



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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TABLE OF CONTENTS

Certificate of Originality	i
Acknowledgements	ii
List of Figures	vi
List of Tables	ix
Nomenclature	xi
ABSTRACT	xvii
CHAPTER 1. INTRODUCTION TO THE THESIS	1
1.1 Introduction	1
1.2 Background to Study	1
1.3 The Need for the Present Study	6
1.4 Objective and Significance	8
1.5 Thesis Organization	10
CHAPTER 2. LITERATURE REVIEW	14
2.1 Introduction	14
2.2 Evaporative Cooling	14
2.3 Indirect Cycle Energy Recovery (ICER)	27
2.4 Dual Indirect Cycle Energy Recovery (DICER)	35
2.5 Design Evaluation Check List Based on Literature Review	39
2.6 Conclusion	41
CHAPTER 3. ANALYSIS OF THE DICER SYSTEM PERFORMANCE	42
3.1 Introduction	42
3.2 Primary/Secondary Air Inlet and Outlet Conditions	42
3.3 Heat Transfer in a Primary/Secondary Channel	45
3.4 Effectiveness Model for the DICER type of Heat Exchanger	53
3.5 COP of Indirect Evaporative Cooling	69
3.6 Thermo-economic Optimization	74
3.7 Conclusion	79
CHAPTER 4. DESIGN PROCESS, ASSESSMENT AND ENERGY RECOVERY AS A CASE STUDY	81
4.1 Introduction	81
4.2 Design Process	83
4.3 Conceptual versus Detail Design Changes	85
4.4 Technology Assessment (Heat Recovery Option)	87
4.5 Technology Assessment (General Air Conditioning)	95
4.6 Energy Recovery Demonstration Project – A Case Study	105
4.7 Economic Evaluation of Heat Recovery System	119
4.8 Guidelines for Energy Recovery Design	121
4.9 Conclusion	126

CHAPTER 5. LIFE CYCLE ENGINEERING	127
5.1 Introduction	127
5.2 Life Cycle Cost, Design Approach	129
5.3 Goal and Scope Definition	130
5.4 Life Cycle Cost Analysis	131
5.5 Life Cycle Costing (LCC) - Case Study	134
5.6 Conclusion	146
CHAPTER 6. MATERIALS AND MANUFACTURING	148
6.1 Introduction	148
6.2 Engineering Materials	149
6.3 Outline of Composites – Fibre-Reinforced Polymer (FRP)	152
6.4 Common Matrix Materials (Resins) Overview	161
6.5 Resin to Glass Ratio	164
6.6 Catalyst Promoters and Inhibitors	164
6.7 Additives and Fillers	166
6.8 Gelcoat and Flowcoat	167
6.9 Estimating Strength and Thickness of FRP	167
6.10 Characteristics of Laminates	169
6.11 Quantity Determination	173
6.12 Manufacturing Process	178
6.13 Conclusion	192
CHAPTER 7. ECONOMICS AND VOLUME PRODUCTION	193
7.1 Introduction	193
7.2 Cost Focus – Design for Affordability	193
7.3 Product Cost Breakdown and Estimation of Total Capital Investment – A Case Study Using FRP Technology.	195
7.4 Production cost Comparison	198
7.5 Effect of Size on Cost and Fabricating Methods	204
7.6 Conclusion – Minimizing Production Cost	207
CHAPTER 8. CONCLUSIONS AND RECOMMENDATIONS	210
8.1 Introduction	210
8.2 Summary, Conclusion and Contribution	210
8.3 Future Work	213
Reference	215
Appendices	225

List of Figures

Figure 1.1: Total System Under Study.

Figure 2.1: Direct Evaporative Cooler, Legends: 1 – Housing, 2 – Louvered pad frame for air inlet, 3 – Shaft, 4 – Water distribution around the periphery, 5 – Water pump, 6 – Drive motor for fan, 7 – Float valve.

Figure 2.2: GLASdek[®] Pad.

Figure 2.3: Psychrometric process of Direct Evaporative Cooling, Legends: CAN – Canberra, SYD – Sydney, DAR – Darwin, DEC – Direct Evaporative Cooling, CWBT – Coincident Wet Bulb Temperature. Note: Area enclosed by points 1, 2, 3 and 4 represents ASHRAE Comfort Chart.

Figure 2.4 Schematic of Indirect Evaporative Cooling System.

Figure 2.5: Several Variants of Indirect Evaporative Cooling with Combined Heat Exchanger and Direct Evaporative Cooling.

Figure 2.6: Indirect Evaporative Cooling with Regenerative Room Exhaust Air.

Figure 2.7: Schematic of Indirect Cooling with Second Stage Direct Evaporative Cooling.

Figure 2.8: Indirect Evaporative Cooling System.

Figure 2.9: Cross-flow Exchanger Legends: 1 – Outdoor air, 2 – Supply air, 3 – Exhaust from room, 4 – Exhaust to outdoor.

Figure 2.10: Method of Joining Plates.

Figure 2.11: Assembly of Plates for Cross-flow Heat Exchanger.

Figure 2.12: Psychrometric Chart Showing the Performance of an Indirect Evaporative Cooling System. Outdoor Condition (1) is Alice Springs with Heat Exchanger Effectiveness of 80 Percent.

Figure 2.13: Schematic of DICER Showing Reverse Cycle Heat Pump and Cross-flow Heat Exchanger.

Figure 2.14: DICER System Future Configuration as a Package System.

Figure 2.15: DICER Air conditioning Process Shown on Psychrometric Chart; Figure Legends, 1 – Outdoor condition, 2 – Supply air, 3 – Room, 4 – Duct heat gain, 5 – Cooling and dehumidification of exhaust air, 6 – State of air after PPHE, 8 – State of air due to condenser.

Figure 3.1: Psychrometric Chart Showing the State Points for DICER. Figure Legends: 1 - Outdoor condition, 2 – Supply condition to room, 3 – Room condition, 4

– Air on condition to VC coil, 5 – Air off condition of VC Coil, 6 – Air off condition of DICER Heat Exchanger.

Figure 3.2: Schematic Section of a Cross-flow Heat Exchanger Showing Primary/Secondary Air Flow as well as the Direction of the Heat Flow.

Figure 3.3: Overall Heat Transfer Coefficient vs. Thickness for PVC and Aluminium.

Figure 3.4: DICER Psychrometric Chart Showing Maximum and Actual Heat Transfer Process.

Figure 3.5: Effectiveness Vs. Approach Velocity.

Figure 3.6: Effectiveness Vs Water Spraying Rate.

Figure 3.7: IEC Effectiveness Based on Capacity Ratio.

Figure 3.8: Psychrometric Chart Showing the Variation of Outdoor Conditions and the Heat Exchange Process in the DICER Heat Exchanger.

Figure 3.9: Variation of Effectiveness with Sensible Heat Ratio.

Figure 3.10: Variation of Effectiveness with Flow Ratio.

Figure 3.11: COP Variation of an IEC at Different Outdoor Air Temperatures

Figure 3.12: Variation of Total Cost vs. Exit Enthalpy at the Cooling/DX Coil for the DICER System.

Figure 4.1: Cost Impact of the Design Stages.

Figure 4.2: Objective Tree with Weighted Values.

Figure 4.3: Package Rooftop System.

Figure 4.4: Ducted Split System.

Figure 4.5: Cassette Type Split System.

Figure 4.6: The DICER System.

Figure 4.7: Main Components and Operating Principle of the DICER Integrated with Chilled Water Coils of the Main Central Plant.

Figure 4.8: Flow Chart for Energy Simulation Method.

Figure 4.9: Sydney Weather Conditions Throughout the Year.

Figure 4.10: Psychrometric Chart for Sydney Critical Design Conditions.

Figure 4.11: Variation of Enthalpy of Ambient Air Showing Energy Recovered and Auxiliary Heating and Cooling Required Using Indirect Cycle Energy Recovery.

Figure 4.12: Sensitivity analysis for the DICER System.

Figure 4.13: Sensitivity analysis for an Enthalpy Wheel.

Figure 4.14: Comparative Cost vs. Market Price for DICER and Rotary Heat Exchangers.

Figure 5.1: Summer Cooling Operation of the DICER System.

Figure 5.2: Winter Heating Operation of the DICER System.

Figure 5.3: Summer Cooling Operation of an Enthalpy Wheel.

Figure 5.4: Winter Heating Operation of an Enthalpy Wheel.

Figure 5.5: Equivalent Annual Cost Comparison of Design Alternatives.

Figure 5.6: Life Cycle Cost Comparison of Design Alternatives.

Figure 6.1: Outline of Materials and Manufacturing.

Figure 6.2: Formation of Composite Material.

Figure 6.3: Continuous and Short Fibre Composites.

Figure 6.4: Typical Fabrics, Top Left – Rovings, Top Right – Chopped Strand (A type of random fibre), Bottom Left – Weave and Bottom Right – Stitched.

Figure 6.5: Surfacing Veil.

Figure 6.6: Casing Manufacturing Process.

Figure 6.7: Rolling Out a Laminate.

Figure 6.8: Using Flat Table Surface as a Mould.

Figure 6.9: Schematics of Hand Lay - Up Process.

Figure 6.10: Semi Finished Product Using Hand lay-up Technique, DICER with Fan and Heat Exchanger Assembly.

Figure 6.11: Spray - up Technique.

Figure 6.12: Schematic of Spray - Up Technique.

Figure 6.13: RTM Process, Source.

Figure 6.14: Heat Seal of Cross-flow Heat Exchanger.

Figure 6.15: Heat Exchanger Plate Surface.

Figure 7.1: Breakdown of Total Capital Investment.

Figure 7.2: Manufacturing Cost Model for DICER System.

Figure 7.3: Hand Lay-Up process Cost vs. Quantity.

Figure 7.4: RTM Process Cost vs. Quantity.

Figure 7.5: Effect of Size on Cost and Fabricating Method Selection for Cost Reduction.

List of Tables

- Table 2.1: Check List for System Design for Different Variant of Evaporative Cooling at Functional Level.
- Table 3.1 Inlet/Outlet conditions.
- Table 3.2: Heat Transfer Calculations for ICER1B0900 at Flow Rate of 700L/s.
- Table 3.3: IEC Effectiveness Based on Capacity Ratio.
- Table 3.4: Outdoor Conditions and Variation of Effectiveness with Sensible Heat Ratio.
- Table 3.5: COP for a Plate type Indirect Evaporative Cooling.
- Table 3.6: COP of the DICER System at Different Mean Values.
- Table 3.7: Cost per Unit Flow of a Plate Heat Exchanger
- Table 3.8: Cost per Unit kW of a Vapour Compression System.
- Table 4.1: Evaluation Scale.
- Table 4.2: Evaluation Matrix.
- Table 4.3: Definition of Rating for Assessment.
- Table 4.4: Results of Technology Assessment by System and Applications.
- Table 4.5: Selection Matrix
- Table 4.6: State Points of Air for Peak Demand Reduction.
- Table 4.7: Parameters and Properties of the DICER Heat Exchangers.
- Table 4.8: Peak Demand Reduction Using the DICER System.
- Table 4.9: Summary Table Showing Annual Energy Recovery for a Typical Commercial Building Operating 11 hours Weekday and 3 hours Weekend with Economy Cycle Across Different Cities.
- Table 4.10: Summary Table Showing Energy Recovery and Cost Savings.
- Table 4.11: Payback for the DICER at 7 Percent Interest Rate with Yearly Benefit of \$8,348.00.
- Table 4.12: Payback for Enthalpy Wheel at 7 Percent Interest Rate with Yearly Benefit of \$2,740.
- Table 4.13: Range of Equipment Capacity and Heat Exchanger Size.
- Table 5.1: General Design Data.
- Table 5.2: DICER Heat Exchanger Parameters.
- Table 5.3: Operating Cost of the DICER System with Chilled Water Coils and DX System.
- Table 5.4 Enthalpy Wheel Heat Exchanger Parameters.

Table 5.5: Operating Cost of a Rotary Heat Exchanger (Enthalpy Wheel)

Table 5.6: Total Operating Cost Summary for DICER System and Enthalpy Wheel.

Table 5.7: Life Cycle Cost and Equivalent Annual Investment

Table 6.1: Typical Coverage of Gelcoat.

Table 6.2: Fibre Content and Resin to Glass Ratio.

Table 6.3 Cycle Time and Production Rate.

Table 7.1: Cost Breakdown Structure for Fixed Capital Investment.

Table 7.2: Manufacturing Cost Estimates for the Wet lay up and RTM Processes.

Table 7.3: Manufacturing Cost Comparison.

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 (\$)
- C_{P1-2} – Average specific heat capacity of air in the primary passages (kJ/kg K)
- C_{P5-7} – 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

- n_s – Number of secondary passages
- 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)
- q – Heat transfer rate through control volume or simply the heat transfer (W)
- q_L – Latent heat transfer (W)
- q_{max} – Maximum possible heat transfer (W)
- q_P – Primary passages heat transfer rate (W)
- q_S – Secondary passages heat transfer rate (W)
- q_{Sen} – Sensible heat transfer (W)
- q_t – Actual total heat transfer (W)
- 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 ($W/m^2 K$)
- $u_{W_{tet}}$ – Heat transfer coefficient of wet surface secondary passages ($W/m^2 K$)
- 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} – Humidity ratio of secondary air entering the heat exchanger (g/kg)
- W_{Sae} – Humidity ratio of secondary air exiting the heat exchanger (g/kg)
- v - Velocity of air (m/s)
- v_l - 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.