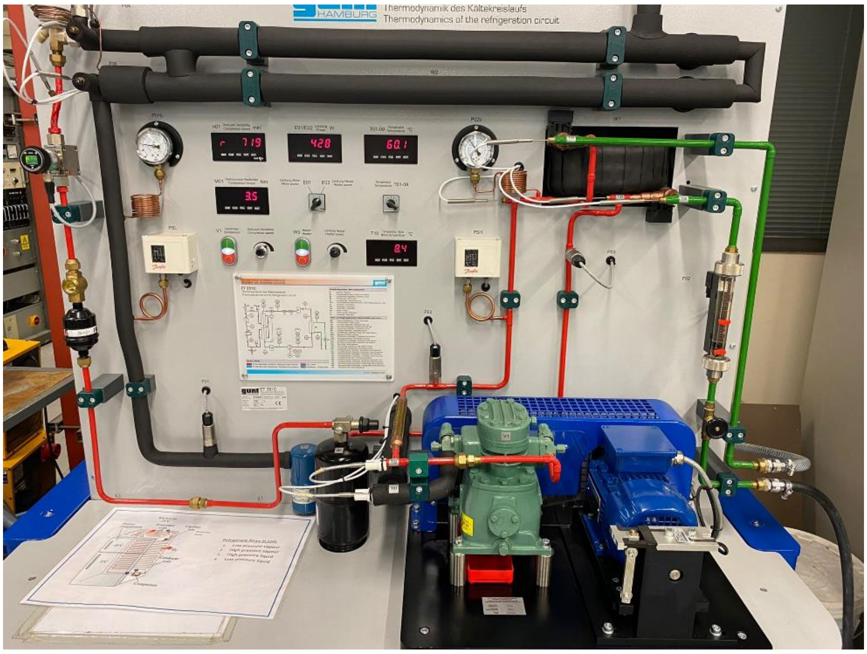
EG4013

Refrigeration Experiment



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Contents

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Name and K number	***Contribution***
Denise Ekugwum K2101876	Front page (1) Discussion (1)
Mark Malejevs K2160238	Abstract (1) Conclusion (1)
Dylan Kannemeyer K2103895	Theory (1) Results (1)
Abdalla Roble K2103899	Methods (1)
Adam Ahmed K2160707	Introduction (1)

Abstract

This experiment is aimed to study the thermodynamics of refrigeration cycle and temperature changes of liquid refrigerant throughout all four stages.

During the experiment we kept collecting measurements of changes in temperature and gauge pressure as refrigerant was flowing through the system. Afterwards we proceeded to analyze taken measurements and calculate the following values: absolute pressure, refrigerant flow rate, refrigerating capacity/power and efficiency of the condenser, compressor and evaporator and total coefficient of efficiency of the closed system.

Further analysis of calculated results gave us enough information to conclude that, first, compressing cycle appears to be the most inefficient and second is that judging by calculated CoP, this system can efficiently perform heat absorption.

Introduction

Through the revolution of modern science, we now know that cooling preserves food and drinks because it slows down or even prevents the growth of microorganisms that render food unfit for human consumption. This is because molecules move slower at lower temperatures consequentially slowing down the chemical reactions in microorganisms that allow them to pollute our world.

Refrigeration is the removal of heat from an enclosed space or substance for the purpose of lowering the temperature. Before innovative technology, hunters and gatherers consumed the food they were able to get hold of instantly. As times changed and hunting for food diminished, people started to find different methods of preservation such as salting, smoking, pickling, and drying. These techniques successfully preserved food but at the cost of flavor and texture which are the necessities of modern cuisine. Furthermore, natural sources such as streams and caves were a being used as great cooling options in places where ice was not available until William Cullen, a Scottish doctor, observed that evaporation had a cooling effect in the 1720s. He then demonstrated his ideas in 1748 by evaporating ethyl ether in a vacuum. Later in 1835 Jacob Perkins received a patent for a vapor compression cycle using liquid ammonia which placed a milestone in the breakthrough of refrigeration (*live science, 2017*).

The compression refrigeration cycle consists of circulating a liquid refrigerant through four stages of a closed system: compressor, condenser, restrictor (expansion valve) and evaporator. During this experiment we are studying the thermodynamics of a vapor compression refrigeration cycle and the energy changes of the refrigerant at various stages of the cycle. This is done by identifying the state of the fluid by directly measuring the temperature and pressure, which then allows us to investigate the thermodynamic cycle using pressure-enthalpy and P-h charts.

Methods

Health and safety

There were not that many hazards when doing this experiment as the technician was doing it. Some of the hazards that the technicians could have faced and how they were avoided are as followed.

Brine has toxic properties if there was a spillage the technician could succumb to some harm. The Technician did as a result wear a lab coat and gloves when handling the machinery as to minimise the amount of direct contact they had with the brine

When the fridge system is on, the compressor gets hot this could potentially cause the technician to burn themselves. A precaution taken was the compressor was placed under the desk where it would be out of reach and had a “CAUTION: HOT SURFACE” sticker attached.

All the students wore PPE to ensure our safety.

Procedures

The technician did the lab work, so we did not get a chance to do it alone. But the basic outline of the experiment was that we allowed the refrigerant through the compressor and the condenser. To measure the temperature before and after each of the components we allowed the refrigerant to take its normal route around the system but once it reached the compressor, we closed the system. To calculate temperature change and how much the temperature rose before putting the brine in we measured the temperature of the brine b4 it entered the system.

Apparatus

Compressor - The compressor helps the system lose heat by pushing the refrigerant through the copper tubing between the condenser and evaporator coil

Condenser - The condenser operates at a high temperature and moves gas around at a high pressure and helps the system lose heat through the condenser coils.

Expansion valve - The expansion valve reduces the pressure of the liquid refrigerant that is coming from the condenser

Evaporator - The Evaporator removes the heat that is within the fridge. Essentially lowering the inside temperature by removing the warm air.

R134a - The Refrigerant used during the experiment.

ET 351C - The machine was used rather than a commercial fridge as everything was laid out and easy to follow

Background information

The expansion valve was opened during the experiment this allowed the refrigerant to flow through to the once the refrigerant has contacted the temperature within the fridge the refrigerant expands and turns into a gas, as its going through the coils it absorbs heat released by the food inside. The compressor then squeezes the refrigerant causing it to increase in pressure and temperature. It then goes through the condenser coils located at the back of the fridge to lose the heat absorbed to the atmosphere and going back into liquid form as a result. It then re-enters the expansion valve at starts the process again

Theory

Refrigerant used: R134a

Chemical Name: 1.1.1.2 tetrafluorineethane

Chemical Formula: $CH_2F\text{-}CF_3$

This experiment studies the changes in thermodynamic properties and characteristics experienced by a vapour under compression and expansion during a refrigeration cycle, as well as the energy changes experienced by the refrigerant throughout the various stages of the refrigeration cycle. The changes in thermodynamic properties demonstrate the 4 laws of thermodynamics.

The refrigeration cycle is an example of multiple processes, as the system changes states multiple times; and is a 4-process cycle because it is made up of 4 processes and returns to its initial state at the end of each cycle.

During the refrigeration cycle, the refrigerant is compressed, often utilizing a motorised compressor. Which transfers chemical-potential or thermal energy to rotational energy using an electric motor or a combustion engine. The rotational energy is transferred into lateral translational energy as the refrigerant is compressed. During this process, the First Law of Thermodynamics is demonstrated. This law is demonstrated because of the law of Conservation of Energy, which states that "Energy can neither be created nor destroyed, only converted from one form of energy to another." *(J.M.K.C Donev, 2021).* Meaning that in a perfect system, unless additional energy is added to the system, it will have the same amount of energy as its' initial state. However, due to being an imperfect system, some energy may be lost to the surrounding environment in forms such as heat and sound due to imperfect mechanical processes (i.e., friction, etc.).

When the low-pressure, low-temperature refrigerant is compressed its' internal energy (which is the sum of its total intermolecular Potential Energy and its total random Kinetic Energy) rises.

$$\Delta U = Q - W$$

Where:

ΔU : $change\ in\ internal\ energy\ (U)$ of the system $(Joules)$

Q : $net\ heat\ transfer\ into\ the\ system$ $(Joules)$

W : $net\ work\ done\ by\ the\ system$ $(Joules)$

Macroscopic Internal Energy formula, in Joules *(The First Law of Thermodynamics | Physics, 2022).*

Along with the rise in internal energy the refrigerant's temperature and pressure rise (this is because it is an isochoric process), causing a rise in the refrigerant's Specific Enthalpy.

$$H = U + pV$$

Where:

H	$:$ *Enthalpy*	$(Joules)$
U	$:$ *Internal Energy*	$(Joules)$
p	$:$ *Pressure*	(Pa)
V	$:$ *Volume*	(m^3)

Specific Enthalpy Formula:

$$h = \frac{H}{m}$$

Where:

h	$:$ *Specific Enthalpy*	(J/kg)
H	$:$ *Enthalpy*	(Joules)
m	$:$ *Mass*	(kg)

Enthalpy and Specific Enthalpy Formulae, (Enthalpy, 2021).

The refrigerant, which is now a high-pressure, high–temperature vapour, then travels along with the condenser coils by means of natural convection [which occurs when most fluids are heated and expand. Due to the fluid's then lower density, its' buoyancy increases causing it to rise. *(Convection | physics, 2019).*]
While travelling the fluid transfers heat to its' surrounding environment, this is because of the Second Law of Thermodynamics, which states the Entropy of a system, and the environment is to increase. *(Second Law of Thermodynamics, 2021).*
Meaning that there will be a heat transfer from the higher temperature medium to the lower temperature medium until the Zeroth Law of Thermodynamics is achieved. The Zeroth Law states that, between systems that are in thermal equilibrium (i.e., are the same temperature), there will be no heat transfer. *(The Zeroth Law of Thermodynamics | Boundless Physics, n.d.).*
The change in heat lowers the refrigerant's internal energy which causes it to change its' state into a high-pressure liquid.

Within the capillary tube, the available volume is increased which reverses the effects of the fluid compression causing the refrigerant's pressure and temperature to decrease. This then changes the refrigerant's state to a low-pressure, low-temperature liquid.

This low-temperature liquid is then transported through the evaporator coils, where the fluid absorbs heat from the higher temperature medium (in a refrigerator this would be the stored food); this causes the higher temperature medium's temperature to decrease thus achieving refrigeration.

The low-pressure, low-temperature liquid then travels to the compressor unit for the refrigeration cycle to begin again.

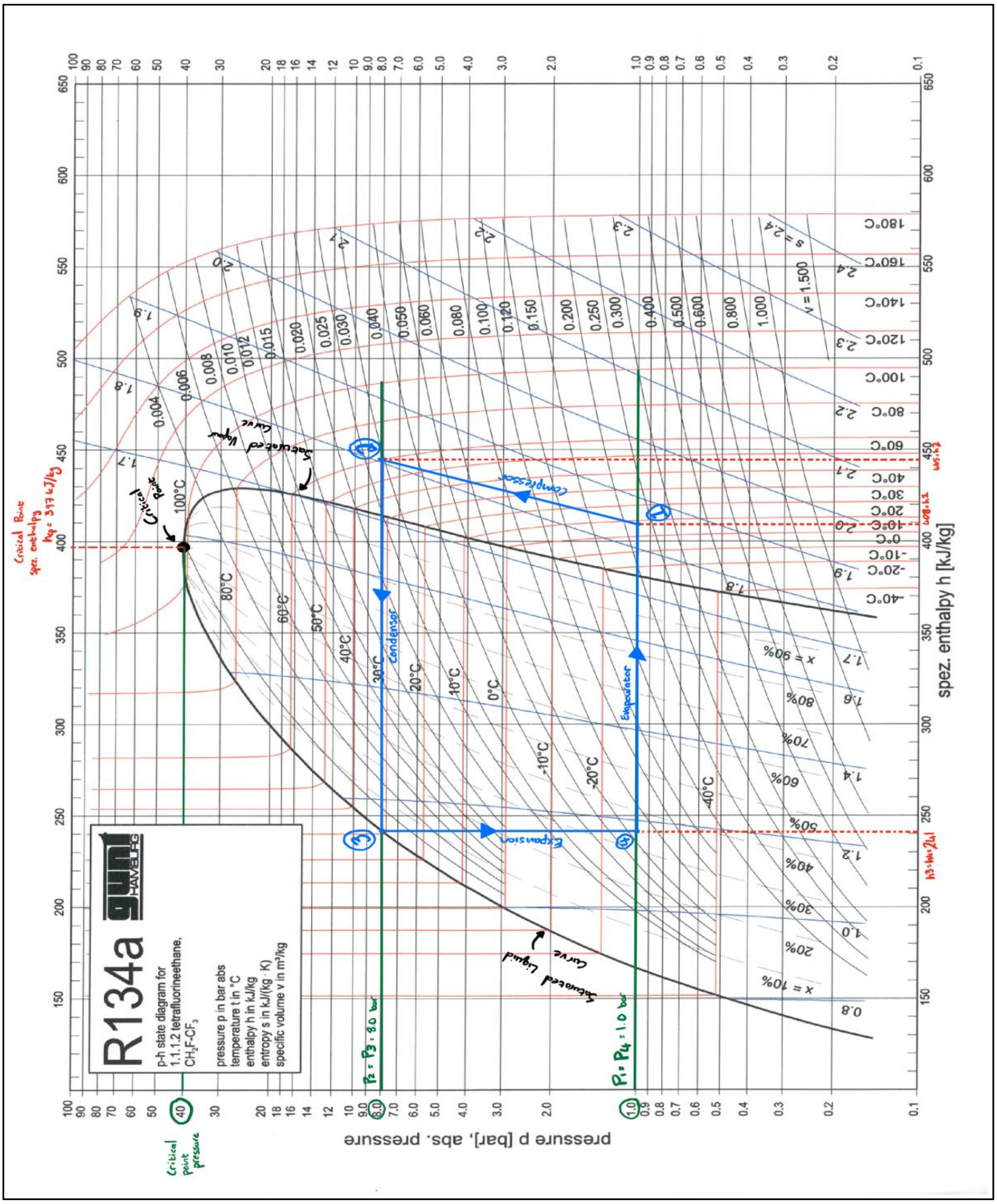
Results of the refrigeration cycle can be measured by observing the change in pressure and temperature of the refrigerant before and after various stages of the refrigeration cycle.
Further deductions can be made as to the refrigerator's performance and efficiency by observing the amount of work put in by the compressor unit and the achieved outcome (measured by the thermal power achieved, this may be heating or cooling).
This can then be used to calculate the refrigerator's Coefficient of Performance (COP) and Efficiency. By analysing these, the refrigerator can be further optimised to require less energy input while still achieving the same or a more desired result.

$$Coefficient\ Of\ Performance = \frac{Energy_{ouput}}{Energy_{input}} = \frac{refrigerating\ effect}{work\ done}$$

Coefficient of Performance Formula, is a unit less quantity.

Results

R134a Pressure-Specific Enthalpy (P-h) state diagram:



Annotated R134a Pressure-Specific Enthalpy (P-h) state diagram, with various instruments temperature (°C) and pressure values plotted, to indicate the thermodynamic refrigeration cycle, which is used to generate various specific enthalpy (kJ/kg) values for set points during the refrigeration cycle. The diagram also shows the saturated liquid curve, saturated vapour curve as well as R134a's Critical Point. *(P-h chart R134a - Refrigeration, n.d.)*

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All pressure reading instruments report Gauge Pressure (P_{gauge}), the final values are required in Absolute Pressure (P_{abs}), and therefore require Atmospheric Pressure (P_{atm}) to be added to the reported gauge pressure.

Atmospheric Pressure recorded at the time of the experiment: 1.018 bar.

Absolute Pressure Equation, unit: bar

$$P_{abs} = 1.018 + P_{gauge}$$

Parameter	Symbol	Unit	Values (P_{gauge})	Values ($P_{absolute}$)
Compressor Inlet Temperature	T_1	Degrees Celsius (°C)	9.2	9.2
Compressor Outlet Temperature	T_2	°C	61.4	61.4
Condenser Inlet Temperature	T_3	°C	54.3	54.3
Condenser Outlet Temperature	T_4	°C	34.3	34.3
Expansion Valve Inlet Temperature	T_5	°C	29.6	29.6
Evaporator Inlet Temperature	T_6	°C	-6.8	-6.8
Evaporator Outlet Temperature	T_7	°C	6.5	6.5
Cooling Water Inlet Temperature	T_8	°C	12.9	12.9
Cooling Water Outlet Temperature	T_9	°C	34.5	34.5
Brine Temperature	T_{10}	°C	8.7	8.7
Heater Power	P_{el2}	Watts (W)	406	406
Evaporator Outlet Pressure	P_1	bar	1	2.018
Condenser Inlet Pressure	P_2	bar	8	9.018
Condenser Outlet Pressure	$P_3 = P_2$	bar	8	9.018
Evaporator Inlet Pressure	$P_4 = P_1$	bar	1	2.018
Compressor Speed	N	rpm (rev/min)	719	719
Compressor Torque	T_{comp}	Newton-metre (Nm)	3.5	3.5
Refrigerant Volume Flow Rate	V_R	Litres/minute (L/min)	0.15	0.15
Cooling Water Mass Flow Rate	M_w	Grams/second (g/s)	5.3	5.3

Table A showing the Temperature (°C), Pressure (bar), Power (W), rpm, Torque (Nm), Volume Flow Rate (L/min) and Mass Flow Rate (g/s) for the various measurement apparatuses used during the refrigeration cycle at the time of the experiment.

Critical Point [Read off chart]		
Temperature, T, (°C)	Absolute Pressure, P_{abs}, (bar)	Specific Enthalpy, h, (kJ/kg)
106	40	397

Table B showing the Critical Point Temperature (°C), Absolute Pressure (bar), and specific enthalpy (kJ/kg) of the refrigerant R134a during the refrigeration cycle at the time of the experiment.

Specific Enthalpy Values [Read off chart]	(kJ/kg)
h1	408
h2	445
h3 = h4	241
h4 = h3	241

Table C showing the specific enthalpy values, read off the chart, using the generated refrigerant cycle chart (R134a) at the time of the experiment.

For the Compressor:

Compressor Mechanical Power:

$$W_{12} = 2\pi\left(\frac{N}{60}\right)T_{comp}$$

$$= 2\pi\left(\frac{719}{60}\right)3.5$$

$$= \frac{5033}{60}\pi$$

$$\approx\ 263.527\ \ Watts\quad (3dp.)$$

Symbol	Description	Value	Unit
N	Compressor Speed	719	rpm
T_{comp}	Compressor Torque	3.5	Nm

Table showing the Compressor Speed and Torque.

Rate of Energy transfer to refrigerant, during compression:

$$Converting\ V_R\ to\ m_R:$$

$$Refrigerant\ Volume\ Flow\ Rate\ (V_R):\ \ 0.15L/min$$

$$Refrigerant\ Density\ (\rho_R):\ \ 1229kg/m^3 \qquad (Dembele\ S., 2021)$$

$$m_R = (\rho_R)(V_R)$$

$$= (1229)(0.15)$$

$$=\ 184.35\ g/min$$

$$h_1 = 408 \qquad h_2 = 445 \qquad (kJ/kg)$$

$$Q_{12-chart} = m_R(h_2 - h_1)$$

$$= 184.35(445 - 408)$$

$$= 6821\ J/min$$

$$= 113.6833\ J/sec$$

Units:

$1m^3 = 1000L$

$$m_R: \left(\frac{kg}{m^3}\right)\left(\frac{L}{min}\right) = \frac{\cancel{1000}\cancel{L}g}{\cancel{1000}\cancel{L}min} = \ g/min$$

$$Q_{12-chart}: \left(\frac{g}{min}\right)\left(\frac{kJ}{kg}\right) = \left(\frac{g}{min}\right)\left(\frac{J}{g}\right) = \frac{\cancel{g}J}{\cancel{g}min}$$

$$= \frac{J}{min}$$

V_R to m_R unit conversion.

Compressor Efficiency:

$$Efficiency = \frac{Q_{12-chart}}{W_{12}}$$

$$= \frac{113.6833}{263.527}$$

$$= 0.43207$$

$$= 43.21\%$$

This shows that 56.79% of inputted energy is lost.

Reasons for inefficiency:

- Thermal energy is lost to the environment, due to the resistance in the coils of the motor windings.
- Energy is lost as heat and sound due to the friction between the moving parts of the drive motor and compressor unit, i.e., the drive belt and associated drive wheels, as well as the various bearings, shafts, and pistons.

For the Condenser:

Condenser Power:

$$Q_{23-chart} = m_R(h_2 - h_3)$$

$$= 184.35(445 - 241)$$

$$= 37607.4\ J/min$$

$$= 626.79\ J/sec$$

$$= 626.79\ Watts$$

Symbol	Description	Value	Unit
m_R	Mass Flow Rate	184.35	g/min
h_2	Enthalpy 2	445	kJ/kg
h_3	Enthalpy 3	241	kJ/kg

Table showing the Mass Flow Rate, Enthalpy 2 and Enthalpy 3

$$Watt = \frac{Joule}{second}$$

Watt formula

Rate of energy absorbed by the cooling water:

$$Q_W = m_W(T_7 - T_6) \times C$$

$$= 5.3(6.5 - (-6.8)) \times 4.18$$

$$= 294.648\ J/s$$

Symbol	Description	Value	Unit
m_W	Mass Flow Rate of Water	5.3	g/s
T_6	Evaporator Inlet Temperature	-6.8	$°C$
T_7	Evaporator Outlet Temperature	6.5	$°C$
C	Specific heat of water *(Dembele S., 2021)*	4.18	$\frac{kJ}{kg\ °C}$

Table showing Mass Flow Rate of Water, Evaporator Inlet and Outlet Temperatures, as well as the Specific heat of water.

Comparing $Q_{23\text{-chart}}$ and Q_W:

$$Q_{23-chart} = 626.79\,J/sec$$
$$Q_W = 294.648\,J/s$$

$$Efficiency = \frac{W_{out}}{W_{in}} = \frac{Q_W}{Q_{23-chart}} = 0.47009 = 47.01\%$$

this shows that 52.99% of inputted energy is lost

Possible Reasons for energy loss:

- Thermal energy may be lost due to insufficient thermal insulation of refrigeration pipes and coils.
- Energy may be lost due to friction between the flowing refrigerant and the various pipes and coils.

Evaporator Refrigerating Capacity:

$$Q_{41-chart} = m_R(h_1 - h_4)$$
$$= 184.35(408 - 241)$$
$$= 30786.45\,J/min$$
$$= 513.12\,J/s$$
$$= 513.12\,W$$

Symbol	Description	Value	Unit
m_R	Mass Flow Rate	184.35	g/min
h_1	Enthalpy 1	408	kJ/kg
h_4	Enthalpy 4	241	kJ/kg

Table showing Mass Flow Rate, Enthalpy 1 and Enthalpy 4

Comparing $Q_{41\text{-chart}}$ and P_{el2}:

$$Q_{41-chart} = 513.12\,W$$
$$P_{el2} = 406\text{ W}$$

$$Efficiency = \frac{W_{out}}{W_{in}} = \frac{P_{el2}}{Q_{41-chart}} = 0.7912 = 79.12\%$$

This shows that 20.88% of inputted energy is lost.

Coefficient of Power:

$$COP = \frac{refrigerating\ effect}{work\ done} = \frac{h_1 - h_4}{h_2 - h_1} = \frac{408 - 241}{445 - 408} = 4.514\ \ (3dp)$$

The coefficient of performance is defined as the relationship between the thermal power achieved (heating or cooling) and the power supplied to the compressor. This shows that for every 1kW of power supplied to and consumed by the compressor, 4.514 kW of cooling power is achieved.

Difference between Coefficient of Performance (COP) and Efficiency:

While both are unitless quantities, COP is the ratio of the heat absorbed to the work done on the system (per unit time). Whereas efficiency is the ratio of work done to the work supplied to the system (per unit time).

Other types of refrigerants used in modern fridges/freezers:

- R134a Tetrafluoroethene, this refrigerant is non-ozone depleting but is a greenhouse gas that may contribute to global warming and various environmental changes and will therefore soon be phased out of mainstream use.
- R438a Freon, is non-ozone depleting and not a greenhouse gas, causing its' mainstream popularity to rise, in the use of modern fried/freezer units.
- R600a Isobutane is also non-ozone depleting and not a greenhouse gas but is flammable, which could be a potential safety factor. However, this refrigerant can be found quite often in small modern fridge/freezer units.

Before these refrigerants were featured in mainstream use, there were various other refrigerants being used most of which have been phased out of use, or use of being made illegal due to safety and environmental impacts. As many of these refrigerants were ozone-depleting and greenhouse gases. Examples of such refrigerants were: R12 Freon, and R22 Chlorofluorocarbons. *(Toor, 2021)*

Why R12 Freon use is now illegal:

R12 Freon use in fridge/freezer and automobile coolant units was outlawed because of the Montreal Protocol *(Johnson, 2014)* on 1st January 1989, due to the ozone-depleting and potent greenhouse gas properties of the refrigerant if it were to leak (or be vented). *(Johnson, 2018)*

Difference between heat pump and fridge:

The only difference between a refrigerator and a heat pump is the location of the condenser and evaporator coils.
In a refrigerator the fluid flows from the compressor unit to the condenser coils where heat is expelled to the surrounding environment, the fluid then flows to the evaporator coils where heat is absorbed from the item(s) being cooled.
In a heat pump, the fluid also flows from the compressor unit to the condenser coils. However, in a heat pump, the condenser coils are in the area desired to be heated up, the heat is expelled into this desired surrounding environment, increasing the air temperature in this area. The fluid then also flows to the evaporator coils, but the evaporator coils in the heat pump are located outside the area desired to be heated.

The overall result of a refrigerator is to cool item(s) or an area, whereas the result of a heat pump is to warm item(s) or an area, but the means of doing both are the same.

Discussion/Analysis

Our main objective was to explore thermodynamics through vapour compression. This is modelled through the refrigeration cycle and the energy changes of the refrigerant in this cycle was explored.

The results we recorded, supports our objective as we can see that due to the different processes, there are various energy states that the refrigerant goes through. In the pressure and specific enthalpy graph it highlights the 4 phases that this refrigerant is going through due to the changes of pressure and temperature.

Phase $_{1\text{-}2}$, the compression takes place where the low temperature and pressured refrigerant enters and leaves as a vapour that has an elevated temperature and pressured as shown in Table A. The compression process is adiabatic as the change in $h_{12} = W_{in}$

The compressor power input is greater than the output which is an inaccuracy we predicted as the energy supplied is not entirely used to compress the refrigerant vapour. Energy is lost through friction in coils and vibrations, thermal energy, and the quality of the refrigerant itself.

Errors may be present due to the possibility of pressure losses from imperfect seals in pipes or thermal lost throughout the system or through convection and conduction.

This experiment is significant as it uses vapour compression to bring temperature from low to high mechanically. This is impossible to do naturally which is the Second law of Thermodynamics. There may be slight discrepancies in the results due to friction between the refrigerant itself and the coils and pipes.

Conclusion and Recommendations

During our analysis of the results, we have drawn two conclusions. After calculating the efficiency of each cycle, we concluded that the most inefficient turned out to be compression cycle, where more than half of energy supplied is being lost in the process. Second conclusion was made after we calculate the COP of refrigerator, which is 4.514, from which, after some research, we concluded that with such COP, refrigerator can perform its main task, which is to slow down the activity of bacteria and keep food fresh for longer.

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