Parametric Studies of Refrigeration Cycles

Advanced Thermodynamics – ME 4571

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Table of Contents

Introduction

Problem Analysis

This project aims to design an optimum refrigeration system for a warehouse with freezing and refrigerated spaces. Within this report, various refrigeration systems are investigated, comparing the input power required by the compressor(s) and the coefficient of performance. A parametric study is conducted to investigate the effects of the temperature of the freezer, refrigerator, and ambient temperature have on the coefficient of performance of each system.

There are specific design constraints that each system must adhere to. These constraints are as follows:

- Working Fluid: R-134a
- Freezer temperature range: -24° C<$T_{freezer}$<-18° C
- Refrigerator Temperature range: 3° C < $T_{refrigerator}$<7° C
- Ambient Temperature: $T_0 = 25°C$
- Compressor efficiency: 80%
- Temperature difference between the refrigerant and hot and cold reservoir: $\Delta\mathrm{T} = 10°\mathrm{C}$
- Freezer Cooling load: $\mathrm{Q_F} = 20$ Tons of refrigeration
- Refrigerator Cooling load: $\mathrm{Q_R} = 40$ Tons of refrigeration

System 1: Two Evaporators + Two Compressors + One Flash Tank

Part 1: Parametric Solution

System 1 consists of two evaporators, two compressors, and one flash tank. A schematic of the system is displayed in Figure 1: System 1 Diagram below.

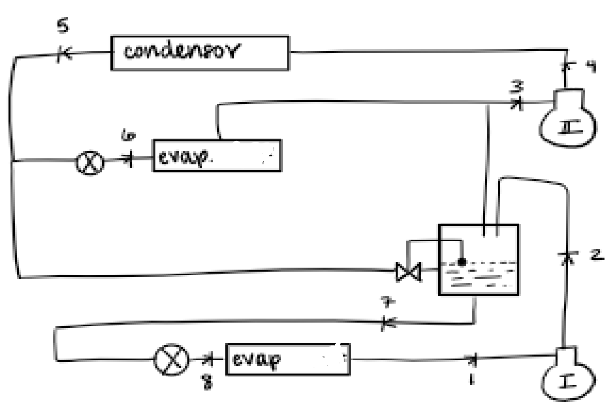


Figure 1: System 1 Diagram

The coefficient of performance for a cycle can be express as

$$\mathrm{COP} = \frac{\mathrm{Q_{in}}}{W_{in}}$$

Where Q_{in} is the total heat transfer of the system and $W_{in}$is the total work of the system. In this system, the components cause work are the two compressors, which can be express, in terms of enthalpies, as $W_{compressor} = \dot{m} * \Delta h$. While the heat transfer comes from the two evaporators. The heat transfer is also expresses by the mass flow rate going through the component times the change in enthalpies, $Q_{evaporator} = \dot{m} * \Delta h$. Based the schematic of system 1, the coefficient of performance can be rewritten as

$$\mathrm{COP} = \frac{\dot{m}_1(h_1 - h_8) + \dot{m}_2(h_3 - h_6)}{\dot{m}_{total}(h_4 - h_3) + \dot{m}_1(h_2 - h_1)}$$

Part 2: Reference Calculations

For the initial study of the system, the following parameters were used:

- Freezer temperature, $T_{freezer}$ =-18° C
- Refrigerator Temperature, $T_{refrigerator}$ =4° C
- Ambient Temperature: $T_0 = 25°C$
- Compressor efficiency: 80%
- Temperature difference between the refrigerant and hot and cold reservoir: $\Delta \mathrm{T} = 10°\mathrm{C}$
- Freezer Cooling load: $Q_F = 20$ Tons of refrigeration
- Refrigerator Cooling load: $Q_R = 40$ Tons of refrigeration

Detailed hand calculations are available in the appendix of this report. The T-S and P-H diagrams of the system are shown below.

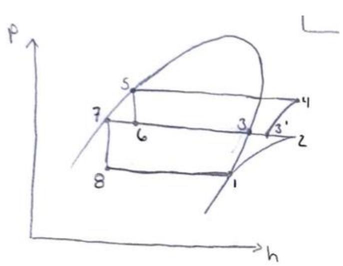


Table 1: System 1 Results below presents a summary of each state's values.

Table 1: System 1 Results

State	T(°C)	P(Bar)	$s\left(\frac{kJ}{kg*K}\right)$	$h\left(\frac{kJ}{kg}\right)$	Condition
1	-28	0.9305	0.9411	230.38	Saturated Vapor
2s	4	3.3765	0.9411	256.25	Superheated
2	4	3.3765	0.9169	262.72	Superheated
3	4	3.3765	0.9169	249.53	Saturated Vapor
4s	25	6.6548	0.9169	263.73	
4	25	6.6548	0.9086	267.28	Superheat

5	25	6.6548	0.3161	84.325	Saturated Liquid
6	4	3.3765	-	84.325	Mixture
7	4	3.3765	-	55.35	Saturated Liquid
8	-18	1.4483	-	55.35	Mixture

The mass flow rate of each part of the system is shown in Table 2.

Table 2: Mass flow Rate

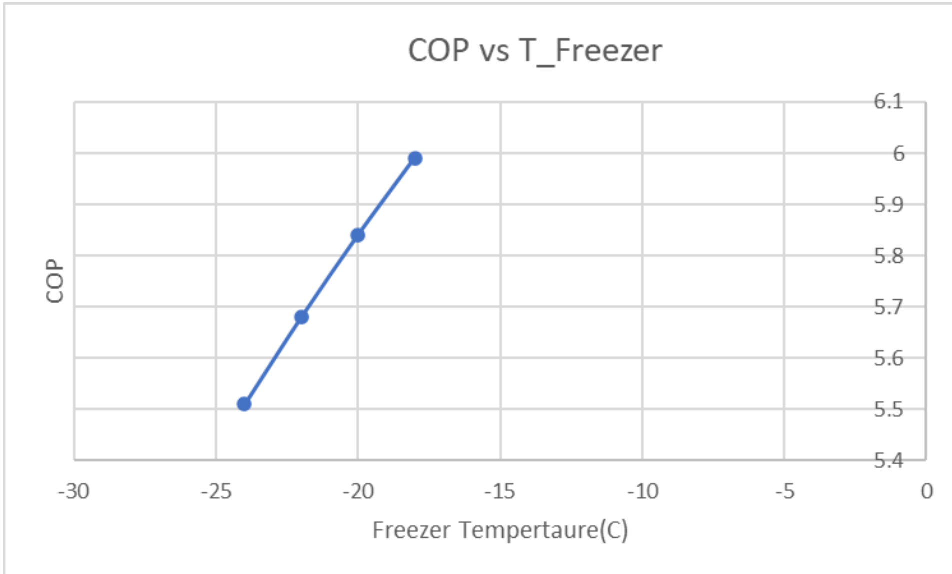
$\dot{m}_1 \left(\frac{kg}{s}\right)$	$\dot{m}_2 \left(\frac{kg}{s}\right)$	$\dot{m}_{total} \left(\frac{kg}{s}\right)$
$.4018$	$.8515$	1.2533

Part 3: Parametric Study

Effects of $T_{freezer}$ on COP

In this examination, we will assess the system by modifying the freezer temperature range from -24°C to -18°C, while maintaining the refrigerator temperature at 4°C and the ambient temperature at 25°C. An observable trend emerges as the freezer temperature rises, leading to an increase in the Coefficient of Performance (COP), as illustrated in Figure 4. According to Table 3, the COP ascends from 5.51 at -24°C to 5.99 at -18°C, representing a notable 0.48 improvement over the 6-degree temperature shift. In summary, it is evident that an elevation in freezer temperature correlates with an augmentation in the system's COP.

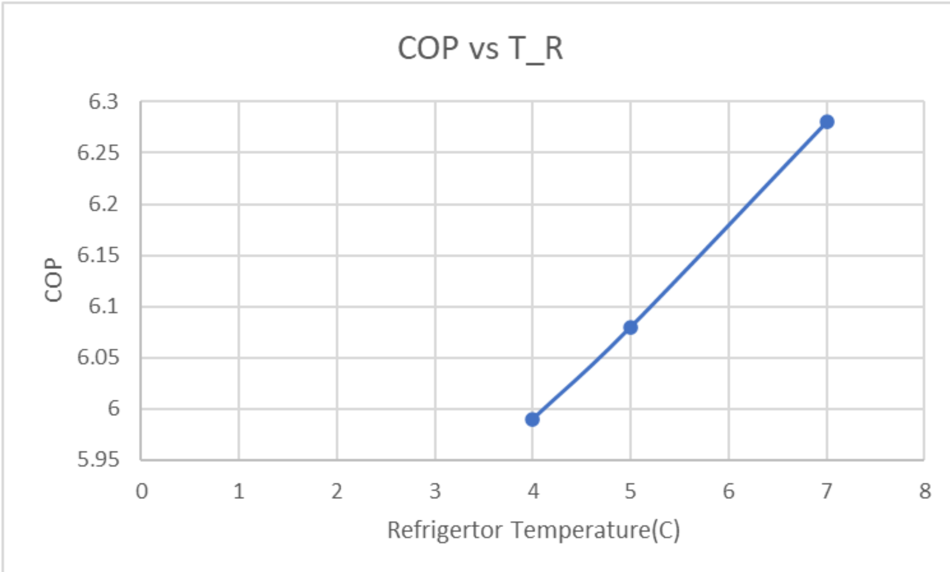
T_freezer	COP
-18	5.99
-20	5.84
-22	5.68
-24	5.51



Effects of $T_{Refrigerator}$ on COP

This study delves into the impact of refrigeration temperature on the Coefficient of Performance (COP). Specifically, we manipulate the refrigerator temperature within the range of 4°C to 7°C, while maintaining the freezer temperature at -18°C and the ambient temperature at 25°C. Similar to the freezer, an elevation in refrigerator temperature corresponds to an increase in COP, as depicted in Figure 5. According to the findings presented in Table 3, the COP rises from 5.99 at 4°C to 6.28 at 7°C, representing a noteworthy 0.29 improvement over the 4-degree temperature variation. In summary, it is evident that an increase in refrigerator temperature correlates with an enhancement in the system's COP

T_R	COP
4	5.99
5	6.08
7	6.28

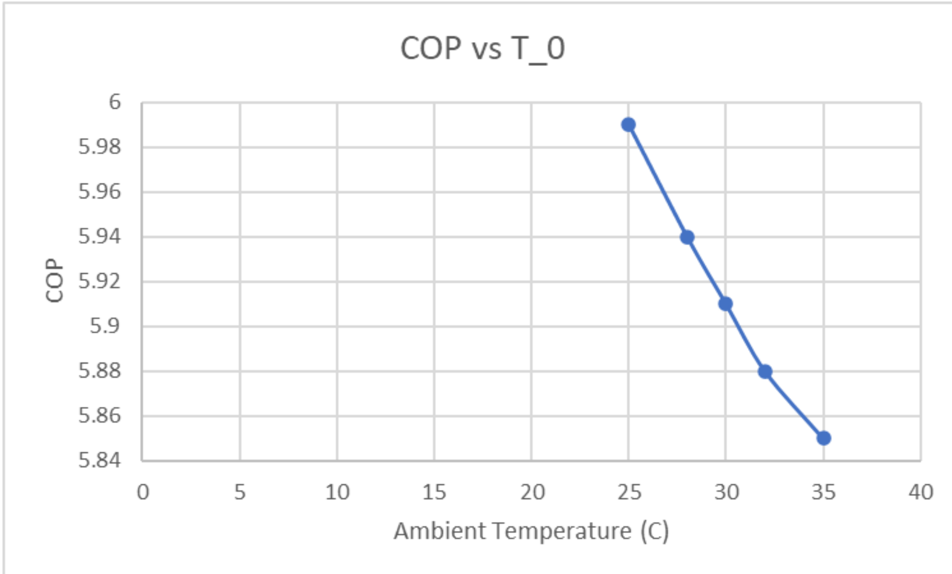


Effects of T_0 on COP

his study focuses on examining the influence of ambient temperature on the system. The ambient temperature undergoes a transition from 25°C to 35°C, while maintaining the refrigerator temperature at 4°C and the freezer temperature at -18°C. Notably, as the ambient temperature rises, there is a corresponding decrease in the Coefficient of Performance (COP), as depicted in Figure 6.

As outlined in Table 4, the COP decreases from 5.99 at 25°C to 5.85 at 35°C, signifying a substantial 0.14 reduction over the 9-degree temperature shift. Despite the ambient temperature variation, the heat transfer of the evaporators remains constant. However, there is an increase in the power input required for compressors. Consequently, it is evident that an escalation in ambient temperature is associated with a decline in the system's COP.

T_0	COP
25	5.99
28	5.94
30	5.91
32	5.88
35	5.85



Summary of Parametric Study

When the freezer temperature is raised from -24°C to -18°C, with the refrigerator and ambient temperatures held constant at 4°C and 25°C respectively, the COP of the system experiences an increase. Similarly, an increase in refrigerator temperature from 4°C to 7°C, with the freezer and ambient temperatures held constant at -18°C and 25°C, results in an increased COP for the system. In contrast, elevating the ambient temperature from 25°C to 35°C, with the refrigerator and freezer temperatures held constant at 4°C and -18°C, leads to a decrease in the COP of the system.

System 2: Two Evaporators + Two Compressors + One Heat Exchanger

Part 1: Parametric Solution

The second refrigeration and freezer system was designed with two evaporators, two compressors, and one heat exchanger. The schematic for this refrigeration cycle is shown below.

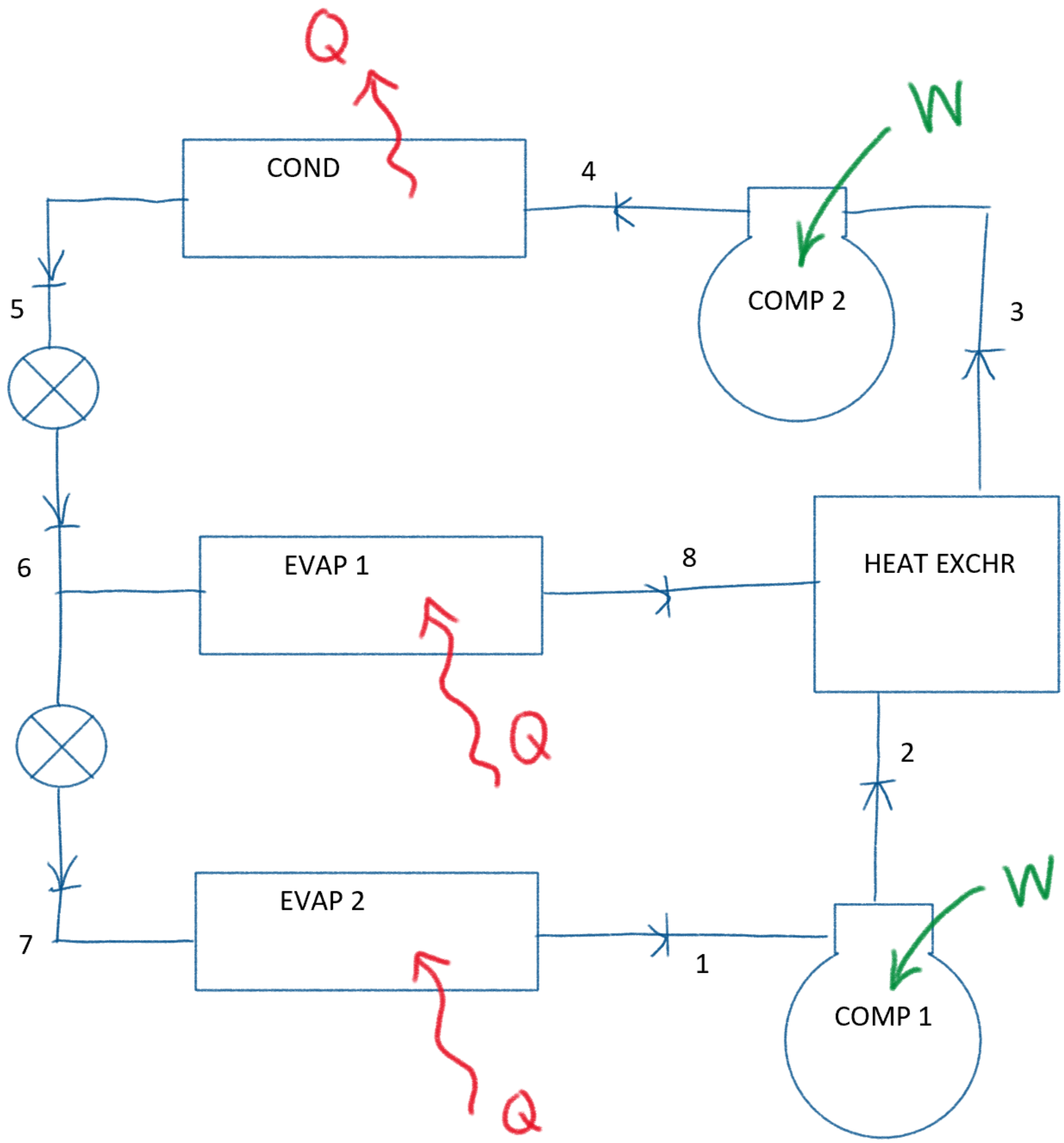


Figure 2 Refrigeration Cycle 2

To determine the coefficient of performance (CoP), the energy transfer throughout the system must be calculated. It is depicted where heat will be extracted and rejected as well as where work is input. CoP can be defined as:

$$CoP = \frac{\dot{Q}_{in}}{\dot{W}_{in}}$$

Where Q_in is the heat extracted from the fridge and freezer space by each evaporator, and W_in is the work required by each compressor to run the system.

The energy transferred in each component can be solved using the energy balance equation:

$$\dot{Q_{cv}} + \dot{m_i} h_i = \dot{m_e} h_e + \dot{W_{cv}}$$

For each component, the energy balance equations turn into:

Evaporator 1 (Freezer)	$\dot{Q_F} = \dot{m_F}(h_1 - h_7)$
Evaporator 2 (Refrigerator)	$\dot{Q_R} = \dot{m_R}(h_8 - h_6)$
Compressor 1	$\dot{W_{C1}} = \dot{m_F}(h_2 - h_1)$
Compressor 2	$\dot{W_{C2}} = \dot{m_{total}}(h_4 - h_3)$

The CoP can then be evaluated as:

$$CoP = \frac{\dot{Q_F} + \dot{Q_R}}{W_{C1} \dot{+} W_{C2}} = \frac{\dot{m_F}(h_1 - h_7) + \dot{m_R}(h_8 - h_6)}{\dot{m_F}(h_2 - h_1) + \dot{m_{total}}(h_4 - h_3)}$$

Part 2: Reference Calculations

The following parameters were used to solve a sample hand calculation:

- Freezer temperature, T_F =-18° C
- Refrigerator Temperature, T_R =4° C
- Ambient Temperature: $T_0 = 25°C$
- Compressor efficiency: 80%
- Temperature difference between the refrigerant and hot and cold reservoir: $\Delta T = 10°C$
- Freezer cooling load: $Q_F = 20$ Tons of refrigeration
- Refrigerator cooling load: $Q_R = 40$ Tons of refrigeration

Part 3: Parametric Study

System 3: Two Evaporators + One Compressor **(Paige)**

Part 1: Parametric Solution

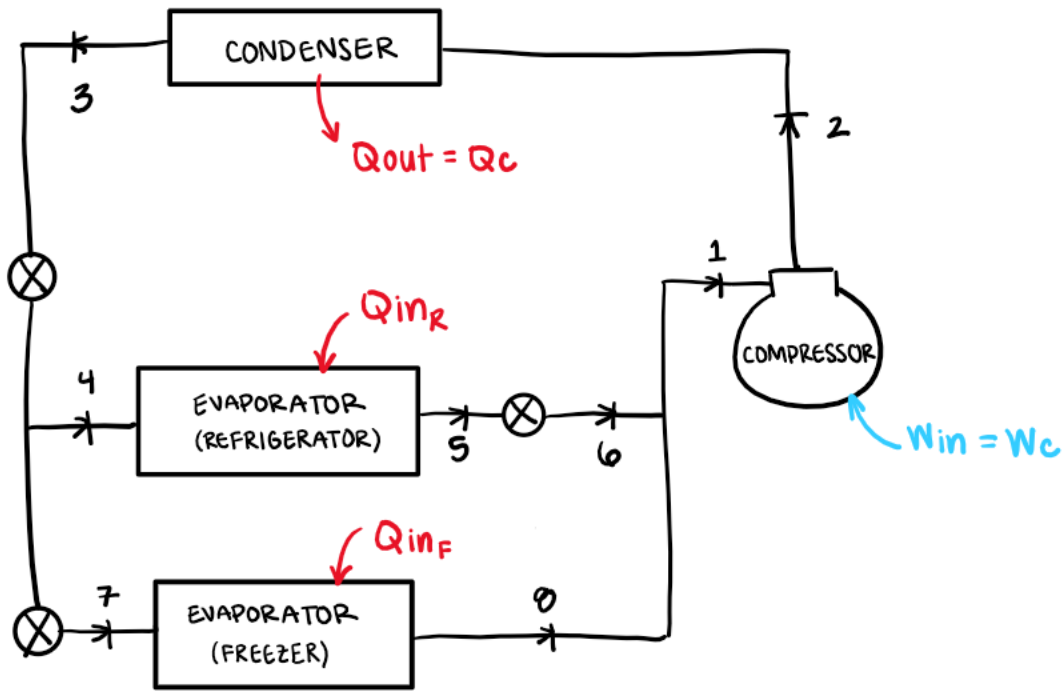


Figure 3: System 3 schematic

A schematic of the system is shown above, including work and heat transfers at each device. To find the coefficient of performance of the system, we must define each energy transfer in the system. The steps taken to solve the COP of the system are listed below.

First, the mass and energy balance equations are used to solve the heat and work transfer at each device in the system. These equations are shown below for reference.

$$\dot{m} = \dot{m_R} + \dot{m_F}$$

$$\dot{Q_{cv}} + \dot{m_i} * h_i = \dot{m_e} * h_e + \dot{W_{cv}}$$

The equations for heat and work transfer to and from the system at the refrigerator, freezer, condenser, and compressor are as follows:

$$\dot{Q_{in_R}} = \dot{m_R}(h_5 - h_4)$$

$$\dot{Q_{in_F}} = \dot{m_F}(h_8 - h_7)$$

$$\dot{Q_{out}} = \dot{Q_c} = \dot{m}(h_2 - h_3)$$

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

The ratio of total heat entering the system and work entering the system defines our coefficient of performance for the entire system.

$$COP = \frac{\dot{Q_{in}}}{\dot{W_{in}}} = \frac{\dot{Q_{in_R}} + \dot{Q}_{in_F}}{\dot{W_c}} = \frac{\dot{m_R}(h_5 - h_4) + \dot{m_F}(h_8 - h_7)}{\dot{m}(h_2 - h_1)}$$

Part 2: Reference Calculations

After choosing the operating temperatures for the refrigerator and freezer to fit within the project requirements, we can use the thermodynamic tables for R-134a to solve the desired variables above.

T, Refrigerator	T, Freezer
4 °C	-22 °C

Figure 4: Chosen temperatures of each evaporator

Knowing that the compressor efficiency is 80%, we can relate equations to find the enthalpies at states 2 and 2s. These values can be used to find the work entering the compressor and essentially the COP. All essential values at each state are found and listed in the table below.

State	Pressure (bar)	Temperature (°C)	Enthalpy (kJ/kg)	Entropy (kJ/kg*K)	Description
1	1.2192		244.0376		superheat
2s	6.6548		517.0009	0.0000	superheat
2	6.6548		585.2417		superheat
3	6.6548	25	84.3250	0.3161	sat liquid
4	3.3765	4	84.3250		mixture
5	3.3765	4	249.5300	0.9169	sat vapor
6	1.2192		249.5300		superheat
7	1.2192	-22	84.3250		mixture
8	1.2192	-22	234.0800	0.9351	sat vapor

Figure 5: Solved variables at each state

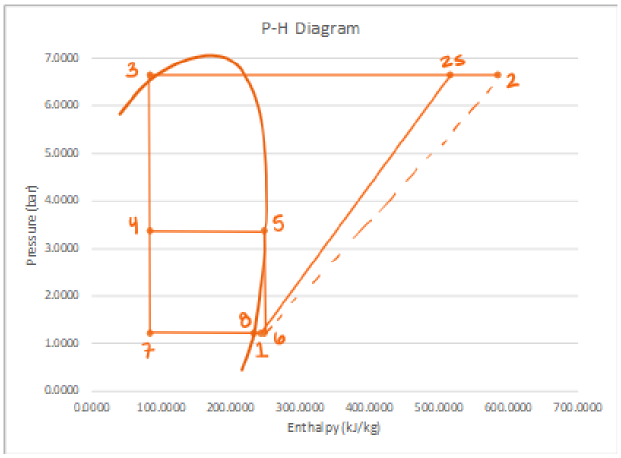
Solutions			
Mass Flow Rate, R	mR	0.852	kg/s
Mass Flow Rate, F	mF	0.470	kg/s
Mass Flow Rate, Total	m	1.322	kg/s
Heat In, R	Qin, R	140.800	kW
Heat In, F	Qin, F	70.400	kW
Work In	Win	451.200	kW
Compressor Efficiency	nc	0.8	

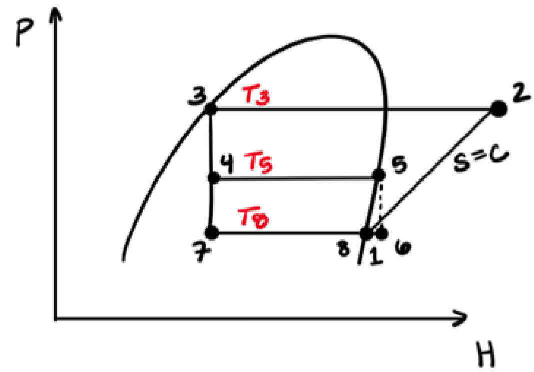
Figure 6: Solutions for mass flow rates and energy transfers

COP
0.468085106

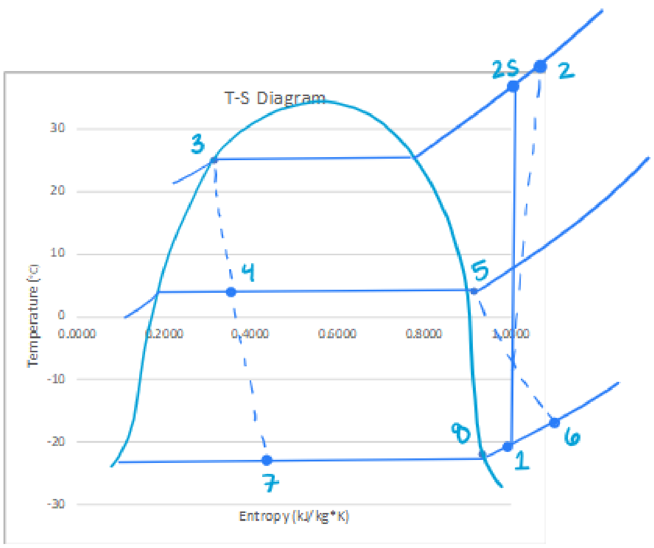
Figure 7: Solved COP

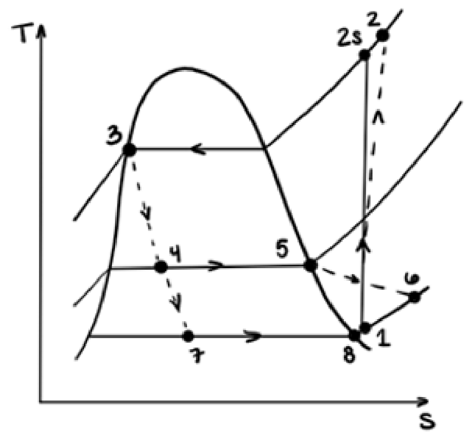
A plotted graph alongside a sketch of a P-H diagram is shown below for the system.





A plotted graph alongside a sketch of a T-S diagram for the system is shown below for the system.





Part 3: Parametric Study

To determine which parameters of the system directly affect the coefficient of performance, we run a study varying each temperature of the system. First, we will vary the freezer temperature.

T, Freezer	COP
-24 °C	0.489795918
-22 °C	0.468085106
-20 °C	0.444444444
-18 °C	0.418604651

Figure 8: Freezer temperature study results

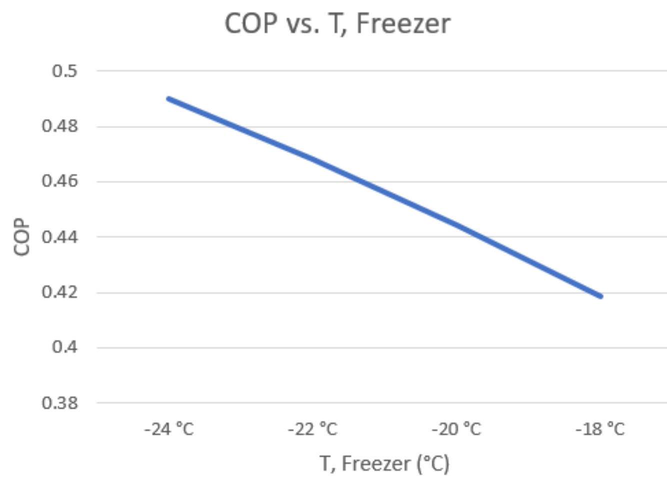


Figure 9: COP vs. T, Freezer

The results of this study conclude that increasing the temperature of the freezer in the system will decrease the coefficient of performance. This is shown in the table and graph plotted above.

Next, we will vary the temperature of the refrigerator to see the effects on the coefficient of performance of the system. The results are shown below.

T, Refrigerator	COP
3 °C	0.468085106
4 °C	0.468085106
5 °C	0.468085106
6 °C	0.468085106

Figure 10: Refrigerator temperature study results

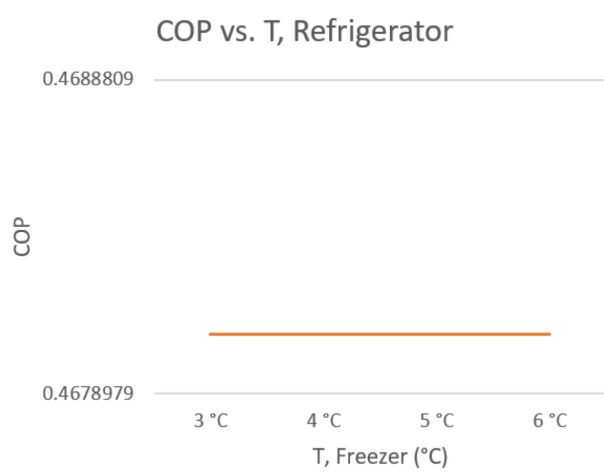


Figure 11: COP vs. T, Refrigerator

The results of this study conclude that increasing the temperature of the refrigerator in the system will not affect the coefficient of performance. This is shown in the table and graph plotted above with a constant slope of COP.

Finally, we will vary the ambient temperature to see the effects on the coefficient of performance of the system. The results are shown below.

T, Ambient	COP
24 °C	0.47826087
25 °C	0.468085106
26 °C	0.458333333
28 °C	0.44

Figure 12: Ambient temperature study results

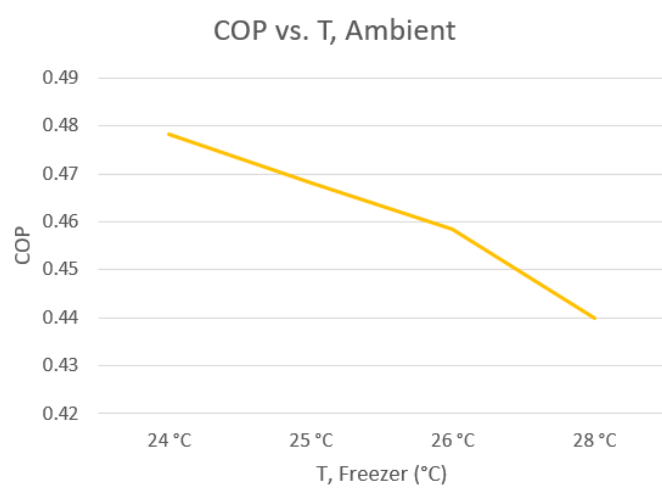


Figure 13: COP vs. T, Ambient

The results of this study conclude that increasing the ambient temperature in the system will decrease the coefficient of performance. This is shown in the table and graph plotted above.

Appendix

System 3.xlsx