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# A13. Test 3 (Operating Condition A)

In this set of experimental data (Table 10), 2.5 kg water of around 73$^0$C was taken in Cylinder-1 and after the process, we got 0.35 kg of condensed water in Cylinder-2 though around 0.45 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2.5 kg
S= Specific heat of water 4.18 kJ/kg-K
ΔT= 79 K

Energy required to heat up 21$^0$C water into 100$^0$C water = msΔT
= 825.6 kJ

Energy required to convert 100$^0$C 0.35 kg water into 100$^0$C 0.35 kg vapour
= mass x latent heat
= 0.35 kg x 2260 kJ/kg
= 791 kJ

Total energy required for getting 0.35 kg of condensed water from 2.5 kg of water in conventional process is 1616.6 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 135 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 135 sec = 120 Watt x 135s = 16.2 kJ

$$\text{\% of distillation in our process} = \frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1} \text{ x } 100 = \frac{0.35}{2.5} \text{ x } 100$$

$$= 14\%$$

$$\text{Total Energy Savings} = \frac{(1616.6\ - 16.2)\text{ kJ}}{1616.6\ \text{ kJ}} \text{ x } 100\ = 99\%$$

*Table 10 Experimental Data: Test 3*

**Vacuum Desalination Experiment** **Data Set** **3**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (º C) : | 21 | R Humidity (%): | 68 | Weight of Feed (1) water (kg): | 2.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (º C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (º C) | Gauge Pressure 2 (kPa) | Temperature 3 (º C) |
| Before start (Empty) | 4.45 | 21 | -2 | 4.45 | 21 | 0 | 21 |
| After Start (00min)<br>Pump on | 6.95 | 73 | -2 | 4.45 | 21.3 | 0 | 21 |
| After Start (02min 15sec)<br>Pump off | | 47 | -99 | | 21.8 | -97 | 23 |
| After Start (10min) | | 32 | -100 | | 22.3 | -97 | 23.2 |
| After Start (15min) | | 29 | -100 | | 22.5 | -97 | 23.2 |
| Finish (16min) | 6.5 | 29 | -2 | 4.8 | 22.5 | 0 | 23.3 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 3. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.0 | 2.50 | 0.01 | 23.8 | 2.3 | 70.7 | 10.0 |
| 70.7 | 2.49 | 0.01 | 23.8 | 2.3 | 68.4 | 10.0 |
| 68.4 | 2.48 | 0.01 | 23.8 | 2.3 | 66.1 | 10.0 |
| 66.1 | 2.47 | 0.01 | 23.8 | 2.3 | 63.8 | 10.0 |
| 63.8 | 2.46 | 0.01 | 23.8 | 2.3 | 61.5 | 10.0 |
| 61.5 | 2.45 | 0.01 | 23.8 | 2.3 | 59.1 | 10.0 |
| 59.1 | 2.44 | 0.01 | 23.8 | 2.3 | 56.8 | 10.0 |
| 56.8 | 2.43 | 0.01 | 23.8 | 2.4 | 54.4 | 10.0 |
| 54.4 | 2.42 | 0.01 | 23.8 | 2.4 | 52.1 | 10.0 |
| 52.1 | 2.41 | 0.01 | 23.8 | 2.4 | 49.7 | 10.0 |
| 49.7 | 2.40 | 0.01 | 23.8 | 2.4 | 47.3 | 10.0 |
| 47.3 | 2.39 | 0.01 | 23.8 | 2.4 | 44.9 | 10.0 |
| 44.9 | 2.38 | 0.01 | 23.8 | 2.4 | 42.5 | 10.0 |
| 42.5 | 2.37 | 0.01 | 23.8 | 2.4 | 40.1 | 10.0 |
| 40.1 | 2.36 | 0.01 | 23.8 | 2.4 | 37.7 | 10.0 |
| 37.7 | 2.35 | 0.01 | 23.8 | 2.4 | 35.2 | 10.0 |
| 35.2 | 2.34 | 0.01 | 23.8 | 2.4 | 32.8 | 10.0 |
| 32.8 | 2.33 | 0.01 | 23.8 | 2.5 | 30.3 | 10.0 |
| 30.3 | 2.32 | 0.01 | 23.8 | 2.5 | 27.9 | 10.0 |
| 27.9 | 2.31 | 0.01 | 23.8 | 2.5 | 25.4 | 10.0 |
| 25.4 | 2.30 | 0.01 | 23.8 | 2.5 | 22.9 | 10.0 |
| 22.9 | 2.29 | 0.01 | 23.8 | 2.5 | 20.4 | 10.0 |

From the above calculation, we found that water will evaporate until 22.9$^0$C and 0.22 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.22 kg of water in Cylinder-2. But from the experiment we got 0.35 kg of condensed water in Cylinder-2. This has been discussed in Test Results. We can calculate 0-gram step as done earlier in Test 1.

# Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.0 | 2.50 | 0.0050 | 11.9 | 1.1 | 71.9 | 5.0 |
| 71.9 | 2.50 | 0.0050 | 11.9 | 1.1 | 70.7 | 5.0 |
| 70.7 | 2.49 | 0.0050 | 11.9 | 1.1 | 69.6 | 5.0 |
| 69.6 | 2.49 | 0.0050 | 11.9 | 1.1 | 68.4 | 5.0 |
| 68.4 | 2.48 | 0.0050 | 11.9 | 1.2 | 67.3 | 5.0 |
| 67.3 | 2.48 | 0.0050 | 11.9 | 1.2 | 66.1 | 5.0 |
| 66.1 | 2.47 | 0.0050 | 11.9 | 1.2 | 65.0 | 5.0 |
| 65.0 | 2.47 | 0.0050 | 11.9 | 1.2 | 63.8 | 5.0 |
| 63.8 | 2.46 | 0.0050 | 11.9 | 1.2 | 62.6 | 5.0 |
| 62.6 | 2.46 | 0.0050 | 11.9 | 1.2 | 61.5 | 5.0 |
| 61.5 | 2.45 | 0.0050 | 11.9 | 1.2 | 60.3 | 5.0 |
| 60.3 | 2.45 | 0.0050 | 11.9 | 1.2 | 59.1 | 5.0 |
| 59.1 | 2.44 | 0.0050 | 11.9 | 1.2 | 58.0 | 5.0 |
| 58.0 | 2.44 | 0.0050 | 11.9 | 1.2 | 56.8 | 5.0 |
| 56.8 | 2.43 | 0.0050 | 11.9 | 1.2 | 55.6 | 5.0 |
| 55.6 | 2.43 | 0.0050 | 11.9 | 1.2 | 54.5 | 5.0 |
| 54.5 | 2.42 | 0.0050 | 11.9 | 1.2 | 53.3 | 5.0 |
| 53.3 | 2.42 | 0.0050 | 11.9 | 1.2 | 52.1 | 5.0 |
| 52.1 | 2.41 | 0.0050 | 11.9 | 1.2 | 50.9 | 5.0 |
| 50.9 | 2.41 | 0.0050 | 11.9 | 1.2 | 49.7 | 5.0 |
| 49.7 | 2.40 | 0.0050 | 11.9 | 1.2 | 48.5 | 5.0 |
| 48.5 | 2.40 | 0.0050 | 11.9 | 1.2 | 47.3 | 5.0 |
| 47.3 | 2.39 | 0.0050 | 11.9 | 1.2 | 46.1 | 5.0 |
| 46.1 | 2.39 | 0.0050 | 11.9 | 1.2 | 45.0 | 5.0 |
| 45.0 | 2.38 | 0.0050 | 11.9 | 1.2 | 43.8 | 5.0 |
| 43.8 | 2.38 | 0.0050 | 11.9 | 1.2 | 42.6 | 5.0 |
| 42.6 | 2.37 | 0.0050 | 11.9 | 1.2 | 41.3 | 5.0 |
| 41.3 | 2.37 | 0.0050 | 11.9 | 1.2 | 40.1 | 5.0 |
| 40.1 | 2.36 | 0.0050 | 11.9 | 1.2 | 38.9 | 5.0 |
| 38.9 | 2.36 | 0.0050 | 11.9 | 1.2 | 37.7 | 5.0 |
| 37.7 | 2.35 | 0.0050 | 11.9 | 1.2 | 36.5 | 5.0 |
| 36.5 | 2.35 | 0.0050 | 11.9 | 1.2 | 35.3 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 35.3 | 2.34 | 0.0050 | 11.9 | 1.2 | 34.1 | 5.0 |
| 34.1 | 2.34 | 0.0050 | 11.9 | 1.2 | 32.8 | 5.0 |
| 32.8 | 2.33 | 0.0050 | 11.9 | 1.2 | 31.6 | 5.0 |
| 31.6 | 2.33 | 0.0050 | 11.9 | 1.2 | 30.4 | 5.0 |
| 30.4 | 2.32 | 0.0050 | 11.9 | 1.2 | 29.2 | 5.0 |
| 29.2 | 2.32 | 0.0050 | 11.9 | 1.2 | 27.9 | 5.0 |
| 27.9 | 2.31 | 0.0050 | 11.9 | 1.2 | 26.7 | 5.0 |
| 26.7 | 2.31 | 0.0050 | 11.9 | 1.2 | 25.5 | 5.0 |
| 25.5 | 2.30 | 0.0050 | 11.9 | 1.2 | 24.2 | 5.0 |
| 24.2 | 2.30 | 0.0050 | 11.9 | 1.2 | 23.0 | 5.0 |
| 23.0 | 2.29 | 0.0050 | 11.9 | 1.2 | 21.7 | 5.0 |
| 21.7 | 2.29 | 0.0050 | 11.9 | 1.2 | 20.5 | 5.0 |
| 20.5 | 2.28 | 0.0050 | 11.9 | 1.3 | 19.2 | 5.0 |
| 19.2 | 2.28 | 0.0050 | 11.9 | 1.3 | 18.0 | 5.0 |
| 18.0 | 2.27 | 0.0050 | 11.9 | 1.3 | 16.7 | 5.0 |
| 16.7 | 2.27 | 0.0050 | 11.9 | 1.3 | 15.5 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became $23^{0}$C and 0.215 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.215 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 210 gram of water should be evaporated for 0-gram step from the graph below.

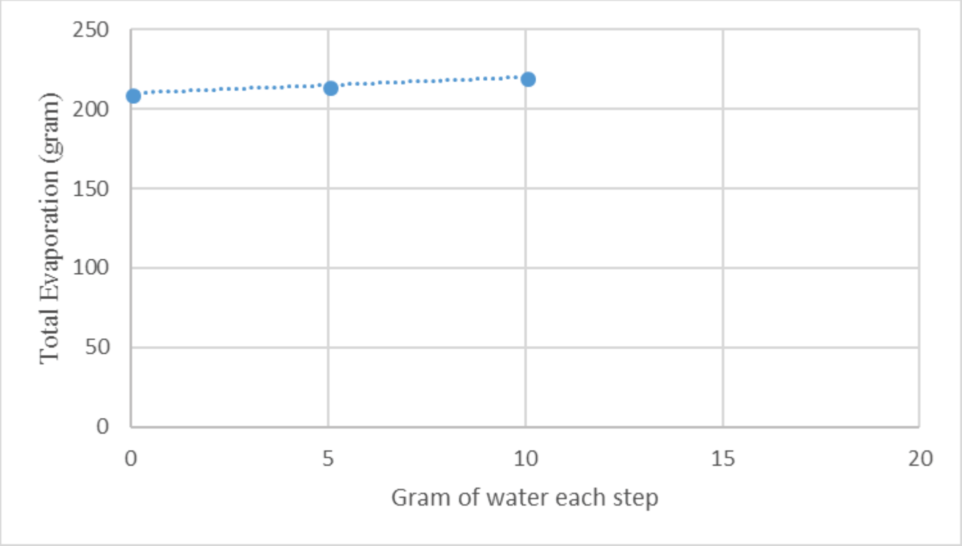

Figure 60 Extrapolation for 0-gram step

# A14 Test 4 (Operating Condition A)

In this set of experimental data (Table 11), 2 kg water of around $74^0$C was taken in Cylinder-1 and after the process, we got 0.3 kg of condensed water in Cylinder-2 though around 0.4 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 79 K

Energy required to heat up $21^0$C water into $100^0$C water = ms$\Delta$T
= 660.44 kJ

Energy required to convert $100^0$C 0.3 kg water into $100^0$C 0.3 kg vapour
= mass x latent heat
= 0.3 kg x 2260 kJ/kg
= 678 kJ

Total energy required for getting 0.3 kg of condensed water from 2 kg of water in conventional process is 1338.4 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 121 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 121 sec = 120 Watt x 121s = 14.5 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.3}{2}$ x 100
= 15%

Total Energy Savings = $\frac{(1338.4\ - 14.5)\ \text{kJ}}{1338.4\ \ \text{kJ}}$ x 100 = 98.9%

*Table 11 Experimental Data: Test 4*

**Vacuum Desalination Experiment** **Data Set** **4**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 21 | R Humidity (%): | 68 | Weight of Feed (1) water (kg): | 2 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | **Feed Water Vessel (Cylinder-1)** | | | **Desalinated Water Vessel (Cylinder-2)** | | | **Condenser** |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 21 | -2 | 4.45 | 21 | 0 | 20 |
| After Start (00min) Pump on | 6.45 | 74 | -2 | 4.45 | 21.5 | 0 | 20 |
| After Start (02min 01sec) Pump off | | 45 | -99 | | 22 | -97 | 22.7 |
| After Start (08min) | | 31 | -100 | | 22.5 | -97 | 22.8 |
| After Start (10min) | | 29.5 | -100 | | 22.5 | -97 | 23 |
| Finish (11min) | 6.05 | 29 | -2 | 4.75 | 22.5 | 0 | 23 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 4. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 74.0 | 2.00 | 0.01 | 23.8 | 2.9 | 71.1 | 10.0 |
| 71.1 | 1.99 | 0.01 | 23.8 | 2.9 | 68.3 | 10.0 |
| 68.3 | 1.98 | 0.01 | 23.8 | 2.9 | 65.4 | 10.0 |
| 65.4 | 1.97 | 0.01 | 23.8 | 2.9 | 62.5 | 10.0 |
| 62.5 | 1.96 | 0.01 | 23.8 | 2.9 | 59.5 | 10.0 |
| 59.5 | 1.95 | 0.01 | 23.8 | 2.9 | 56.6 | 10.0 |
| 56.6 | 1.94 | 0.01 | 23.8 | 3.0 | 53.7 | 10.0 |
| 53.7 | 1.93 | 0.01 | 23.8 | 3.0 | 50.7 | 10.0 |
| 50.7 | 1.92 | 0.01 | 23.8 | 3.0 | 47.7 | 10.0 |
| 47.7 | 1.91 | 0.01 | 23.8 | 3.0 | 44.7 | 10.0 |
| 44.7 | 1.90 | 0.01 | 23.8 | 3.0 | 41.7 | 10.0 |
| 41.7 | 1.89 | 0.01 | 23.8 | 3.0 | 38.7 | 10.0 |
| 38.7 | 1.88 | 0.01 | 23.8 | 3.0 | 35.6 | 10.0 |
| 35.6 | 1.87 | 0.01 | 23.8 | 3.1 | 32.6 | 10.0 |
| 32.6 | 1.86 | 0.01 | 23.8 | 3.1 | 29.5 | 10.0 |
| 29.5 | 1.85 | 0.01 | 23.8 | 3.1 | 26.4 | 10.0 |
| 26.4 | 1.84 | 0.01 | 23.8 | 3.1 | 23.3 | 10.0 |
| 23.3 | 1.83 | 0.01 | 23.8 | 3.1 | 20.1 | 10.0 |
| 20.1 | 1.82 | 0.01 | 23.8 | 3.1 | 17.0 | 10.0 |
| 17.0 | 1.81 | 0.01 | 23.8 | 3.2 | 13.8 | 10.0 |
| 13.8 | 1.80 | 0.01 | 23.8 | 3.2 | 10.6 | 10.0 |

From the above calculation, we found that water will evaporate until 23.3$^0$C and 0.18 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.18 kg of water in Cylinder-2. But from the experiment we got 0.3 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 74.0 | 2.00 | 0.0050 | 11.9 | 1.4 | 72.6 | 5.0 |
| 72.6 | 2.00 | 0.0050 | 11.9 | 1.4 | 71.1 | 5.0 |
| 71.1 | 1.99 | 0.0050 | 11.9 | 1.4 | 69.7 | 5.0 |
| 69.7 | 1.99 | 0.0050 | 11.9 | 1.4 | 68.3 | 5.0 |
| 68.3 | 1.98 | 0.0050 | 11.9 | 1.4 | 66.8 | 5.0 |
| 66.8 | 1.98 | 0.0050 | 11.9 | 1.4 | 65.4 | 5.0 |
| 65.4 | 1.97 | 0.0050 | 11.9 | 1.4 | 63.9 | 5.0 |
| 63.9 | 1.97 | 0.0050 | 11.9 | 1.5 | 62.5 | 5.0 |
| 62.5 | 1.96 | 0.0050 | 11.9 | 1.5 | 61.0 | 5.0 |
| 61.0 | 1.96 | 0.0050 | 11.9 | 1.5 | 59.6 | 5.0 |
| 59.6 | 1.95 | 0.0050 | 11.9 | 1.5 | 58.1 | 5.0 |
| 58.1 | 1.95 | 0.0050 | 11.9 | 1.5 | 56.6 | 5.0 |
| 56.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 55.2 | 5.0 |
| 55.2 | 1.94 | 0.0050 | 11.9 | 1.5 | 53.7 | 5.0 |
| 53.7 | 1.93 | 0.0050 | 11.9 | 1.5 | 52.2 | 5.0 |
| 52.2 | 1.93 | 0.0050 | 11.9 | 1.5 | 50.7 | 5.0 |
| 50.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 49.2 | 5.0 |
| 49.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 47.7 | 5.0 |
| 47.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 46.2 | 5.0 |
| 46.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 44.7 | 5.0 |
| 44.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 43.2 | 5.0 |
| 43.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 41.7 | 5.0 |
| 41.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 40.2 | 5.0 |
| 40.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 38.7 | 5.0 |
| 38.7 | 1.88 | 0.0050 | 11.9 | 1.5 | 37.2 | 5.0 |
| 37.2 | 1.88 | 0.0050 | 11.9 | 1.5 | 35.7 | 5.0 |
| 35.7 | 1.87 | 0.0050 | 11.9 | 1.5 | 34.1 | 5.0 |
| 34.1 | 1.87 | 0.0050 | 11.9 | 1.5 | 32.6 | 5.0 |
| 32.6 | 1.86 | 0.0050 | 11.9 | 1.5 | 31.1 | 5.0 |
| 31.1 | 1.86 | 0.0050 | 11.9 | 1.5 | 29.5 | 5.0 |
| 29.5 | 1.85 | 0.0050 | 11.9 | 1.5 | 28.0 | 5.0 |
| 28.0 | 1.85 | 0.0050 | 11.9 | 1.5 | 26.4 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26.4 | 1.84 | 0.0050 | 11.9 | 1.6 | 24.9 | 5.0 |
| 24.9 | 1.84 | 0.0050 | 11.9 | 1.6 | 23.3 | 5.0 |
| 23.3 | 1.83 | 0.0050 | 11.9 | 1.6 | 21.8 | 5.0 |
| 21.8 | 1.83 | 0.0050 | 11.9 | 1.6 | 20.2 | 5.0 |
| 20.2 | 1.82 | 0.0050 | 11.9 | 1.6 | 18.6 | 5.0 |
| 18.6 | 1.82 | 0.0050 | 11.9 | 1.6 | 17.1 | 5.0 |
| 17.1 | 1.81 | 0.0050 | 11.9 | 1.6 | 15.5 | 5.0 |
| 15.5 | 1.81 | 0.0050 | 11.9 | 1.6 | 13.9 | 5.0 |
| 13.9 | 1.80 | 0.0050 | 11.9 | 1.6 | 12.3 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became $23.3^{0}$C and 0.175 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.175 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 170 gram of water should be evaporated for 0-gram step from the graph below.

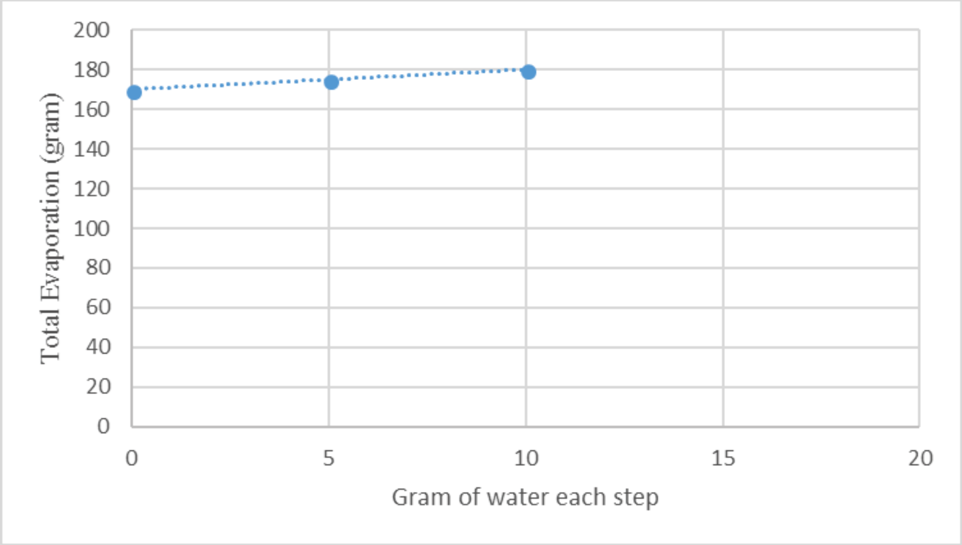

Figure 61 Extrapolation for 0-gram step

# A15 Test 7 (Operating Condition A)

In this set of experimental data (Table 12), 2 kg water of around 50$^0$C was taken in Cylinder-1 and after the process, we got 0.25 kg of condensed water in Cylinder-2 though around 0.35 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 77 K

Energy required to heat up 23$^0$C water into 100$^0$C water = ms$\Delta$T
= 643.7 kJ

Energy required to convert 100$^0$C 0.25 kg water into 100$^0$C 0.25 kg vapour
= mass x latent heat
= 0.25 kg x 2260 kJ/kg
= 565 kJ

Total energy required for getting 0.25 kg of condensed water from 2 kg of water in conventional process is 1208.7 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 120 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 120 sec = 120 Watt x 120s = 14.4 kJ

$$\% \text{ of distillation in our process} = \frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1} \text{ x } 100 = \frac{0.25}{2} \text{ x } 100$$

$$= 12.5\%$$

$$\text{Total Energy Savings} = \frac{(1208.7\ - 14.4)\text{ kJ}}{1208.7\ \text{ kJ}} \text{ x } 100\ = 98.8\%$$

*Table 12 Experimental Data: Test 7*

**Vacuum Desalination Experiment** **Data Set** **7**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 23 | R Humidity (%): | 70 | Weight of Feed (1) water (kg): | 2 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 23 | -2 | 4.45 | 23 | 0 | 22 |
| After Start (00min) Pump on | 6.45 | 50 | -2 | 4.45 | 23 | 0 | 22 |
| After Start (01min) | | 42 | -95 | | 23.5 | -97 | 23 |
| After Start (02min) Pump off | | 31 | -99 | | 23.5 | -97 | 23 |
| After Start (10min) | | 28.5 | -99 | | 24 | -97 | 23.5 |
| After Start (20min) | | 25 | -100 | | 23.9 | -98 | 23.3 |
| Finish (21min) | 6.1 | 25 | -2 | 4.7 | 23.9 | 0 | 23.3 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 7. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^{0}$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^{0}$C) | Final Temperature ($^{0}$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 2.00 | 0.01 | 23.8 | 2.9 | 47.1 | 10.0 |
| 47.1 | 1.99 | 0.01 | 23.8 | 2.9 | 44.3 | 10.0 |
| 44.3 | 1.98 | 0.01 | 23.8 | 2.9 | 41.4 | 10.0 |
| 41.4 | 1.97 | 0.01 | 23.8 | 2.9 | 38.5 | 10.0 |
| 38.5 | 1.96 | 0.01 | 23.8 | 2.9 | 35.5 | 10.0 |
| 35.5 | 1.95 | 0.01 | 23.8 | 2.9 | 32.6 | 10.0 |
| 32.6 | 1.94 | 0.01 | 23.8 | 3.0 | 29.7 | 10.0 |
| 29.7 | 1.93 | 0.01 | 23.8 | 3.0 | 26.7 | 10.0 |
| 26.7 | 1.92 | 0.01 | 23.8 | 3.0 | 23.7 | 10.0 |
| 23.7 | 1.91 | 0.01 | 23.8 | 3.0 | 20.7 | 10.0 |
| 20.7 | 1.90 | 0.01 | 23.8 | 3.0 | 17.7 | 10.0 |
| 17.7 | 1.89 | 0.01 | 23.8 | 3.0 | 14.7 | 10.0 |
| 14.7 | 1.88 | 0.01 | 23.8 | 3.0 | 11.6 | 10.0 |
| 11.6 | 1.87 | 0.01 | 23.8 | 3.1 | 8.6 | 10.0 |
| 8.6 | 1.86 | 0.01 | 23.8 | 3.1 | 5.5 | 10.0 |
| 5.5 | 1.85 | 0.01 | 23.8 | 3.1 | 2.4 | 10.0 |
| 2.4 | 1.84 | 0.01 | 23.8 | 3.1 | -0.7 | 10.0 |
| -0.7 | 1.83 | 0.01 | 23.8 | 3.1 | -3.9 | 10.0 |
| -3.9 | 1.82 | 0.01 | 23.8 | 3.1 | -7.0 | 10.0 |
| -7.0 | 1.81 | 0.01 | 23.8 | 3.2 | -10.2 | 10.0 |
| -10.2 | 1.80 | 0.01 | 23.8 | 3.2 | -13.4 | 10.0 |

From the above calculation, we found that water will evaporate until 23.7$^{0}$C and 0.1 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.1 kg of water in Cylinder-2. But from the experiment we got 0.25 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 2.00 | 0.0050 | 11.9 | 1.4 | 48.6 | 5.0 |
| 48.6 | 2.00 | 0.0050 | 11.9 | 1.4 | 47.1 | 5.0 |
| 47.1 | 1.99 | 0.0050 | 11.9 | 1.4 | 45.7 | 5.0 |
| 45.7 | 1.99 | 0.0050 | 11.9 | 1.4 | 44.3 | 5.0 |
| 44.3 | 1.98 | 0.0050 | 11.9 | 1.4 | 42.8 | 5.0 |
| 42.8 | 1.98 | 0.0050 | 11.9 | 1.4 | 41.4 | 5.0 |
| 41.4 | 1.97 | 0.0050 | 11.9 | 1.4 | 39.9 | 5.0 |
| 39.9 | 1.97 | 0.0050 | 11.9 | 1.5 | 38.5 | 5.0 |
| 38.5 | 1.96 | 0.0050 | 11.9 | 1.5 | 37.0 | 5.0 |
| 37.0 | 1.96 | 0.0050 | 11.9 | 1.5 | 35.6 | 5.0 |
| 35.6 | 1.95 | 0.0050 | 11.9 | 1.5 | 34.1 | 5.0 |
| 34.1 | 1.95 | 0.0050 | 11.9 | 1.5 | 32.6 | 5.0 |
| 32.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 31.2 | 5.0 |
| 31.2 | 1.94 | 0.0050 | 11.9 | 1.5 | 29.7 | 5.0 |
| 29.7 | 1.93 | 0.0050 | 11.9 | 1.5 | 28.2 | 5.0 |
| 28.2 | 1.93 | 0.0050 | 11.9 | 1.5 | 26.7 | 5.0 |
| 26.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 25.2 | 5.0 |
| 25.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 23.7 | 5.0 |
| 23.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 22.2 | 5.0 |
| 22.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 20.7 | 5.0 |
| 20.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 19.2 | 5.0 |
| 19.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 17.7 | 5.0 |
| 17.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 16.2 | 5.0 |
| 16.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 14.7 | 5.0 |
| 14.7 | 1.88 | 0.0050 | 11.9 | 1.5 | 13.2 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 23.7$^0$C and 0.095 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.095 kg of water in Cylinder-2.

Appendix

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 93 gram of water should be evaporated for 0-gram step from the graph below.

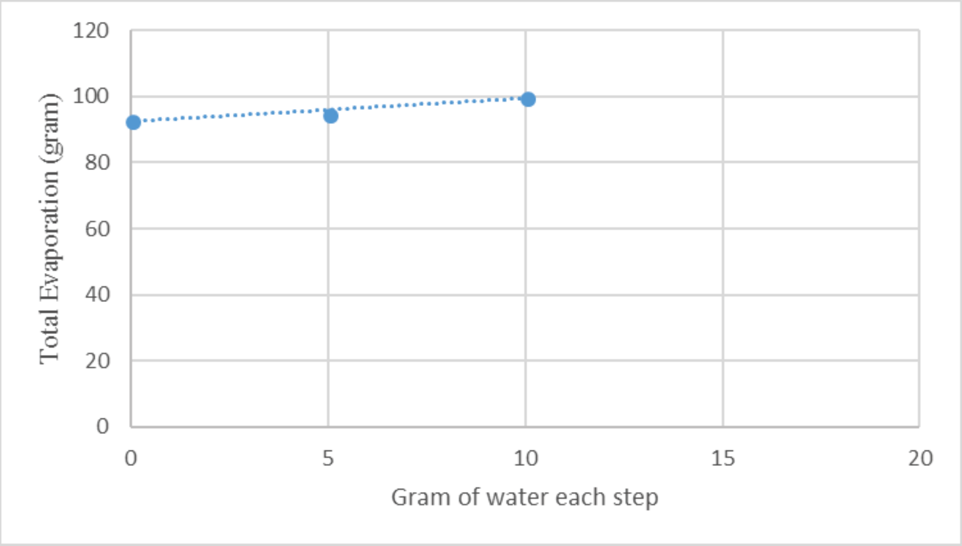

Figure 62 Extrapolation for 0-gram step

# A16. Test 9 (Operating Condition B)

In this set of experimental data (Table 13), 1.5 kg water of around $45^0$C was taken in Cylinder-1 and after the process, we got 0.25 kg of condensed water in Cylinder-2 though around 0.3 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.5 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 79 K

Energy required to heat up $21^0$C water into $100^0$C water = ms$\Delta$T
= 495.3 kJ

Energy required to convert $100^0$C 0.25 kg water into $100^0$C 0.25 kg vapour
= mass x latent heat
= 0.25 kg x 2260 kJ/kg
= 565 kJ

Total energy required for getting 0.25 kg of condensed water from 1.5 kg of water in conventional process is 1060.3 kJ

In our process, water would be heated up by solar energy. So the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 85 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 85 sec = 120 Watt x 85s = 10.2 kJ

$$\% \text{ of distillation in our process} = \frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1} \text{ x } 100 = \frac{0.25}{1.5} \text{ x } 100$$
$$= 16.6\%$$

$$\text{Total Energy Savings} = \frac{(1060.3\ -10.2)\text{ kJ}}{1060.3\ \text{ kJ}} \text{ x } 100\ = 99\%$$

*Table 13 Experimental Data: Test 9*

**Vacuum Desalination Experiment** **Data Set** **9**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 21 | R Humidity (%): | 70 | Weight of Feed (1) water (kg): | 1.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 21 | -2 | 4.45 | 21 | 0 | 20 |
| After Start (00min) Pump on | 5.95 | 45 | -2 | 4.45 | 21.5 | 0 | 20.1 |
| After Start (01min 25sec) Pump off | | 40.5 | -97 | | 22 | -98 | 21 |
| After Start (06min) | | 29 | -100 | | 22.5 | -98 | 22 |
| After Start (12min) | | 25.8 | -100 | | 22.5 | -98 | 23.1 |
| Finish (18min) | 5.65 | 24.7 | -2 | 4.7 | 22.5 | 0 | 22.9 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 9. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 45.0 | 1.50 | 0.01 | 23.8 | 3.8 | 41.2 | 10.0 |
| 41.2 | 1.49 | 0.01 | 23.8 | 3.8 | 37.3 | 10.0 |
| 37.3 | 1.48 | 0.01 | 23.8 | 3.9 | 33.5 | 10.0 |
| 33.5 | 1.47 | 0.01 | 23.8 | 3.9 | 29.6 | 10.0 |
| 29.6 | 1.46 | 0.01 | 23.8 | 3.9 | 25.6 | 10.0 |
| 25.6 | 1.45 | 0.01 | 23.8 | 4.0 | 21.7 | 10.0 |
| 21.7 | 1.44 | 0.01 | 23.8 | 4.0 | 17.7 | 10.0 |
| 17.7 | 1.43 | 0.01 | 23.8 | 4.0 | 13.7 | 10.0 |
| 13.7 | 1.42 | 0.01 | 23.8 | 4.0 | 9.6 | 10.0 |
| 9.6 | 1.41 | 0.01 | 23.8 | 4.1 | 5.6 | 10.0 |
| 5.6 | 1.40 | 0.01 | 23.8 | 4.1 | 1.5 | 10.0 |
| 1.5 | 1.39 | 0.01 | 23.8 | 4.1 | -2.7 | 10.0 |
| -2.7 | 1.38 | 0.01 | 23.8 | 4.2 | -6.8 | 10.0 |
| -6.8 | 1.37 | 0.01 | 23.8 | 4.2 | -11.0 | 10.0 |
| -11.0 | 1.36 | 0.01 | 23.8 | 4.2 | -15.2 | 10.0 |
| -15.2 | 1.35 | 0.01 | 23.8 | 4.3 | -19.5 | 10.0 |
| -19.5 | 1.34 | 0.01 | 23.8 | 4.3 | -23.8 | 10.0 |
| -23.8 | 1.33 | 0.01 | 23.8 | 4.3 | -28.1 | 10.0 |
| -28.1 | 1.32 | 0.01 | 23.8 | 4.3 | -32.4 | 10.0 |
| -32.4 | 1.31 | 0.01 | 23.8 | 4.4 | -36.8 | 10.0 |
| -36.8 | 1.30 | 0.01 | 23.8 | 4.4 | -41.2 | 10.0 |

From the above calculation, we found that water will evaporate until 21.7$^0$C and 0.07 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.07 kg of water in Cylinder-2. But from the experiment we got 0.25 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 45.0 | 1.50 | 0.0050 | 11.9 | 1.9 | 43.1 | 5.0 |
| 43.1 | 1.50 | 0.0050 | 11.9 | 1.9 | 41.2 | 5.0 |
| 41.2 | 1.49 | 0.0050 | 11.9 | 1.9 | 39.3 | 5.0 |
| 39.3 | 1.49 | 0.0050 | 11.9 | 1.9 | 37.3 | 5.0 |
| 37.3 | 1.48 | 0.0050 | 11.9 | 1.9 | 35.4 | 5.0 |
| 35.4 | 1.48 | 0.0050 | 11.9 | 1.9 | 33.5 | 5.0 |
| 33.5 | 1.47 | 0.0050 | 11.9 | 1.9 | 31.5 | 5.0 |
| 31.5 | 1.47 | 0.0050 | 11.9 | 2.0 | 29.6 | 5.0 |
| 29.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 27.6 | 5.0 |
| 27.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 25.7 | 5.0 |
| 25.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 23.7 | 5.0 |
| 23.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 21.7 | 5.0 |
| 21.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 19.7 | 5.0 |
| 19.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 17.7 | 5.0 |
| 17.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 15.7 | 5.0 |
| 15.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 13.7 | 5.0 |
| 13.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 11.7 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 21.7$^0$C and 0.065 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.065 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 63 gram of water should be evaporated for 0-gram step from the graph below.

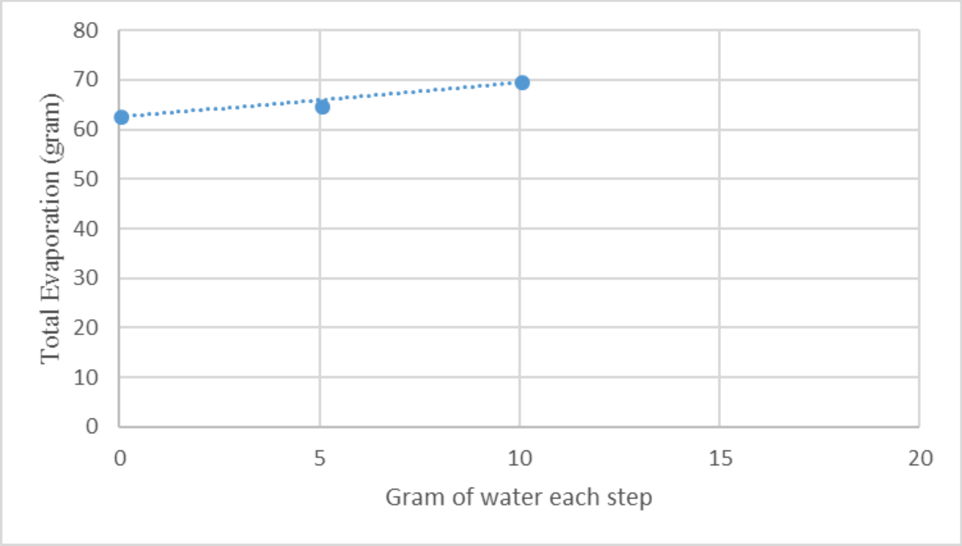

Figure 63 Extrapolation for 0-gram step

# A17. Test 11 (Operating Condition C)

In this set of experimental data (Table 14), 2 kg water of around 74$^0$C was taken in Cylinder-1 and after the process, we got 0.3 kg of condensed water in Cylinder-2 though around 0.35 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 79 K

Energy required to heat up 21$^0$C water into 100$^0$C water = ms$\Delta$T
= 660.4 kJ

Energy required to convert 100$^0$C 0.3 kg water into 100$^0$C 0.3 kg vapour
= mass x latent heat
= 0.3 kg x 2260 kJ/kg
= 678 kJ

Total energy required for getting 0.3 kg of condensed water from 2 kg of water in conventional process is 1338.4 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 121 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 121 sec = 120 Watt x 121s = 14.5 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.3}{2}$ x 100
= 15%

Total Energy Savings = $\frac{(1338.4\ -14.5)\ \text{kJ}}{1338.4\ \text{kJ}}$ x 100 = 99%

*Table 14 Experimental Data: Test 11*

**Vacuum Desalination Experiment** **Data Set** **11**

Notes: Cylinder-1 on upper level than Condenser, Cylinder-2 on lower level than Condenser, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (º C) : | 21 | R Humidity (%): | 68 | Weight of Feed (1) water (kg): | 2 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (º C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (º C) | Gauge Pressure 2 (kPa) | Temperature 3 (º C) |
| Before start (Empty) | 4.45 | 21 | -2 | 4.45 | 21 | 0 | 20 |
| After Start (00min) Pump on | 6.45 | 74 | -2 | 4.45 | 21 | 0 | 20 |
| After Start (02min 01sec) Pump off | | 44 | -99 | | 22 | -97 | 22 |
| After Start (08min) | | 32 | -100 | | 22 | -97 | 22.5 |
| After Start (10min) | | 29.5 | -100 | | 22.5 | -97 | 23 |
| Finish (15min) | 6.1 | 26 | -2 | 4.75 | 22.5 | 0 | 22.8 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 11. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 74.0 | 2.00 | 0.01 | 23.8 | 2.9 | 71.1 | 10.0 |
| 71.1 | 1.99 | 0.01 | 23.8 | 2.9 | 68.3 | 10.0 |
| 68.3 | 1.98 | 0.01 | 23.8 | 2.9 | 65.4 | 10.0 |
| 65.4 | 1.97 | 0.01 | 23.8 | 2.9 | 62.5 | 10.0 |
| 62.5 | 1.96 | 0.01 | 23.8 | 2.9 | 59.5 | 10.0 |
| 59.5 | 1.95 | 0.01 | 23.8 | 2.9 | 56.6 | 10.0 |
| 56.6 | 1.94 | 0.01 | 23.8 | 3.0 | 53.7 | 10.0 |
| 53.7 | 1.93 | 0.01 | 23.8 | 3.0 | 50.7 | 10.0 |
| 50.7 | 1.92 | 0.01 | 23.8 | 3.0 | 47.7 | 10.0 |
| 47.7 | 1.91 | 0.01 | 23.8 | 3.0 | 44.7 | 10.0 |
| 44.7 | 1.90 | 0.01 | 23.8 | 3.0 | 41.7 | 10.0 |
| 41.7 | 1.89 | 0.01 | 23.8 | 3.0 | 38.7 | 10.0 |
| 38.7 | 1.88 | 0.01 | 23.8 | 3.0 | 35.6 | 10.0 |
| 35.6 | 1.87 | 0.01 | 23.8 | 3.1 | 32.6 | 10.0 |
| 32.6 | 1.86 | 0.01 | 23.8 | 3.1 | 29.5 | 10.0 |
| 29.5 | 1.85 | 0.01 | 23.8 | 3.1 | 26.4 | 10.0 |
| 26.4 | 1.84 | 0.01 | 23.8 | 3.1 | 23.3 | 10.0 |
| 23.3 | 1.83 | 0.01 | 23.8 | 3.1 | 20.1 | 10.0 |
| 20.1 | 1.82 | 0.01 | 23.8 | 3.1 | 17.0 | 10.0 |
| 17.0 | 1.81 | 0.01 | 23.8 | 3.2 | 13.8 | 10.0 |
| 13.8 | 1.80 | 0.01 | 23.8 | 3.2 | 10.6 | 10.0 |

From the above calculation, we found that water will evaporate until 23.3$^0$C and 0.18 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.18 kg of water in Cylinder-2. But from the experiment we got 0.3 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 74.0 | 2.00 | 0.0050 | 11.9 | 1.4 | 72.6 | 5.0 |
| 72.6 | 2.00 | 0.0050 | 11.9 | 1.4 | 71.1 | 5.0 |
| 71.1 | 1.99 | 0.0050 | 11.9 | 1.4 | 69.7 | 5.0 |
| 69.7 | 1.99 | 0.0050 | 11.9 | 1.4 | 68.3 | 5.0 |
| 68.3 | 1.98 | 0.0050 | 11.9 | 1.4 | 66.8 | 5.0 |
| 66.8 | 1.98 | 0.0050 | 11.9 | 1.4 | 65.4 | 5.0 |
| 65.4 | 1.97 | 0.0050 | 11.9 | 1.4 | 63.9 | 5.0 |
| 63.9 | 1.97 | 0.0050 | 11.9 | 1.5 | 62.5 | 5.0 |
| 62.5 | 1.96 | 0.0050 | 11.9 | 1.5 | 61.0 | 5.0 |
| 61.0 | 1.96 | 0.0050 | 11.9 | 1.5 | 59.6 | 5.0 |
| 59.6 | 1.95 | 0.0050 | 11.9 | 1.5 | 58.1 | 5.0 |
| 58.1 | 1.95 | 0.0050 | 11.9 | 1.5 | 56.6 | 5.0 |
| 56.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 55.2 | 5.0 |
| 55.2 | 1.94 | 0.0050 | 11.9 | 1.5 | 53.7 | 5.0 |
| 53.7 | 1.93 | 0.0050 | 11.9 | 1.5 | 52.2 | 5.0 |
| 52.2 | 1.93 | 0.0050 | 11.9 | 1.5 | 50.7 | 5.0 |
| 50.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 49.2 | 5.0 |
| 49.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 47.7 | 5.0 |
| 47.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 46.2 | 5.0 |
| 46.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 44.7 | 5.0 |
| 44.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 43.2 | 5.0 |
| 43.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 41.7 | 5.0 |
| 41.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 40.2 | 5.0 |
| 40.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 38.7 | 5.0 |
| 38.7 | 1.88 | 0.0050 | 11.9 | 1.5 | 37.2 | 5.0 |
| 37.2 | 1.88 | 0.0050 | 11.9 | 1.5 | 35.7 | 5.0 |
| 35.7 | 1.87 | 0.0050 | 11.9 | 1.5 | 34.1 | 5.0 |
| 34.1 | 1.87 | 0.0050 | 11.9 | 1.5 | 32.6 | 5.0 |
| 32.6 | 1.86 | 0.0050 | 11.9 | 1.5 | 31.1 | 5.0 |
| 31.1 | 1.86 | 0.0050 | 11.9 | 1.5 | 29.5 | 5.0 |
| 29.5 | 1.85 | 0.0050 | 11.9 | 1.5 | 28.0 | 5.0 |
| 28.0 | 1.85 | 0.0050 | 11.9 | 1.5 | 26.4 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 26.4 | 1.84 | 0.0050 | 11.9 | 1.6 | 24.9 | 5.0 |
| 24.9 | 1.84 | 0.0050 | 11.9 | 1.6 | 23.3 | 5.0 |
| 23.3 | 1.83 | 0.0050 | 11.9 | 1.6 | 21.8 | 5.0 |
| 21.8 | 1.83 | 0.0050 | 11.9 | 1.6 | 20.2 | 5.0 |
| 20.2 | 1.82 | 0.0050 | 11.9 | 1.6 | 18.6 | 5.0 |
| 18.6 | 1.82 | 0.0050 | 11.9 | 1.6 | 17.1 | 5.0 |
| 17.1 | 1.81 | 0.0050 | 11.9 | 1.6 | 15.5 | 5.0 |
| 15.5 | 1.81 | 0.0050 | 11.9 | 1.6 | 13.9 | 5.0 |
| 13.9 | 1.80 | 0.0050 | 11.9 | 1.6 | 12.3 | 5.0 |
| 12.3 | 1.80 | 0.0050 | 11.9 | 1.6 | 10.7 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 21.7$^0$C and 0.175 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.175 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 170 gram of water should be evaporated for 0-gram step from the graph below.

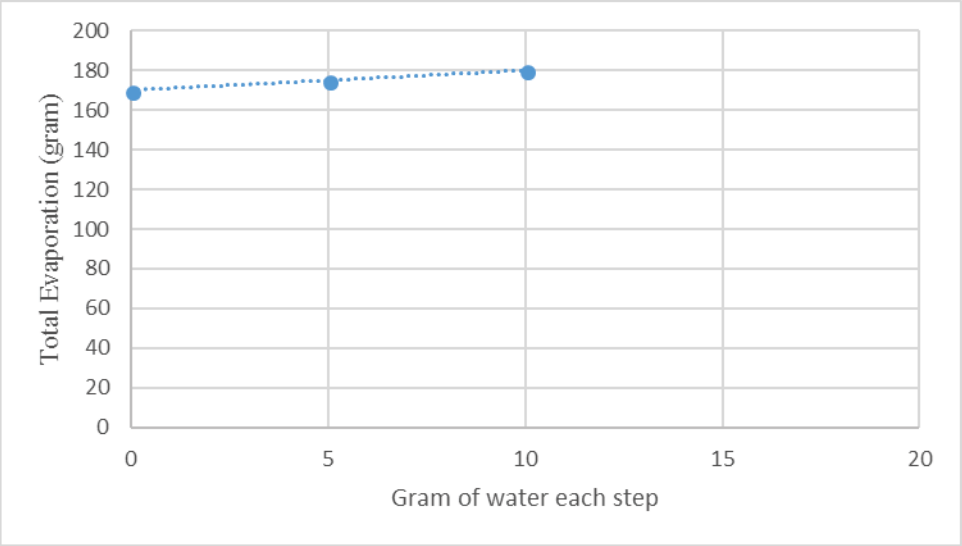

Figure 64 Extrapolation for 0-gram step

# A18. Test 12 (Operating Condition C)

In this set of experimental data (Table 15), 1.5 kg water of around 50$^0$C was taken in Cylinder-1 and after the process, we got 0.15 kg of condensed water in Cylinder-2 though around 0.2 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 1.5 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 74 K

Energy required to heat up 26$^0$C water into 100$^0$C water = ms$\Delta$T
= 464 kJ

Energy required to convert 100$^0$C 0.15 kg water into 100$^0$C 0.15 kg vapour
= mass x latent heat
= 0.15 kg x 2260 kJ/kg
= 339 kJ

Total energy required for getting 0.15 kg of condensed water from 1.5 kg of water in conventional process is 803 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 80 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 80 sec = 120 Watt x 80s = 9.6 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.15}{1.5}$ x 100
= 10%

Total Energy Savings = $\frac{(803\ -9.6)\text{ kJ}}{803\text{ kJ}}$ x 100 = 98.8%

### *Table 15 Experimental Data: Test 12*

**Vacuum Desalination Experiment** **Data Set** **12**

Notes: Cylinder-1 on upper level than Condenser, Cylinder-2 on lower level than Condenser, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 26 | R Humidity (%): | 60 | Weight of Feed (1) water (kg): | 1.5 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 26 | -2 | 4.45 | 26 | 0 | 26 |
| After Start (00min) Pump on | 5.95 | 50 | -2 | 4.45 | 26 | 0 | 26 |
| After Start (01min 20sec) Pump off | | 35 | -97 | | 26 | -98 | 26.5 |
| After Start (06min) | | 30 | -100 | | 26.3 | -98 | 26.5 |
| After Start (12min) | | 28.5 | -100 | | 26.5 | -98 | 26.8 |
| Finish (18min) | 5.75 | 28 | -2 | 4.6 | 27 | 0 | 27 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 12. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 1.50 | 0.01 | 23.8 | 3.8 | 46.2 | 10.0 |
| 46.2 | 1.49 | 0.01 | 23.8 | 3.8 | 42.3 | 10.0 |
| 42.3 | 1.48 | 0.01 | 23.8 | 3.9 | 38.5 | 10.0 |
| 38.5 | 1.47 | 0.01 | 23.8 | 3.9 | 34.6 | 10.0 |
| 34.6 | 1.46 | 0.01 | 23.8 | 3.9 | 30.6 | 10.0 |
| 30.6 | 1.45 | 0.01 | 23.8 | 4.0 | 26.7 | 10.0 |
| 26.7 | 1.44 | 0.01 | 23.8 | 4.0 | 22.7 | 10.0 |
| 22.7 | 1.43 | 0.01 | 23.8 | 4.0 | 18.7 | 10.0 |
| 18.7 | 1.42 | 0.01 | 23.8 | 4.0 | 14.6 | 10.0 |
| 14.6 | 1.41 | 0.01 | 23.8 | 4.1 | 10.6 | 10.0 |
| 10.6 | 1.40 | 0.01 | 23.8 | 4.1 | 6.5 | 10.0 |
| 6.5 | 1.39 | 0.01 | 23.8 | 4.1 | 2.3 | 10.0 |
| 2.3 | 1.38 | 0.01 | 23.8 | 4.2 | -1.8 | 10.0 |
| -1.8 | 1.37 | 0.01 | 23.8 | 4.2 | -6.0 | 10.0 |
| -6.0 | 1.36 | 0.01 | 23.8 | 4.2 | -10.2 | 10.0 |
| -10.2 | 1.35 | 0.01 | 23.8 | 4.3 | -14.5 | 10.0 |
| -14.5 | 1.34 | 0.01 | 23.8 | 4.3 | -18.8 | 10.0 |
| -18.8 | 1.33 | 0.01 | 23.8 | 4.3 | -23.1 | 10.0 |
| -23.1 | 1.32 | 0.01 | 23.8 | 4.3 | -27.4 | 10.0 |
| -27.4 | 1.31 | 0.01 | 23.8 | 4.4 | -31.8 | 10.0 |
| -31.8 | 1.30 | 0.01 | 23.8 | 4.4 | -36.2 | 10.0 |

From the above calculation, we found that water will evaporate until 26.7$^0$C and 0.06 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.06 kg of water in Cylinder-2. But from the experiment we got 0.15 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 50.0 | 1.50 | 0.0050 | 11.9 | 1.9 | 48.1 | 5.0 |
| 48.1 | 1.50 | 0.0050 | 11.9 | 1.9 | 46.2 | 5.0 |
| 46.2 | 1.49 | 0.0050 | 11.9 | 1.9 | 44.3 | 5.0 |
| 44.3 | 1.49 | 0.0050 | 11.9 | 1.9 | 42.3 | 5.0 |
| 42.3 | 1.48 | 0.0050 | 11.9 | 1.9 | 40.4 | 5.0 |
| 40.4 | 1.48 | 0.0050 | 11.9 | 1.9 | 38.5 | 5.0 |
| 38.5 | 1.47 | 0.0050 | 11.9 | 1.9 | 36.5 | 5.0 |
| 36.5 | 1.47 | 0.0050 | 11.9 | 2.0 | 34.6 | 5.0 |
| 34.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 32.6 | 5.0 |
| 32.6 | 1.46 | 0.0050 | 11.9 | 2.0 | 30.7 | 5.0 |
| 30.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 28.7 | 5.0 |
| 28.7 | 1.45 | 0.0050 | 11.9 | 2.0 | 26.7 | 5.0 |
| 26.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 24.7 | 5.0 |
| 24.7 | 1.44 | 0.0050 | 11.9 | 2.0 | 22.7 | 5.0 |
| 22.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 20.7 | 5.0 |
| 20.7 | 1.43 | 0.0050 | 11.9 | 2.0 | 18.7 | 5.0 |
| 18.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 16.7 | 5.0 |
| 16.7 | 1.42 | 0.0050 | 11.9 | 2.0 | 14.7 | 5.0 |
| 14.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 12.7 | 5.0 |
| 12.7 | 1.41 | 0.0050 | 11.9 | 2.0 | 10.6 | 5.0 |
| 10.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 8.6 | 5.0 |
| 8.6 | 1.40 | 0.0050 | 11.9 | 2.0 | 6.5 | 5.0 |
| 6.5 | 1.39 | 0.0050 | 11.9 | 2.1 | 4.5 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 26.7$^0$C and 0.065 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.065 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 68 gram of water should be evaporated for 0-gram step from the graph below.

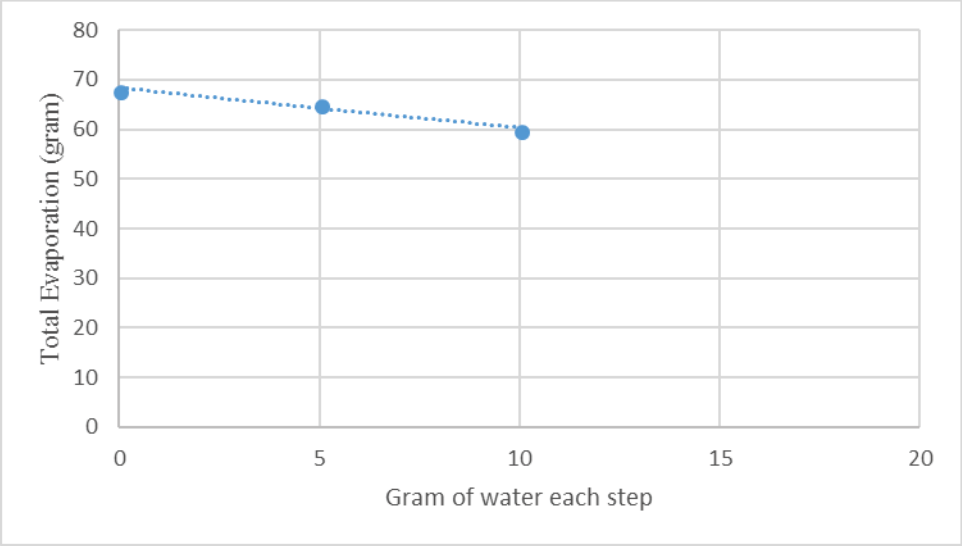

Figure 65 Extrapolation for 0-gram step

# A19. Test 13 (Operating Condition B)

In this set of experimental data (Table 16), 2 kg water of around $50^0$C was taken in Cylinder-1 and after the process, we got 0.25 kg of condensed water in Cylinder-2 though around 0.3 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2 kg

S= Specific heat of water 4.18 kJ/kg-K

$\Delta$T= 77 K

Energy required to heat up $23^0$C water into $100^0$C water = ms$\Delta$T

= 643.7 kJ

Energy required to convert $100^0$C 0.25 kg water into $100^0$C 0.25 kg vapour

= mass x latent heat

= 0.25 kg x 2260 kJ/kg

= 565 kJ

Total energy required for getting 0.25 kg of condensed water from 2 kg of water in conventional process is 1208.7 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 120 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 120 sec = 120 Watt x 120s = 14.4 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.25}{2}$ x 100

= 12.5%

Total Energy Savings = $\frac{(1208.7\ -14.4)\ \text{kJ}}{1208.7\ \ \text{kJ}}$ x 100 = 98.8%

*Table 16 Experimental Data: Test 13*

**Vacuum Desalination Experiment** **Data Set** **13**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level, Immediately after one process

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 23 | R Humidity (%): | 68 | Weight of Feed (1) water (kg): | 2 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 23 | -2 | 4.45 | 23 | 0 | 22 |
| After Start (00min) Pump on | 6.45 | 50 | -2 | 4.45 | 23 | 0 | 22 |
| After Start (01min) | | 41 | -95 | | 23.5 | -97 | 23 |
| After Start (02min) Pump off | | 31 | -99 | | 23.8 | -97 | 23 |
| After Start (10min) | | 29 | -99 | | 23.8 | -97 | 23.5 |
| After Start (20min) | | 25.3 | -100 | | 23.9 | -98 | 23.8 |
| Finish (21min) | 6.15 | 25 | -2 | 4.7 | 23.9 | 0 | 23.3 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 13. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp ($^{0}$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^{0}$C) | Final Temperature ($^{0}$C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 50.0 | 2.00 | 0.01 | 23.8 | 2.9 | 47.1 | 10.0 |
| 47.1 | 1.99 | 0.01 | 23.8 | 2.9 | 44.3 | 10.0 |
| 44.3 | 1.98 | 0.01 | 23.8 | 2.9 | 41.4 | 10.0 |
| 41.4 | 1.97 | 0.01 | 23.8 | 2.9 | 38.5 | 10.0 |
| 38.5 | 1.96 | 0.01 | 23.8 | 2.9 | 35.5 | 10.0 |
| 35.5 | 1.95 | 0.01 | 23.8 | 2.9 | 32.6 | 10.0 |
| 32.6 | 1.94 | 0.01 | 23.8 | 3.0 | 29.7 | 10.0 |
| 29.7 | 1.93 | 0.01 | 23.8 | 3.0 | 26.7 | 10.0 |
| 26.7 | 1.92 | 0.01 | 23.8 | 3.0 | 23.7 | 10.0 |
| 23.7 | 1.91 | 0.01 | 23.8 | 3.0 | 20.7 | 10.0 |
| 20.7 | 1.90 | 0.01 | 23.8 | 3.0 | 17.7 | 10.0 |
| 17.7 | 1.89 | 0.01 | 23.8 | 3.0 | 14.7 | 10.0 |
| 14.7 | 1.88 | 0.01 | 23.8 | 3.0 | 11.6 | 10.0 |
| 11.6 | 1.87 | 0.01 | 23.8 | 3.1 | 8.6 | 10.0 |
| 8.6 | 1.86 | 0.01 | 23.8 | 3.1 | 5.5 | 10.0 |
| 5.5 | 1.85 | 0.01 | 23.8 | 3.1 | 2.4 | 10.0 |
| 2.4 | 1.84 | 0.01 | 23.8 | 3.1 | -0.7 | 10.0 |
| -0.7 | 1.83 | 0.01 | 23.8 | 3.1 | -3.9 | 10.0 |
| -3.9 | 1.82 | 0.01 | 23.8 | 3.1 | -7.0 | 10.0 |
| -7.0 | 1.81 | 0.01 | 23.8 | 3.2 | -10.2 | 10.0 |
| -10.2 | 1.80 | 0.01 | 23.8 | 3.2 | -13.4 | 10.0 |

From the above calculation, we found that water will evaporate until 23.7$^{0}$C and 0.09 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.09 kg of water in Cylinder-2. But from the experiment we got 0.25 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 50.0 | 2.00 | 0.0050 | 11.9 | 1.4 | 48.6 | 5.0 |
| 48.6 | 2.00 | 0.0050 | 11.9 | 1.4 | 47.1 | 5.0 |
| 47.1 | 1.99 | 0.0050 | 11.9 | 1.4 | 45.7 | 5.0 |
| 45.7 | 1.99 | 0.0050 | 11.9 | 1.4 | 44.3 | 5.0 |
| 44.3 | 1.98 | 0.0050 | 11.9 | 1.4 | 42.8 | 5.0 |
| 42.8 | 1.98 | 0.0050 | 11.9 | 1.4 | 41.4 | 5.0 |
| 41.4 | 1.97 | 0.0050 | 11.9 | 1.4 | 39.9 | 5.0 |
| 39.9 | 1.97 | 0.0050 | 11.9 | 1.5 | 38.5 | 5.0 |
| 38.5 | 1.96 | 0.0050 | 11.9 | 1.5 | 37.0 | 5.0 |
| 37.0 | 1.96 | 0.0050 | 11.9 | 1.5 | 35.6 | 5.0 |
| 35.6 | 1.95 | 0.0050 | 11.9 | 1.5 | 34.1 | 5.0 |
| 34.1 | 1.95 | 0.0050 | 11.9 | 1.5 | 32.6 | 5.0 |
| 32.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 31.2 | 5.0 |
| 31.2 | 1.94 | 0.0050 | 11.9 | 1.5 | 29.7 | 5.0 |
| 29.7 | 1.93 | 0.0050 | 11.9 | 1.5 | 28.2 | 5.0 |
| 28.2 | 1.93 | 0.0050 | 11.9 | 1.5 | 26.7 | 5.0 |
| 26.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 25.2 | 5.0 |
| 25.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 23.7 | 5.0 |
| 23.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 22.2 | 5.0 |
| 22.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 20.7 | 5.0 |
| 20.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 19.2 | 5.0 |
| 19.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 17.7 | 5.0 |
| 17.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 16.2 | 5.0 |
| 16.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 14.7 | 5.0 |
| 14.7 | 1.88 | 0.0050 | 11.9 | 1.5 | 13.2 | 5.0 |
| 13.2 | 1.88 | 0.0050 | 11.9 | 1.5 | 11.7 | 5.0 |
| 11.7 | 1.87 | 0.0050 | 11.9 | 1.5 | 10.1 | 5.0 |
| 10.1 | 1.87 | 0.0050 | 11.9 | 1.5 | 8.6 | 5.0 |
| 8.6 | 1.86 | 0.0050 | 11.9 | 1.5 | 7.1 | 5.0 |
| 7.1 | 1.86 | 0.0050 | 11.9 | 1.5 | 5.5 | 5.0 |
| 5.5 | 1.85 | 0.0050 | 11.9 | 1.5 | 4.0 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became 23.7$^0$C and 0.095 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.095 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 98 gram of water should be evaporated for 0-gram step from the graph below.

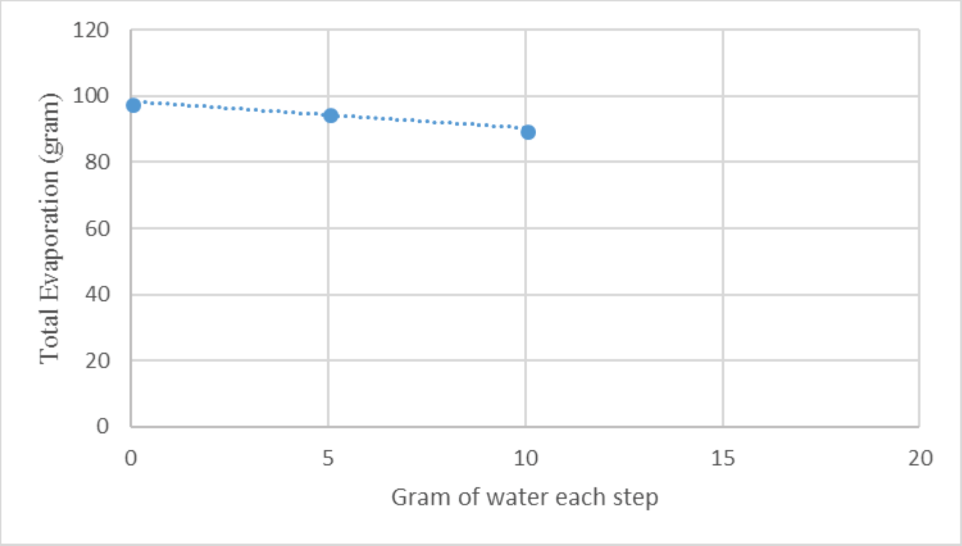

Figure 66 Extrapolation for 0-gram step

# A20. Test 14 (Operating Condition A)

In this set of experimental data (Table 17), 2 kg water of around $73^0$C was taken in Cylinder-1 and after the process, we got 0.3 kg of condensed water in Cylinder-2 though around 0.4 kg of water from Cylinder-1 is missing. If we compare between the energy required for conventional distillation and this process, we can get the following result:

Here, m= mass of water 2 kg
S= Specific heat of water 4.18 kJ/kg-K
$\Delta$T= 74 K

Energy required to heat up $26^0$C water into $100^0$C water = ms$\Delta$T
= 618.6 kJ

Energy required to convert $100^0$C 0.3 kg water into $100^0$C 0.3 kg vapour
= mass x latent heat
= 0.3 kg x 2260 kJ/kg
= 678 kJ

Total energy required for getting 0.3 kg of condensed water from 2 kg of water in conventional process is 1296.6 kJ

In our process, water would be heated up by solar energy. So, the only energy required is to create the vacuum pressure.

Energy required to run the vacuum pump for 121 sec as we got the required pressure (-97 kPa gauge) by turning on the pump only for 121 sec = 120 Watt x 121s = 14.5 kJ

% of distillation in our process = $\frac{\text{Mass of water we got in cylinder}-2}{\text{Mass of initial water in Cylinder}-1}$ x 100 = $\frac{0.3}{2}$ x 100
= 15%

Total Energy Savings = $\frac{(1296.6\ -14.5)\ \text{kJ}}{1296.6\ \text{kJ}}$ x 100 = 98.8%

*Table 17 Experimental Data: Test 14*

**Vacuum Desalination Experiment** **Data Set** **14**

Notes: Cylinder-1 and Condenser on same level, Cylinder-2 on lower level

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Room Temperature (° C) : | 26 | R Humidity (%): | 58 | Weight of Feed (1) water (kg): | 2 | Volume of FW Tank (1) (L): | 4 |
| Ambient Pressure (kPa): | 101.325 | Density of Feed (1) water (kg/m³): | 1000 | Density of D (2) water (kg/m³): | 1000 | Volume of DW Tank (2) (L): | 4 |

| Time | Feed Water Vessel (Cylinder-1) | | | Desalinated Water Vessel (Cylinder-2) | | | Condenser |
|---|---|---|---|---|---|---|---|
| | Weight of water 1 + rig (kg) | Temperature 1 (° C) | Gauge Pressure 1 (kPa) | Weight of water 2 + rig (kg) | Temperature 2 (° C) | Gauge Pressure 2 (kPa) | Temperature 3 (° C) |
| Before start (Empty) | 4.45 | 26 | -2 | 4.45 | 25.9 | 0 | 25 |
| After Start (00min)<br>Pump on | 6.45 | 73 | -2 | 4.45 | 26 | 0 | 25 |
| After Start (02min 01sec)<br>Pump off | | 44 | -99 | | 26 | -97 | 25.7 |
| After Start (08min) | | 31 | -99 | | 26.5 | -97 | 26 |
| After Start (10min) | | 29.7 | -100 | | 26.8 | -97 | 26.5 |
| Finish (11min) | 6.05 | 29 | -2 | 4.75 | 26.8 | 0 | 26.5 |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |
| | | | | | | | |

* Here, Water 1 = Water of Cylinder-1; Water 2 = Water of Cylinder-2; Temperature 1 = Temp. of Cylinder-1; Temperature 2 = Temp. of Cylinder-2; Temperature 3 = Temp. of Condenser

Appendix

**Theoretical Rate of Evaporation Based on Experimental Data:**

If we study water's latent heat and specific heat, we can get the following finding for Data set 14. (To be interpreted similarly as Test 1)

Assumptions:

- Avg. Latent Heat of water: 2381 kJ/kg
- 10 grams of water evaporated at each step

| Initial Temp (⁰C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest (⁰C) | Final Temperature (⁰C) | Evaporated water (gram) |
|---|---|---|---|---|---|---|
| 73.0 | 2.00 | 0.01 | 23.8 | 2.9 | 70.1 | 10.0 |
| 70.1 | 1.99 | 0.01 | 23.8 | 2.9 | 67.3 | 10.0 |
| 67.3 | 1.98 | 0.01 | 23.8 | 2.9 | 64.4 | 10.0 |
| 64.4 | 1.97 | 0.01 | 23.8 | 2.9 | 61.5 | 10.0 |
| 61.5 | 1.96 | 0.01 | 23.8 | 2.9 | 58.5 | 10.0 |
| 58.5 | 1.95 | 0.01 | 23.8 | 2.9 | 55.6 | 10.0 |
| 55.6 | 1.94 | 0.01 | 23.8 | 3.0 | 52.7 | 10.0 |
| 52.7 | 1.93 | 0.01 | 23.8 | 3.0 | 49.7 | 10.0 |
| 49.7 | 1.92 | 0.01 | 23.8 | 3.0 | 46.7 | 10.0 |
| 46.7 | 1.91 | 0.01 | 23.8 | 3.0 | 43.7 | 10.0 |
| 43.7 | 1.90 | 0.01 | 23.8 | 3.0 | 40.7 | 10.0 |
| 40.7 | 1.89 | 0.01 | 23.8 | 3.0 | 37.7 | 10.0 |
| 37.7 | 1.88 | 0.01 | 23.8 | 3.0 | 34.6 | 10.0 |
| 34.6 | 1.87 | 0.01 | 23.8 | 3.1 | 31.6 | 10.0 |
| 31.6 | 1.86 | 0.01 | 23.8 | 3.1 | 28.5 | 10.0 |
| 28.5 | 1.85 | 0.01 | 23.8 | 3.1 | 25.4 | 10.0 |
| 25.4 | 1.84 | 0.01 | 23.8 | 3.1 | 22.3 | 10.0 |
| 22.3 | 1.83 | 0.01 | 23.8 | 3.1 | 19.1 | 10.0 |
| 19.1 | 1.82 | 0.01 | 23.8 | 3.1 | 16.0 | 10.0 |
| 16.0 | 1.81 | 0.01 | 23.8 | 3.2 | 12.8 | 10.0 |
| 12.8 | 1.80 | 0.01 | 23.8 | 3.2 | 9.6 | 10.0 |

From the above calculation, we found that water will evaporate until 25.4⁰C and 0.17 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.17 kg of water in Cylinder-2. But from the experiment we got 0.3 kg of condensed water in Cylinder-2. We can calculate 0-gram step as done earlier in Test 1.

Appendix

## Extrapolation for 0-gram step

In the previous section we have assumed 10 gram of water would be evaporated in each step for all the tests to find out the theoretical rate of evaporation based on experimental data. In this section we will extrapolate 0-gram step for this test. If we consider only 5 gram of water would be evaporated in each step, we can find the below data for the similar conditions of this test.

| Initial Temp ($^0$C) | Initial weight of Water (kg) | Amount to be evaporated (kg) | Heat needed (kJ) | Temperature Fall of rest ($^0$C) | Final Temperature ($^0$C) | Evaporated water (gram) |
|---:|---:|---:|---:|---:|---:|---:|
| 73.0 | 2.00 | 0.0050 | 11.9 | 1.4 | 71.6 | 5.0 |
| 71.6 | 2.00 | 0.0050 | 11.9 | 1.4 | 70.1 | 5.0 |
| 70.1 | 1.99 | 0.0050 | 11.9 | 1.4 | 68.7 | 5.0 |
| 68.7 | 1.99 | 0.0050 | 11.9 | 1.4 | 67.3 | 5.0 |
| 67.3 | 1.98 | 0.0050 | 11.9 | 1.4 | 65.8 | 5.0 |
| 65.8 | 1.98 | 0.0050 | 11.9 | 1.4 | 64.4 | 5.0 |
| 64.4 | 1.97 | 0.0050 | 11.9 | 1.4 | 62.9 | 5.0 |
| 62.9 | 1.97 | 0.0050 | 11.9 | 1.5 | 61.5 | 5.0 |
| 61.5 | 1.96 | 0.0050 | 11.9 | 1.5 | 60.0 | 5.0 |
| 60.0 | 1.96 | 0.0050 | 11.9 | 1.5 | 58.6 | 5.0 |
| 58.6 | 1.95 | 0.0050 | 11.9 | 1.5 | 57.1 | 5.0 |
| 57.1 | 1.95 | 0.0050 | 11.9 | 1.5 | 55.6 | 5.0 |
| 55.6 | 1.94 | 0.0050 | 11.9 | 1.5 | 54.2 | 5.0 |
| 54.2 | 1.94 | 0.0050 | 11.9 | 1.5 | 52.7 | 5.0 |
| 52.7 | 1.93 | 0.0050 | 11.9 | 1.5 | 51.2 | 5.0 |
| 51.2 | 1.93 | 0.0050 | 11.9 | 1.5 | 49.7 | 5.0 |
| 49.7 | 1.92 | 0.0050 | 11.9 | 1.5 | 48.2 | 5.0 |
| 48.2 | 1.92 | 0.0050 | 11.9 | 1.5 | 46.7 | 5.0 |
| 46.7 | 1.91 | 0.0050 | 11.9 | 1.5 | 45.2 | 5.0 |
| 45.2 | 1.91 | 0.0050 | 11.9 | 1.5 | 43.7 | 5.0 |
| 43.7 | 1.90 | 0.0050 | 11.9 | 1.5 | 42.2 | 5.0 |
| 42.2 | 1.90 | 0.0050 | 11.9 | 1.5 | 40.7 | 5.0 |
| 40.7 | 1.89 | 0.0050 | 11.9 | 1.5 | 39.2 | 5.0 |
| 39.2 | 1.89 | 0.0050 | 11.9 | 1.5 | 37.7 | 5.0 |
| 37.7 | 1.88 | 0.0050 | 11.9 | 1.5 | 36.2 | 5.0 |
| 36.2 | 1.88 | 0.0050 | 11.9 | 1.5 | 34.7 | 5.0 |
| 34.7 | 1.87 | 0.0050 | 11.9 | 1.5 | 33.1 | 5.0 |
| 33.1 | 1.87 | 0.0050 | 11.9 | 1.5 | 31.6 | 5.0 |
| 31.6 | 1.86 | 0.0050 | 11.9 | 1.5 | 30.1 | 5.0 |
| 30.1 | 1.86 | 0.0050 | 11.9 | 1.5 | 28.5 | 5.0 |
| 28.5 | 1.85 | 0.0050 | 11.9 | 1.5 | 27.0 | 5.0 |
| 27.0 | 1.85 | 0.0050 | 11.9 | 1.5 | 25.4 | 5.0 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 25.4 | 1.84 | 0.0050 | 11.9 | 1.6 | 23.9 | 5.0 |
| 23.9 | 1.84 | 0.0050 | 11.9 | 1.6 | 22.3 | 5.0 |
| 22.3 | 1.83 | 0.0050 | 11.9 | 1.6 | 20.8 | 5.0 |
| 20.8 | 1.83 | 0.0050 | 11.9 | 1.6 | 19.2 | 5.0 |
| 19.2 | 1.82 | 0.0050 | 11.9 | 1.6 | 17.6 | 5.0 |
| 17.6 | 1.82 | 0.0050 | 11.9 | 1.6 | 16.1 | 5.0 |
| 16.1 | 1.81 | 0.0050 | 11.9 | 1.6 | 14.5 | 5.0 |
| 14.5 | 1.81 | 0.0050 | 11.9 | 1.6 | 12.9 | 5.0 |

From the above calculation, we find that water would be evaporated until the temperature became $25.4^{0}$C and 0.165 kg of water should evaporate from Cylinder-1 and if it totally condensed we should get 0.165 kg of water in Cylinder-2.

Now, if we extrapolate the data we got for 5 gram and 10 gram, we can get that 163 gram of water should be evaporated for 0-gram step from the graph below.

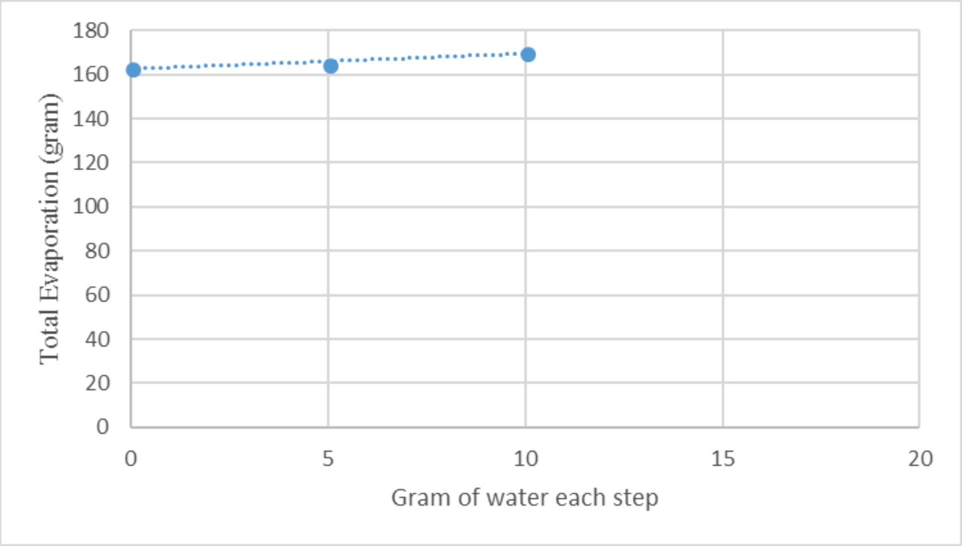

Figure 67 Extrapolation for 0-gram step

# Appendix