Hogeschool van Arnhem en Nijmegen
HAN University of Applied Sciences

HAN Minor Project

Automotive Air-conditioning System

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SUMMARY

In this project, an air conditioning system for BMW 318i has been modelled for a given constant power input. This was achieved in the following manner:

- The differential equations for each automotive air conditioner component namely, compressor, condenser, expansion valve and evaporator were formulated.
- These equations were modelled using the MATLAB/SIMULINK tool and the temperature change of the refrigerant flowing through the system was investigated in detail.
- Individual graphs for each component were investigated for verification purposes.
- Once the model was verified, validation was done by sensitivity analysis. In this method, two variables namely 'number of passengers in the car' and 'volume of cabin' were varied and the behaviour was studied. The behaviour of the output graphs validated the modelled system.
- A study on various refrigerants was also conducted at the end, which provided a scope for future research by using a different refrigerant, having different thermodynamic properties.

The following goals were achieved after successful completion of this project:

- ✓ A better understanding of the functioning of an automotive air conditioning system.
- ✓ The designed system was found to be suitable for provided powertrain.
- ✓ Theoretical comparison of various refrigerants.

CONTENTS

1 INTRODUCTION

In the past century, cars for personal use exploded in popularity. Because of the exponential growth rate of technology, the standards for comfort of today's vehicles are very high. One of the most important factors for comfort inside an automobile's habitat is the temperature. Imagine a hot summer day, it does not matter if you are driving in Mexico City, London or Rio de Janeiro, most likely your car is equipped with a cooling system popularly known as A/C or air conditioning.

1.1 Background

The air conditioning technology refers to the process of modifying properties of the atmosphere, such as temperature and humidity, of an occupied space with the purpose of meeting the needs of the user. An air conditioning has two connected coils, the evaporator, which is placed inside the chamber that the user intends to cool, and the condenser which is placed outside. Inside the coils, there is a continuously flowing refrigerant. The working principle states that the evaporator should be kept colder than the room and the condenser hotter than the surroundings. The continuously flowing fluid will absorb heat from the cabin with the help of the evaporator coil and the condenser will release that heat to the exterior. To increase the pressure of the refrigerant, a compressor is used. The temperature at the condenser outlet will be far higher than that of the atmosphere; therefore this gas being passed through the condenser will release heat. During this heat exchanging phase the gas will be condensed into a liquid. At the output of the condenser, an expansion valve is added to control the flow of the refrigerant, therefore regulating the pressure of the fluid. This drop in pressure causes part of the refrigerant liquid to be evaporated. For this evaporation to take place, some energy should be supplied to the process. This energy comes from the refrigerant in the form of heat. Consequently, the refrigerant's temperature drops. This is how the cold refrigerant that runs in the evaporator is obtained. Air from the cabin passing through the evaporator coil will give away heat converting all the refrigerant to vapor. This vapor is the initial input of the compressor, completing the functioning cycle of this system. Modern systems are also equipped with particle filters.

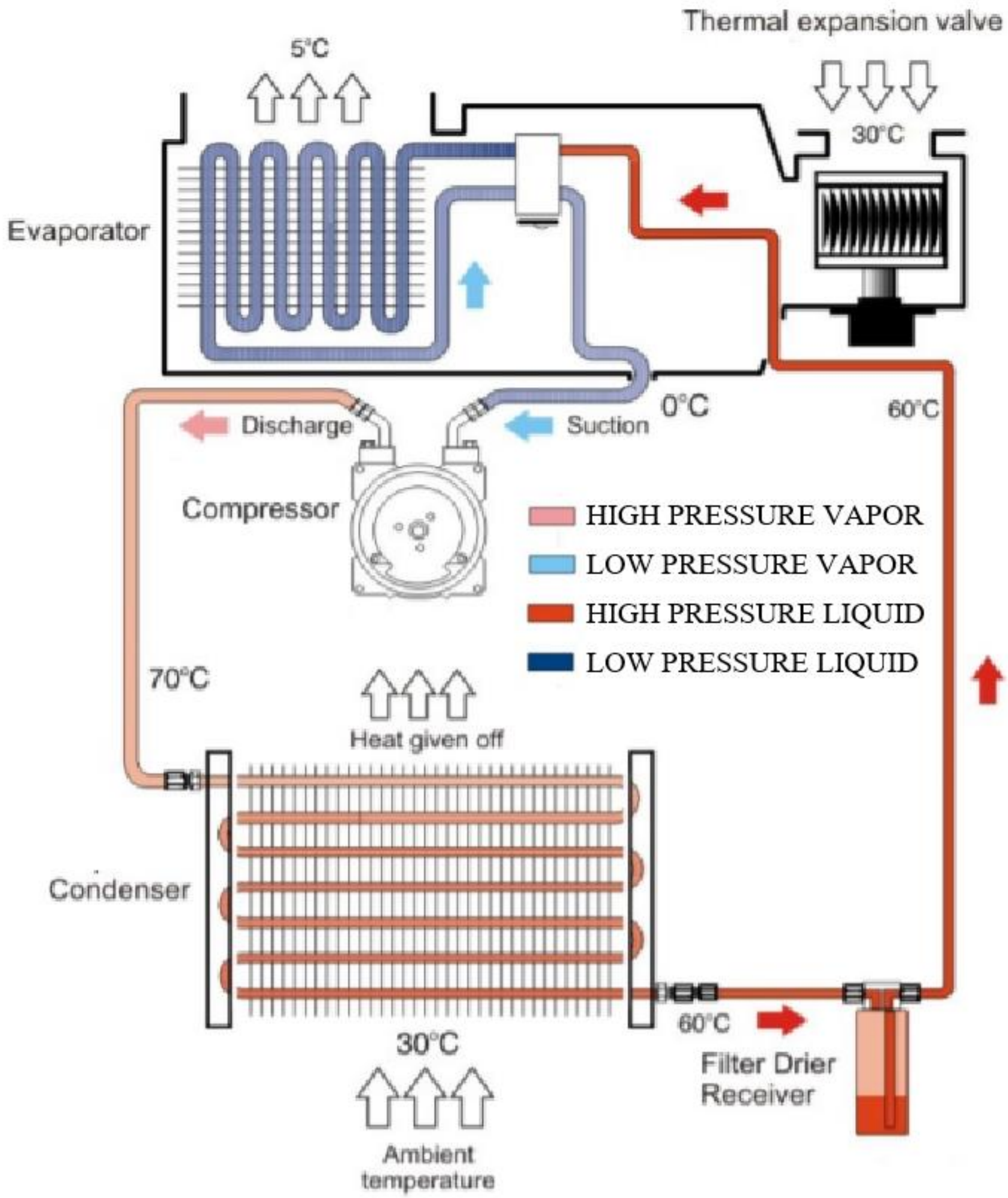

Figure 1.1 General layout of an air conditioning cycle (Ariazone)

1.2 Problem definition

- To understand the functioning of the entire process, it is required to create a working simulink model of the air conditioning system.
- Verify if the designed system is suitable for the provided powertrain.
- Theoretical comparison for the refrigerant is to be performed.

1.3 Objectives

Goals of control:

- The main goal of the process is for the temperature inside the cabin to be kept constant at a set point;

Process output:

- Temperature inside the cabin (Thermocouple) [°C].

Control inputs:

- Power supplied to the compressor (from the motor) [W].

Major disturbances:

- Temperature outside the cabin of the vehicle [°C].

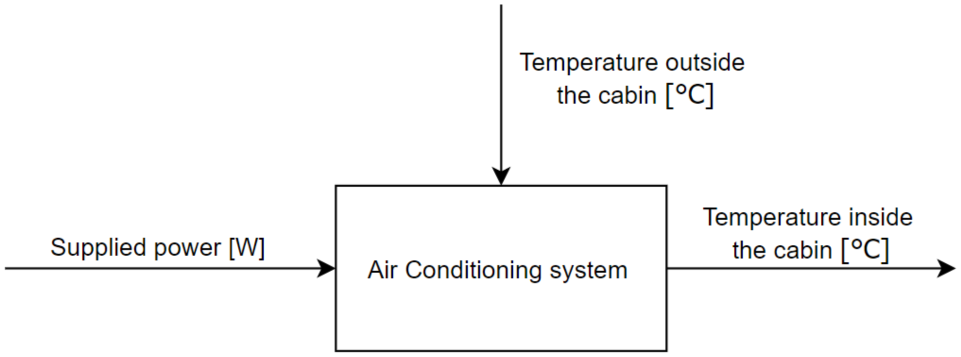

Figure 1.2 White box model of the process

1.4 Approach

For a comprehensive model the whole process must be divided in smaller sub-processes, the relationships between these sub-processes must be identified and the energy storages must be recognized. Energy is stored in the form of heat in the refrigerant and this heat is later released outside with the help of the condenser.

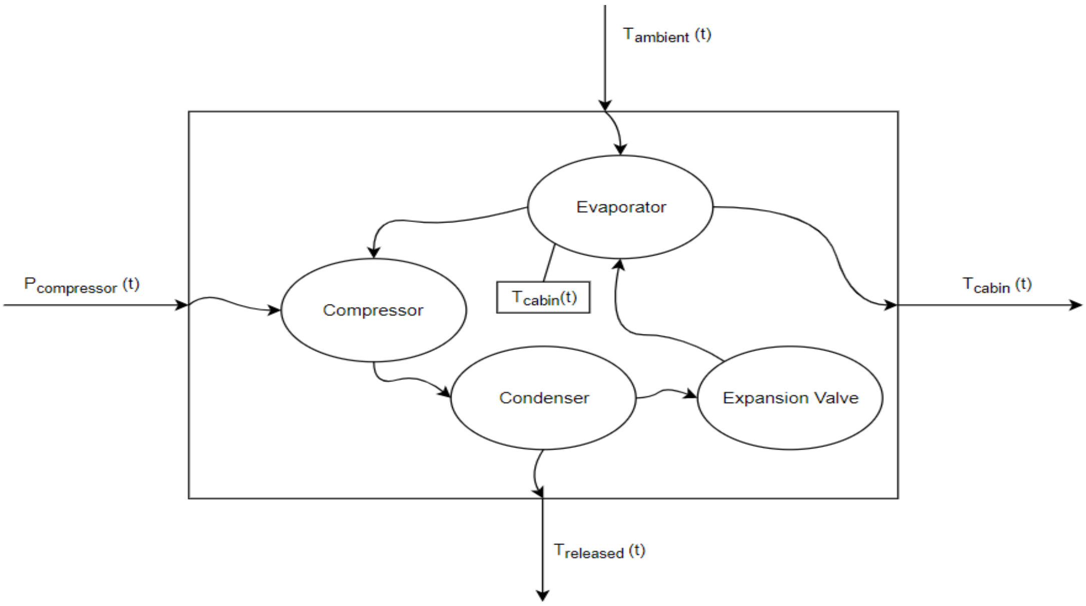

Figure 1.3 Data flow diagram of the process

1.5 Literature survey

Various papers were referred in order to provide the required information to successfully formulate a model.

The air-conditioning system posed many complications during its early stage where the work of S. Arul Selvan and P. Seethalakshmi from Anna University Tiruchirapalli(Subramaniyan & Pandian, 2010) were of great help. This paper discusses the development of a state space model for an air-conditioning system in a steady as well as a transient mode. This publication aided in deciding the key variables and assumptions required for the cabin, compressor and the evaporator. The authors set their main goal to attain stable fuel economy without compromising passenger comfort which was very close the goals set for this minor project. Hence most of the control variables and equations were of great help in formulating the primary differential equations for each component in the air-conditioning system.

The work of Tibor Kiss and Lawrence Chaney, "A new automotive air-conditioning system simulation tool developed in MATLAB/Simulink" presented a great understanding on the auxiliary load the air-conditioning system has on a vehicle's engine. This facilitated our project as we were working on optimising an AAC model for a downsized engine and analysing the system's efficiency and cooling capabilities. This publication also was of great help as the authors had also used the same modelling software to model the AAC(Kiss, Chaney, & Meyer, 2013).

The refrigerant used was R134a (1,1,1,2-tetrafluoroethane) and all of its thermodynamic properties were taken from the work of M.L. Huber and M.O. McLinden from the National Institute of Standards and Technology. Their work gave a proper understanding of processes the refrigerant goes through during the refrigeration cycle and the phase changes before and at the end of each of those processes(Huber & McLinden, 1992).

The AAC diagnostics manual from Nissens Cooling solutions was referred to make sure that the results produced were meaningful. It listed all of the temperature and pressure characteristics for each process and component. The manual also presented us with the safe operating conditions of the components in an AAC.

2 METHODS

The main tool that was used for the development of this project is MATLAB Simulink from MathWorks. MATLAB is a programming platform widely used in the engineering industry. The heart of MATLAB is the MATLAB language, a language based on matrixes that allows a natural way of computing mathematics. Simulink is a matlab based graphical programming environment designed for modelling, simulation and analysis of multiple system domains.

All the values for all the variables were declared in the matlab environment for them to be later imported to the simulink blocks. The block used in simulink are basic mathematic blocks like multiplication, summing, integration, gain and for another method of modelling we used the transfer function block. In order to visualise the results, the scope block was used which acts as a virtual osciloscope. The matlab command 'plot' gave freedom of representing the results in any required manner.

2.1 Description of research design

After the literature survey was done, it has been decided to use the equations presented in point 3.2 in order to build an accurate model of the system. After the powertrain specifications were offered by the project supervisor, parameters for compressor and all the other components and type of refrigerant were established based on the research papers. Following this step, the differential equations were built and a transfer function model was also derived. Both of these models were obtained with the help of MATLAB Simulink. The comparison between the models was done. Interpretation of the results was later accomplished, validated and verified.

2.2 Justification of research design

All the components were modelled using the concept of energy balance because in order to accomplish the main focus of this project – cooling the cabin to a certain set point- it is only required to analyse the evolution of temperature over time. Temperature is another way to measure the amount of heat contained by a substance (in this case refrigerant and air inside cabin). Heat is a form of energy therefore it has been considered that energy balance strategy is the best for this project.

Refrigerant R134a was chosen because of its cooling performances, cost efficiency and widespread use in the automotive industry and based on the fact that documentation is widely available for it. The differential equations model was built because that it is the first step in determining the transfer function of a system. The transfer function is a very useful modelling technique because it is very easy to analyse a system just by looking at its transfer function. Since the transfer function is derived from the differential equations, a comparison between the two models is crucial to verify that the systems have the same behaviour.

Validation of the system with the help of the sensitivity analysis was done because there is no physical model available and by interpretation of the results from set sensitivity analysis a clear conclusion can be drawn in regards to the correct behaviour of the system.

Verification is another tool for increasing the confidence in the systems result. Verification is done changing by changing the input of the system and interpreting the results.

3 RESULTS

On a successful run of the Simulink model, meaningful results were observed. Graphs were plotted for every major component to study the performance in detail at the end of each process.

3.1 Figures

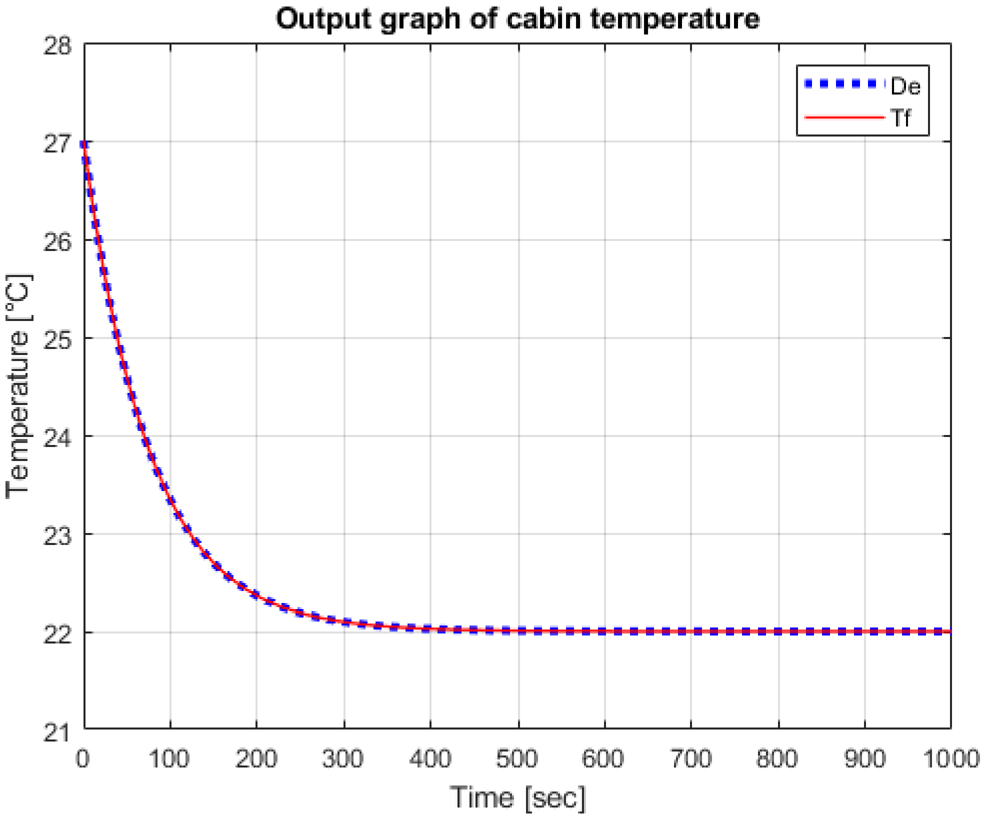

Figure 3.1 Cabin temprature

Figure 3.1 shows that the air-conditioning system has gradually lowered the temperature of air inside the cabin from an initial value of 27.3°C to around 22°C which is considered to be the most comfortable temperature for humans. And the time taken to reach the cooling temprature approximately takes 4–5 minutes.

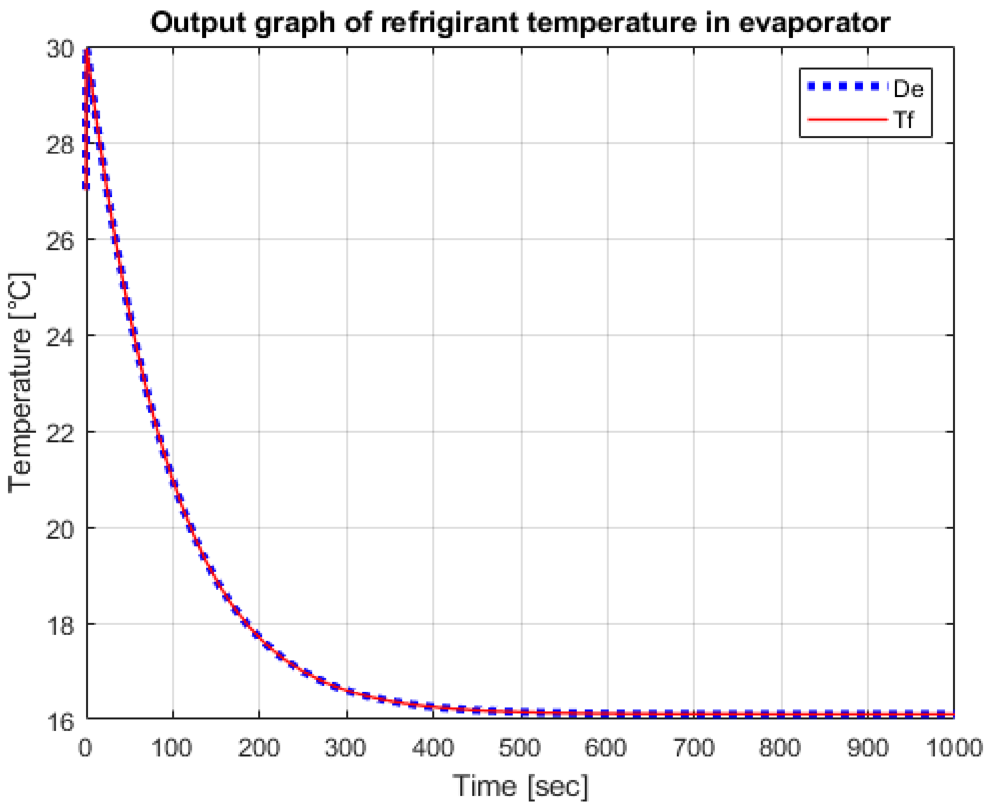

Figure 3.2 Evaporator output

Figure 3.2 It is here that the liquid refrigerant is expanded and evaporated. It acts as a heat exchanger that transfers heat from the substance being cooled so there is temprature drop to 16°C.

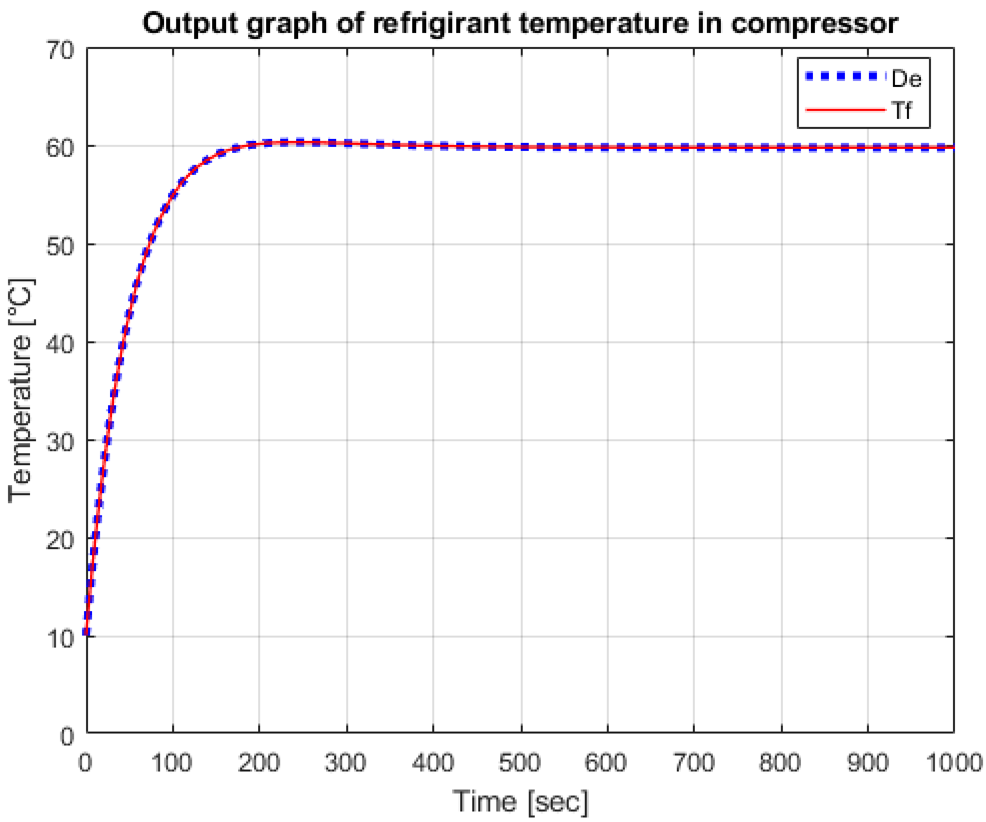

Figure 3.3 Compressor output

Figure 3.3 The compressor increases the pressure, and corresponding saturation temperature (boiling point) of the refrigerant vapor to high enough level so the refrigerant can condense by rejecting its heat through the condenser, it can be seen that the temprature is increased upto 60°C.

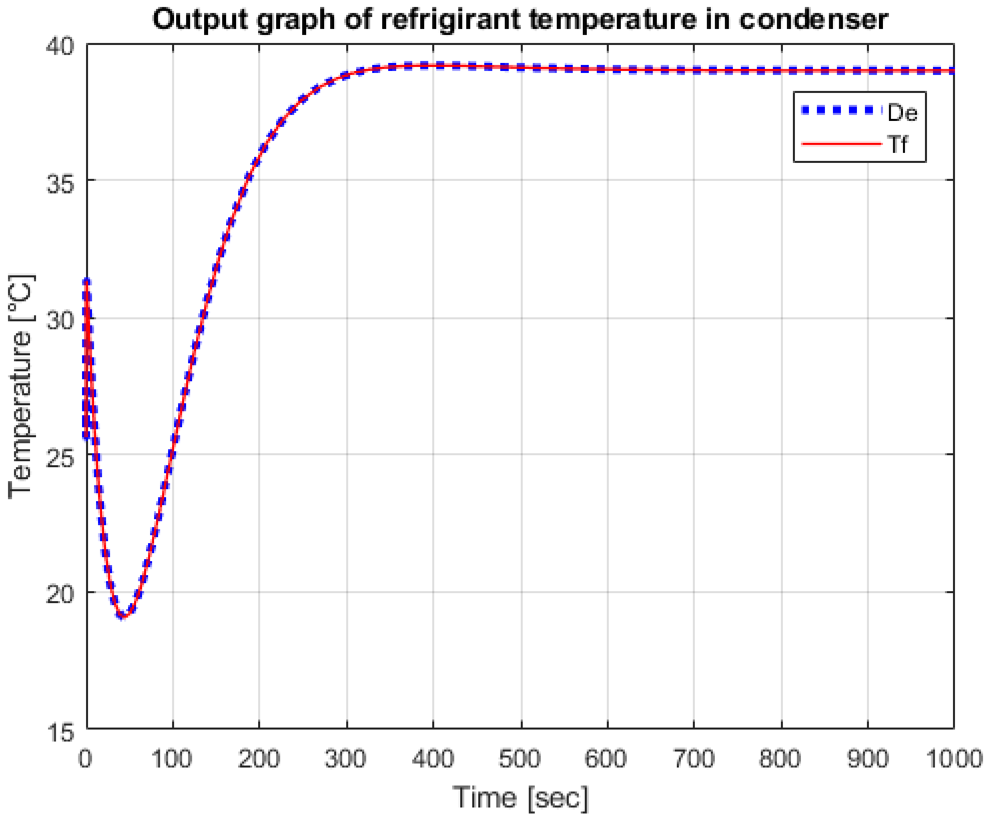

Figure 3.4 Condernser output

Figure 3.4 In a cooling cycle of a refrigeration system, heat is absorbed by the vapor refrigerant in the evaporator followed by the compression of the refrigerant by the compressor. The high pressure and high temperature state of the vapor refrigerant is then converted to liquid at the condenser. It is designed to condense effectively the compressed refrigerant vapor. The temperature is increased from 15 degrees to approximately 48°C after 8.3 minutes.

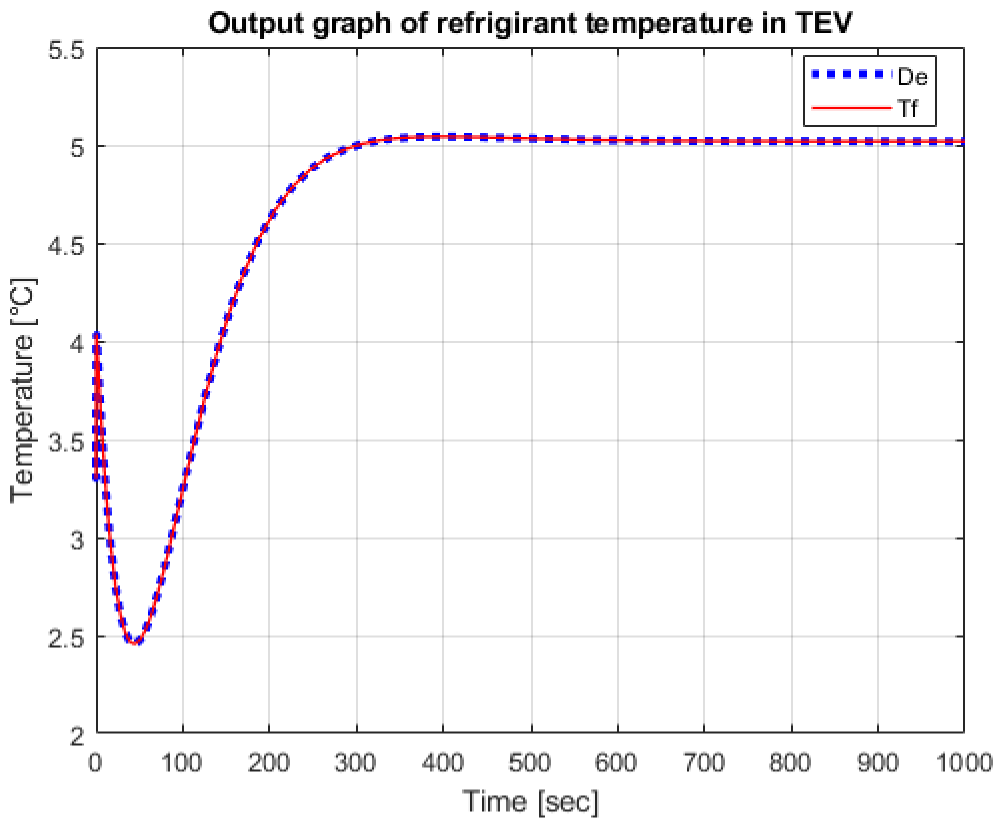

Figure 3.5 Thermal expansion valve output

The expansion valve removes pressure from the liquid refrigerant to allow expansion or change of state from a liquid to a vapor in the evaporator. The high-pressure liquid refrigerant entering the expansion valve is quite warm. In *figure 3.5*, the graph shows a drop suggesting temperature drop compared to condenser temperature due to expansion. The temperature drops from 40°C to 5.8°C.

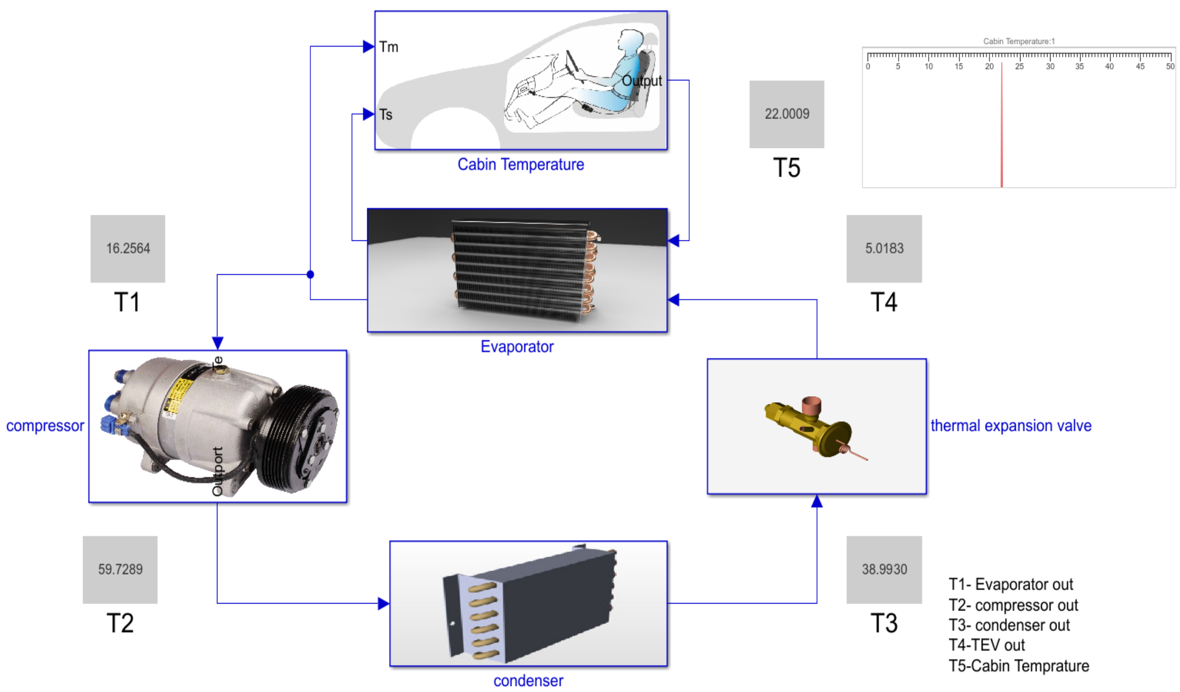

Figure 3.6 Simulink block showing the temprature across the components

3.2 Equations

Cabin:

- The heat exchanged by the cabin with the exterior is given by:

$$M_r C_{pr}\frac{dT_r}{dt} = -C_{pe}\rho f(T_m - T_s) + Q_s + Q_{ps} + U_0 A_0(T_a - T_r) + m_f C_{pa}(T_a - T_r) + K_{spl} f \quad [1]$$

- Energy balance of air inside cabin is offered by:

$$M_r h_{fg}\frac{dW_r}{dt} = -\rho f h_{fg}(W_m - W_s) + M_f h_{fg}(W_a - W_r) + Q_{pl} \quad [2]$$

Evaporator:

- Energy balance for the dry part of the evaporator is described by:

$$C_p\rho V_{h1}\frac{dT_d}{dt} = C_p\rho f(T_m - T_d) + \alpha_1 A_1\left(T_w - \frac{T_m+T_d}{2}\right) \quad [3]$$

- Energy balance of refrigerant inside evaporator:

$$\rho f C_{pm}\frac{dT_m}{dt} = m_f C_{pa}T_a + (\rho f - m_f)C_{pm}T_r + T_m m_f C_{pm} \quad [4]$$

- Energy balance and enthalpy balance for the wet part of the evaporator is expressed by:

$$C_p\rho V_{h2}\frac{dT_s}{dt} = C_p\rho f(T_d - T_s) + \rho f h_{fg}(W_m - W_g) + \alpha_2 A_2\left(T_w - \frac{T_d-T_s}{2}\right) \quad [5]$$

- Energy balance equation for the heat absorbed by evaporator wall is:

$$(C_p\rho V)_w\frac{dT_w}{dt} = \alpha_1 A_1\left(\frac{T_m+T_d}{2} - T_w\right) + \alpha_2 A_2\left(\frac{T_d+T_s}{2} - T_w\right) - M_{ref}(h_{r2} - h_{r1}) \quad [6]$$

Compressor:

- Mass flow rate of refrigerant into evaporator is characterised by:

$$M_{ref} = n\frac{\pi}{4}D_c^2 S_p N_c\frac{\eta v}{v_s} \quad [7]$$

- Energy balance in the compressor:

$$M_{ref}C_{prf}\frac{dT_1}{dt} = T_{in}M_{in}C_{prf} - T_{out}M_{out}C_{prf} \quad [8]$$

Condenser:

- Energy balance for the cold part of the condenser is described by:

$$C_p\rho V_{h1}\frac{dT_d}{dt} = C_p\rho f(T_m - T_d) + \alpha_1 A_1\left(T_w - \frac{T_m+T_d}{2}\right) \quad [9]$$

- Energy balance of refrigerant inside condenser:

$$\rho f C_{pm}\frac{dT_m}{dt} = m_f C_{pa}T_a + (\rho f - m_f)C_{pm}T_r \quad [10]$$

- Energy balance and enthalpy balance for the wet part of the condenser is expressed by:

$$C_p\rho V_{h2}\frac{dT_s}{dt} = C_p\rho f(T_d - T_s) + \rho f h_{fg}(W_m - W_g) + \alpha_2 A_2\left(T_w - \frac{T_d-T_s}{2}\right) \quad [11]$$

- Energy balance equation for the heat given by evaporator wall is:

$$(C_p\rho V)_w\frac{dT_w}{dt} = \alpha_1 A_1\left(\frac{T_m+T_d}{2} - T_w\right) + \alpha_2 A_2\left(\frac{T_d+T_s}{2} - T_w\right) - M_{ref}(h_{r2} - h_{r1}) \quad [12]$$

Expansion valve

- Energy balance equation for the expansion valve:

$$T_{in}M_{fv}C_{pv} - T_{out}M_{fl}C_{pl} = 0 \quad [13]$$

3.3 Tables

Parameter	Description	Value	Units
T_r	Temp inside the vehicle cabin	22.15	ºC
T_m	Temp of the mixture air to the evaporator inlet	16.26	ºC
T_a	Temp of the ambient air	27	ºC
T_s	Temp of the supply air to the vehicle cabin	16.6	ºC
T_d	Air temp leaving the dry-cooling region (or) superheated region of the evaporator core cooling coil	15.5	ºC
T_w	Evaporator surface (or) Evaporator wall temperature	6.3	ºC
M_r	Mass of the air inside the vehicle cabin	9	kg
m_f	Mass flow rate of infiltration and/or ventilation air	0.01	kg/s
C_{pr}	Specific heat at constant pressure at room	1.008	kJ/kg K
C_{pe}	Specific heat at constant pressure at evaporator	1.366	kJ/kg K
C_c	Specific heat at constant pressure at interior mass (or) core	1.33	kJ/kg K
C_{pa} ,C_{pm}	Specific heat at constant pressure at ambient and mixing point before evaporator	1.366	kJ/kg K KW
	Heat load of solar radiation		
Q_{ps}	Sensible heat load of passenger	70	KW
U_o	Overall heat transfer co-efficient of vehicle cabin wall	4	W/ m² K
A_o	Surface of the vehicle cabin	30	m²
K_{spl}	Heat gain co-efficient of supply fan	1.1	KJ/ m³
f	Volumetric air flow rate in m³/s h_{im} - Convective heat transfer coefficient between interior mass and cabin air	0.15	KW/ m² K
ρ	Density of the moisture air	1.2	kg/ m³
V_{h1}	Air side volume of the evaporator core in dry-cooling region	0.004	m³
α_1	Heat transfer coefficient between air and evaporator wall in dry cooling region	0.125	KW/ m² ºC
A_1	Heat transfer area of the evaporator core (or) cooling coil in dry – cooling region	3.265	m²
V_{h2}	Air side volume of the evaporator core in wetcooling region	0.016	m³
W_m	Moisture content of the mixture air to the evaporator inlet	0.0113	kg/ kg-
α_2	Heat transfer coefficient between air and evaporator wall in wet-cooling region	0.027	KW/ m² ºC
A_2	Heat transfer area of the evaporator core (or) cooling coil in wet – cooling region	0.53	m²
h_{fg}	Latent heat of vaporization of water	2450	kJ/kg
V	Volume of the vehicle cabin	8	m³
M_{ref}	Mass flow rate of refrigerant into evaporator core	110	kg/s
h_{r1}	Enthalpy of refrigerant at the evaporator core (or) cooling coil inlet	393.8	kJ/kg
h_{r2}	Enthalpy of refrigerant at the evaporator core (or) cooling coil outlet	233.5	kJ/kg
W_r	Moisture content of the air inside the vehicle cabin - dry air	0.009	kg/ kg
Q_{pl}	Heat load due to solar radiation	50	KW

Table 3.1 - Parameter Description

3.4 Model Validation

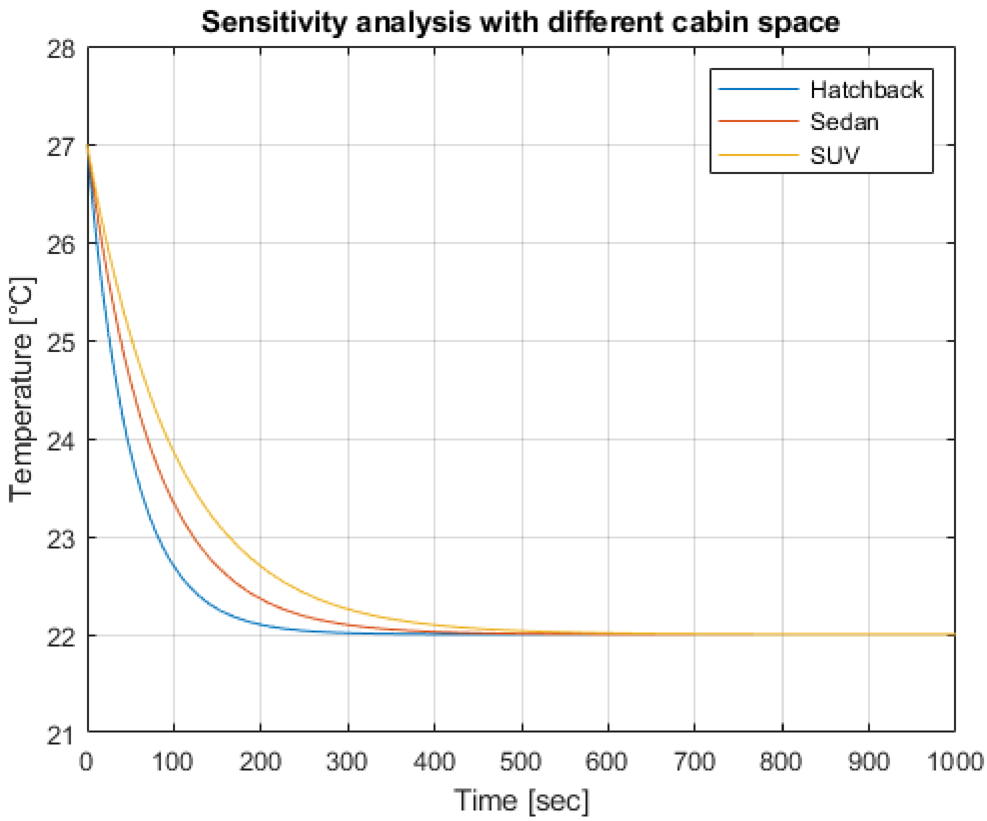

Figure 3.7 Comparison of cabin temperature for different car models

Figure 3.7 shows that different models have been considered, a Hatchback, sedan and an SUV and tested the model with same parameters, as the mass of the air (cabin space is assumed to be proportional) is increased, the AC takes more time to cool the cabin and it can be clearly seen that hatch back which is smaller in size cools down faster than the actual model and an comparatively larger SUV which takes long time to cool.

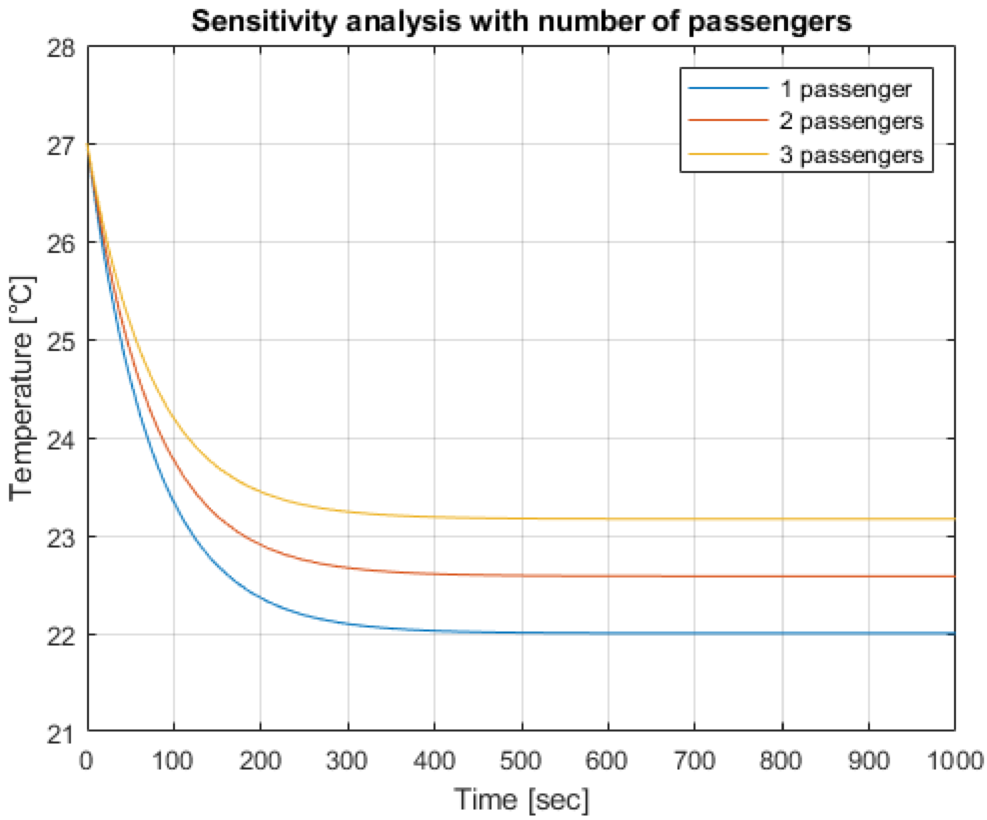

Figure 3.8 Comparison for cabin temperature for different number of passengers

In *figure 3.8* 'N' denotes the number of passengers in the car. As the number of passengers were increased, the AC takes more time to cool the car. If there are 2 or more passengers, the final cabin temperature value does not reach the desired value of approximately 22^{o}C. This suggests that the power input to the compressor is suitable for the AC to work efficiently, only for two passengers. In order to make it efficient for four passengers, the power input to the compressor needs to be increased.

Verification of the system was performed by providing the system with different inputs. The behaviour is as expected since, when a lower power is provided to the compressor, it results in a slower cooling process for all the components. Similarly, an increase in power to the compressor leads to an increased rate of cooling. condensor and thermal expansion valve show temprature drops for increase in power leading to increased cooling rate in evaporator. This effect on each component is shown from *figures 3.9-3.12*.

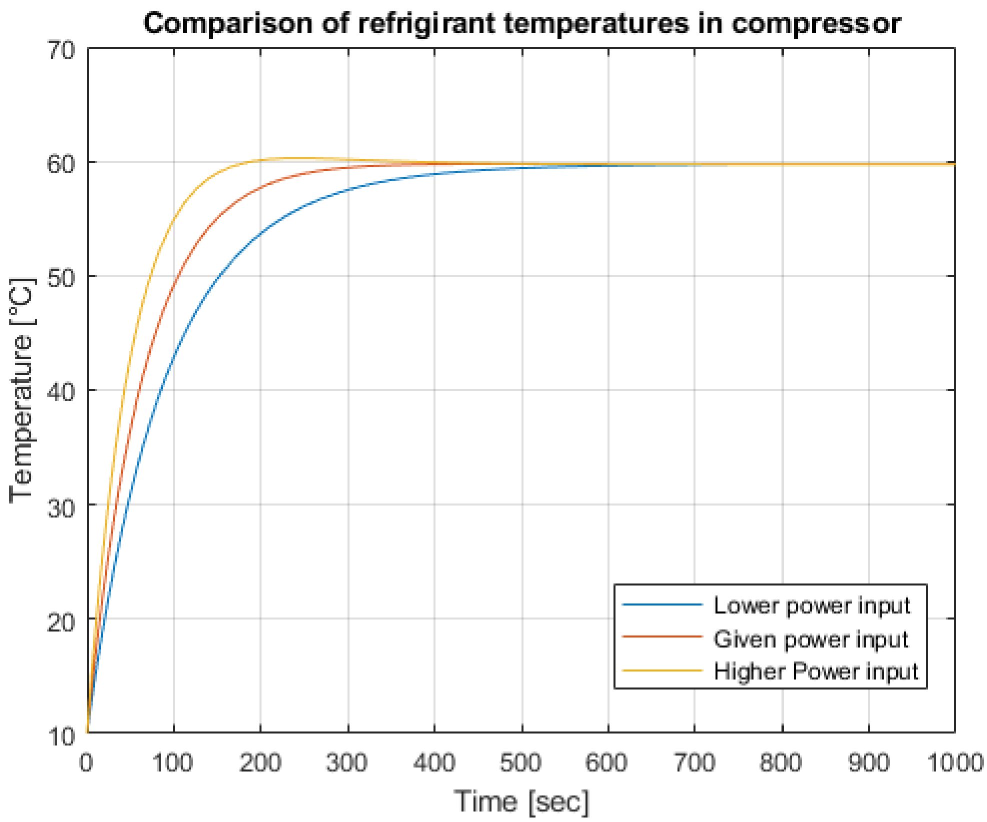

Figure 3.9 – Comparison of compressor temperature with respect to different power inputs

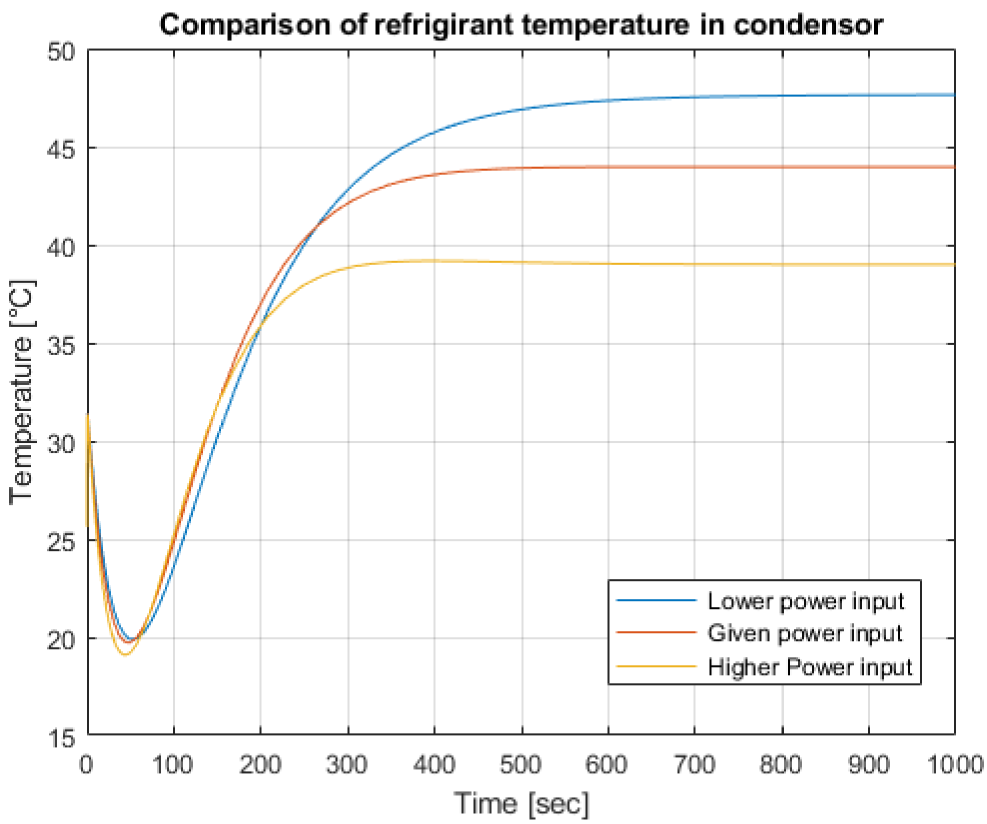

Figure 3.10 - Comparison of condenser temperature with respect to different power inputs

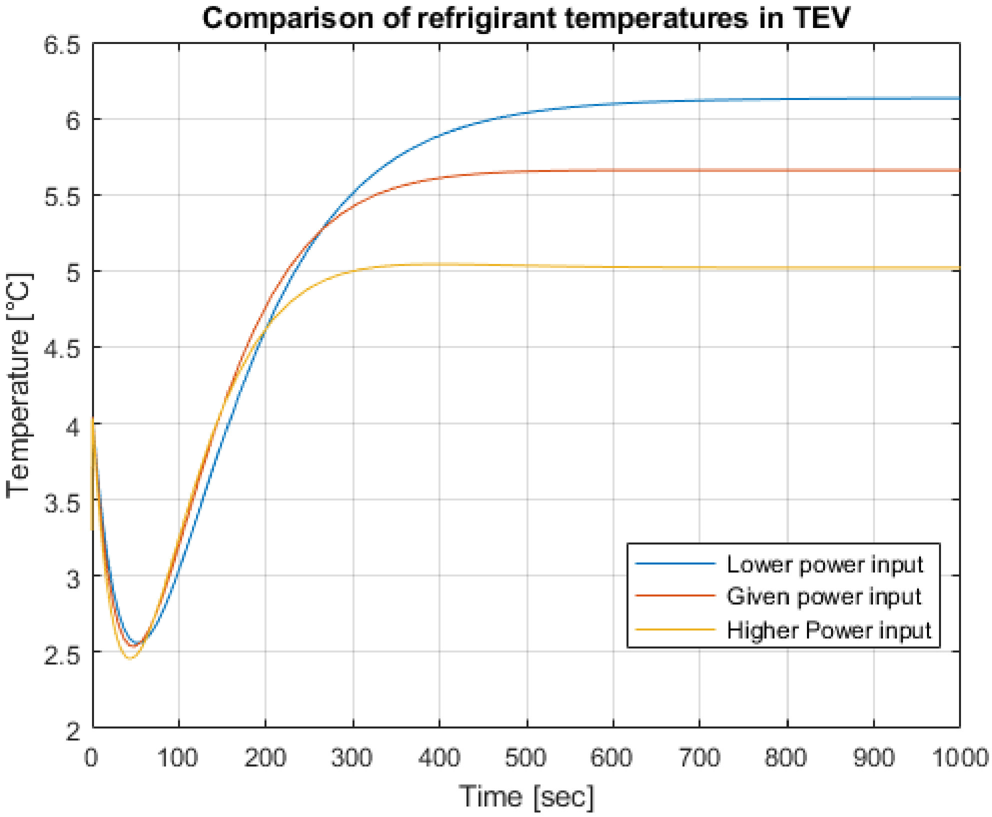

Figure 3.11 - Comparison of TEV temperature with respect to different power inputs

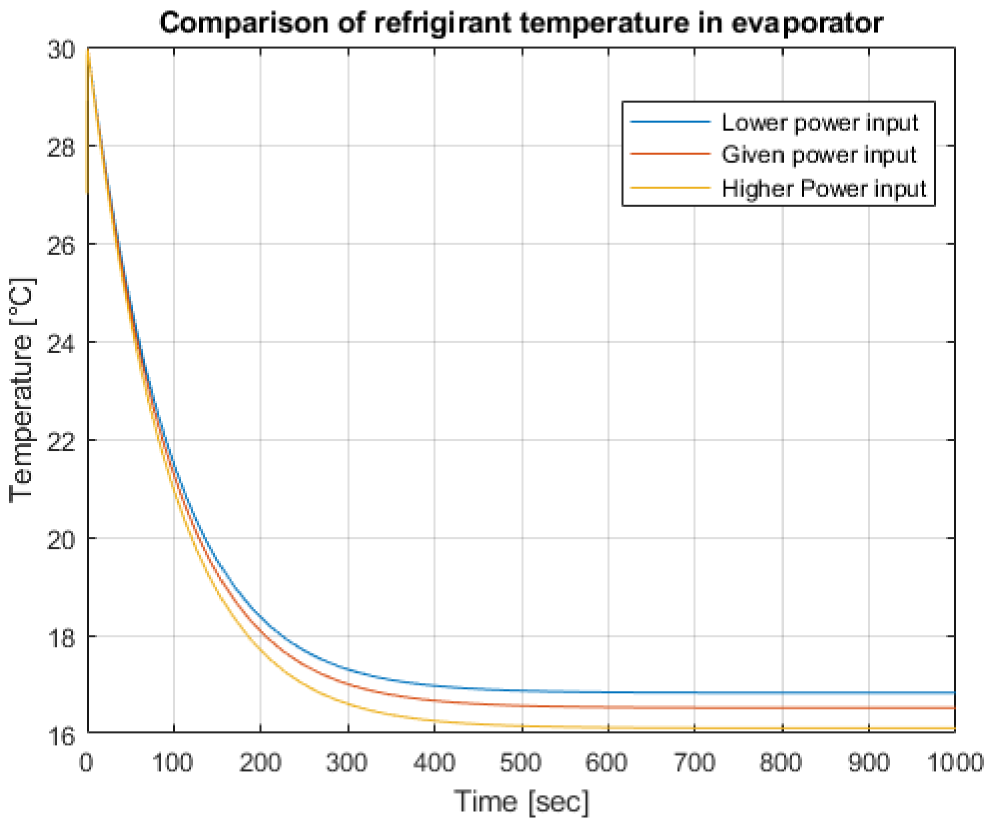

Figure 3.12 - Comparison of evaporator emperature with respect to different power inputs

4 CONCLUSION

The objective of the current study was to develop an air conditioning system for the provided power train of BMW 3 series 2009 318i. The main goal of maintaining the temperature inside the cabin constant at a certain set point has been achieved in a satisfying time period by the designed model. The model includes the cabin and every component of an air conditioning system except the air filter by using energy balance equations. As modelling techniques, differential equations method and transfer functions were used. In order to analyze the results, the models were compared based on the temperature inside the cabin. The validation of the model was done by using sensitivity analysis. The usage of the widely known refrigerant - R134a gives confidence in the results.

Validation of the model was performed by changing few parameters of the system while verification of the system was performed by varying the input of the system, which is power supply to the compressor. The interpretation of these results assures the proper functionality of the system even further.

The widely known principle of conservation of energy which states that energy cannot be created or destroyed, rather it can only be transformed or transferred, was used in deriving the governing differential equations since that is the fastest way to reach the goal of the project, control of temperature.

The developed model will be useful for designing a controller for the air conditioning system of the 2009 version of the BMW 3 series 318i in order to obtain even better results and improving comfort inside the cabin or making the system more energy efficient.

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Appendix A General report conventions

Comparative study of refrigerants

The following conclusions were made from a reference research paper [6]

Refrigerant	Discharge Temp. T_{2n} (°C)	Pressure Ratio	COP	Refrigerating Effect RE (kJ/kg)	Compressor Work W (kW)
R290	103.4	3.245	2.499	266.8	1.601
R600a	92.96	3.787	2.64	251.4	1.515
R407C	119.8	3.844	2.36	152.6	1.695
R410A	122.8	3.44	2.256	152.9	1.773
R404A	100.7	3.411	2.185	104.2	1.831
R134a	105.7	3.954	2.562	141.8	1.561
R152a	119.7	3.923	2.668	233.8	1.499
R1234yf	88.7	3.658	2.4	61.64	1.667

Table 2. Calculated thermodynamic data of R134a and its alternatives

Thermodynamic properties of different alternative refrigerants i.e. R290, R600a, R407C, R410A, R404A, R152a and R1234yf are compared to R134a which is used in AAC system. R290 and R600a cannot be substituted in AAC system due to its high flammability issue. From thermodynamic property analysis it is clear that R407C, R410A and R404A has very high saturation pressure so it cannot be used in an AAC system. R152a can be substituted of R134a if and only if safety mitigations are provided. From thermodynamic cycle analysis, it is derived that R1234yf has 6.3% lower COP compared to R134a; however, it is best suitable alternative refrigerants as a drop in substitute of R134a AAC system and can be substituted in the existing AAC system with minimum modification.