INDIAN INSTITUTE OF TECHNOLOGY, GANDHINAGAR

ES 211 Thermodynamics

Project Report

By Group :

Madhur
24110188(20%)

Rishi Pinara
24110257 (20%)

Sanidhya Bhandari
24110315 (20%)

Shreyas Purkar
24110333 (20%)

Shubham Chandak
24110335 (20%)

Under the supervision of:

Prof. Atul Bhargav

Contents

1 Introduction

1.1 Background and Motivation

The thermodynamic behavior of pure substances near the liquid vapor dome plays a crucial role in a wide range of mechanical and energy systems. Technologies like heat pumps, heat engines, and refrigeration are based on a substance's capacity to absorb or reject large amounts of heat during phase change without experiencing a significant change in temperature. In this project, we selected R134a as the working fluid. After visiting the chiller plant at our college, we were interested in this refrigerant, more of which is later explained in the report.

1.2 Objectives

The project is divided into two main tasks:

1. **Task 1:** Generation of a 3D model of the p(v-T) surface of R-134a near the dome using Cantera and CAD tools.
2. **Task 2:** Application study of R-134a in a practical refrigeration system, analyzing its thermodynamic cycle, component behavior, and efficiency.

The aim of the study is to visualize the relationship between R134a's pressure, specific volume and temprature P(v,T) near the liquid vapor dome. It is widely used in vapor compression refrigeration systems due to its favorable thermodynamic properties, safety, and environmental compatibility.

1.3 Overview

We examined R134a's thermodynamical characteristics using the Cantera Thermodynamic Library. We wrote our code using Matlab and further converting the mesh file into .stl format, which was 3D printing ready. Then we printed the model which helped us visualize and enhance our understanding of the concepts involved.

This report provides a thorough summary of the theoretical knowledge, modeling procedure, and useful insights we discovered during our investigation.

2 Theoretical Background

2.1 The Liquid Vapour Dome

A pure substance can exist in three primary phases solid, liquid or vapor depending on its thermodynamic state. These phases coexist and change under different pressures and temperatures, as the figure shows. The dome shaped region on this surface corresponds to the two phase (liquid-vapor mixture) region, bounded by the saturated liquid and saturated vapor lines.

The characteristics of vapor and liquid are indistinguishable at the critical point. The superheated vapor region is located above the dome, and the subcooled/compressed liquid region is located below it.

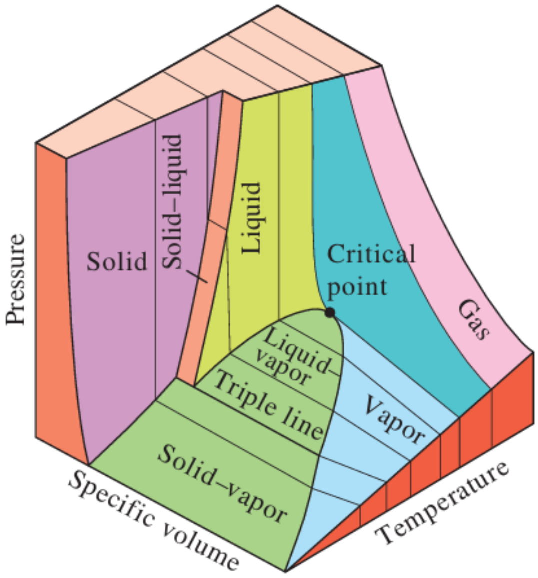

Figure 1: P(v,T) surface

2.2 Key Thermodynamic Properties

For R134a P,v and T define how the refrigerant transitions between different phases. At constant temperature, vapor turns into liquid through condensation when pressure rises, and vaporization occurs when pressure falls. These changes take place beneath the curved liquid-vapor dome, which represents the two phase region. Inside the dome, both liquid and vapor phases coexist in equilibrium.

- **To the left of the dome:** The substance exists as a compressed or subcooled liquid.
- **To the right of the dome:** It exists as a superheated vapor.
- **On the saturated liquid line (x = 0):** The substance is about to start vaporizing.
- **On the saturated vapor line (x = 1):** The substance is about to start condensing
- **inside the dome (0 < x < 1): liquid-vapour mixture**.

At the critical point, the saturated liquid and vapor lines meet, where the difference between the two phases disappears. Beyond this point, the fluid is in a supercritical state. It behaves neither as a distinct liquid nor as a vapor.

R134a is the perfect refrigerant for vapor compression systems because of its smooth and consistent P(v,T) relationships as it allows us to compute crucial parameters like entropy, internal energy, and enthalpy. These relationships are crucial for the design and analysis of refrigeration cycles.

Property	Symbol	Value	Units
Molecular Weight	M	102.03	g/mol
Critical Temperature	T_c	101.1	°C
Critical Pressure	p_c	4.059	MPa
Normal Boiling Point	T_b	-26.1	°C
Triple Point Temperature	T_t	-103.3	°C
Triple Point Pressure	p_t	0.003	MPa
Critical Specific Volume	v_c	0.00196	m^3/kg

Table 1: Thermodynamic properties of R134a

2.3 Equation of State and Cantera Implementation

Equations of state explain how pressure, specific volume, and temperature connect for a substance. For real fluids like R134a, the ideal gas relationships don't work well near the liquid, vapor boundary, so we need better real fluid models.

In this project, the Cantera Thermodynamic Library provided accurate P(v,T) data for R134a. We used MATLAB to calculate these properties, create the P(v,T) surface, and turn the resulting mesh into a 3D printable .stl model. This made it easier to see how R134a behaves during phase changes.

2.4 Saturation Properties and Quality (x) Concept

Inside the liquid, vapor dome, a substance exists as a mix of saturated liquid and saturated vapor. The quality (x) shows the mass fraction of vapor in the mix:

$$x = \frac{m_v}{m_l + m_v}$$

Key terms:

- **Saturated Liquid (x = 0):** About to vaporize.
- **Saturated Vapor (x = 1):** About to condense.
- **Two-Phase Region (0 < x < 1):** Liquid and vapor coexist.
- **Critical Point:** Liquid and vapor become indistinguishable.

These properties are important for understanding evaporation, condensation, and the performance of the refrigeration cycle.

2.5 Physical Phenomena Governing the System

The behavior of R134a in both the P(v,T) surface and the refrigeration cycle is driven by basic thermodynamic principles.

- **Phase Change:** When we add or remove heat at constant pressure, R134a vaporizes or condenses at nearly constant temperature. This creates the boundaries of saturated liquid and vapor, which forms the liquid-vapor dome.

- **Latent Heat:** Large amounts of heat are absorbed or released during phase change but with little temperature change. This latent heat causes the cooling effect in air conditioners.
- **Pressure-Volume Relationship:** In the subcooled region, small changes in specific volume lead to large changes in pressure. Whereas the fluid acts more like a gas and is highly compressible in the superheated region.
- **Critical Point Behavior:** At the critical point, the liquid and vapor phases become similar. R134a becomes a supercritical fluid beyond this point.
- **Isenthalpic Expansion:** Through the expansion valve, R134a undergoes throttling at constant enthalpy, which results in a drop in temperature and partial vaporization.
- **Isentropic Compression:** The compressor ideally raises pressure and temperature at constant entropy, increasing the refrigerant's enthalpy.

  These principles define the surfaces and curves in the P(v,T) model and control the thermodynamic cycle operation.

3 3D Model Development

3.1 What does the 3D plot represent?

The P(v,T) surface represents the complete thermodynamic behaviour of R134a at different values of its pressure, specific volume, and Temperature. Distinct regions of the surface represent the different phases of liquid, vapour, and the liquid-vapor region, forming a characteristic dome where phase change occurs. This model helps us to clearly identify and visualise regions of sub-cooled liquid, saturated mixture, and superheated vapor. The solid part is not included in the model as we used liquidvapor.yaml which does not include solid phase. The following image represents the MATLAB image whose csv file is later trasnsformed into .stl for 3D Modeling.

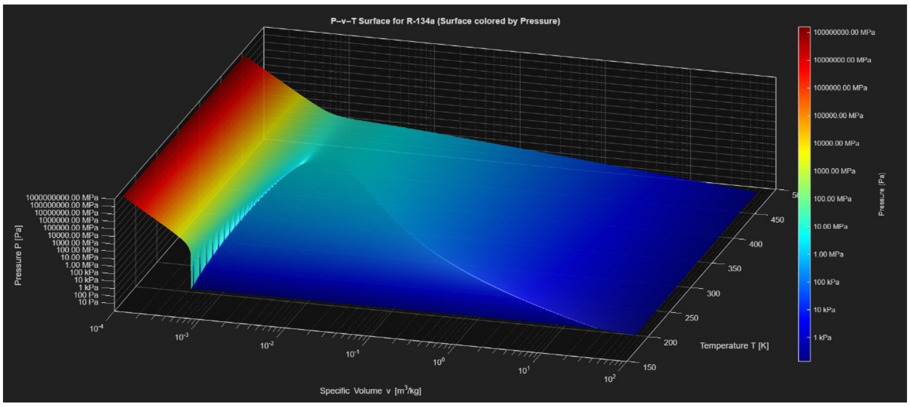

Figure 2: Matlab P(v,T) graph

3.2 Data Generation Using Cantera

1. This Cantera code plots the 3D figure in MATLAB. The code begins with a grid of 600 temperature points (linearly scaled from 170K to 455K) and 600 specific volume points (log scaled from 10^{-4} to 10^{2} m^3/kg). Then, pressure is tabulated for each of these points. It then generates a point cloud in the form of a .csv file of 360,000 distinct points.

2. This Python code takes the point cloud in the form of a .csv file, triangulates it to create a mesh, and converts it to a .stl file with 717,602 facets.
   Note: that this code was executed on our systems in a different environment. The code will not work in Google Colab as the CSV files are not loaded there.

3.3 Mesh Model Construction

- **Software and design process**
  To begin, a quick recap on the workflow: We started off by making a point cloud and saved it in a .csv file. Then, to convert this into a workable surface, we used a Python script to convert the point cloud into a mesh in the form of an .stl file. The outcome of this is a P(v,T) surface that has no enclosed volume, making it unprintable in its current form. To change this, it was necessary to enclose this surface, so it has an enclosed volume, and additionally ensure that this enclosed surface does not have holes or NaN gaps. To compute this, we employed three software: Blender, Fusion, and SolidWorks (Ultimately, only Blender would produce a printable .stl file). Before going into the blender workflow, it is necessary to understand what went wrong in Fusion and SolidWorks.

- **Fusion**
  The workflow seemed simple; the mesh first had to be imported, and then, using the 'Repair Mesh' feature, all the holes would be automatically patched. The output of this process should just produce a solid that can be altered and shaped accordingly. However, as soon as we attempt to import the mesh, the program immediately freezes and crashes after a short while. The most probable reason for these crashes was the size of this file; loading all 700k+ facets is something Fusion was not designed to handle.

- **SolidWorks**
  Unlike Fusion, the workflow is slightly longer; the mesh must be imported into the workspace and then converted to a surface. After that, create a cube that is slightly smaller than the surface, and then use the surface to split the cube into a printable solid. Now, unlike Fusion, SolidWorks was able to open the file, and we was able to compute everything until splitting the cube, where, like Fusion, the count of facets would cause the program to freeze up and eventually crash. Again, the reason for crashes was the sheer size of the mesh.

- **Blender**
  This was the only software which was able to produce an output. The workflow is quite different from the other two. Firstly, import the mesh into the workspace. Now, to modify this mesh (extrude), it had to be converted to quads. After converting to quads, it was downscaled using the modifier tab and the un-subdivide

type in the decimate feature to reduce the facet count to a workable range of 50k, while still maintaining enough detail so that the size of individual faces doesn't exceed the axis resolution of the 3D printer. Finally, the mesh was closed by taking each side of the open mesh and covering with a plane, and an additional plane was added to the bottom to create a closed mesh. The file was finally exported as an .stl file, ready for printing.

3.4 3D Printing Process

The model was imported into Creality Print. It was scaled to match the footprint of a cube with a side of 11 cm. The configurations were adapted for Creality K1 Max, Hyper PLA filament and additions like skirt loops to ensure the print would be successful.
This is our final 3D Printed Model.

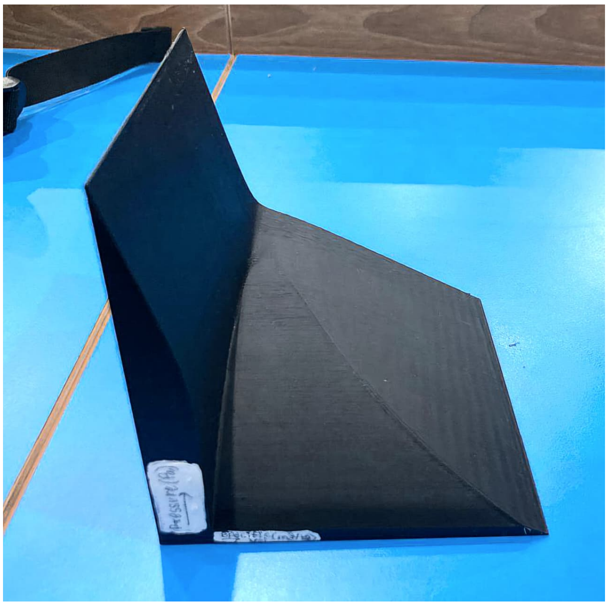

Figure 3: 3D Model

4 Engineering and Thermodynamics of R134a in ACs

4.1 Overview

The objective of the AC is to lower and maintain the temperature of a particular system. It operates on the vapour-compression refrigeration cycle (VCRC), in which the refrigerant R134a is the working fluid. The AC includes a compressor, condenser, expansion valve, and evaporator. The compressor compresses the vapor R134a, thus increasing its pressure and temperature. Now this high pressure, high-temperature vapor will enter the condenser. This cold condenser absorbs the heat from the vapor and cools it completely to a liquid state. The condenser is cooled by an external source. Now, this high-pressure, high-temperature liquid R134a enters the expansion valve, where the refrigerant undergoes expansion, thereby reducing its pressure and temperature. Now, a mixture of low-temperature, low-pressure liquid and vapor refrigerant enters the evaporator. The main cooling effect is produced in the evaporator. This very cold refrigerant absorbs all the heat present in the evaporator coils, converting itself into a low-pressure vapor while simultaneously cooling down the surrounding target region. Finally, this low pressure refrigerant enters the compressor, and the cycle continues.

4.2 Why R134a?

We chose R134a as the fluid we wanted to fabricate the model because we wanted to further analyse Air Conditioner systems due to our in-campus industrial visit. We picked R134a since it's commonly used in air conditioners, operates safely under moderate pressures, and has good efficiency. It's also non-flammable, stable, and sustainable, which made it a suitable choice for our project.

4.3 Thermodynamic Cycle Involved

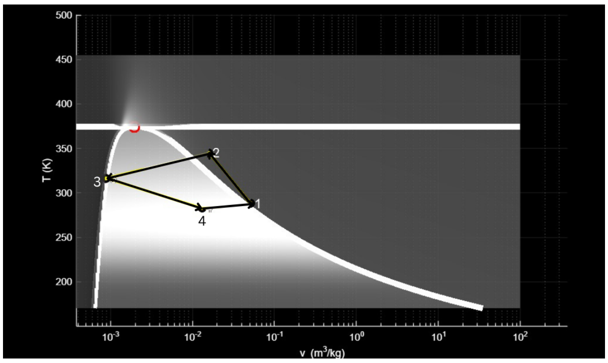

Figure 4: T vs v

Table 2: R134a Refrigeration Cycle Processes

Process	**Component**	**Description**	**Phase of R134a**
1–2	Compressor	Isentropic compression	Low-pressure superheated vapor → high-pressure superheated vapor
2–3	Condenser	Constant-pressure heat rejection	Superheated vapor → saturated liquid
3–4	Expansion Valve	Isenthalpic throttling	High-pressure saturated liquid → low-pressure liquid mixture
4–1	Evaporator	Constant-pressure heat absorption	Liquid-vapor mixture → superheated vapor

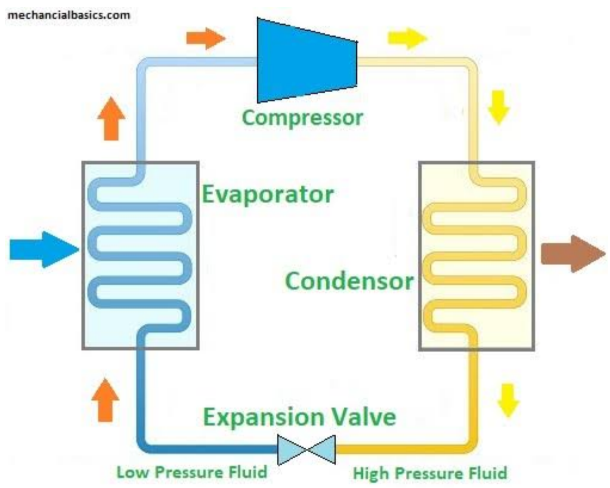

Figure 5: vapor compression cycle

Figure 4 demonstrates the working cycle of a refrigerant.

5 Integration of 3D Model with Application

5.1 Interpreting the 3D Model in the Context of the Application

Table 3: Thermodynamic states of R134a in the air-conditioning cycle.

Region	**Location on Model**	**Physical Meaning**	**Observation**
Subcooled liquid Phase	Left of the dome	Compressed or sub-cooled liquid	Steep slope, small v change causes large p rise
Superheated Vapor Phase	Right of the dome	Superheated vapor	Flatter surface, highly compressible
Saturated Liquid–Vapor Mixture	Inside dome	Saturation region	Constant p during phase change; mixture of liquid and vapor
Critical Point	Top of the dome	Liquid and vapor are indistinguishable	$T_c = 101°\text{C}$, $p_c = 4.06$ MPa
Triple Point	Low p–T corner	Solid–liquid–vapor co-existence	The boundary where solid R134a exists
Supercritical Region	Beyond the dome apex	Supercritical fluid	No distinct phases

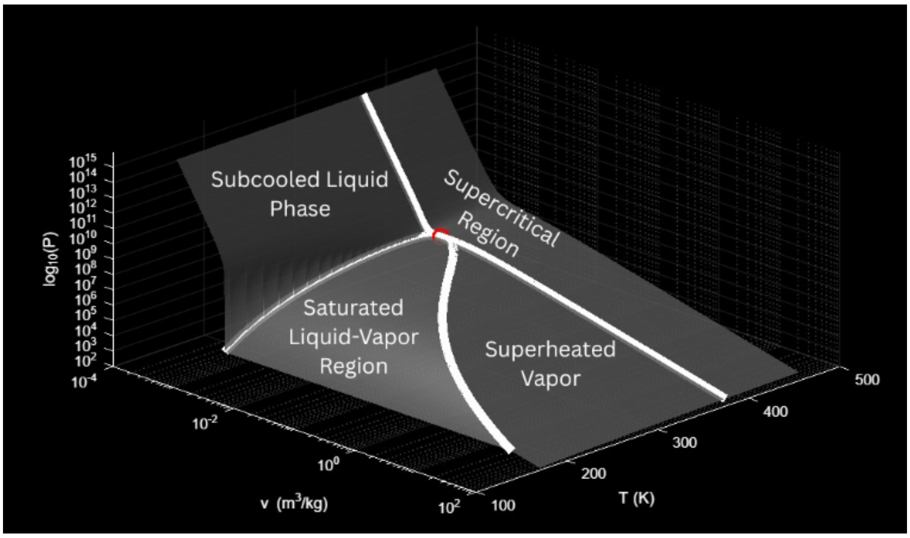

Figure 6: log(P)-v-T

6 Thermodynamic Analysis

To analyse the vapour-compression refrigeration cycle using R134a, the four major states of the system were identified: the compressor inlet, the compressor outlet, the condenser outlet, and the evaporator inlet. The corresponding temperature, pressure, and specific volume data were obtained from reference sources (the link to the reference source is attached), which represent typical operating conditions of an air conditioner. The thermodynamic properties (enthalpies) for these states were obtained from standard R134a property tables from the reference book given to us. The data were then used to compute the specific work, heat transfers, and coefficient of performance (COP) of the system.

6.1 Input Data

Table 4: Thermodynamic States of the R134a Refrigeration Cycle

State	Component	P (kPa)	T (°C)	Phase	v (m^3/kg)
1	Compressor inlet (Evaporator outlet)	411.6	14.782	Superheated vapor	0.051146
2	Compressor outlet (Condenser inlet)	1428.6	71.815	Superheated vapor	0.015822
3	Condenser outlet (before expansion)	1428.6	43.089	Subcooled liquid	0.00087999
4	Expansion valve outlet (Evaporator inlet)	411.6	9.782	Two-phase mixture (x = 0.2498)	0.049795

6.2 Property Evaluation Method

Table 5: Methods Used for Evaluating R134a States

State Type	Method Used	Equation / Description
Saturated or Two-phase	Saturation tables	$h = h_f + x(h_g - h_f)$
Superheated vapor	Superheated tables	Interpolated from tabulated $h(P, T)$ values
Subcooled liquid	Subcooled tables	Taken at given (P, T); minor effect of pressure
Expansion valve	Isenthalpic assumption	$h_3 = h_4$ (no work or heat exchange)

Thermodynamic properties at each state point were obtained using pressure–temperature inputs for the superheated vapour and liquid regions, and pressure–enthalpy inputs for the expansion valve outlet. Superheated properties (states 1 and 2) were evaluated at the specified pressure (P) and temperature (T). The condenser outlet (state 3) was set as a subcooled liquid with 9.90 K subcooling from the saturation temperature at 1.4286 MPa. The expansion process was treated as isenthalpic; therefore, h4 = h3. Quality at state 4 was calculated from saturated liquid and vapour enthalpies at the evaporator pressure. Compressor outlet properties (state 2) were obtained using isentropic compression, followed by the application of an isentropic efficiency of 0.70.

6.3 Enthalpy Data (from R134a Tables(Reference book))

Table 6: Enthalpy of R134a at Various States in the Refrigeration Cycle

State	Phase Region	Property Source	h (kJ/kg)	Remarks
1	Superheated vapor	Superheated table at 0.41 MPa, 14.78°C	208.77	Evaporator outlet
2	Superheated vapor	Isentropic compression from State 1 to 1.43 MPa, then $\eta_{\text{is}} = 0.70$ applied	246.682	Compressor outlet
3	Subcooled liquid	Subcooled liquid at 1.43 MPa, $T = T_{\text{sat}} - 9.90$ K	60.850	Condenser outlet
4	Two-phase mixture ($x = 0.2498$)	Isenthalpic expansion of State 3 at 0.41 MPa	60.850	Expansion valve outlet

The enthalpies were interpolated from R134a superheated and saturated tables. States 3 and State 4 share the same enthalpy as the expansion valve is an isenthalpic device. These enthalpy values serve as the basis for all subsequent energy and performance calculations.

Thermodynamic Relations

Table 7: Thermodynamic Parameters of the R134a Refrigeration Cycle

Parameter	Equation Used	Physical Meaning
Compressor work	$w_{\text{comp}} = h_2 - h_1$	Energy input to compress vapor
Refrigeration effect	$q_L = h_1 - h_4$	Heat absorbed in the evaporator
Heat rejected	$q_H = h_2 - h_3$	Heat is released in the condenser
Energy balance	$q_H - q_L = w_{\text{comp}}$	Verifies First Law of Thermodynamics
Coefficient of Performance	$\text{COP} = \dfrac{q_L}{w_{\text{comp}}}$	Cooling efficiency of the system

Table 8: Thermodynamic Parameters for R134a in the Heat Cycle

Parameter	Equation Used	Physical Meaning
Compressor work	$w_{comp} = h_2 - h_1$	Work input to compress vapor
Heating effect	$q_H = h_2 - h_3$	Heat delivered in condenser
Energy balance	$q_H - q_L = w_{comp}$	First law check
COP (heat cycle)	$COP_{HEAT} = q_H/w_{comp}$	Heating efficiency

These equations represent the energy interactions at each component of the cycle. They are derived from the First Law of Thermodynamics and relate enthalpy differences to heat and work transfers. The COP indicates how efficiently the air conditioner converts work into a cooling effect.

7 Engineering Analysis

Table 9: Calculated Thermodynamic Quantities for the R134a Refrigeration Cycle

Quantity	Expression	Result (kJ/kg)	Description
Compressor work (w_{comp})	$h_2 - h_1$	37.912	Energy input by the compressor
Refrigeration effect (q_L)	$h_1 - h_4$	147.92	Heat absorbed in the evaporator
Heat rejected (q_H)	$h_2 - h_3$	185.832	Heat is released in the condenser
Energy check	$q_H - q_L$	37.912	Matches w_{comp}
Coefficient of Performance (COP)	q_L/w_{comp}	**3.902**	Cooling efficiency

Table 10: Calculated Heating Performance Quantities for the R134a Heat Pump Cycle

Quantity	Expression	Result (kJ/kg)	Description
Compressor work (w_{comp})	$h_2 - h_1$	37.912	Energy input by the compressor
Heating effect (q_H)	$h_2 - h_3$	185.832	Useful heat delivered in the condenser
Energy check	$q_H - q_L$	37.912	Matches w_{comp}
Coefficient of Performance (Heat COP)	q_H/w_{comp}	**4.90**	Heating efficiency

8 Discussion and Observations

The evaporator inlet quality is $x_4 = 0.2498$, indicating a two-phase mixture entering the evaporator, which is acceptable for typical R134a systems, provided the evaporator fully evaporates the liquid before the compressor inlet. The compressor discharge temperature of 71.815 °C is within normal operating limits for R134a. The calculated COP of 3.902 falls within the expected range for a vapor compression cycle operating at these pressures. The energy balance is satisfied, as the difference between the condenser heat rejection and the refrigeration effect matches the compressor work input.

9 Conclusion

9.1 Summary

IN this project we generated the P(v,T) surface of R134a using MATLAB and Cantera and turned it into a 3D-printed model, which made the phase behaviour around the saturation dome much easier to understandd. Working on this helped us better understand how phase changes occur, how the vapour-compression refrigeration cycle operates, and why refrigerant properties are important in real engineering applications. Our thermodynamic analysis gave correct and realistic values , such as enthalpies, quality, and COP that matched expected trends and confirmed that our modelling approach was accurate. Overall we learned theory and working of air conditioner, simulation on matlab, and hands on fabrication, which gave us a clear and intuitive picture of how R134a actually behaves in cooling systems.

9.2 Learning Outcomes

This project provided insight into the behavior of pure substances near the phase-change region and how these properties are applied in real-world engineering systems, in this case, R134a and air conditioners. We gained practical experience in the following areas:

- Interpreting thermodynamic data for R134a.
- Understanding how theory connects with practical systems through modeling and calculation.
- Reading and using thermodynamic property tables accurately.

- Observing how R134a undergoes phase changes and how its pressure, temperature, and enthalpy vary.
- Using *Cantera* to visualize multi-variable relationships P(v,T).
- Learning the basics of *Blender*, which was used to convert the STL file to make it print-ready.
- Connecting theoretical thermodynamics with practical AC cycle design.

10 References

- Refrigerant Pressure Charts
- "Thermodynamics - An Engineering Approach | 9th Edition", Cengel and Boles, McGraw Hill Education (India) Private Ltd., 2011 (9th ed.)
- Cantera Documentation
- Science Direct
- Purdue Engineering

11 Acknowledgment

We sincerely thank Prof Atul Bhargav and Tarun Sir for their guidance and valuable advice throughout the project. Their assistance at every step enabled a smooth conduct of the project, which led to a great understanding of the topics.