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Investigation on Low-Pressure Desalination Method

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ABSTRACT

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. Several investigations have been underway to address the shortfall in freshwater supply in the world. Seawater can be a huge source of fresh water. Seawater is desalinated to provide drinking water at many locations throughout the world. Desalination is used to get salt and mineral-free water from seawater, but for this process, a huge amount of energy is required. A cost-effective and efficient method needs to be introduced to get freshwater by desalination. A solar water heater can warm up the seawater easily during normal daylight conditions. Then, this warm water can be boiled at a lower temperature than normal when surrounding pressure is reduced. In this study, desalination of seawater at low pressure was introduced and tested. This study also documents works towards this methodology to develop an experimental setup to test characteristics of the boiling point of water toward pressure, including the review of literature and data collection from the test rig, which considers various parameters and CFD analysis of this method. CFD simulation indicates the evaporation rate and feasibility of low-pressure desalination method.

1. INTRODUCTION

In this study, water evaporation followed by condensation under reduced pressure (below atmospheric pressure) is simulated using ANSYS Fluent. Prior to CFD analysis, a test rig was built, and the concept was tested practically. The main concept is to desalinate water at low temperature and pressure. The system consists of two cylinders and a coil. Three kilograms of fresh water is to be evaporated in one cylinder at a temperature of 60°C and pressure of 12.33 kPa; the vapor is then transferred through the coil, which connects the two cylinders under the same pressure but at a reduced temperature of 25°C. Hence, condensation occurs at the coil, and condensed liquid is collected in the second cylinder. A second simulation is done using three and a half kilograms of seawater, in which the evaporation occurs at 60°C as well. For CFD simulation, a Lee model was set up, and coefficients were calculated based on experimental data. Figuring out the amount of freshwater used in this process is the main aim of the CFD study. So, the objective of this study is to investigate the evaporation and condensation rates at the described conditions.

2. PRACTICAL SETUP AND TEST DATA

Two cylinders were looped with a condensing coil. A 120-watt vacuum pump was connected to the 2nd cylinder to reduce the pressure inside the whole system. We took preheated seawater of 60°C inside cylinder one and turned on the vacuum pump. The whole system had a constant situation after achieving 12.1kPa pressure inside. At this pressure level, water should boil at 50°C as water's boiling point is related to atmospheric pressure. The condenser coil was at room temperature (25°C). In a closed system, hot water was taken in cylinder one, and the vacuum pump was turned on to reach the required vacuum pressure. Several similar tests were conducted, and data was recorded for each instance. One sample of data is listed in TABLE 1, which was conducted in the UTS laboratory [3].

Vacuum Desalination Experiment							
Room Temp:	25°C	RH:	65%	Weight of Feed (1) water:	3.0kg	Volume of FW Cylinder-1:	9.0L
Ambient Pressure:	101.325 kPa	Density of Feed (1) water:	1000 kg/m³			Volume of CW Cylinder-2:	9.0L

Time	**Cylinder-1 (Feed Water)**			**Cylinder-2 (Condensed Water)**			**Cond. Coil**
	Weight (kg)	Temp (°C)	Pressure (kPa)	Weight (kg)	Temp (°C)	Pressure (kPa)	Temp (°C)
Before Start V pump	7.45	60	101	4.45	25	101	25
After Start(01min)		59.3	12.1		25	12.1	25
After Start(10min)		38	12.1		26.5	12.1	25.5
After Start(25min)	7	32	12.1	4.85	27	12.1	25.5

TABLE 1: VACUUM DESALINATION EXPERIMENT DATA

3. CFD ANALYSIS

The two cases to be simulated are as TABLE 2.

i. Pure water (total simulation time = 30 minutes, initial mass of water = 3 kg)

Component name	Temperature ($°C$)	Pressure (kPa)
Evaporation cylinder	60	12.33
Coil	25	12.33
Condensation cylinder	25	12.33

ii. Seawater (total simulation time = 45 minutes, initial mass of water = 3.5 kg)

Component name	Temperature ($°C$)	Pressure (kPa)
Evaporation cylinder	60	12.33
Coil	25	12.33
Condensation cylinder	25	12.33

TABLE 2: EXPERIMENTAL PARAMETERS

3.1 Simulation Setup

As discussed previously, the system consists of two cylinders with the same volume, connected by a coil. The system design is shown in FIGURE 1 with a summary of the main dimensions and initial liquid phase volume fraction.

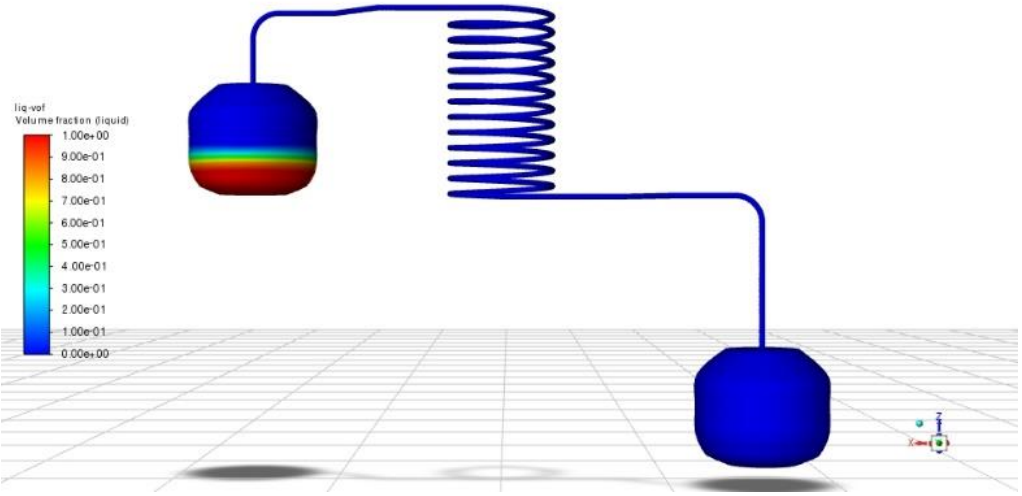

FIGURE 1: INITIAL VOLUME FRACTION OF WATER FOR FRESHWATER (COLORED IN RED)

3.1 Meshing

The system is meshed with the default meshing setting using an element size of elements, resulting in a total of 1227915 elements. FIGURE 2 and 3 are the meshed system, showing the orthogonal quality, and as shown, the minimum orthogonal quality is 0.2, which is considered a good value. Note that this is a closed system, so it contains no inlets or outlets.

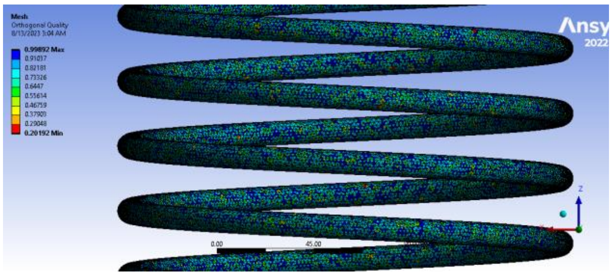

FIGURE 2: ORTHOGONAL QUALITY CONTOUR CLOSE-UP AT THE COIL

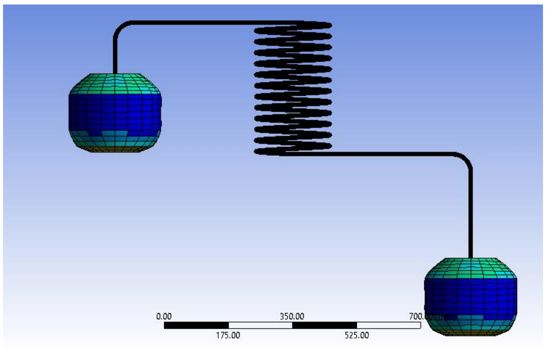

FIGURE 3: ORTHOGONAL QUALITY CONTOUR

3.2 Simulation Methodology

As discussed previously, two simulations would be conducted: one with freshwater, and the second with seawater, with the properties of seawater [1] with salinity of 30 g/kg shown in TABLE 3.

Properties of seawater	
Density [kg/m³] :	Constant (1005.3)
Cp (Specific Heat) [J/(kg K)] :	Constant (4037.8)
Thermal Conductivity [W/(m K)] :	Constant (0.649)
Viscosity [kg/(m s)] :	Constant (0.000502)
Molecular Weight [kg/kmol] :	Constant (18.0152)
Standard State Enthalpy [J/(kg mol)] :	Constant (-2.858e+08)
Reference Temperature [C] :	Constant (60)

TABLE 3: PROPERTIES OF SEAWATER SETTINGS

In the two simulation cases, two phases are modelled which are water liquid and vapor. The two phases are modelled using the mixture multiphase model and using the Lee evaporation-condensation model to simulate the mass transfer of one phase to the other. Turbulence is modelled using the realizable k-epsilon model. Below tables show the parameters used in the Lee model. At a pressure of 12.33 kPa, the saturation temperature is approximately 50 $°C$. According to the ANSYS Fluent Theory Guide for the Evaporation-Condensation Model, the model constants are coefficients in the mass transfer equations that can be fine-tuned according to experimental data or calculated assuming a flat interface between the two phases, a dispersed regime with constant diameter, and a known accommodation coefficient which is a physical quantity that describes the vapor particles collisions with the accompanying liquid or solid surface. This value depends on several parameters such as the surface state as well as the composition and pressure of the surrounding gas mixture [2]. Calculating the theoretical value of this coefficient is quite difficult, hence it is more realistic to fine-tune it to match experimental data. When the applied temperature is higher than the saturation temperature, evaporation occurs and the mass transfer from liquid to vapor phase can be described as follows:

$$m_{\dot{e}\rightarrow v} = coeff * \alpha_l \rho_l \frac{T - T_{sat}}{T_{sat}}$$

Similarly, when the temperature is lower than the saturation temperature, condensation occurs, and the mass transfer can be described as follows:

$$m_{\dot{v}\rightarrow e} = coeff * \alpha_v \rho_v \frac{T - T_{sat}}{T_{sat}}$$

Where, α and ρ are the phase volume fraction and density, respectively. The subscripts l and v are for liquid and vapor phases, respectively. According to the given initial and boundary conditions as well as the given time for the simulation, the constant $coeff$ was optimized for the two simulations and set as 0.001 for evaporation, and 3 for condensation based on the experimental data acquired from the test rig. As the properties of seawater and freshwater are almost similar in terms of Cp, viscosity, molecular weight and standard state enthalpy, using the same coefficients in Lee model seems to be appropriate. TABLE 4 outlines model settings.

Component name	**Property name**	**Property value**
Evaporation cylinder	Volume (L) Initial liquid volume fraction (SW)	9
	Initial liquid volume fraction (FW)	0.33409
	Initial liquid volume fraction (SW)	0.38702
Coil	Tube's inner diameter (mm)	11
	Length (mm)	370.6
	Number of turns	13

Evaporation-Condensation Model Settings	
Evaporation/Condensation Model:	Lee
Wall Model:	Not Semi-Mechanistic Boiling
Model Constants	
From Phase Frequency [/s] :	0.001
To Phase Frequency [/s] :	3
Saturation Properties	
Saturation Temperature [C] :	50

TABLE 4: SIMULATION MODEL SETTINGS

4. RESULTS

4.1 Freshwater simulation results

FIGURE 4-7 are the results of the first simulation using fresh water, showing the plot of volume fraction variations with time of the liquid phase in the evaporation cylinder, and the vapor phase inside the coil and the condensation cylinder, as well as the contour of the liquid phase volume fraction at 1800 seconds at the end of the simulation. The red color represents a high-volume fraction of the liquid phase, while the blue represents low values. The results illustrate how the liquid phase gets evaporated from the left cylinder and the vapor flows into the coil, at which it gets condensed due to the temperature drop below the saturation temperature and then gets collected in the right cylinder. FIGURE 7 shows that there is mixture of vapor and condensed water in the coil at the end of the procedure. This indicates that the condensation process would go longer even after 1800 seconds, and thus, it is certain that more condensed water would accumulate. Hence, the condensation rate we have is confirmed through this method, and it would be higher rather than less.

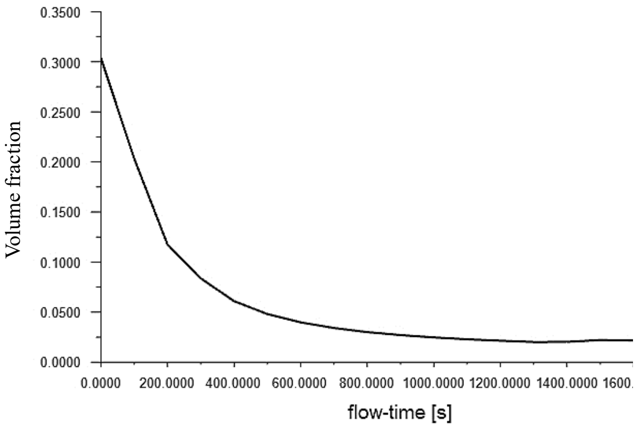

FIGURE 4: VOLUME FRACTION OF LIQUID PHASE AT EVAPORATOR WITH TIME

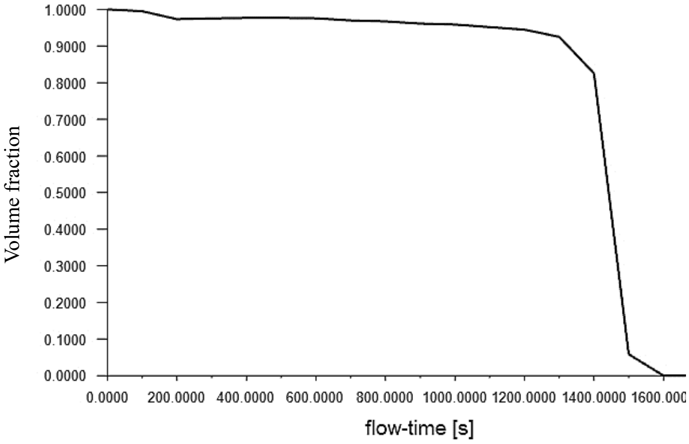

FIGURE 5: VOLUME FRACTION OF VAPOR PHASE AT CONDENSER WITH TIME

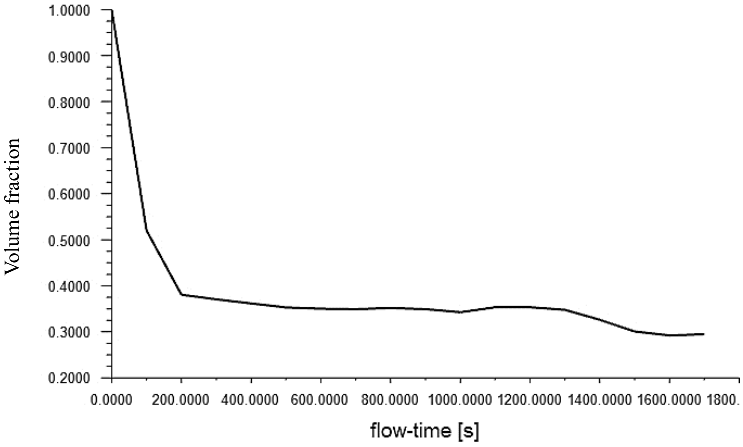

FIGURE 6: VOLUME FRACTION OF VAPOR PHASE IN COIL WITH TIME

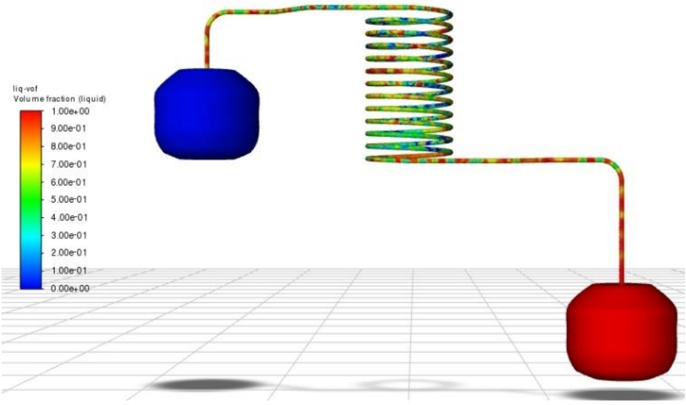

FIGURE 7: CONTOUR OF LIQUID PHASE VOLUME FRACTION AT 30 MINUTES

4.2 Seawater simulation results

The overall trend in the resulting plots and contours is quite similar to that of freshwater simulation. However, there are some noticeable differences in the values. In the evaporation cylinder a lesser amount of the liquid gets evaporated, while a more efficient condensation occurs in the coil and the condenser. That means that seawater takes more time to evaporate completely compared to freshwater. Also, since the water is evaporated at a lower temperature, that may explain the improvement in the condensation of vapor. FIGURE 11 shows that there is still mixture of vapor and condensed water in the coil at the end of the procedure but less than what we have seen in FIGURE 8. This indicates that the condensation process would go longer even after 2700 seconds and thus it is certain that more condensed water would accumulate. Hence, the condensation rate we have is confirmed through this method, and it would be higher rather than less. FIGURE 8-11 are the results for seawater simulation.

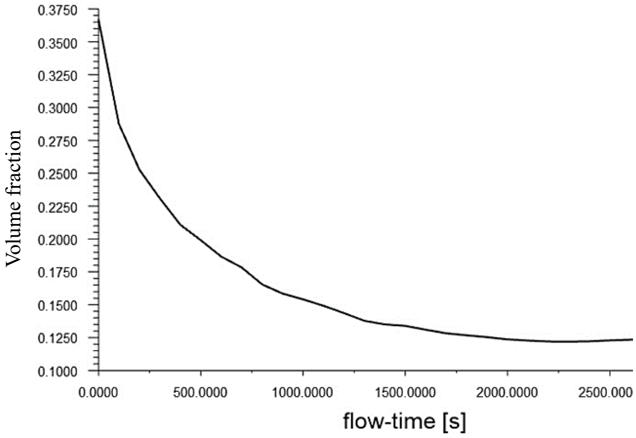

FIGURE 8: VOLUME FRACTION OF LIQUID PHASE AT EVAPORATOR WITH TIME

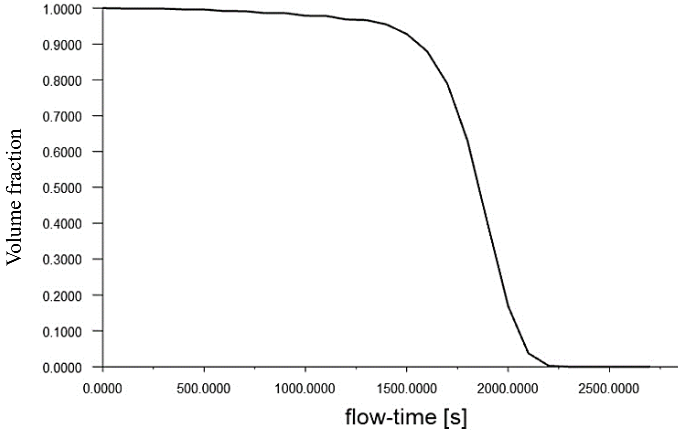

FIGURE 9: VOLUME FRACTION OF VAPOR PHASE AT CONDENSER WITH TIME

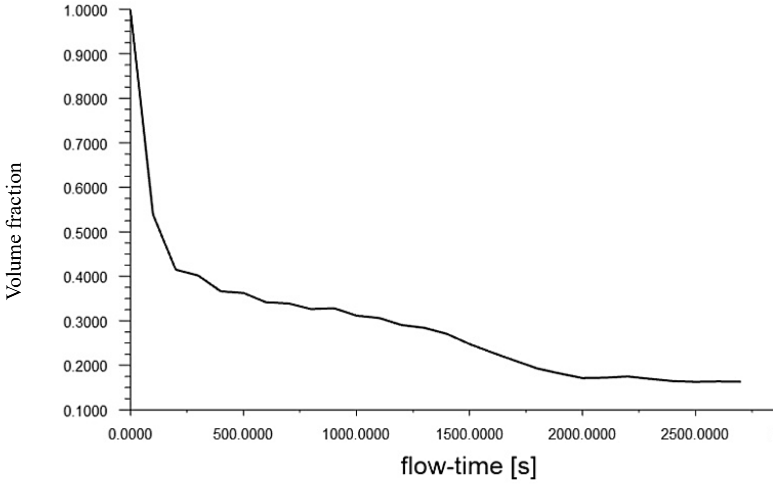

FIGURE 10: VOLUME FRACTION OF VAPOR PHASE IN COIL WITH TIME

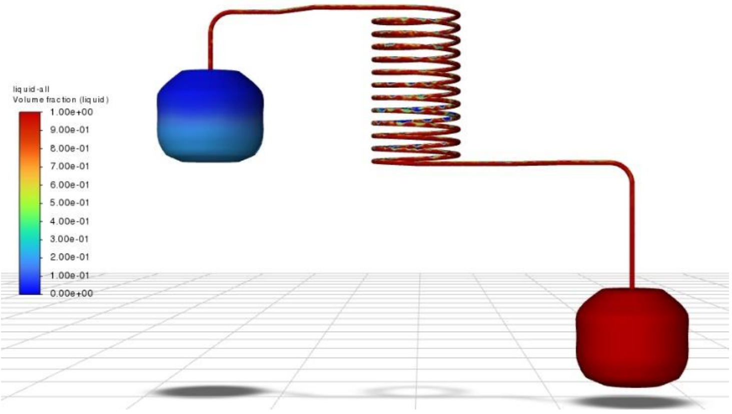

FIGURE 11: CONTOUR OF LIQUID PHASE VOLUME FRACTION AT 45 MINUTES

4.3 Comparison of results

Comparison between freshwater and seawater results are listed in TABLE 5.

Liquid phase volume fraction	**Freshwater (at t=30 min)**	**Seawater (at t=45 min)**
In evaporation cylinder	0.020778	0.123509
In coil	0.707598	0.837086
In condensation cylinder	1	1

TABLE 5: COMPARISON BETWEEN FRESHWATER AND SEAWATER RESULTS

Comparison between CFD simulation and practical data are as shown in TABLE 6.

Condensation of water in Simulation		**Condensation of water in Experiment**	
Volume (Ltr)	Mass (kg)	Volume (Ltr)	Mass (kg)
0.47	.47	0.4	0.4
Desalination rate: 18gram/min		Desalination rate: 16gram/min	

TABLE 6: COMPARISON BETWEEN CFD SIMULATION AND PRACTICAL DATA

5. CONCLUSION

Our CFD simulation justifies our theoretical and practical approach, as the desalination rates in both cases are very similar. This indicates that low-pressure vacuum desalination is feasible in most applications. Section TABLE 6 shows that we had 70 grams less condensed water in cylinder-2 in a practical experiment in terms of mass and 0.07Ltr less in terms of volume. We checked the moisture level in the exhaust air from the vacuum pump and found that there was additional moisture present. This indicates that missing water vapor could have been pumped out by the vacuum pump. Evaporation and condensation both take longer in seawater. In the case of seawater, in the evaporation cylinder, a smaller fraction of the liquid gets evaporated, while a more efficient condensation occurs in the coil and the condenser. That means that seawater takes more time to evaporate completely compared to freshwater. However, if we refer to FIGURE 7 & 11, after 2700 sec, there is still a mixture of liquid and vapor in the coil. This indicated that our estimated finding of getting freshwater through this method is very certain, and in practice, we can even get more freshwater produced than estimated. Also, external heat supply is only via solar as we need to raise the water temperature to a very minimum level, and energy saving is significant.

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