Design of a Desiccant Wheel of Thermally Driven Dehumidification System

By

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CERTIFICATION OF APPROVAL

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Approved by,

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(Dr. Khairul Habib)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHAMAD HANIF BIN SHAMSUDIN

ABSTRACT

This project is about a designing and modeling for a desiccant wheel of thermally driven dehumidification systems. This system is for controlling the indoor air condition by installs it as a Heat, Ventilation and Air Conditioning system. Previously, there have been several efforts in modeling the operating performance of the desiccant wheels.

This study presents the development of an equation based model to expect the operating performance desiccant wheels, based upon fundamental scientific and engineering principles. This model has correlated the desiccant wheel's performance to its design parameters and operating conditions. The moisture transfer processes have been developed based on the physical analysis of desiccant materials. The model has been compared with the conventional air conditioning system based on the energy usage to control the indoor environment.

ACKNOWLEDGEMENT

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NOMENCLATURE

Abbreviations:

DW	Dessicant Wheel
HE	Heat Exchanger
EV	Evaporative Cooler
RH	Regenerative Heater

Parameters/Variables:

Cp	Specific heat, J/kg-K
h	Enthalpy or convective heat transfer coefficient, J/kg or W/m^2-K
h_m	Convective mass transfer coefficient, kg/m^2-s
ΔH	Heat of adsorption or vaporization, J/kg
t	Time or temperature, s or ^oC
T	Temperature, K
Δt	Time step, s
Δx	Dehumidification capacity or grid size x domain, g/kg or m
u	Air velocity, m/s
x	Distance in axial direction, m
γ	Moisture loading in the desiccant, kg moisture/kg dry desiccant
ρ	Density, kg/m
$\emptyset$	Relative water vapor concentration
No_x	Number of discretization in the space (x) domain
No_t	Number of discretization in the time (t) domain

it	Indicator of the element in t domain
ix	Indicator of the element in x domain
RSHI	Regeneration Specific Heat Input, kJ/g
η_{dehum}	Dehumidification efficiency
Δh	Enthalpy change, kJ/kg
$\dot{Q}$	Thermal power, W
$\dot{m}$	Process mass flow rate, kg/s
η	Regeneration efficiency

Subscripts:

dehum	Dehumidification
amb	ambient
p	Process
g	Air
in	Inlet
m	Desiccant matrix or mass transfer
max	Maximum
min	Minimum
out	Outlet
pair	Process air
reg	Regeneration
rair	Regeneration air
sub	Substrate
v	Water vapor

vg	Concentration water in air
vm	Concentration water in desiccant material
ads	Adsorption

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CHAPTER 1

PROJECT BACKGROUND

1.1 BACKGROUND STUDY

People today tend to spend most of their time in indoor spaces such as at home, office and school. Thus indoor air quality plays an important role to create a healthy indoor environment. The World Health Organization (WHO) has published report on the 'The Right to Health Indoor Air' which talks about the fundamental principal in the human rights field, biomedical ethics and ecological sustainability [1]. These statements tell the society for healthy indoor air about their right and obligation. Moisture is one of the air qualities that need to be control in most of the building. Moisture management and humidity control is required because of high humidity is associated with the increased in mold growth, allergic responses and respiratory responses. However to accomplish this it will be energy demanding to renovate the building design or install special system to control the humidity. In United Kingdom, energy used is about one third of all energy in that country [2]. By using this desiccant technology, the cooling demand can be reduced to 30% of that of a conventional system [3] [4]. Failed in energy management will lead to negative impact on the sustainability of global life support. This impact can be reduced by doing research about the building design and new technology to reduce the energy consumption. Today the application of desiccant technology will change how the moisture and energy management to the building design.

1.2 PROBLEM STATEMENT

The desiccant wheel has been design to ensure the moisture or humidity will be under control. Most of the humidity will be cause by the nature for example according to online forecast website[1] in Malaysia the humidity level is around 60% while in South America region is about 40% based on weather forecast for middle of June 2012. Mostly building will may not be desirable the high humidity for their indoor environment. For example building which is used to store materials that easily affected by humidity such as museum. This is because of majority of the artifacts in historic house are made of natural organic materials and the recommended levels of humidity in range 30-70% in relative humidity (RH) and some of items need 50-60% RH which is valuable objects such as painting and antique furniture [5]. Thus this project is undertaken to design desiccant wheel which is thermally driven to control the humidity level together with saving the energy to operate this system.

1.3 OBJECTIVE AND SCOPE OF STUDY

The main objective is to design a desiccant wheel which is energy efficient to control the humidity of the indoor environment specifically. To accomplish this main objective, the other factors need to consider as well such as system design and system configuration. The main task and objective can be summarized as follows:

- To analyze the efficiency of this desiccant wheel of thermally driven dehumidification system.
- To verify whether the desiccant wheel is energy conservative and suitable to apply in building design.

[1] http://www.timeanddate.com/weather/

CHAPTER 2

LITERATURE REVIEW

2.1 DESICCANT WHEELS

For a comfortable indoor environment the complete set of system of desiccant wheel need to establish by installing the essential component like desiccant wheel, solar collector, heat exchanger and evaporative cooling. All this components have their own function for creating a controlled indoor humidity. Figure 2-1 shown simple dehumidification systems that commonly apply in most building design. Nevertheless from that figure, this study only focuses the desiccant wheel where dehumidification process occurs during first phase to controlling the indoor air condition. Desiccant wheel devices have different forms such as the enthalpy recovery which is one of the most common types in commercial applications due to its high performance as a result of its large heat and mass transfer area. The first concept of desiccant cooling was established in the 1930s but commercialize the system was unsuccessful. Later Pennington patented the first desiccant cooling cycle which known as Pennington's cycle is now routinely referred to as the ventilation cycle as shown in Figure 2-2. After few years Carl Munters improved the design in the 1960s by introducing the parallel passages [6] and honeycomb channel structure.

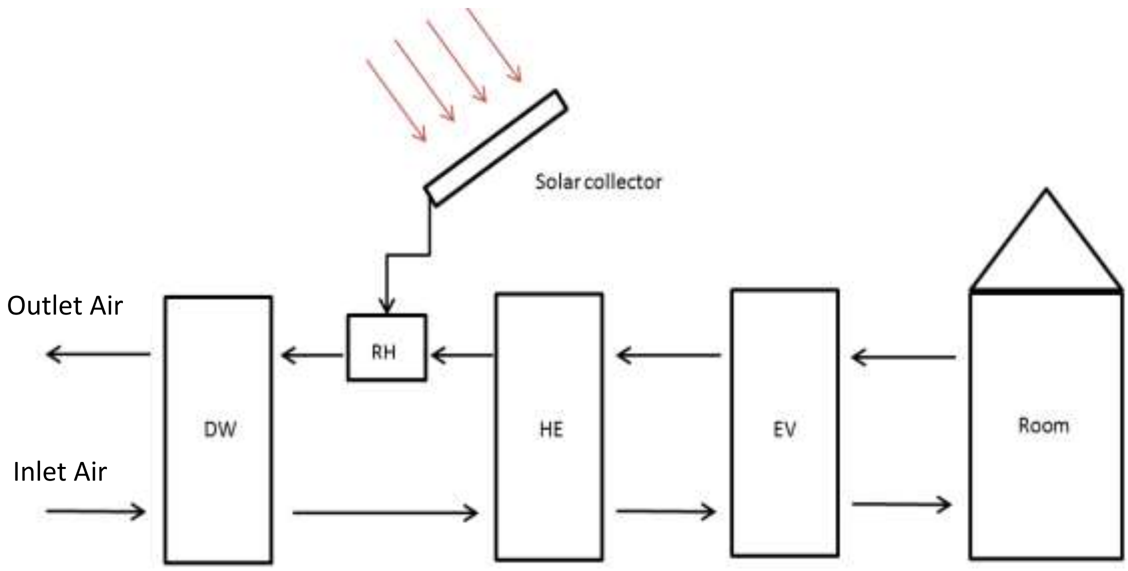


Figure 2-1 Simple Dehumidification Systems Block Diagram

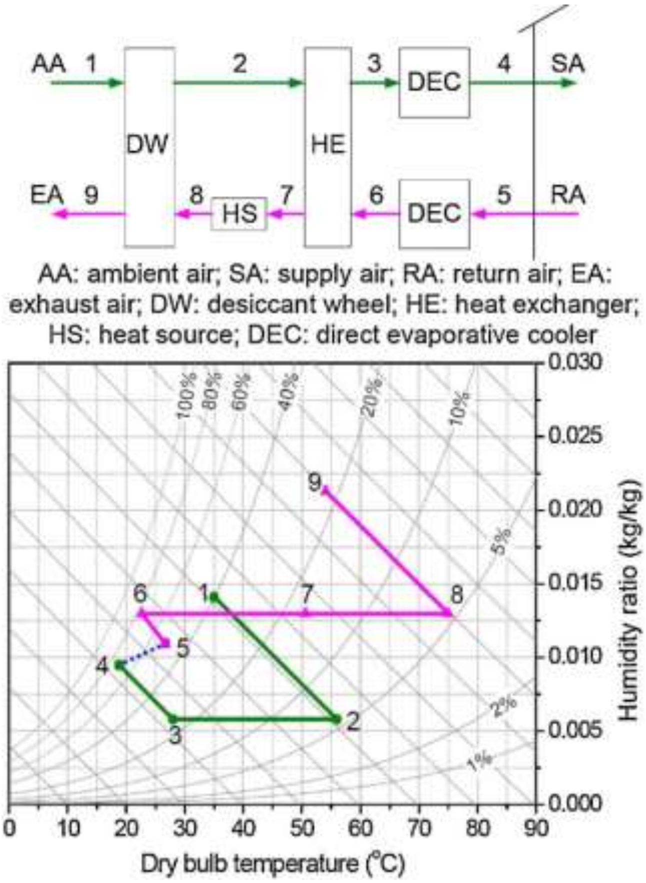


Figure 2-2 Pennington's Cycle [7]

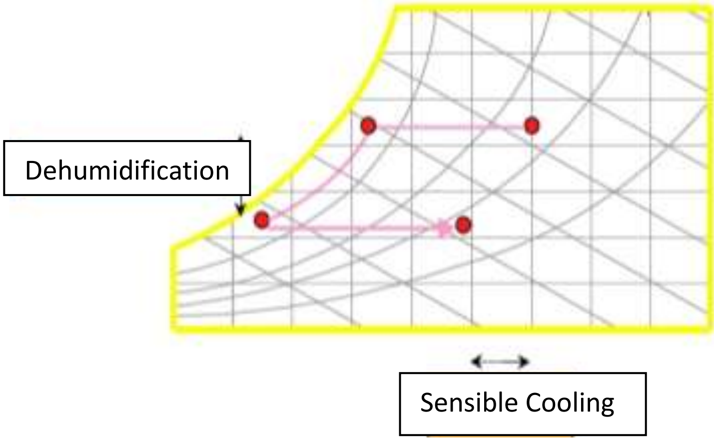


Figure 2-3 Explanation Psychometric Chart [8]

From Figure 2-3, it explains how the dehumidification and sensible cooling affect the Psychometric chart. The dehumidification happens when the humidity ratio drops while sensible cooling results from the decreasing dry bulb temperature. Figure 2-4 shows the example of rotary enthalpy recovery wheel that commercially used in cool country area because of dehumidification process can only be done by this device. This device has large heat and mass transfer that result in high performance. The area result comes from the type structure used on the wheel which is honeycomb structure which provides numerous small and parallel channels. This structure as shown in Figure 2-5 was developed by Carl Munter to increase the efficiency by increasing the surface area of air contact to the desiccant materials. Air flow through these channels will exchange the heat and moisture with the surrounding desiccant materials. With this contact the desiccant material will able to adsorb the moisture from the air by natural phenomenon called adsorption results from differences of vapor pressure between the desiccant materials and air passes through in the channel.

Adsorption process the first layer of water molecules binds chemically on the surface of the solid desiccant material followed later by physical absorption. An important characteristic of adsorbents is their isotherms which determine their vapor adsorption capacity as a function of temperature and vapor pressure.

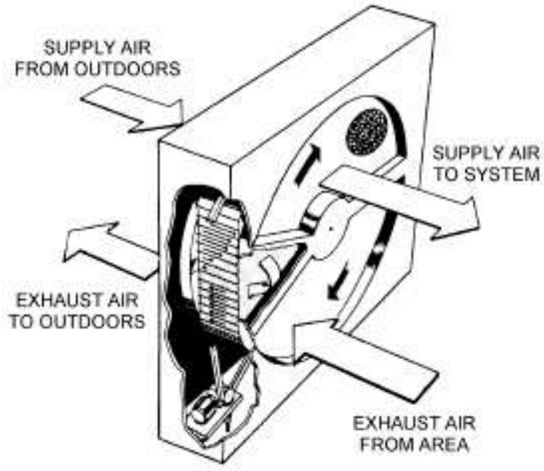


Figure 2-4 Rotary Enthalpy Recovery Wheels [9]

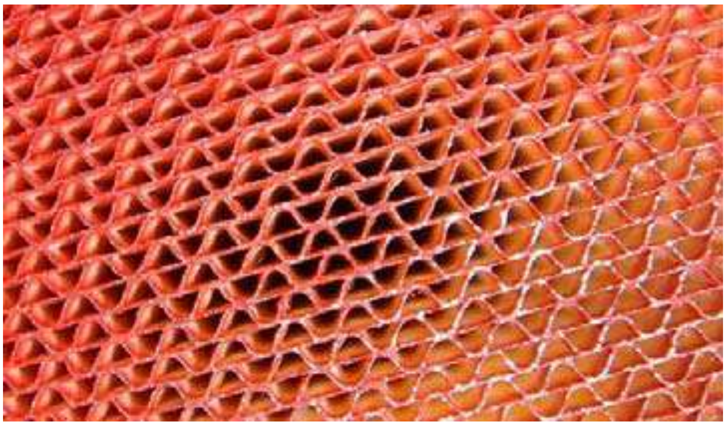


Figure 2-5 Honeycomb Structure on Desiccant Wheel [9]

2.2 DESICCANT MATERIALS

Almost all materials have the capacity to adsorb and hold water vapor but commercial desiccants such as silica gel has significant capacity for holding the water. These desiccants adsorb large amount of molecules into pores on their surface. This is made possible by the fact that these pores have a large active surface area in the range of $500m^2/g$ [15]. Desiccant materials may be in a liquid or solid form and the most commonly used desiccants are silica gel, lithium chloride or molecular sieves for example zeolites. Silica gel which is solid desiccant will adsorb water in its highly porous structure. The silica gel has properties to adsorb up to 20% of its own weight in water vapor and can be regenerated and reused by simply apply heat to the gel to drive off the adsorbed [10]. While the lithium chloride which is a liquid form of desiccant is easily to manufacture but need to use an apparatus in which continuous transport of liquid solution is carried out. Early desiccant wheel used the honeycomb paper impregnated with lithium chloride because of easy to manufacture. However this type will have a short life span because of the loss of the desiccant material during operation due to nature of lithium chloride. Recently, silica gel and molecular sieves have been used because they are stable and have lower equilibrium capacity.

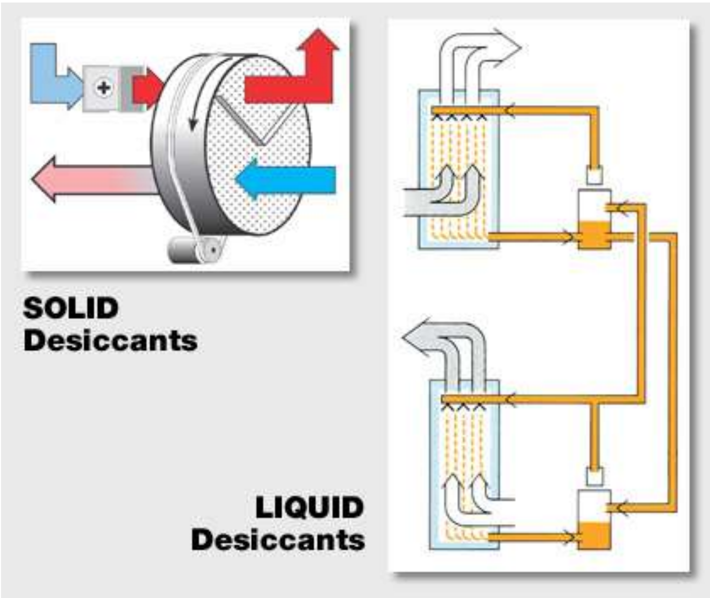
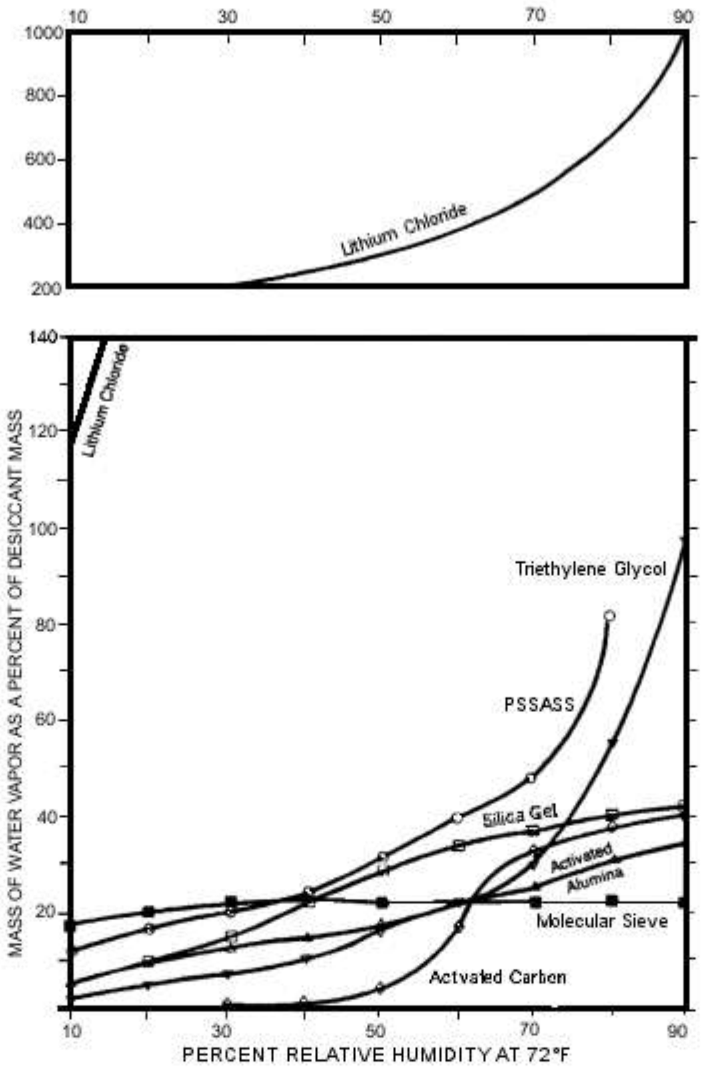


Figure 2-6 Difference of Solid and Liquid Desiccants [10]

According ASHRAE Handbook as shown in Figure 2-7, lithium chloride is the higher in the percentage, it has seen little use in Heating, Ventilation, and Air Conditioning (HVAC) industry until now because of this desiccant material is corrosive and need a great care to insure it does not get carries away to airstream. New types of techniques have been used to replace the original coating. One of them is to mix together the desiccant material with pulp and binder and to make the desiccant paper from this mixture and grooved into a desiccant wheel. The other technique is to form the silica gel in-situ by making a honeycomb wheel from a glass fiber paper backbone which is first impregnated with concentrated water glass and then reacted with an acid wash.



	Percent RH in Air Stream		
Desiccant	30%	50%	90%
Lithium Chloride	200	300	1000
Silica Gel	17	30	41
Molecular Sieve	22	22	22
Activated Alumina	10	18	33
Triethylene Glycol	4	18	98

Figure 2-7 ASHRAE Desiccant Comparison Charts [11]

2.3 TYPE OF DESICCANT WHEELS

Basically there are two types of desiccant wheels which commonly used in HVAC system for building or plant:

- The enthalpy recovery wheel or passive desiccant wheel
- Active desiccant wheel

The first type of wheel is operated between the outside and the building exhaust air stream as shown in Figure 2-4. For example during summer season, the outside air is warmer which the humidity level is high and thus will transferred the heat and moisture from the outside air to the channels of enthalpy recovery wheel. Since the building exhaust air is cooler and less humid compared to the outside, the heat and moisture is transferred back from the wheel to the exhaust air while the winter season is vice versa. This type is also known as passive desiccant wheel because of there is no external thermal energy input besides the limited amount of power input to rotate the wheel.

While for second type of wheel is known as active desiccant wheel which transfer the moisture from the outside air supply stream to the heated regeneration system as shown in Figure 2-8. This regeneration system can be done from direct-fired gas, solar thermal collector or sensible heat exchanger. The different in these two types of wheel is the characteristic to adsorb the moisture. For active desiccant wheels the moisture transfer is more important than heat transfer thus the mass fraction of desiccant material is about 50-60% higher. The wheel for active desiccant wheel will rotates at slower rate than enthalpy recovery wheel, in order to provide sufficient time for the moisture adsorption and pre cool the regenerated desiccant before it can adsorb again.

Table 2-1 shows an example of parameter involve designing the desiccant wheel alone.

Table 2-1 Parameter involve in designing both type of wheel [9]

	Enthalpy Recovery Wheel	Active Desiccant Wheel
Wheel diameter (mm)	787	787
Wheel depth (mm)	152	102
Wheel split ratio	1/2	2/3
Rotary speed (rpm)	30	0.42
Channel size (mm)	1.8*4.2	1.5*3.4
Desiccant thickness (microns)	25	65
Substrate thickness (microns)	15	75
Desiccant material	3Å molecular sieves	Silica gel
Desiccant density (kg/m^3)	760	700
Desiccant specific heat (J/kg-K)	1,000	1,000
Desiccant conductivity (W/m-K)	0	0
Separation factor	0.1	1
Maximum moisture loading (kg/kg)	0.2	0.36
Heat of adsorption (J/kg)	2,791,000	2,791,000
Substrate material	Aluminum	Glass fiber paper
Substrate density (kg/m^3)	2,700	500
Substrate specific heat (J/kg-K)	900	900
Substrate conductivity (W/m-K)	237	0
Convective heat transfer coefficient (W/m^2-K)	36.2	43.3
Convective mass transfer coefficient (m/s)	0.030	0.036

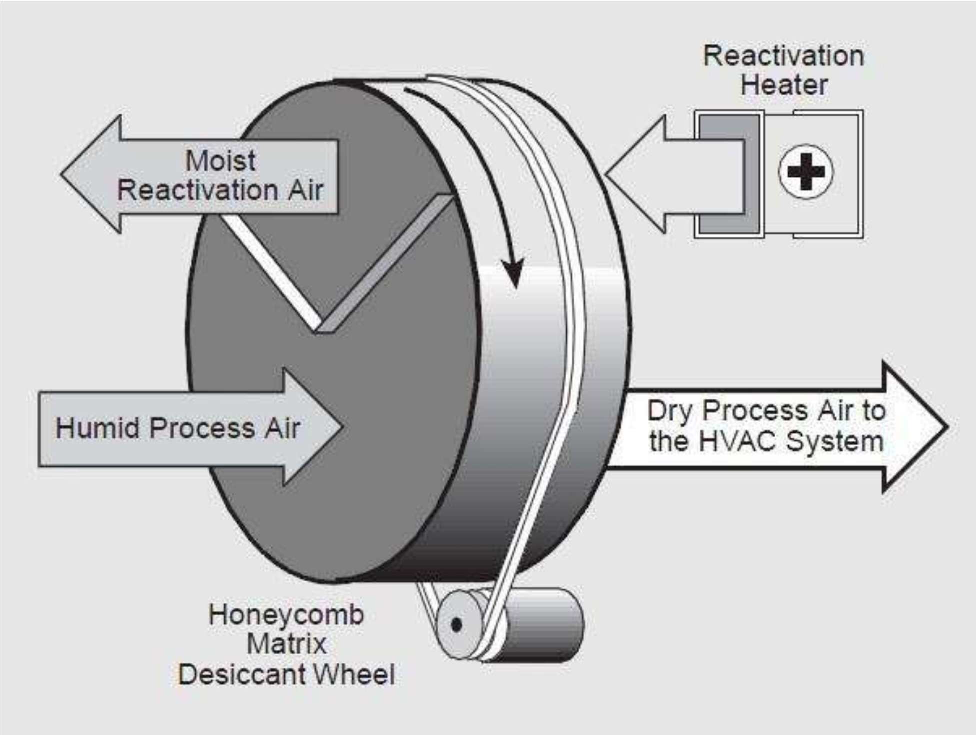


Figure 2-8 Active Desiccant Wheels [10]

2.4 PRINCIPLE OF DEHUMIDIFICATION SYSTEM

The process to removing the moisture called as dehumidification and specially for this it will be focusing on the dehumidifying the incoming air stream by forcing it through desiccant material and then drying the air to the desired indoor temperature. To ensure this system is continuously operated, water vapour adsorbed must be taken out through process called regeneration so that the desiccant materials is dried enough to adsorb more water vapor in next cycle. The regeneration process can be done by applying the heat from any of thermal source to its temperature of regeneration which is depending to the nature of desiccant materials [12]. From this statement, the parameter involve will be humidity and temperature. These two parameters are very crucial in controlling the indoor air quality. Therefore the dehumidification system comprises of three basic components which is regeneration heat source, the dehumidifier (desiccant material) and cooling unit.

2.5 GOVERNING EQUATION

In this chapter, a governing equation has been developed to predict the operating performance for this desiccant wheels which is based on fundamental scientific and engineering principles.

The design parameter will include:

- Wheel dimension (wheel depth, wheel diameter and split between adsorption and desorption sections)
- Channel dimension (channel shape and size)
- Desiccant composite (desiccant material properties)

The operating variable will include:

- The speed of the wheel
- The inlet process air properties (temperature, humidity and flow rate)
- The inlet regeneration air properties (temperature, humidity and flow rate)

The result from model prediction:

- The temperature and humidity of inlet for process air and regeneration air at any given time and location.
- The temperature and moisture loading of the desiccant composite at any given time and location.

To establish a governing equation, model assumptions are essential to make the prediction is easier and not very complex. The following assumptions are made in developing the model [9]:

1. The axial heat conduction and water vapor diffusion in the air are negligible.

2. The axial water vapor and adsorbed water diffusion in the desiccant are negligible.

3. The convective heat and mass transfer rates are represented using the bulk mean air temperature and humidity.

4. Heat conduction in the desiccant is negligible. Heat may be conducted axially through the substrate.

5. The mid plane, indicated as dash lines and two ends of the desiccant composite are adiabatic and impermeable.

6. The airflow in the channel is fully developed laminar flow.

7. The heat of adsorption is released in the desiccant composite.

8. The inlet air conditions are uniform across the wheel surface, but they can vary with time.

9. Thermodynamic properties of the dry air, desiccant material, and substrate, such as density, specific heat and heat of adsorption, remain constant during the wheel operation.

10. The convective heat and mass transfer coefficients remain constant during the wheel operation. They are determined based on published coefficients between gases and solid surfaces.

11. There is no heat or moisture storage in the wheel when it completes one rotation.

From above assumption, the dry air properties and air velocity remain constant and the moisture balance of the air stream can be written as:

$$h_m p\left(\rho_{vg} - \rho_{vm}\right) + uA\frac{\partial \rho_{vg}}{\partial x} + A\frac{\partial \gamma_m}{\partial t} = 0$$

Equation 2-1

The first term in this equation represents the rate of convective mass transfer between the air and the desiccant, which is represented by the difference in water vapor concentration between the bulk mean air and the desiccant, and a constant convective mass transfer coefficient. The second term represents the rate of moisture flux as a result of airflow. The third term represents the moisture storage in the air.

The moisture balance of the desiccant is written as:

$$h_m p(\rho_{vg} - \rho_{vm}) - A\frac{\partial \gamma_m}{\partial t} = 0$$

Equation 2-2

The first term in this equation represents the rate of convective mass transfer between the air and the desiccant, same as Equation 2.1. The second term represents the moisture storage in the desiccant material.

The energy balance of the air stream is written as:

$$hp(t_m - t_g) - uA\rho_g Cp_g \frac{\partial t_g}{\partial x} + A\rho_g Cp_g \frac{\partial t_g}{\partial t} = 0$$

Equation 2-3

The first term in this equation represents the rate of convective heat transfer between the air and the desiccant composite, which is represented by the temperature difference between the bulk mean air and the desiccant composite, and a constant convective heat transfer coefficient. The second term represents the rate of heat flux in the air as a result of airflow, and the third term represents the energy storage in the air. The sensible heat exchange associated with the moisture transfer is small compared to the convective heat exchange term and it is ignored.

The energy balance of the desiccant composite is written as:

$$h_m p(\rho_{vg} - \rho_{vm})\Delta H_{ads} - hp(t_m - t_g) - (\rho_m A_m Cp_m)\frac{\partial t_m}{\partial t} = 0$$

Equation 2-4

The first term in this equation represents the rate of heat conduction through the substrate, if it is present in the wheel. If the substrate is not present, this term will be eliminated. The heat conduction through the desiccant is ignored due to low heat conductivity of the material. The second term represents the rate of heat generation as a result of moisture adsorption. The rate of heat generation is represented by the product of the rate of moisture exchange and the heat of adsorption. As assumed earlier, the heat of adsorption is entirely released in the desiccant composite. The third term represents the rate of convective heat transfer between the air and the desiccant composite, corresponding to the first term in Equation 2-3. The last term represents the energy storage in the desiccant composite, including the energy stored in the desiccant and the substrate.

To solve all this equation a boundary condition is required:

- The inlet process air and inlet regeneration air temperature and water vapor concentration

$$t_g|_{x=0} = t_{pair,in}$$
$$\rho_{vg}|_{x=0} = \rho_{v,pair,in}$$
$$t_g|_{x=L} = t_{rair,in}$$
$$\rho_{vg}|_{x=L} = \rho_{v,rair,in}$$

- The adiabatic and impermeable conditions of the two ends of the desiccant composite

$$\frac{\partial t_m}{\partial x}|_{x=0} = \frac{\partial t_m}{\partial x}|_{x=L} = 0$$
$$\frac{\partial \rho_{vm}}{\partial x}|_{x=0} = \frac{\partial \rho_{vm}}{\partial x}|_{x=L} = 0$$

From above governing equation, there are five unknown variables from four equations: temperature of the air t_g, temperature of the desiccant composite tm, water vapor concentration in the air ρ_{vg}, water vapor concentration in equilibrium with the desiccant ρ_{vm} and moisture loading in the desiccant γ_m. Another equation is needed to solve the entire unknowns. The fifth equation will be desiccant adsorption isotherm, which related to moisture loading in the desiccant γ_m.

$$\frac{\gamma_m}{\gamma_{max}} = \frac{1}{1 - c + \frac{c}{\emptyset}}$$

$$\emptyset = \frac{\rho_{vm}}{\rho_{vm,sat}}$$

All of the equations above known as partial differential equation and to solve this type of equation, all four equations need to convert to four linear algebraic finite difference equations by substitution. The substitution is method involve is explicit finite difference method. Figure 2-9 shows how the wheel is divided into *No_x* elements in the space (*x*) and *No_t* element in the time (t) domain. The corresponding steps in the space and time domains are Δx and Δt. The indexes for the space and time domains are represented by ix and it and the double line shows the separation between the adsorption and desorption sections.

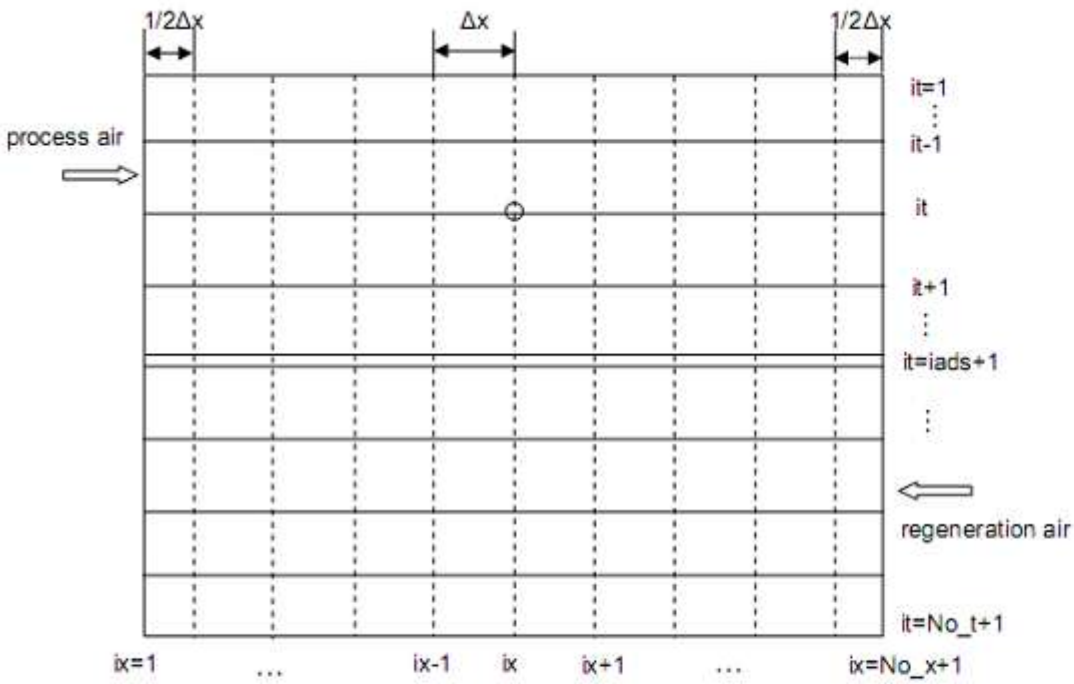


Figure 2-9 Schematic of the Finite Difference Representation of the Desiccant Wheel Model [9]

The following equations are after the substitution is made. Now the five unknown variable now be represented as:

- $t_g(it,ix)$ temperature of the air;
- $t_m(it,ix)$ temperature of the desiccant composite;
- $\rho_{vg}(it,ix)$ water vapor concentration in the air;
- $\rho_{vm}(it,ix)$ water vapor concentration at the desiccant air interface, which is in equilibrium with the desiccant;
- $\gamma_m(it,ix)$ moisture loading of the desiccant, which is a function of $t_m(it,ix)$ and $\rho_{vm}(it,ix)$.

Energy balance equation of air for adsorption section is:

$$\left(hp + \frac{u_p A \rho_g C p_g}{\Delta x} + \frac{A \rho_g C p_g}{\Delta t}\right) t_g(it,ix) - hpt_m(it,ix) = \frac{u_p A \rho_g C p_g}{\Delta x} t_g(it,ix-1) + \frac{A \rho_g C p_g}{\Delta t} t_g(it-1,ix)$$

Equation 2-5

Energy balance equation of desiccant composite:

$$hpt_g(it,ix) - \left(hp + \frac{A_m \rho_m C p_m}{\Delta t}\right) t_m(it,ix) + h_m p dH_{ads} \rho_{vg}(it,ix) - h_m p dH_{ads} \rho_{vm}(it,ix) = -\left(\frac{A_m \rho_m C p_m}{\Delta t}\right) t_m(it-1,ix)$$

Equation 2-6

Moisture balance equation of the air:

$$\left(h_m p + \frac{u_p A}{\Delta x} + \frac{A}{\Delta t}\right) \rho_{vg}(it, ix) - h_m p \rho_{vm}(it, ix) = \frac{u_p A}{\Delta x} \rho_{vg}(it, ix - 1) + \left(\frac{A}{\Delta t}\right) \rho_{vg}(it - 1, ix)$$

Equation 2-7

Moisture balance equation of the desiccant material:

$$\frac{\partial \gamma_m}{\partial t_m} \frac{A_m \rho_m}{\Delta t} t_m(it, ix) - h_m p \rho_{vg}(it, ix) + \left(h_m p + \frac{\partial \gamma_m}{\partial \rho_{vm}} \frac{A_m \rho_m}{\Delta t}\right) \rho_{vm}(it, ix) = \frac{A_m \rho_m}{\Delta t} \left[\frac{\partial \gamma_m}{\partial t_m} t_m(it - 1, ix) + \frac{\partial \gamma_m}{\partial \rho_{vm}} \rho_{vm}(it - 1, ix)\right]$$

Equation 2-8

Reduction of γ_m into γ_{max}:

$$\frac{\partial \gamma_m}{\partial t_m} = \frac{\partial \gamma_m}{\partial \emptyset} \frac{\partial \emptyset}{\partial t_m} = \frac{c \gamma_{max}}{(1 - c + \frac{c}{\emptyset})^2 \emptyset^2} \left[4.09x10^{-9} \rho_{vm} e^{\left(\frac{5196}{T_m}\right)} - \frac{2.13x10^{-5}}{T_m} \rho_{vm} e^{\left(\frac{5196}{T_m}\right)}\right]$$

Equation 2-9

$$\frac{\partial\gamma_m}{\partial\rho_{vm}} = \frac{\partial\gamma_m}{\partial\emptyset}\frac{\partial\emptyset}{\partial\rho_{vm}} = \frac{c\gamma_{max}}{(1-c+\frac{c}{\emptyset})^2\emptyset^2} x4.09x10^{-9}T_m e^{\left(\frac{5196}{T_m}\right)}$$

Equation 2-10

Boundary condition also converted to finite difference forms:

$$t_g(it,1) = t_{pair\_in}$$

$$\rho_{vg}(it,1) = \rho_{v,pair\_in}$$

$$t_g(it, No\_x+1) = t_{rair\_in}$$

$$\rho_{vg}(it, No\_x+1) = \rho_{v,rair\_in}$$

$$\frac{t_m(it,2) - t_m(it,1)}{\frac{dx}{2}} = 0$$

$$\frac{\rho_{vm}(it,2) - \rho_{vm}(it,1)}{\frac{dx}{2}} = 0$$

$$\frac{t_m(it, No\_x+1) - t_m(it, No\_x)}{\frac{dx}{2}} = 0$$

$$\frac{\rho_{vm}(it, No\_x+1) - \rho_{vm}(it, No\_x)}{\frac{dx}{2}} = 0$$

The governing equations shown in Equation 2-5 through Equation 2-10 and the boundary conditions in finite difference form complete the finite difference formulation of the combined heat and mass transfer problem for the performance modeling of desiccant wheels. The four independent unknown variables involved in this problem are $t_g(it,ix)$, $t_m(it,ix)$, $\rho_{vg}(it,ix)$ *and* $\rho_{vm}(it,ix)$, which can be obtained by Gaussian elimination method.

2.6 PERFORMANCE FUNDAMENTAL

There are almost more than 20 variables that affect the performance of the desiccant wheel. In general, desiccant wheel manufacturer will fix most of the variable to provide predictable performance [13]. Thus basically the performance of the desiccant wheel depends on several parameters like ambient air temperature and humidity, regeneration air, volume flow rates, geometry structure of the wheel and sorption properties of materials [3]. To calculate the performance of the desiccant wheel several of characteristic properties need to be considered:

- Dehumidification capacity (Δx) in [g/kg] referred as "performance" figure
- Regeneration Specific Heat Input (*RSHI*) in [kJ/g] referred as "energy efficiency" figure
- Dehumidification efficiency (η_{dehum}) as a type of "quality" figure
- Enthalpy change of process air (Δh) in [kJ/kg] as a type of "thermal quality" figure

The dehumidification capacity (Δx) is defined as the amount of moisture removed from the process airflow. While *RSHI* is the thermal power or heat energy rate supplied to the device for regeneration ($\dot{Q}_{reg}$) over the dehumidification capacity flux which is the product of process mass flow ($\dot{m}_{process}$) and dehumidification capacity (Δx) :

Equation 2-11

$$RSHI = \frac{\dot{Q}_{reg}}{\Delta \mathrm{x} \cdot \dot{m}_{pair}} \left[\frac{kJ}{g}\right]$$

From the equation above, the thermal power or heat energy rate ($\dot{Q}_{reg}$) for regeneration can acquired from basic energy equation which is the regeneration mass flow ($\dot{m}_{reg}$) and the temperature difference between the regeneration airs (T_{reg}) and room exhaust air (T_{room}) multiply to the specific heat capacity ($c_{p,air}$). If the ambient air is used for regeneration, the ambient air temperature replaces the room temperature.

$$\dot{Q}_{reg} = c_{p,air}\dot{m}_{reg}(T_{reg} - T_{amb})$$

Equation 2-12

Apart from that, the regeneration effectiveness can be used, which is given by the latent load for example the heat of evaporation of water (h_{latent}) multiplied with the moisture removed by the wheel (Δx), divided by the regeneration heat required per unit mass flow.

$$\eta_{reg} = \frac{\Delta \mathrm{x}\, h_{latent}}{\dot{Q}_r / \dot{m}_r} \qquad \text{Equation 2-13}$$

The dehumidification efficiency (η_{dehum}) is defined as the ratio of the reached dehumidification capacity (Δx) to the theoretical possible dehumidification (Δx_{max}).

$$\eta_{dehum} = \frac{\Delta \mathrm{x}}{\Delta \mathrm{x}_{max}} \qquad \text{Equation 2-14}$$

This calculation of dehumidification efficiency was performed where the maximum dehumidification capacity is achieved from the sorption isotherm of the adsorption material. The model is based on the assumption that the equilibrium water charge is only a function of the relative humidity and independent of temperature $(X = f(\varphi))$ and that the process is known as isenthalpic where the enthalpy will not affected throughout the system. With these simplifications it follows that the maximum possible dehumidification capacity is reached when the process airflow with the relative humidity φ_0 and the absolute humidity x_0 reaches the relative humidity of the regeneration airflow φ_{reg}, which gives the minimum possible charge. For a given process air enthalpy the absolute humidity can then be calculated.

CHAPTER 3

METHODOLOGY

3.1 PROJECT FLOW

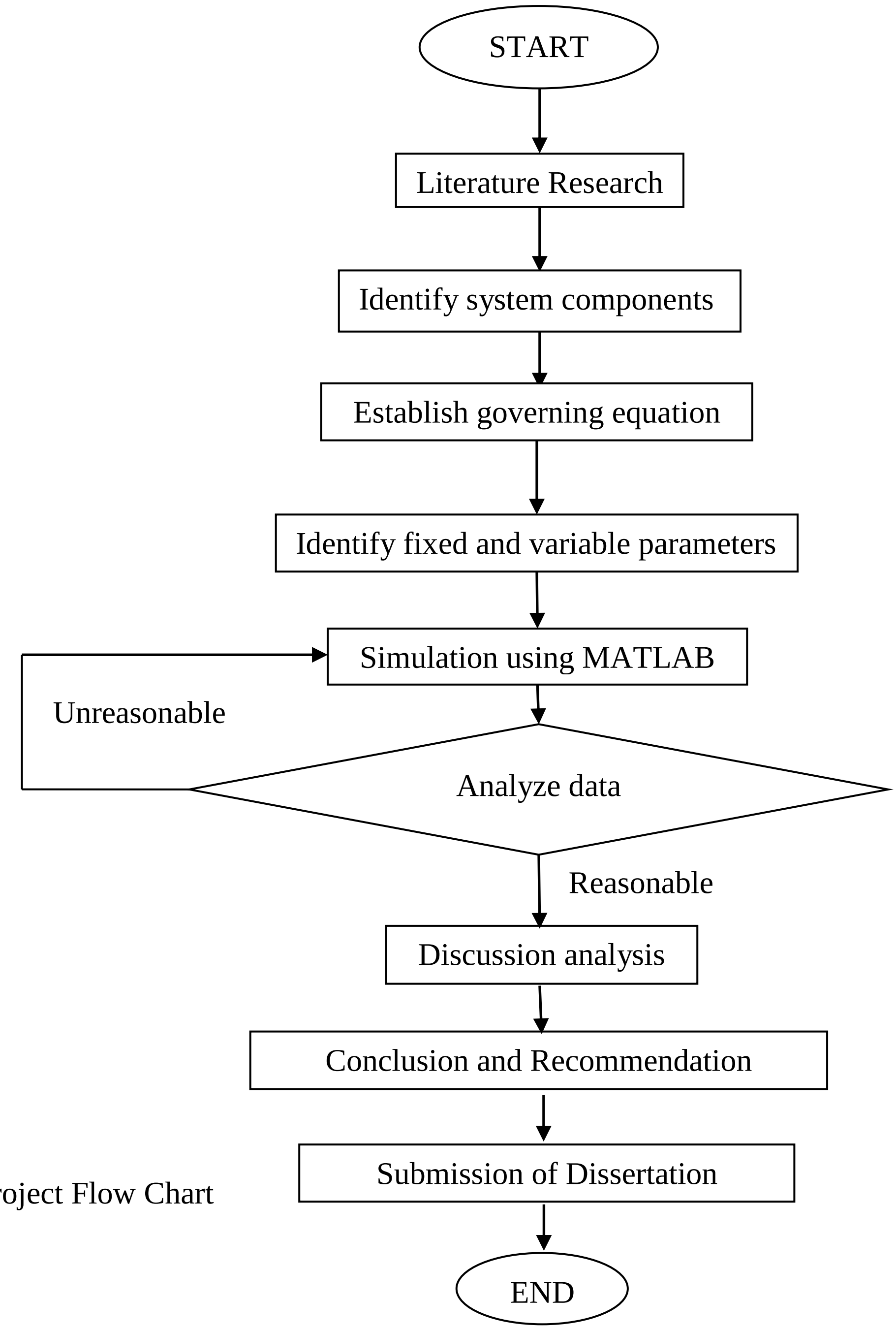


Figure 3-1 Project Flow Chart

3.2 GANTT CHART

Refer Appendix

3.3 TOOLS AND SOFTWARE

To accomplish this project successfully several of tools and software are used regularly. All these tools and software basically an engineering type which need a good knowledge to handle or operate it. The tools and software are:

1. MATLAB
   - Short form from matrix laboratory is a numerical computing environment and fourth-generating programming language. This software is developed by MathWorks and this software allows the matrix manipulations, plotting of function of data, implementation of algorithms, creation of user interfaces and interfacing with programs written in other languages, including C, C++, Java and FORTRAN. Basically this software will be using for complex calculation and simulation of the control system.
2. TRNSYS
   - Short form from transient system simulation program is an extremely flexible graphically based software environment used to simulate the behavior of transient systems. This simulation software used primarily in the renewable energy engineering and building simulation for passive and active solar design.
3. Microsoft Office
   - In this project there will be involve a basic software from Microsoft Office which include Microsoft Word, Microsoft Excel and Microsoft PowerPoint. Microsoft Word will be involving documentation of the report while Microsoft Excel will assist the simulation of MATLAB and TRANSYS. The last software which is Microsoft PowerPoint will be used during the presentation later.

CHAPTER 4

RESULT AND DISCUSSION

The design parameters of the desiccant wheel used to obtain the following simulation are shown in Table 4-1. While the average of inlet air conditions are shown in Table 4-2. From the psychometric chart the humidity of process air is reduced and its temperature is increased as a result of the heat adsorption. While for the temperature of regeneration air is reduced and its humidity is increased.

Table 4-1 Design Parameter of the Desiccant Wheels Used in the Simulation

Wheel diameter, t (mm)	400
Wheel depth, i (mm)	100
Rotary speed (rpm)	0.42
Channel size, A (mm)	1.5x3.4
Desiccant material	Silica gel
Desiccant thickness, d (microns)	65
Desiccant density, ρ_m (kg/m^3)	700
Desiccant specific heat (J/kg-K)	1000
Maximum moisture loading (kg/kg)	0.36
Heat of adsorption, ΔH (J/kg)	2791000
Convective heat transfer coefficient, h (W/m^2-K)	43.3
Convective mass transfer coefficient, h_m (m/s)	0.0351

Table 4-2 Average of Inlet air conditions

	Average process air inlet	Average regeneration air inlet
Temperature	27	100
Vapor concentration (kg/m^3)	0.00823	0.02

The schematic diagram of the desiccant wheel used in the simulation is shown in Figure 4-1. The process air enter the wheel from *x*=0 which is initial condition for process air. While for the regeneration air will enter the desiccant wheel from *x*=*L* which is initial condition for regeneration air. The wheel split ratio is 3/4 and the adsorption and desorption sections are separated by brush seals to prevent any unnecessary adsorption or desorption. This wheel also rotated by mechanical motor clockwise at 0.42 rpm.

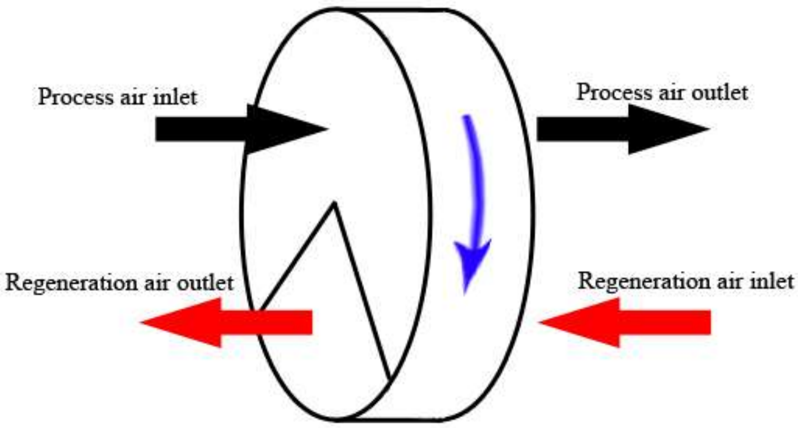


Figure 4-1 Schematic Diagram of Desiccant Wheel

The profiles of the air conditions with respect to time are plotted based on their respective time whether for dehumidification and regeneration phase. The plotted graphs are shown from Figure 4-2 to Figure 4-5.

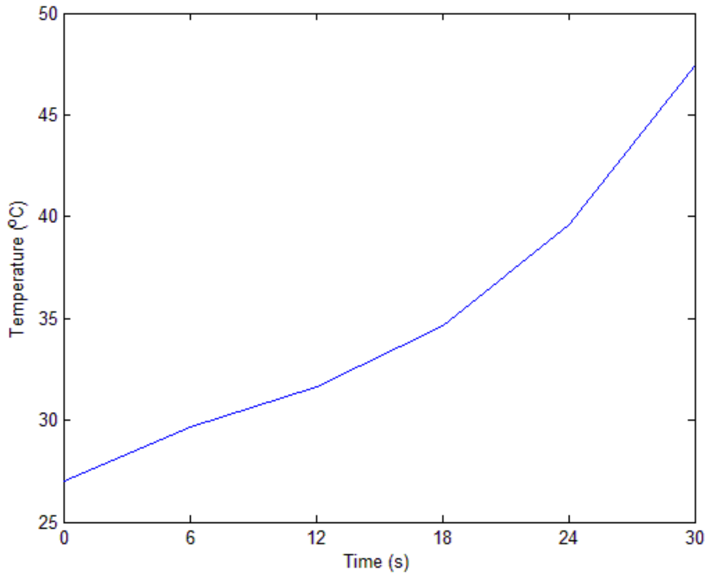


Figure 4-2 Temperature versus Time for Dehumidification Phase

From the Figure 4-2, it clearly shown that during the dehumidification process the temperature will rise with time which is from 27^{o}C to 47^{o}C. The reason in increasing temperature is because of during the dehumidification process the removing moisture in air cause the rise in temperature. This increasing of temperature also happens because of heat adsorption between desiccant material and air.

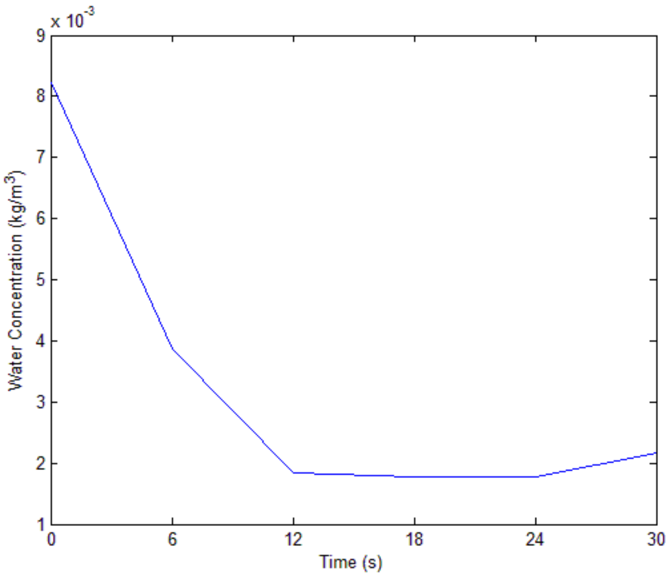


Figure 4-3 Water Concentration versus Time for Dehumidification Phase

The above Figure 4-3 shows the process during the dehumidification process, the water vapor concentration will decrease with time which is approximately from

0.0082 kg/m^3 to 0.0021 kg/m^3. The decreasing line in graph is because of during the dehumidification process, the nature of desiccant material which is low in vapor pressure causes the removal of moistures between the desiccant material and air.

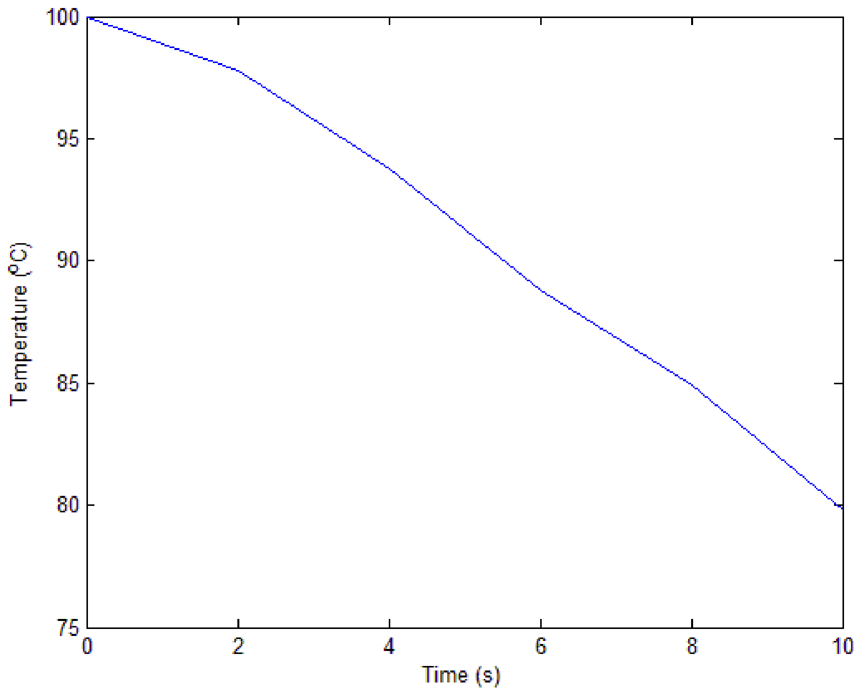


Figure 4-4 Temperature versus Time for Regeneration Phase

From Figure 4-4, the temperature will drop from 100^{o}C to 80^{o}C for regeneration process. This is because of the regeneration temperature is reduced as the desiccant material will absorb the temperature to achieve equilibrium. It also can be explained that the regenerative heat is been transfer from air to desiccant material to heat it up and thus will lead to removal of moisture and it is suitable to absorb back the moisture from air.

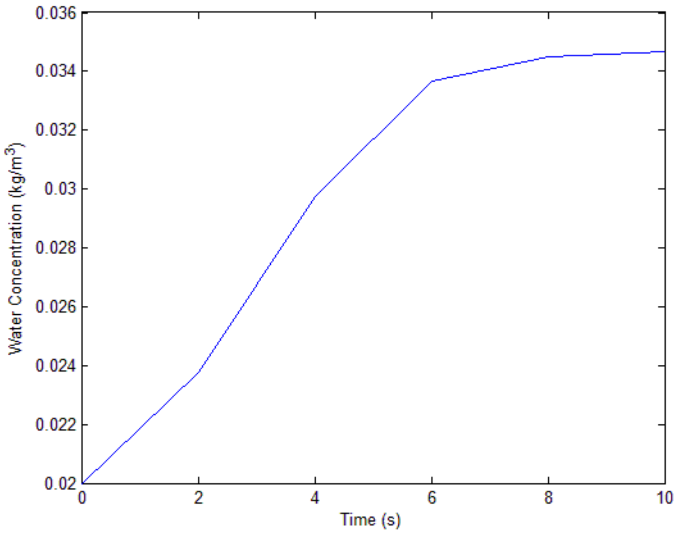


Figure 4-5 Water Concentration versus Time for Regeneration Phase

From Figure 4-5 it showed an increasing line approximately from 0.02 kg/m^3 to 0.0345 kg/m^3. For the reason that the condition of desiccant materials that allows it to absorb back because of increasing of temperature of desiccant material by regenerative air.

The result that obtained will be compared with the previous study performed by Ursula Eicker et al [14].

The only important desiccant material that needs to be compared in this study is silica gel. In this study, parameter for wheel depth is same while for rotational speed in this study is 0.42 rpm which is equivalent with 25.5 RPH which is approximately same with the work done by Ursula Eicker et al [14].

Table 4-3 explains the performance indicator for designated parameter which is stated in Table 4-1 that is compared between present study and work done by Ursula Eicker et al [14].

Table 4-3 Performance Indicator from Present Study and Previous Work

Performance Indicator	Present Study	Previous Work [14]
Regeneration Specific Heat Input, *RSHI* [kJ/g]	2.522	3.800
Dehumidification efficiency, η_{dehum}	0.38	0.49

The comparison between these two data in above table, Table 4-3 it clearly can see that present study shows a less value for *RSHI* and dehumidification efficiency compares to previous work [14]. The difference in both results may cause from the slightly different in rotation speed. The speed in present study is 25.5 RPH while for previous work [14] is 24 RPH. From the extrapolation graph that been made by Ursula Eicker et al [14] the result that been obtained in present study is reasonable with the experimental result [14]. Thus this result is valid and able to be continuing discuss.

The plotted graph is produced using simulation of MATLAB and formulas discussed in Section 2.5. Figure 4-3 through Figure 4-6 plot the profiles of temperature of the air and the water vapor concentration in the air and at the air desiccant lines which is in equilibrium with the desiccant, at x=0 and x=L (initial and last condition).

Overall, the cooler process air enters the wheel from x=0, and then the hotter regenerative air enter it from x=L. This is why the region at x=L is higher in temperature compared to x=0. While for other parameter which is water vapor concentration in the air is in equilibrium with the desiccant at x=0 is higher than those at x=L during all time of the rotating wheel. This is because the moisture that contains in the process air is adsorbed by desiccant wheel as it flows in the channel and the moisture in the wheel is transferred back to the regeneration air in the same time.

While for desorption section which is removing moisture, there is a moment where the desiccant temperature, water vapor concentration and moisture loading at x=L remain constant. This is conditions happens because of the desiccant material which is silica gel and the regenerative air at this location reach state of steadiness and nothing will affects this thing. Due to that, the other sectors of the wheel (x<L) have not reached adsorption equilibrium with the incoming regenerative air, there is still removing moisture going on and the vapor concentration of the regenerative air outlet is still higher than that of the regeneration air inlet.

The comparison between the conventional air conditioning and desiccant dehumidification air conditioning can be seen in Figure 4-9 and Figure 4-10. From that two figures, it can be clearly see that the conventional air conditioning consume a much higher energy compare to the desiccant dehumidification air conditioning.

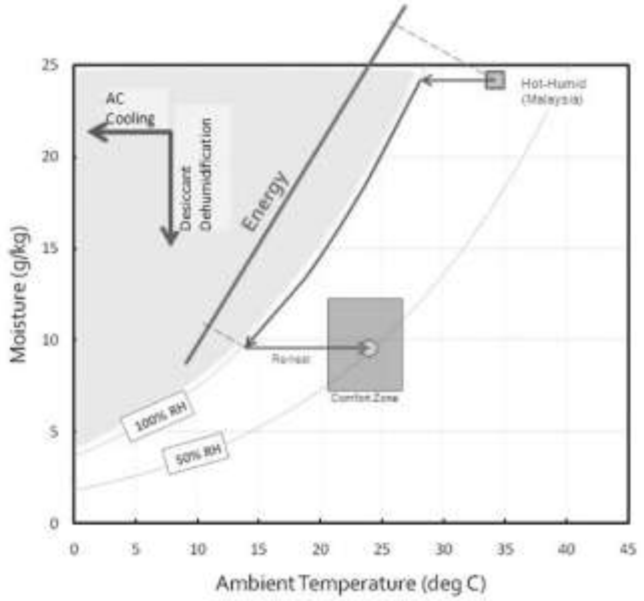


Figure 4-6 Psychometric charts for Conventional Air Conditioning

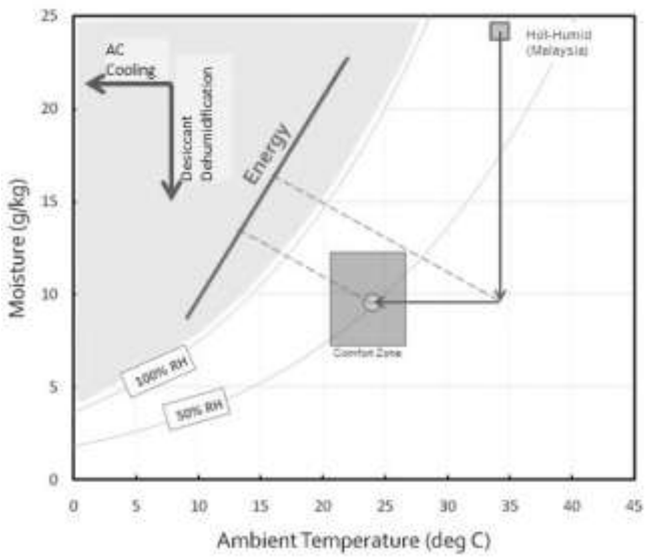


Figure 4-7 Psychometric charts for Desiccant Dehumidification Air Conditioning

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 CONCLUSION

The application of desiccant wheel is seems to be a promising approach to improve the indoor environment. By conducting researches and simulation, the result shows the energy efficiency of this system when it is applies to the real building. From the result, the desiccant wheel of thermally driven of dehumidification system can be applied to a lot more commercial building that required a specific ventilation system. It shows that the energy used to operate this system is far less than conventional air conditioning. Thus desiccant dehumidification system is more suitable to be used to control the indoor air conditioning based on energy efficient. This system also has a desirable efficiency that makes it suitable to be installing in Malaysia climate conditions.

5.2 FUTURE WORK

This project is only focusing for desiccant wheel for dehumidification system but it need others mechanical equipment such as heat exchanger, evaporator, solar collector and regenerative heater. To achieve an accurate results all these equipment need to be included in calculation and simulation.

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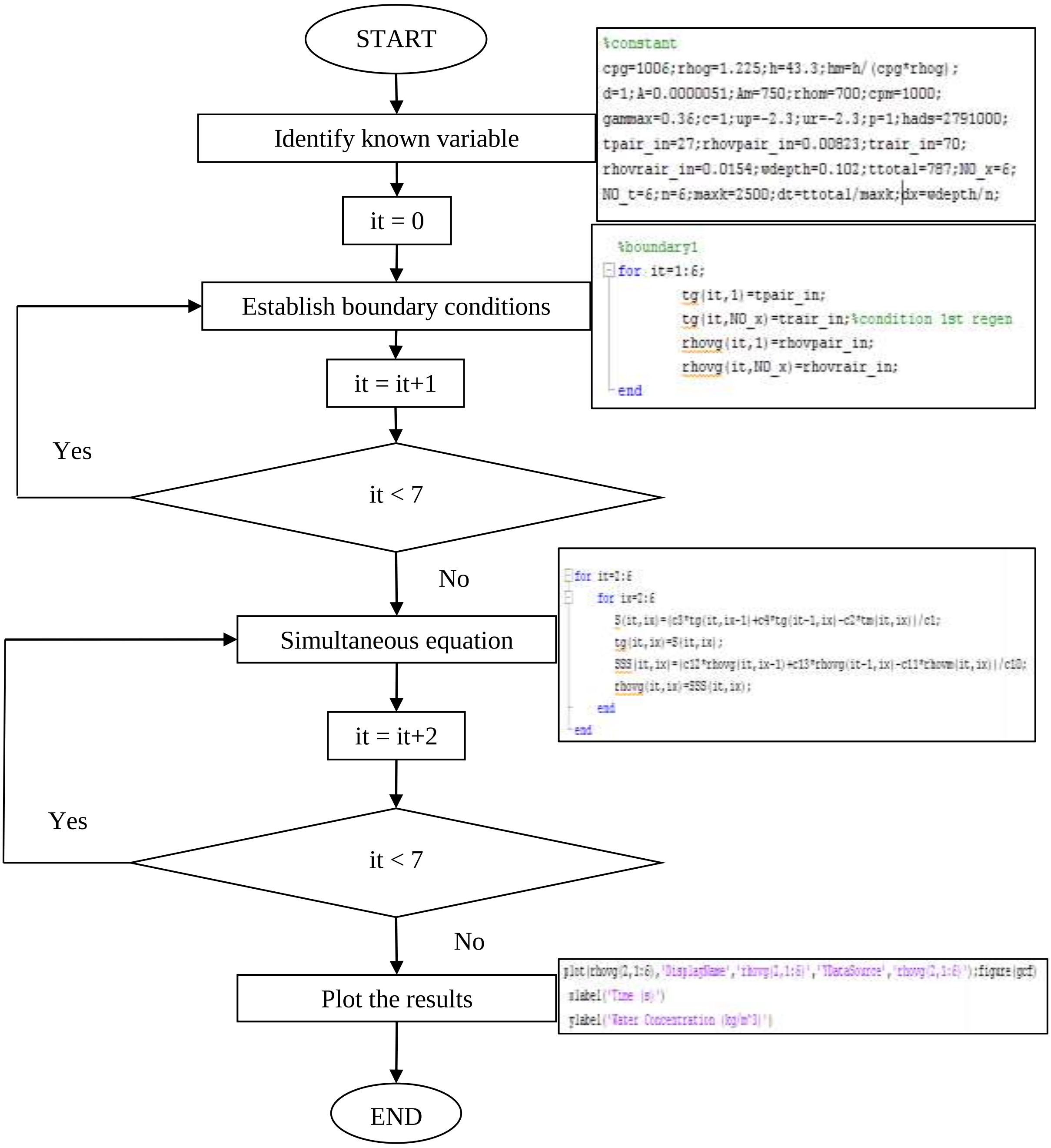
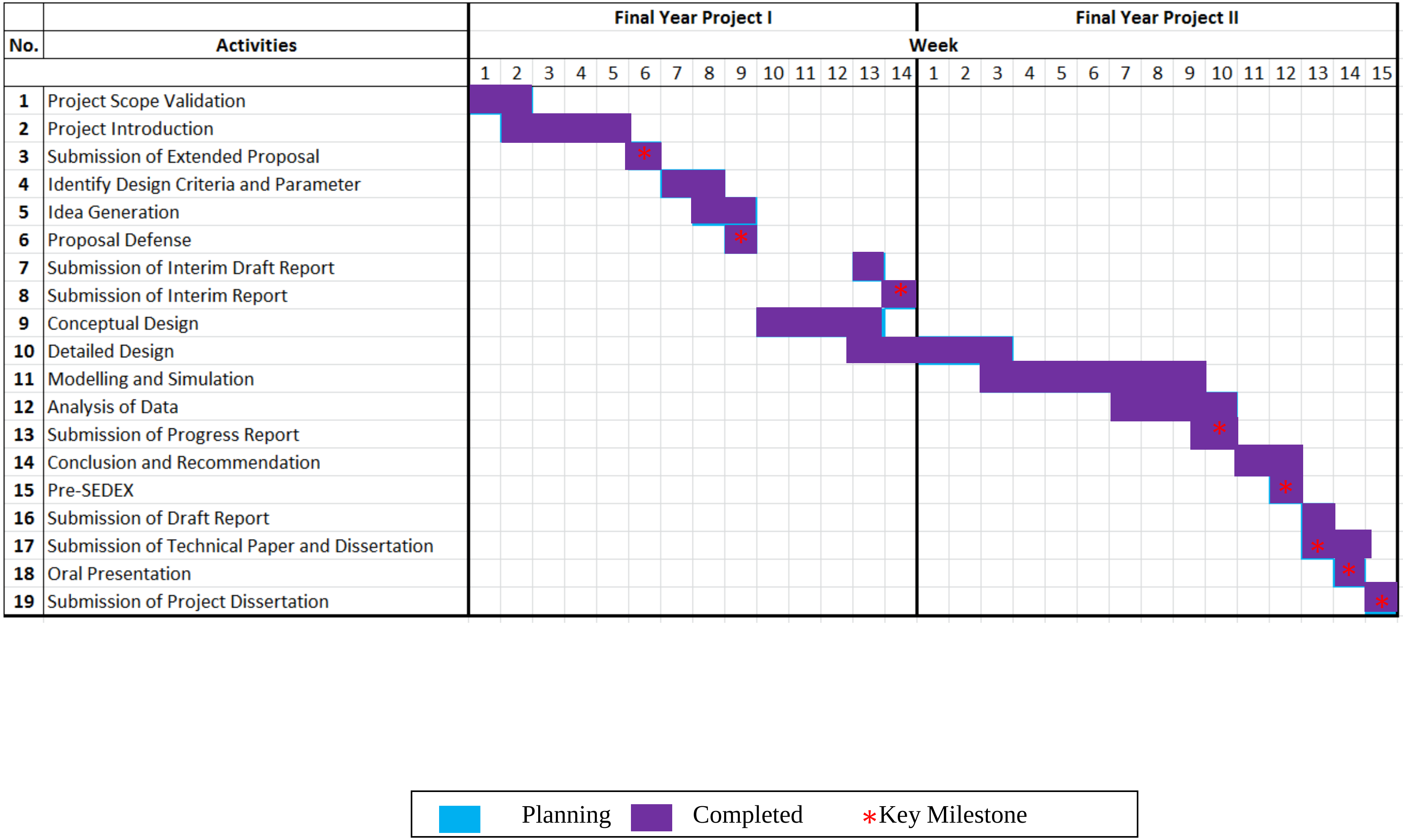
APPENDIX

Appendix 1



Appendix 2


Final Year Project I
Final Year Project II
No.
Activities
Week
1 2 3 4 5 6 7 8 9 10 11 12 13 14
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
1 Project Scope Validation
2 Project Introduction
3 Submission of Extended Proposal
4 Identify Design Criteria and Parameter
5 Idea Generation
6 Proposal Defense
7 Submission of Interim Draft Report
8 Submission of Interim Report
9 Conceptual Design
10 Detailed Design
11 Modelling and Simulation
12 Analysis of Data
13 Submission of Progress Report
14 Conclusion and Recommendation
15 Pre-SEDEX
16 Submission of Draft Report
17 Submission of Technical Paper and Dissertation
18 Oral Presentation
19 Submission of Project Dissertation
Planning
Completed
*Key Milestone