AN INVESTIGATION OF A NEW REFRIGERATION CYCLE BASED ON MEMBRANE ENABLED DEHUMIDIFICATION AND COOLING

A Thesis

by

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ABSTRACT

This work is an investigation of a novel refrigeration method called the Claridge-Culp-Pate process / cycle (referred to as CCP) that has been developed based on membrane-enabled dehumidification and cooling. Water is considered to be the primary working fluid, considering that water vapor is removed from flowing air, thus drying it. The water is then added back in as a liquid in an evaporative cooler, thus cooling the same air previously dried. One of the unique features of the CCP is the technology involved with transferring a sub-atmospheric water vapor to liquid water at atmospheric pressure in a manner that minimizes energy consumption.

The primary focus of this work is to investigate the theoretical performance of this novel refrigeration cycle/ process for various configurations of dehumidifiers and evaporative coolers and then to compare these results to those of the conventional refrigeration method, namely the theoretical vapor compression refrigeration cycle. Theoretical models of both the novel and conventional refrigeration systems were developed to determine thermodynamic variables and performance parameters while subjecting these systems to realistic operational moist air conditions, such as outdoor and indoor air temperatures and relative humidity.

The coefficient of performance (COP) as the main performance parameter of interest was calculated by using the theoretical models developed herein. In addition to determining the COP for different configurations of the Claridge-Culp-Pate (CCP) refrigeration system, the COP of the conventional vapor compression refrigeration cycle was determined for two refrigerants, namely water and R-410A, when operating between the same temperature conditions as those of the CCP system so that comparisons could be made. Using the calculated COPs as the measure of performance, the different configurations of the CCP system were compared with each other to determine the optimum arrangement of dehumidifiers and evaporative coolers for a range of outdoor temperatures and relative humidity. Comparing the above configurations of COPs to the calculated COPs for the conventional refrigeration system shows that significant energy savings are possible for air conditioning with the CCP system for all climate zones and regions.

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CHAPTER I

INTRODUCTION AND PROBLEM STATEMENT

Background

The cooling of indoor air spaces to maintain a comfortable environment for humans is an essential need for any building in modern society. Typically, the cooling loads of any building are met by air conditioners that operate on a conventional vapor compression refrigeration cycle by using electricity to run compressors and fans. Presently, the most widely used refrigerant for cooling applications in conventional air conditioning systems are R-22 and R-410A, with the usage of the latter expanding.

The most important parameter associated with running an air conditioner is the cooling capacity relative to the cost of operation, mostly associated with operating the compressor. The average cooling load during summer, for a 2000 square foot residential unit, in a place like Texas is about 3 Tons. This requires an air conditioner capable of cooling at the rate of 36,000 BTU/ hour with an average temperature difference between outdoor and indoor air being about 20^0F during the day. The cost of operation of such an air conditioning system can be more than \$5 per day when used for 12 hours a day, which can add up to more than \$1,000 per year. Such high operational costs and widespread usage of air conditioning, ranging from residential units to commercial buildings and industrial facilities, has created the need for developing more economically feasible air conditioners.

Dehumidification and Cooling Concept

A novel refrigeration system called the Claridge-Culp-Pate refrigeration process/cycle, based on membrane-enabled dehumidification and cooling, shows promise as a method to replace conventional vapor refrigeration systems for dehumidifying and cooling air. This new system integrates a membrane dehumidification unit and evaporative cooler that essentially uses water as the working fluid or refrigerant. Specially, the membrane dehumidification unit dries flowing air (i.e. removes water vapor from moist air) and then after condensing the removed water vapor, liquid water is put back into the flowing air in an evaporative cooler, where the temperature of moist air drops, creating the ability to perform cooling. The concept seems simple and appears straightforward; however, the technology to transform this concept to an energy efficient working system is complicated. As a starter, the membrane dehumidification unit has the daunting task of selectively removing water vapor from a flowing air stream, which obviously requires a system that creates a water vapor driving pressure difference across a membrane. Furthermore, the water vapor that has been removed from the air through the membrane has to be condensed to liquid water for injection into the evaporative cooler. Achieving this condensation requires heat removal, a driving temperature difference, a heat sink and a pressure change by use of a water vapor compressor to obtain an appropriate saturation pressure and temperature.

From a technical standpoint, the dehumidification unit is designed with a membrane that has selective permeability so as to allow for the transfer of water vapor from a high-pressure region (flowing air) to a low-pressure region (compressor inlet) while air is blocked from passing through the membrane. The specific mechanism used by the membrane for separating water vapor and gases is beyond the scope of this study, and it is sufficient to state that this membrane promotes dehumidification of a flowing air stream, meaning the membrane creates an effective way to separate water vapor from air. It should be noted that flowing moist air on the upstream side of the membrane system is subjected to near-atmospheric pressure conditions, with the partial pressure of water vapor in the moist air being significantly less, while the water vapor downstream (across the membrane) of this system is subjected to a vacuum pressure between 0.5 - 1.6 kPa. A difference across the membrane of water vapor partial pressure drives the dehumidification process.

The water vapor extracted by this membrane system is at a vacuum pressure, namely 0.5-1.6 kPa, and must be pressurized to an outlet pressure of about 4-10 kPa for it to be condensed by a conventional condenser. The heat sink temperature sets this compressor outlet pressure based on the condenser temperature available for condensation, which is usually close to the wet bulb temperature of outdoor air, assuming a cooling tower is used. The existence of this high-pressure ratio across the compressor and large water vapor specific volume at the inlet caused by low pressure necessitates the requirement for a compressor having a high power rating and large sizing, which shows the importance of investigating in detail the system performance of the CCP process and cycle for a range of outdoor conditions. After extracting water vapor and condensing it to a liquid, the liquid water is sent to an evaporative cooler where the air is cooled to a wet bulb temperature as the liquid water evaporates back to a vapor causing humidity of air to increase.

If this combination setup of membrane dehumidifiers and evaporative coolers is arranged in a closed system then it forms the Claridge-Culp–Pate cycle while, if arranged in-line with each other in a open system with a well defined inlet and exit then it forms a Claridge-Culp-Pate refrigeration process. The technology that is being investigated in the study reported herein is described in more detail in any of the several PhD and MS thesis [1,2,3] and patents [4,5,6,7,8,9]

Problem Statement

The two main parameters that influence the performance of the Claridge-Culp-Pate cycle/ process are the water vapor partial pressure conditions on each side of the membrane and the condensation of water vapor by the condenser. Of special importance is the effect that these parameters have on the compression energy required to pressurize the water vapor from the low-pressure membrane conditions to the high pressure condenser conditions or low pressure to thigh pressure. In order to extract enough moisture from air, so as to take the air to a comfortable indoor condition of about 25^0C and 50% relative humidity, the water vapor partial pressure on the membrane side should be at sub-atmospheric conditions of about 0.5 – 1.6 kPa and to effectively condense all of the extracted vapor, the condenser pressure or the compressor outlet pressure on the vapor side should be between 4-10 kPa. These conditions can require a compressor with a large power rating, making compressor the most power intensive component.

The main parameter that reflects the performance of any cooling and/or dehumidification process or cycle is the coefficient of performance (COP). It is defined as the ratio of cooling capacity or cooling effect to the energy, which is usually input to a compressor to achieve this cooling/dehumidification. If we assume that multiple CCP configurations or technologies have similar cooling capacities, meaning they operate between the same inlet and exit airside moist air conditions, then the COP is inversely proportional to the energy consumed, which in the case of the investigation reported herein is the compressor energy or power. One can see that the best performance (i.e. largest COP) is achieved by the approach that minimizes the compressor work.

Hence, this work is directed towards a theoretical performance study, based on compressor energy of the CCP cycle and process while operating with different configurations of dehumidifiers and evaporative coolers for different compressors based on isothermal and one/two-stage isentropic assumptions. It is also essential to compare the performances of the CCP systems to conventional system with R-410A in order to quantify possible performance advantages of this new technology.

CHAPTER II

DEHUMIDIFICATION AND PSYCHROMETRICS

Introduction to Membrane Enabled Dehumidification System

A membrane enabled dehumidification system consists of two main components, which are a membrane-enabled dehumidifier and an evaporative cooler. The performance of the membrane dehumidification system can be altered by arranging these two components in different configurations. The simplest configuration of a membrane dehumidification system is illustrated in Figure 1 below.

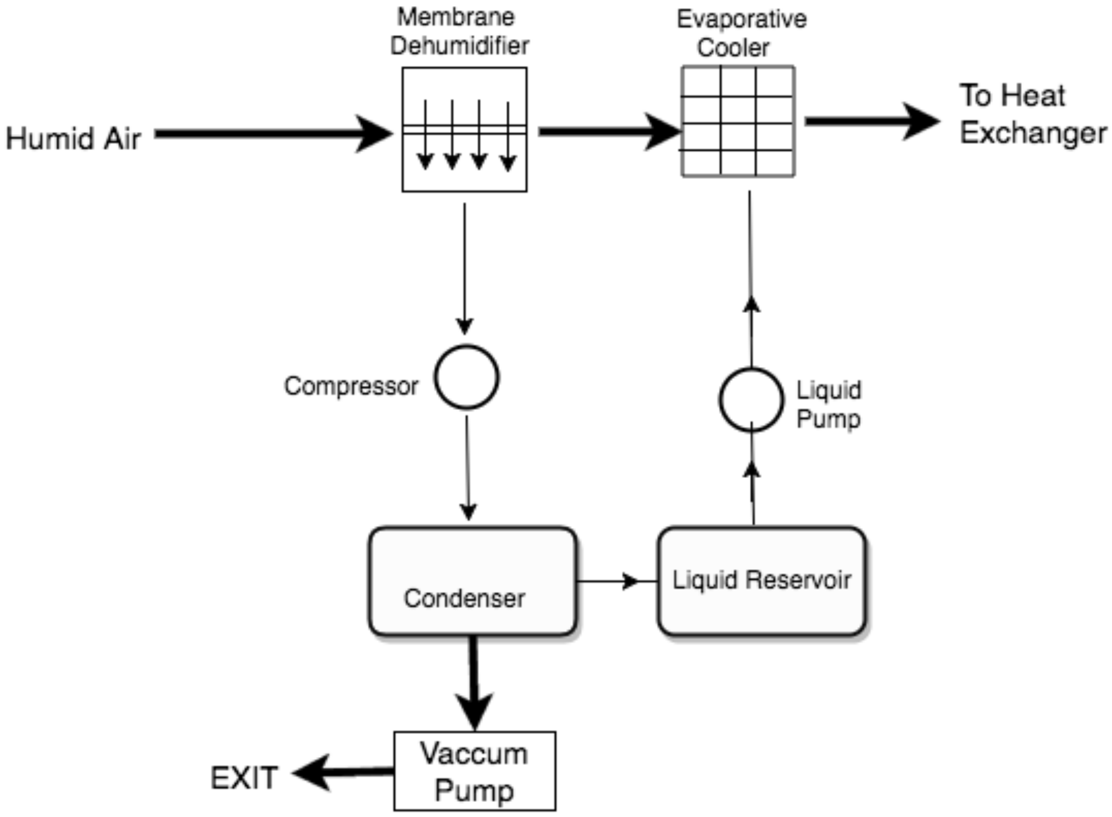

Figure 1:Dehumidification system setup

The dehumidification system consists of a membrane dehumidifier placed in series with an evaporative cooler. Humid air entering the dehumidifier is dried by selective absorption of water vapor by the membrane and is then cooled by in an evaporative cooler. This water vapor extracted from the humid air in the membrane dehumidifier is then compressed before being sent to the condenser where it is liquefied. This water is then stored in a reservoir before being re-circulated to the evaporative cooler, where it is vaporized to cool the hot, dehumidified air exiting the membrane dehumidifier.

The incondensable gases that pass through the membrane are flushed out of the system by a vacuum pump located downstream of the condenser.

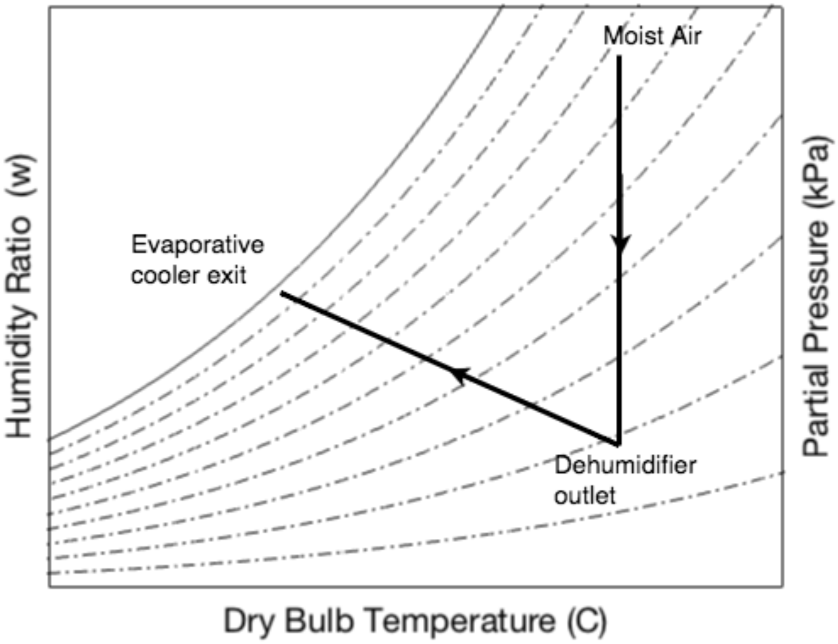

Figure 2: Representation of dehumidification processes on psychrometric chart

The process of a membrane dehumidification system can be represented on a psychrometric chart (in Figure 2) for better understanding of the thermodynamic state of the moist air in the system. Membrane dehumidification process is represented as a constant temperature process, which is a vertical line on the psychrometric chart (constant dry bulb temperature) and a constant enthalpy line represents evaporative cooling of air until the air reaches its wet bulb temperature.

Basics of Psychrometrics

A psychrometric chart is a graphical representation of thermodynamic state of moist air at a constant pressure, and this chart can be used to illustrate the processes of a CCP cycle/process. A typical psychrometric chart is a plot of dry bulb temperature versus specific humidity ratio with constant relative humidity, enthalpy and specific volume lines shown. Any two properties of most air allow one to determine all of the other state points.

A standard psychrometric chart is shown in Figure 3 and the properties of moist air that define a particular state point, which are indicated on a psychrometric chart are described herein.

Dry bulb temperature forms the X-axis of the psychrometric chart, and it is defined as the temperature reading obtained by exposing the thermometer to dry air that is protected from direct thermal radiation. [10]

Humidity ratio is the ratio of the mass of water vapor to a unit mass of dry air in the moist air mixture. This parameter forms the Y-axis of the psychrometric chart and is given by the following relation.

$$\omega = \frac{m_v}{m_a}$$

A mixture of two or more gases mutually exerts pressure on each other. The fraction of pressure exerted by one substance on another is the partial pressure of that substance. Moist air mixture contains air and water vapor and the pressure exerted by water vapor on dry air is its partial pressure. This is represented on the Y-axis of the psychrometric chart and the following relationships apply.

$$P = P_v + P_a$$

$$P_a = P - P_v$$

$$P_v = P - P_a$$

Dew point temperature is defined as the temperature at which the moisture in the air starts condensing. One can find the dew point temperature of moist air by reaching the saturation line from the point of interest by following a constant humidity ratio line (parallel to x axis) on a psychrometric chart. The dew point temperature remains constant for a given humidity ratio.

$$T_{dew} = T_{sat}(P_v)$$

Wet bulb temperature is defined as the temperature that the air would reach if the mixture is cooled until saturation by the evaporation of water [11]. Another view is that the wet bulb temperature is reached as moist air is cooled in a constant enthalpy process.

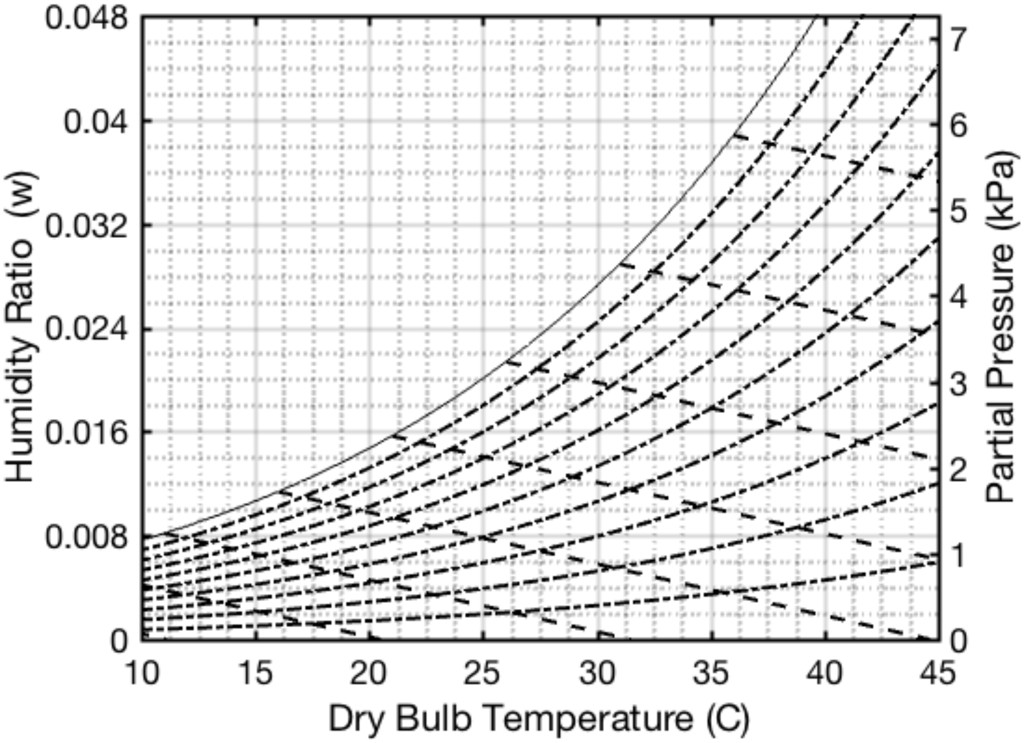

Figure 3:Psychrometric chart

CHAPTER III

CONSTUCTION AND MODELLING A PSYCHROMETRIC CHART

Construction and Modeling

Psychrometric representation helps in better understanding of thermodynamic processes that involve moist air. Since this study primarily focuses on dehumidification and evaporative cooling, representing them on a psychrometric chart is key in graphical communications of important processes. Therefore a model to represent the processes of the membrane dehumidification process/ cycle on a psychrometric chart has been developed using matlab.

A convenient temperature scale between 10^0C and 45^0C has been chosen to represent the psychrometric processes of the membrane dehumidification system. The steps in constructing the psychrometric chart are shown below.

a) Humidity ratio (kgv/kga) was determined for the above temperature range using the relationship between saturation pressure and relative humidity. The derivation is shown below:

$$\omega = \frac{m_v}{m_a}$$

Using ideal gas equation for air and vapor:

$$\frac{P_a V}{m_a} = R_a T$$

$$\frac{P_v V}{m_v} = R_v T$$

$$\frac{m_v}{m_a} = \frac{R_a P_v}{R_v P_a}$$

$$\frac{m_v}{m_a} = \frac{18}{28.393} \frac{P_v}{(P - P_v)}$$

$$\frac{m_v}{m_a} = \omega = \ 0.622 \frac{P_v}{(P - P_v)}$$

b) The humidity ratios were plotted against dry bulb temperature for every 10% increase in relative humidity until the saturation line (RH=100%).

c) The vapor pressure (kPa) was determined using the following equation:

$$\omega = \ 0.622 \frac{P_v}{(P - P_v)}$$

$$\omega \ (P - P_v) = \ 0.622 P_v$$

$$P_V = \frac{101.325\omega}{\omega + 0.622}$$

These vapor pressures were set to scale on the second Y-axis to the right hand side of the psychrometric chart.

d) Constant enthalpy lines were plotted by connecting the enthalpies at 100% relative humidity to the enthalpies a 0% relative humidity over the selected temperature range [12]. Steps in determining the enthalpy are shown below:

$$h = m_a C_p T_a + m_v h_v$$

Considering specific enthalpy (per kg of air)

$$\frac{h}{m_a} = H = C_{pa}T_a + \frac{m_v}{m_a}h_{gv}$$

$$H = h_a + \omega h_{gv}$$

$$H = (1.007T - 0.026) + \omega\,(2501 + 1.84T)\,\frac{kJ}{kga}$$

These aforementioned variables form a background plot, which is used as the reference on which the actual processes of the membrane dehumidification cycle are plotted. The thermodynamic relationships for some of the common processes in a CCP process/ cycle are shown in the next section.

General Energy Equation

All the equations relating to the psychrometric processes are derived from the general energy equation as applied to the control volume shown below.

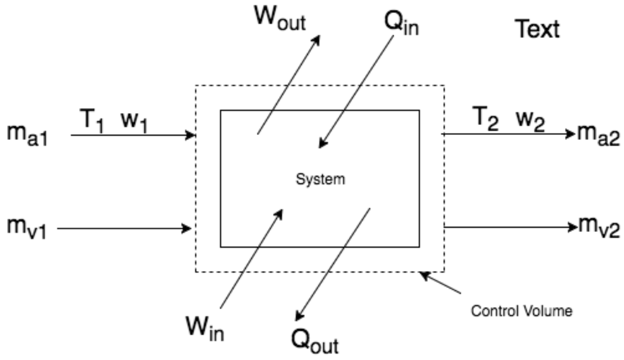

Figure 4: Control volume as applied to general energy equation

$$\frac{\partial E}{\partial t} = Q - W + \Sigma m_{in}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \Sigma m_{out}(h_2 + \frac{V_2^2}{2} + gz_2)$$

Psychrometric Chart Processes

1. Sensible heating and cooling (A – B):

Sensible heat addition process in shown by the line A1 – B1 on the psychrometric chart and sensible cooling of moist air mixture is shown by the line A2 – B2. The sensible heating/ cooling take place at a constant humidity ratio. Meaning, no addition or removal of vapor takes place in the system during this process.($\Delta\omega$=0). The heat change in this process is represented by the following equation:

$$Q_{in} = C_{pa}(T_{B1} - T\_A_1)$$

$$Q_{out} = C_{pa}(T_{A2} - T\_A_{B2})$$

2. Dehumidification process (C- D)

Membrane in the novel dehumidification system separates water vapor from moist air. This process is shown by line C-D on the psychrometric chart. This process of addition or removal of water vapor is assumed to take place at a constant temperature. The work done in removing moisture through this process as follows:

$$\Delta\omega = \omega_C - \omega_D$$

$$W_{CD} = m_a \Delta\omega W_{compressor}$$

3. Constant enthalpy process (E- F)

Constant enthalpy process is shown by line E – F on the psychrometric chart. One of the ways of achieving a constant enthalpy process is by evaporative cooling, where water that is at a lower temperature is vaporized into a flowing air stream at a higher temperature. This results in reduction of temperature of the air with the increase in humidity ratio.

4. Condensation

Saturated mixture of air and vapor is condensed along its saturation pressure line, by removing the latent heat of the mixture. The line G – H on the psychrometric chart in Figure 5, shows this process.

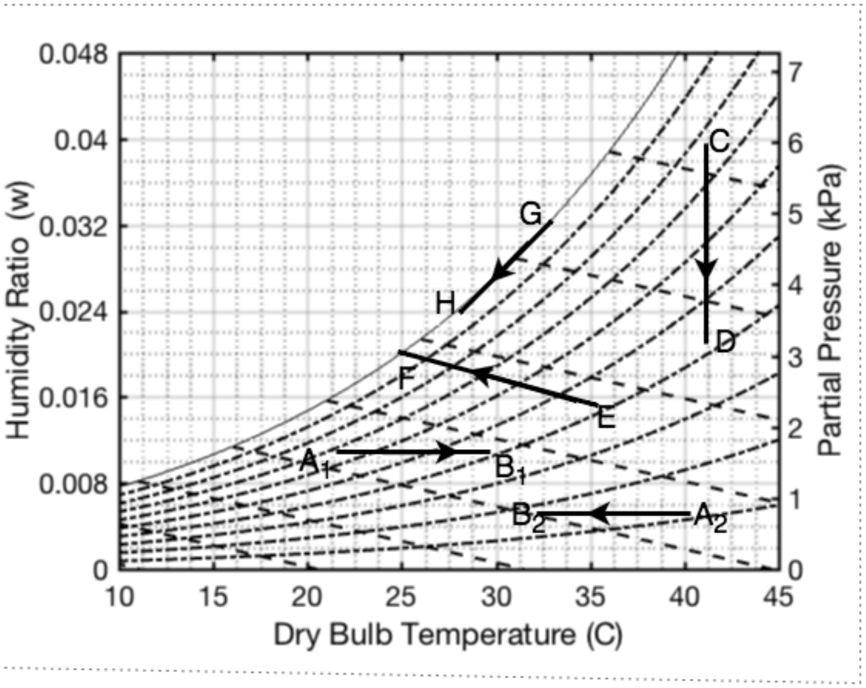

Figure 5: Common CCP cycle processes shown on a psychrometric chart

CHAPTER IV

AIRSIDE COMPONENTS OF DEHUMIDIFICATION UNIT

This chapter describes from a thermodynamic standpoint the major components that are normally found in the membrane-enabled dehumidification and cooling process and/or the equivalent closed cycle (Claridge-Culp-Pate cycle or CCP cycle).

Of special importance is the formulating a CCP cycle thermodynamic model, by applying the conservation laws of energy and/or mass and then in turn use it to solve for design and analysis.

Components

The components derived and modeled from a thermodynamic standpoint are

1. Membrane dehumidification unit
2. Evaporative cooler
3. Condenser (chapter 4)
4. Fan and Pump
5. Compressor (Chapter 4)

The functions and working of these main components of a dehumidification system is described below:

1. Membrane Dehumidifier: A membrane dehumidification unit separates water vapor from a stream of flowing moist air through a special selective absorption property of a novel membrane.

2. Evaporative Cooler: An evaporative cooler reduces the temperature of a stream of dry air by vaporizing cool water into the flowing air stream, thereby increasing the humidity content of the air in the process.

3. Inlet Fan: Inlet fan, supplies the system with outdoor air drawn from the atmospheric conditions.

4. Compressor: Water vapor exiting the membrane at sub atmospheric pressure conditions is compressed to a condensable high-pressure vapor in a compressor.

5. Condenser: A condenser liquefies high-pressure water vapor exiting the compressor by extracting heat form it.

6. Water supply pump: A water supply pump receives water from the condenser and supplies it to the evaporative cooler. The pump is also connected to a water reservoir where it either sheds excess water received from the condenser or draws makeup water to meet the water requirements of the evaporative cooler.

The current chapter focuses on the thermodynamics of the airside components that were listed and described above.

The two main airside components that are a part of dehumidification system are the membrane dehumidification unit and the evaporative cooler. The governing equations of both these systems have been derived from the general energy equation and their working is described form a mathematical standpoint herein.

Membrane Dehumidification Unit

As mentioned in the previous chapter, a membrane dehumidification unit separates water from moist air with the help of a novel zeolite membrane.

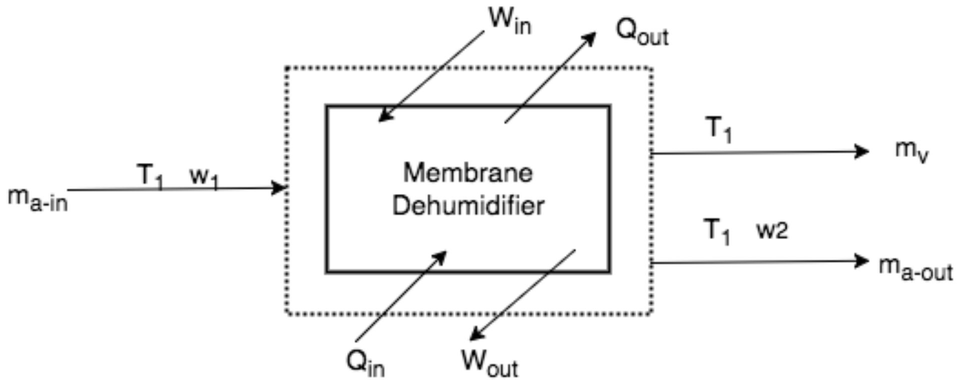

Figure 6: Control volume applied to a membrane dehumidifier

Figure 6 shows a block diagram with the energy and mass transfers across the control volume boundary of a membrane dehumidification unit. General energy equation can be applied to this control volume as follows:

$$\frac{\partial E}{\partial t} = Q - W + \Sigma m_{in}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \Sigma m_{out}(h_2 + \frac{V_2^2}{2} + gz_2)$$

Neglecting the kinetic and potential energy change across the system, work done in separating water vapor from humid air in the membrane system can be determined as follows

$$W_{out} = 0$$

$$m_{in} = m_{a-in}$$

$$m_{out} = m_{a-out} + m_v$$

Applying these conditions to the general energy equation above,

$$W_{in} + m_{a-in}h_1 = m_{a-out}h_2 + m_v h_v$$

$$W_{in} = m_{a-out}h_2 + m_v h_v - \ m_{a-in}h_1$$

$$W_{in} = m_{a-out}(C_{pT_1} + \omega_2 h_v) + m_v h_v - \ m_{a-in}(C_p T_1 + \ \omega_1 h_v)$$

$$W_{in} = C_p T_1 \Delta m_a + h_v(\ m_{a-out}\Delta\omega(1-\omega_1))$$

The isothermal dehumidification process of a membrane dehumidification unit is represented on a psychrometric chart in the figure below.

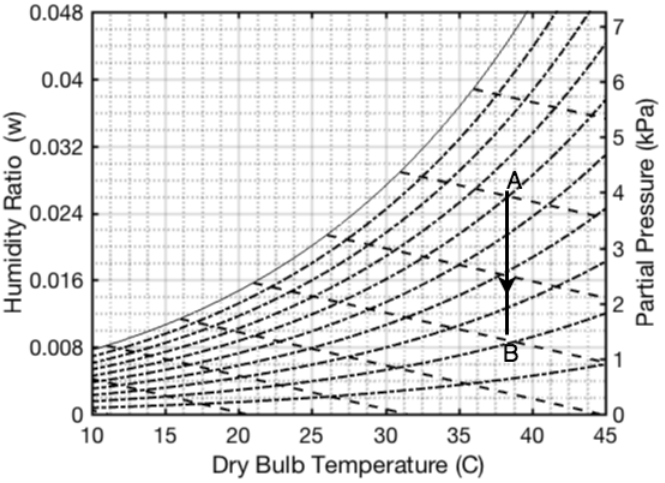

Figure 7: Representation of membrane dehumidification on a psychrometric chart

Evaporative Cooler

A block diagram with all the major energy and mass flows into and out of the evaporative cooling system is shown below. The general energy equation can be applied to the evaporative cooler system as follows:

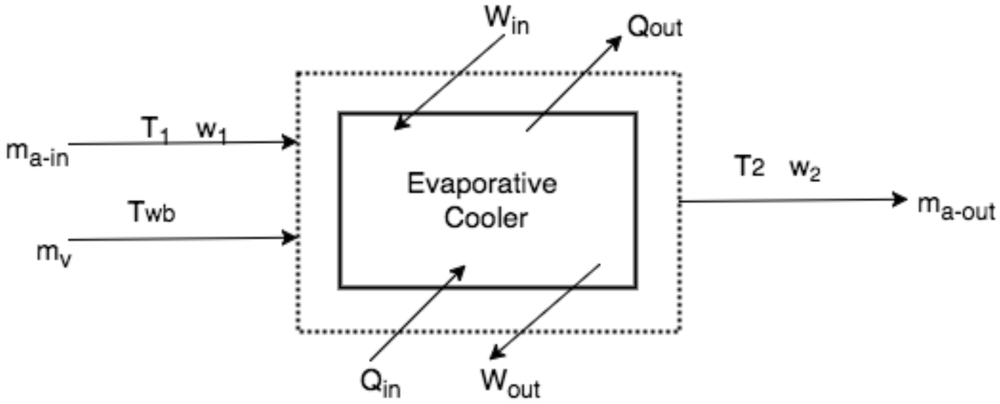

Figure 8: Control volume applied to an evaporative cooler

$$\frac{\partial E}{\partial t} = Q - W + \Sigma m_{in}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \Sigma m_{out}(h_2 + \frac{V_2^2}{2} + gz_2)$$

Neglecting the kinetic and potential energy change across the system, the mass of vapor added into the evaporative cooler can be determined as follows:

$$m_{a-in}h_1 + m_v h_{v(T_{wb})} = m_{a-out}h_2$$

$$h_2 = h_1$$

$$m_v h_{v(T_{wb})} = \Delta m_a(C_{pa}T_1 + \omega_1 h_{v1})$$

$$m_v = \frac{\Delta m_a}{C_{pa}T_{wb}}(\,C_{pa}T_1 + \omega_1 h_{v1})$$

An evaporative cooling process from state A to state B is shown on a psychrometric chart below.

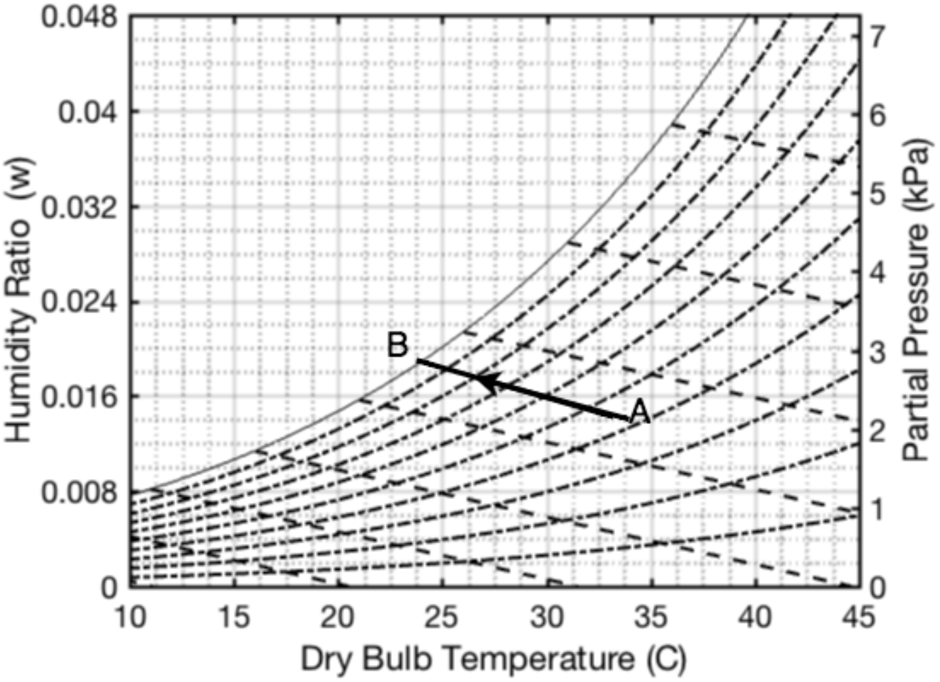

Figure 9: Representation of evaporative cooling on a psychrometric chart

CHAPTER V

COMPRESSOR

Background

The water-vapor compressor, which operates at sub-atmospheric pressures, is an important component of the Claridge-Culp-Pate process/ cycle. This compressor takes water vapor extracted from the membrane at low pressure (0.5-1.7kPa) and increases it to a higher pressure (6-10kPa) that is suitable for the water vapor to be condensed in a standard condensation process. This sub-atmospheric inlet pressure to the compressor and high-pressure ratio may require a large size compressor with a relatively high power consumption, which makes an analysis of water-vapor compression even more important.

The schematic below shows the placement of the compressor with respect to the other two important CCP cycle/process components, namely a dehumidifier unit and an evaporative cooler. It should be noted that the CCP refrigeration system allows for multiple arrangements of dehumidification units and evaporative coolers, and the configuration shown in the schematic is a simple one to illustrate the placement of major components.

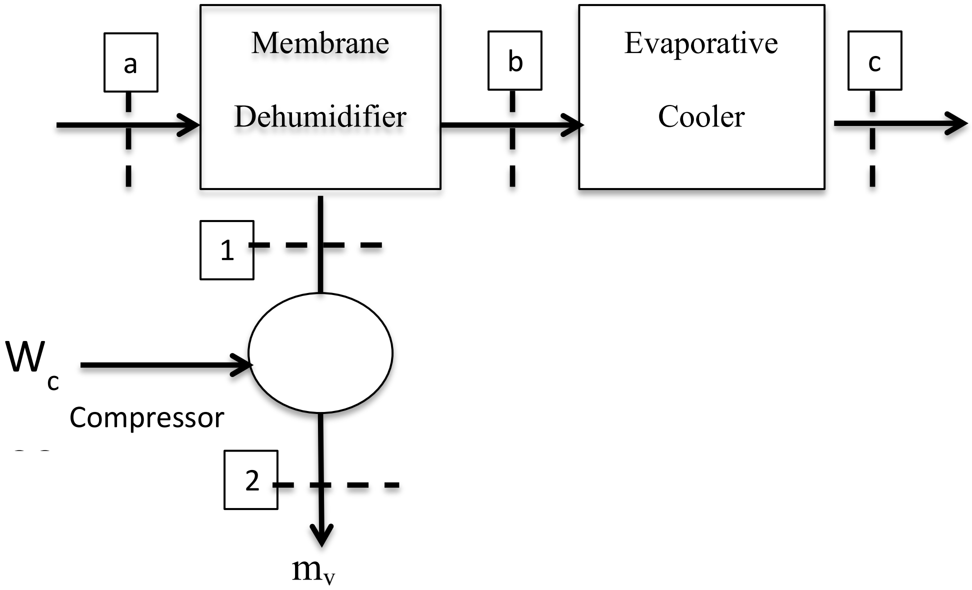

Figure 10: CCP process schematic

The different state points and properties shown in Figure 10 will be used to derive the governing design and analysis equations are presented below:

State – a: Moist air at the membrane dehumidification unit inlet

- T_a = Dry bulb dehumidifier unit inlet temperature.
- h_a = Dry air specific enthalpy.
- ω_a = specific humidity ratio.
- $\emptyset_a$ = Relative humidity.

State – b: Moist air at dehumidifier exit

- T_b= Dry bulb temperature = T_a

- h_b= Dry air specific enthalpy
- ω_b= Humidity ratio.
- $\emptyset_b$ = Relative humidity.

State – c: Moist air at evaporative cooler exit

- T_c = Saturated cool air at evaporative cooler exit.
- h_c = Specific enthalpy of dry air at cooler exit = $h_{b.}$
- ω_c = Humidity ratio at evaporative cooler exit.
- $\emptyset_c$ = Relative humidity at cooler exit = 100%

States 1 & 2: Water vapor entering and exiting the compressor

- T_1 , P_1= Water vapor temperature and pressure at compressor inlet = T_a
- T_2 ,P_2= Water vapor temperature and pressure at compressor exit.
- PR = Pressure ratio of compressor = $\frac{P_2}{P_1}$
- m_V = Mass flow rate of water vapor in the compressor = $m_a(\omega_1-\omega)$

To investigate the effects of water-vapor compression on the Claridge-Culp-Pate process/cycle, three different types of compressors are theoretically modeled. They are:

1) Isothermal compression	($\Delta T = 0$)
2) Single-stage adiabatic compression	($\Delta S_1 = 0$)
3) Two-stage adiabatic compression	($\Delta S_2 = 0$)

The working principles and thermodynamic relations used in determining the work for each of the above mentioned compression processes are discussed, described and presented in this section.

General Energy Equation Applied to Compressor

Starting from the general energy equation, the specific work input for the above mentioned compressor types are obtained by applying certain generalizations and assumptions. The general energy equation, as applied to a compressor operating between states 1 and 2, is shown in Figure 11 below.

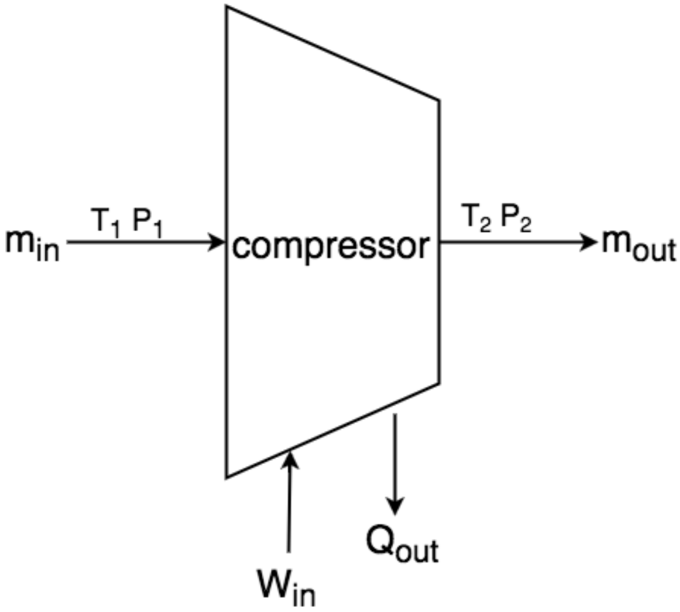

Figure 11: Control volume applied to a compressor

$$\frac{\partial E}{\partial t} = Q - W + \Sigma m_{in}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) - \Sigma m_{out}(h_2 + \frac{V_2^2}{2} + gz_2)$$

The applicable assumptions are:

- Compression is a steady state process ($\frac{\partial E}{\partial t}$=0)
- No work is output from the system ($W_{out} = 0$).
- Mass flow of water vapor into and out of the system is equal. (m_1=m_2)
- The change in kinetic and potential energy are neglected (ΔKE=$\Delta PE = 0$)
- No heat transfer into the system ($Q_{in} = 0$)

Applying the above assumptions, work input to the compressor can be deduced as:

$$W_{in} = m(h_2 - h_1) + Q_{out}$$

If the compression process is assumed to be adiabatic, meaning zero heat transfer to the surroundings, then the result is:

$$W_{in} = m(h_2 - h_1)$$

Furthermore if an ideal gas assumption is applied, then the change in specific enthalpy between exit and inlet of the compressor can be derived expressed as:

$$h_2\text{-}h_1 = C_P\,(T_2\text{-}T_1)$$

Ideal Compressor Work

The well-known equation for specific work during compression, based on combining the first and second law of thermodynamics is

$$\mathrm{w} = -\int_1^2 v dp + \frac{V_1^2 - V_2^2}{2} + g(z_1 - z_2)$$

If the change in kinetic and potential energy is neglected, then the result is

$$\mathrm{w} = -\int_1^2 v dp$$

Polytropic Process and Specific Work

Any compression process that can be expressed as a product of fluid pressure and its specific volume is called a polytropic process. A polytropic process adheres to the following pressure-volume relationship at any state during the compression.

$$PV^n = \text{Constant}$$

A polytropic process between state 1 and state 2, results in

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

where, n is the polytropic index of a given compression process. It should be noted that up to this point no ideal gas assumption has been made. Ideal fluids have polytropic index (or polytropic exponent) fixed for a specific compression process, while real fluids do not have a fixed polytropic index value. However, it may be possible to find the value of ‘n’ that can approximate real process. If the specific work equation and the polytropic equation are combined, the result for specific work is:

$$\left(\frac{W}{m}\right) = -\int_1^2 vdp = constant^{1/n} \int_1^2 \frac{dp}{p^{1/n}}$$

and after integrating,

$$\left(\frac{W}{m}\right) = \frac{n}{n-1}(P_2 v_2 - P_1 v_1)$$

This equation can be used to find the work for any value of n except when n=1, and for this special case,

$$(\frac{W}{m}) = -\int_1^2 vdp = constant \int_1^2 \frac{dp}{p}$$

$$(\frac{W}{m}) = P_1 v_1 \ln \frac{P_2}{P_1}$$

As emphasized before, using the above polytropic equation for state points and work values does not require an ideal gas. Rather, the above equations apply to any fluid with a polytropic exponent. However, they can be modified for the special case of an indeal gas as follows:

Substituting PV with RT as per ideal gas assumption, results in

$$(\frac{W}{m}) = \frac{nR}{n-1}(T_2 - T_1)$$

The temperature can be found from

$$\frac{T_2}{T_1} = (\frac{p_2}{P_1})^{\frac{n-1}{n}}$$

then the specific work for any ideal gas with any wxponent n, except n=1 is,

$$(\frac{W}{m}) = \frac{nRT_1}{n-1}[(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1]$$

For an ideal gas undergoing undergoing isothermal process (n=1) the result is,

$$(\frac{W}{m}) = RT \ln \frac{P_2}{P_1}$$

It is also possible to use the above work equations and results of the energy equaition found previously to determine the heat transfer from the compressor as follows:

$$Q = W + m(h_2 - h_1)$$

or on a per buit mass basis as

$$q = w + (h_2 - h_1)$$

again where work (w) is found from the above polytropic process equation.

Isothermal Compressor (ΔT = 0)

A PvT chart, which is a plot of pressure versus specific volume with constant temperature curves (isotherms), which is used to represent the three polytropic compressions considered for the CCP compressor model.

The first compression process described is the ideal gas isothermal process with n=1 as noted previously, at least for an ideal gas. As the name suggests, isothermal compression takes place at a constant temperature as shown below on a PvT chart, with a polytropic index of unity. (n=1).

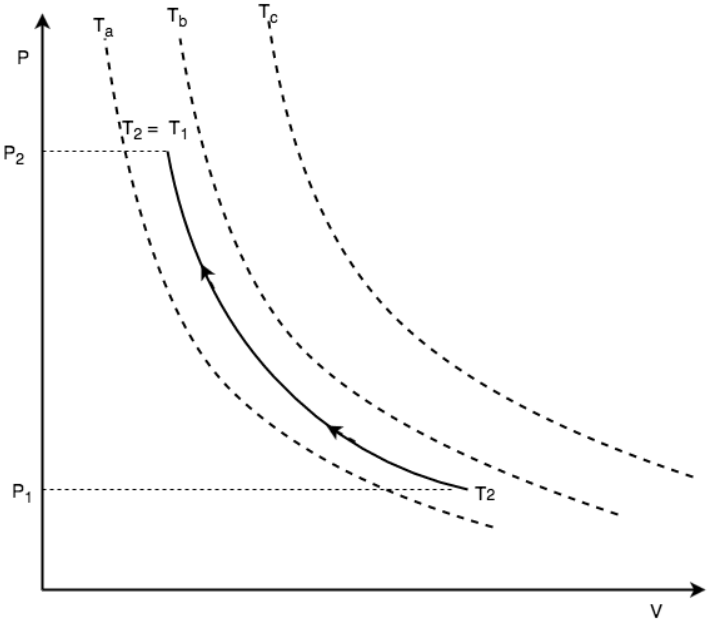

Figure 12**:** PvT chart representing isothermal compression

The specific work input to the compressor is a function of gas constant (R), temperature (T) and the pressure ratio. To achieve an isothermal process, heat transfer from the compressor must exist during the compression process.

The specific work done in an isothermal process is given by the following relationship.

$$w_{T=0} = RT_1 \ln \left(\frac{P_2}{P_1}\right)$$

As noted previously, the area represented by the symbols T_2, T_1, P_2, P_1 in the above PvT plot, which is the area to the left of the isotherm is the specific work.

Single-Stage Isentropic Compressor **($\Delta S_1 = 0$)**

An isentropic process or a variation of it is based on inefficiencies is the most common type of compression assumption used to model real-world applications. The polytropic exponent (n) for an ideal gas is the specific heat ratio with n = k = $\frac{C_p}{C_v}$, and for isentropic compression of air, the value is 1.4 while for water it is 1.34. Unlike an isothermal process, the isentropic process has zero heat transfer inflow or out of the compressor, as a result, the temperature of the fluid being compressed is increased in an isentropic compression process and the outlet temperature of the compressed fluid is determined as per the following relation:

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}$$

Figure 13 shows a PvT chart representing a single-stage isentropic compression process from point 1 to 2

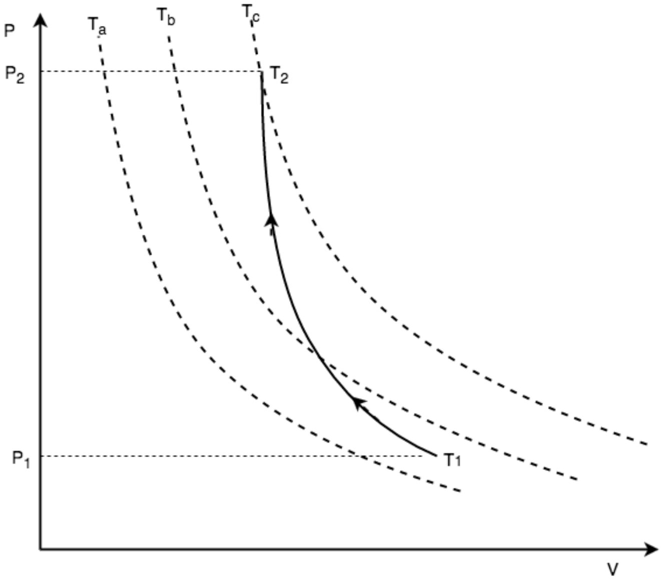

Figure 13: PvT chart representing isentropic compression

The compressor specific work done during an isentropic process, assuming zero heat transfer and an ideal gas, as found in the CCP process/cycle is calculated by using the following relation:

$$w_{\Delta S_1=0} = C_P(T_2 - T_1)$$

As with the isothermal process, the compression work is the PvT chart area to the left of the process curve from 1 to 2 . Comparing the areas under the isothermal process line in this PvT chart to that of the isentropic curve, one can see a larger area for the isentropic case, meaning it requires more specific work to compress isentropically than isothermally.

Two-Stage Isentropic Compressor ($\Delta S_2 = 0$)

The two-stage isentropic process is a variation of the previous single-stage isentropic process, but has the fluid compressed in two-stages instead of one. The advantage of this process is that an intercooler cools the fluid being compressed as it proceeds from one-stage to the second stage resulting in a decrease in overall compression work. Specifically, the intercooler allows for reduction of the temperature of the fluid exiting the first stage of the compressor to its original inlet temperature before it enters the second stage, thereby reducing the overall work input to the system. This lower temperature maybe the original inlet temperature or a lower temperature possibly limited by a saturated condition. The effect of intercooler on the work input can be seen in the PvT chart below where the process from 1 to 2 is compared to the one-stage case presented earlier. One can see that the area to the left of the process line in figure 14, which represents specific work, is less for two-stages compared to one-stage compression.

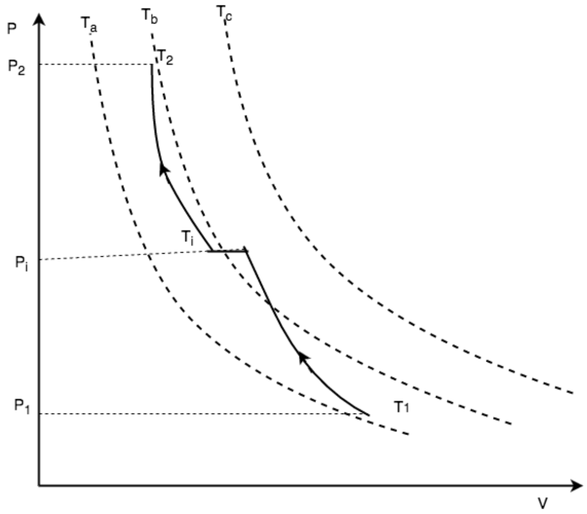

Figure 14: PvT chart representing two-stage isentropic process

The optimum intermediate pressure, P_i, is determined by the relationship that follows, which results in same work input for each of the two-stages and in fact minimizes the overall total work for the two-stage process.

$$P_i = \sqrt{P_1 \; X \; P_2}$$

The intermediate temperature, which is also the exit temperature of the first stage, is determined by using the following relationship, which is a variation of one-stage compression process.

$$T_i = T_1 \left(\frac{P_i}{P_1}\right)^{\frac{k-1}{k}}$$

The work input to each of the two-stages of the compressor is determined individually and the total work input into the two-stage system is the sum of these two work inputs, which are the same if the optimum intermediate pressure value is used.

$$W_{1S2=0} = C_P (T_i - T_1)$$

$$W_{2S2=0} = W_{1S2=0}$$

$$W_{S2} = W_{1S2=0} + W_{2S2=0}$$

Where W_{S2} is the total work input to the two-stage isentropic compressor system.

Theoretical Compression Model for Water and R-410A

Based on the theory and equations presented earlier in this chapter, a model was developed for simulating the ideal gas behavior of water vapor. The model assumes a value of n=1 (isothermal) for an isothermal process and n=k=1.34 (isentropic) for an isentropic process and is then used to create PvT plots and calculate compressor work. This model is also used to calculate the polytropic exponent when the compression follows a saturation line, based on the fact that the saturation line forms a limit. The saturation limit exists because when the vapor is being compressed and simultaneously losses heat, then it is possible that the saturation point is reached and if the temperature of the fluid being compressed goes below the saturation temperature, then condensation occurs.

It is important to note that only water vapor is treated as an ideal gas with assumed values for the exponents in the polytropic process equation. The second fluid, R-410a, that is used in vapor compression refrigeration (VCR) cycle is not an ideal gas and therefore, property tables must be used to find the state points during any of the different compression process analyzed. It should be noted that for the purpose of this study that isothermal R-410A compression process is not used to calculate the work. However, once R-410A process is plotted a PvT then an exponent n can be found.

Because the focus of this thesis is on water vapor that is treated as an ideal gas, the previous compression work equations can be rewritten for an ideal gas. Therefore, the steps involved in modeling ideal gas, along with determining and comparing their specific works is shown below:

Isothermal Compression Process

Isotherms (constant temperature lines) are plotted on the PvT chart by determining the specific volume of water vapor at different pressure values by using the ideal gas equation.

$$v = \frac{RT}{P}$$

The theoretical work done during an isothermal compression process is then calculated for any of the above determined states by using the following ideal gas relation equation based on n=1.

$$w = RT \ln \frac{P_2}{P_1}$$

Isentropic Compression Process

The specific volume of gas at different pressure conditions in an isentropic process is determined by using the polytropic equation, and n=k. In the case of an ideal gas these pressure and volume values are plotted on a PvT chart and a curve is fit to get a polytropic exponent (n) for the isentropic process. This polytropic exponent is then used for calculating specific work as follows:

$$w = \frac{k}{k-1} R \left(T_2 - T_1\right)$$

Saturation - Polytropic Compression Process

Here, the vapor is compressed along its saturation curve, meaning that the compression process follows a path such that the vapor remains in its saturated state throughout the process. which as discussed previously forms a low temperature unit.

The values of saturation temperature and pressure, along with vapor specific volume, are obtained from the property tables. These are then plotted on a PvT chart to fit a curve to determine a polytropic exponent (n). The theoretical specific work input to this compression process is then determined by using the following relationship, which is similar to the isentropic equation with a generic n still to be determined replacing k.

$$w = \frac{n}{n-1} \mathrm{R} \left(T_2 - T_1\right)$$

PvT Plot and Compression Process

The resulting PvT plots for the two fluids undergoing compression between an inlet temperature of 10^{0}C to 50^{O}C during an isentropic process and a saturated condition process are shown in Figure 15 and 16:

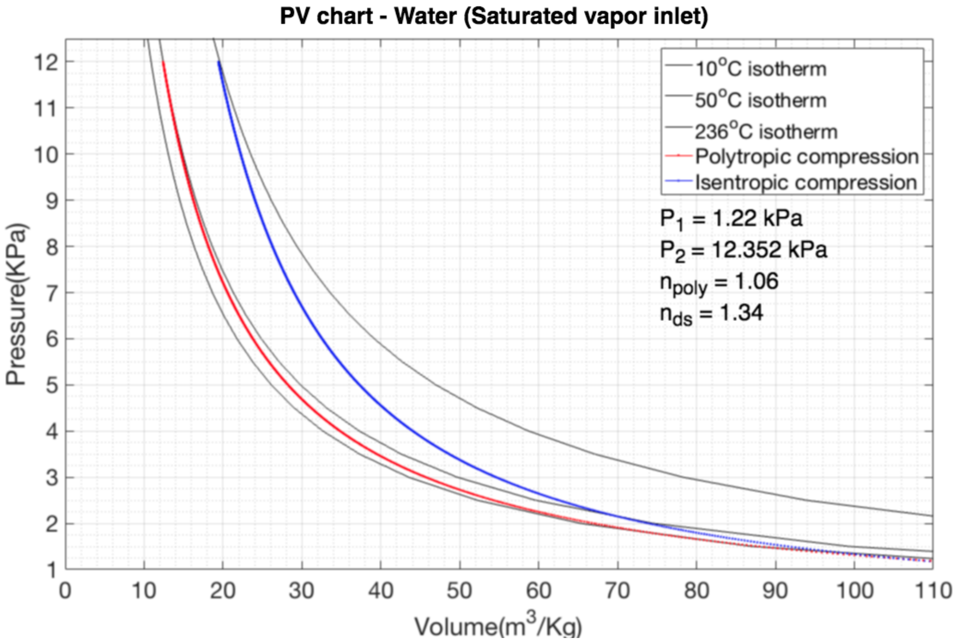

Figure 15: Water vapor PvT plot

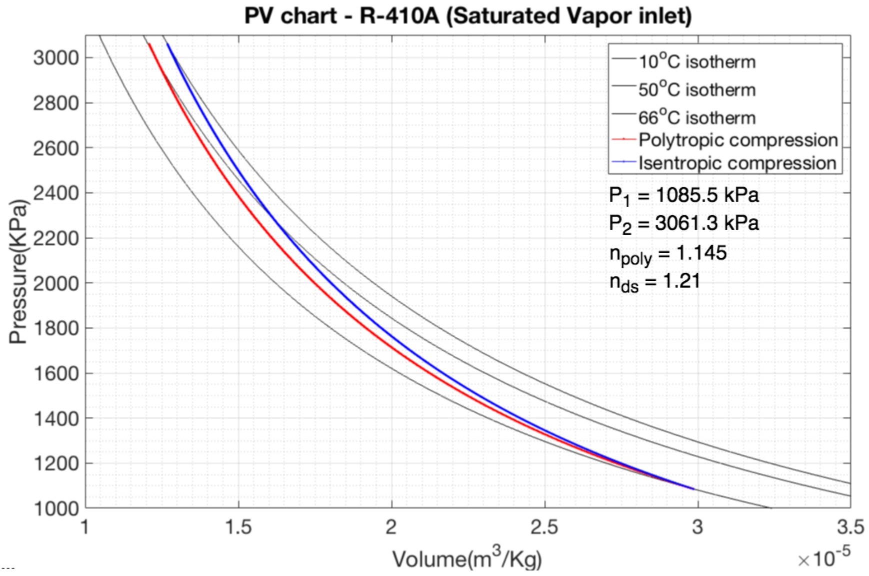

Figure 16: PvT plot for R-410A

The polytropic indices for the saturated condition process of the two fluids being compressed are shown in the plots. These polytropic indices suggest that water, while being compressed along the saturation curve follows a near-isothermal process (n=1.06), while the saturation compression curve of R-410a largely differs from ideal isothermal compression (n=1.145). We may thus conclude that isothermal/ near-isothermal compression is realistically achievable with water but not with R-410a.The significance of this condition is that a minimum work scenario represented by the isothermal compression maybe possible for water vapor but it is not possible for typical refrigerants such as R-410A.

This same conclusion made by focusing on the polytropic exponent values for the saturated condition line can also be made by visually comparing the saturated line to the curve for the isentropic and isothermal processes. As discussed previously, the saturation line on a PvT plot forms a limit that is for R-410A close to the isentropic compression line. In contrast the water vapor saturation line is close to the isothermal line, meaning that the saturation line is a possible replacement for isothermal line, vice versa, at least for water only. Meaning that isothermal compression for R-410A is impossible.

In the above compression process, saturated water and R-410A vapor at 10^0C enters the compressor. In addition to this compression scenario, a similar compression situation was modeled with superheated water vapor at 10^0C entering the compressor at a lower pressure of 0.5 kPa with the results presented in Figure 17.

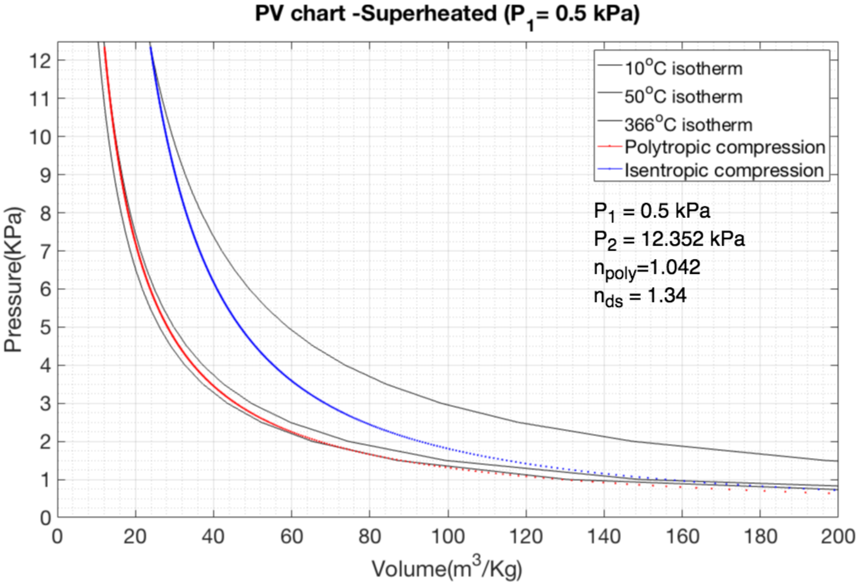

Figure 17: PvT plot for superheated water vapor at 0.5kPa

The polytropic exponent (n) for the saturated compression in this case was found to be 1.042 compared to n=1.06 for the higher pressure saturation case, suggesting that the polytropic compression process for the saturation curve may be approaching isothermal compression with decreases in inlet vapor pressure.

The same conclusion can be arrived at by visually comparing the two water-vapor PvT plots for saturated and superheated compressor inlet conditions.

Work Comparison

As noted, specific work can be calculated by using polytropic equations assuming value of n are known. For each of the three cases shown in PvT plot, specific works are shown below. In each case, the inlet vapor is at 10^0C while the exit pressure corresponds to the saturation condition at 50^0C, which are 12.35 kPa for water and 3061.3 kPa for R-410a. The cases calculated and presented below are isothermal and isentropic compression, along with compression that follows a saturation curve on a PvT plot. In the case of water vapor following saturation line, work is determined for two inlet pressures representing saturated and superheated condition.

<u>Water Vapor</u>

$w = 298.7\,\frac{kJ}{kg}$ [n=1 (isothermal compression)]

$w = 313.4\,\frac{kJ}{kg}$ [n=1.042 (saturated vapor compression)]

$w=319.46\,\frac{kJ}{Kg}$ [n=1.06 (saturated vapor compression)]

$w=406.2\,\frac{kJ}{Kg}$ [n=1.34 (isentropic compression)]

<u>R-410A</u>

As discussed previously, R-410A work values come from property table rather than from polytropic process equations. So they are presented here only for comparison purpose.

$w=33.6\,\frac{kJ}{kg}$ [n=1 (isothermal compression)]

$w=83.22\,\frac{kJ}{kg}$ [n=1.145 (saturated vapor compression)]

$w=91.16\,\frac{kJ}{kg}$ [n=1.21 (isentropic compression)]

The specific work for the isentropic compression process is the largest of all the processes for both fluids. In addition, the specific work for saturated-vapor compression process of water vapor is similar to isothermal work, which is about 60% larger while R-410a is significantly higher than its respective isothermal compression value being about 200%. The significance of this is that one can remove significant amount of heat during water vapor compression so that the process follows the saturation line, which is close to the isothermal line, resulting in an energy saving over the adiabatic, isentropic compression. This energy reduction is not possible for R-410A because the saturation condition line is not even close to the isothermal line.

CHAPTER VI

VAPOR COMPRESSION REFRIGERATION CYCLE

Introduction

A vapor compression refrigeration (VCR) cycle involves a refrigerant that transfers thermal energy from an evaporator at a low pressure to a condenser that is at a higher pressure and temperature. A compressor and a throttle valve separate the high and low-pressure sides of the system while helping in regulating the refrigerant flow rate. The compressor increases the pressure of the refrigerant vapor exiting the evaporator, taking it to a more superheated state, while the throttle valve expands the saturated (or subcooled) refrigerant exiting the condenser, thereby decreasing the pressure. Figure 18 shows the major system components and flow paths of the refrigerant and other fluids along with the heat and work energy transfers of the vapor compression cycle.

Vapor compression refrigeration is the most widely used refrigeration method and as such is considered to be the conventional approach to cooling. Only when the new and transformative technology of the membrane dehumidification cycle is compared to the conventional vapor compression refrigeration cycle or reference case, can one evaluate the validity of this new technology. To achieve this evaluation of the membrane dehumidification system, the comparison with the VCR should be based on making comparative, parametric estimates of the variables in both these systems.

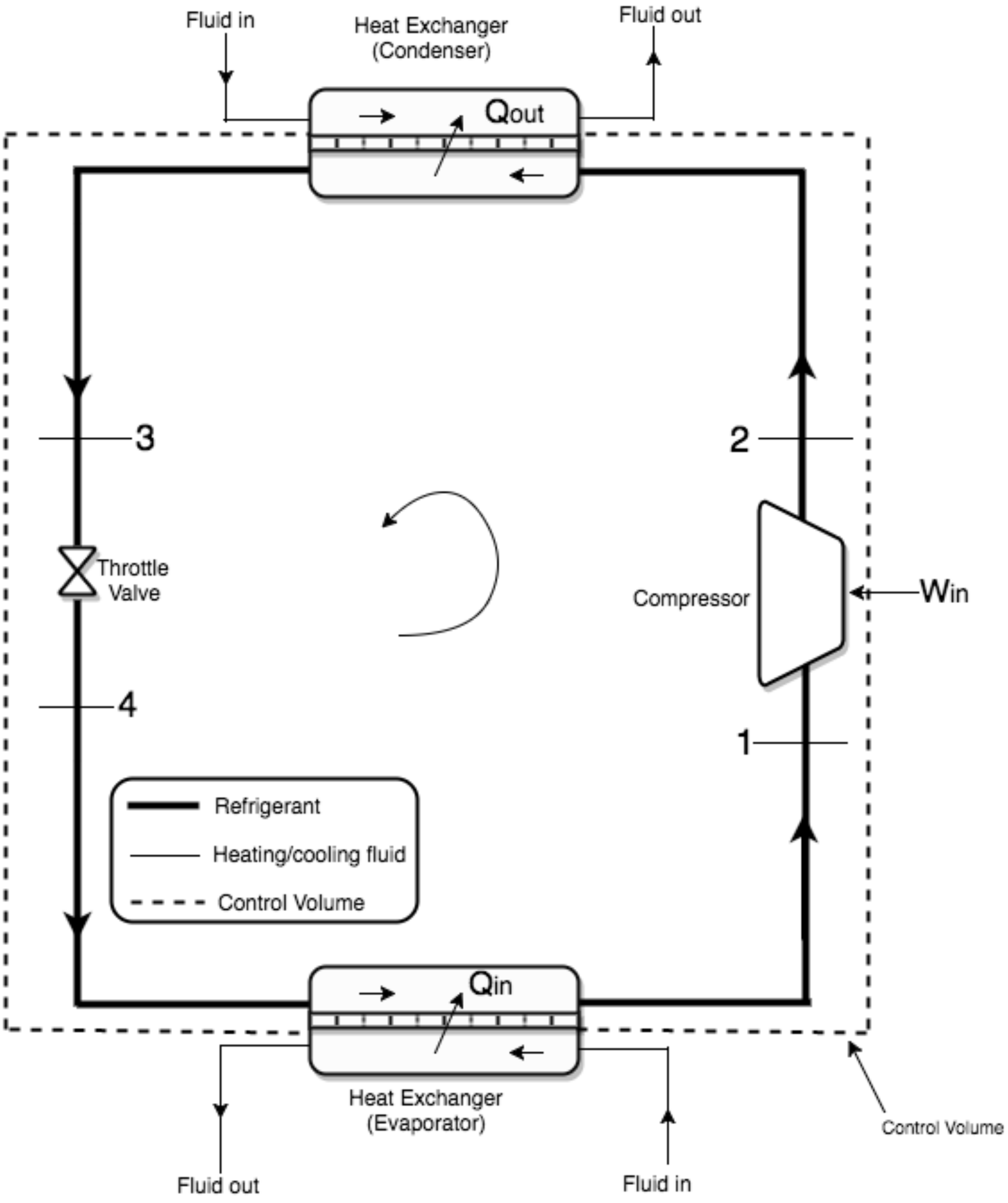

Figure 18: Schematic of vapor compression refrigeration cycle

Therefore in this light, a vapor compression refrigeration system was modeled by using matlab, and the objective of this model was to accurately estimate the coefficient of performance of the vapor compression system with different working fluids. The particular focus of VCR was on water and R410A, with the latter being the working fluid of choice for air conditioning.

The thermodynamic states of the refrigerant in a theoretical VCR cycle is shown on a TS diagram below:

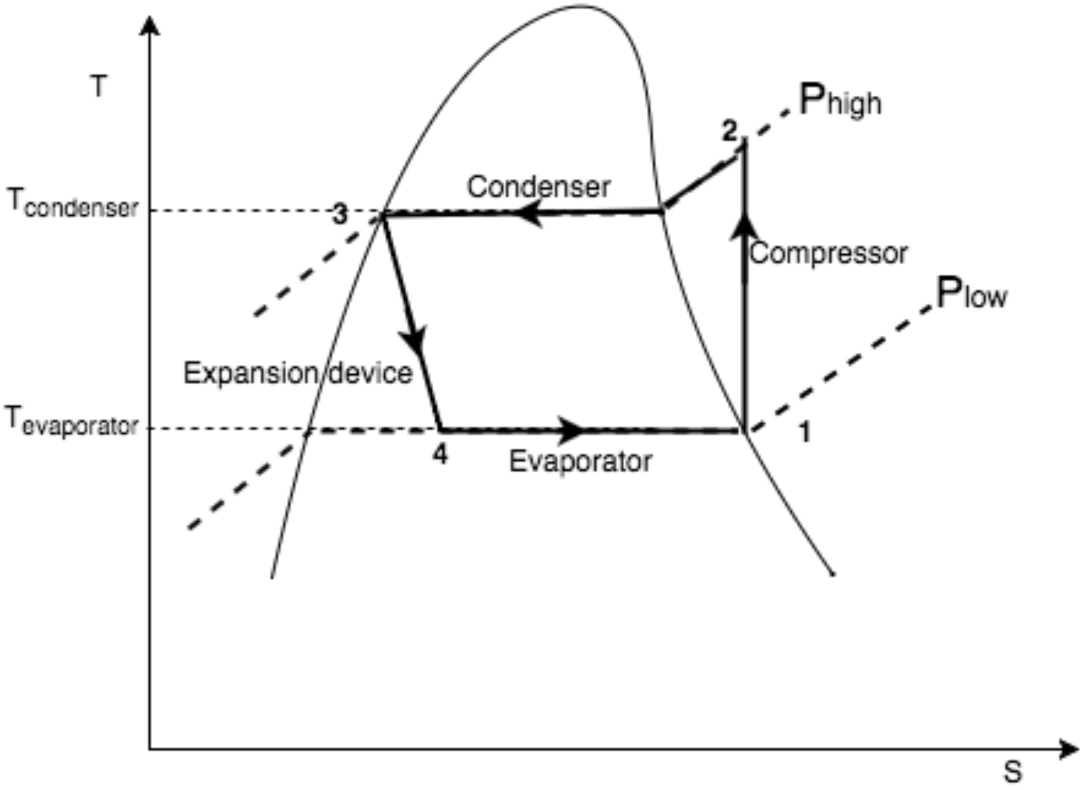

Figure 19: Representation of vapor compression cycle on a T-S diagram

The VCR cycle represented on the TS diagram above depicts an ideal cycle where all the processes are locally reversible except for throttling. In addition to this irreversibility condition, the theoretical VCR cycle modeled for this study is based on assumptions that follow:

1. The compressors operating between state 1 and 2 follows an ideal isentropic process with no heat transfer to the surroundings.
2. The operating efficiency of the isentropic compressor is 100%.
3. The pressure in the condenser and evaporator remain constant, without any pressure drop across the heat transfer section.
4. The kinetic and potential energy changes in the cycle processes are neglected.
5. The difference between the refrigerant temperature and the airside temperature in the evaporator and condenser remains constant.

Processes

The processes of an ideal VCR cycle and their working relations used to determine the values of state variables are listed in the following section.

1. An isentropic compressor increases the pressure of saturated (or slightly superheated) vapor exiting the evaporator to a more heated state and the work done during compression is given by;

$$W_C = m_r(h_2 - h_1)$$

2. The superheated refrigerant passes through a condenser at a constant pressure to reach a saturated (or subcooled) liquid state after losing heat. The heat transfer in the condenser is given by the following equation.

$$Q_{condenser} = m_r(h_3 - h_2)$$

3. Refrigerant exiting the condenser passes through the throttle valve to a lower pressure following a constant enthalpy process until reaching the evaporator.

$$h_3 = h_4$$

4. Liquid refrigerant entering the evaporator gains heat at a constant pressure to reach it’s saturated vapor state, and this heat transfer process is represented by the equation

$$Q_{evaporator} = m_r(h_1 - h_4)$$

COP Definition and Determinations

The COP of a refrigeration system is defined as the ratio to the useful cooling effect produced by the system to the work input into the system. In this case, the cooling effect is the heat extracted by the working fluid in the evaporator and the work input is the work supplied to the compressor.

$$\text{COP} = \frac{Useful\ Cooling\ Effect}{Total\ Work\ input} = \frac{Heat\ extracted\ from\ Evaporator}{Work\ input\ to\ the\ compressor}$$

After plugging in component energy equations derived above, COP is

$$COP = \frac{m_r(h_1 - h_4)}{m_r(h_2 - h_1)} = \frac{h_1 - h_4}{h_2 - h_1}$$

The temperature of the evaporator and the exit temperature of the condenser are the inputs to the VCR model. The numerical model determines the COP of the VCR system as follows:

Input: $T_{Evaporator} = T_L$

$T_{Condenser} = T_H$

State 1: Temperature = T_L

Pressure = P_{LOW}

$h_1 = h_g$ (saturated vapor)

$S_1 = S_g$

Process 1 -2: Isentropic Compression

State 2: $S_2 = S_1$

$P_2 = P_{HIGH}$

Using tables, program finds T_2 and h_2

Process 2-3: Condenser

State 3: $T_3 = T_H$

$P_3 = P_{sat}(T_H)$

$h_3 = h_f$ (saturated liquid)

Process 3-4: Isenthalpic Expansion (Throttling)

State 4: $T_4 = T_L$

$P_4 = P_{LOW}$

$h_4 = h_3$

The calculation of COP is the major function of the VCR model presented herein, so that the COP values can be compared with that of membrane dehumidification system or Claridge-Culp-Pate cycle. If one assumes a cooling capacity (e.g. 10 tons) then one can calculate mass flow rate and specific volume of the refrigerant and compressor work for a specific cooling capacity. Determining these parameters enables a detailed comparison of vapor compression refrigeration system with the membrane dehumidification system. Calculating these parameters from the state variables determined in the previous step is shown below:

Mass Flow Rate (m_r)

The mass flow rate of refrigerant is determined by the heat transfer rate required to maintain the temperature of the evaporator. For a given cooling capacity, the mass flow rate in the evaporator is calculated as:

$$m_r = \frac{Q_{evaporator}}{h_4 - h_1}$$

Compressor Work (W_c)

As presented previously, it is the work supplied to compress the saturated vapor exiting the evaporator to a superheated vapor state at a higher pressure.

$$W_C = m_r(h_2 - h_1)$$

Volume Flow Rate (V)

The volume of refrigerant entering the compressor per unit time and is the product of mass flow rate of refrigerant and its specific volume at the compressor inlet.

$$V = m_r v$$

The VCR model was used to analyze R-410A at different condenser and evaporator conditions and the results obtained are tabulated below:

Results

Table 1: Temperature conditions and results of vapor compression cycle

T_H (^{0}F)	**105**	**95**	**115**	**110**
T_{LOW} (^{0}F)	**57**	**67**	**47**	**55**
COP	8.87	18.17	5.7	6.45
Mass Flow (lb/min)	29.45	27.51	31.89	30.53
Compressor Work (BTU/min)	253.31	110.04	382.77	309.9
Volume flow rate (ft^3/lb)	9.97	7.88	12.81	10.7
Specific Volume inlet (ft^3/lb)	0.34	0.29	0.4	0.35

The results in the table were validated with previous studies and agreement was found. Furthermore, the VCR model was run with water as the working fluid and a comparison of performance of the model with water and 410A as working fluids at similar conditions were carried out. The results are presented below.

Table 2: Comparison of vapor compression refrigeration cycle results for water and R-410A

T_{LOW}	T_{HIGH}	**Water**			**R-410a**			**Specific work ratio**	**Compressor work ratio**
		P_1 (Psig)	**P_2 (Psig)**	**PR**	**P_1 (Psig)**	**P_2 (Psig)**	**PR**	**RSW**	**0.1* RSW**
34	97	0.096	0.868	9.04	120	320	2.67	0.56	0.056
34	110	0.096	1.276	13.29	120	380	3.17	0.56	0.056
43	97	0.137	0.868	6.34	140	320	2.29	0.55	0.055
43	110	0.137	1.276	9.31	140	380	2.71	0.55	0.055
50	97	0.178	0.868	4.88	162	320	1.98	0.58	0.058
50	110	0.178	1.276	7.17	162	380	2.35	0.57	0.057
65	97	0.306	0.868	2.84	200	320	1.60	0.55	0.055
65	110	0.306	1.276	4.17	200	380	1.90	0.55	0.055

CHAPTER VII

SINGLE-STAGE CCP PROCESS

System Description

A schematic of a single-stage membrane dehumidification process is shown in Figure 19. As the name suggests, a single-stage membrane dehumidifier system differs from a two-stage dehumidifier system in the number of dehumidifier units that it houses. Here, a single dehumidifying system is used to dehumidify the outdoor air, which is then passed through an evaporative cooler where the dry air is cooled to its wet bulb temperature by the addition of liquid water that evaporates, drawing energy from air.

A single-stage dehumidification setup requires less energy to operate when compared to a two-stage dehumidification system for the same outdoor conditions, because only one compressor is required for single-stage. However, the overall cooling effect produced by one-stage system is less than the two-stage system, so that the overall effect that each system has on the COP is not obvious. Even with that said, one can make several observations, that are described below:

1. It is possible that the energy saved in a single-stage membrane dehumidification system when compared to a two-stage membrane dehumidification system more than compensates for the reduced cooling capacity of the single-stage.

2. Most of the cooling effect in a two-stage system is produced by the first stage dehumidification and cooling units. The cooling effect produced by the second-stage dehumidification and cooling units is limited.

In a single-stage system, the outdoor air may pass through either one or two different evaporative coolers depending on the outdoor humidity conditions. These two possible paths, which the outdoor air can take, are designated as path A and path B. Path A (1-2-3-4), which has an evaporative cooler upstream of the dehumidifier is chosen for dry outdoor conditions while path B (1-Bypass-2-3-4), which bypasses the upstream evaporative cooler is chosen for more humid outdoor conditions.

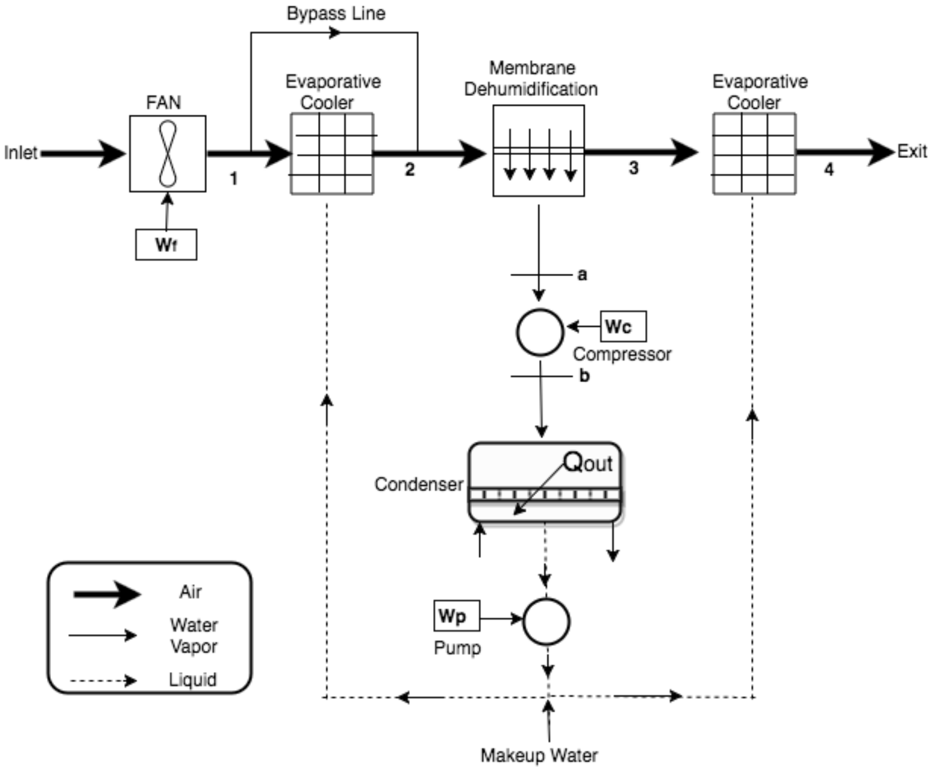

Figure 20: Schematic of one-stage Claridge-Culp-Pate process

Comparison of Path A and B

The outdoor air entering the system follows one of two aforementioned paths depending on the humidity conditions. These two paths and their differences are described in this section.

Path A (1-2-3-4)

This path is chosen if the outdoor air entering the system is dry. Here, the outdoor air is humidified before it passes through the membrane dehumidifier by passing the outdoor air through an evaporative cooler where it is humidified to the saturation point (i.e. 100% relative humidity) meaning, its wet bulb temperature is reached. To follow this path, the air enters the system at state 1 and passes through the first evaporative cooler to state 2. Followed by state 3 and 4 at the dehumidifier unit exit and the second evaporative cooler exit.

Path B (1-Bypass-2-3-4)

This path is chosen if the outdoor air condition is humid. Here, the outdoor air enters the system and directly undergoes the membrane dehumidification process without having to go through the first evaporative cooler. The air enters through the bypass line, and this point onwards follows path A to reach the exit.

An example of CCP process operating with membrane dehumidification and evaporative cooling along path A and B for a single-stage membrane dehumidification system are shown on the psychrometric chart in Figure 21 below.

The example shown in the Figure are for air entering at 35^0C and 70% relative humidity, which could be a typical summer weather condition that is somewhat humid and drier than it could be. The exit temperature for path A is lesser than that of Path B at least for the inlet conditions assumed.

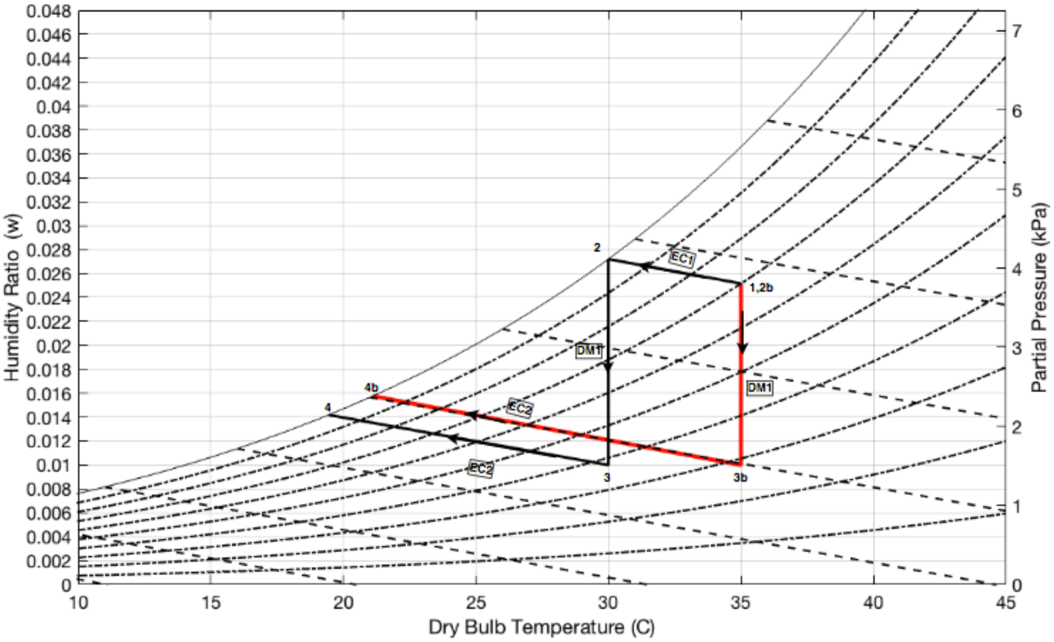

Figure 21: Psychrometric representation of one-stage Claridge-Culp-Pate process

The table that follows provides the values of state variables at each stage of the CCP process of the two paths.

One can see from table values that the path A exit is slightly cooler that path B being 19.4^{0}C to 21.1^{0}C. If the relative humidity of the inlet had been greater than 70% then the advantage of path A over path B might disappear. One can also see that the path A exit has lower relative humidity ratio compared to path B which means path A is drier.

Table 3: Results of one-stage membrane dehumidification process

Path A (1-2-3-4)

	T (C)	RH (%)	ω $(\frac{kgv}{kga})$	h $(\frac{kJ}{kg})$	Pv (kPa)
1	35	70	0.025167	117.61	3.9403
2	30	100	0.027211	117.61	4.2469
3	30	37.75	0.01	73.576	1.6032
4	19.4	100	0.01419	73.576	2.26

	$\Delta\,\omega$ $(\frac{kgv}{kga})$	Δh $(\frac{kJ}{kg})$	ΔP (kPa)
1-2	0.002	0.000	4.237
2-3	-0.017	-44.034	1.593
3-4	0.004	0.000	-0.010

Path B(1-2b-3b-4b)

	T (C)	RH (%)	ω $(\frac{kgv}{kga})$	h $(\frac{kJ}{kg})$	Pv (kPa)
1	35	70	0.025167	117.61	3.9403
2b	35	70	0.025167	117.61	3.9403
3b	35	28.482	0.01	78.693	1.6032
4b	21.1	100	0.015769	78.693	2.5053

	$\Delta\,\omega$ $(\frac{kgv}{kga})$	Δh $(\frac{kJ}{kg})$	ΔP (kPa)
1-2b	0.000	0.000	3.930
2b-3b	-0.015	-38.92	1.593
3b-4b	0.006	0.000	2.495

The outlet temperature (T) and humidity ratio ($\boldsymbol{\omega}$) are a measure of performance comparison for path A and B, but so is COP, which is defined as the ratio of cooling capacity to the work, which can also be a relationship for comparing path A and B

$$\frac{COP_A}{COP_B} = \frac{(h_1 - h_4)}{(h_1 - h_{4b})}\frac{(\omega_{2B} - \omega_{3B})}{(\omega_2 - \omega_3)}$$

$$\frac{COP_A}{COP_B} = \frac{44.034}{38.917}\, X\, \frac{0.0151}{0.0172} = 0.997$$

This COP ratio corresponds to less than 1% difference in COPs. The change in temperature between inlet and exit in the two cases is about 11%, which is similar to the difference in water vapor required by the compressor.

CHAPTER VIII

TWO-STAGE CLARIDGE-CULP-PATE (CCP) PROCESS

Setup

A schematic that shows components and flow paths for a two-stage membrane dehumidification process is shown in Figure 22. The most extensive flow path for this two-stage membrane dehumidification process involves outdoor air passing through all 5 components namely, 2 dehumidification units and 3 evaporative coolers. As one can see in the schematic evaporative coolers are strategically placed at the system inlet and outlet along with locations one between the two dehumidifying units.

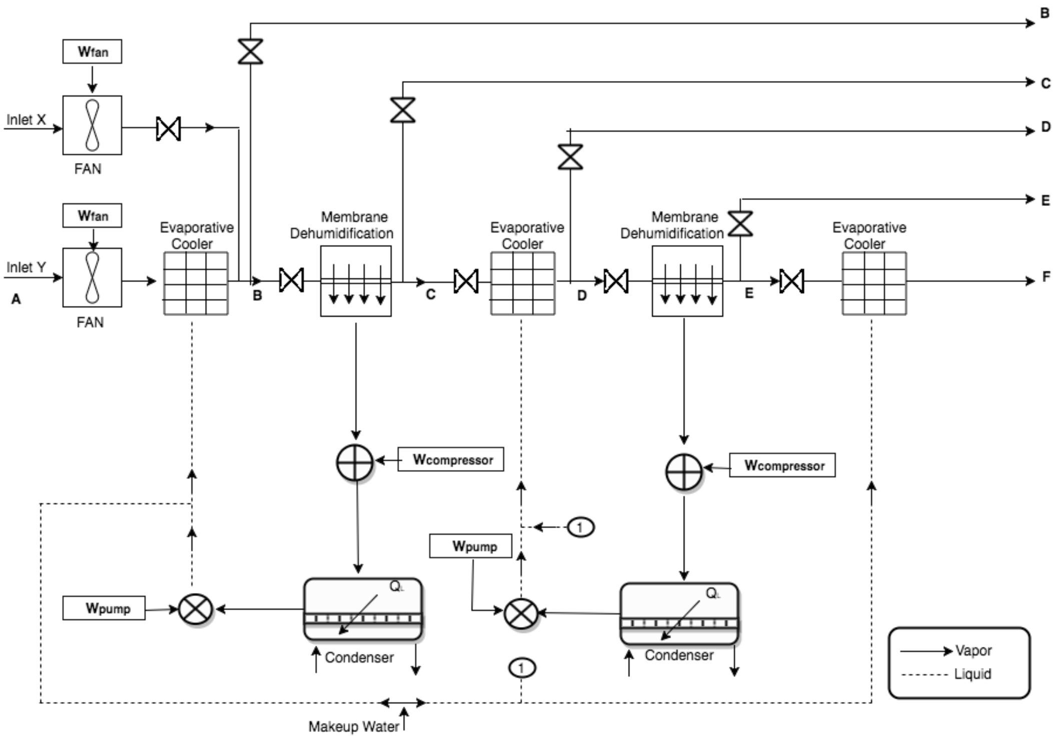

Figure 22: Schematic of two-stage Claridge- Culp-Pate process

The two-stage membrane dehumidification process is setup such that the air passing through the system, can exit the system downstream of any of the 5 components, thus bypassing other components by controlling a series of outlet valves. As a final note, the air entering the system can directly enter an evaporative cooler or bypass it similar to the one-stage Path A and B as presented in the previous chapter. However for the two-stage system these two paths are designated as path X and path Y.

Paths X and Y

Similar to the single-stage dehumidification system, a two-stage dehumidification system follows any one of the two available paths, with the optimum path depending upon the outdoor humidity conditions, either humid or dry.

Path X

This path bypasses the inlet evaporative cooler and is chosen if the outdoor air condition is humid, meaning inlet evaporative cooler will have minimal effect, as will be shown later. Specifically, The air enters at inlet X and passes through to point B; meaning points X and B are at the same condition when let into the membrane dehumidifier. After exiting the first membrane dehumidifier, the air follows the path CDE and F, with each of these letter designations representing a location where the air can wither be withdrawn from the system or continue onward to the next component.

Path Y

This path is chosen if the outdoor air entering the system is dry, meaning that the entering relative humidity is on the lower side. With the low inlet humidity, it may be worthwhile having the outdoor air pass through an evaporative cooler where it can be humidified to the saturation point as the wet bulb temperature is reached. To follow this path, the air enters the system through inlet Y and exits the first evaporative cooler at state B. Past this point, air following path Y undergoes the same processes as that of Path X, where it passes through points CDE and F.

Effect of Outdoor Conditions

Simulations for two cases were carried out by using the developed membrane dehumidification model and then state variables at each stage of the dehumidification process for path X and path Y were determined. The outdoor air temperatures, entering the systems for both the cases was fixed at 95^0F and the inlet relative humidities were set at high and low values.

The representation of the two cases has been plotted on psychrometric charts with one chart being for case 1 (95^0C and 40% RH) and the other for case 2 (95^0C and 70% RH). Path X and Y are plotted on each plot so that the air conditions (Temperature and humidity) at each location designated by ABCDE and F can be compared. Later these state points are tabulated in the tables, showing the effects of inlet conditions and flow paths.

Case -1: Dry Inlet (95^0F 40% RH)

Path X and path Y for an entering outdoor temperature of 95^0F (35^0C) and a relative humidity of 40% are shown in Figure 22 with the red line representing path X and the blue line representing path Y. As can be seen on the psychrometric chart the exit of each dehumidifying unit is set at a water vapor partial pressure of 1.5 kPa

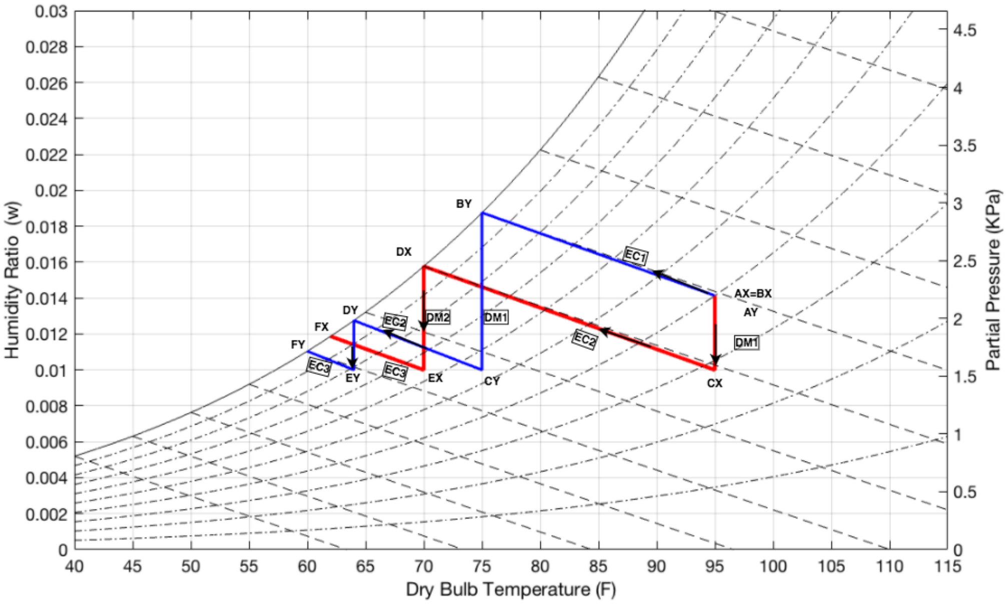

Figure 23: Psychrometric representation of two-stage Claridge-Culp-Pate process for 95^0C and 40% relative humidity

The values of state variables at location A-F for both the paths namely, X and Y are shown in the following table. These are the same state values shown earlier in the above Figure, which provided an opportunity to visually compare the two paths, specially the evaporative cooler and the dehumidification processes.

Table 4: Results of two-stage Claridge-Culp-Pate process

	T (F)	RH (%)	ω (lbv/lba)	h (Btu/lb)	Pv (Kpa)	Δω (lbv/lba)	Δh (Btu/lb)	ΔP (Kpa)
AX	95	40.0	0.014136	38.394	2.2516	0.014	38.394	2.242
BX	95	40.0	0.014136	38.394	2.2516	0.000	0.000	2.242
CX	95	28.5	0.01	33.832	1.6032	-0.004	-4.562	1.593
DX	70	100.0	0.015769	33.832	2.5053	0.006	0.000	2.495
EX	70	64.0	0.01	27.721	1.6032	-0.006	-6.111	1.593
FX	62	100.0	0.011872	27.721	1.8978	0.002	0.000	1.888
AY	95	40.0	0.014136	38.394	2.2516	0.014	38.394	2.242
BY	75	100.0	0.018756	38.394	2.9659	0.005	0.000	2.956
CY	75	54.1	0.01	28.943	1.6032	-0.009	-9.451	1.593
DY	64	100.0	0.012755	28.943	2.036	0.003	0.000	2.026
EY	64	78.7	0.01	26.254	1.6032	-0.003	-2.689	1.593
FY	60	100.0	0.011045	26.254	1.7678	0.001	0.000	1.758

Case -2: Humid Inlet (95^{0}F 70% RH)

Similar to dry inlet condition plotted above, the state points for path X and path Y for humid inlet conditions are plotted here on a second psychrometric chart The higher inlet relative humidity of 70% is obvious on this new chart.

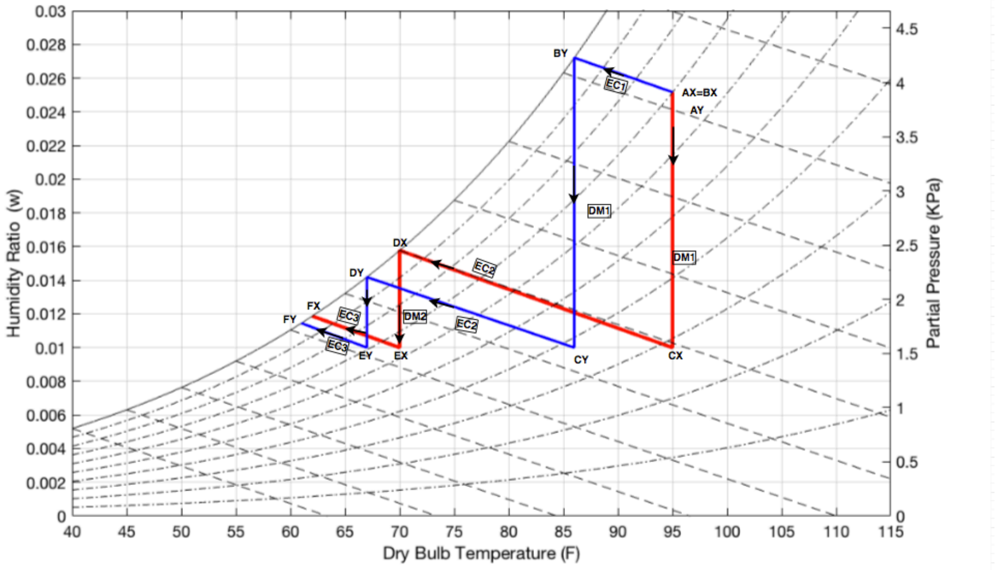

Figure 24: Psychrometric representation of two-stage Claridge-Culp-Pate process for 95^0C 70% relative humidity

As before, the state point values shown in Figure 24 are tabulated in table 5 for both Path X and Y.

Table 5: Results of two-stage Claridge-Culp-Pate process

	T	RH	ω	h	Pv	Δω	Δh	ΔP
	(F)	(%)	(lbv/lba)	(Btu/lb)	(Kpa)	(lbv/lba)	(Btu/lb)	(Kpa)
AX	95	70	0.025	50.564	3.9403	0.025	50.564	3.930
BX	95	70	0.025	50.564	3.9403	0.000	0.000	3.930
CX	95	28.5	0.010	33.832	1.6032	-0.015	-16.732	1.593
DX	70	100	0.016	33.832	2.5053	0.006	0.000	2.495
EX	70	63.9	0.010	27.721	1.6032	-0.006	-6.111	1.593
FX	62	100	0.012	27.721	1.8978	0.002	0.000	1.888
AY	95	70	0.025	50.564	3.9403	0.025	50.564	3.930
BY	86	100	0.027	50.564	4.2469	0.002	0.000	4.237
CY	86	37.7	0.010	31.632	1.6032	-0.017	-18.932	1.593
DY	67	100	0.014	31.632	2.26	0.004	0.000	2.250
EY	67	70.9	0.010	26.987	1.6032	-0.004	-4.645	1.593
FY	61	100	0.011	26.987	1.8318	0.001	0.000	1.822

Discussion of Results

The results plotted and tabulated above can be analyzed and a number of conclusions can be reached regarding component configuration for the CCP system. As one can expect, the optimum configuration is a function of outdoor relative humidity and possibly the inlet temperature, which was not the focus of this investigation.

The analysis of results focus on two aspects

1) Number of dehumidification units to be used
2) The path to be followed (Either X or Y)

The following are the major results drawn from comparing a one-stage and a two-stage membrane dehumidification processes

- In a two-stage CCP process, the first membrane dehumidifier extracts about twice the mass of vapor from moist air than the second membrane unit, which can be seen in both the plots and tables. Therefore, it can be said that the work input required for the first membrane unit is about twice that of the second membrane unit.
- The first evaporative cooler has about 3 times more cooling effect than the second evaporative cooler in a 2-stage CCP process.
- The collective cooling effect of 2 evaporative coolers in path X is nearly the same as the total cooling effect of 3 evaporative coolers operating in path Y of a two-stage CCP – process.

CHAPTER IX

MEMBRANE-ENABLED AND CONVENTIONAL COOLING PROCESS COMPARISONS

Background

The objective of this chapter is to compare the COP of a conventional air conditioning system with that of a novel membrane-enabled cooling system with both of them operating between the same low and high temperature reservoirs. The indoor air condition (low temperature) is fixed at 25^0C and 50% relative humidity while the outdoor air conditions (high temperature) are varied between 30^0C and 40^0C in steps of 5^0C.

The psychrometric chart below shows two paths namely, path A and path B where path A is followed by a conventional air conditioning system while path B is followed by membrane enabled cooling system (CCP system) between a common outdoor condition (point 1) and a common indoor condition (point 4A same as point 3B). A more detailed description of the two paths is presented in two sentences that follow.

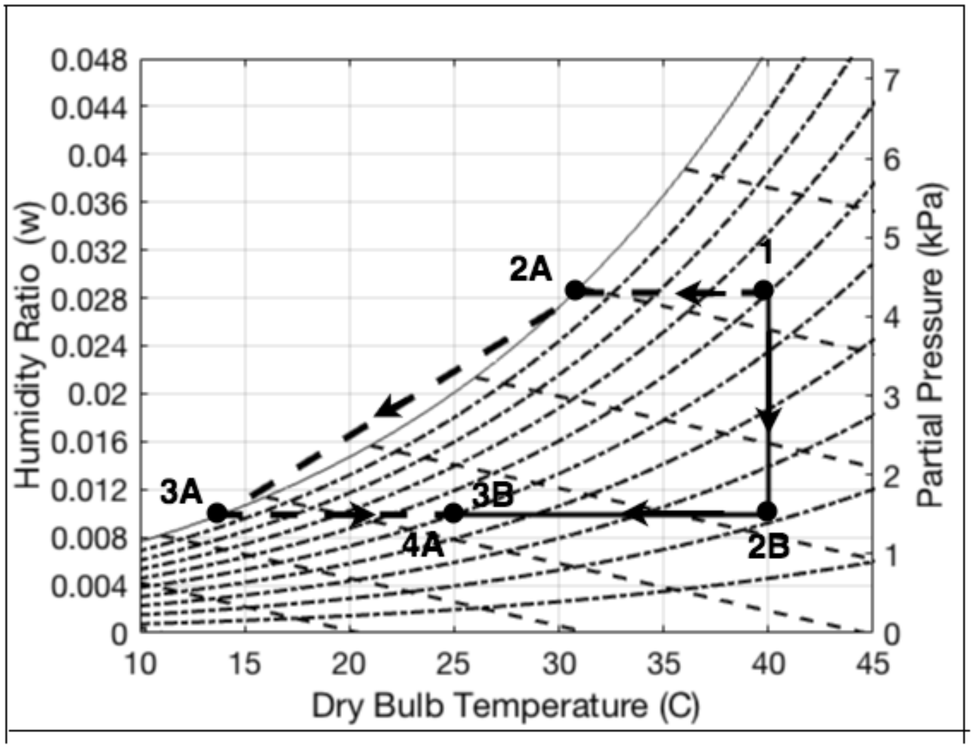

Figure 25: Psychrometric representation of a conventional cooling processes and Claridge-Culp-Pate cooling process

Description of Path-A (Conventional System)

The dotted line in the above psychrometric chart represents path A that is followed by outdoor air being cooled by a conventional air-conditioning system to a comfortable indoor environment of 25^{0}C and 50% relative humidity.

The conventional air conditioning system processes that are involved in reaching the indoor environment condition is presented in Figure 25 and described herein:

1. Sensible cooling (1 – 2A) : Outdoor air at state 1 is cooled in the evaporator of the conventional refrigeration system by removing sensible heat until the dew point is reached at state 2A.

2. Latent cooling (2A – 3A): Air that is at 100% relative humidity at point 2A is further cooled in evaporator until it reaches point 3A, which is the dew point temperature for 25^0C at 100 % relative humidity and vapor partial pressure of 1.5 kPa.

3. Sensible reheating (4A -4): Cool air at 100% relative humidity is reheated until the comfort point of 25^0C at 50% relative humidity is reached.

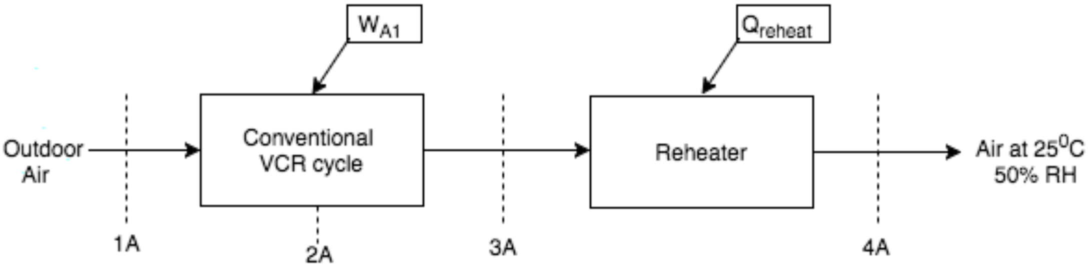

Figure 26: Schematic of conventional cooling

The total work associated with path A is as follows:

- Work input to vapor compression refrigeration (VCR) compressor with the result being sensible and latent cooling of air from state 1 to state 3A (W_{A1}).
- Thermal energy input to reheat the air from state 3A to 25^0C 50% relative humidity (Q_{reheat}).

The total work associated with path A is $W_{A1} + Q_{reheat}$

Description of Path-B (Claridge–Culp–Pate cooling system)

Path B is the cooling path that is followed by the membrane-enabled cooling system. The outdoor air is first dehumidified from state 1 to state 2B, and then, a conventional VCR system sensibly cools the dehumidified air to the 25^0C at 50 % relative humidity (3B). This combination of dehumidification and VCR system eliminates the need of latent cooling in a VCR system.

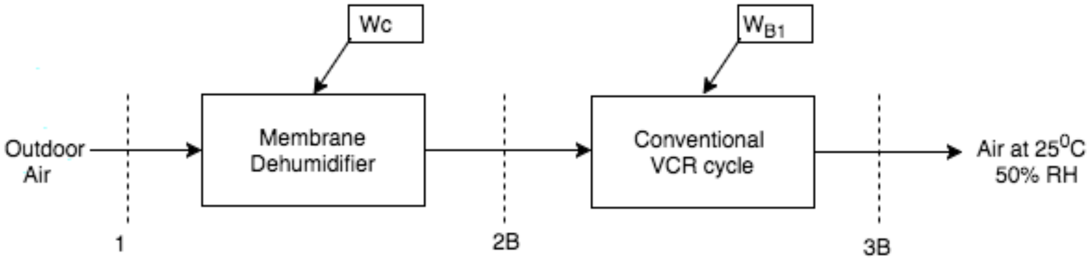

Figure 27: Schematic of Claridge-Culp-Pate cooling process

The work associated with the membrane cooling system that follows path B is as follows:

- Work input to the dehumidification compressor (W_C)
- Work input to the VCR system through the VCR compressor thus cooling the dehumidified air (W_{B1}).

The total work associated with path B is $W_C + W_{B1}$

The cooling effect produced by both systems, namely the conventional VCR in path A and the membrane-enabled in in path B is equal as both systems operate between the same end points, Therefore the cooling load met by these systems for a given mass flow rate of air (m_a) is:

$$Q_{cool} = m_a(h_{4a} - h_{1a})$$

COP for Path A (Conventional System)

The COP for path A is the ratio of the cooling effect produced by the conventional air conditioner to the total work done to produce this cooling effect.

$$\mathrm{COP}_{A1} = \frac{Q_{cool}}{W_{A1}+W_{A2}}$$

where

$$W_{A1} = m_a \frac{(h_{1a}-h_{3a})}{(h_{1r}-h_{3r})} (h_{2r} - h_{1r})$$

The second work term (W_{A2}), which represents reheating work is to convert work energy and thermal energy to a similar cost level because, the actual COP definition is useful energy transfer (cooling effect) over the cost of energy in terms of energy, so that COP can be non-dimensional. Therefore 0.33 is an approximation that is based on an electrical work unit produced by a power plant requiring 3 times as much energy or 3 thermal units. It is similar to assuming 33% power plant efficiency.

$$W_{A2} = \frac{1}{3} Q_{reheat} = 0.33 \text{ x } m_a (h_{4A} - h_{3A})$$

It should be noted that the above thermal energy, replaced by a work term might be supplied by combustion of a fossil fuel that contributes to energy cost. However, another possibility is that no reheat occurs or the warmer outdoor air through a heat exchanger provides it. Either way reheat, W_{A2} is taken out of the COP equation.

COP of path A has been calculated for two conditions namely, with reheat and without reheat. COP_{A1} represents the COP of the cycle with one third of reheat work accounted to calculate the COP. The second condition COP_{A2} does not account for this work for reheating the air from state 3A to 4A ($W_{A2} = 0$). This case assumes that the outdoor air supplies enough work to reheat the cooled air from state 3A to 4A. Therefore the COP without accounting for reheat is:

$$COP_{A2} = \frac{Qcool}{W_{A1}}$$

$$W_{A1} = m_a \frac{(h_{1a} - h_{3a})}{(h_{1r} - h_{3r})} (h_{2r} - h_{1r})$$

COP of Path B

The COP of path B is calculated for two cases as presented below.

<u>Case - B1</u> (Decoupled membrane dehumidification and VCR systems)

The first case is when the membrane dehumidification unit and vapor compression unit are disconnected and no interaction is observed between the two units.

COP in this case is calculated as the ratio of cooling capacity (which is same as path A) to the total system work; that is combined membrane dehumidifier work (W_C) and the VCR cycle work (W_{B1}) as shown in the previous Figure.

$$\mathrm{COP}_{B1} = \frac{Q_{cool}}{W_C + W_{B1}}$$

where, the CCP work is

$$W_C = m_a\, \Delta\omega w$$

$$W_{B1} = m_a \frac{(h_{3b} - h_{2b})}{(h_{1R} - h_{3R})}\ (h_{2R} - h_{1R})$$

Case- B2 (Coupled System)

The second case under consideration is the use of water vapor from the dehumidification membrane to cool the air exiting the dehumidifier. Here the dehumidification membrane is coupled with the conventional cooling system (VCR) such that the water vapor leaving the dehumidification membrane is first condensed to liquid water at its dew point temperature, and this water is then used to reduce the temperature of outdoor dehumidified air. Doing so helps reduce the cooling load and hence the net work input required by the conventional vapor compression system (VCR). The COP for this case is determined as,

$$\mathrm{COP}_{B2} = \frac{Q_{cool}}{W_C + W_{B1}}$$

Where

$$W_C = m_a\, \Delta\omega W$$

$$W_{B1} = m_a \frac{(h_{R2} - h_{R1})}{(h_{1R} - h_{3R})} (h_{1B} - h_{3B})$$

Presentation of Results and Plots

The COP of both these paths (A and B) were determined and compared for each of the aforementioned conditions under two circumstances, as follow:

1. Ideal heat exchanger scenario ($\Delta T=0$)
2. Real-world heat exchanger scenario ($\Delta T\neq 0$).

The assumed temperature differences for the real-world heat exchanger were 5^0C between the airside and the condensing fluid, 8^0C difference between the airside and the evaporator refrigerant for a conventional VCR cycle, and finally a 3^0C difference for the compressor condenser in case of the membrane dehumidifier.

The calculated COPs are represented in the table for each of the two cases, namely path A and B and subcases, namely $\Delta T = 0$ or $\Delta T \neq 0$ for a real word heat exchanger.

Table 6: : Conventional and membrane enabled cooling comparison for ΔT=0

T_{OUT}	**phi**	**ΔT**	**Q_{cool}**	**Work-Path A**		**Work - Path B**		**COP(A)**		**COP(B)**	
				A2	**A1**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**
(C)	%	(C)	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$				
30.00	40.00	0.00	6.97	1.20	5.00	0.08		1.39	5.80	84.74	
30.00	60.00	0.00	20.88	2.11	5.91	0.96	0.62	3.53	9.88	21.71	33.76
30.00	80.00	0.00	35.02	3.04	6.84	2.25	1.90	5.12	11.52	15.57	18.46
30.00	100.00	0.00	49.42	3.98	7.78	3.86	3.86	6.35	12.41	12.78	12.79
35.00	40.00	0.00	21.16	2.78	6.58	0.86	0.43	3.22	7.61	24.64	48.76
35.00	60.00	0.00	39.92	4.38	8.18	2.91	2.17	4.88	9.11	13.71	18.38
35.00	80.00	0.00	59.11	6.02	9.81	5.53	5.06	6.02	9.82	10.70	11.69
35.00	100.00	0.00	78.76	7.70	11.50	8.80	8.80	6.85	10.23	8.95	8.95
40.00	40.00	0.00	38.02	5.44	9.23	2.58	1.62	4.12	6.99	14.76	23.49
40.00	60.00	0.00	63.17	8.20	12.00	6.40	5.11	5.26	7.70	9.86	12.35
40.00	80.00	0.00	89.09	4.73	8.52	11.41	10.62	10.45	18.85	7.81	8.39
40.00	100.00	0.00	115.83	14.00	17.79	17.16	17.16	6.51	8.28	6.75	6.75

Table 7: Conventional and membrane enabled cooling comparison for ΔT= 3/5/8

T_{OUT}	**phi**	**ΔT**	**Q_{cool}**	**Work-Path A**		**Work - Path B**		**COP(A)**		**COP(B)**	
				A2	**A1**	**B1**	**B2**	**A1**	**A2**	**B1**	**B2**
(C)	**%**	**(C)**	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$				
30	40	5	6.97	1.57	5.37	0.14		1.30	4.44	51.38	
30	60	5	20.88	2.76	6.55	1.42	1.11	3.19	7.57	14.71	18.88
30	80	5	35.02	3.96	7.76	3.13	2.84	4.51	8.83	11.19	12.32
30	100	5	49.42	5.19	8.99	5.19	5.19	5.50	9.51	9.52	9.52
35	40	5	21.16	3.58	7.38	1.18	0.72	2.87	5.91	17.93	29.40
35	60	5	39.92	5.64	9.44	3.80	3.00	4.23	7.07	10.51	13.29
35	80	5	59.11	7.76	11.55	7.00	6.47	5.12	7.62	8.45	9.13
35	100	5	78.76	9.92	13.71	10.88	10.88	5.74	7.94	7.24	7.24
40	40	5	38.02	6.99	10.78	3.44	2.26	3.53	5.44	11.05	16.85
40	60	5	63.17	10.44	14.24	8.25	6.51	4.44	6.05	7.66	9.70
40	80	5	89.09	14.08	17.87	14.28	13.30	4.98	6.33	6.24	6.70
40	100	5.	115.83	17.82	21.62	21.10	21.10	5.36	6.50	5.49	5.49

Observations of the results tabulated above, shows that the membrane enabled dehumidification and cooling produces COPs higher than conventional VCR air conditioning systems for nearly all outdoor air conditions of temperature and humidity. Specifically one can see that the COP (B) is larger than COP(A) for cases 1and 2 and for $\Delta T = 0$ or $\Delta T \neq 0$.

The path A and path B COP ratios are divided into two categories to observe the effect of using the dehumidifier condensed water to cool the VCR condensed air, referred to as coupling. The two categories shown thus are coupling and decoupling. In each plot a series of 4 subplots are plotted representing $\Delta T = 0$ and $\Delta T \neq 0$ either with or without reheat.

Additional insight regarding performance differences between path A (conventional) and path B (membrane dehumidification) can be gained by forming the ratio of COP(B) and COP(A) so that if the value of this ratio is greater than unity then the novel cooling system outperforms the conventional VCR system. Plotting these ratios for various conditions and parameters can then be used to analyze results.

Path A and B Comparison – Reusing Condensed Water

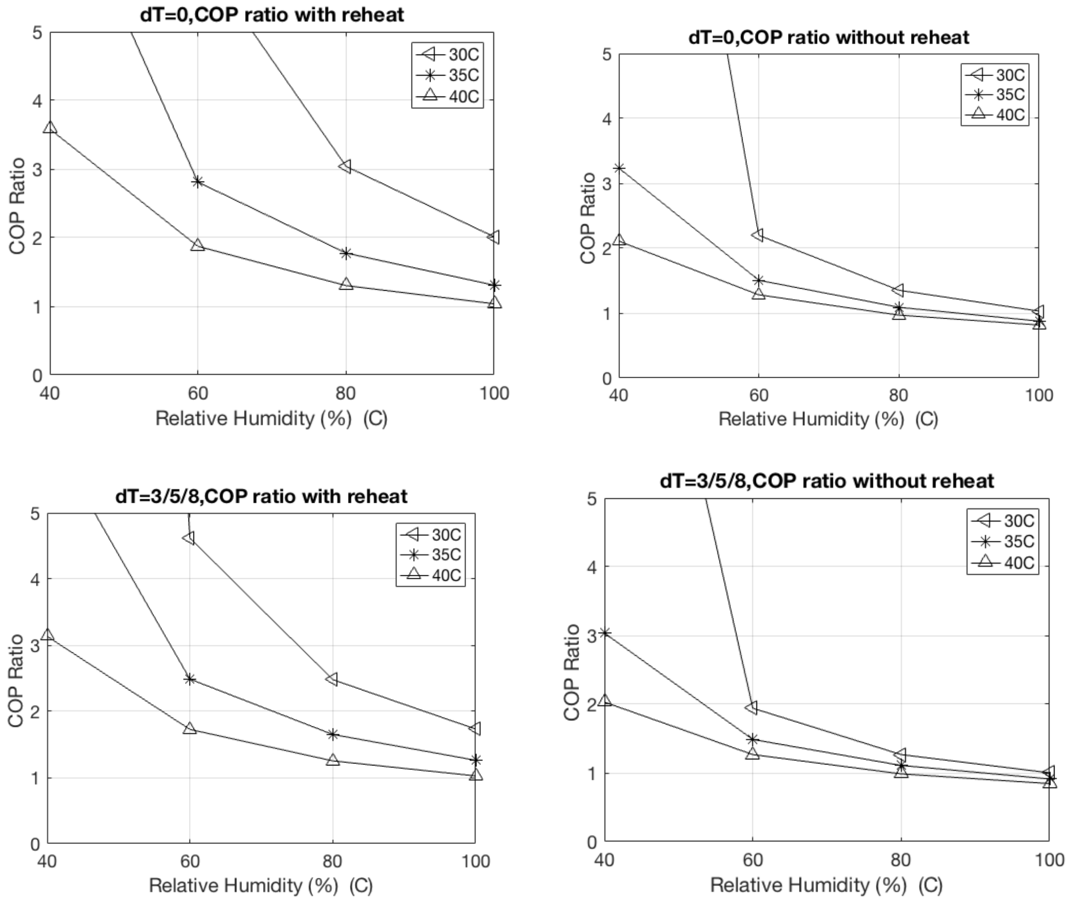

Figure 28:COP ratio of membrane enabled cooling to conventional cooling without coupling between systems

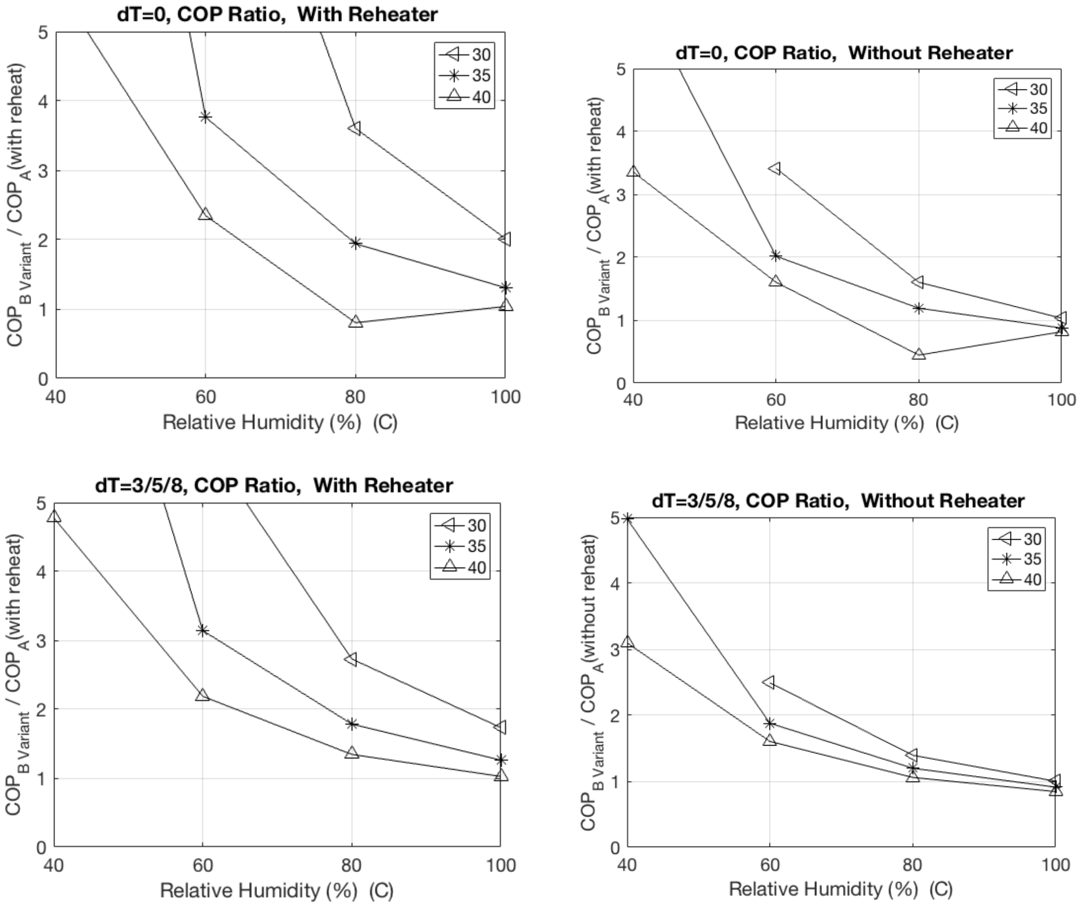

Figure 29: COP ratio of membrane enabled cooling to conventional cooling with coupling between the two systems

Analysis of Results

The tables and plots presented in this chapter are analyzed and compared in order to provide insight into how the novel membrane dehumidification system (Path B) behaves, compared to the conventional VCR system (path A). Of particular importance are insights provided by the plots of COP ratio. Major observations of the results are presented below.

For the range of humidities investigated (40% to 100%), the COP ratio decreases as the outdoor the relative humidity increases. This trend indicates that at outdoor conditions where the relative humidity is high, the advantage of operating a membrane dehumidification cooler decreases against the VCR cooler. The rate of decrease of this ratio is found to be a maximum between 40 and 60 % relative humidity and the gradient being reduced with increase in relative humidity.

This behavior of decreasing ratio as the relative humidity increases can be accounted for by looking at the COP trends of conventional VCR cooler and the CCP cooler. Referring to values in the table, the COP of the conventional cooler increases with the increase with relative humidity of outdoor air while the COP of the CCP cooler decreases, owing to an increase in the compressor power required to compress additional moisture extracted from humid air.

The COP values in the table also show that COP of the CCP cycle decreases with increase in outdoor temperature because the water vapor compressor requires more work to compress vapor to a higher temperature, while the COP of conventional VCR increases with an increase in temperature. The result of these opposing effects, the ratio decreases as the outdoor temperature rises, meaning the advantage of the membrane dehumidifier system over the VCR system decreases. Even still, the ratio is greater than unity, in fact, even larger than 5, which is the maximum value shown at the highest outdoor temperature of 40^0C.

It can also be seen in the ratio plots that the existence of reheat in the VCR system magnifies the advantage of the membrane dehumidification system. Specifically, for all other conditions being the same the ratio for VCR system with reheat is found to be the highest.

Another observation from the ratio plots is for all other conditions being similar, coupling increases the ratio. In other words, the advantage of path B is magnified over the path A (VCR air conditioning system) if the liquid water produced by the membrane dehumidification system is added to the VCR system that cools the dry air. Specifically, this liquid water evaporatively cools to the wet bulb temperature, the outdoor air used to remove the heat from the VCR condenser.

A final observation from the ratio plot is to compare cases representing ideal heat exchanger to cases with real-world heat exchangers. The plots show that the assumed temperature difference only have a minor effect on the COP ratio, meaning that the analysis is somewhat independent on the accuracy of ΔT assumptions. The reason for this maybe that the COPs are affected similarly if ΔT assumptions are applied equally to path A and B. With this said, there is a slight increase in the ratios as real-world heat exchanger with non-zero temperature difference between air and the fluid are assumed.

CHAPTER X

CLARIDGE-CULP-PATE REFRIGERATION CYCLE MODEL

Background of CCP Cycle

A new cooling cycle has been developed based on configuring membrane-enabled dehumidification in a closed loop with an evaporative cooler. This novel approach is known as the Claridge-Culp-Pate refrigeration cycle (CCP).

This cycle works by using moist air and water as the refrigerants, transporting heat between two heat exchangers. A stream of dry air is created as moist air flows through the membrane dehumidification unit by transferring water vapor through the membrane to a low-pressure region. The low-pressure water vapor is compressed to a higher pressure where it can be condensed by transferring heat to an evaporatively cooled outdoor air or cooling tower water.

The liquid condensed water is injected into an evaporative cooler and dry air exiting the membrane dehumidifier decreases the temperature to the wet bulb value while increasing the humidity of the air. This cool, humid air is passed through a heat exchanger to complete the cycle. The above components and fluid flow paths that make up the CCP cycle are shown in Figure 29.

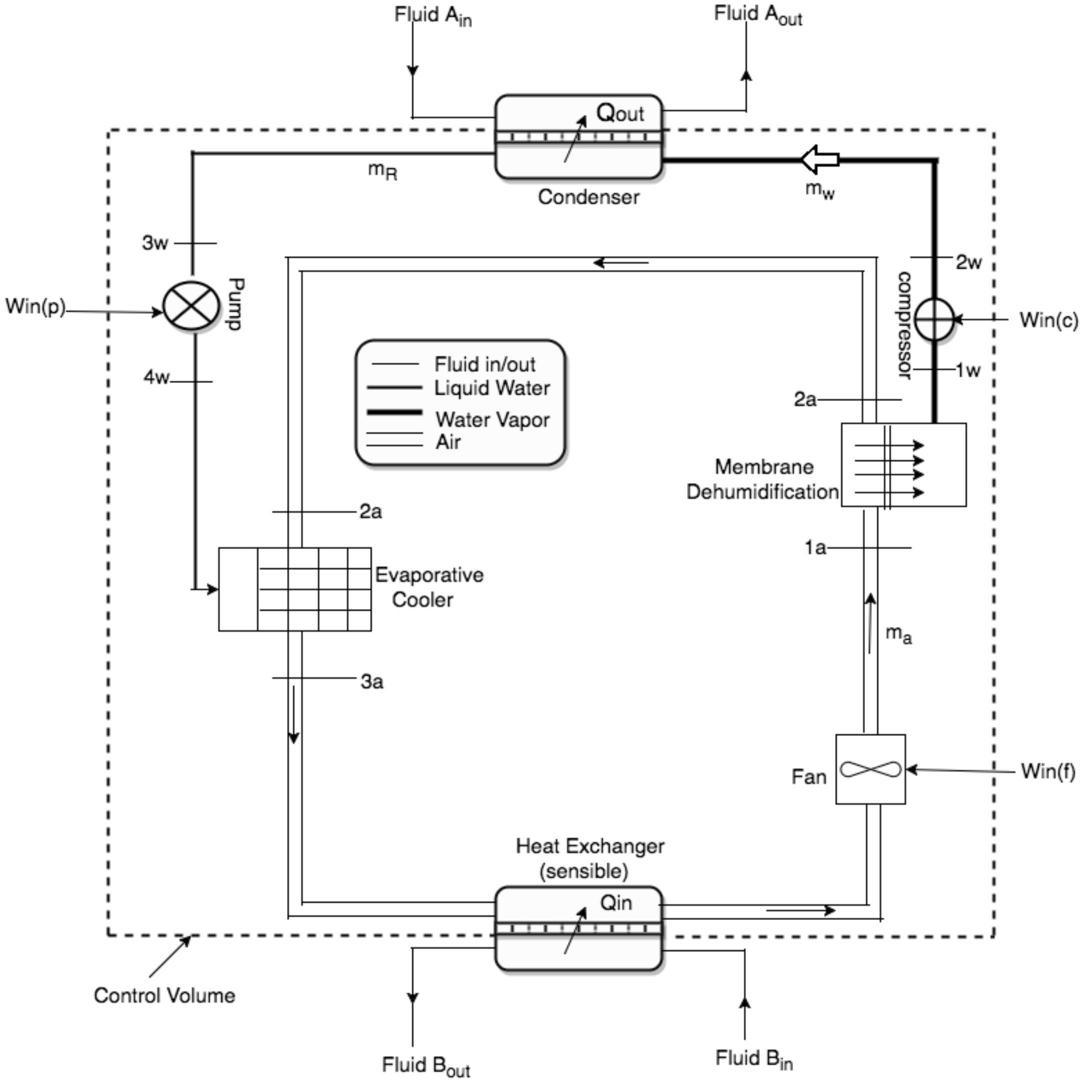

Figure 30: Schematic of a theoretical Claridge-Culp-Pate refrigeration cycle

CCP Cycle State Points

The performance of the CCP cycle is affected by the properties of dry air and water vapor mixture at certain critical locations in the cycle, which are inlet and exit points of each component. The schematic of the CCP cycle shows these critical locations, and they are marked by a series of numbers and letters. A brief description of the thermodynamic and physical conditions of both air and water vapor at these locations is presented below.

Air Conditions and States

1a - Warm Humid Air: Warm humid air exits the heat exchanger after providing a useful cooling effect (i.e. removing heat from a fluid being cooled). This warm air mixture is represented as point 1 on a CCP cycle psychrometric chart and by state 1a on the Figure.

2a - Warm Dry Air: Warm air entering the dehumidifier at state 1a losses water vapor and exits the dehumidifier at 2a on the schematic and is represented by state 2 on a psychrometric chart of a CCP cycle.

3a - Saturated Cool Air: After warm dry air at state 2a is cooled to its wet bulb temperature by an evaporative cooler the resulting cool saturated air exits the evaporative cooler at 3a on the schematic and is represented on the psychrometric chart.

Water Vapor Conditions and States

1w – Extracted water vapor: As hot humid air passes through the membrane dehumidifier, water vapor is transferred through the membrane while, the stream of dry air passes through the air side of the membrane unaffected (2a). The water vapor that is separated from air goes to the low-pressure side of the membrane and is shown in state 1w.

2w - Compressed vapor – The water vapor separated from the moist air mixture is compressed from low pressure point 1w to high-pressure point at 2w by the compressor. The temperature of water vapor at 2w depends on the compression process, however the state is superheated vapor.

3w – The compressed vapor at 2w is passed through a condenser where it is condensed to a liquid with the condensation temperature corresponding to the saturation pressure. This condensed cool water exiting the condenser is represented by state 3w, which is typically a saturated liquid, but can also be in its subcooled state.

4w -The liquid water exiting the condenser is where it is collected and then pumped to the atmospheric pressure at state 4w and then injected into an evaporative cooler.

Components of CCP Cycle

The function and operation of each component in the Claridge-Culp-Pate cycle is listed and described below along with associated energy or mass flow parameters and appropriate assumptions.

Membrane-dehumidification Unit

This CCP cycle component separates water vapor from a flowing moist air stream, hence drying the air stream, by transferring water vapor through the membrane subjected to different pressure conditions on either side. The result is that warm humid air enters the unit and a drier air with a reduced humidity ratio exits. This process of air and water vapor separation is assumed to take place in an isothermal process.

Evaporative Cooler

Warm dry air that exits the membrane dehumidifier needs to be cooled before it can be passed through the sensible heat exchanger. An evaporative cooler brings about this cooling of hot dry air by vaporizing liquid water injected into the stream of warm dry air. As a result of this process, exiting the evaporative cooler is cool air that has been saturated to its wet bulb temperature. The process of evaporative cooling is assumed to take place at constant enthalpy.

$$h_{2a} = h_{3a}$$

Heat Exchanger (sensible)

Cool moist air exiting the evaporative cooler is passed through a sensible heat exchanger where the air – vapor mixture absorbs heat from fluid B, which could be either air or water. This heat gain, which represents the cycle's cooling capacity, is assumed to take place in the sensible region, meaning that heat gained during this process does not alter the phase of either of the mixture components but only increases the temperature of the air-vapor mixture. The vapor content of moist air is assumed to stay constant, which corresponds to a constant humidity ratio process. The heat gained by the vapor-air mixture is determined as:

$$Q_{in} = m_a C_p (T_{out} - T_{in})$$

Compressor

The water vapor extracted from the moist air by the membrane in the membrane dehumidifier is sent to a compressor where it is pressurized. Pressurizing the vapor plays a key role in determining the COP of the CCP cycle as the work done in running the compressor dominates the energy input into the cycle and the COP is assumed as follows.

$$COP = \frac{Q_{cool}}{m_a W_C}$$

where compressor work (W_C) is determined either for an isothermal or for single and double-stage adiabatic cases.

Condenser

The high-pressure water vapor exiting the compressor is condensed in a heat exchanger condenser, which is at a saturation temperature corresponding to the compressor exit pressure. The heat removed is transferred to either water or air at a lower temperature that is approximately the wet bulb temperature of the outdoor. In the case of cooling fluid being water, it comes from a cooling tower and in case of air it comes from evaporative cooler.

Pump

Condensed water leaving the low-pressure condenser is pumped back to atmospheric pressure to the evaporative cooler. The work supplied to the pump is negligible when compared to work supplied to run the compressor and is neither a part of COP nor the theoretical system model.

Fan

A fan in the closed air loop circulates the moist and dry air through the three major components, namely membrane dehumidifier, evaporative cooler and sensible heat exchanger. In that order, the work supplied to the fan has thus been neglected, assuming to be small compared to work supplied to run the compressor. The work input to fan us not included in the theoretical CCP model herein.

Special Considerations for the CCP Cycle

Similar to a vapor compression cycle, the COP of the membrane dehumidification cycle is the ratio of the useful cooling effect produced to the total work input to produce this cooling effect.

$$\text{COP} = \frac{Useful\ Cooling\ Effect}{Total\ Work\ input}$$

However, determining the COP of the Claridge-Culp-Pate cycle is not as straight forward as in the case of conventional vapor compression cycle (VCR) because of the following reasons:

1) Work input in case of vapor compression cycle (VCR) is the work done in compressing the refrigerant. However, in case of the Claridge-Culp–Pate cycle, the total

work input into the system is the sum of work done in running the membrane compressor, the fan used to circulate air in the closed loop and the pump that is used to circulate the condensed water. However, with that said, just as the theoretical VCR model neglected air fan work or water pump work in the case of chilled water, so does the theoretical CCP model that is the focus of this chapter.

2) The water vapor extracted from the dehumidification membrane is compressed, condensed and then re-circulated to the evaporative cooler in order to reduce the temperature of the working fluid (i.e. dry air) increasing its humidity ratio. It is essential to consider the effect of re-circulation of condensed water on the COP of the system. Similarly, the different processes taking place in the three major components of the airside also affect the COP. The bottom line is that the CCP model is more complicated than the VCR model and requires more assumptions.

3) In case of a vapor compression system, the refrigerant is treated as a pure substance whereas in CCP cycle, the working fluids are a mixture of air and water vapor, pure water and dry air or at least close to it at the dehumidifier exit. This necessitates the study of operations at different humidity ratios and its effect on the performance of the cycle. Simply out, the VCR cycle has multiple working fluids.

Representation of CCP Cycle on a Psychrometric Chart

The CCP cycle is a closed loop system that that was shown on Figure 29 schematic and can also be shown on a psychrometric chart as in Figure 30. The representation of the airside loop of the CCP cycle can be plotted on a psychrometric chart; however, this chart is not applicable to the waterside loop. The working of a CCP cycle in terms of air-loop processes and state points on a psychrometric chart are described below:

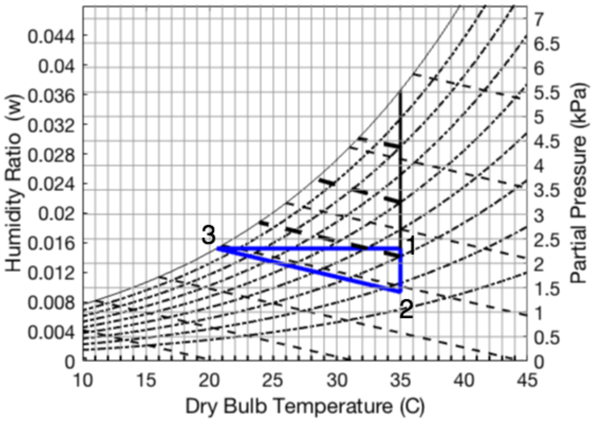

Figure 31: Representation of Claridge-Culp-Pate cycle on a psychrometric chart

Warm humid air at a high humidity ratio, starts off the cycle at point 1, when the air enters the dehumidifier. The outdoor air temperature limits the temperature at point 1; meaning that the outdoor air is a maximum temperature point. However the actual temperature at point 1 is dependent on the entering temperature of the fluid being cooled in the heat exchanger.

Air exits the membrane dehumidifier at point 2, which a preset vapor pressure or assumed depending on the waterside compressor inlet pressure. Specifically, the vapor pressure at point 2 must be higher than the compressor inlet so that the water vapor can be transferred through the membrane driven by a pressure difference. For the theoretical model, the assumptions are, a minimum partial pressure and zero pressure difference.

This dry air at point 2 is then cooled to its wet bulb temperature using an evaporative cooler. This is represented by point 3 in the above psychrometric chart.

Saturated cool air from point 3 is then sent to a sensible heat exchanger where it gains heat to reach it's original temperature, reducing the relative humidity in the process.

Of special importance, as can be seen on the psychrometric chart, the partial pressure and hence humidity ratio is determined by the wet bulb temperature at point 3. The process from point 3 to 1 on the chart is a horizontal line because the moist air increases its temperature along a constant humidity ratio process through the sensible heat exchanger. The change in moist air enthalpy from point 3 to 1 represents the CCP cooling capacity of the CCP cycle. The major work input into the cycle is the compressor work, which is used to operate the compressor that functions to dehumidify the air from point 1 to point 2. This compressor work is dependent on the inlet partial pressure, which is dependent on point 1and on the water vapor mass passing through the membrane, which is dependent on the humidity ratio difference between points 1 and 2 shown on the psychrometric chart.

As one can see from the above discussions, it is essential to determine all the state points of this cycle based on assumed properties and conditions along with an air-side component process and behaviors before proceeding with the developing the model to determine the COP of the cycle.

Procedure for Determining State and Process Variables

The theoretical CCP cycle model is based on using the component model to solve for state and process variables depending on inputs and available assumptions. The equations used to determine the actual state points and process variables are derived and presented below. The theoretical CCP model is based on point 2 being known after values for temperature and pressure are assumed. Once state 2 is defined, then states 1 and 3 are on the airside as can be seen on the psychometric chart. Specifically state 2 air passes through the evaporative cooler then it exits at T_3 or the wet bulb temperature. Next, the intersection of horizontal line and T_2 defines state 1.

The steps below describe the procedure to be followed by the CCP cycle model in determining the numerical values of state points.

Input: P_{V2} and T_2

State 2: $\omega_2 = \frac{0.622\ x\ P_{V2}}{101.325 - P_{v2}}$

$$\phi_2 = \frac{101.325 \text{ x } \omega_2}{P_{sat2}\ (0.622 + \omega_2)}$$

$$h_2 = (1.007T_2 - 0.026) + \omega_2(2501 + 1.84T_2)$$

State 3: $h_3 = h_2$

$\phi_3 = 1$

$P_{V3} = P_{sat3}$

Model finds T_3 from tables using the relation h_3=h_2 and $P_{V3} = P_{sat3}$

$$h_3 = (1.007T_3 - 0.026) + \omega_3(2501 + 1.84T_3)$$

$$\omega_3 = \frac{0.622\ x\ P_{V3}}{101.325 - P_{v3}}$$

State 1: $\omega_1 = \omega_3$

T_1=T_2

$$\phi_1 = \frac{101.325 \text{ x } \omega 1}{Psat2\ x\ (0.622 + \omega 1)}$$

$$h_1 = (1.007T_1 - 0.026) + \omega_1(2501 + 1.84T_1)$$

Process Variables

In addition to the above state points, the process variables can also be found. Specifically, the energy transfer (Q_{in}) and mass transfer (m_a,m_v) for the major components can be calculated based on energy and mass balance, as was shown in earlier chapters. The results were

$$m_v = m_a \Delta\omega$$

$$Q_{in} = m_a C_p (T_{out} - T_{in})$$

$$Q_{in} = m_a C_p (T_{out} - T_{wb-outdoor})$$

It is essential to determine other process variables of the cycle such as a compressor work by using equations presented in the earlier chapter.

COP of CCP cycle

Work input for compressors and the assumed cooling capacity is used to calculate COPs for CCP cycle. A total of three COPs can be calculated for any assumed state 2 and outdoor air condition; one COP for each compressor type. The COP is determined by using the following relation:

$$\text{COP} = \frac{Q}{m_v \ X \, W_c}$$

The procedure described above was used to develop a benchmark model, which is used in calculating the CCP cycle COP for all the cases of this work.

A validation check was also done to determine the accuracy of the described model by comparing it with manual calculations. The outdoor condition for this verification was assumed to be 35^0C and 60% relative humidity. The state 2 inlet temperature is also 35^0C and the partial pressure for the membrane outlet is assumed to be 1.5 kPa. These values were chosen as they represent the mid-range of input conditions that were used in an extensive analysis of CCP cycle performance in the next chapter.

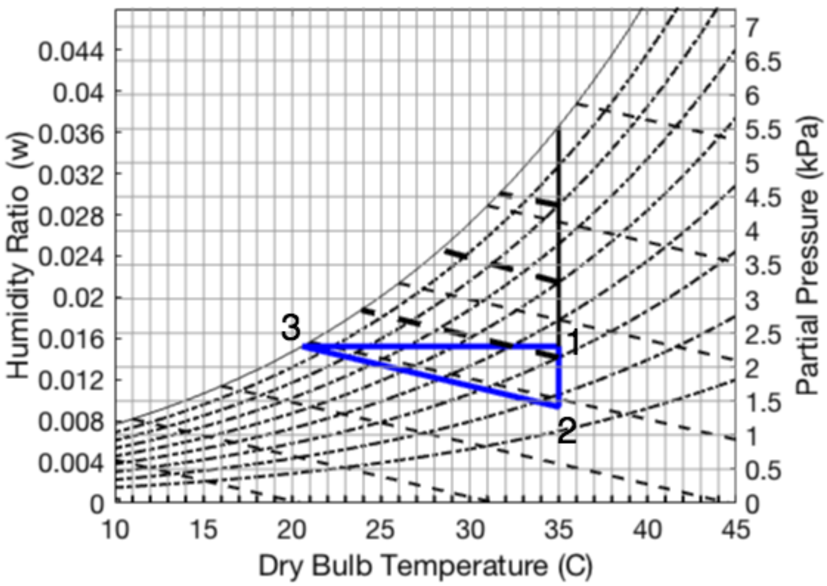

Figure 32: Representation of membrane enabled cooling cycle on a psychrometric chart

Sample CCP Cycle Performance Calculation

The CCP cycle model presented above was programmed and solved by matlab. Once it was programmed, the only input required to solve for all state points and process variables was the numerical values for state 2 partial pressure and temperature, in other words, one must assume a value for the dehumidification exit water vapor partial pressure and the temperature of air entering and leaving the dehumidifier.

As a check on computer model assumption, a hand calculation was performed as presented below, using all the equations presented earlier.

Calculations of State Variables

As a first step on calculating the performance variables, the dehumidifier exit temperature and partial pressure conditions of 35^{0}C and 1.5 kPa are assumed. State 2 with these assumed values can be seen in the psychrometric chart shown in Figure 32.

Input: $T_2 = 35^0$C $P_{V2}= 1.5$kPa

$P_{sat2} = 5.629$kPa

State 2

- Humidity Ratio

$$\omega_2 = \frac{0.622\ P_{v2}}{101.325 - P_v} = \frac{0.622\ X\ 1.5}{101.325 - 1.5} = 0.009364 \frac{kg_v}{kg_a}$$

- Enthalpy

$$h_2 = (1.007T_2 - 0.026) + \omega_2(2501 + 1.84T_2)$$

$$h_2 = (1.007 \times 35 - 0.026) + 9.34\times10^{-3}(2501 + 1.84\times35)$$

$$h_2 = 59.2 \frac{kJ}{kg}$$

- Relative Humidity

$$\emptyset_2 = \frac{101.325\omega_2}{P_{sat2}(0.622 + \ \omega_2)} = 26.6\%$$

State 3

The constant enthalpy process in the evaporative cooler along with the assumption that that the moisture exits at a saturated relative humidity (i.e.100%) fixes state 3 as follows:

$$h_3 = h_2 = 59.2\frac{kJ}{kg}, \emptyset_3 = 1$$

- Temperature
  $From\ Tables\ ; T_3 = 21^0C$

- Humidity Ratio

$$h_3 = 59.2 = (1.007T_3 - 0.026) + \omega_3(2501 + 1.84T_3)$$

$$\omega_3 = 0.015\ \frac{kgv}{kga}$$

- Vapor Pressure

$$P_{v3} = \frac{101.325\omega_3}{\omega_3 + 0.622} = 2.4\ kPa$$

State 1

The sensible heat is a constant humidity ratio process with flowing air absorbing heat until its temperature reaches T_2 such tha$_t$ T_1=T_2 , with the result being

$$P_{v1} = P_{v3}2.4\ kPa\ ; T_1 = 35^0C\ ;\ \omega_1 = \omega_3 = 0.015\frac{kga}{kga}$$

- Enthalpy

$$h_1 = (1.007T_1 - 0.026) + \omega_1(2501 + 1.84T_1)$$

$$h_1 = 73.4\frac{kJ}{kg}$$

- Relative Humidity

$$\emptyset_1 = \frac{101.325\omega_1}{P_{sat1}(0.622 + \ \omega_1)} = 42.3\%$$

The above-calculated state variables are summarized in the table shown below and compared to computer program values. Also shown are the percentage differences between calculated and program values with differences being typically less than 1%.

Table 8: Validation of state variables by manual comparison

State	**T (C)**		**h (kJ/kg)**		**Phi (%)**		**W (kgv/kga)**		**Pv (kPa)**	
	Calc	Prog	Calc	Prog	Calc	Prog	Calc	Prog	Calc	Prog
1	35	35	73.4	74.2788	42.3	43.01	0.015	0.0152	2.4	2.421
2	35	35	59.2	59.1961	26.6	26.65	0.0093	0.0093	1.5	1.5
3	21	20.556	59.2	59.1961	100	100	0.015	0.0152	2.4	2.421

Percent Errors

Error%	0.000	1.183	1.651	1.316	0.867
	0.000	0.007	0.188	0.688	0.000
	2.160	0.007	0.000	1.316	0.867

Calculation of Mass Flow Variables

Just as state 2 numerical values were assumed, a value for cooling capacity rate is also assumed. As a result, mass flow rate of both water and air can be calculated along with compressor power and their COPs. For this calculation, a cooling capacity of 1 ton is selected.

$$Q_{ref} = 1\,Ton = 3.516\,kW;\ \Delta h = h_1 - h_2 = 14.3\,\frac{kJ}{kga}$$

And knowing that

$$Q_{ref} = m_a h \Delta\omega$$

And rearranging, the dry air mass flow rate is calculated as follows

$$m_a = \frac{Q_{ref}}{\Delta\omega} = \frac{3.516\ kW}{5.65\times10^{-3}\frac{kgv}{kga}\times2564.5\frac{kJ}{kgv}}$$

$$m_a = 0.2458\frac{kga}{sec}$$

$$m_v = m_a\Delta\omega = 0.2458\frac{kga}{sec} = 5.65\times10^{-3}\frac{kgv}{kga}$$

$$m_v = 0.0014\frac{kgv}{sec}$$

Calculation of Compressor Work and COP

The previous state point calculations were for the closed cycle air-loop, represented by three state points 1-3, with additional assumptions about outdoor air required to solve for work and COP. The reason is because ultimately heat is rejected to the outdoor from the condenser located downstream of the compressor. An additional assumption is that the temperature of the condensing water vapor must be greater than the fluid removing condenser heat so a temperature difference ΔT is assumed, which ultimately determines the compressor outlet pressure and the pressure ratio.

- Assumed Conditions for outdoor air

$\mathrm{T_{outdoor}} = 35^0\mathrm{C}$; $\emptyset_{\mathrm{out}} = 60\%$; $\mathrm{T_{wb}} = 28^0\mathrm{C}$

$\Delta\mathrm{T} = 4^0\mathrm{C}$; $\mathrm{T_{condenser}} = \mathrm{T_{wb}} + \Delta\mathrm{T} = 32^0\mathrm{C}$

- Compressor and Condenser Pressure Conditions

$\mathrm{P_2} = \mathrm{P_{sat}(condenser)} = \mathrm{P_{sat}}(32) = 4.4\ \mathrm{kPa}$

$$\text{Compressor Pressure Ratio} = \frac{P_{out}}{P_{in}}\frac{4.4}{1.5} = 2.93$$

$$\text{Intermediare pressure} = P_i = \sqrt{P_1P_2} = 2.57\ \text{kPa}$$

$$\text{Pressure ratio for 2 stages} = PR_{3i} = 1.713$$

Isothermal Compressor Work

$$W_{\Delta T} = RT \ln\frac{P_2}{P_1}$$

$$W_{\Delta T} = \frac{308K\times 8.314 \times 10^3}{18}$$

$$W_{\Delta T} = 153\ \frac{kJ}{kg}$$

One-stage Adiabatic Compressor Work (n=k=1.34)

- Outlet Temperature

$$T_2 = T_1(PR)^{\frac{n-1}{n}}$$

$$T_2 = 308\ (2.93)^{\frac{0.34}{1.34}}$$

$$T_2 = 404.6\ K$$

- Work

$$W_{\Delta S} = C_P(\Delta T)$$

$$W_{\Delta S} = 2\frac{kJ}{kg}(404.6 - 308)K$$

$$W_{\Delta S} = 193.2\ \frac{kJ}{kg}$$

Two-stage Adiabatic Compressor Work

- Intermediate and outlet temperatures

$$T_{iout} = T_1(PR)^{\left(\frac{n-1}{n}\right)}$$

$$T_{iout} = 308(1.713)^{\frac{0.34}{1.34}} = 353K$$

$$T_{iin} = T_{dew}(T_1) = T_{dew}(35) = 26.3^0C$$

$$T_2 = (26.3 + 273)(1.713)^{\frac{0.34}{1.34}}$$

- Work

$$W_{\Delta S} = C_P(\Delta T)$$

$$W_1 = 2\frac{kJ}{kg}(353 - 308)k = 90\frac{kJ}{kg}$$

$$W_2 = 2\frac{kJ}{kg}(353 - 299.3)k = 87.4\frac{kJ}{kg}$$

$$W_{\Delta S_2} = W_1 + W_2 = 177.4$$

Calculation of COP (Cycle Performance)

$$COP = \frac{Q_{ref}}{m_v W_{compressor}} = \frac{3.516\ kW}{0.0014\ W_c}$$

Substituting for compressor works each of the 3 cases

Isothermal COP = $COP_{\Delta T=0} = 16.41$

Isentropic COP (1 stage) $= COP_{\Delta S_1=0} = 13$

$$\text{Isentropic COP (2 stage)} = \text{COP}_{\Delta S_2=0} = 14.18$$

The above calculated process and performance variables are summarized in table 10 and also compared with program values.

Table 9: Validation of Process variables of Claridge-Culp-Pate process

	Calc	**Prog**	**%Error**
m_a(kg/sec)	0.24	0.235	1.911
m_v(kg/sec)	0.0014	0.0013	1.156
W_dt	153	152.59	0.269
Wds1	193.2	192.67	0.275
Wds2	177.4	177.05	0.198
COP_dt	16.41	16.46	0.296
COP_ds1	13	13.03	0.268
COP_ds2	14.18	14.18	0.034

CHAPTER XI

CASE 2 – PERFORMANCE COMPARISON OF CCP AND VCR CYCLES

Background

The CCP cycle model developed in the previous chapter and used to calculate the state variables, compressor work and the coefficient of performance (COP) for one set of conditions is now used for studying the performance of CCP cycles for a wide range of conditions. Specifically, the output of the CCP cycle model for a range of input variables, form the basis for an analysis of how the cycle performance varies with outdoor and state 2 conditions. These results will be useful for developing the operating conditions of the CCP cycle, for setting the state 2 conditions, and for identifying locations and outdoor weather conditions conducive to use of the CCP cycle technology.

The modeling and analysis in this chapter assumes that the outdoor temperature and the state 1 and 2 temperatures are equal, hence coupled. This assumption is referred to as Case 1 in contrast to the Case 2 modeling and analysis presented in the next chapter where the outdoor temperature is decoupled from the state 1 and 2 temperatures. Coupled temperatures in Case 1 and as presented in this chapter are where outdoor conditions and state 1 and state 2 temperatures are all equal, which can occur if the sensible heat exchanger cooling the outdoor air is 100% effective so that the airside outlet of the heat exchanger equals, but can not exceed, the inlet temperature of the fluid being cooled.

As mentioned in the earlier section, vapor compression is the most widely used refrigeration technology that is presently in use. Hence a detailed comparative study of the CCP cycle and VCR cycle is made and presented for a range of outdoor conditions and, in case of the CCP cycle, for a range of state 2 conditions.

The COP of two different cycles is compared for two different working conditions. With the first called Case 1A assuming an ideal CCP and VCR cycle, meaning a zero temperature difference exists between two fluids in the heat exchangers. The second working condition, called, case – 1B assuming the heat exchangers operate in real-world conditions of non-zero heat exchanger temperature differences between two fluids.

Assumed Case-1 Model Conditions

As was discussed in the first section, case 1 is when the outdoor temperature along with the state 1 and 2 temperatures are coupled, meaning equal to each other. As noted, the CCP cycle model is solved for a range of variables with the outdoor temperature varying between 20^0C and 40^0C in steps of 5^0C and the humidity ratio of the outdoor air varying between 40 and 80% in steps of 20% for each of these outdoor temperatures. Based on coupling, $T_1=T_2$ follows the above outdoor temperature values and increments. The vapor pressure at the exit of the membrane dehumidifier varies between 0.5kPa and 1.5kPa in steps of 0.5kPa for the outdoor temperature of 20^0C with this range being gradually increased for other temperatures until reaching 0.5kPa - 3kPa for an outdoor temperature of 40^0C.

Case -1: Airside State Points for the Ideal CCP Cycle ($T_{OUTDOOR} = T_1 = T_2$)

As a first step in comparing the theoretical Claridge-Culp-Pate cycle with a typical theoretical vapor compression cycle, psychrometric plots for the airside of the CCP cycle operating at the aforementioned assumed conditions were developed. Specifically each chart represents a CCP cycle working at a different membrane dehumidifier exit, water-vapor partial pressure and specific outdoor temperature, which is also equal to the inlet and exit temperatures of the membrane dehumidifier.

Each point on the psychrometric chart also represents an airside state point, either 1,2 or 3 as was discussed in the previous chapter. These state points correspond to inlets and exits of the three major airside components making up the CCP cycle, namely the dehumidification unit, the evaporative cooler and the heat exchanger as was shown in the Chapter 10 cycle schematic.

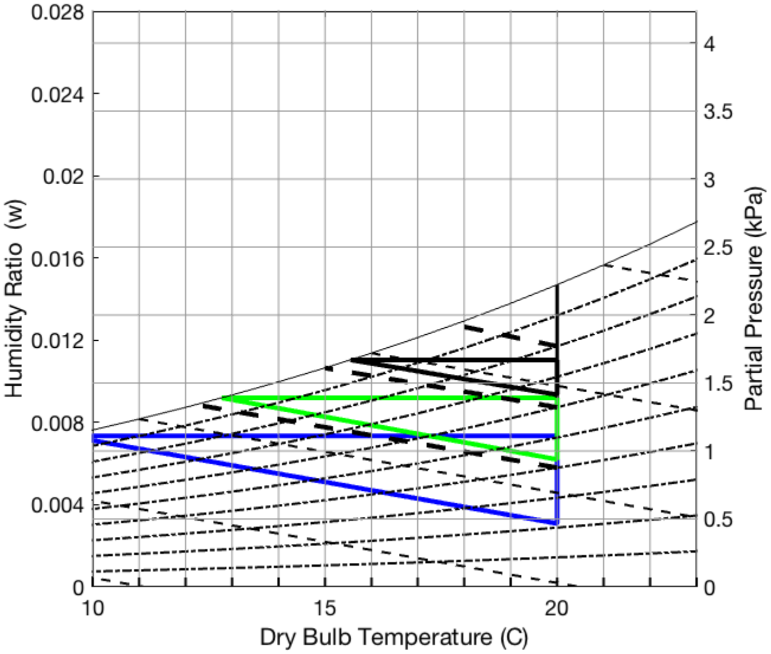

Figure 33: CCP cycle for different dehumidifier exit conditions at 20^0C

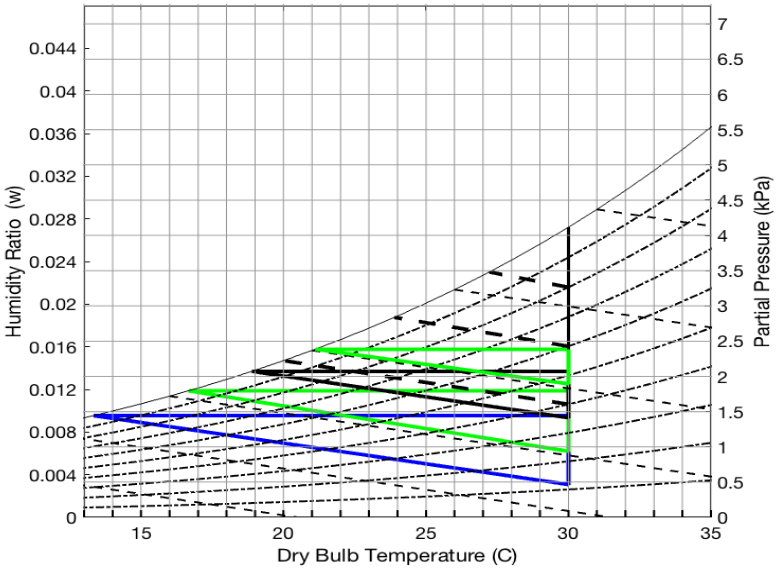

Figure 34: CCP cycle for different dehumidifier exit conditions at 30^0C

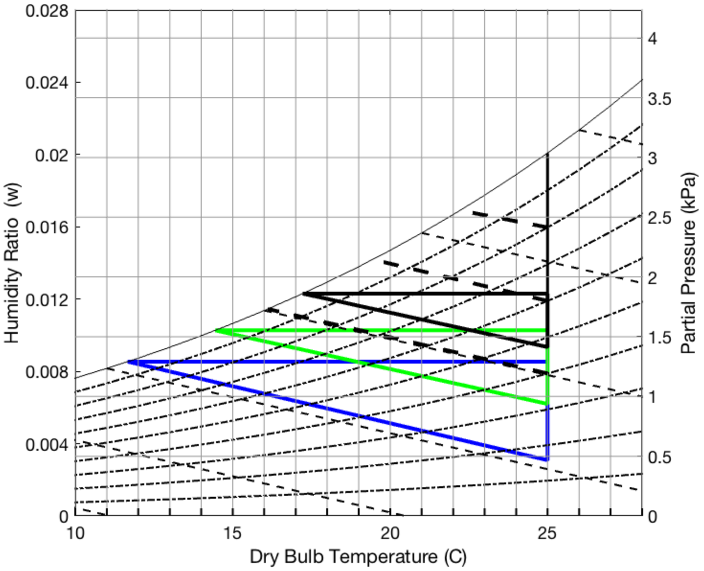

Figure 35: CCP cycle for different dehumidifier exit conditions at 25^0C

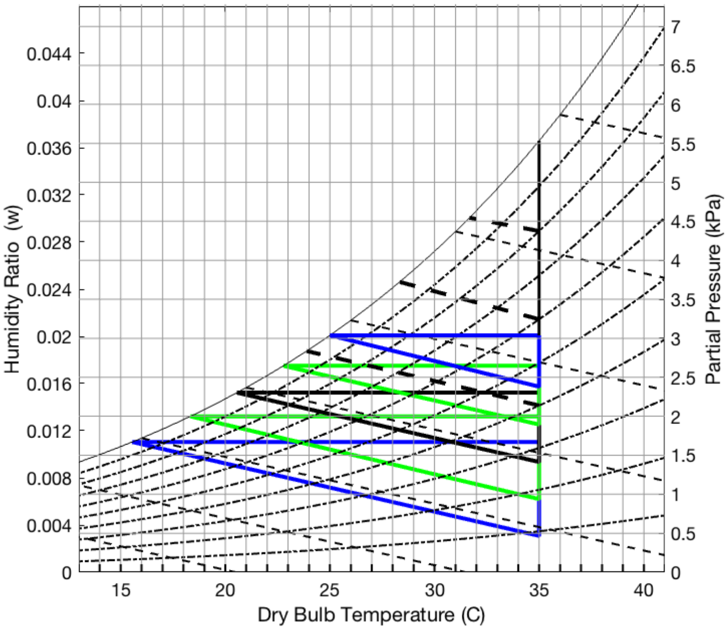

Figure 36: CCP cycle for different dehumidifier exit conditions at 35^0C

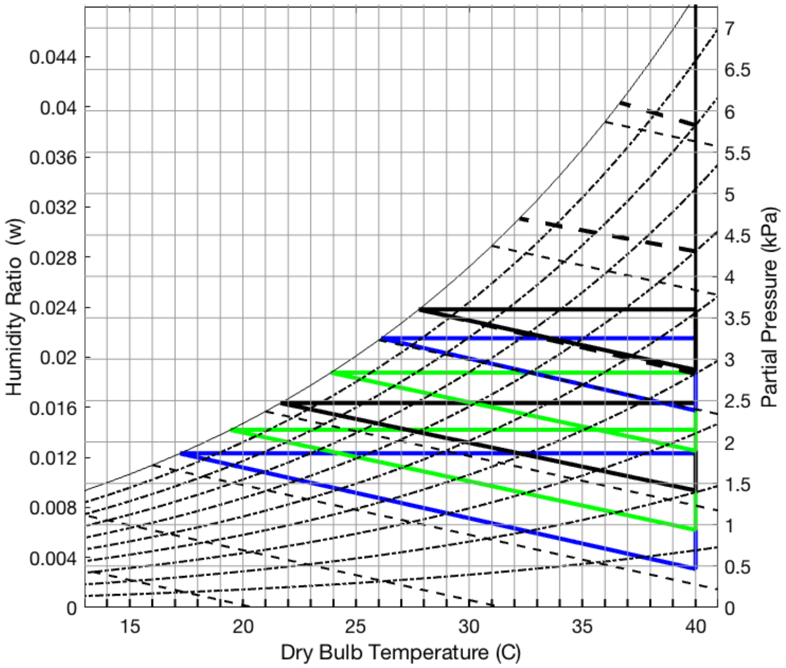

Figure 37**:** CCP for different dehumidifier exit conditions at 40^{0}C

A common theme that can be observed in all of the above psychrometric charts is that as the water vapor partial pressure is decreased from 3.5 kPa to 0.5 kPa, then the CCP airside temperature of the air entering the heat exchanger decreases. For example, the chart shown in Figure 36, namely, a 40^{0}C outdoor temperature, this temperature decreases from 30^{0}C at the highest pressure to 17^{0}C at the lowest pressure. Another example is the lowest outdoor temperature of 20^{0}C where the temperature range varies from 20^{0}C to 10^{0}C .

The above psychrometric charts, based on the CCP model, were used to find the humidity range change ($\Delta\omega$), through the dehumidifier and enthalpy change for the sensible heat exchanger as described in detail in the previous chapter, These two parameters are in turn used in sections that follow to find the airside flow and then the water vapor flow rate through the membrane. All of the state point variables shown in the above psychrometric chart are tabulated in Table 10, based on psychrometric chart values.

Table 10: Results of Claride-Culp-Pate cycle for different membrane operating temperatures and membrane exit conditions

$T_1 = T_2$	P_{V2}	$\omega_1 = \omega_3$	ω_2	$\Delta\omega$	T_3	h_1	h_2	Δh	$\Delta h/\Delta\omega$
(^{0}C)	(kPa)	$(\frac{kgv}{kga})$	$(\frac{kgv}{kga})$	$(\frac{kgv}{kga})$	(^{0}C)	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$
20	0.5	0.00735	0.00308	0.00426	9.4	38.77	27.99	10.77	2525.97
20	1	0.00920	0.00620	0.00300	12.8	43.46	36.06	7.40	2467.06
20	1.5	0.01105	0.00935	0.00170	15.6	48.14	43.58	4.57	2688.04
25	0.5	0.00854	0.00308	0.00546	11.7	46.90	33.26	13.64	2499.59
25	1	0.01027	0.00620	0.00407	14.4	51.31	40.48	10.83	2661.28
25	1.5	0.01231	0.00935	0.00296	17.2	56.49	48.49	8.01	2705.87
30	0.5	0.00954	0.00308	0.00646	13.3	54.58	37.50	17.08	2643.92
30	1	0.01187	0.00620	0.00567	16.7	60.53	46.81	13.72	2418.50
30	1.5	0.01370	0.00935	0.00435	18.9	65.19	53.73	11.47	2636.79
30	2	0.01577	0.01253	0.00324	21.1	70.49	61.28	9.21	2838.78
35	0.5	0.01105	0.00308	0.00796	15.6	63.55	43.58	19.98	2509.42
35	1	0.01322	0.00620	0.00702	18.3	69.13	51.94	17.19	2449.24
35	1.5	0.01523	0.00935	0.00588	20.6	74.28	59.33	14.95	2542.69
35	2	0.01751	0.01253	0.00498	22.8	80.13	67.42	12.70	2550.40
35	2.5	0.02009	0.01574	0.00435	25.0	86.75	76.31	10.44	2398.35
40	0.5	0.01231	0.00308	0.00922	17.2	71.94	48.49	23.45	2543.32
40	1	0.01419	0.00620	0.00799	19.4	76.79	55.55	21.24	2657.79
40	1.5	0.01633	0.00935	0.00698	21.7	82.30	63.28	19.01	2722.91
40	2	0.01876	0.01253	0.00623	23.9	88.54	71.76	16.78	2692.99
40	2.5	0.02151	0.01574	0.00577	26.1	95.62	81.08	14.54	2519.24
40	3	0.02380	0.01898	0.00482	27.8	101.53	88.69	12.84	2662.87

Case-1: CCP Cycle Process Variables

The CCP cycle model used to find the airside state points (1-3), as displayed on the above psychrometric charts and Table 11, is now used to compute process variables such as mass flow rates, energy transfers, and COPs. The process variables including the COP performance variable is determined for both the CCP cycle and a conventional VCR cycle operating with R-410a and water. Furthermore, the COP of the CCP cycle and VCR cycle is determined for two separate situations. The first situation (case - 1A) represents an ideal heat exchanger condition ($\Delta T = 0$) for the VCR and the CCP cycles and the second situation (case – 1B) represents the real-world working condition of heat exchangers in both the cycles (VCR and CCP) operating with temperature differences between the two fluids.

Case -1A: Description

This situation assumes ideal heat transfer for the evaporator and condenser, meaning $\Delta T = 0$, and compressor efficiencies of 100% for both cycles.

In this regard, these assumptions are mathematically described for the VCR cycle as follows:

1. The difference between the airside temperature and the refrigerant temperature of the VCR condenser is zero. [$\Delta T_{Condenser} = 0$]
2. The difference between airside temperature and the refrigerant temperature of VCR evaporator is zero. [$\Delta T_{Evaporator} = 0$]

3. The compressor functions ideally, meaning that the pressure on the high side of the compressor (P_2)is the saturation pressure (P_{SAT}) of the outdoor dry bulb temperature. Similar to item 3, above for the VCR compressor, the CCP cycle compressor outlet is at the saturation pressure of the outdoor wet bulb temperature.

Case -1B: Description

The second situation, designated as B, assumes more realistic conditions that represent the real-world situation with non-zero fluid temperature differences.

As before, only the VCR model assumptions are presented because the CCP cycle conditions were presented in a previous chapter. These VCR assumptions maybe mathematically described as follows:

1. The difference between airside temperature and the refrigerant temperature of the VCR condenser is 5^0C. [$\Delta T_{Condenser} = 5^0C$]
2. The difference between airside temperature and the temperature of VCR evaporator is 8^0C. [$\Delta T_{Evaporator} = 8^0C$]
3. The pressure on the high side of the VCR compressor (P_2) is the saturation pressure (P_{SAT}) of the refrigerant temperature that is slightly above (3^0C) outdoor dry bulb temperature.

For situation B, an important assumption is that the CCP cycle compressor outlet is the water-vapor saturation pressure for a temperature that is 3^0C higher than the outdoor wet bulb temperature.

Determining COP

Each outdoor temperature condition, which is also equal to the airside state 1 and 2 temperature ($T_1 = T_2$) shown previously in Table 10 was used to determine the compressor work for the CCP cycle for three assumptions namely, isothermal, two-stage isentropic and single-stage isentropic ($W\Delta_{T=0}$, $W\Delta_{S2=0}$ and $W\Delta_{S1=0}$). These three compressor works for the CCP cycle were in turn used to determine COPs for each of three compressors, for each outdoor temperature with four preset relative humidity values of 40%, 60%, 80% and 100%.

The VCR cycle model was also simulated for each temperature condition shown in Table 10, with the high side temperature being the outdoor temperature These simulations were repeated for two different working fluids, namely water and R-410A, so that the COPs for both water and R-410A can be compared to the CCP cycle COP values.

A table containing all the results pertaining to this case (case 1) is presented in the appendix.

Determining COP Ratios

The performance of the CCP cycle was compared to that of the conventional VCR cycle by forming COP ratios of the CCP to VCR cycles at the same condition. At each outdoor condition, a total of 5 COPs were determined, with 3 representing the COPs of the membrane dehumidification cycle for each of the 3 compressor assumptions and the remaining 2 representing the VCR system COPs operating with water and R-410 as the refrigerants.

A ratio value greater than unity signifies a better performance for the CCP cycle compared to the VCR cycle.

The 6 COP ratios based on COPs for the CCP cycle (3 COPs) and the COP of VCR cycle (2 COPs) were determined for each outdoor temperature and relative humidity. These ratios can be classified in two groups, one for water as the working fluid and the second for R-410A as the working fluid.

Case -1: Results and Analysis

Plots of COP ratios against the outdoor temperature were made for each CCP compressor assumption and the plots were sorted based on the relative humidity values. On each plot, lines of constant water-vapor partial pressure at the dehumidifier exit (Point 2), which is the same as the CCP compressor inlet, are created. The plots obtained are shown below with the CCP cycle performance referenced to R-410A presented first and then water as the VCR refrigerant presented second.

Case -1A: Plots for R-410A as VCR Working Fluid

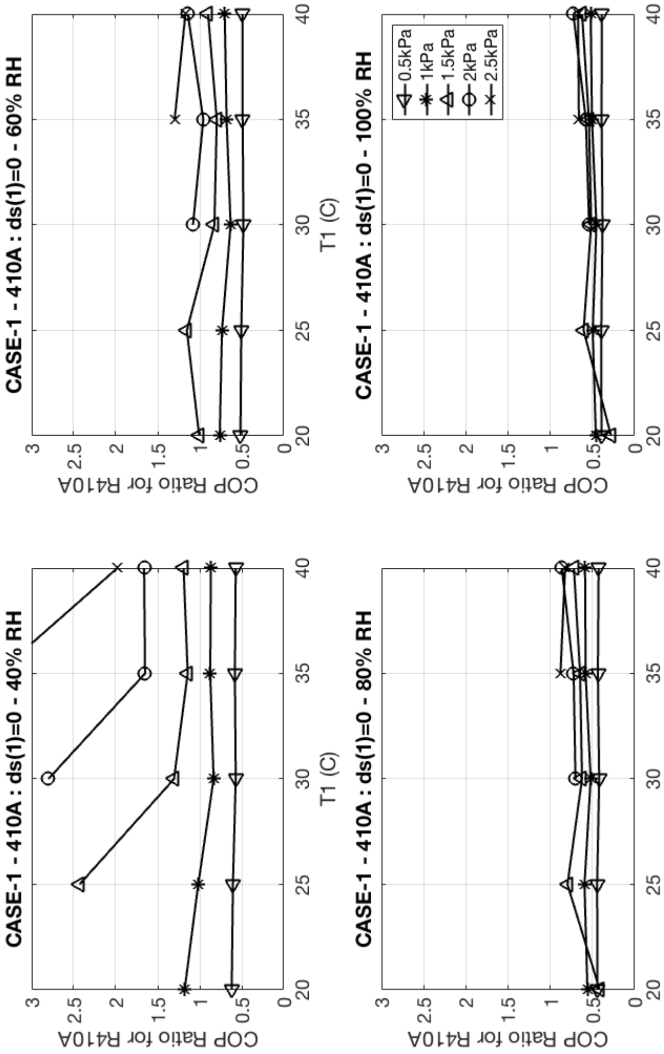

Figure 38: Single-stage adiabatic COP ratio for R410A with ideal condenser assumption

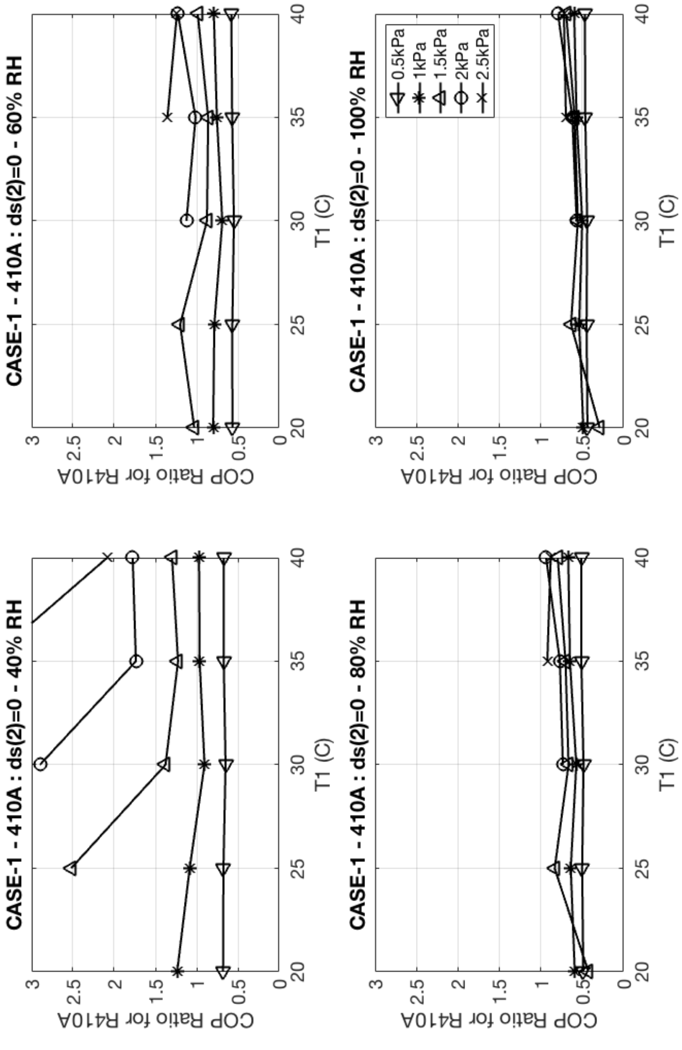

Figure 39**:** Double-stage adiabatic COP ratio for R410A with ideal condenser assumption

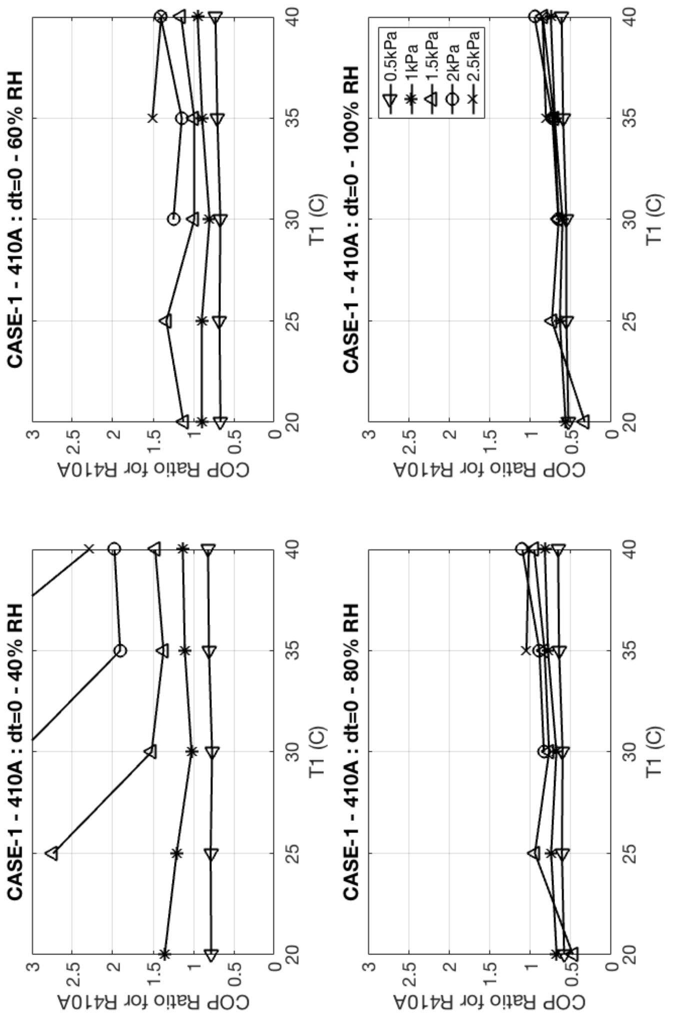

Figure 40: Isothermal COP ratio for R410A with ideal condenser assumption

Case 1A - Plots from Water as VCR Working Fluid

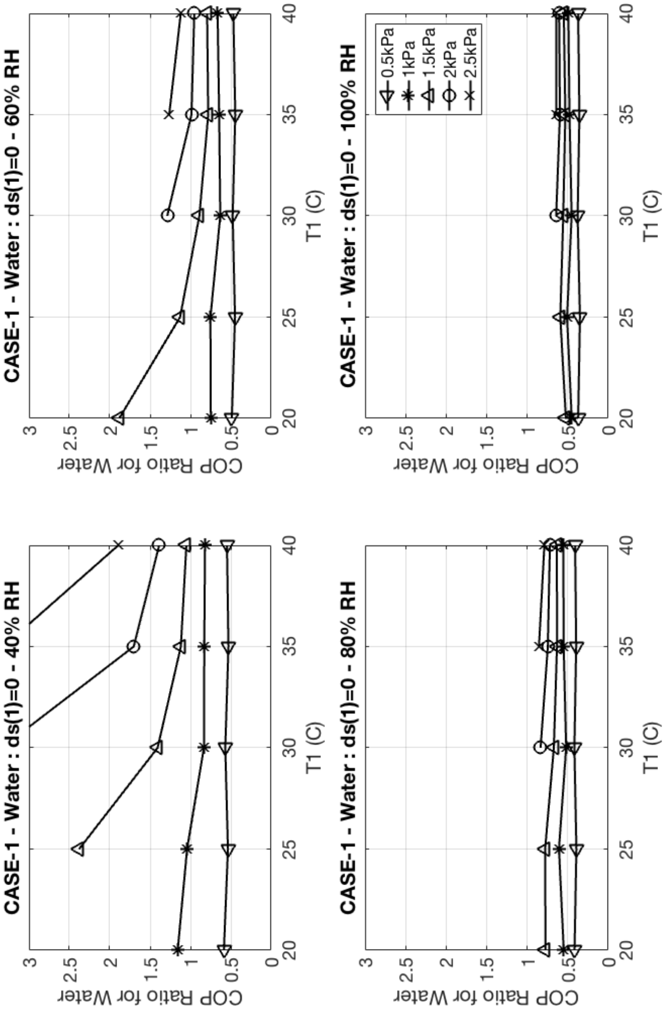

Figure 41: Single-stage adiabatic COP ratio for water with ideal condenser assumption

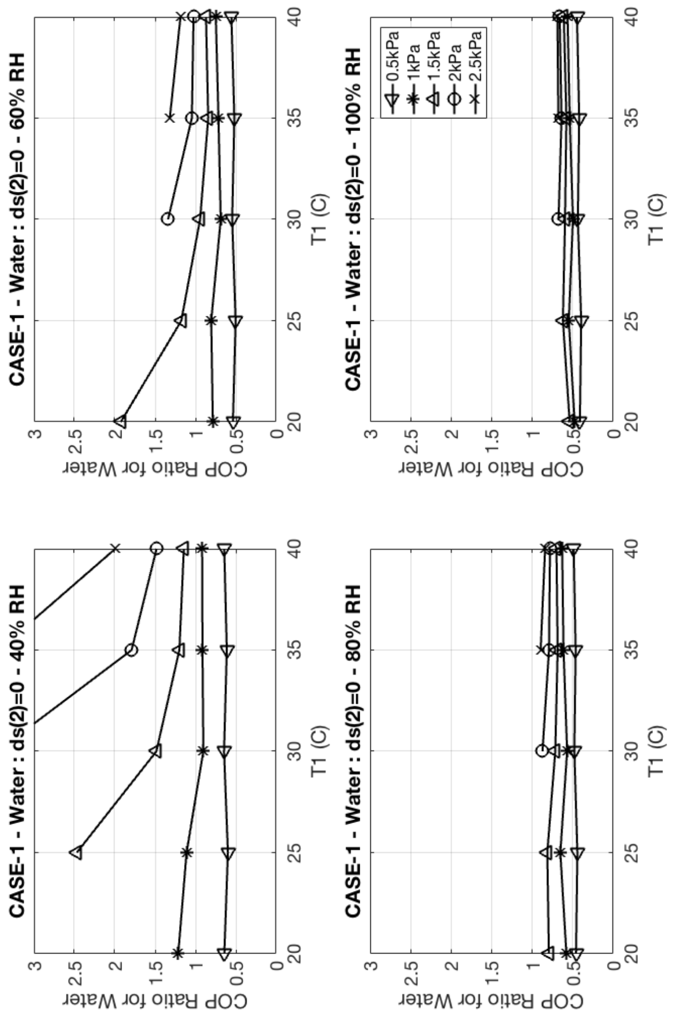

Figure 42**:** Double-stage adiabatic COP ratio for water with ideal condenser assumption

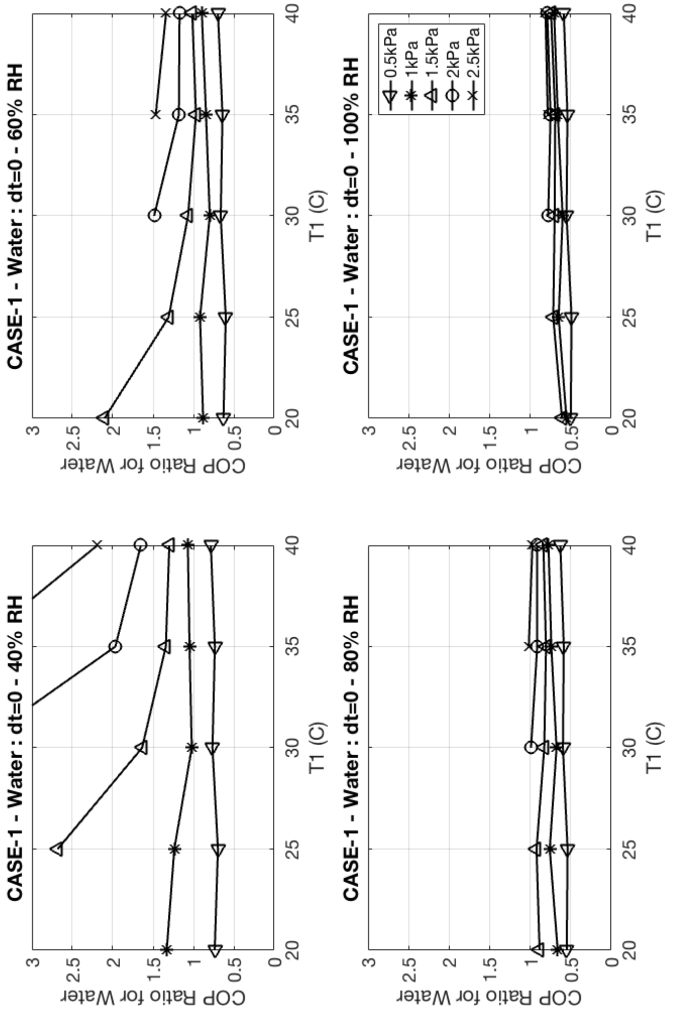

Figure 43: Isothermal COP ratio for R410A with ideal condenser assumption

Case-1A: Discussion

A number of important observations regarding the CCP cycle performance, relative to the conventional VCR cycle performance, can be made by analyzing the results in the ratio plots. These observations pertain to R-410A refrigerant only, which is presently used in actual systems. These important observations are:

1. The single-stage isentropic compressor requires the largest specific work and produces the lowest COP among the 3 COPs calculated for the CCP system, and as evidenced by the plots, the lowest ratio values. In contrast the isothermal water-vapor compressor for the CCP cycle has the highest ratios, with ratio values usually being greater than unity and sometimes much greater than unity. As discussed in the earlier chapter, it is possible for a water vapor compressor to operate isothermally but impossible for R410-A compressor, because the saturation condition is close to the isentropic process line.
2. It can be seen that the performance of the CCP cycle decreases or stays constant with outdoor temperature, and in most cases it outperforms the VCR system, meaning ratios are greater than unity even at higher temperatures.
3. It can be seen from the ratio plots that the CCP cycle performs best, based on high ratio values at lower outdoor relative humidities, similar to real-world conditions. At the lowest value of 40%, the COP ratio is 2 or greater even at the highest outdoor temperature of 40^0C for certain specified partial pressures. Only at the highest relative humidities of 80% and 100% does the CCP cycle have a reduced performance.

4. As shown in the plots, it is desirable to operate the CCP cycle at higher water vapor partial pressures. It may reduce the ability of the cycle to achieve lower temperatures, as was seen on the airside state points shown on the psychrometric charts presented in the previous section, but it still results in COP ratios greater than unity.

Case -1B: Results and Analysis

All the COP ratios and plots presented in the previous section were repeated for the non-ideal, real-world situation (Case 1-B) of the heat exchangers operating with temperature differences between the two fluids, discussed at the beginning of this section. All of the results pertaining to this subsection are provided in the Appendix, similar to case 1A.

Plots of COP ratios versus the outdoor temperatures for various partial pressures, relative humidities, compressor assumptions and VCR refrigerants are presented below for the case 1B situation.

Case-1B: Plots for 410A

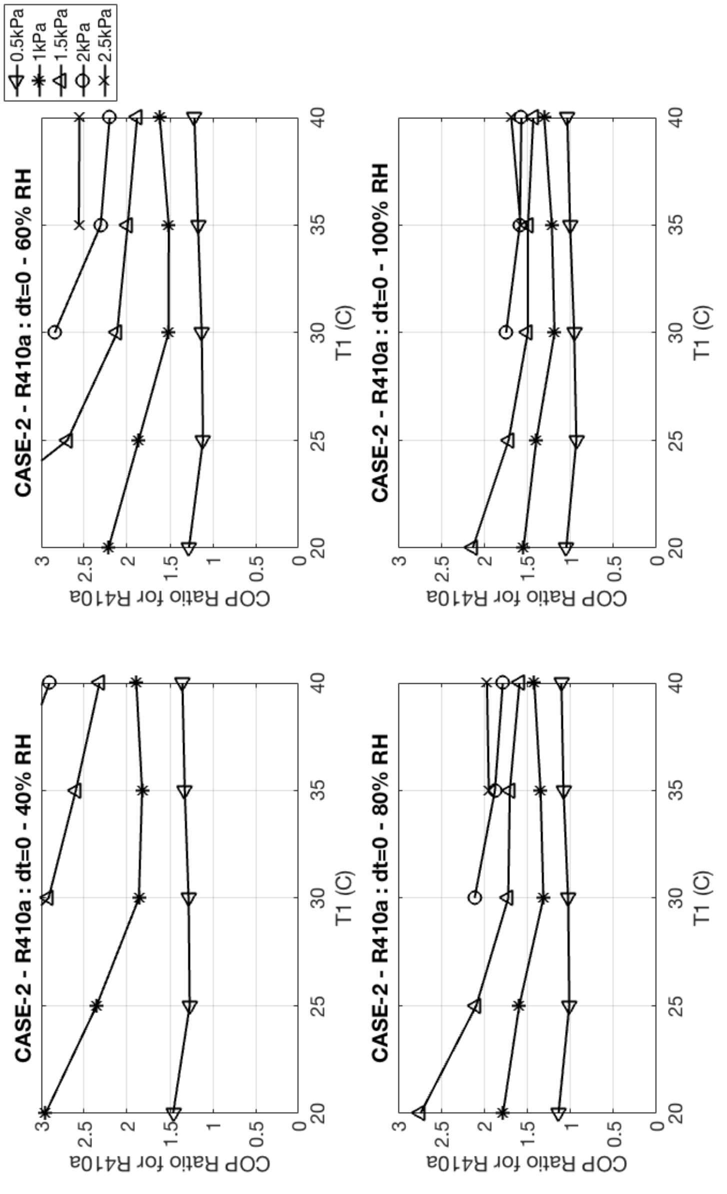

Figure 44: Isothermal COP ratios for R-410A

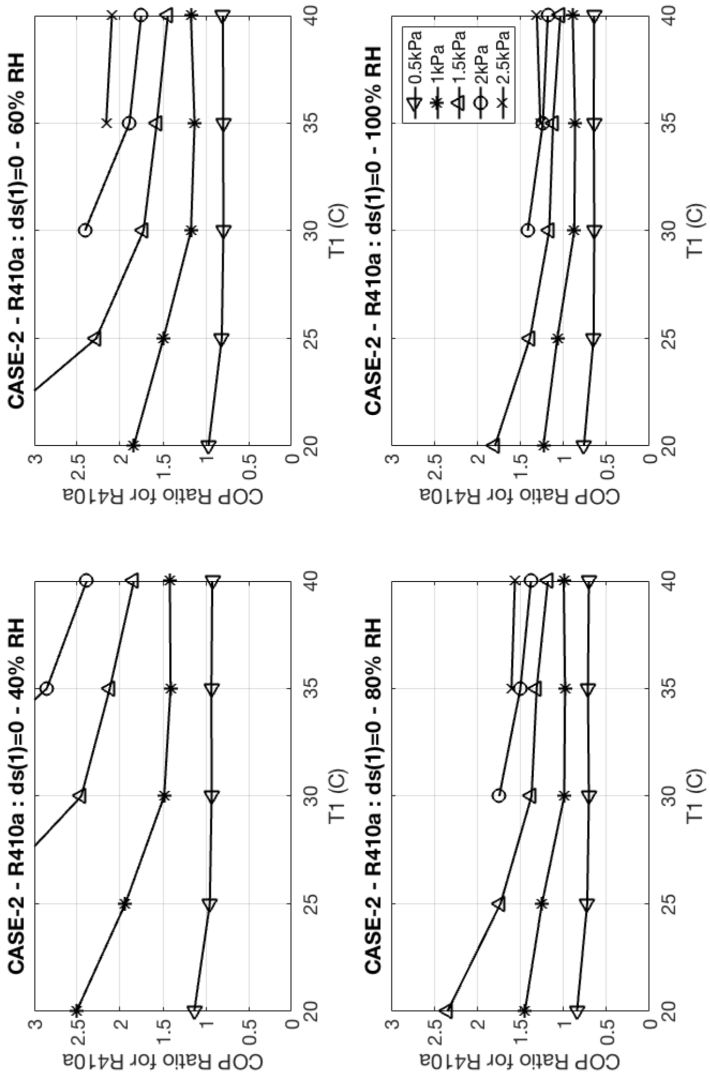

Figure 45: Single-stage adiabatic COP ratio for R410A

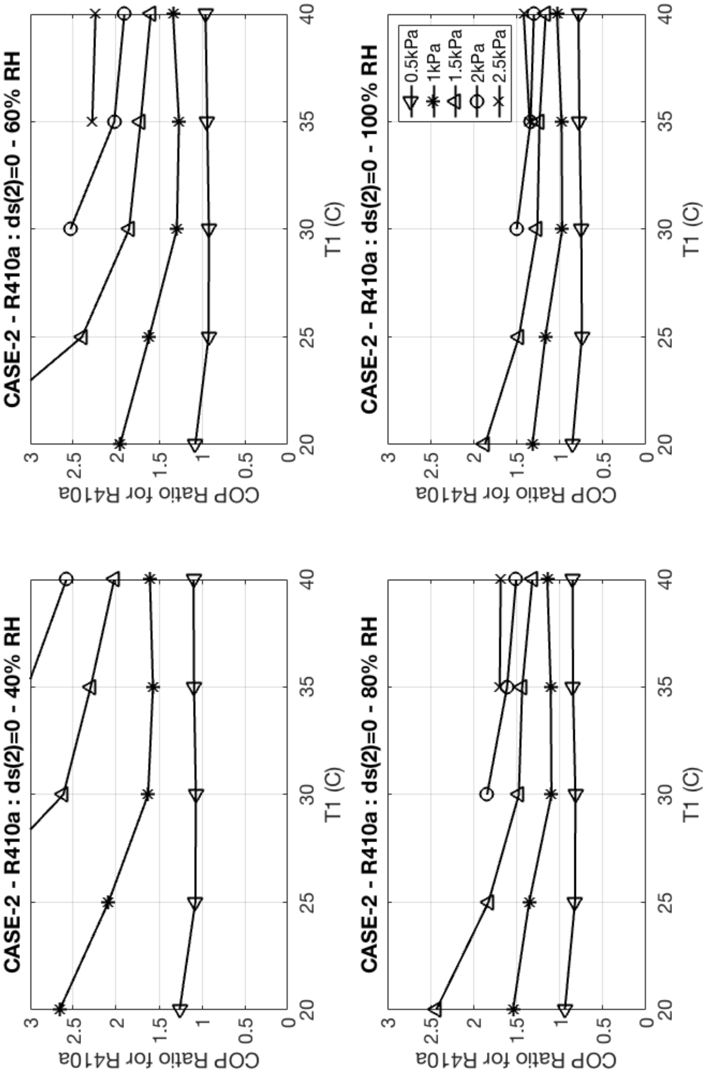

Figure 46: Double-stage adiabatic COP ratio for R410A

Case 1B -Plots for Water

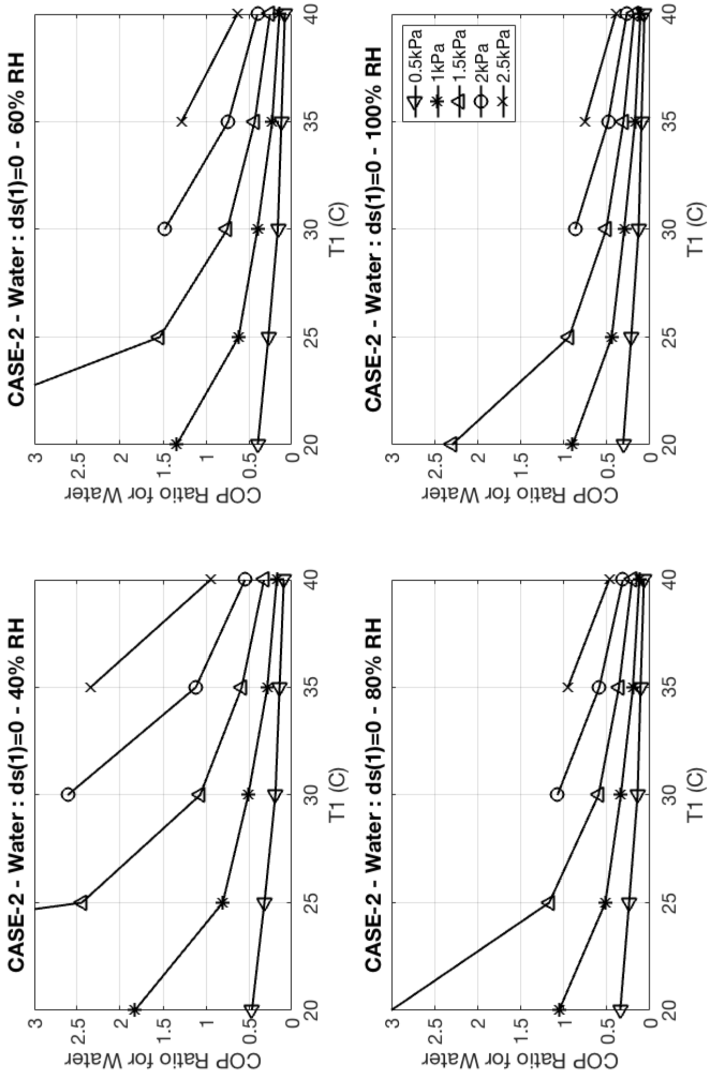

Figure 47: Single-stage adiabatic COP ratio for water

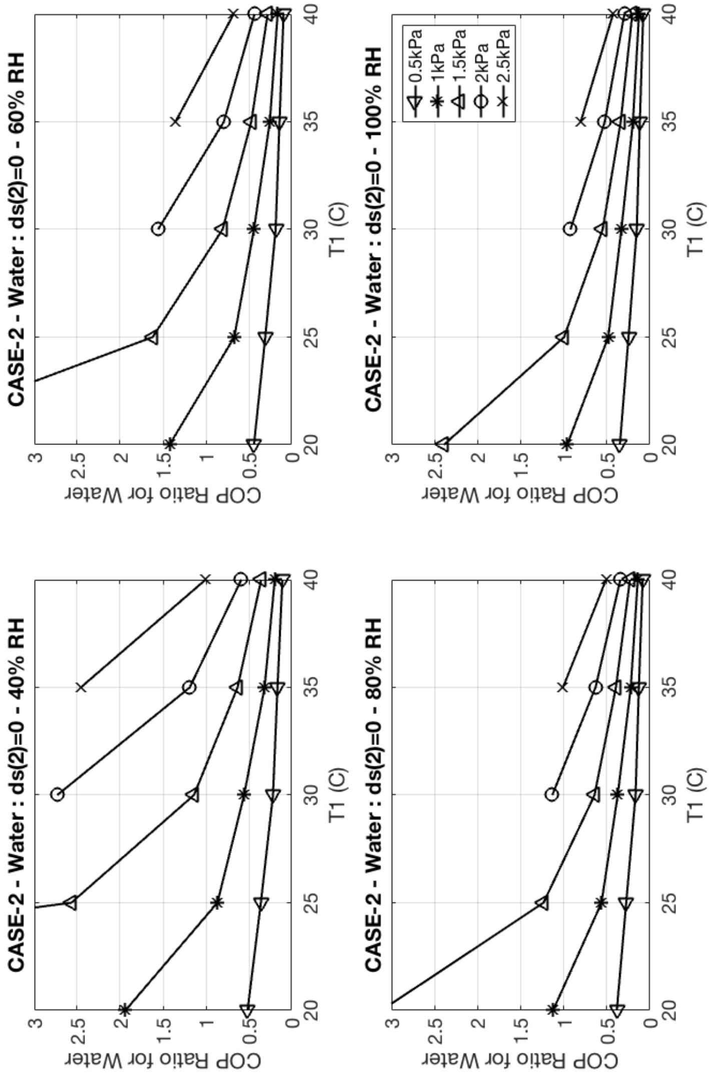

Figure 48: Double-stage adiabatic COP ratio for water

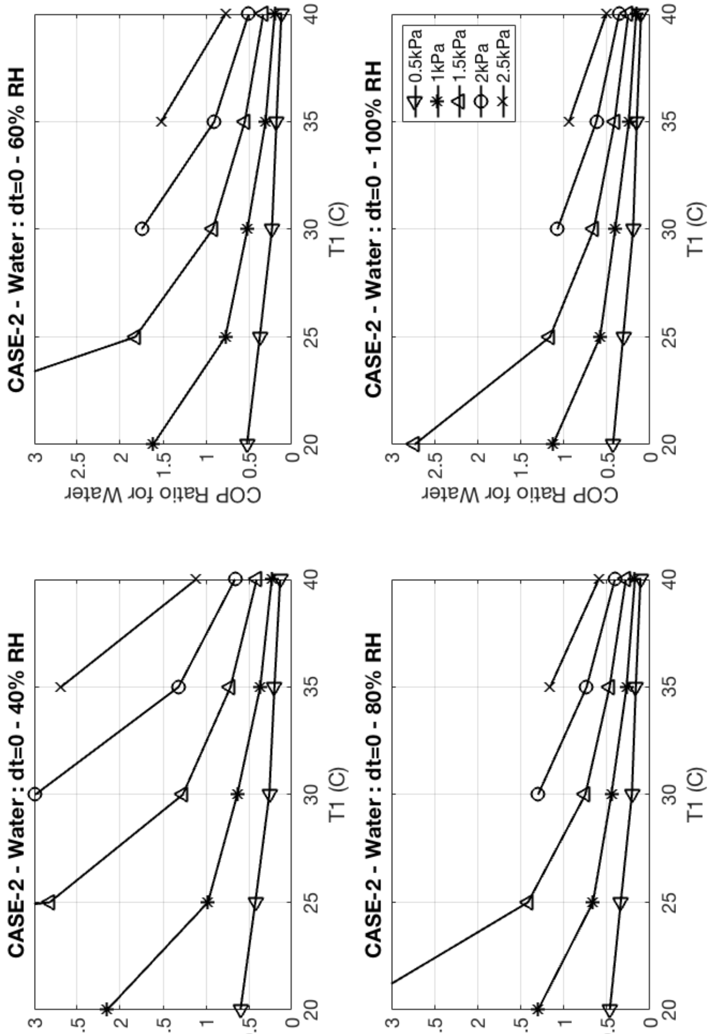

Figure 49: Isothermal COP ratio for water

Case -1B: Discussion

A comparison of ratio plots for the ideal (A) and real-world (B) temperature differences presented have shown that the performance of the CCP cycle is significantly increased for the situation of real-world heat exchanger conditions. Some of the observations presented below are similar to the previous case of the ideal heat exchanger (A) but many are significantly different.

1. The COP of the CCP cycle is found to be the highest when operating with an isothermal compressor and the lowest when operating with a single-stage adiabatic compressor.

2. Across the spectrum of conditions, the COP ratio for the real world condition (B) is significantly larger than in the ideal heat exchanger situation (A), with the ratios here being mostly above unity for all except the lowest water-vapor partial pressure of 0.5 kPa.

3. The COP significantly increases with the decrease in outdoor temperature, yet the performance of the CCP cycle is still better than the VCR cycle at the higher outdoor temperature conditions.

4. Unlike the ideal heat exchanger case, the CCP cycle for the non-ideal heat exchanger outperforms the VCR cycle for all humidities; even larger relative humidities of 80% and 100%.

CHAPTER XII

CASE 2- CYCLE COMPARISON WITH DECOUPLED AIRSIDE AND OUTDOOR TEMPERATURE

Background

The previous chapter dealt with the comparisons of the two cycles namely, CCP cycle and VCR cycle, with the membrane operational temperature assumed to be equal to the outdoor temperature. However, in applications of cooling indoor air or in real-world situations where it is not possible to cool outdoor air with a heat exchanger effectiveness of 100%, which would result in T_1=T_2= $T_{outdoor}$, then, the airside temperature exiting the sensible heat exchanger is usually less than the outdoor air temperature.

Therefore in this chapter, the membrane dehumidifier operational temperature (T_1=T_2) is decoupled from the outdoor temperature, meaning, the membrane operates at a temperature lower than the outdoor temperature, which is a scenario applicable to most real-world cooling situations.

Assumed Model Conditions

The membrane operational temperature and the outdoor conditions were set to represent real-world working situations for a hot day. The outdoor temperature conditions being varied between 30^0C and 40^0C in steps of 5^0C while the membrane operational temperature of T_1=T_2 was varied between 20^0C and 30^0C in steps of 5^0C. As one can see the airside operational temperature of the CCP cycle is up to 20^0C less than the outdoor temperature. The relative humidity of outdoor air was varied between 40% and 100% in steps of 20% for all these cases, similar to chapter 11.

Case-2: Airside State Points for Decoupled CCP Cycle Temperature

The airside conditions of CCP cycles working with decoupled temperature differences for specified cases are shown on the psychrometric charts below.

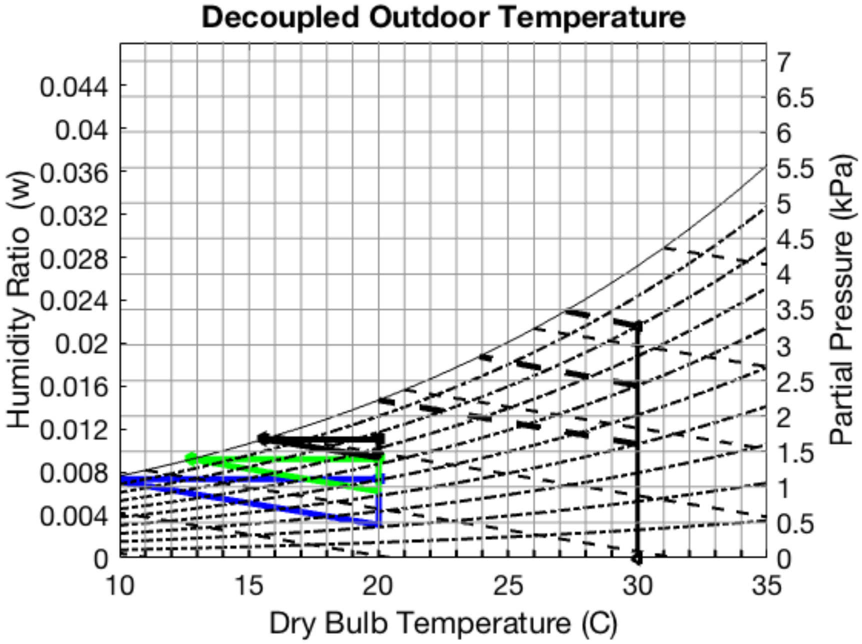

Figure 50: Claridge-Culp-Pate cycle for decouple outdoor conditions of 30^0C and membrane temperature of 20^0C

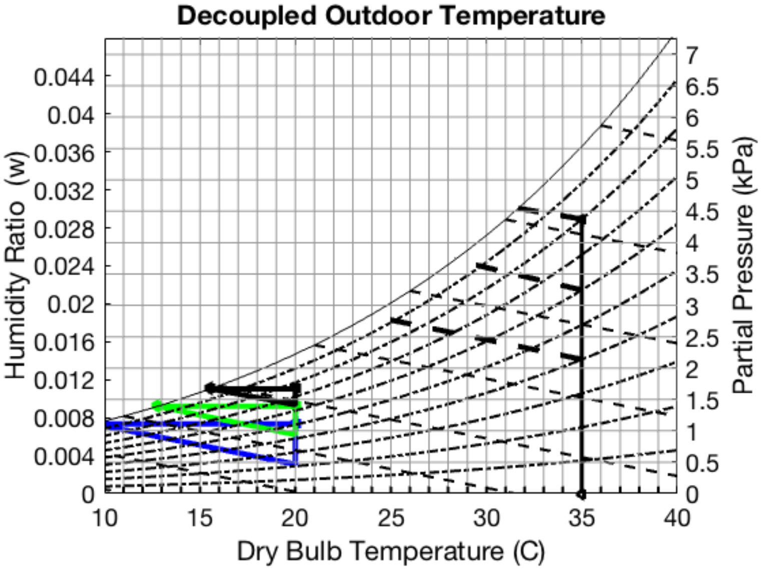

Figure 51: Claridge-Culp-Pate cycle for decouple outdoor conditions of 35^{0}C and membrane temperature of 20^{0}C

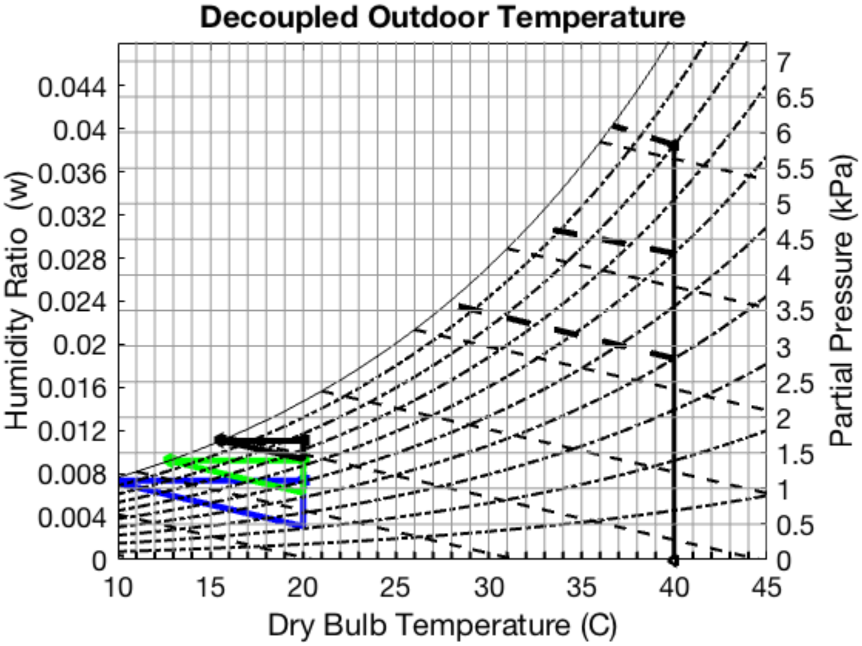

Figure 52: Claridge-Culp-Pate cycle for decouple outdoor conditions of 40^{0}C and membrane temperature of 20$_0$C

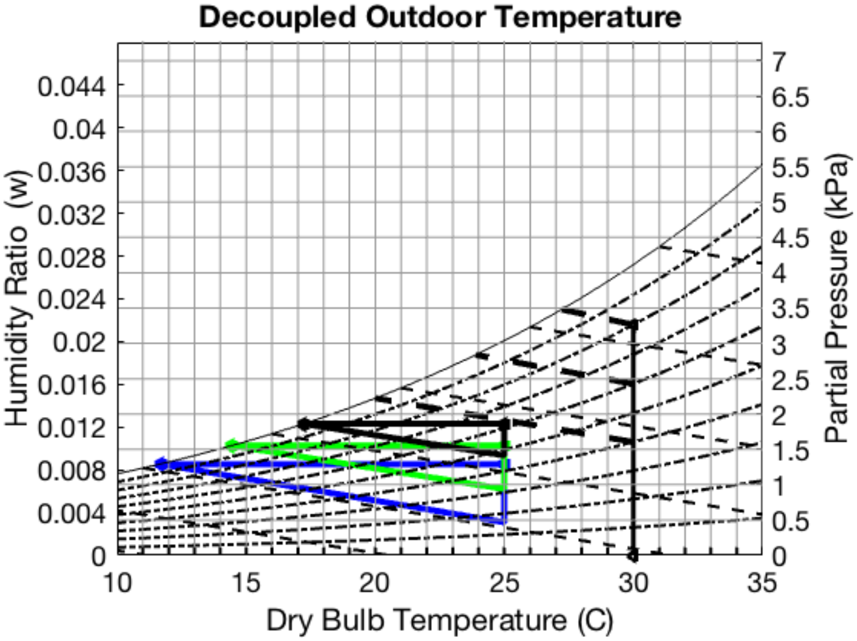

Figure 53: Claridge-Culp-Pate cycle for decouple outdoor conditions of 30^{0}C and membrane temperature of 25^{0}C

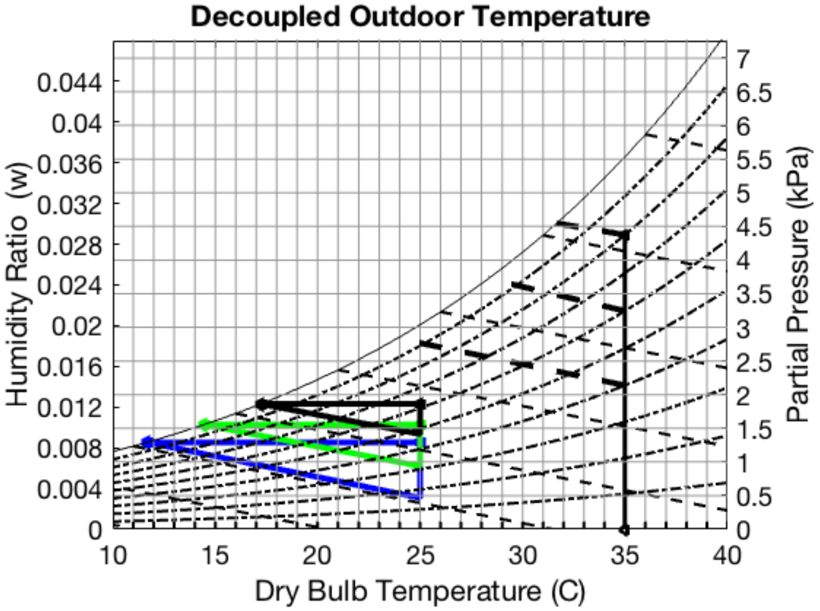

Figure 54: Claridge-Culp-Pate cycle for decouple outdoor conditions of 35^{0}C and membrane temperature of 25^{0}C

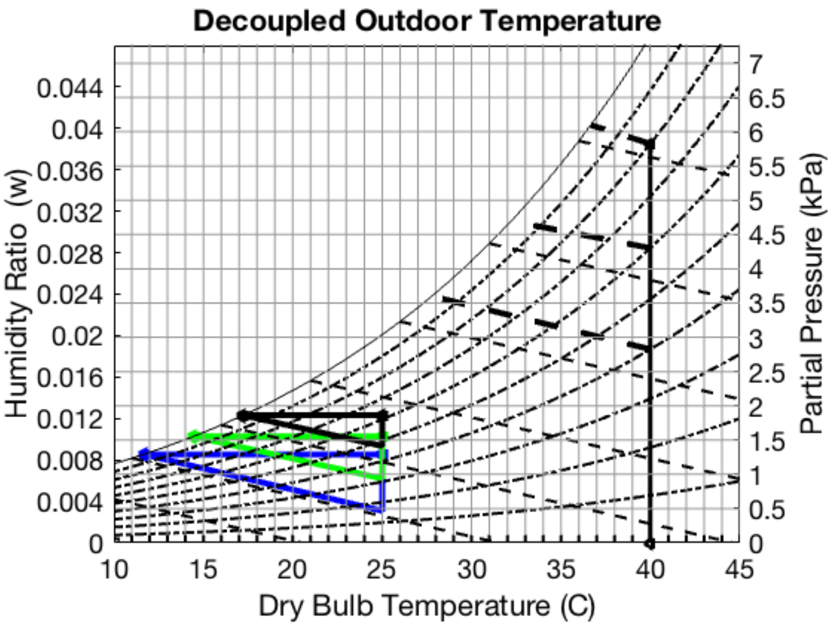

Figure 55: Claridge-Culp-Pate cycle for decouple outdoor conditions of 40^{0}C and membrane temperature of 25^{0}C

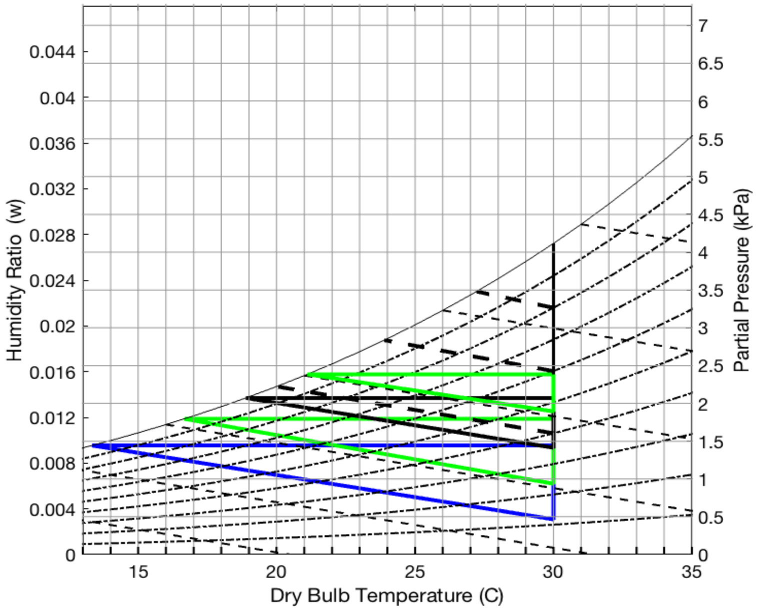

Figure 56: Claridge-Culp-Pate cycle for decouple outdoor conditions of 30^{0}C and membrane temperature of 30^{0}C

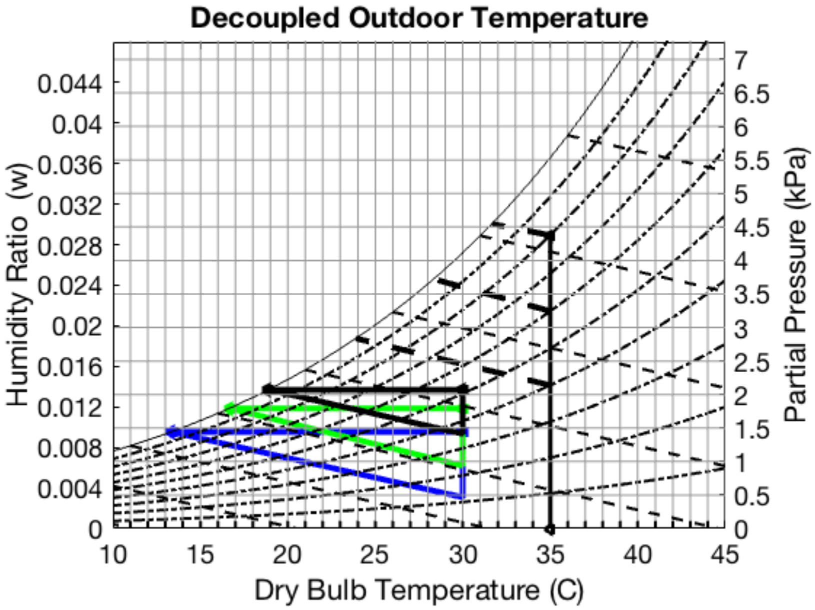

Figure 57: Claridge-Culp-Pate cycle for decouple outdoor conditions of 35^0C and membrane temperature of 30^0C

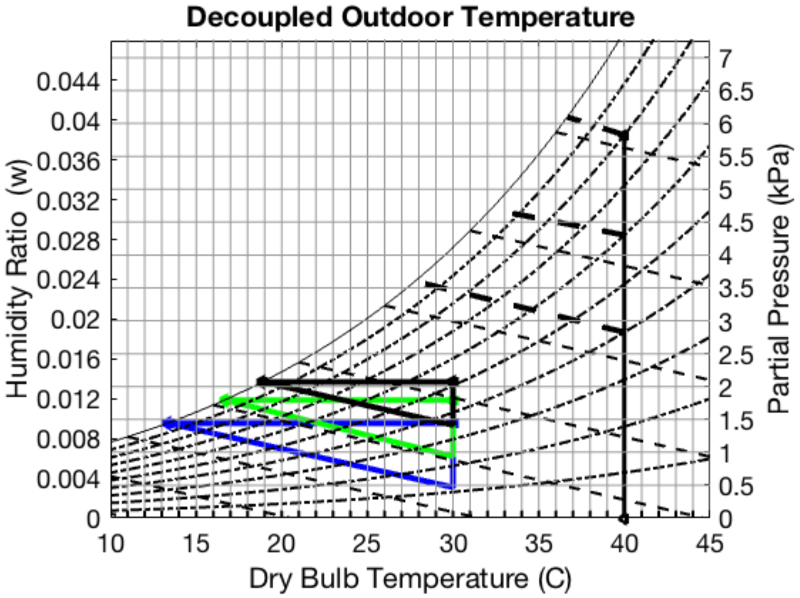

Figure 58**:** Claridge-Culp-Pate cycle for decouple outdoor conditions of 40^0C and membrane temperature of 30^0C

The obvious difference between the above case 2 psychrometric plots and the coupled plots of case 1 in the previous chapter is that here a much lower temperature can be achieved at state 3, witch is the inlet to the sensible heat exchanger. In many cases, these low temperatures of the CCP cycle approach 10^0C, which again is lower than case 1 temperatures.

Table 11 shows the important state variables obtained from simulating the CCP cycles as per the stated conditions.

Table 11: Claridge-Culp-Pate cycle results for decouple outdoor conditions

$T_1 = T_2$	P_{V2}	T_C	$\omega_1 = \omega_3$	ω_2	$\Delta\omega$	h_A	h_B	Δh	$\Delta h/\Delta\omega$
(C)	(kPa)	(C)	$(\frac{kgv}{kga})$	$(\frac{kgv}{kga})$	$(\frac{kgv}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kga})$	$(\frac{kJ}{kgv})$
20	0.5	9.4	0.00735	0.00308	0.00426	38.77	27.99	10.77	2525.97
20	1	12.8	0.00920	0.00620	0.00300	43.46	36.06	7.40	2467.06
20	1.5	15.6	0.01105	0.00935	0.00170	48.14	43.58	4.57	2688.04
20	2	18.3	0.01322	0.01253	0.00069	53.66	51.94	1.72	2480.38
25	0.5	11.7	0.00854	0.00308	0.00546	46.90	33.26	13.64	2499.59
25	1	14.4	0.01027	0.00620	0.00407	51.31	40.48	10.83	2661.28
25	1.5	17.2	0.01231	0.00935	0.00296	56.49	48.49	8.01	2705.87
25	2	20.0	0.01470	0.01253	0.00218	62.59	57.42	5.17	2377.10
25	2.5	22.2	0.01691	0.01574	0.00117	68.21	65.33	2.88	2458.31
30	0.5	13.3	0.00954	0.00308	0.00646	54.58	37.50	17.08	2643.92
30	1	16.7	0.01187	0.00620	0.00567	60.53	46.81	13.72	2418.50
30	1.5	18.9	0.01370	0.00935	0.00435	65.19	53.73	11.47	2636.79
30	2	21.1	0.01577	0.01253	0.00324	70.49	61.28	9.21	2838.78
30	2.5	23.3	0.01812	0.01574	0.00239	76.50	69.57	6.94	2908.01
30	3	25.6	0.02079	0.01898	0.00181	83.32	78.67	4.65	2570.84
35	0.5	15.6	0.01105	0.00308	0.00796	63.55	43.58	19.98	2509.42
35	1	18.3	0.01322	0.00620	0.00702	69.13	51.94	17.19	2449.24
35	1.5	20.6	0.01523	0.00935	0.00588	74.28	59.33	14.95	2542.69
35	2	22.8	0.01751	0.01253	0.00498	80.13	67.42	12.70	2550.40
35	2.5	25.0	0.02009	0.01574	0.00435	86.75	76.31	10.44	2398.35
40	0.5	17.2	0.01231	0.00308	0.00922	71.94	48.49	23.45	2543.32
40	1	19.4	0.01419	0.00620	0.00799	76.79	55.55	21.24	2657.79
40	1.5	21.7	0.01633	0.00935	0.00698	82.30	63.28	19.01	2722.91
40	2	23.9	0.01876	0.01253	0.00623	88.54	71.76	16.78	2692.99
40	2.5	26.1	0.02151	0.01574	0.00577	95.62	81.08	14.54	2519.24
40	3	27.8	0.02380	0.01898	0.00482	101.53	88.69	12.84	2662.87

Case - 2: CCP Cycle Process Variables for

Similar to case 1 in the previous chapter, the simulated data for this case (case 2) is used to obtain the mass flow rates of water vapor for each condition, which is then used in determining the COP of the CCP cycle as presented in the earlier chapter. Also similar to before, COPs of the CCP cycle and the VCR cycle are determined for two separate situations. The first situation (case - 2A) represents an ideal heat exchanger condition while the second situation (case – 2B) represents the real-world heat exchangers with fluid temperature differences in both cycles (VCR and CCP).

Case 2A Description

This situation assumes an ideal working situation for the evaporator and condenser detailed in the previous chapter. All of the discussions and descriptions in the previous chapter apply here to the decoupled temperatures.

Case 2B Description

A second set of assumptions (case -2B) that represent more realistic heat exchanger conditions usually seen in the real-world are applied here. These conditions again are the same as for the previous chapter, Chapter 11, namely: (a) a temperature difference of 5^0C between the airside and the refrigerant side on the condenser of the VCR cycle, (b) a temperature difference of 8^0C between the airside and the refrigerant side on the evaporator of the VCR cycle and (c) a high side pressure of the VCR cycle compressor corresponding to the saturation pressure of the above condenser.

As before for case 1B in Chapter 11, the CCP cycle compression side is at a saturation pressure corresponding condenser temperature, which is to 3^0C above the outdoor wet bulb temperature.

Determining COPs and COP Ratios

The same procedures described previously in detail, in the corresponding sections of Chapter 11 are applied to the decoupled temperature analysis here in chapter 12. One exception is that rather than presenting results for all 3 compressor assumptions, only the case with highest work input, which is the one-stage isentropic compressor, is presented.

Results and Analysis

The COP ratio versus the membrane operational temperature of T_1=T_2 are plotted and presented in the ratio plots for a range of outdoor temperature and relative humidities, with varying water-vapor partial pressure also being shown. As noted, only the one-stage isentropic compressor results are presented. In addition to the ratio plots shown below, a table containing all of the results pertaining to this case is presented in the appendix.

Case -2A: Results

<u>Case- 2A: Plots for R-410A as VCR Working Fluid</u>

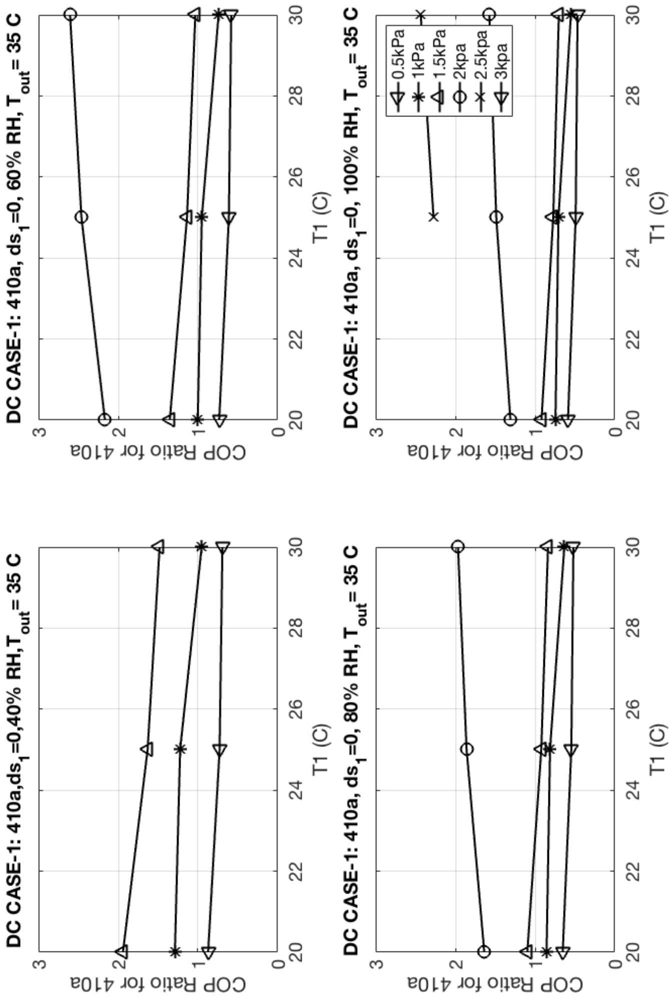

Figure 59: Single-stage adiabatic COP ratio for R410A under ideal condenser condition for outdoor temperature of 35^{0}C

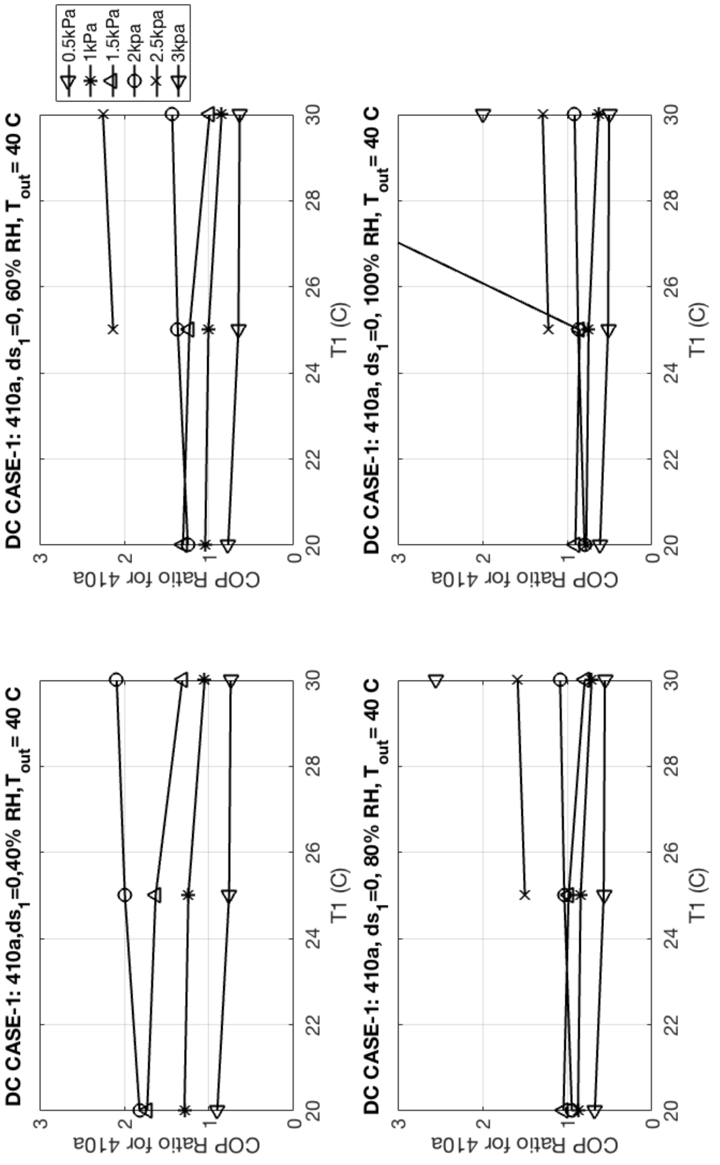

Figure 60**:** Single-stage adiabatic COP ratio for R410A under ideal condenser condition for outdoor temperature of 40^0C

Case -2A: Plots for water as VCR Working Fluid

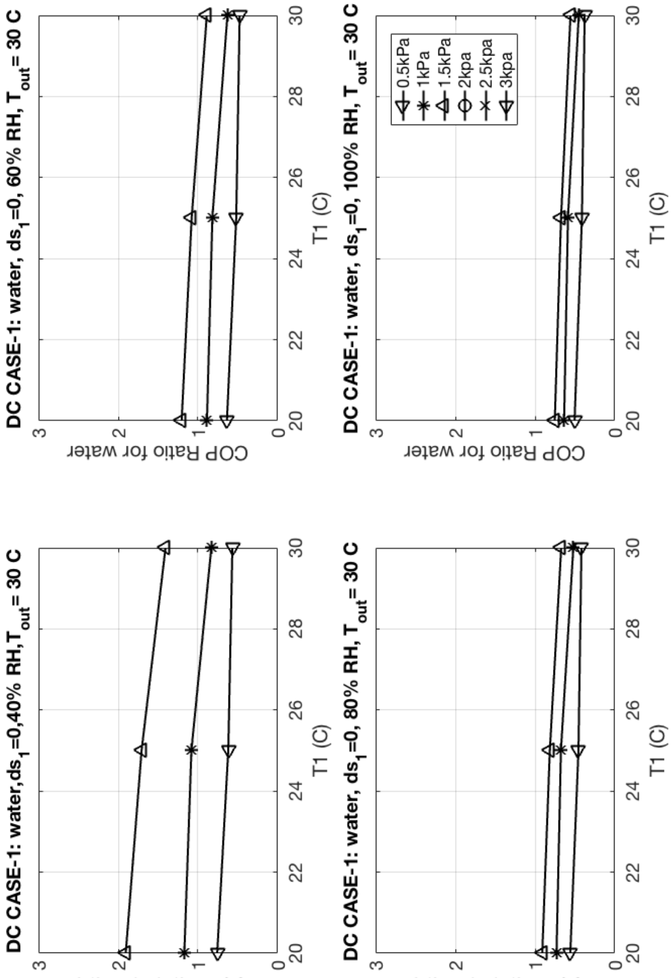

Figure 61: Single-stage adiabatic COP ratio for water under ideal condenser condition for outdoor temperature of 30^0C

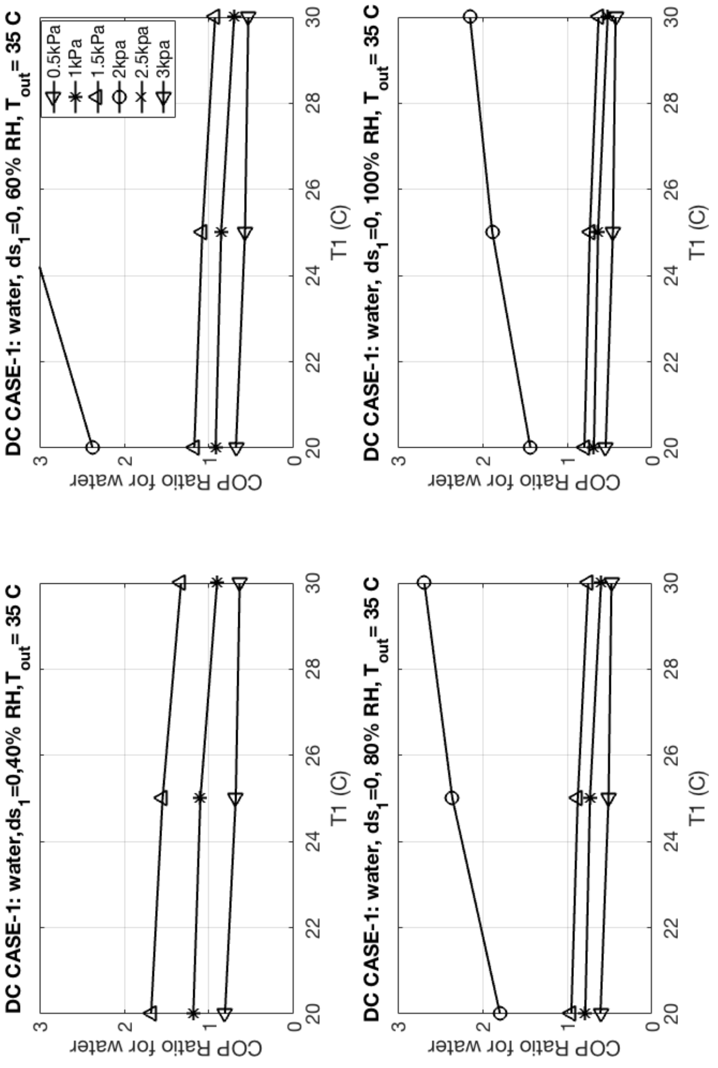

Figure 62: Single-stage adiabatic COP ratio for water under ideal condenser condition for outdoor temperature of 35^{0}C

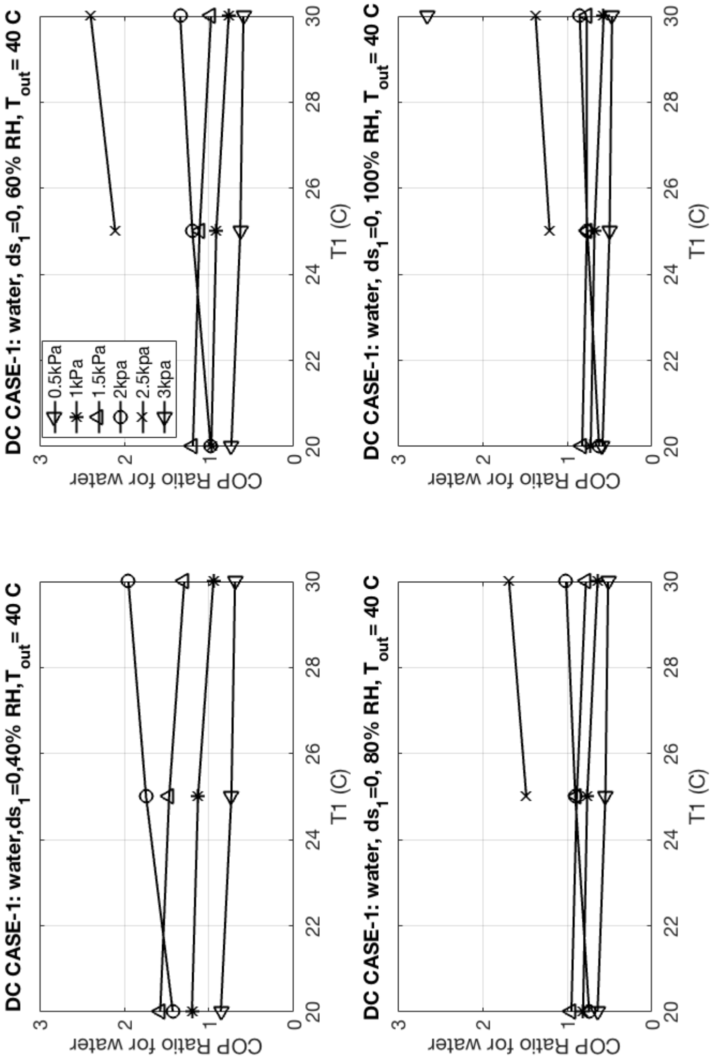

Figure 63: Single-stage adiabatic COP ratio for water under ideal condenser condition for outdoor temperature of 40^{0}C

Case-2B: Results

Case--2B: Plots for R-410A as VCR Working Fluid

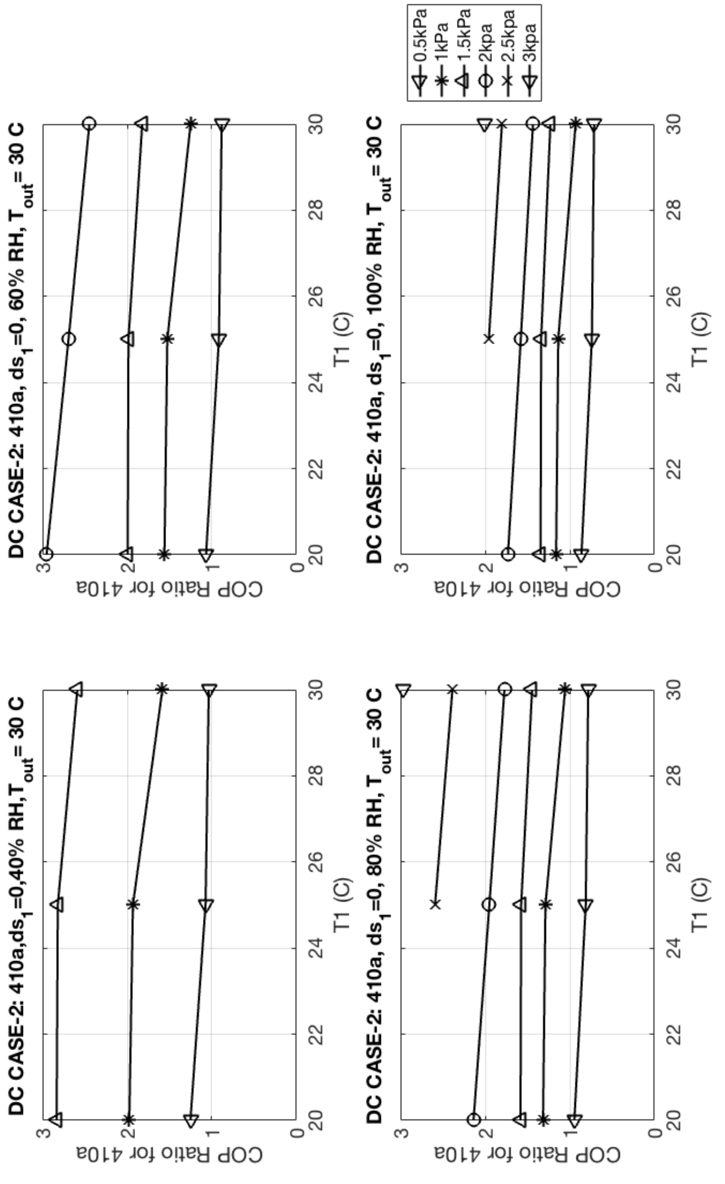

Figure 64: Single-stage adiabatic COP ratio for R410A at outdoor temperature of 30^0C

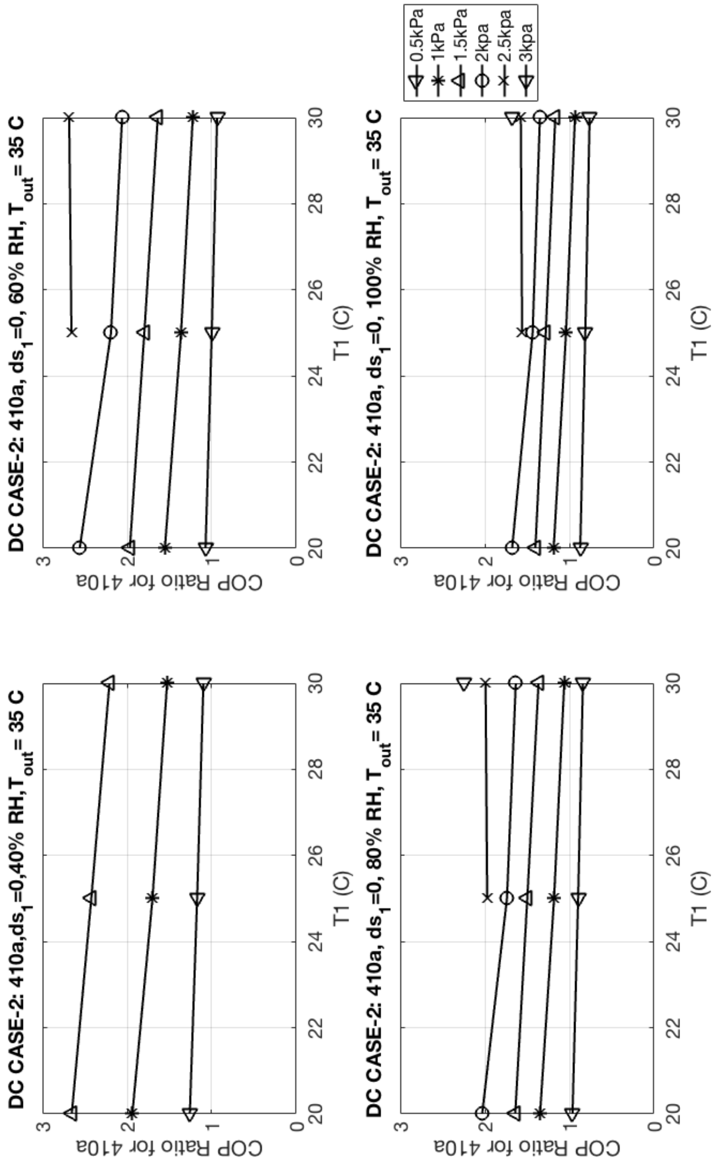

Figure 65: Single-stage adiabatic COP ratio for R410A at outdoor temperature of 35^{0}C

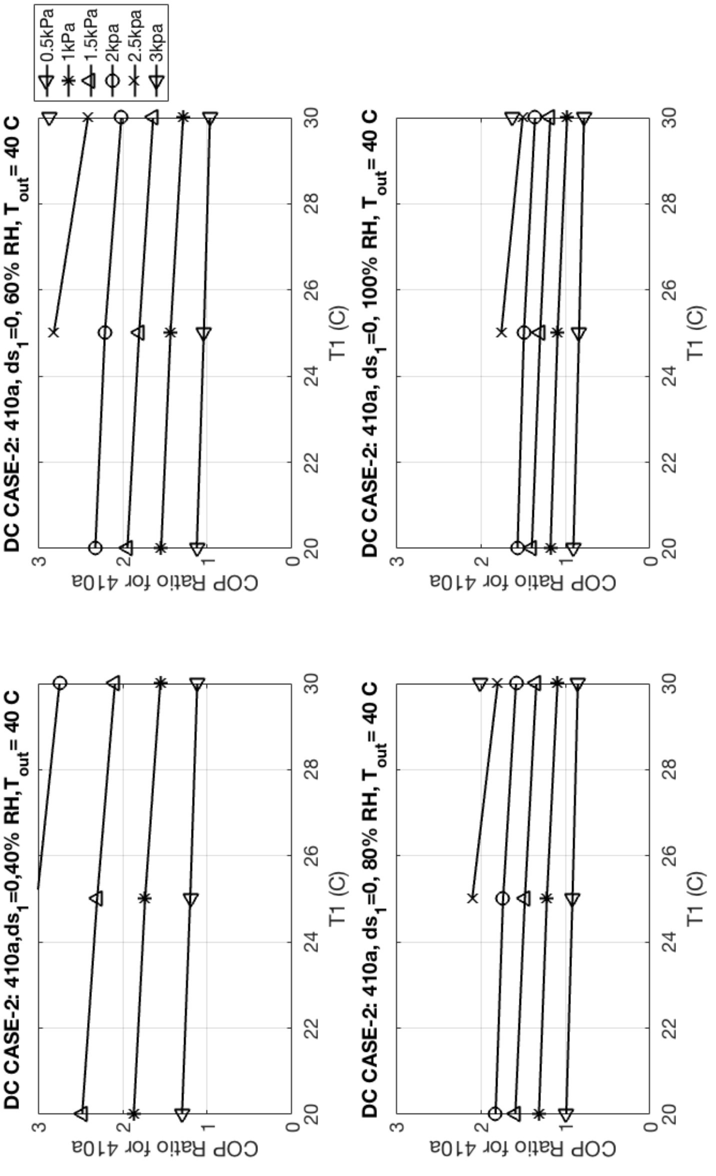

Figure 66: Single-stage adiabatic COP ratio for R410A at outdoor temperature of 40^{0}C

Case - 2B: Plots for Water as VCR Working Fluid

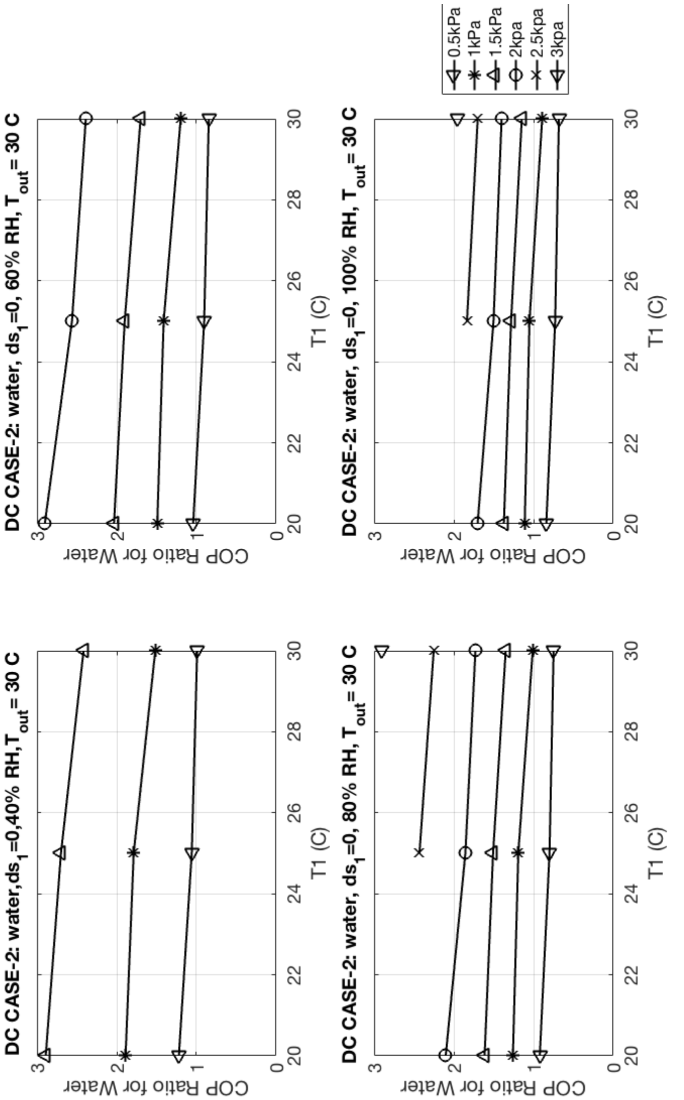

Figure 67: Single-stage adiabatic COP ratio for water at outdoor temperature of 30^{0}C

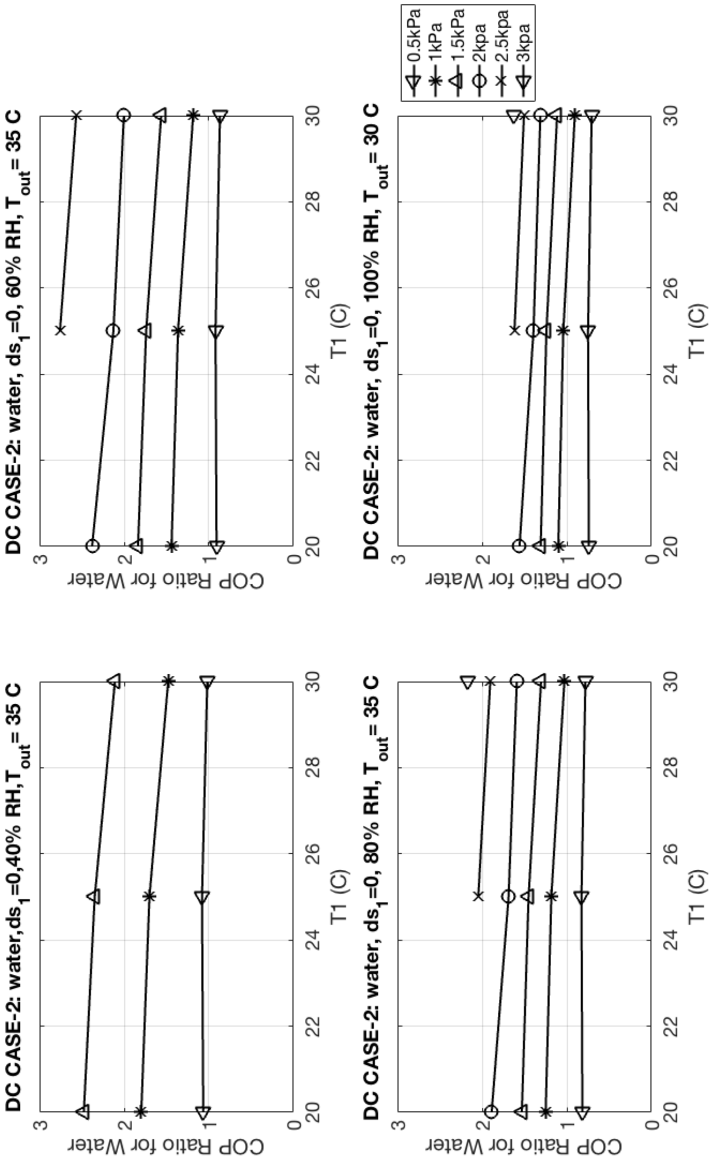

Figure 68: Single-stage adiabatic COP ratio for R410A at outdoor temperature of 35^0C

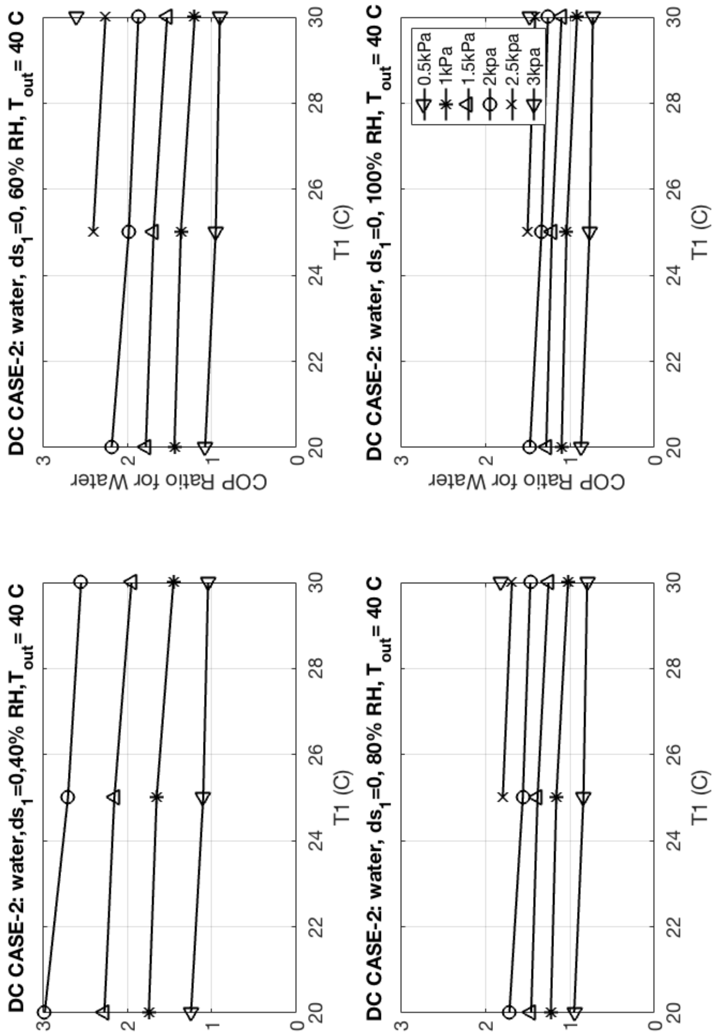

Figure 69: Single-stage adiabatic COP ratio for R410A at outdoor temperature of 40^0C

Case-2B: Discussion

It should be noted that for a given outdoor temperature, the cycle operation temperatures (T_1 and T_2) do not vary with the relative humidity of the outdoor environment.

Similar to the previous case in Chapter 11, the COP ratios are found to decrease with the increase of outdoor temperature. Also, similar to the previous case, the ratio increases with water-vapor partial pressure increases and outdoor relative humidity decreases.

The plots show that the ratios are only weakly affected by the airside operational temperatures T_1 and T_2.

Of special importance, there is always a partial pressure set point that results in the CCP cycle performing better than the VCR cycle, meaning the COP ratio is greater than unity, and oftentimes it is significantly greater, having a 2 or 3 times better performance.

CHAPTER XIII

CONCLUSIONS

A detailed study of the theoretical performance of a novel membrane-enabled dehumidification and cooling system, known as the Claridge-Culp-Pate refrigeration process/cycle has been performed for a range of outdoor temperatures and relative humidities that could be encountered in any climatic zone/region. This study investigated and compared the performances of several different arrangements of the two major components making up the novel system, namely a membrane dehumidification unit and an evaporative cooler. These components and processes were configured in an open system and as a cycle in a closed system A performance comparison was also made with a conventional vapor compression refrigeration system operating under similar conditions, with two different working fluids, namely water and R-410A.

The main conclusions drawn from this study are presented below.

1. A comparison of water vapor compression and compressing a typical refrigerant such as R-410A shows that an isothermal compression assumption can be approached for water vapor but not R-410A. This result means that water-vapor compression can be designed with lower energy consumptions, at least relative to using typical isentropic compressors. In contrast, it is impossible to operate a R-410A system isothermally because of the temperature going below the saturation temperature for any given pressure.

2. For an open system configuration, the Claridge-Culp-Pate process consisting of an airside membrane dehumidification unit taking in air from either the outdoors or an indoor space and an evaporative cooler in series produces cooling with a higher COP than a conventional VCR system operating at similar conditions. This better performance of CCP cooling process over the conventional VCR cooling system applies to nearly all temperature and humidity conditions.

3. Any number of dehumidification unit and evaporative cooler combinations and configurations are possible with each arrangement having its' own performance. However, the advantage of having a second membrane dehumidification unit in line with a first one, to achieve better cooling of outdoor air, might have diminished returns, owing to the very low dehumidification and vapor removal rate associated with the second membrane dehumidification unit. Another demerit of adding a second downstream dehumidification unit is that a second compressor increases the work input to the system, at least relative to the increase in cooling capacity, so that there can be a reduction in the overall COP.

4. The COP of the novel Claridge-Culp-Pate cycle was found to be higher than the COP of the conventional vapor compression refrigeration cycle, with both being closed systems, for all climatic zone conditions of outdoor temperatures and relative humidities. However, it is necessary to find the optimum membrane-side water-vapor partial pressure, which is the compressor inlet pressure, because below a threshold vapor

pressure value the COP of the novel system decreases below the conventional VCR system in some cases. This slipping in the relative performance of a CCP cycle can be accounted for by the fact that the work input to the compressor increases as the vapor pressure at the membrane exit or the compressor inlet pressure decreases. This threshold vapor pressure is a function of relative humidity and increases with increased relative humidities because of the wet bulb temperature that is associated with the CCP cycle condenser increases, which in turn increases the condenser saturation temperature and pressure.

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[6] United States Patent No.8,641,806 B2, "Systems and methods for multi stage air dehumidification and cooling" Claridge,D.E , Culp,C.H.,and Liu,Wei issued February 4 2014.

[7] United States Patent No.8, 685,142 B2, "Systems and methods for efficient air dehumidification and liquid recovery with evaporative cooling" Claridge,D.E , Culp,C.H., Haberl, Jeffrey S, and Liu,Wei issued April 1 2014.

[8] United States Patent No.8, 685,144 B2, "Systems and methods for efficient air dehumidification and liquid recovery" Claridge, D.E , Culp,C.H., Haberl, Jeffrey S, and Liu,Wei issued April 1 2014.

[9] United States Patent No.8, 685,145 B2, "Systems and methods for multi stage air dehumidification and liquid recovery" Claridge,D.E , Culp,C.H., Haberl, Jeffrey S, and Liu,Wei issued April 1 2014.

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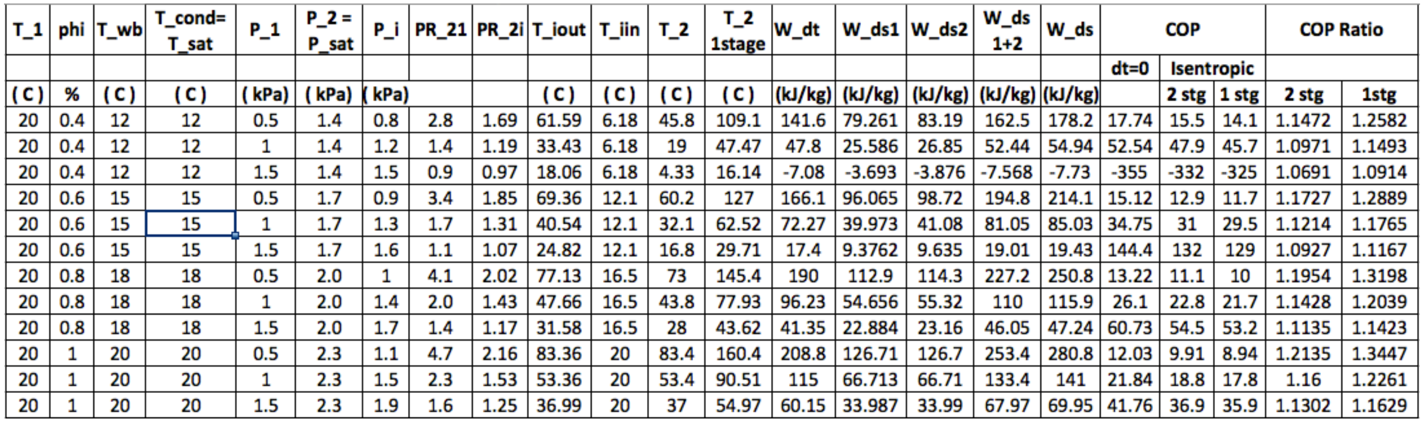
APPENDIX 1

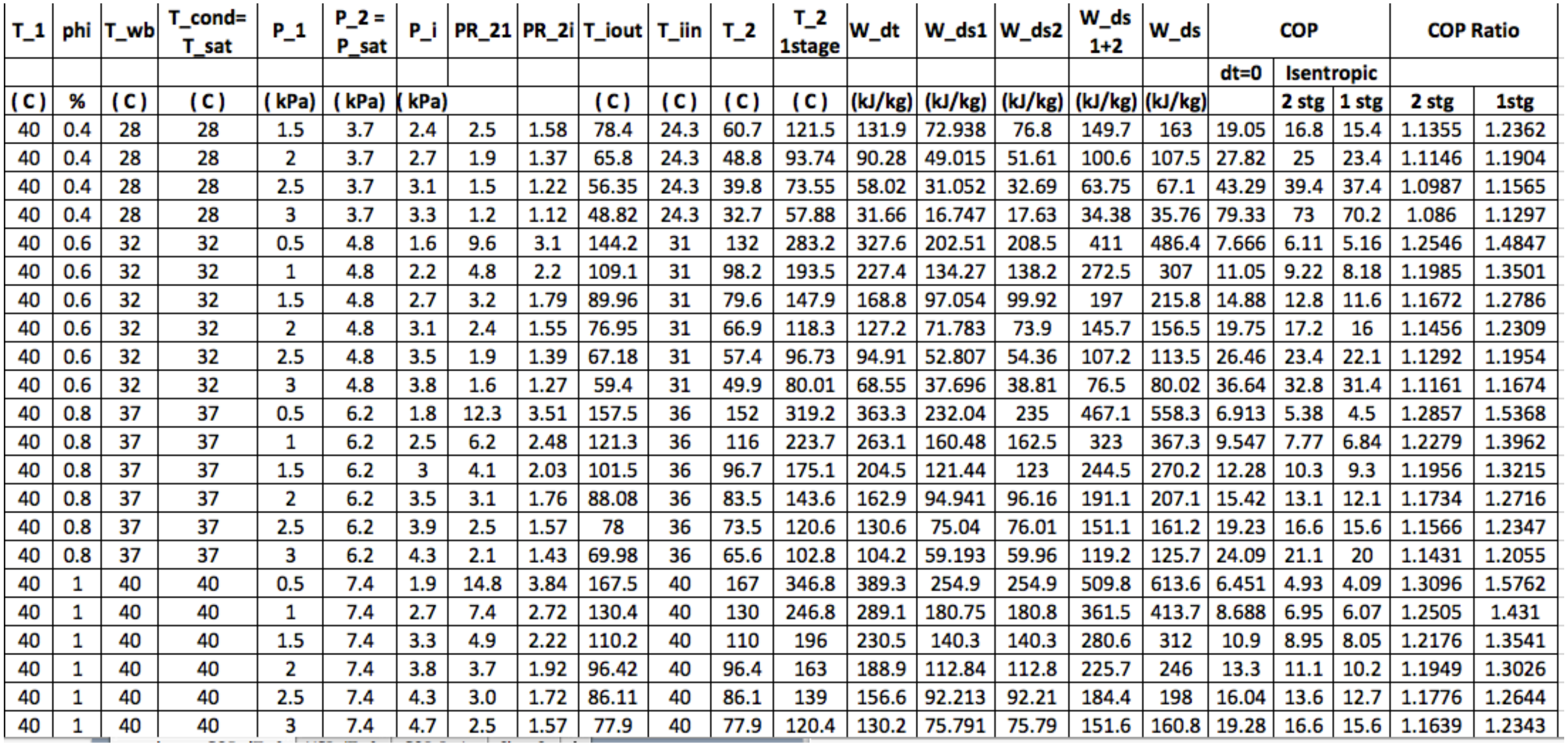


T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
20	0.4	12	12	0.5	1.4	0.8	2.8	1.69	61.59	6.18	45.8	109.1	141.6	79.261	83.19	162.5	178.2	17.74	15.5	14.1	1.1472	1.2582
20	0.4	12	12	1	1.4	1.2	1.4	1.19	33.43	6.18	19	47.47	47.8	25.586	26.85	52.44	54.94	52.54	47.9	45.7	1.0971	1.1493
20	0.4	12	12	1.5	1.4	1.5	0.9	0.97	18.06	6.18	4.33	16.14	-7.08	-3.693	-3.876	-7.568	-7.73	-355	-332	-325	1.0691	1.0914
20	0.6	15	15	0.5	1.7	0.9	3.4	1.85	69.36	12.1	60.2	127	166.1	96.065	98.72	194.8	214.1	15.12	12.9	11.7	1.1727	1.2889
20	0.6	15	15	1	1.7	1.3	1.7	1.31	40.54	12.1	32.1	62.52	72.27	39.973	41.08	81.05	85.03	34.75	31	29.5	1.1214	1.1765
20	0.6	15	15	1.5	1.7	1.6	1.1	1.07	24.82	12.1	16.8	29.71	17.4	9.3762	9.635	19.01	19.43	144.4	132	129	1.0927	1.1167
20	0.8	18	18	0.5	2.0	1	4.1	2.02	77.13	16.5	73	145.4	190	112.9	114.3	227.2	250.8	13.22	11.1	10	1.1954	1.3198
20	0.8	18	18	1	2.0	1.4	2.0	1.43	47.66	16.5	43.8	77.93	96.23	54.656	55.32	110	115.9	26.1	22.8	21.7	1.1428	1.2039
20	0.8	18	18	1.5	2.0	1.7	1.4	1.17	31.58	16.5	28	43.62	41.35	22.884	23.16	46.05	47.24	60.73	54.5	53.2	1.1135	1.1423
20	1	20	20	0.5	2.3	1.1	4.7	2.16	83.36	20	83.4	160.4	208.8	126.71	126.7	253.4	280.8	12.03	9.91	8.94	1.2135	1.3447
20	1	20	20	1	2.3	1.5	2.3	1.53	53.36	20	53.4	90.51	115	66.713	66.71	133.4	141	21.84	18.8	17.8	1.16	1.2261
20	1	20	20	1.5	2.3	1.9	1.6	1.25	36.99	20	37	54.97	60.15	33.987	33.99	67.97	69.95	41.76	36.9	35.9	1.1302	1.1629

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
25	0.4	16	16	1.5	1.8	1.7	1.2	1.11	32.65	10.7	18	40.5	27.51	14.569	15.3	29.87	31	91.3	84.1	81	1.086	1.1269
25	0.6	19	19	0.5	2.3	1.1	4.5	2.13	87.85	16.9	78	164	207.7	122.28	125.7	248	277.9	12.1	10.1	9.04	1.1943	1.3385
25	0.6	19	19	1	2.3	1.5	2.3	1.5	57.48	16.9	48.5	93.49	112.2	63.181	64.95	128.1	137	22.38	19.6	18.3	1.1416	1.2205
25	0.6	19	19	1.5	2.3	1.8	1.5	1.23	40.91	16.9	32.3	57.66	56.43	30.946	31.82	62.76	65.33	44.51	40	38.4	1.1123	1.1578
25	0.8	22	22	0.5	2.7	1.2	5.4	2.32	95.77	21.4	91.3	183.3	231.2	139.82	141.5	281.4	316.7	10.86	8.93	7.93	1.217	1.3698
25	0.8	22	22	1	2.7	1.6	2.7	1.64	64.72	21.4	60.6	109.7	135.8	78.485	79.45	157.9	169.5	18.5	15.9	14.8	1.1632	1.2483
25	0.8	22	22	1.5	2.7	2	1.8	1.34	47.79	21.4	43.9	72.32	79.96	45.029	45.58	90.61	94.65	31.41	27.7	26.5	1.1332	1.1837
25	1	25	25	0.5	3.2	1.3	6.3	2.52	103.7	25	104	203.1	254.2	157.36	157.4	314.7	356.3	9.879	7.98	7.05	1.238	1.4014
25	1	25	25	1	3.2	1.8	3.2	1.78	71.97	25	72	126.4	158.8	93.942	93.94	187.9	202.7	15.81	13.4	12.4	1.1831	1.2764
25	1	25	25	1.5	3.2	2.2	2.1	1.45	54.67	25	54.7	87.3	103	59.349	59.35	118.7	124.6	24.38	21.2	20.2	1.1525	1.2098

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
30	0.4	20	20	1.5	2.3	1.9	1.6	1.25	47.57	15.2	32	66.17	62.2	33.435	35.15	68.58	72.33	40.38	36.6	34.7	1.1027	1.1629
30	0.4	20	20	2	2.3	2.2	1.2	1.08	36.08	15.2	21	42.29	21.93	11.576	12.17	23.75	24.58	114.5	106	102	1.0825	1.1208
30	0.6	24	24	0.5	3.0	1.2	5.9	2.44	106.8	21.6	96.2	203	249.2	149.3	153.6	302.9	346	10.08	8.29	7.26	1.2155	1.3888
30	0.6	24	24	1	3.0	1.7	3.0	1.72	74.81	21.6	65.2	126.3	152.2	87.135	89.62	176.8	192.5	16.51	14.2	13	1.1617	1.2651
30	0.6	24	24	1.5	3.0	2.1	2.0	1.41	57.37	21.6	48.2	87.22	95.41	53.225	54.74	108	114.4	26.32	23.3	21.9	1.1316	1.1994
30	0.6	24	24	2	3.0	2.4	1.5	1.22	45.53	21.6	36.7	61.86	55.15	30.202	31.06	61.27	63.72	45.54	41	39.4	1.1109	1.1554
30	0.8	27	27	0.5	3.6	1.3	7.2	2.69	116.4	26.3	112	227.5	276.9	170.74	172.9	343.6	395.1	9.071	7.31	6.36	1.2411	1.4269
30	0.8	27	27	1	3.6	1.9	3.6	1.9	83.65	26.3	79.3	146.8	179.9	105.99	107.3	213.3	233.6	13.96	11.8	10.8	1.1858	1.2989
30	0.8	27	27	1.5	3.6	2.3	2.4	1.55	65.77	26.3	61.6	105.8	123.1	70.661	71.54	142.2	151.5	20.4	17.7	16.6	1.1551	1.2308
30	0.8	27	27	2	3.6	2.7	1.8	1.34	53.63	26.3	49.6	79.1	82.85	46.678	47.26	93.94	98.21	30.32	26.7	25.6	1.1339	1.1854
30	1	30	30	0.5	4.2	1.5	8.5	2.91	124.5	30	124	248.4	299.4	188.96	189	377.9	436.8	8.388	6.65	5.75	1.2622	1.4589
30	1	30	30	1	4.2	2.1	4.2	2.06	91.02	30	91	164.3	202.4	122.04	122	244.1	268.7	12.41	10.3	9.35	1.2058	1.3273
30	1	30	30	1.5	4.2	2.5	2.8	1.68	72.77	30	72.8	121.6	145.7	85.535	85.54	171.1	183.1	17.24	14.7	13.7	1.1744	1.2573
30	1	30	30	2	4.2	2.9	2.1	1.46	60.38	30	60.4	93.8	105.4	60.751	60.75	121.5	127.6	23.83	20.7	19.7	1.1528	1.2106

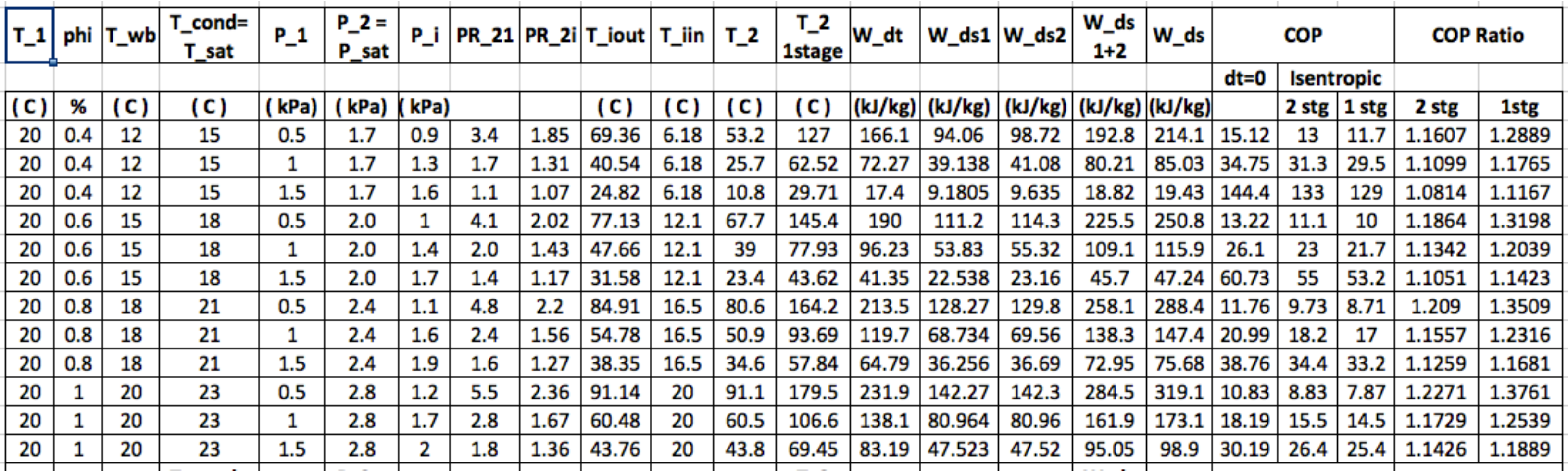
T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
35	0.4	24	24	2	3.0	2.4	1.5	1.22	50.79	19.8	34.8	67.39	56.06	30.015	31.58	61.59	64.77	44.8	40.8	38.8	1.0987	1.1554
35	0.4	24	24	2.5	3.0	2.7	1.2	1.09	41.75	19.8	26.2	48.65	24.31	12.833	13.5	26.34	27.3	103.3	95.4	92	1.0831	1.1227
35	0.6	28	28	0.5	3.9	1.4	7.7	2.78	126.1	26.3	115	244.2	290.7	177.13	182.3	359.4	418.5	8.64	6.99	6	1.2365	1.4397
35	0.6	28	28	1	3.9	2	3.9	1.96	92.53	26.3	82.2	160.8	192.1	111.82	115.1	226.9	251.6	13.08	11.1	9.98	1.1814	1.3102
35	0.6	28	28	1.5	3.9	2.4	2.6	1.6	74.21	26.3	64.4	118.4	134.4	76.202	78.41	154.6	166.8	18.69	16.2	15.1	1.1507	1.2414
35	0.6	28	28	2	3.9	2.8	1.9	1.39	61.76	26.3	52.3	90.85	93.44	52.017	53.53	105.5	111.7	26.88	23.8	22.5	1.1296	1.1955
35	0.6	28	28	2.5	3.9	3.1	1.5	1.24	52.42	26.3	43.2	70.82	61.69	33.855	34.84	68.69	71.65	40.71	36.6	35.1	1.1135	1.1613
35	0.8	32	32	0.5	4.7	1.5	9.3	3.06	135.9	31.1	131	270	317.9	199.36	201.9	401.2	469.9	7.9	6.26	5.34	1.2622	1.4783
35	0.8	32	32	1	4.7	2.2	4.7	2.16	101.5	31.1	96.8	182.4	219.3	131.37	133	264.4	294.8	11.45	9.5	8.52	1.2058	1.3444
35	0.8	32	32	1.5	4.7	2.6	3.1	1.76	82.74	31.1	78.3	137.9	161.6	94.282	95.48	189.8	205.8	15.54	13.2	12.2	1.1743	1.2733
35	0.8	32	32	2	4.7	3.1	2.3	1.53	69.99	31.1	65.7	109	120.7	69.103	69.98	139.1	147.9	20.81	18.1	17	1.1526	1.2257
35	0.8	32	32	2.5	4.7	3.4	1.9	1.37	60.42	31.1	56.2	87.93	88.92	50.195	50.83	101	105.9	28.24	24.9	23.7	1.1362	1.1905
35	1	35	35	0.5	5.6	1.7	11.3	3.36	145.7	35	146	296.3	344.5	221.48	221.5	443	522.6	7.291	5.67	4.81	1.286	1.5172
35	1	35	35	1	5.6	2.4	5.6	2.37	110.5	35	110	204.5	245.8	150.98	151	302	339	10.22	8.32	7.41	1.2283	1.3789
35	1	35	35	1.5	5.6	2.9	3.8	1.94	91.26	35	91.3	157.8	188.2	112.53	112.5	225.1	245.6	13.35	11.2	10.2	1.1962	1.3054
35	1	35	35	2	5.6	3.4	2.8	1.68	78.21	35	78.2	127.5	147.2	86.416	86.42	172.8	185	17.06	14.5	13.6	1.174	1.2563
35	1	35	35	2.5	5.6	3.8	2.3	1.5	68.41	35	68.4	105.4	115.5	66.81	66.81	133.6	140.9	21.75	18.8	17.8	1.1572	1.2199



T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
40	0.4	28	28	1.5	3.7	2.4	2.5	1.58	78.4	24.3	60.7	121.5	131.9	72.938	76.8	149.7	163	19.05	16.8	15.4	1.1355	1.2362
40	0.4	28	28	2	3.7	2.7	1.9	1.37	65.8	24.3	48.8	93.74	90.28	49.015	51.61	100.6	107.5	27.82	25	23.4	1.1146	1.1904
40	0.4	28	28	2.5	3.7	3.1	1.5	1.22	56.35	24.3	39.8	73.55	58.02	31.052	32.69	63.75	67.1	43.29	39.4	37.4	1.0987	1.1565
40	0.4	28	28	3	3.7	3.3	1.2	1.12	48.82	24.3	32.7	57.88	31.66	16.747	17.63	34.38	35.76	79.33	73	70.2	1.086	1.1297
40	0.6	32	32	0.5	4.8	1.6	9.6	3.1	144.2	31	132	283.2	327.6	202.51	208.5	411	486.4	7.666	6.11	5.16	1.2546	1.4847
40	0.6	32	32	1	4.8	2.2	4.8	2.2	109.1	31	98.2	193.5	227.4	134.27	138.2	272.5	307	11.05	9.22	8.18	1.1985	1.3501
40	0.6	32	32	1.5	4.8	2.7	3.2	1.79	89.96	31	79.6	147.9	168.8	97.054	99.92	197	215.8	14.88	12.8	11.6	1.1672	1.2786
40	0.6	32	32	2	4.8	3.1	2.4	1.55	76.95	31	66.9	118.3	127.2	71.783	73.9	145.7	156.5	19.75	17.2	16	1.1456	1.2309
40	0.6	32	32	2.5	4.8	3.5	1.9	1.39	67.18	31	57.4	96.73	94.91	52.807	54.36	107.2	113.5	26.46	23.4	22.1	1.1292	1.1954
40	0.6	32	32	3	4.8	3.8	1.6	1.27	59.4	31	49.9	80.01	68.55	37.696	38.81	76.5	80.02	36.64	32.8	31.4	1.1161	1.1674
40	0.8	37	37	0.5	6.2	1.8	12.3	3.51	157.5	36	152	319.2	363.3	232.04	235	467.1	558.3	6.913	5.38	4.5	1.2857	1.5368
40	0.8	37	37	1	6.2	2.5	6.2	2.48	121.3	36	116	223.7	263.1	160.48	162.5	323	367.3	9.547	7.77	6.84	1.2279	1.3962
40	0.8	37	37	1.5	6.2	3	4.1	2.03	101.5	36	96.7	175.1	204.5	121.44	123	244.5	270.2	12.28	10.3	9.3	1.1956	1.3215
40	0.8	37	37	2	6.2	3.5	3.1	1.76	88.08	36	83.5	143.6	162.9	94.941	96.16	191.1	207.1	15.42	13.1	12.1	1.1734	1.2716
40	0.8	37	37	2.5	6.2	3.9	2.5	1.57	78	36	73.5	120.6	130.6	75.04	76.01	151.1	161.2	19.23	16.6	15.6	1.1566	1.2347
40	0.8	37	37	3	6.2	4.3	2.1	1.43	69.98	36	65.6	102.8	104.2	59.193	59.96	119.2	125.7	24.09	21.1	20	1.1431	1.2055
40	1	40	40	0.5	7.4	1.9	14.8	3.84	167.5	40	167	346.8	389.3	254.9	254.9	509.8	613.6	6.451	4.93	4.09	1.3096	1.5762
40	1	40	40	1	7.4	2.7	7.4	2.72	130.4	40	130	246.8	289.1	180.75	180.8	361.5	413.7	8.688	6.95	6.07	1.2505	1.431
40	1	40	40	1.5	7.4	3.3	4.9	2.22	110.2	40	110	196	230.5	140.3	140.3	280.6	312	10.9	8.95	8.05	1.2176	1.3541
40	1	40	40	2	7.4	3.8	3.7	1.92	96.42	40	96.4	163	188.9	112.84	112.8	225.7	246	13.3	11.1	10.2	1.1949	1.3026
40	1	40	40	2.5	7.4	4.3	3.0	1.72	86.11	40	86.1	139	156.6	92.213	92.21	184.4	198	16.04	13.6	12.7	1.1776	1.2644
40	1	40	40	3	7.4	4.7	2.5	1.57	77.9	40	77.9	120.4	130.2	75.791	75.79	151.6	160.8	19.28	16.6	15.6	1.1639	1.2343

APPENDIX 2

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
25	0.4	16	19	1.5	2.2	1.8	1.5	1.21	39.53	10.7	24.5	54.77	51.66	27.668	29.06	56.73	59.54	48.62	44.3	42.2	1.0982	1.1526
25	0.6	19	22	0.5	2.7	1.2	5.4	2.32	95.77	16.9	85.7	183.3	231.2	137.67	141.5	279.2	316.7	10.86	9	7.93	1.2077	1.3698
25	0.6	19	22	1	2.7	1.6	2.7	1.64	64.72	16.9	55.5	109.7	135.8	77.278	79.45	156.7	169.5	18.5	16	14.8	1.1543	1.2483
25	0.6	19	22	1.5	2.7	2	1.8	1.34	47.79	16.9	39	72.32	79.96	44.337	45.58	89.92	94.65	31.41	27.9	26.5	1.1246	1.1837
25	0.8	22	25	0.5	3.2	1.3	6.3	2.52	103.7	21.4	99.1	203.1	254.2	155.45	157.4	312.8	356.3	9.879	8.03	7.05	1.2305	1.4014
25	0.8	22	25	1	3.2	1.8	3.2	1.78	71.97	21.4	67.8	126.4	158.8	92.804	93.94	186.8	202.7	15.81	13.4	12.4	1.1759	1.2764
25	0.8	22	25	1.5	3.2	2.2	2.1	1.45	54.67	21.4	50.7	87.3	103	58.63	59.35	118	124.6	24.38	21.3	20.2	1.1455	1.2098
25	1	25	28	0.5	3.7	1.4	7.5	2.73	111.6	25	112	223.4	276.8	173.19	173.2	346.4	396.7	9.074	7.25	6.33	1.2515	1.4333
25	1	25	28	1	3.7	1.9	3.7	1.93	79.22	25	79.2	143.3	181.4	108.43	108.4	216.9	236.6	13.85	11.6	10.6	1.1958	1.3045
25	1	25	28	1.5	3.7	2.4	2.5	1.58	61.56	25	61.6	102.6	125.6	73.115	73.12	146.2	155.2	20	17.2	16.2	1.1647	1.2361



T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
20	0.4	12	15	0.5	1.7	0.9	3.4	1.85	69.36	6.18	53.2	127	166.1	94.06	98.72	192.8	214.1	15.12	13	11.7	1.1607	1.2889
20	0.4	12	15	1	1.7	1.3	1.7	1.31	40.54	6.18	25.7	62.52	72.27	39.138	41.08	80.21	85.03	34.75	31.3	29.5	1.1099	1.1765
20	0.4	12	15	1.5	1.7	1.6	1.1	1.07	24.82	6.18	10.8	29.71	17.4	9.1805	9.635	18.82	19.43	144.4	133	129	1.0814	1.1167
20	0.6	15	18	0.5	2.0	1	4.1	2.02	77.13	12.1	67.7	145.4	190	111.2	114.3	225.5	250.8	13.22	11.1	10	1.1864	1.3198
20	0.6	15	18	1	2.0	1.4	2.0	1.43	47.66	12.1	39	77.93	96.23	53.83	55.32	109.1	115.9	26.1	23	21.7	1.1342	1.2039
20	0.6	15	18	1.5	2.0	1.7	1.4	1.17	31.58	12.1	23.4	43.62	41.35	22.538	23.16	45.7	47.24	60.73	55	53.2	1.1051	1.1423
20	0.8	18	21	0.5	2.4	1.1	4.8	2.2	84.91	16.5	80.6	164.2	213.5	128.27	129.8	258.1	288.4	11.76	9.73	8.71	1.209	1.3509
20	0.8	18	21	1	2.4	1.6	2.4	1.56	54.78	16.5	50.9	93.69	119.7	68.734	69.56	138.3	147.4	20.99	18.2	17	1.1557	1.2316
20	0.8	18	21	1.5	2.4	1.9	1.6	1.27	38.35	16.5	34.6	57.84	64.79	36.256	36.69	72.95	75.68	38.76	34.4	33.2	1.1259	1.1681
20	1	20	23	0.5	2.8	1.2	5.5	2.36	91.14	20	91.1	179.5	231.9	142.27	142.3	284.5	319.1	10.83	8.83	7.87	1.2271	1.3761
20	1	20	23	1	2.8	1.7	2.8	1.67	60.48	20	60.5	106.6	138.1	80.964	80.96	161.9	173.1	18.19	15.5	14.5	1.1729	1.2539
20	1	20	23	1.5	2.8	2	1.8	1.36	43.76	20	43.8	69.45	83.19	47.523	47.52	95.05	98.9	30.19	26.4	25.4	1.1426	1.1889

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
30	0.4	20	23	1.5	2.8	2	1.8	1.36	54.57	15.2	38.6	81.14	86.03	46.752	49.15	95.9	102.3	29.19	26.2	24.6	1.1147	1.1889
30	0.4	20	23	2	2.8	2.4	1.4	1.18	42.83	15.2	27.5	56.21	45.76	24.415	25.67	50.08	52.42	54.88	50.1	47.9	1.0944	1.1455
30	0.6	24	27	0.5	3.5	1.3	7.0	2.65	114.8	21.6	104	223.4	272.3	164.95	169.7	334.6	386.8	9.223	7.51	6.49	1.2288	1.4205
30	0.6	24	27	1	3.5	1.9	3.5	1.87	82.18	21.6	72.3	143.4	175.3	101.46	104.4	205.8	226.7	14.33	12.2	11.1	1.1742	1.2932
30	0.6	24	27	1.5	3.5	2.3	2.3	1.53	64.37	21.6	55	102.6	118.5	66.836	68.74	135.6	145.3	21.19	18.5	17.3	1.1437	1.2256
30	0.6	24	27	2	3.5	2.6	1.7	1.32	52.28	21.6	43.3	76.2	78.28	43.325	44.56	87.89	92.4	32.08	28.6	27.2	1.1227	1.1804
30	0.8	27	30	0.5	4.2	1.5	8.5	2.91	124.5	26.3	120	248.4	299.4	186.63	189	375.6	436.8	8.388	6.69	5.75	1.2544	1.4589
30	0.8	27	30	1	4.2	2.1	4.2	2.06	91.02	26.3	86.5	164.3	202.4	120.54	122	242.6	268.7	12.41	10.4	9.35	1.1985	1.3273
30	0.8	27	30	1.5	4.2	2.5	2.8	1.68	72.77	26.3	68.5	121.6	145.7	84.482	85.54	170	183.1	17.24	14.8	13.7	1.1671	1.2573
30	0.8	27	30	2	4.2	2.9	2.1	1.46	60.38	26.3	56.3	93.8	105.4	60.003	60.75	120.8	127.6	23.83	20.8	19.7	1.1457	1.2106
30	1	30	33	0.5	5.0	1.6	9.9	3.15	132.5	30	133	269.7	321.5	205.04	205	410.1	479.4	7.811	6.12	5.24	1.2754	1.4912
30	1	30	33	1	5.0	2.2	5.0	2.23	98.38	30	98.4	182.2	224.5	136.76	136.8	273.5	304.4	11.19	9.18	8.25	1.2184	1.3559
30	1	30	33	1.5	5.0	2.7	3.3	1.82	79.76	30	79.8	137.7	167.8	99.52	99.52	199	215.4	14.97	12.6	11.7	1.1865	1.284
30	1	30	33	2	5.0	3.2	2.5	1.58	67.12	30	67.1	108.8	127.5	74.235	74.24	148.5	157.6	19.7	16.9	15.9	1.1646	1.236

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
35	0.4	24	27	1.5	3.5	2.3	2.3	1.53	69.94	19.8	53	108.8	120.5	66.421	69.88	136.3	147.7	20.84	18.4	17	1.1311	1.2256
35	0.4	24	27	2	3.5	2.6	1.7	1.32	57.65	19.8	41.3	81.96	79.57	43.056	45.3	88.35	93.92	31.56	28.4	26.7	1.1104	1.1804
35	0.4	24	27	2.5	3.5	3	1.4	1.18	48.42	19.8	32.5	62.42	47.82	25.511	26.84	52.35	54.85	52.51	48	45.8	1.0946	1.1468
35	0.6	28	31	0.5	4.5	1.5	9.1	3.01	134.3	26.3	123	265.6	313.4	193.02	198.6	391.6	461.3	8.013	6.41	5.44	1.2496	1.4718
35	0.6	28	31	1	4.5	2.1	4.5	2.13	100	26.3	89.5	178.8	214.8	126.37	130	256.4	287.5	11.69	9.79	8.73	1.1938	1.3387
35	0.6	28	31	1.5	4.5	2.6	3.0	1.74	81.32	26.3	71.3	134.6	157.1	90.023	92.64	182.7	199.2	15.99	13.7	12.6	1.1627	1.2679
35	0.6	28	31	2	4.5	3	2.3	1.5	68.62	26.3	59	105.9	116.2	65.342	67.24	132.6	141.8	21.62	18.9	17.7	1.1412	1.2207
35	0.6	28	31	2.5	4.5	3.4	1.8	1.35	59.08	26.3	49.7	85.05	84.43	46.809	48.17	94.98	100.1	29.75	26.4	25.1	1.1249	1.1856
35	0.8	32	34	0.5	5.5	1.7	10.9	3.3	144.1	31.1	139	291.9	340.1	215.49	218.2	433.7	513.7	7.385	5.79	4.89	1.2753	1.5107
35	0.8	32	34	1	5.5	2.3	5.5	2.34	109	31.1	104	200.8	241.5	146.14	148	294.1	331.5	10.4	8.54	7.58	1.2181	1.3731
35	0.8	32	34	1.5	5.5	2.9	3.6	1.91	89.84	31.1	85.3	154.5	183.8	108.31	109.7	218	238.9	13.67	11.5	10.5	1.1863	1.3
35	0.8	32	34	2	5.5	3.3	2.7	1.65	76.84	31.1	72.5	124.4	142.8	82.631	83.68	166.3	178.7	17.58	15.1	14.1	1.1643	1.2512
35	0.8	32	34	2.5	5.5	3.7	2.2	1.48	67.07	31.1	62.8	102.5	111.1	63.346	64.15	127.5	135	22.61	19.7	18.6	1.1477	1.215
35	1	35	38	0.5	6.6	1.8	13.1	3.62	153.9	35	154	318.7	366.1	237.8	237.8	475.6	567.4	6.86	5.28	4.43	1.2992	1.5499
35	1	35	38	1	6.6	2.6	6.6	2.56	118	35	118	223.3	267.5	165.92	165.9	331.8	376.5	9.39	7.57	6.67	1.2407	1.4078
35	1	35	38	1.5	6.6	3.1	4.4	2.09	98.36	35	98.4	174.8	209.8	126.72	126.7	253.4	279.5	11.97	9.91	8.99	1.2081	1.3324
35	1	35	38	2	6.6	3.6	3.3	1.81	85.05	35	85.1	143.2	168.9	100.1	100.1	200.2	216.5	14.87	12.5	11.6	1.1856	1.2819
35	1	35	38	2.5	6.6	4	2.6	1.62	75.06	35	75.1	120.3	137.1	80.111	80.11	160.2	170.6	18.32	15.7	14.7	1.1685	1.2445

T_1	phi	T_wb	T_cond= T_sat	P_1	P_2 = P_sat	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_2 1stage	W_dt	W_ds1	W_ds2	W_ds 1+2	W_ds	COP			COP Ratio	
																		dt=0	Isentropic			
(C)	%	(C)	(C)	(kPa)	(kPa)	(kPa)			(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)	(kJ/kg)		2 stg	1 stg	2 stg	1stg
40	0.4	28	31	1.5	4.4	2.6	2.9	1.71	85.62	24.3	67.6	137.9	155.1	86.665	91.25	177.9	195.8	16.2	14.1	12.8	1.1473	1.2626
40	0.4	28	31	2	4.4	3	2.2	1.48	72.77	24.3	55.4	109	113.5	62.251	65.54	127.8	138	22.13	19.7	18.2	1.1261	1.2156
40	0.4	28	31	2.5	4.4	3.3	1.8	1.32	63.12	24.3	46.2	87.95	81.22	43.918	46.24	90.16	95.9	30.92	27.9	26.2	1.1101	1.1808
40	0.4	28	31	3	4.4	3.6	1.5	1.21	55.44	24.3	38.9	71.63	54.86	29.319	30.87	60.19	63.26	45.78	41.7	39.7	1.0972	1.1532
40	0.6	32	35	0.5	5.6	1.7	11.3	3.36	152.5	31	140	305.5	350	218.63	225.1	443.7	531.1	7.175	5.66	4.73	1.2676	1.5172
40	0.6	32	35	1	5.6	2.4	5.6	2.37	116.7	31	106	212.2	249.8	149.04	153.4	302.5	344.5	10.05	8.3	7.29	1.2108	1.3789
40	0.6	32	35	1.5	5.6	2.9	3.8	1.94	97.18	31	86.6	164.8	191.2	111.08	114.4	225.4	249.6	13.14	11.1	10.1	1.179	1.3054
40	0.6	32	35	2	5.6	3.4	2.8	1.68	83.91	31	73.7	134	149.6	85.304	87.82	173.1	188	16.79	14.5	13.4	1.1572	1.2563
40	0.6	32	35	2.5	5.6	3.8	2.3	1.5	73.95	31	64	111.6	117.4	65.95	67.9	133.8	143.2	21.4	18.8	17.5	1.1406	1.2199
40	0.6	32	35	3	5.6	4.1	1.9	1.37	66.01	31	56.3	94.19	90.99	50.539	52.03	102.6	108.4	27.6	24.5	23.2	1.1273	1.1912
40	0.8	37	39	0.5	7.2	1.9	14.3	3.79	165.8	36	160	342.2	385	248.4	251.6	500	604.3	6.523	5.02	4.16	1.2987	1.5696
40	0.8	37	39	1	7.2	2.7	7.2	2.68	128.9	36	124	243	284.8	175.46	177.7	353.2	405.9	8.819	7.11	6.19	1.2401	1.4252
40	0.8	37	39	1.5	7.2	3.3	4.8	2.19	108.7	36	104	192.5	226.2	135.67	137.4	273.1	305	11.1	9.2	8.23	1.2075	1.3486
40	0.8	37	39	2	7.2	3.8	3.6	1.89	95.03	36	90.4	159.7	184.6	108.66	110.1	218.7	239.5	13.61	11.5	10.5	1.185	1.2974
40	0.8	37	39	2.5	7.2	4.2	2.9	1.69	84.76	36	80.2	135.9	152.3	88.377	89.52	177.9	191.8	16.49	14.1	13.1	1.1679	1.2594
40	0.8	37	39	3	7.2	4.6	2.4	1.55	76.58	36	72.1	117.4	126	72.225	73.16	145.4	154.9	19.94	17.3	16.2	1.1542	1.2295
40	1	40	43	0.5	8.6	2.1	17.1	4.14	175.7	40	176	370.3	410.5	271.44	271.4	542.9	660.6	6.118	4.63	3.8	1.3225	1.6092
40	1	40	43	1	8.6	2.9	8.6	2.92	138	40	138	266.5	310.3	195.89	195.9	391.8	453.1	8.094	6.41	5.54	1.2627	1.4603
40	1	40	43	1.5	8.6	3.6	5.7	2.39	117.3	40	117	213.8	251.7	154.68	154.7	309.4	347.6	9.98	8.12	7.23	1.2293	1.3812
40	1	40	43	2	8.6	4.1	4.3	2.07	103.4	40	103	179.5	210.1	126.7	126.7	253.4	279.1	11.96	9.91	9	1.2064	1.3285
40	1	40	43	2.5	8.6	4.6	3.4	1.85	92.85	40	92.8	154.6	177.8	105.69	105.7	211.4	229.2	14.13	11.9	11	1.1889	1.2892
40	1	40	43	3	8.6	5.1	2.9	1.69	84.48	40	84.5	135.3	151.4	88.964	88.96	177.9	190.6	16.58	14.1	13.2	1.1749	1.2585

APPENDIX 3

Membrane cycle - Compressor work and COP

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	_21stag	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
20.00	30.00	0.40	20.00	20.00	0.50	2.34	1.08	4.68	2.16	83.36	6.18	66.55	160.41	208.83	120.73	126.71	247.44	280.82	12.03	10.15	8.94
20.00	30.00	0.60	24.00	24.00	0.50	2.97	1.22	5.93	2.44	94.25	12.13	84.38	187.31	240.95	144.51	148.49	293.00	334.62	10.42	8.57	7.51
20.00	30.00	0.80	27.00	27.00	0.50	3.61	1.34	7.23	2.69	103.58	16.51	99.10	211.01	267.73	165.18	167.17	332.34	382.02	9.38	7.56	6.57
20.00	30.00	1.00	30.00	30.00	0.50	4.25	1.46	8.49	2.91	111.36	20.00	111.36	231.21	289.54	182.72	182.72	365.45	422.42	8.67	6.87	5.95
20.00	30.00	0.40	20.00	20.00	1.00	2.34	1.53	2.34	1.53	53.36	6.18	37.96	90.51	115.02	63.57	66.71	130.28	141.02	21.84	19.28	17.81
20.00	30.00	0.60	24.00	24.00	1.00	2.97	1.72	2.97	1.72	63.33	12.13	54.30	113.07	147.14	84.34	86.66	171.00	186.15	17.07	14.69	13.49
20.00	30.00	0.80	27.00	27.00	1.00	3.61	1.90	3.61	1.90	71.88	16.51	67.77	132.95	173.92	102.53	103.77	206.29	225.90	14.44	12.17	11.12
20.00	30.00	1.00	30.00	30.00	1.00	4.25	2.06	4.25	2.06	79.01	20.00	79.01	149.89	195.73	118.01	118.01	236.02	259.79	12.83	10.64	9.67
20.00	30.00	0.40	20.00	20.00	1.50	2.34	1.87	1.56	1.25	36.99	6.18	22.37	54.97	60.15	32.38	33.99	66.37	69.95	41.76	37.84	35.91
20.00	30.00	0.60	24.00	24.00	1.50	2.97	2.11	1.98	1.41	46.47	12.13	37.89	75.33	92.27	51.52	52.94	104.45	110.66	27.22	24.04	22.70
20.00	30.00	0.80	27.00	27.00	1.50	3.61	2.33	2.41	1.55	54.59	16.51	50.69	93.27	119.05	68.36	69.18	137.54	146.53	21.10	18.26	17.14
20.00	30.00	1.00	30.00	30.00	1.50	4.25	2.52	2.83	1.68	61.36	20.00	61.36	108.55	140.85	82.71	82.71	165.42	177.10	17.83	15.18	14.18
20.00	35.00	0.40	24.00	24.00	0.50	2.97	1.22	5.93	2.44	94.25	6.18	76.92	187.31	240.95	141.49	148.49	289.99	334.62	10.42	8.66	7.51
20.00	35.00	0.60	28.00	28.00	0.50	3.86	1.39	7.71	2.78	106.70	12.13	96.50	219.04	276.51	168.73	173.39	342.12	398.08	9.08	7.34	6.31
20.00	35.00	0.80	32.00	32.00	0.50	4.67	1.53	9.34	3.06	116.03	16.51	111.39	243.52	302.41	189.76	192.05	381.81	447.04	8.30	6.58	5.62
20.00	35.00	1.00	35.00	35.00	0.50	5.63	1.68	11.26	3.36	125.35	20.00	125.35	268.57	327.67	210.70	210.70	421.39	497.15	7.66	5.96	5.05
20.00	35.00	0.40	24.00	24.00	1.00	2.97	1.72	2.97	1.72	63.33	6.18	47.47	113.07	147.14	82.58	86.66	169.24	186.15	17.07	14.84	13.49
20.00	35.00	0.60	28.00	28.00	1.00	3.86	1.96	3.86	1.96	74.73	12.13	65.39	139.69	182.70	106.52	109.46	215.99	239.38	13.75	11.63	10.49
20.00	35.00	0.80	32.00	32.00	1.00	4.67	2.16	4.67	2.16	83.28	16.51	79.03	160.22	208.60	125.05	126.55	251.60	280.44	12.04	9.98	8.96
20.00	35.00	1.00	35.00	35.00	1.00	5.63	2.37	5.63	2.37	91.81	20.00	91.81	181.23	233.86	143.63	143.63	287.26	322.46	10.74	8.74	7.79
20.00	35.00	0.40	24.00	24.00	1.50	2.97	2.11	1.98	1.41	46.47	6.18	31.40	75.33	92.27	50.44	52.94	103.38	110.66	27.22	24.29	22.70
20.00	35.00	0.60	28.00	28.00	1.50	3.86	2.41	2.57	1.60	57.30	12.13	48.43	99.34	127.82	72.59	74.59	147.18	158.68	19.65	17.06	15.83
20.00	35.00	0.80	32.00	32.00	1.50	4.67	2.65	3.11	1.76	65.41	16.51	61.38	117.87	153.72	89.75	90.83	180.57	195.73	16.34	13.91	12.83
20.00	35.00	1.00	35.00	35.00	1.50	5.63	2.91	3.75	1.94	73.52	20.00	73.52	136.82	178.98	107.05	107.05	214.09	233.65	14.03	11.73	10.75
20.00	40.00	0.40	28.00	28.00	0.50	3.73	1.37	7.47	2.73	105.14	6.18	87.30	215.02	272.13	162.25	170.28	332.53	390.04	9.23	7.55	6.44
20.00	40.00	0.60	32.00	32.00	0.50	4.82	1.55	9.64	3.10	117.58	12.13	107.09	247.66	306.66	189.92	195.16	385.08	455.32	8.19	6.52	5.52
20.00	40.00	0.80	37.00	37.00	0.50	6.17	1.76	12.34	3.51	130.00	16.51	125.20	281.31	340.07	217.39	220.01	437.40	522.62	7.39	5.74	4.81
20.00	40.00	1.00	40.00	40.00	0.50	7.39	1.92	14.77	3.84	139.31	20.00	139.31	307.20	364.42	238.62	238.62	477.23	574.39	6.89	5.26	4.37
20.00	40.00	0.40	28.00	28.00	1.00	3.73	1.93	3.73	1.93	73.31	6.18	56.97	136.31	178.32	101.59	106.62	208.20	232.63	14.08	12.06	10.80
20.00	40.00	0.60	32.00	32.00	1.00	4.82	2.20	4.82	2.20	84.70	12.13	75.09	163.69	212.85	125.93	129.40	255.33	287.38	11.80	9.84	8.74
20.00	40.00	0.80	37.00	37.00	1.00	6.17	2.48	6.17	2.48	96.08	16.51	91.68	191.91	246.26	150.35	152.16	302.50	343.83	10.20	8.30	7.30
20.00	40.00	1.00	40.00	40.00	1.00	7.39	2.72	7.39	2.72	104.60	20.00	104.60	213.63	270.61	169.20	169.20	338.40	387.25	9.28	7.42	6.49
20.00	40.00	0.40	28.00	28.00	1.50	3.73	2.37	2.49	1.58	55.94	6.18	40.43	96.30	123.45	68.50	71.89	140.38	152.59	20.34	17.89	16.46
20.00	40.00	0.60	32.00	32.00	1.50	4.82	2.69	3.21	1.79	66.77	12.13	57.64	121.00	157.98	91.02	93.53	184.55	201.99	15.90	13.61	12.43
20.00	40.00	0.80	37.00	37.00	1.50	6.17	3.04	4.11	2.03	77.57	16.51	73.40	146.46	191.38	113.78	115.15	228.92	252.92	13.12	10.97	9.93
20.00	40.00	1.00	40.00	40.00	1.50	7.39	3.33	4.92	2.22	85.67	20.00	85.67	166.05	215.73	131.33	131.33	262.67	292.10	11.64	9.56	8.60

Membrane cycle - Compressor work and COP

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	_21stag	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
25.00	30.00	0.80	27.00	27.00	0.50	3.61	1.34	7.23	2.69	110.01	21.39	105.37	219.27	272.30	167.96	170.02	337.98	388.54	9.22	7.43	6.46
25.00	30.00	1.00	30.00	30.00	0.50	4.25	1.46	8.49	2.91	117.92	25.00	117.92	239.81	294.48	185.84	185.84	371.68	429.63	8.53	6.76	5.85
25.00	30.00	0.40	20.00	20.00	1.00	2.34	1.53	2.34	1.53	58.93	10.72	43.01	96.71	116.98	64.60	67.85	132.45	143.43	21.47	18.96	17.51
25.00	30.00	0.60	24.00	24.00	1.00	2.97	1.72	2.97	1.72	69.07	16.86	59.73	119.66	149.65	85.74	88.14	173.88	189.32	16.78	14.44	13.27
25.00	30.00	0.80	27.00	27.00	1.00	3.61	1.90	3.61	1.90	77.77	21.39	73.52	139.88	176.89	104.26	105.54	209.79	229.76	14.20	11.97	10.93
25.00	30.00	1.00	30.00	30.00	1.00	4.25	2.06	4.25	2.06	85.01	25.00	85.01	157.11	199.07	120.02	120.02	240.05	264.22	12.62	10.46	9.51
25.00	30.00	0.40	20.00	20.00	1.50	2.34	1.87	1.56	1.25	42.28	10.72	27.17	60.57	61.17	32.91	34.57	67.48	71.14	41.06	37.22	35.30
25.00	30.00	0.60	24.00	24.00	1.50	2.97	2.11	1.98	1.41	51.92	16.86	43.05	81.27	93.84	52.37	53.84	106.21	112.55	26.76	23.65	22.32
25.00	30.00	0.80	27.00	27.00	1.50	3.61	2.33	2.41	1.55	60.18	21.39	56.15	99.52	121.08	69.51	70.36	139.87	149.03	20.74	17.96	16.85
25.00	30.00	1.00	30.00	30.00	1.50	4.25	2.52	2.83	1.68	67.06	25.00	67.06	115.06	143.26	84.12	84.12	168.25	180.12	17.53	14.93	13.94
25.00	35.00	0.40	24.00	24.00	0.50	2.97	1.22	5.93	2.44	100.51	10.72	82.61	195.16	245.06	143.79	151.03	294.82	340.33	10.25	8.52	7.38
25.00	35.00	0.60	28.00	28.00	0.50	3.86	1.39	7.71	2.78	113.17	16.86	102.63	227.44	281.23	171.53	176.35	347.88	404.88	8.93	7.22	6.20
25.00	35.00	0.80	32.00	32.00	0.50	4.67	1.53	9.34	3.06	122.66	21.39	117.87	252.34	307.57	192.96	195.33	388.29	454.67	8.17	6.47	5.52
25.00	35.00	1.00	35.00	35.00	0.50	5.63	1.68	11.26	3.36	132.15	25.00	132.15	277.81	333.26	214.29	214.29	428.58	505.63	7.54	5.86	4.97
25.00	35.00	0.40	24.00	24.00	1.00	2.97	1.72	2.97	1.72	69.07	10.72	52.67	119.66	149.65	83.92	88.14	172.06	189.32	16.78	14.60	13.27
25.00	35.00	0.60	28.00	28.00	1.00	3.86	1.96	3.86	1.96	80.67	16.86	71.01	146.73	185.82	108.29	111.33	219.62	243.46	13.52	11.44	10.32
25.00	35.00	0.80	32.00	32.00	1.00	4.67	2.16	4.67	2.16	89.36	21.39	84.97	167.61	212.16	127.15	128.71	255.87	285.22	11.84	9.82	8.81
25.00	35.00	1.00	35.00	35.00	1.00	5.63	2.37	5.63	2.37	98.04	25.00	98.04	188.98	237.85	146.08	146.08	292.16	327.96	10.56	8.60	7.66
25.00	35.00	0.40	24.00	24.00	1.50	2.97	2.11	1.98	1.41	51.92	10.72	36.35	81.27	93.84	51.26	53.84	105.10	112.55	26.76	23.90	22.32
25.00	35.00	0.60	28.00	28.00	1.50	3.86	2.41	2.57	1.60	62.93	16.86	53.76	105.70	130.01	73.80	75.87	149.66	161.39	19.32	16.78	15.56
25.00	35.00	0.80	32.00	32.00	1.50	4.67	2.65	3.11	1.76	71.19	21.39	67.02	124.54	156.35	91.26	92.38	183.64	199.07	16.06	13.68	12.62
25.00	35.00	1.00	35.00	35.00	1.50	5.63	2.91	3.75	1.94	79.44	25.00	79.44	143.82	182.04	108.87	108.87	217.74	237.63	13.80	11.53	10.57
25.00	40.00	0.40	28.00	28.00	0.50	3.73	1.37	7.47	2.73	111.59	10.72	93.16	223.35	276.78	164.88	173.19	338.07	396.69	9.07	7.43	6.33
25.00	40.00	0.60	32.00	32.00	0.50	4.82	1.55	9.64	3.10	124.25	16.86	113.40	256.54	311.90	193.07	198.49	391.56	463.09	8.05	6.41	5.42
25.00	40.00	0.80	37.00	37.00	0.50	6.17	1.76	12.34	3.51	136.88	21.39	131.92	290.77	345.87	221.05	223.76	444.82	531.54	7.26	5.65	4.72
25.00	40.00	1.00	40.00	40.00	0.50	7.39	1.92	14.77	3.84	146.34	25.00	146.34	317.10	370.64	242.69	242.69	485.38	584.20	6.78	5.17	4.30
25.00	40.00	0.40	28.00	28.00	1.00	3.73	1.93	3.73	1.93	79.22	10.72	62.33	143.30	181.36	103.24	108.43	211.67	236.60	13.85	11.87	10.62
25.00	40.00	0.60	32.00	32.00	1.00	4.82	2.20	4.82	2.20	90.81	16.86	80.87	171.14	216.48	128.02	131.61	259.63	292.28	11.60	9.67	8.59
25.00	40.00	0.80	37.00	37.00	1.00	6.17	2.48	6.17	2.48	102.38	21.39	97.83	199.85	250.46	152.88	154.75	307.64	349.69	10.03	8.16	7.18
25.00	40.00	1.00	40.00	40.00	1.00	7.39	2.72	7.39	2.72	111.04	25.00	111.04	221.93	275.23	172.09	172.09	344.17	393.86	9.13	7.30	6.38
25.00	40.00	0.40	28.00	28.00	1.50	3.73	2.37	2.49	1.58	61.56	10.72	45.52	102.60	125.55	69.61	73.12	142.72	155.20	20.00	17.60	16.18
25.00	40.00	0.60	32.00	32.00	1.50	4.82	2.69	3.21	1.79	72.56	16.86	63.13	127.72	160.67	92.53	95.13	187.66	205.44	15.63	13.38	12.23
25.00	40.00	0.80	37.00	37.00	1.50	6.17	3.04	4.11	2.03	83.56	21.39	79.24	153.62	194.65	115.69	117.11	232.81	257.24	12.90	10.79	9.76
25.00	40.00	1.00	40.00	40.00	1.50	7.39	3.33	4.92	2.22	91.79	25.00	91.79	173.54	219.41	133.58	133.58	267.15	297.09	11.45	9.40	8.45

Membrane cycle - Compressor work and COP

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	_21stag	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
30.00	30.00	0.80	27.00	27.00	0.50	3.61	1.34	7.23	2.69	116.44	26.27	111.64	227.53	276.87	170.74	172.87	343.62	395.06	9.07	7.31	6.36
30.00	30.00	1.00	30.00	30.00	0.50	4.25	1.46	8.49	2.91	124.48	30.00	124.48	248.42	299.42	188.96	188.96	377.92	436.84	8.39	6.65	5.75
30.00	30.00	0.40	20.00	20.00	1.00	2.34	1.53	2.34	1.53	64.50	15.24	48.06	102.92	118.95	65.63	68.99	134.62	145.83	21.11	18.66	17.22
30.00	30.00	0.60	24.00	24.00	1.00	2.97	1.72	2.97	1.72	74.81	21.59	65.16	126.25	152.16	87.14	89.62	176.76	192.50	16.51	14.21	13.05
30.00	30.00	0.80	27.00	27.00	1.00	3.61	1.90	3.61	1.90	83.65	26.27	79.26	146.81	179.86	105.99	107.31	213.29	233.61	13.96	11.78	10.75
30.00	30.00	1.00	30.00	30.00	1.00	4.25	2.06	4.25	2.06	91.02	30.00	91.02	164.33	202.41	122.04	122.04	244.08	268.65	12.41	10.29	9.35
30.00	30.00	0.40	20.00	20.00	1.50	2.34	1.87	1.56	1.25	47.57	15.24	31.96	66.17	62.20	33.44	35.15	68.58	72.33	40.38	36.62	34.72
30.00	30.00	0.60	24.00	24.00	1.50	2.97	2.11	1.98	1.41	57.37	21.59	48.21	87.22	95.41	53.23	54.74	107.97	114.43	26.32	23.26	21.95
30.00	30.00	0.80	27.00	27.00	1.50	3.61	2.33	2.41	1.55	65.77	26.27	61.60	105.77	123.11	70.66	71.54	142.20	151.53	20.40	17.66	16.57
30.00	30.00	1.00	30.00	30.00	1.50	4.25	2.52	2.83	1.68	72.77	30.00	72.77	121.57	145.66	85.54	85.54	171.07	183.14	17.24	14.68	13.71
30.00	35.00	0.40	24.00	24.00	0.50	2.97	1.22	5.93	2.44	106.78	15.24	88.29	203.02	249.18	146.08	153.56	299.65	346.04	10.08	8.38	7.26
30.00	35.00	0.60	28.00	28.00	0.50	3.86	1.39	7.71	2.78	119.65	21.59	108.76	235.84	285.95	174.33	179.31	353.64	411.67	8.78	7.10	6.10
30.00	35.00	0.80	32.00	32.00	0.50	4.67	1.53	9.34	3.06	129.30	26.27	124.35	261.15	312.73	196.16	198.61	394.77	462.30	8.03	6.36	5.43
30.00	35.00	1.00	35.00	35.00	0.50	5.63	1.68	11.26	3.36	138.94	30.00	138.94	287.06	338.85	217.89	217.89	435.77	514.11	7.41	5.76	4.89
30.00	35.00	0.40	24.00	24.00	1.00	2.97	1.72	2.97	1.72	74.81	15.24	57.87	126.25	152.16	85.26	89.62	174.88	192.50	16.51	14.36	13.05
30.00	35.00	0.60	28.00	28.00	1.00	3.86	1.96	3.86	1.96	86.60	21.59	76.62	153.77	188.94	110.06	113.20	223.26	247.54	13.29	11.25	10.15
30.00	35.00	0.80	32.00	32.00	1.00	4.67	2.16	4.67	2.16	95.44	26.27	90.90	175.01	215.72	129.26	130.87	260.13	290.01	11.64	9.65	8.66
30.00	35.00	1.00	35.00	35.00	1.00	5.63	2.37	5.63	2.37	104.27	30.00	104.27	196.73	241.84	148.53	148.53	297.06	333.47	10.39	8.45	7.53
30.00	35.00	0.40	24.00	24.00	1.50	2.97	2.11	1.98	1.41	57.37	15.24	41.28	87.22	95.41	52.08	54.74	106.82	114.43	26.32	23.51	21.95
30.00	35.00	0.60	28.00	28.00	1.50	3.86	2.41	2.57	1.60	68.57	21.59	59.09	112.05	132.19	75.00	77.14	152.14	164.10	19.00	16.51	15.30
30.00	35.00	0.80	32.00	32.00	1.50	4.67	2.65	3.11	1.76	76.96	26.27	72.65	131.21	158.97	92.77	93.93	186.70	202.41	15.80	13.45	12.41
30.00	35.00	1.00	35.00	35.00	1.50	5.63	2.91	3.75	1.94	85.35	30.00	85.35	150.81	185.09	110.70	110.70	221.40	241.62	13.57	11.34	10.39
30.00	40.00	0.40	28.00	28.00	0.50	3.73	1.37	7.47	2.73	118.05	15.24	99.00	231.68	281.42	167.51	176.09	343.61	403.35	8.92	7.31	6.23
30.00	40.00	0.60	32.00	32.00	0.50	4.82	1.55	9.64	3.10	130.91	21.59	119.70	265.43	317.13	196.22	201.82	398.04	470.86	7.92	6.31	5.33
30.00	40.00	0.80	37.00	37.00	0.50	6.17	1.76	12.34	3.51	143.76	26.27	138.63	300.23	351.68	224.72	227.52	452.23	540.46	7.14	5.55	4.65
30.00	40.00	1.00	40.00	40.00	0.50	7.39	1.92	14.77	3.84	153.38	30.00	153.38	327.00	376.86	246.76	246.76	493.52	594.00	6.66	5.09	4.23
30.00	40.00	0.40	28.00	28.00	1.00	3.73	1.93	3.73	1.93	85.13	15.24	67.69	150.28	184.41	104.88	110.25	215.14	240.57	13.62	11.67	10.44
30.00	40.00	0.60	32.00	32.00	1.00	4.82	2.20	4.82	2.20	96.91	21.59	86.64	178.59	220.12	130.10	133.82	263.92	297.18	11.41	9.52	8.45
30.00	40.00	0.80	37.00	37.00	1.00	6.17	2.48	6.17	2.48	108.68	26.27	103.98	207.78	254.66	155.41	157.35	312.77	355.56	9.86	8.03	7.06
30.00	40.00	1.00	40.00	40.00	1.00	7.39	2.72	7.39	2.72	117.49	30.00	117.49	230.23	279.84	174.97	174.97	349.95	400.47	8.97	7.18	6.27
30.00	40.00	0.40	28.00	28.00	1.50	3.73	2.37	2.49	1.58	67.17	15.24	50.60	108.90	127.66	70.72	74.34	145.06	157.80	19.67	17.31	15.92
30.00	40.00	0.60	32.00	32.00	1.50	4.82	2.69	3.21	1.79	78.36	21.59	68.61	134.44	163.37	94.04	96.72	190.76	208.89	15.37	13.17	12.02
30.00	40.00	0.80	37.00	37.00	1.50	6.17	3.04	4.11	2.03	89.54	26.27	85.08	160.78	197.92	117.61	119.08	236.69	261.55	12.69	10.61	9.60
30.00	40.00	1.00	40.00	40.00	1.50	7.39	3.33	4.92	2.22	97.91	30.00	97.91	181.04	223.09	135.82	135.82	271.63	302.07	11.26	9.25	8.31

APPENDIX 4

Membrane cycle - Compressor Work Table

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
20.00	30.00	0.40	20.00	23.00	0.50	2.77	1.18	5.55	2.36	91.14	6.18	73.96	179.54	231.87	135.56	142.27	277.83	319.08	10.83	9.04	7.87
20.00	30.00	0.60	24.00	27.00	0.50	3.50	1.32	7.00	2.65	102.03	12.13	91.96	207.02	263.32	159.65	164.06	323.71	374.04	9.54	7.76	6.71
20.00	30.00	0.80	27.00	30.00	0.50	4.25	1.46	8.49	2.91	111.36	16.51	106.78	231.21	289.54	180.55	182.72	363.27	422.42	8.67	6.91	5.95
20.00	30.00	1.00	30.00	33.00	0.50	4.97	1.58	9.95	3.15	119.13	20.00	119.13	251.81	310.90	198.27	198.27	396.54	463.62	8.08	6.33	5.42
20.00	30.00	0.40	20.00	23.00	1.00	2.77	1.67	2.77	1.67	60.48	6.18	44.75	106.56	138.06	77.15	80.96	158.11	173.11	18.19	15.88	14.51
20.00	30.00	0.60	24.00	27.00	1.00	3.50	1.87	3.50	1.87	70.46	12.13	61.23	129.61	169.51	98.21	100.92	199.12	219.21	14.82	12.61	11.46
20.00	30.00	0.80	27.00	30.00	1.00	4.25	2.06	4.25	2.06	79.01	16.51	74.81	149.89	195.73	116.60	118.01	234.62	259.79	12.83	10.70	9.67
20.00	30.00	1.00	30.00	33.00	1.00	4.97	2.23	4.97	2.23	86.12	20.00	86.12	167.17	217.09	132.25	132.25	264.50	294.34	11.57	9.50	8.53
20.00	30.00	0.40	20.00	23.00	1.50	2.77	2.04	1.85	1.36	43.76	6.18	28.82	69.45	83.19	45.28	47.52	92.81	98.90	30.19	27.06	25.39
20.00	30.00	0.60	24.00	27.00	1.50	3.50	2.29	2.33	1.53	53.24	12.13	44.48	90.25	114.63	64.69	66.48	131.16	140.49	21.91	19.15	17.88
20.00	30.00	0.80	27.00	30.00	1.50	4.25	2.52	2.83	1.68	61.36	16.51	57.37	108.55	140.85	81.73	82.71	164.44	177.10	17.83	15.27	14.18
20.00	30.00	1.00	30.00	33.00	1.50	4.97	2.73	3.32	1.82	68.12	20.00	68.12	124.14	162.21	96.24	96.24	192.47	208.28	15.48	13.05	12.06
20.00	35.00	0.40	24.00	27.00	0.50	3.50	1.32	7.00	2.65	102.03	6.18	84.34	207.02	263.32	156.32	164.06	320.37	374.04	9.54	7.84	6.71
20.00	35.00	0.60	28.00	31.00	0.50	4.53	1.50	9.05	3.01	114.47	12.13	104.06	239.40	298.14	183.87	188.94	372.81	438.81	8.42	6.74	5.72
20.00	35.00	0.80	32.00	34.00	0.50	5.46	1.65	10.92	3.30	123.79	16.51	119.07	264.36	323.51	205.12	207.59	412.71	488.72	7.76	6.09	5.14
20.00	35.00	1.00	35.00	38.00	0.50	6.55	1.81	13.11	3.62	133.11	20.00	133.11	289.88	348.25	226.21	226.21	452.43	539.75	7.21	5.55	4.65
20.00	35.00	0.40	24.00	27.00	1.00	3.50	1.87	3.50	1.87	70.46	6.18	54.26	129.61	169.51	96.16	100.92	197.07	219.21	14.82	12.74	11.46
20.00	35.00	0.60	28.00	31.00	1.00	4.53	2.13	4.53	2.13	81.85	12.13	72.32	156.77	204.33	120.38	123.71	244.09	273.53	12.29	10.29	9.18
20.00	35.00	0.80	32.00	34.00	1.00	5.46	2.34	5.46	2.34	90.39	16.51	86.06	177.70	229.69	139.11	140.78	279.89	315.39	10.93	8.97	7.96
20.00	35.00	1.00	35.00	38.00	1.00	6.55	2.56	6.55	2.56	98.92	20.00	98.92	199.10	254.44	157.84	157.84	315.68	358.20	9.87	7.96	7.01
20.00	35.00	0.40	24.00	27.00	1.50	3.50	2.29	2.33	1.53	53.24	6.18	37.85	90.25	114.63	63.34	66.48	129.81	140.49	21.91	19.35	17.88
20.00	35.00	0.60	28.00	31.00	1.50	4.53	2.61	3.02	1.74	64.06	12.13	55.01	114.75	149.45	85.76	88.12	173.88	189.50	16.80	14.44	13.25
20.00	35.00	0.80	32.00	34.00	1.50	5.46	2.86	3.64	1.91	72.17	16.51	68.06	133.63	174.82	103.10	104.34	207.45	227.27	14.37	12.11	11.05
20.00	35.00	1.00	35.00	38.00	1.50	6.55	3.14	4.37	2.09	80.27	20.00	80.27	152.94	199.57	120.55	120.55	241.09	265.89	12.58	10.42	9.45
20.00	40.00	0.40	28.00	31.00	0.50	4.38	1.48	8.77	2.96	112.92	6.18	94.71	235.30	293.85	177.07	185.83	362.90	430.60	8.55	6.92	5.83
20.00	40.00	0.60	32.00	35.00	0.50	5.63	1.68	11.26	3.36	125.35	12.13	114.65	268.57	327.67	205.04	210.70	415.73	497.15	7.66	6.04	5.05
20.00	40.00	0.80	37.00	39.00	0.50	7.17	1.89	14.34	3.79	137.76	16.51	132.87	302.85	360.40	232.71	235.52	468.23	565.70	6.97	5.36	4.44
20.00	40.00	1.00	40.00	43.00	0.50	8.55	2.07	17.10	4.14	147.05	20.00	147.05	329.18	384.26	254.09	254.09	508.19	618.37	6.54	4.94	4.06
20.00	40.00	0.40	28.00	31.00	1.00	4.38	2.09	4.38	2.09	80.43	6.18	63.76	153.32	200.04	115.16	120.86	236.02	266.64	12.56	10.64	9.42
20.00	40.00	0.60	32.00	35.00	1.00	5.63	2.37	5.63	2.37	91.81	12.13	82.02	181.23	233.86	139.77	143.63	283.40	322.46	10.74	8.86	7.79
20.00	40.00	0.80	37.00	39.00	1.00	7.17	2.68	7.17	2.68	103.18	16.51	98.70	209.98	266.59	164.38	166.36	330.74	379.96	9.42	7.59	6.61
20.00	40.00	1.00	40.00	43.00	1.00	8.55	2.92	8.55	2.92	111.69	20.00	111.69	232.07	290.45	183.37	183.37	366.75	424.13	8.65	6.85	5.92
20.00	40.00	0.40	28.00	31.00	1.50	4.38	2.56	2.92	1.71	62.71	6.18	46.87	111.64	145.16	81.39	85.42	166.81	183.29	17.30	15.06	13.70
20.00	40.00	0.60	32.00	35.00	1.50	5.63	2.91	3.75	1.94	73.52	12.13	64.22	136.82	178.98	104.17	107.05	211.22	233.65	14.03	11.89	10.75
20.00	40.00	0.80	37.00	39.00	1.50	7.17	3.28	4.78	2.19	84.32	16.51	80.06	162.76	211.72	127.11	128.64	255.75	285.52	11.86	9.82	8.80
20.00	40.00	1.00	40.00	43.00	1.50	8.55	3.58	5.70	2.39	92.40	20.00	92.40	182.69	235.57	144.80	144.80	289.60	325.38	10.66	8.67	7.72

Membrane cycle - Compressor Work Table

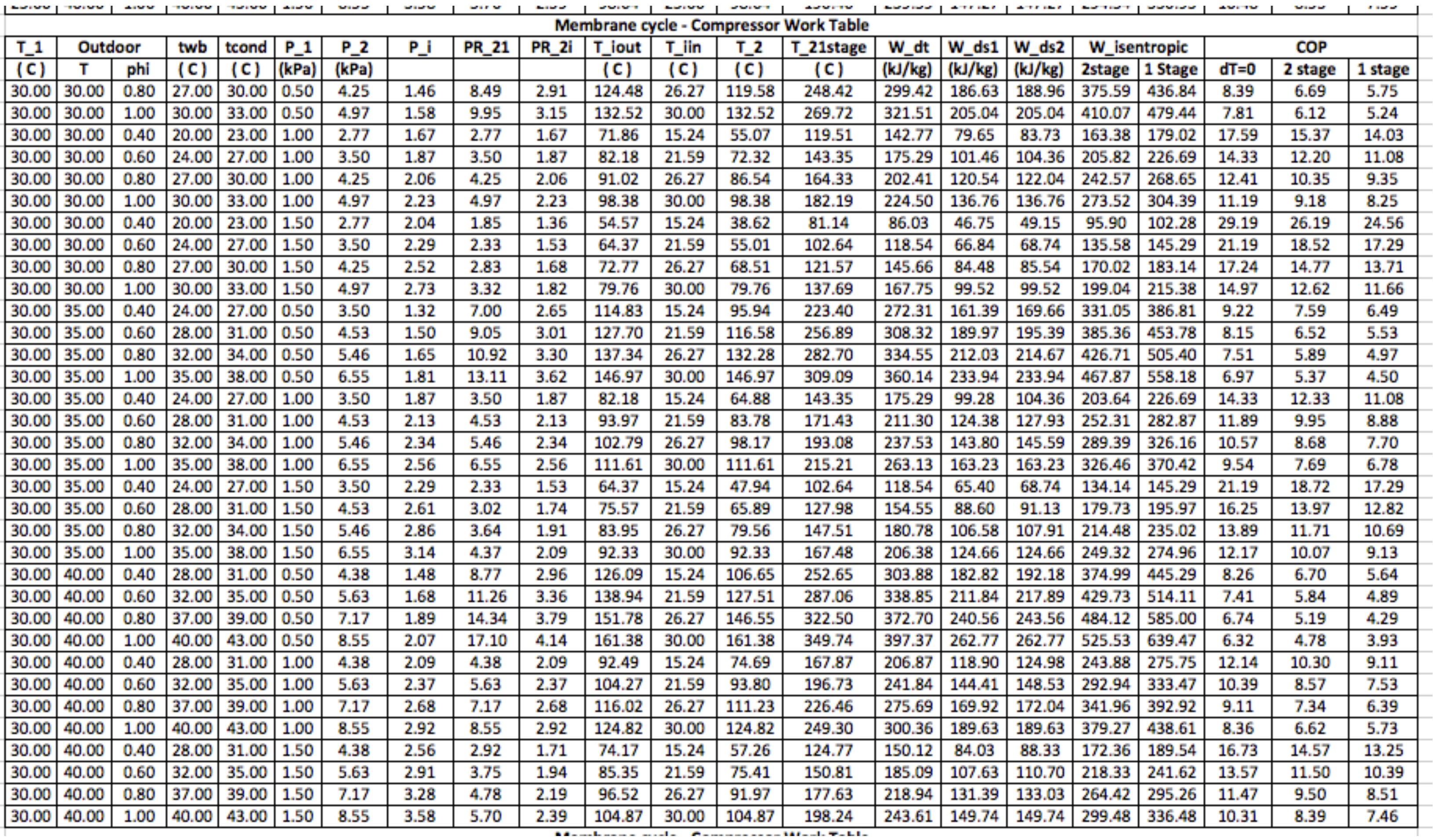
T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
20.00	30.00	0.80	27.00	30.00	2.00	4.25	2.91	2.12	1.46	49.37	16.51	45.53	81.69	101.92	58.05	58.75	116.79	123.38	24.64	21.50	20.36
20.00	30.00	1.00	30.00	33.00	2.00	4.97	3.15	2.49	1.58	55.89	20.00	55.89	96.18	123.28	71.79	71.79	143.57	152.36	20.37	17.49	16.48
20.00	35.00	0.40	24.00	27.00	2.00	3.50	2.65	1.75	1.32	41.55	6.18	26.71	64.68	75.70	41.06	43.09	84.15	89.35	33.18	29.85	28.11
20.00	35.00	0.60	28.00	31.00	2.00	4.53	3.01	2.26	1.50	51.98	12.13	43.25	87.45	110.52	62.25	63.96	126.21	134.91	22.72	19.90	18.62
20.00	35.00	0.80	32.00	34.00	2.00	5.46	3.30	2.73	1.65	59.80	16.51	55.84	105.01	135.88	78.66	79.60	158.26	170.02	18.48	15.87	14.77
20.00	35.00	1.00	35.00	38.00	2.00	6.55	3.62	3.28	1.81	67.61	20.00	67.61	122.96	160.63	95.22	95.22	190.45	205.92	15.64	13.19	12.20
20.00	40.00	0.40	28.00	31.00	2.00	4.38	2.96	2.19	1.48	50.68	6.18	35.41	84.57	106.23	58.46	61.36	119.82	129.13	23.64	20.96	19.45
20.00	40.00	0.60	32.00	35.00	2.00	5.63	3.36	2.81	1.68	61.10	12.13	52.13	107.97	140.05	80.00	82.21	162.21	175.95	17.93	15.48	14.27
20.00	40.00	0.80	37.00	39.00	2.00	7.17	3.79	3.58	1.89	71.51	16.51	67.41	132.09	172.78	101.80	103.03	204.83	224.17	14.54	12.26	11.20
20.00	40.00	1.00	40.00	43.00	2.00	8.55	4.14	4.28	2.07	79.30	20.00	79.30	150.61	196.64	118.61	118.61	237.22	261.22	12.77	10.59	9.61

Membrane cycle - Compressor Work Table

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
25.00	30.00	0.80	27.00	30.00	0.50	4.25	1.46	8.49	2.91	117.92	21.39	113.18	239.81	294.48	183.59	185.84	369.43	429.63	8.53	6.80	5.85
25.00	30.00	1.00	30.00	33.00	0.50	4.97	1.58	9.95	3.15	125.83	25.00	125.83	260.77	316.21	201.65	201.65	403.30	471.53	7.94	6.23	5.33
25.00	30.00	0.40	20.00	23.00	1.00	2.77	1.67	2.77	1.67	66.17	10.72	49.91	113.03	140.42	78.40	82.35	160.74	176.07	17.89	15.62	14.26
25.00	30.00	0.60	24.00	27.00	1.00	3.50	1.87	3.50	1.87	76.32	16.86	66.78	136.48	172.40	99.84	102.64	202.47	222.95	14.57	12.40	11.26
25.00	30.00	0.80	27.00	30.00	1.00	4.25	2.06	4.25	2.06	85.01	21.39	80.68	157.11	199.07	118.57	120.02	238.60	264.22	12.62	10.53	9.51
25.00	30.00	1.00	30.00	33.00	1.00	4.97	2.23	4.97	2.23	92.25	25.00	92.25	174.68	220.79	134.50	134.50	269.01	299.36	11.38	9.34	8.39
25.00	30.00	0.40	20.00	23.00	1.50	2.77	2.04	1.85	1.36	49.17	10.72	33.72	75.29	84.61	46.02	48.33	94.35	100.59	29.68	26.62	24.97
25.00	30.00	0.60	24.00	27.00	1.50	3.50	2.29	2.33	1.53	58.81	16.86	49.75	96.44	116.59	65.76	67.61	133.37	142.89	21.54	18.83	17.58
25.00	30.00	0.80	27.00	30.00	1.50	4.25	2.52	2.83	1.68	67.06	21.39	62.94	115.06	143.26	83.11	84.12	167.23	180.12	17.53	15.02	13.94
25.00	30.00	1.00	30.00	33.00	1.50	4.97	2.73	3.32	1.82	73.94	25.00	73.94	130.91	164.98	97.88	97.88	195.76	211.83	15.22	12.83	11.86
25.00	35.00	0.40	24.00	27.00	0.50	3.50	1.32	7.00	2.65	108.43	10.72	90.14	215.21	267.81	158.86	166.86	325.71	380.43	9.38	7.71	6.60
25.00	35.00	0.60	28.00	31.00	0.50	4.53	1.50	9.05	3.01	121.08	16.86	110.32	248.15	303.23	186.92	192.17	379.09	446.29	8.28	6.62	5.63
25.00	35.00	0.80	32.00	34.00	0.50	5.46	1.65	10.92	3.30	130.57	21.39	125.68	273.53	329.03	208.57	211.13	419.71	497.06	7.63	5.98	5.05
25.00	35.00	1.00	35.00	38.00	0.50	6.55	1.81	13.11	3.62	140.04	25.00	140.04	299.48	354.20	230.07	230.07	460.15	548.97	7.09	5.46	4.57
25.00	35.00	0.40	24.00	27.00	1.00	3.50	1.87	3.50	1.87	76.32	10.72	59.57	136.48	172.40	97.72	102.64	200.36	222.95	14.57	12.54	11.26
25.00	35.00	0.60	28.00	31.00	1.00	4.53	2.13	4.53	2.13	87.91	16.86	78.06	164.10	207.82	122.38	125.82	248.20	278.20	12.09	10.12	9.03
25.00	35.00	0.80	32.00	34.00	1.00	5.46	2.34	5.46	2.34	96.59	21.39	92.12	185.39	233.61	141.45	143.19	284.64	320.77	10.75	8.82	7.83
25.00	35.00	1.00	35.00	38.00	1.00	6.55	2.56	6.55	2.56	105.27	25.00	105.27	207.16	258.78	160.53	160.53	321.07	364.31	9.70	7.82	6.89
25.00	35.00	0.40	24.00	27.00	1.50	3.50	2.29	2.33	1.53	58.81	10.72	42.90	96.44	116.59	64.37	67.61	131.98	142.89	21.54	19.03	17.58
25.00	35.00	0.60	28.00	31.00	1.50	4.53	2.61	3.02	1.74	69.81	16.86	60.45	121.37	152.00	87.18	89.63	176.81	192.73	16.52	14.20	13.03
25.00	35.00	0.80	32.00	34.00	1.50	5.46	2.86	3.64	1.91	78.06	21.39	73.81	140.57	177.80	104.84	106.12	210.96	231.15	14.13	11.91	10.87
25.00	35.00	1.00	35.00	38.00	1.50	6.55	3.14	4.37	2.09	86.30	25.00	86.30	160.21	202.97	122.60	122.60	245.21	270.43	12.37	10.24	9.29
25.00	40.00	0.40	28.00	31.00	0.50	4.38	1.48	8.77	2.96	119.50	10.72	100.69	243.97	298.86	179.94	189.00	368.95	437.95	8.40	6.81	5.73
25.00	40.00	0.60	32.00	35.00	0.50	5.63	1.68	11.26	3.36	132.15	16.86	121.08	277.81	333.26	208.44	214.29	422.73	505.63	7.54	5.94	4.97
25.00	40.00	0.80	37.00	39.00	0.50	7.17	1.89	14.34	3.79	144.77	21.39	139.71	312.67	366.55	236.64	239.54	476.17	575.35	6.85	5.27	4.37
25.00	40.00	1.00	40.00	43.00	0.50	8.55	2.07	17.10	4.14	154.22	25.00	154.22	339.46	390.81	258.43	258.43	516.86	628.92	6.43	4.86	3.99
25.00	40.00	0.40	28.00	31.00	1.00	4.38	2.09	4.38	2.09	86.46	10.72	69.23	160.60	203.45	117.03	122.92	239.95	271.19	12.34	10.47	9.26
25.00	40.00	0.60	32.00	35.00	1.00	5.63	2.37	5.63	2.37	98.04	16.86	87.91	188.98	237.85	142.09	146.08	288.17	327.96	10.56	8.72	7.66
25.00	40.00	0.80	37.00	39.00	1.00	7.17	2.68	7.17	2.68	109.60	21.39	104.97	218.22	271.14	167.15	169.20	336.35	386.44	9.26	7.47	6.50
25.00	40.00	1.00	40.00	43.00	1.00	8.55	2.92	8.55	2.92	118.25	25.00	118.25	240.68	295.40	186.50	186.50	373.01	431.37	8.50	6.73	5.82
25.00	40.00	0.40	28.00	31.00	1.50	4.38	2.56	2.92	1.71	68.44	10.72	52.07	118.21	147.64	82.71	86.88	169.59	186.41	17.01	14.81	13.47
25.00	40.00	0.60	32.00	35.00	1.50	5.63	2.91	3.75	1.94	79.44	16.86	69.81	143.82	182.04	105.90	108.87	214.77	237.63	13.80	11.69	10.57
25.00	40.00	0.80	37.00	39.00	1.50	7.17	3.28	4.78	2.19	90.42	21.39	86.02	170.20	215.33	129.25	130.84	260.09	290.39	11.66	9.66	8.65
25.00	40.00	1.00	40.00	43.00	1.50	8.55	3.58	5.70	2.39	98.64	25.00	98.64	190.46	239.59	147.27	147.27	294.54	330.93	10.48	8.53	7.59

Membrane cycle - Compressor Work Table

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
25.00	30.00	0.80	27.00	30.00	2.00	4.25	2.91	2.12	1.46	54.87	21.39	50.90	87.74	103.66	59.03	59.75	118.77	125.49	24.23	21.15	20.01
25.00	30.00	1.00	30.00	33.00	2.00	4.97	3.15	2.49	1.58	61.51	25.00	61.51	102.48	125.38	73.01	73.01	146.02	154.96	20.03	17.20	16.21
25.00	30.00	0.40	20.00	23.00	2.50	2.77	2.63	1.11	1.05	28.95	10.72	14.48	32.95	14.29	7.52	7.90	15.42	15.91	175.75	162.82	157.87
25.00	30.00	0.60	24.00	27.00	2.50	3.50	2.96	1.40	1.18	37.98	16.86	29.49	51.53	46.27	25.26	25.97	51.23	53.07	54.28	49.03	47.33
25.00	30.00	0.80	27.00	30.00	2.50	4.25	3.26	1.70	1.30	45.72	21.39	41.86	67.89	72.94	40.94	41.45	82.39	85.77	34.43	30.48	29.28
25.00	30.00	1.00	30.00	33.00	2.50	4.97	3.53	1.99	1.41	52.17	25.00	52.17	81.81	94.67	54.34	54.34	108.67	113.63	26.53	23.11	22.10
25.00	35.00	0.40	24.00	27.00	2.00	3.50	2.65	1.75	1.32	46.91	10.72	31.58	70.44	76.99	41.73	43.83	85.55	90.88	32.62	29.36	27.64
25.00	35.00	0.60	28.00	31.00	2.00	4.53	3.01	2.26	1.50	57.53	16.86	48.50	93.61	112.40	63.28	65.06	128.33	137.21	22.34	19.57	18.30
25.00	35.00	0.80	32.00	34.00	2.00	5.46	3.30	2.73	1.65	65.48	21.39	61.38	111.46	138.20	79.98	80.96	160.94	172.92	18.17	15.61	14.52
25.00	35.00	1.00	35.00	38.00	2.00	6.55	3.62	3.28	1.81	73.43	25.00	73.43	129.72	163.37	96.85	96.85	193.70	209.44	15.37	12.97	11.99
25.00	35.00	0.40	24.00	27.00	2.50	3.50	2.96	1.40	1.18	37.98	10.72	23.08	51.53	46.27	24.72	25.97	50.69	53.07	54.28	49.55	47.33
25.00	35.00	0.60	28.00	31.00	2.50	4.53	3.36	1.81	1.35	48.30	16.86	39.53	73.43	81.69	45.33	46.60	91.94	96.85	30.74	27.32	25.93
25.00	35.00	0.80	32.00	34.00	2.50	5.46	3.69	2.18	1.48	56.03	21.39	52.05	90.30	107.49	61.31	62.07	123.38	130.60	23.37	20.36	19.23
25.00	35.00	1.00	35.00	38.00	2.50	6.55	4.05	2.62	1.62	63.76	25.00	63.76	107.55	132.66	77.51	77.51	155.02	165.10	18.93	16.20	15.21
25.00	40.00	0.40	28.00	31.00	2.00	4.38	2.96	2.19	1.48	56.20	10.72	40.42	90.67	108.04	59.41	62.40	121.81	131.34	23.25	20.62	19.12
25.00	40.00	0.60	32.00	35.00	2.00	5.63	3.36	2.81	1.68	66.81	16.86	57.53	114.48	142.44	81.33	83.61	164.94	178.95	17.63	15.23	14.03
25.00	40.00	0.80	37.00	39.00	2.00	7.17	3.79	3.58	1.89	77.39	21.39	73.15	139.00	175.73	103.52	104.79	208.30	228.00	14.29	12.06	11.02
25.00	40.00	1.00	40.00	43.00	2.00	8.55	4.14	4.28	2.07	85.32	25.00	85.32	157.84	199.99	120.63	120.63	241.26	265.68	12.56	10.41	9.45
25.00	40.00	0.40	28.00	31.00	2.50	4.38	3.31	1.75	1.32	47.01	10.72	31.67	70.65	77.32	41.91	44.02	85.94	91.30	32.48	29.22	27.51
25.00	40.00	0.60	32.00	35.00	2.50	5.63	3.75	2.25	1.50	57.32	16.86	48.30	93.15	111.72	62.88	64.64	127.52	136.29	22.48	19.70	18.43
25.00	40.00	0.80	37.00	39.00	2.50	7.17	4.23	2.87	1.69	67.61	21.39	63.49	116.32	145.01	84.19	85.23	169.42	182.64	17.32	14.82	13.75
25.00	40.00	1.00	40.00	43.00	2.50	8.55	4.62	3.42	1.85	75.31	25.00	75.31	134.12	169.27	100.63	100.63	201.26	218.25	14.84	12.48	11.51



Membrane cycle - Compressor Work Table

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
30.00	30.00	0.80	27.00	30.00	0.50	4.25	1.46	8.49	2.91	124.48	26.27	119.58	248.42	299.42	186.63	188.96	375.59	436.84	8.39	6.69	5.75
30.00	30.00	1.00	30.00	33.00	0.50	4.97	1.58	9.95	3.15	132.52	30.00	132.52	269.72	321.51	205.04	205.04	410.07	479.44	7.81	6.12	5.24
30.00	30.00	0.40	20.00	23.00	1.00	2.77	1.67	2.77	1.67	71.86	15.24	55.07	119.51	142.77	79.65	83.73	163.38	179.02	17.59	15.37	14.03
30.00	30.00	0.60	24.00	27.00	1.00	3.50	1.87	3.50	1.87	82.18	21.59	72.32	143.35	175.29	101.46	104.36	205.82	226.69	14.33	12.20	11.08
30.00	30.00	0.80	27.00	30.00	1.00	4.25	2.06	4.25	2.06	91.02	26.27	86.54	164.33	202.41	120.54	122.04	242.57	268.65	12.41	10.35	9.35
30.00	30.00	1.00	30.00	33.00	1.00	4.97	2.23	4.97	2.23	98.38	30.00	98.38	182.19	224.50	136.76	136.76	273.52	304.39	11.19	9.18	8.25
30.00	30.00	0.40	20.00	23.00	1.50	2.77	2.04	1.85	1.36	54.57	15.24	38.62	81.14	86.03	46.75	49.15	95.90	102.28	29.19	26.19	24.56
30.00	30.00	0.60	24.00	27.00	1.50	3.50	2.29	2.33	1.53	64.37	21.59	55.01	102.64	118.54	66.84	68.74	135.58	145.29	21.19	18.52	17.29
30.00	30.00	0.80	27.00	30.00	1.50	4.25	2.52	2.83	1.68	72.77	26.27	68.51	121.57	145.66	84.48	85.54	170.02	183.14	17.24	14.77	13.71
30.00	30.00	1.00	30.00	33.00	1.50	4.97	2.73	3.32	1.82	79.76	30.00	79.76	137.69	167.75	99.52	99.52	199.04	215.38	14.97	12.62	11.66
30.00	35.00	0.40	24.00	27.00	0.50	3.50	1.32	7.00	2.65	114.83	15.24	95.94	223.40	272.31	161.39	169.66	331.05	386.81	9.22	7.59	6.49
30.00	35.00	0.60	28.00	31.00	0.50	4.53	1.50	9.05	3.01	127.70	21.59	116.58	256.89	308.32	189.97	195.39	385.36	453.78	8.15	6.52	5.53
30.00	35.00	0.80	32.00	34.00	0.50	5.46	1.65	10.92	3.30	137.34	26.27	132.28	282.70	334.55	212.03	214.67	426.71	505.40	7.51	5.89	4.97
30.00	35.00	1.00	35.00	38.00	0.50	6.55	1.81	13.11	3.62	146.97	30.00	146.97	309.09	360.14	233.94	233.94	467.87	558.18	6.97	5.37	4.50
30.00	35.00	0.40	24.00	27.00	1.00	3.50	1.87	3.50	1.87	82.18	15.24	64.88	143.35	175.29	99.28	104.36	203.64	226.69	14.33	12.33	11.08
30.00	35.00	0.60	28.00	31.00	1.00	4.53	2.13	4.53	2.13	93.97	21.59	83.78	171.43	211.30	124.38	127.93	252.31	282.87	11.89	9.95	8.88
30.00	35.00	0.80	32.00	34.00	1.00	5.46	2.34	5.46	2.34	102.79	26.27	98.17	193.08	237.53	143.80	145.59	289.39	326.16	10.57	8.68	7.70
30.00	35.00	1.00	35.00	38.00	1.00	6.55	2.56	6.55	2.56	111.61	30.00	111.61	215.21	263.13	163.23	163.23	326.46	370.42	9.54	7.69	6.78
30.00	35.00	0.40	24.00	27.00	1.50	3.50	2.29	2.33	1.53	64.37	15.24	47.94	102.64	118.54	65.40	68.74	134.14	145.29	21.19	18.72	17.29
30.00	35.00	0.60	28.00	31.00	1.50	4.53	2.61	3.02	1.74	75.57	21.59	65.89	127.98	154.55	88.60	91.13	179.73	195.97	16.25	13.97	12.82
30.00	35.00	0.80	32.00	34.00	1.50	5.46	2.86	3.64	1.91	83.95	26.27	79.56	147.51	180.78	106.58	107.91	214.48	235.02	13.89	11.71	10.69
30.00	35.00	1.00	35.00	38.00	1.50	6.55	3.14	4.37	2.09	92.33	30.00	92.33	167.48	206.38	124.66	124.66	249.32	274.96	12.17	10.07	9.13
30.00	40.00	0.40	28.00	31.00	0.50	4.38	1.48	8.77	2.96	126.09	15.24	106.65	252.65	303.88	182.82	192.18	374.99	445.29	8.26	6.70	5.64
30.00	40.00	0.60	32.00	35.00	0.50	5.63	1.68	11.26	3.36	138.94	21.59	127.51	287.06	338.85	211.84	217.89	429.73	514.11	7.41	5.84	4.89
30.00	40.00	0.80	37.00	39.00	0.50	7.17	1.89	14.34	3.79	151.78	26.27	146.55	322.50	372.70	240.56	243.56	484.12	585.00	6.74	5.19	4.29
30.00	40.00	1.00	40.00	43.00	0.50	8.55	2.07	17.10	4.14	161.38	30.00	161.38	349.74	397.37	262.77	262.77	525.53	639.47	6.32	4.78	3.93
30.00	40.00	0.40	28.00	31.00	1.00	4.38	2.09	4.38	2.09	92.49	15.24	74.69	167.87	206.87	118.90	124.98	243.88	275.75	12.14	10.30	9.11
30.00	40.00	0.60	32.00	35.00	1.00	5.63	2.37	5.63	2.37	104.27	21.59	93.80	196.73	241.84	144.41	148.53	292.94	333.47	10.39	8.57	7.53
30.00	40.00	0.80	37.00	39.00	1.00	7.17	2.68	7.17	2.68	116.02	26.27	111.23	226.46	275.69	169.92	172.04	341.96	392.92	9.11	7.34	6.39
30.00	40.00	1.00	40.00	43.00	1.00	8.55	2.92	8.55	2.92	124.82	30.00	124.82	249.30	300.36	189.63	189.63	379.27	438.61	8.36	6.62	5.73
30.00	40.00	0.40	28.00	31.00	1.50	4.38	2.56	2.92	1.71	74.17	15.24	57.26	124.77	150.12	84.03	88.33	172.36	189.54	16.73	14.57	13.25
30.00	40.00	0.60	32.00	35.00	1.50	5.63	2.91	3.75	1.94	85.35	21.59	75.41	150.81	185.09	107.63	110.70	218.33	241.62	13.57	11.50	10.39
30.00	40.00	0.80	37.00	39.00	1.50	7.17	3.28	4.78	2.19	96.52	26.27	91.97	177.63	218.94	131.39	133.03	264.42	295.26	11.47	9.50	8.51
30.00	40.00	1.00	40.00	43.00	1.50	8.55	3.58	5.70	2.39	104.87	30.00	104.87	198.24	243.61	149.74	149.74	299.48	336.48	10.31	8.39	7.46

Membrane cycle - Compressor Work Table

T_1	Outdoor		twb	tcond	P_1	P_2	P_i	PR_21	PR_2i	T_iout	T_iin	T_2	T_21stage	W_dt	W_ds1	W_ds2	W_isentropic		COP		
(C)	T	phi	(C)	(C)	(kPa)	(kPa)				(C)	(C)	(C)	(C)	(kJ/kg)	(kJ/kg)	(kJ/kg)	2stage	1 Stage	dT=0	2 stage	1 stage
30.00	30.00	0.80	27.00	30.00	2.00	4.25	2.91	2.12	1.46	60.38	26.27	56.27	93.80	105.40	60.00	60.75	120.75	127.59	23.83	20.80	19.68
30.00	30.00	1.00	30.00	33.00	2.00	4.97	3.15	2.49	1.58	67.12	30.00	67.12	108.78	127.49	74.24	74.24	148.47	157.56	19.70	16.92	15.94
30.00	30.00	0.40	20.00	23.00	2.50	2.77	2.63	1.11	1.05	34.02	15.24	19.07	38.09	14.53	7.64	8.03	15.68	16.18	172.85	160.20	155.27
30.00	30.00	0.60	24.00	27.00	2.50	3.50	2.96	1.40	1.18	43.20	21.59	34.43	56.98	47.05	25.67	26.40	52.07	53.96	53.38	48.23	46.55
30.00	30.00	0.80	27.00	30.00	2.50	4.25	3.26	1.70	1.30	51.07	26.27	47.08	73.61	74.17	41.62	42.14	83.76	87.21	33.86	29.98	28.80
30.00	30.00	1.00	30.00	33.00	2.50	4.97	3.53	1.99	1.41	57.62	30.00	57.62	87.77	96.26	55.25	55.25	110.50	115.53	26.09	22.73	21.74
30.00	30.00	0.40	20.00	23.00	3.00	2.77	2.88	0.92	0.96	27.00	15.24	12.39	24.02	-10.99	-5.71	-6.01	-11.72	-11.95	-228.56	-214.30	-210.13
30.00	30.00	0.60	24.00	27.00	3.00	3.50	3.24	1.17	1.08	35.97	21.59	27.40	42.06	21.53	11.61	11.94	23.55	24.12	116.65	106.62	104.12
30.00	30.00	0.80	27.00	30.00	3.00	4.25	3.57	1.42	1.19	43.66	26.27	39.76	57.94	48.65	26.99	27.32	54.31	55.87	51.62	46.25	44.95
30.00	30.00	1.00	30.00	33.00	3.00	4.97	3.86	1.66	1.29	50.06	30.00	50.06	71.46	70.74	40.13	40.13	80.26	82.92	35.50	31.29	30.29
30.00	35.00	0.40	24.00	27.00	2.00	3.50	2.65	1.75	1.32	52.28	15.24	36.44	76.20	78.28	42.39	44.56	86.95	92.40	32.08	28.88	27.18
30.00	35.00	0.60	28.00	31.00	2.00	4.53	3.01	2.26	1.50	63.07	21.59	53.75	99.76	114.29	64.31	66.15	130.46	139.51	21.97	19.25	18.00
30.00	35.00	0.80	32.00	34.00	2.00	5.46	3.30	2.73	1.65	71.16	26.27	66.92	117.91	140.52	81.31	82.32	163.63	175.82	17.87	15.35	14.28
30.00	35.00	1.00	35.00	38.00	2.00	6.55	3.62	3.28	1.81	79.24	30.00	79.24	136.48	166.11	98.47	98.47	196.95	212.95	15.12	12.75	11.79
30.00	35.00	0.40	24.00	27.00	2.50	3.50	2.96	1.40	1.18	43.20	15.24	27.80	56.98	47.05	25.12	26.40	51.52	53.96	53.38	48.75	46.55
30.00	35.00	0.60	28.00	31.00	2.50	4.53	3.36	1.81	1.35	53.69	21.59	44.63	79.24	83.06	46.07	47.39	93.46	98.48	30.24	26.87	25.50
30.00	35.00	0.80	32.00	34.00	2.50	5.46	3.69	2.18	1.48	61.55	26.27	57.43	96.39	109.29	62.33	63.11	125.44	132.79	22.98	20.02	18.91
30.00	35.00	1.00	35.00	38.00	2.50	6.55	4.05	2.62	1.62	69.41	30.00	69.41	113.94	134.88	78.81	78.81	157.62	167.87	18.62	15.93	14.96
30.00	35.00	0.40	24.00	27.00	3.00	3.50	3.24	1.17	1.08	35.97	15.24	20.92	42.06	21.53	11.36	11.94	23.30	24.12	116.65	107.77	104.12
30.00	35.00	0.60	28.00	31.00	3.00	4.53	3.68	1.51	1.23	46.22	21.59	37.37	63.31	57.54	31.55	32.45	63.99	66.63	43.65	39.25	37.69
30.00	35.00	0.80	32.00	34.00	3.00	5.46	4.05	1.82	1.35	53.90	26.27	49.88	79.69	83.77	47.22	47.81	95.03	99.39	29.98	26.43	25.27
30.00	35.00	1.00	35.00	38.00	3.00	6.55	4.43	2.18	1.48	61.58	30.00	61.58	96.44	109.36	63.15	63.15	126.30	132.89	22.96	19.88	18.90
30.00	40.00	0.40	28.00	31.00	2.00	4.38	2.96	2.19	1.48	61.72	15.24	45.42	96.77	109.85	60.36	63.45	123.81	133.54	22.86	20.29	18.81
30.00	40.00	0.60	32.00	35.00	2.00	5.63	3.36	2.81	1.68	72.51	21.59	62.92	120.98	144.83	82.65	85.01	167.67	181.95	17.34	14.98	13.80
30.00	40.00	0.80	37.00	39.00	2.00	7.17	3.79	3.58	1.89	83.27	26.27	78.89	145.91	178.68	105.23	106.54	211.78	231.82	14.06	11.86	10.83
30.00	40.00	1.00	40.00	43.00	2.00	8.55	4.14	4.28	2.07	91.33	30.00	91.33	165.07	203.35	122.66	122.66	245.31	270.14	12.35	10.24	9.30
30.00	40.00	0.40	28.00	31.00	2.50	4.38	3.31	1.75	1.32	52.38	15.24	36.54	76.42	78.62	42.58	44.76	87.35	92.83	31.94	28.75	27.05
30.00	40.00	0.60	32.00	35.00	2.50	5.63	3.75	2.25	1.50	62.86	21.59	53.54	99.29	113.60	63.90	65.73	129.63	138.58	22.11	19.37	18.12
30.00	40.00	0.80	37.00	39.00	2.50	7.17	4.23	2.87	1.69	73.33	26.27	69.06	122.85	147.45	85.59	86.66	172.24	185.70	17.03	14.58	13.52
30.00	40.00	1.00	40.00	43.00	2.50	8.55	4.62	3.42	1.85	81.16	30.00	81.16	140.96	172.12	102.32	102.32	204.63	221.91	14.59	12.27	11.32
30.00	40.00	0.40	28.00	31.00	3.00	4.38	3.63	1.46	1.21	44.94	15.24	29.46	60.62	53.10	28.43	29.88	58.31	61.24	47.29	43.07	41.01
30.00	40.00	0.60	32.00	35.00	3.00	5.63	4.11	1.88	1.37	55.18	21.59	46.08	82.46	88.08	48.97	50.37	99.34	104.92	28.51	25.28	23.94
30.00	40.00	0.80	37.00	39.00	3.00	7.17	4.64	2.39	1.55	65.41	26.27	61.24	104.96	121.93	69.95	70.82	140.76	149.91	20.60	17.84	16.75
30.00	40.00	1.00	40.00	43.00	3.00	8.55	5.06	2.85	1.69	73.06	30.00	73.06	122.24	146.60	86.12	86.12	172.24	184.48	17.13	14.58	13.61