HEAT PUMP LAB REPORT

Thermodynamics for Aerospace

Abstract

Contained in this report , is the discussion of the operations efficiency of the heat pump system under varying thermal loads. The lab experiment was conducted to assess the performance characteristics and compare them to theoretical predictions from the reversed Carnot cycle. The analysis contains a detailed examination of the results from the heat pump lab presented via pressure enthalpy chart, including interpretation of the thermodynamic properties. The findings offer insights in the use applications of heat pumps.

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Objectives

1. Demonstration and performance analysis of a heat pump cycle.
2. Performance of the heat pump cycle under different heat source and heat sink temperatures.
3. Performance comparison between the actual heat pump cycle and reversed Carnot cycle.

1.0 Introduction

The study of thermodynamics in practical applications significantly contributes to the development and use of technologies in various engineering disciplines, and most especially in aerospace engineering. The report is an analysis consisting of a heat pump that is an essential component to many engineering systems that deal with applications in aerospace for the environmental control systems. The heat pump experiment, was conducted using the TQ heat pump (EC1500V), aims to demonstrate and evaluate the cycle of a heat pump under variable conditions to make it possible for comparison between it the real-word performance vs the idealised reversed Carnot cycle.

Figure 1- TQ heat pump (EC1500V)

By design, heat pumps are processes that transfer heat from a lower temperature region to a higher temperature region, requiring work input. This core function is central to various applications in engineering especially the area of aerospace where environmental controls are paramount.

The Carnot cycle was founded by Nicolas Léonard Sadi Carnot in 1824, marks a cornerstone towards founding the second law of thermodynamics. The French physicist, who is usually considered to be "the father of thermodynamics", introduced this cycle, which operates on two isentropic and two isothermal processes, in his work called "Reflections on the Motive Power of Fire." From his work, he theorised that no heat engine can have a higher efficiency than a Carnot engine, which serves as an ideal benchmark for comparison [2].

This report intends to discuss the analysis of data that will primarily show an overview of the heat pump performance carrying out the basic concepts surrounding it. The foregoing analysis would attempt to provide valuable insights especially with regards to the efficiency and practicality of heat pumps under aerospace applications reflecting in a broader context of utilization of thermodynamics in the available engineering solutions.

Figure 3- Picture of Nicolas Léonard Sadi Carnot [2]

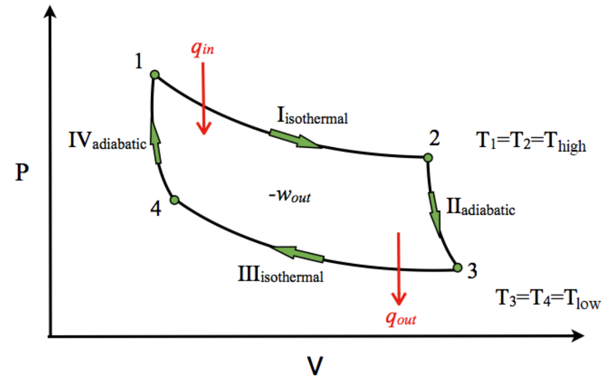

Figure 2 - Carnot Cycle [1]

2.0 Theoretical Analysis

2.1 Heat pump purpose and Functionality

The core purpose of a heat pump is transferring heat from a region of lower temperature to a region of high temperature which requires work input generally in the form of mechanical work. This sort of operation is applicable to many industries.

The dual functionality of heat pumps is due to the fact they can either function as a heat provider or work out as a refrigerator and is determined by the intended application in the direction of heat transfer.

2.2 Heat Pump Components and Cycle

A heat pump consists of four main components that drive the thermodynamic process which the TQ heat pump (EC1500V) was made up of:

1. **Compressor**: This component compresses the refrigerant which increases its temperature and pressure. Once the refrigerant has been compressed, it moves onto the condenser.
2. **Condenser**: In this place, refrigerant releases its heat to the surroundings environment condensing into a liquid this is where it transitions from a refrigerant to a state where it can be expanded and cooled.
3. **Expansion Valve**: this controls the flow into the evaporator. While reducing the pressure and temperature the liquid expands preparing the refrigerant for heat absorption in the evaporator

4. **Evaporator**: Now at a low temperature and pressure it begins to absorb heat from the environment, this causes the liquids to evaporate turning it back into a gas. This goes back to the compressor repeating the cycle again.

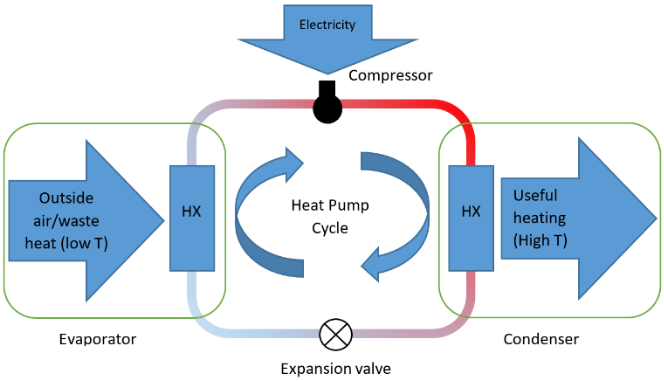

Figure 4-Heat Pump Illustration [3]

To summarise the cycle effectively moves heat from a cooler area to a warmer one using these components making it an efficient tool for temperature regulation.

2.3 Theoretical Concepts and Equations

The operational efficiency of heat pumps is fundamentally governed by the laws of thermodynamics. The first law, emphasising energy conservation, underlies the heat pump's ability to transfer energy from a cooler to a warmer area. The second law, focusing on entropy, dictates the feasibility of such a transfer, asserting that the total entropy of a system and its surroundings cannot decrease over time.

The performance of these stages can be quantitatively described by the following key equations:

1. Actual work of compression ($W_c = h_{R2} - h_{R1}$)
2. Isentropic work of compression ($W_s = h_{R2} - h_{R1}$)
3. Isentropic efficiency of compressor ($\eta_s = \frac{W_s}{W_c} = \frac{h_{R2s}-h_{R1}}{h_{R2}-h_{R1}}$)
4. Pressure ratio ($P_{ratio} = \frac{P_{HIGH\_ABS}}{P_{LOW\_ABS}}$)
5. Heating effect ($Q_h = h_{R2} - h_{R3}$)
6. Refrigerating effect ($Q_c = h_{R1} - h_{R4}$)
7. Heating Coefficient of Performance ($COP_h = \frac{Q_h}{W_c} = \frac{h_{R2}-h_{R3}}{h_{R2}-h_{R1}}$)
8. Heating Coefficient of Performance for the reversed Carnot cycle ($COP_{h\_carnot} = \frac{T_B}{T_B-T_A}$)

2.4 Carnot Cycle and its Relevance

In contrast to the real-life heat pump cycle, the reversed Carnot cycle represents an ideal cycle with the highest efficiency theoretically attainable by a heat pump, defined by two isothermal and two isentropic processes. It provides a benchmark for assessing the performance of actual heat pumps, with the COP of the reversed Carnot cycle given by:

$$COP_{Carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

However, real heat pump cycles deviate from the ideal due to practical constraints such as mechanical losses, thermal resistances, and irreversibilities, leading to a lower actual COP compared to the Carnot COP.

3.0 Sample of calculations

Several key calculations were necessary to analyse the system's performance. These calculations are based on the thermodynamic properties of the refrigerant and the operating conditions of the heat pump. Below are some examples of these calculations:

1. Conversion of Gauge Pressure to Absolute Pressure:

- Absolute Pressure = Gauge Pressure + Atmospheric Pressure

$P_{\{absolute\}} = P_{\{gauge\}} + P_{\{atm\}}$

2. Actual Work of Compression (W_c):

- Equation: ($W_c = h_{R2} - h_{R1}$)

- Where h_{R2} and h_{R1} are the enthalpies at the compressor discharge and suction, respectively.

3. Refrigerating Effect (Q_c):

- Equation: $Q_c = h_{R1} - h_{R4}$

- Where h_{R1} is the enthalpy at the compressor suction and h_{R4} is the enthalpy at the expansion valve outlet.

4. Heating Effect (Q_h):

- Equation: $Q_h = h_{R2} - h_{R3}$

- Where h_{R3} is the enthalpy at the expansion valve inlet.

5. Coefficient of Performance (COP):

- Equation: $COP_h = \frac{Q_c}{W_c}$

6. Comparison with Theoretical COP (COP_{Carnot}):

-Equation: $COP_{Carnot} = \frac{T_{hot}}{T_{hot} - T_{cold}}$

- Where T_{hot} and T_{cold} are the temperatures of the hot and cold reservoirs, respectively, in Kelvin.

4.0 Experimental results

<u>Experimental data and results:</u>

<u>Table 1:</u>

Parameter	Symbol	Experiment case with water pump "ON"
Compressor suction temperature (°C)	T_{R1}	10.1
Compressor discharge temperature (°C)	T_{R2}	43.3
Expansion valve inlet temperature (°C)	T_{R3}	24.3
Expansion valve outlet temperature (°C)	T_{R4}	12.2
Low-side pressure (bar)-gauge pressure	P_{LOW}	0.7
High-side pressure (bar)- gauge pressure	P_{HIGH}	6.62

Table 2:

Parameter	Symbol	Hot Water Tank Temperature T_{W1}(°C), Water Pump is OFF		
		T_{W1}=30°C	T_{W1}=35°C	T_{W1}=40°C
Cold water tank temperature (°C)	T_{W2}	9.4	8.1	6.7
Compressor suction temperature (°C)	T_{R1}	-8.3	10.6	-3
Compressor discharge temperature (°C)	T_{R2}	48.3	50.5	54
Expansion valve inlet temperature (°C)	T_{R3}	34.8	33.5	34.6
Expansion valve outlet temperature (°C)	T_{R4}	-7.4	-9.8	12.5
Low-side pressure (bar) - gauge pressure	P_{LOW}	0.93	0.73	0.55
High-side pressure (bar) - gauge pressure	P_{HIGH}	9.24	10.12	11.15

Results:

Table 3

State Point	Temperature (℃)	Absolute Pressure (bar)	Enthalpy (kJ/kg)
Point 1- Compressor suction	10.1	1.7	411
Point 2- Compressor discharge	43.3	7.62	421
Point 3- Expansion valve inlet	24.3	7.62	235
Point 4- Expansion valve outlet	-14	1.7	$(h_{R3} = h_{R4})$

Table 4

Parameter	Symbol	Result
Refrigerating effect (kJ/kg)	q_c	176
Heating effect (kJ/kg)	q_h	186
Actual work of compression (kJ/kg)	w_c	10
Heating coefficient of performance (COP)	COP_h	18.6

Table 5 using data of the first column in Table 2, T_{w1}=30°C

State Point	Temperature (℃)	Absolute Pressure (bar)	Enthalpy (kJ/kg)
Point 1- Compressor suction	-8.3	1.93	395
Point 2- Compressor discharge	48.3	10.24	424
Point 3- Expansion valve inlet	34.8	10.24	248
Point 4- Expansion valve outlet	-7.4	1.93	$(h_{R3} = h_{R4})$

Table 6 using data of the second column in Table 2, T_{w1}=35°C

State Point	Temperature (℃)	Absolute Pressure (bar)	Enthalpy (kJ/kg)
Point 1- Compressor suction	10.6	1.73	413
Point 2- Compressor discharge	50.5	11.12	432
Point 3- Expansion valve inlet	33.5	11.12	246
Point 4- Expansion valve outlet	-9.8	1.73	$(h_{R3} = h_{R4})$

Table 7 using data of the third column in Table 2, T_{w1}=40°C

State Point	Temperature (℃)	Absolute Pressure (bar)	Enthalpy (kJ/kg)
Point 1- Compressor suction	-3	1.55	378
Point 2- Compressor discharge	54	12.15	435
Point 3- Expansion valve inlet	34.6	12.15	248
Point 4- Expansion valve outlet	12.5	1.55	$(h_{R3} = h_{R4})$

Table 8

Calculated Parameter	Symbol	Hot Water Tank Temperature T_{W1}(°C), Water Pump is OFF		
		T_{W1}=30°C	T_{W1}=35°C	T_{W1}=40°C
Pressure ratio	P_{ratio}	5.31	6.43	7.84
Water temperature difference (°C)	$\Delta T_w = T_{w1} - T_{w2}$	20.6	26.9	33.3
Refrigerating effect (kJ/kg)	q_c	146.25	166.44	129.63
Heating effect (kJ/kg)	q_h	175.25	185.97	186.75
Actual compressor work (kJ/kg)	w_c	29	19.53	57.12
Heating coefficient of performance	COP_h	6.04	9.52	3.27

Table 9

Calculated Parameter	Symbol	Hot Water Tank Temperature T_{W1}(°C), Water Pump is OFF		
		T_{W1}=30°C	T_{W1}=35°C	T_{W1}=40°C
Heating coefficient of performance	COP_h (from Table 8)	6.04	9.52	3.27
Heating coefficient of performance of the reversed Carnot cycle	COP_{h_carnot}	14.72	11.46	9.4

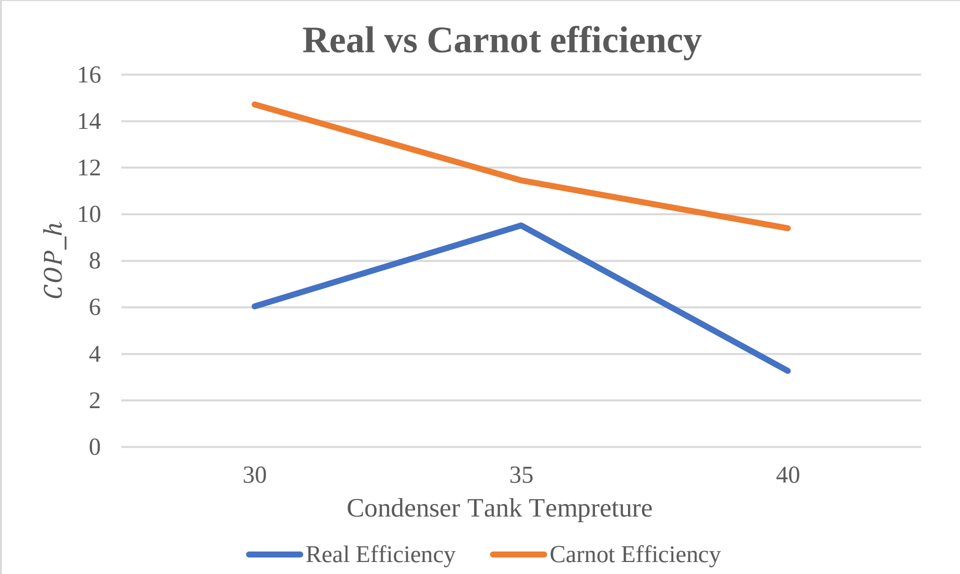

Figure 5 - Real vs Carnot Efficient graph

5.0 Discussion

The evaluation of the heat pump performance compared to the idealised reversed Carnot Cycle reveals several key aspects of a thermodynamic system in a real-life situation.

State Points and Enthalpy (Tables 3, 5, 6, 7)

The enthalpy values at various state points highlight the heat pump cycle's thermodynamic transitions. From state point 1 to 2, there was a slight increase in the enthalpy after compression, and this remained constant towards state point 4 since isenthalpic expansion implied sharp decrease in enthalpy at state point 3. These measurements of enthalpy change are important benchmarks for establishing the heat absorption and rejecting phases of the cycle.

Performance Metrics (Tables 4, 8)

The heat pump performance metrics analysis shows the system's efficiency in heat energy transfer. While the COP_h peak is at a medium temperature of 35°C (COP_h of 9.52) under the "OFF" conditions; it drops sharply at higher temperatures reaching a COP_h of 3.27 at 40°C. So, the heat pump experiences some limitation to the efficiency due to the additional work required for the compressor at higher temperature differentials.

Comparative Analysis with Reversed Carnot Cycle (Table 9)

Comparing the COP of the actual cycle to that of the reversed Carnot cycle's $COP_{h_{carnot}}$ makes a more informative comparison of the ideal performance with the actual performance. This huge difference between the two values highlights the real-world problems that heat pumps face, factors like: friction, non-ideal gas behavior, and unaccounted heat loses plays. In effect, the COP achieved in the experiment though lower than those predicted theoretically would reflect the true efficiency of the heat pump on its actual practical use.

Comparative Analysis of COP Values:

- Temperature-Dependent Performance:

- At TW1=30°C: The actual COP_h of 6.04 contrasts starkly with the theoretical Carnot $COP_{h_{carnot}}$ of 14.72.
- At TW1=35°C: A closer gap between the actual COP_h (9.52) and the Carnot $COP_{h_{carnot}}$ (11.46) is observed. This suggests an increase in operational efficiency at this intermediate temperature, possibly due to more favorable thermodynamic conditions for heat exchange and compression work.
- At TW1=40°C: Here, the actual COP_h reduces to 3.27, whereas the Carnot $COP_{h_{carnot}}$ is 9.4. The widening gap at higher temperatures indicates a decrease in the efficiency of the heat pump, aligning with the theoretical understanding that higher temperature differentials between the heat source and sink decreases the system's efficiency.

Critical Observations and Implications:

Pressure Ratio and Efficiency: The varying pressure ratios (5.31, 6.43, and 7.84 for TW1=30°C, 35°C, and 40°C, respectively) show the delicate balance that compression work and heat transfer have on the heat pumps system, the changing efficiency as the pressure ration changes highlights the need to optimise heat pumps for real life conditions.

Impact of Temperature Differential (ΔTw): The lab results clearly present that a larger differential in temperature lead to a lower COP_h ,which line up with the second law of thermodynamics. This fact points out difficulties in maintaining the efficiency if there is a drastic difference of temperatures between heat source and sink.

Errors

There are a few mistakes that could have occurred during the heat pump lab experiment. These include calibrated instruments and observer bias in finding the enthalpy from the pressure enthalpy diagrams, as parallax error. Which can be rectified by repeating the experiment to confirm the lab results.

6.0 Conclusion

This reports investigation has highlighted the key operational dynamics of the TQ heat pump (EC1500V) through the analysis of the performance results which offer an insight thermodynamics behaviour under several various conditions. The findings from this report highlight the practical deviation from the idealised reversed Carnot cycle, showing the realistic view on how a heat pump in real life conditions.

From the testing and analysis of the lab experiment has show the main purpose and dual functionality that heat pumps have and the role they play in achieving temperature regulation. The efficiency of the cycle, presented by the COP (in table 9) peaked at 35°C before sharp reduction at 40°C .This trend supports the second law of thermodynamics proving that energy systems cannot be 100% efficient.

As is typical of any study, some limitations were identified. The fact that the presence of the random errors such as: fluctuation in the measurements, human error, refrigerant leakage, and other operational inefficiencies -- introduces uncertainties and therefore could have skewed the results presented in this report.

Future studies should focus on improving the design of heat pumps to increase their efficiency by reducing factors that cause entropy and energy loss. Exploring materials and innovative engineering solutions to address these inefficiencies could lead to advancements in this field.

In summary this research holds importance beyond its findings as it raises important questions and establishes a foundation, for future innovation in thermodynamics. The results serve as a driving force for research and development in aerospace engineering with the potential to impact energy conservation strategies and environmental sustainability efforts. Therefore the study of heat pump dynamics remains an area of investigation with ranging implications, for both theory and practical applications.

The heat pump cycle chart

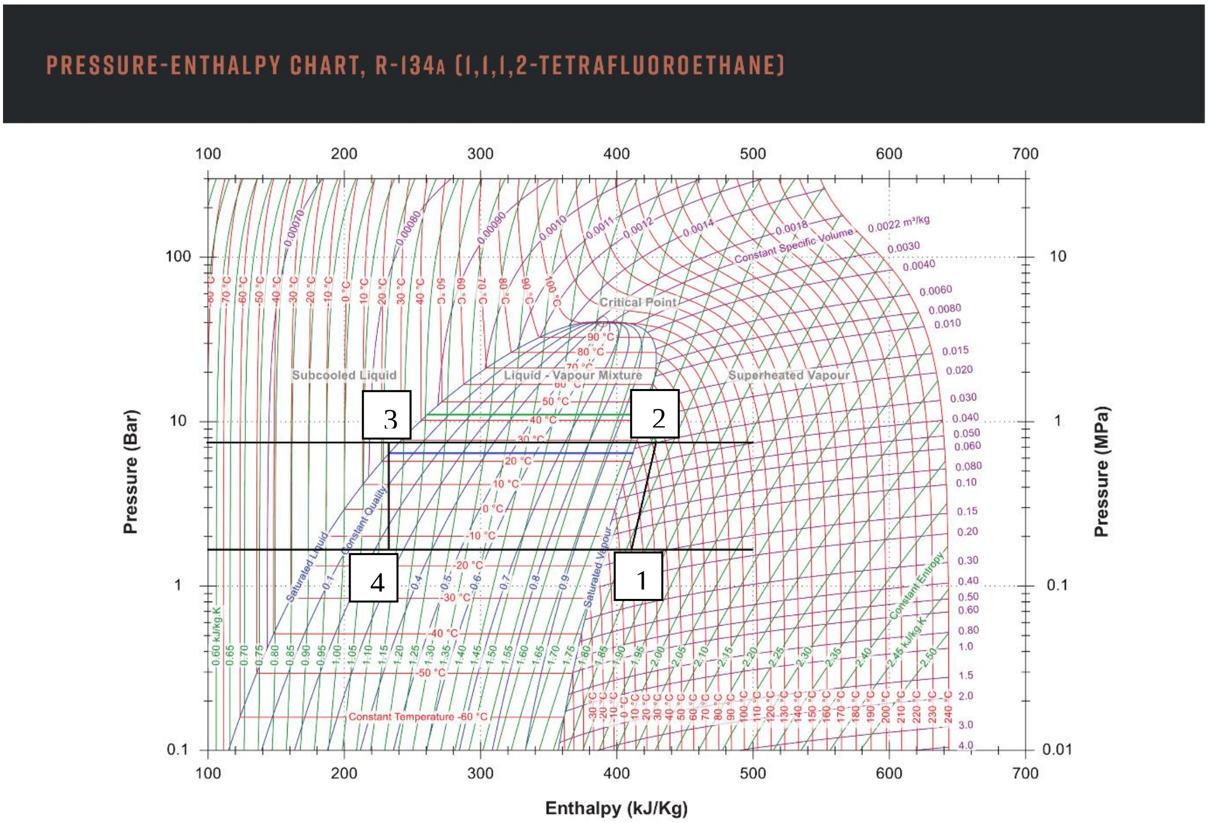

Figure 6 - Table 3 Pressure -Enthalpy Chart

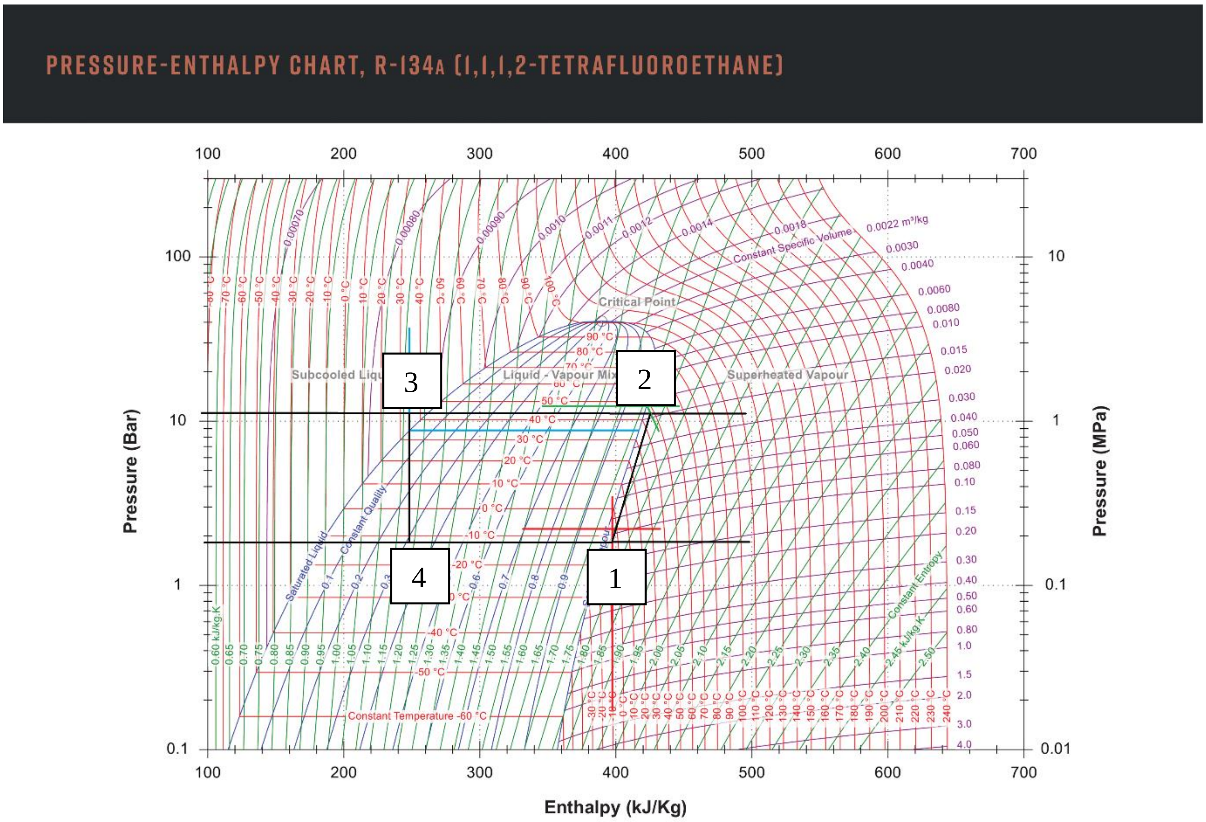

Figure 7 - Table 5 Pressure -Enthalpy Chart

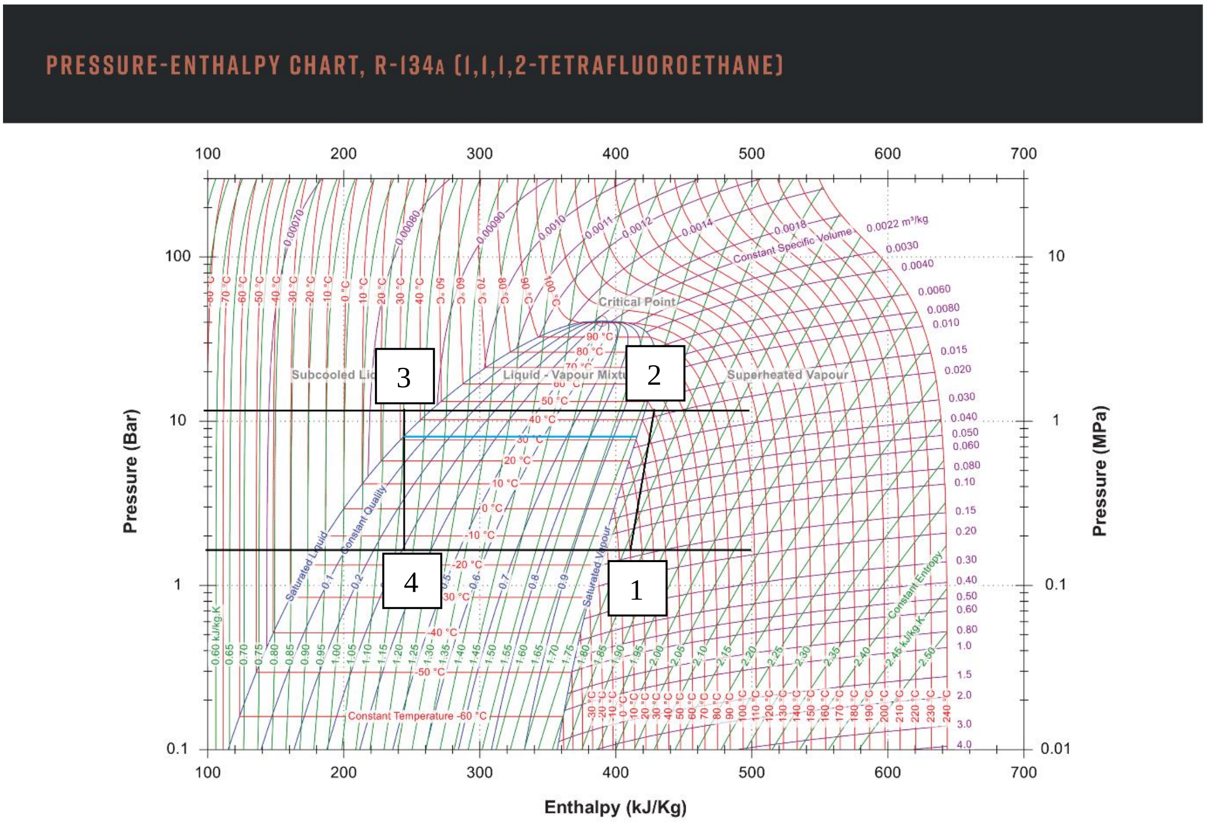

Figure 8 - Table 6 Pressure -Enthalpy Chart

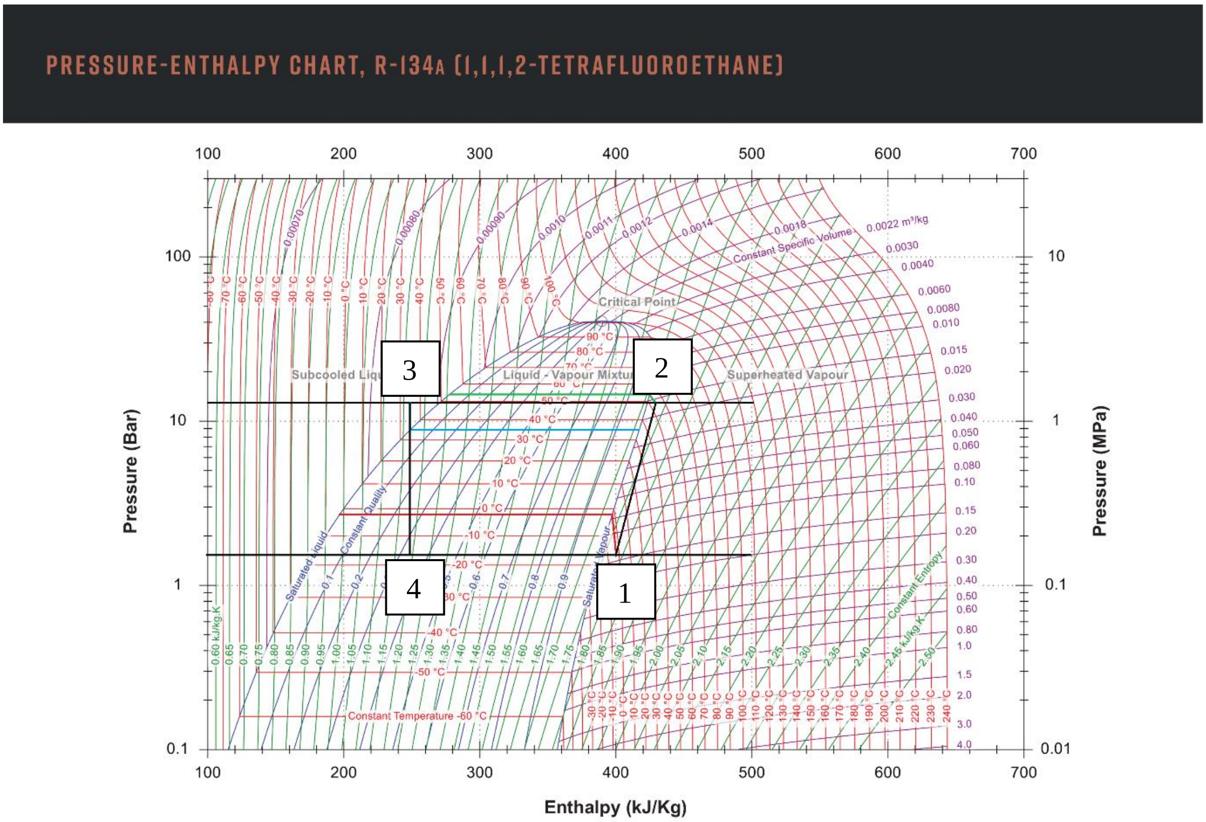

Figure 9 - Table 7 Pressure -Enthalpy Chart

References

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[3] Automatic Heating. (n.d.). Heat Pumps Explained. [online] Available at: https://automaticheating.com.au/complete-guide-to-heat-pumps/heat-pumps-explained/.