University of Technology, Sydney
Faculty of Engineering

AN ASSESSMENT OF INDIRECT EVAPORATIVE COOLING AS AN ENERGY EFFICIENT AND COST EFFECTIVE METHOD OF AIR CONDITIONING WITH ENERGY RECOVERY

By

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CERTIFICATE OF ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Nomenclature

ACRONYMS

AIRAH – Australian Institute of Refrigeration Air-conditioning and Heating

AS – Australian Standard

ASHRAE – American Society of Heating Refrigeration and Air-conditioning Engineers

COP – Coefficient of Performance

CSIRO – Commonwealth Scientific and Industrial Research Organisation

DBT – Dry Bulb Temperature

DC – Direct Cost

DEC – Direct Evaporative Cooling

DICER – Dual Indirect Cycle Energy Recovery

DX – Direct Expansion

FCI – Fixed Capital Investment

HVAC – Heating Ventilation and Air Conditioning

IAQ – Indoor Air Quality

IC – Indirect Cost

IEC – Indirect Evaporative Cooling

ICER – Indirect Cycle Energy Recovery

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCE – Life Cycle Engineering

LMTD – Log Mean Temperature Difference

NTU – Number of Transfer Units

OO – Other Outlay

PPHE – Polymer Plate Heat Exchanger

PV – Present Value

PVC – Polyvinyl Chloride

PVIFA – Present Value Interest Factor Annuity

RH – Relative Humidity

SHR – Sensible Heat Ratio

TCI – Total Capital Investment

WBT – Wet Bulb Temperature

SYMBOLS

A – Surface area of heat exchanger (m^2)

a – A constant for a particular model of a heat exchanger in equation 3.32

C – Present value of owning and operating cost in other words LCC. ($)

C_C – Cost of Catalyst ($)

C_G – Cost of gelcoat/flowcoat ($)

C_i – Initial cost or purchase price ($)

C_k – Cost for given size or capacity ($)

C_L – Labour cost ($)

C_{max} – Maximum heat capacity rate (W/K)

C_{min} – Minimum heat capacity rate (W/K)

C_m – Cost of materials ($)

C_M – Maintenance Cost ($)

C_o – Running cost (operating only)

C_P – Specific heat capacity (kJ/kg K)

C_R – Cost of resins

C_x – Cost at different size or capacity ($)

$Cp_{1\text{-}2}$ -- Average specific heat capacity of air in the primary passages (kJ/kg K)

$Cp_{5\text{-}7}$ – Average specific heat capacity of air in the secondary passages (kJ/kg K)

D_h – Hydraulic diameter (mm)

E_c – Cost of electricity including demand cost ($/kW hr).

E_{PD} – Peak demand energy savings (W)

E_{RC} – Energy recovery due to condensate trap and re-use (W)

F – Future amount ($)

f – Friction factor (Dimensionless)

g – Acceleration due to gravity (m/s^2)

h_1 – Specific enthalpy of primary air entering the heat exchanger passages (kJ/K)

h_2 – Specific enthalpy of primary air leaving the heat exchanger passages (kJ/K)

h_3 – Specific enthalpy of air at room conditions (kJ/K)

h_4 – Specific enthalpy of air after heat gain (kJ/K)

h_5 – Specific enthalpy of air at room conditions (kJ/K)

h_6 – Specific enthalpy of secondary passages air at the exit of the heat exchanger (kJ/K)

h_7 – Maximum possible specific enthalpy rise of secondary passages air at the exit of the heat exchanger (kJ/K)

h_{fg} – Latent heat of evaporation of water (kJ/kg)

h_{sw} – Enthalpy of spray water (kJ/kg)

i – Interest rate (%)

k – Thermal conductivity of the heat exchanger material. (W/m K)

L – Length of the passage of the heat exchanger (mm)

L_r – Labour rate per hour ($/hr)

L_{CC} – Life cycle costs ($)

Le – Lewis number

M_f – Fibre mass fraction

M_m – Matrix mass fraction

m_f – Mass of fibre (kg)

m_R – Mass of resin (kg)

m_G – Mass of gelcoat (kg)

m_C – Mass of catalyst (kg)

$\dot{m}_1$ - Mass flow rate of primary air entering the heat exchanger primary passages (kg/s)

$\dot{m}_2$ - Mass flow rate of primary air exiting the heat exchanger primary passages (kg/s)

$\dot{m}_5$ - Mass flow rate of secondary air entering the heat exchanger secondary passages (kg/s)

$\dot{m}_6$ - Mass flow rate of secondary air exiting the heat exchanger secondary passages (kg/s)

$\dot{m}_b$ - Mass flow rate of bleed water (kg/s)

$\dot{m}_c$ - Mass of condensate water per seconds (kg/s)

$\dot{m}_e$ - Mass flow rate of evaporated air (kg/s)

$\dot{m}_r$ - Mass flow rate of refrigerant (kg/s)

$\dot{m}_{sw}$ - Mass flow rate of spray water (kg/s)

$\dot{m}_P$ - Mass flow rate of primary air (kg/s)

$\dot{m}_S$ - Mass flow rate of secondary air (kg/s)

n – Number of years

n_p – Number of primary passages

$\boldsymbol{n_s}$ – Number of secondary passages

$\boldsymbol{P}$ – Present value ($)

P_{Comp} – Compressor power input required (W)

P_f – Price of fibre per kg ($/kg)

P_r – Price of resin per kg ($/kg)

P_{fan} – Fan power requirements (W)

P_{pump} – Pump power requirements (W)

p_1 – Suction pressure (Pa)

p_2 - Discharge pressure (Pa)

$\dot{q}$ – Heat transfer rate through control volume or simply the heat transfer (W)

$\dot{q}_L$ – Latent heat transfer (W)

$\dot{q}_{\max}$ – Maximum possible heat transfer (W)

$\dot{q}_P$ – Primary passages heat transfer rate (W)

$\dot{q}_S$ – Secondary passages heat transfer rate (W)

$\dot{q}_{Sen}$ – Sensible heat transfer (W)

$\dot{q}_t$ – Actual total heat transfer (W)

$\dot{q}_{VC}$ - Vapour compression cooling capacity (W)

R – Resin to glass ratio

R_c – Compression ratio, (Ratio of discharge pressure (p_2) to suction pressure (p_1)).

r – Rate of return

S_e – Scaling exponent

S_k – Given size or capacity index or unit

S_x – Different size or capacity index or unit

T_c – cycle time of the fabricating process (hour)

T_1 – Outdoor air temperature entering primary passages of a heat exchanger (K)

T_2 – Supply air temperature of the heat exchanger (K)

T_3 – Room air temperature

T_{3WBT} – Secondary air wet bulb temperature at inlet (K)

T_{1WBT} – Outside air wet bulb temperature (K)

T_4 – Temperature rise from T_3 (Room air temperature) due to heat gain (K)

T_5 – Temperature after cooling coil placed on exhaust stream of DICER system before entering the cross-flow heat exchanger (K)

T_6 – Exist temperature at secondary passages of the cross-flow heat exchanger (K)

T_7 – Maximum possible temperature rise in the secondary passages due to maximum possible heat transfer (K)

T_P – Mean temperature of the heat exchanger plate (K)

t_L – Laminate thickness (mm)

U – Overall heat transfer coefficient ($W/m^2 K$)

U_{dry} – Heat transfer coefficient of dry surface primary passages ($W/m^2 K$)

u_{Wtet} – Heat transfer coefficient of wet surface secondary passages (W/m^2K)

V_a – Approach velocity in the inlet section of the heat exchanger. (m/s)

V_f – Fibre volume fraction

V_m – Matrix volume fraction

$\dot{V}$ - Volumetric flow rate (m^3/S)

$\dot{V}_{fan}$ - Volume of air through the fan (m^3/s)

$\dot{V}_{pump}$ - Volume of liquid through the pump (m^3/s)

$\dot{V}_P$ - Volumetric flow rate of primary air (m^3/s)

$\dot{V}_S$ - Volumetric flow rate of secondary air (m^3/s)

W_{Comp} – Compressor work (kJ/kg)

W_1 – Humidity ratio of primary air entering the heat exchanger primary passages (g/kg)

W_2 – Humidity ratio of primary air exiting the heat exchanger primary passages (g/kg)

W_3 – Humidity ratio at the Room condition (g/kg)

W_5 – Humidity ratio of secondary air entering the heat exchanger secondary passages (g/kg)

W_6 – Humidity ratio of secondary air exiting the heat exchanger secondary passages (g/kg)

W_{Sai} – Humidy ratio of secondary air entering the heat exchanger (g/kg)

W_{Sae} – Humidy ratio of secondary air exiting the heat exchanger (g/kg)

v - Velocity of air (m/s)

v_1 - Specific volume of refrigerant at suction. (m^3/kg)

n –Number of quantity to be produced

x – A Constant for the model of the heat exchanger in equation 3.32

ΔP - Pressure drop (kPa)

ΔP_{fan} - External static pressure drop for fan (kPa)

ΔP_{pump} - External static pressure drop for pump (kPa)

Δx – Thickness of the plate. (mm)

ε - Heat exchanger effectiveness

ε_{DEC} – Effectiveness of direct evaporative cooling (%)

ε_{IEC} – Effectiveness of indirect evaporative cooling (%).

ρ – Mass density (kg/m^3)

ρ_{air}– Air standard density (1.2 kg/m^3)

ρ_f– Fibre density (kg/m^3)

ρ_m – Matrix density (kg/m^3)

η_{Comp} - Compressor efficiency

η_{Pump} - Pump efficiency

γ – Polytropic index – a general constant

ABSTRACT

Indirect evaporative cooling (IEC) exhibits favourable potential for energy recovery when operated on its own or when it is integrated with a vapour compression system to form a hybrid system. However, very few systematic and holistic design approaches have been carried out to analyse its strengths and weaknesses relative to other available technologies. This thesis reports research on developing a novel low energy air conditioning system in which an indirect evaporative cooling unit in the form of a polymer plate cross-flow heat exchanger is integrated with a vapour compression system or a chilled water coil.

Two design approaches are taken, one after the other. In the first approach the thermal aspect of this particular heat exchanger is described (Chapters 1 to 3). A model for basic effectiveness is developed from the physical principles involving energy balance, use of moist air properties and a psychrometric chart. This new development explains the sensitivity of effective operating conditions and the link between sensible heat ratio and flow ratio.

In the second part of this thesis, (chapter 4 to 7) a functional design approach is employed that considers criteria which are common to air conditioning system design and product development. For the DICER system, technology assessment and the original case study for ventilation air pre-treatment are described. This part of the thesis also describes life cycle costing, materials, manufacturing and the influence of volume production on cost along with a case study.

When considering manufacturing or fabrication on a larger scale a simple tool using geometrical relations of the mould size, shape and material specifications is used to estimate the material quantity for large scale production. This is illustrated with a specific model of heat exchanger housing and considering fibreglass as a preferred material for fabrication. An economic evaluation is carried out based on the material requirements for existing manufacturing and proposed manufacturing method. Cost reduction opportunity is presented using optimised batch quantity. This cost reduction is then extended to other models of the heat exchanger housing and compared with

existing manufacturing methods. This total approach of combining thermal science with materials, production and engineering design activity identifies the strengths, weaknesses and suitability of this method of air conditioning for commercial exploitation. The research conducted by this approach has provided valuable insights and understanding of the technology as well as its merits and limitations when compared with existing commercial products such as vapour compression systems.

A life cycle cost (LCC) analysis method is developed based on the operating cost, initial cost, performance and discount rate over future time for the economic lifetime of the product. This model compares the life cycle cost of a particular design or product when evaluating several energy recovery options. This costing tool will aid design engineers to establish a balance between performance and cost. Alternatives with different design, performance and initial costs are assessed and analysed for operating life, taking replacement within the comparison period into account.

The key contributions of the work described in this thesis are:

1. A simplified effectiveness model based on sensible heat ratio and using a psychrometric chart which explains sensitivity of effectiveness when considering dry and wet surface heat transfer.
2. The case study involving ventilation air pre-treatment in a commercial building using the DICER method of energy recovery, where the cross-flow polymer plate heat exchanger is integrated with the chilled water coils supplied from the main plant.
3. Qualifications to the benefits of this method of ventilation air pre-treatment for peak demand reduction as well as annual energy conservation combined with site evaluation for potential application in retrofit operation.
4. Guidelines are developed based on the knowledge gained throughout the case study which will aid similar future designs.
5. Technology assessment is carried out to point out the strengths and weaknesses of the DICER system for its next stage of design optimisation.
6. A simplified quantity estimation technique is presented using the geometric relation of mould shape; size and material specification. Optimum batch quantities are presented for the existing and recommended method of manufacturing for further cost optimisation.