Identify and Define Air-Conditioning Parameters Affecting Fuel Economy and Validation on Actual Vehicle

A THESIS

SUBMITTED IN THE FULFILLMENT OF THE REQUIREMENTS
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in
Thermal Engineering

by

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Under the Guidance of

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July 18, 2019

Certificate

I, **Yash Hiteshbhai Vaid** hereby Certified that the thesis entitled "**Identify and Define Air-Conditioning Parameters Affecting Fuel Economy and Validation on Actual Vehicle**" was carried out at the **HVAC Department, ERC-Tata Motors Ltd., Pune** for the award of degree of Master of Engineering in Thermal Engineering, under the guidance of **Dr. S. K. Mohapatra, Senior Professor, Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala** and **Mr. Dwijendra Mani, General Manager, HVAC Department, ERC-Tata Motors Ltd., Pune**. The matter presented in this thesis has not been submitted either partially or fully to any other University or Institution for the award of any other degree to the best of my knowledge.

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It is certified that the above statement made by the student is correct to the best of my/our knowledge and brief.

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Abstract

Due to limited fuel resources, strict emission norms, and to fight with the present threat of global warming, devising techniques to improve the fuel economy in automobiles is need of the hour. Also, the establishment of new automobile industries is increasing more competition among the industries and because of this reason manufacturer wants to deliver pioneering products with the best quality and value to their customers. In addition, air conditioning is critical system as it is second most energy consuming unit in vehicle. The role of HVAC system in vehicle is to balance variation of cabin loads for maintaining thermal comfort for passengers. Efficient design of new HVAC systems and considerable improvement in existing systems can lead reduction of total energy consumption and greenhouse gas emissions in large scales.

This research works has two main purpose: (1) to identify the relation between air-conditioning parameters & the fuel economy of automobile application and (2) Improvement in fuel economy of existing HVAC system. An intelligible model has propounded for the vehicle HVAC parameters and validated on actual vehicle. The proposed model can be employed for calculating vehicle thermal load and sizing of HVAC system component. Graphic user interface (GUI) model has built using MATLAB. The mathematical equation used for developing the model is based on basic principles of heat transfer, fluid mechanics and thermodynamics, etc. The results of the model can be integrated into conventional design work flow and can predict design parameters in early stage of design.

To reduce energy consumption in air-conditioning, one of the possible ways is improvement the heat transfer. The second part presents reduced fuel consumption by some modification in existing system. The prototype vehicle is tested on Pune highway. The results show enhancement in heat transfer and reduction of refrigerant pressure in condenser.

Keywords : HVAC, Heat Transfer, Automobile

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Acronyms

ASHARE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AC	Air-Conditioning
CLF	Cooling Load Factor
CLTD	Cooling Load Temperature Differential
DTM	Deep Thermal Mass
EV	Electrical Vehicle
GUI	Graphical User Interface
HBM	Heat Balance Method
HV	Hybrid Vehicle
HVAC	Heating, Ventilation and Air-Conditioning
RTS	Radiant Time Series
SCL	Solar Cooling Load
TETD	Total Equivalent Temperature Differential
TFM	Transfer Function Method
TXV	Thermal Expansion Valve
VCR	Vapor Compression Refrigeration

Symbols

Greek letters

α_s	Absorptivity of surface
α	Altitude angle, *degrees*
δ	Declination angle, *degrees*
ρ	Density, kg/m^3
ω	Hour angle, *degrees*
θ	Incidence angle, *degrees*
ϕ	Latitude angle, *degrees*
ξ_L	Leakage losses
ρ_g	Reflectivity of ground surface
Φ	Relative humidity, %
ψ	Solar azimuth angle, *degrees*
γ	Surface azimuth angle, *degrees*
λ	Thichness of surface, m
β	Tilt angle, *degrees*
ν	Specific Volume, m^3/kg
τ	Transmissivity
η_v	Volumetric efficiency, %
θ_z	Zenith angle, *degrees*

Nomenclature

A	Area, m^2
c	Specific heat, J/kgK
cc/rev	Cubic capacity per revolution, cm^3/rev
D	Diameter, m

e	Enthalpy, J/kgK
h	convective heat transfer coefficient, W/m^2K
H	Height of person, m
$\dot{I}$	Incidence solar radiation, W/m^2
k	Thermal conductivity, W/mK
L	Stroke, m
m	Mass, kg
$\dot{m}$	Mass flow rate, kg/s
M	Metabolic heat production rate, W/m^2
N	Revolution per minute, rpm
P	Air pressure, kPa
P_s	Water saturation pressure, kPa
$\dot{Q}$	Heat transfer rate, W
S	Surface area, m^2
t	Time, sec
T	Temperature, $^\circ C$
U	Overall heat transfer coefficient, W/m^2K
$\vee$	Volume, m^3
$\dot{\vee}$	Volume flow rate, m^3/m
V	Velocity of vehicle, m/s
W	Weight of person, kg

Subscripts

act	Actual
amb	Ambient
$comp$	Compressor
dif	Diffuse

dir	Direct
Du	Dubois
eng	Engine
exh	Exhaust
$grad$	Glass radiation
met	Metabolic
r	Refrigerant
ref	Reflected
$srad$	Sheet metal radiation
th	Theoretical
ven	Ventilation

Chapter 1

Introduction

1.1 Energy Outlook

There is a strong link between human progress and energy consumption; energy cries is one of the biggest challenges of our time is a dual one: the need to meet rising energy demand while at the same time reducing carbon emissions. The emissions-reduction side of this dual challenge will mean shifting to a lower-carbon energy system, as the world seeks to move to a pathway consistent with meeting the environmental goals. The aim of any manufacturing industry is to deliver their customers economical products within environmental norms. Wherefore, the government have been planed energy efficiency strategies to save . One of those sectors which consume significant portion of energy is automobile manufacturing industry. In addition, air conditioning is critical system as it is second most energy consuming unit in vehicle.The function of HVAC system is to balance variation of cabin loads so as to maintain passenger comfort within the “Thermal comfort” zone. ”Thermal comfort is that condition of mind that expresses satisfaction with the thermal environment” (ASHRAE 1992) [1].

Furthermore, The minister of road, transport and highway had announced air conditioner cabins are mandatory for commercial vehicle. Driver fatigue is believed to be one of the main causes of road accidents, air-conditioned cabin are expected to improve driver comfort, reduce fatigue and ensure good visibility. Now, another factor is fuel consumption. As, air-conditioner takes power from engine will increase fuel consumption. Fuel consumption is a concern for both energy security and environmental reason. So, we have to make energy efficient HVAC system for automobile application.

1.2 Automobile HVAC system

In ancient time, the transportation system embarked with horse drawn carriage. Nicolas Joseph Cugnot, a French engineer has developed the first self-propelled automobile. The automobile cabin were open to atmosphere in early days, where occupants had to adapt their clothes according to weather conditions. Heating, ventilation and air-conditioning has been introduced to meet customer requirement. Clay bricks or fuel are used to produce heating effect inside vehicle compartment. Ventilation has been achieved by window, vents or bulkhead by which we can not get desired mass flow rate as it has only been depended on vehicle speed. Cooling has done by evaporative cooling in which the water would evaporate after absorbing heat for hot air. Main restraint for this cooling is it will be possible only if air entering in cabin have low humidity. Packard had introduced the first mechanical automobile air-conditioning system working on closed cycle in 1939. After second world-war Cadillac had given significant improvement in A/C system and at last Nash-Kelvinator had suggested firm and affordable air-conditioning system for vehicle.

1.2.1 Classification of HVAC system

The whole heating, ventilation and air-conditioning system can be classified based on zone. For example, there may be different condition, due to clothing passengers may feel hot and driver wants cooling. So, occupants can control their respective zones based on requirements. HVAC system can classified based on zones as follows:

- **Dash HVAC** : Dash system is consist of single zone which is to be installed in dashboard. The main benefit of the system is that it is impelling cold air on occupant and giving more cooling and heating effect.

- **Boot HVAC** : HVAC system is installed in available boot space at the back of rear seat. The main drawback of the system is of boot space and the cooling is less efficient than dash HVAC.

- **Dual HVAC** : This system is very popular in case of multi passenger vehicles. This system is installed in dashboard and extended to rear end of vehicle. It allows driver and passenger to set their zone control according to desire.

1.2.2 Heat exchanger

Heater

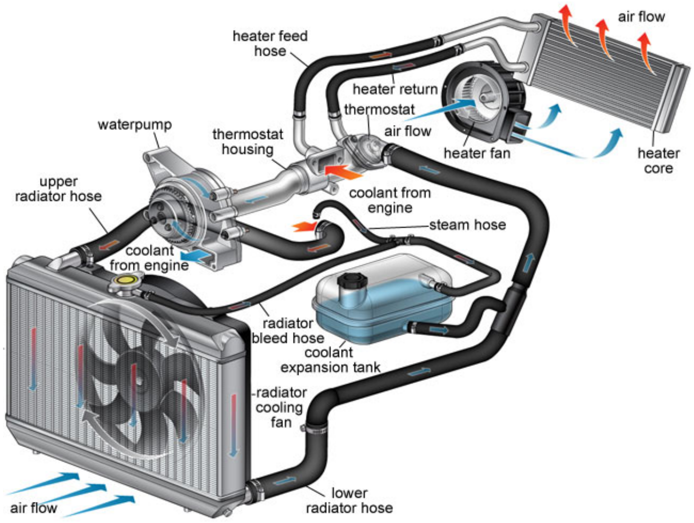


Figure 1.1: Heating system for gasoline vehicle

Heat is the form of energy which can transfer from one form to another form but cannot be destroyed. The heater heats the fresh air or the air which is already in the cabin. The heated air is then directed to various place of cabin through ducts. The air can be heated using different ways say exhaust heat transfer, electrical heater, combustion heat, etc. Generally vehicle used combustion heat for heating purpose that is heat coming out from engine through air or water depending upon engine cooling system i.e. water cooled or air cooled. In petrol/diesel vehicle the heating system is shown in figure 1.1. In case of gasoline vehicles engine exhaust heat work as a source of heat, but in electrical vehicle has not this source so it use general power for heating cabin air. Electrical heater is used in conventional system which is consume more power and decrease driving range. So, heat pump is one of the sole solution as it is work as heating and cooling device. It uses temperature gradient between refrigerant and atmospheric air, prevailing a heating effect without consuming electricity and give heating effect with less power consumption. The heat pump working principle is shown in figure 1.2.

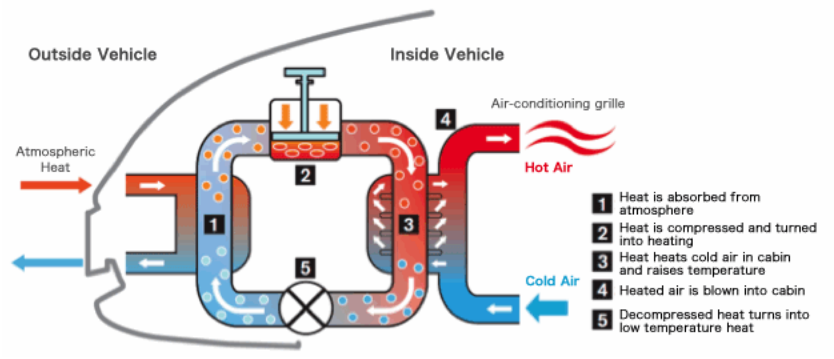


Figure 1.2: Heat pump working principle

Condenser

The condenser is used for dissipating heat absorbed by the refrigerant to atmosphere. The refrigerant at high pressure and high temperature at vapor state enters in the condenser at the top and converts into subcooled liquid which leave from bottom of the condenser. The constraints for the condenser design is; it should be efficient to remove heat from the refrigerant and compactness.

When refrigerant absorbs heat from cabin air and converts in vapor state; to complete the cycle, there must be some device to dissipate that heat from refrigerant and again transfer it into liquid state. The relationship of pressure-temperature is used to accomplish this requirement. Therefore, pressure of refrigerant is increased which increase condensation temperature, then at atmospheric temperature refrigerant will convert in liquid state. The condenser is located at the front of the vehicle so that it can get strong ambient air flow. When vehicle is running in high speed there will be no cooling problem of refrigerant but when vehicle is on idling or at low speed there will requirement of forced convection and this requirement is fulfilled by using single and double fan system. There are mainly two type of condenser; liquid cooled condenser and air-cooled condenser used depending upon application.

Figure 1.3: Condenser

Evaporator

The evaporator has similar construction as of condenser as shown in figure 1.4 and is located inside the vehicle. The evaporator serves as the heat absorption component. The main function of evaporator is to remove heat from the inside of your vehicle and a secondary benefit is dehumidification as on humid days, there is water dripping from the bottom of your vehicle.

The refrigerant coming through expansion/fixed orifice in low pressure and low temperature liquid state is entering at the bottom of the evaporator. Heat from the air flowing through surface of the evaporator is absorbs by refrigerant. The heat is transferred from air to refrigerant where refrigerant reaches its saturation point after that it also absorb some amount of heat and become superheated. The superheated refrigerant will flow through compressor or accumulator in case of thermostatic expansion valve system or fixed orifice valve respectively. The evaporator can be classified on mode of convection say natural convection and forced convection by using fan depending upon the comfort requirement by occupants.

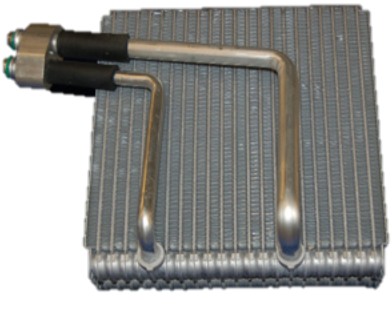


Figure 1.4: Evaporator

1.2.3 Flow Machines

Compressor

The compressor is heart of the HVAC system, it compresses the refrigerant and circulate superheated refrigerant vapor inside the closed loop of HVAC system. The constraint parameters for compressor are refrigerating effect, space available, size and weight of compressor, rotational speed, etc; with these constraint manufacturer select the appropriate compressor. The compressor can be driven by giving mechanical power or electrical power. In case of mechanical power, it is driven by engine driven pulley system as shown in figure 1.5. There is magnetic clutch at the front of compressor which engage and disengage the compressor with engine according to requirement. The refrigerant is drawn by compressor at its suction side from accumulator (i.e. in case of fixed orifice) or evaporator (i.e. in case of filter-drier-receiver). The main precaution is that compressor can only compress the refrigerant in vapor state, any moisture and dirt in refrigerant can damage the compressor. The compressor is mainly classify in three categories:

1. Positive displacement (Reciprocating - swash plate)
2. Rotary-vane
3. Oscillating-scroll type

Figure 1.5: Compressor

Apart from this, there is variable capacity compressor which can vary mass flow rate of refrigerant according to requirement of cooling capacity. The cooling capacity is estimated by sensing refrigerant pressure coming out from evaporator. The electrically driven compressor, which is known as electrical compressor; is used in electrical or hybrid vehicle. In case of hybrid vehicle there is a small engine and electric motor and motor gets powered from battery. So, compressor is engaged with motor. On other side, there is no engine in electric vehicle and battery is charged by fuel cell which works on electrolysis process. The battery provides power to electric motor, which is engaged with electrical compressor.

Blower

A device used to direct the air flow in the vehicle cabin is known as ventilator. Ventilation system in the vehicle classify in two categories:

1. **Natural flow ventilator** : There is positive and negative pressure gradient on the surface of vehicle cabin due to aerodynamic shape of vehicle and by using that manufacturer provide vent. Wherever there is positive pressure gradient those are the ideal places to provide inlet air vent and from negative pressure gradient air can go outside. The main disbenefit of this system are:
    - sometimes the area where vents are located should be sealed for safety purpose as well as comfort purpose
    - The flow rate of air is directly proportional to speed of vehicle which results in less ventilation in case of low speed and undue draughts and noise in case of high speed of vehicle.
2. **Forced flow ventilator** : In this type of ventilation , blower is used for assisting natural ventilation and directs air. Blowers are generally used at low vehicle speed when there is high comfort demand. The function of blower is to force the air over the heating and cooling heat exchanger and distribute the air inside the cabin. Generally, the position of inlet and outlet vent is same as in case of natural ventilation. The position of blower and different modes of HVAC system are shown in figure 1.6.

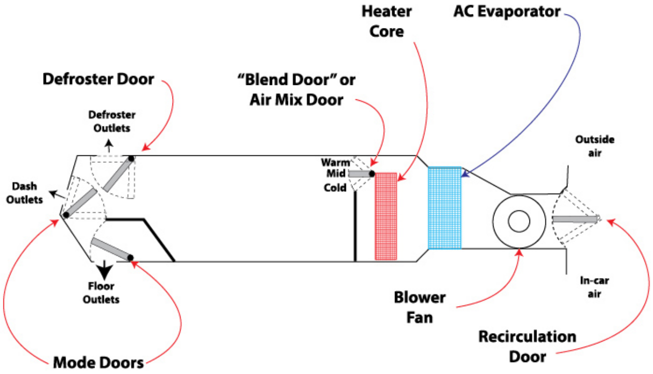


Figure 1.6: Forced ventilation working principle

Pump

Electric vehicle contains large batteries to store the energy. The performance of battery has a strong relation with temperature of cells; while during charging and discharging there is heat generation. The generated heat should be dissipated in such a way that can maintain cell temperature and which indirectly improve life of battery. Battery cooling system is used for maintaining the temperature of the battery cells in which another requirement is circulation of sufficient flow rate of coolant. The pump is used to circulate coolant throughout the system. The commonly used pump in vehicle is centrifugal pump and in order to accurately select the pump, the input parameters are required flow rate, total head, piping geometry, etc. There are three types of pressure drop in pump:

1. Pipe pressure drop
2. Pipe fitting pressure drop
3. Equipment pressure drop

Figure 1.7: Coolant circulating pump

1.2.4 Expansion valve/Fixed orifice valve

There is requirement of device which can control amount of refrigerant flowing through evaporator based on required cooling effect. So, the function of this device is as follow:

- To make partition between high pressure side and low pressure side of the HVAC system
- To measure refrigerant flow rate entering to evaporator
- To ensure that refrigerant exiting from evaporator is in superheated state so that there will no damage in compressor

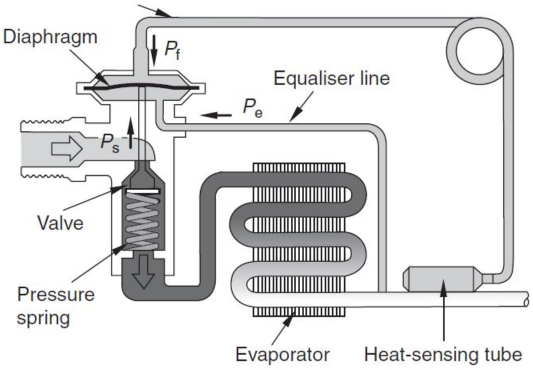


Figure 1.8: Thermostatic expansion valve

There are two devices used for this purpose and depending upon this device we use filter-drier-receiver and accumulator; if system is consist of expansion valve then there will be filter-drier-receiver and if fixed or variable orifice valve then accumulator is used to fulfill functional requirements. The expansion valve in figure 1.8, opens and closes to control the flow of refrigerant into evaporator and the valve is operated by a diaphragm that is connected to a thermal bulb via a capillary tube and diaphragm give response according to change in outlet temperature of evaporator. Figure 1.9 shows an orifice tube, the small brass tube which is enclosed in nylon sleeve that mesh filters of prevent small particles of dirt clogging the orifice. It is located at the end of liquid line where it connects to evaporator inlet. The main advantage of orifice tube is it's inexpensive so that it can be replaced any time.

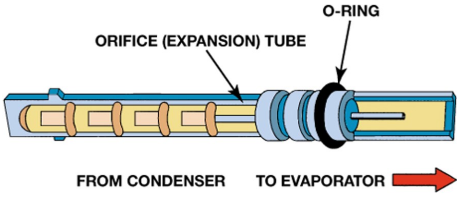


Figure 1.9: Fixed orifice valve

1.2.5 Auxiliary equipment

Condenser fan

The chief requirement of condenser fan is to enhance rate of heat transfer with aid of forced convection and to keep condenser cool so that condenser can cool refrigerant effectively. The condenser fan is driven by battery or electric motor and there are various speeds on which condenser fan can operate. Fans are classified in two types say axial fan and centrifugal fan. In case of axial fan the direction of air in and out are parallel to axis of rotation. However, in case of centrifugal fan air is drawn in on direction of rotation and forced out on perpendicular the direction of rotation which is also the direction of centrifugal force. The fan can also be classified in pull type and push type depending upon it's location.

Receiver-drier & Accumulator

The receiver-drier is also known as filter-receiver-drier (FDR) bottle; is used when the system involved thermostatic expansion valve(TXV). The receiver-drier bottle is placed between the condenser and the thermostatic expansion valve as shown in figure 1.10. The role of receiver-drier in HVAC system is as follow:

- To remove moisture/vapor particles from the refrigerant and ensure that only liquid refrigerant can flow through thermal expansion valve.

- To work as a reservoir as to supply refrigerant when there is more cooling required and to store refrigerant in case of sufficient cooling of cabin.
- To annihilate gunk which can produce undue wear or premature failure of components

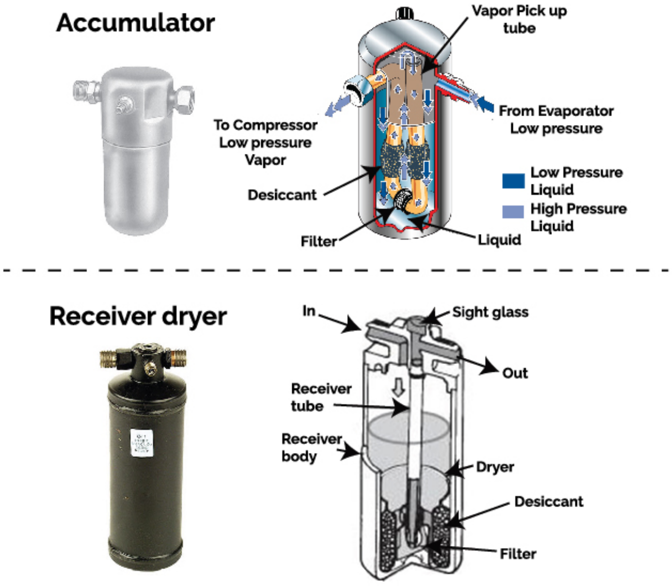


Figure 1.10: Receiver-drier & Accumulator

Accumulator as shown in figure 1.10 is used in the case when there is fixed orifice valve(FOV) instead of thermostatic expansion valve. The accumulator is positioned between the evaporator and the compressor. Desiccant bag contains a chemical that absorbs water. The function of accumulator is as follow:

- To prevent refrigerant particles in liquid state entering to compressor
- To filter the refrigerant & make it free from dirt and also help to overcome premature failure of components
- To supply lubricating oil to compressor
- To annihilate moisture from the refrigerant.

Air-filtration

The one of the objectives of HVAC system is to purify the cabin air for better comfort of occupant. The air filter is located before heat exchanger as shown in figure 1.11. The filter consist of fibers which avert large particulates entering the cabin and also trap small particulates and due to electrostatic charging filter attracts particulates like magnet. The filter remove visible particles as well as dust, pollen and spores etc. entering to cabin space. There are different type of filters say pollen filter, carbon filter, photo catalytic filter, etc.

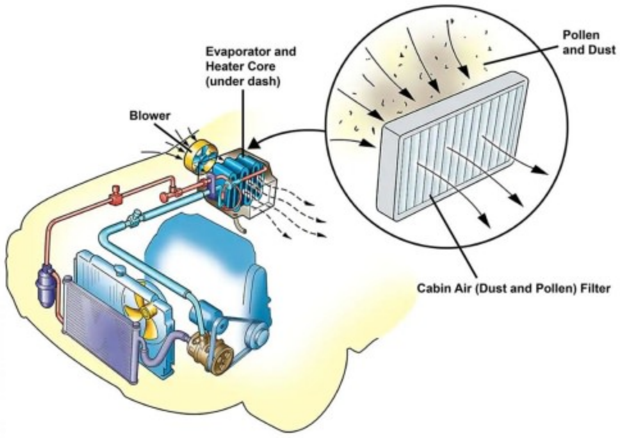


Figure 1.11: Air filter in vehicle

Air-diffuser system

The evenly distribution of air gives occupants effective comfort also eliminate high drift felt by occupants at front seat, which can be achieved by using air-diffuser. There are different type of diffusers according to the application; linear diffuser which provide consistency, mini flow used for quiet delivery with low air velocity, gentle flow air jets and super-flow air jets, etc.

Air & Refrigerant distribution unit

The main function of air-distribution unit in vehicle is to convey specified rate of air flow inside the cabin with minimizing objectionable noise and it should be economical. The air-distribution system generally placed inside the dashboard system of the vehicle and consist of ducts and different mixing/directing doors. The unit houses blower, evaporator, heater core and different sensors, etc. Air flow rate are determined by the help of thermal load with constraints that location of fan and vents are already fixed. Also the design of duct should be integrated and optimum considering all pressure losses. There are some thumb rules for designing the ducts like, air velocity should be in permissible limit otherwise there will be noise issues and less friction in duct material,etc. The distribution unit are classified in low pressure system, medium pressure system and high pressure system. There are mainly two mode of ventilation: 1) Fresh air mode (atmospheric air) 2) Re-circulation mode (inside air). Re-circulation mode prevents unpleasant outside odor entering in cabin and improve air-conditioning efficiency but on other side it will increase humidity of air which can lead fogging on window. So, after some duration there is requirement of fresh air inside the cabin.

There is hose-pipe assembly for circulating the refrigerant through out the circuit which mainly consist of 3 lines; liquid line, suction line and discharge line. The liquid line carries high pressure liquid refrigerant from condenser to evaporator and receiver-drier, orifice tube or expansion valve are in series within liquid line circuit. The liquid line has the smallest diameter of all these three lines. The suction line connects the outlet of the evaporator to compressor suction port and it has largest diameter as it carries low pressure vapor. If HVAC system use orifice tube for refrigerant metering, there will be accumulator in series with suction line. The discharge line carries high pressure vapor from the compressor to condenser; it is larger than the liquid line but smaller than the suction line.

1.3 Need analysis

There are many different projects turn around the optimization and excellent tuning of the HVAC system of an automobile such that there is a upbeat reflection in the form of improved fuel efficiency in the vehicle. Also, HVAC performance in case of commercial vehicle very crucial part at the time of vehicle development.

1.3.1 Need of proposed research

The following areas were identified and a thorough analysis was done and the analysis is presented as follows:

- **Alternative cooling system** : Researchers have been trying to go for alternatives to cool the cabin by using different energy and methods. They use vehicle recovered energy, solar energy, fuel cell energy and electrical energy with different work-actuated and heat-actuated cooling system. But, all the ideas are at premature stage. Also, it will need lots of modification and packaging issues.
- **Different alternative refrigerant**: This idea is not much feasible as it requires so many changes in system and another problem is that, the cost of new equipment. So for increasing fuel economy it will increase the cost of system.
- **Auxiliary thermal load**: An investigation was done for lighting and equipment load in cabin. The objective was to reduce those load which had low usage. This idea cannot implemented as automobile makers generally tend to avoid depriving their customers of in cabin facilities.
- **Optimizing HVAC parameters**: There are so many HVAC parameters which affect the fuel economy. Now, it is feasible idea in term of both cost and does not interfere the needs of the customer. So, we have to develop mathematical model which gives information about how they affects the fuel economy and optimize that parameters by that intelligent algorithm. Mainly parameters are classified in two division as follows:

  - **Uncontrollable parameter**: It is unfeasible to change these parameters however these parameters affects the fuel economy. The parameters are ambient temperature, pressure and humidity, wind velocity, cabin geometry, Engine rpm, road condition etc.
  - **Controllable parameter**: These are the parameters which can control for user convenience. The parameters are metal & glass properties, flow rate, compressor selection, Air change rate, soak temperature etc.

Thus, it can be concluded that by identifying HVAC parameters at early stage of vehicle development and optimizing them, we can get an improvement in the fuel economy of the vehicle is achieved.

The following constraints need to be kept in mind while optimizing the parameters of HVAC system:

- Exergy loss of system should be minimum
- Cost of the system i.e. solution should be economical
- Performance should not be degraded while increasing the fuel economy

Therefore, keeping the above constraints in mind, a methodology is to be developed in order to improve the fuel economy of a vehicle.

1.3.2 Relevance of the Proposal

1. International
   (a) Indirectly, it may decrease global warming
   (b) Expand international market
2. National
   (a) Advantageous to national competitive market
   (b) Organization will get better revenue
   (c) Performance and energy balance can be analyzed in advance
   (d) Model based designs are faster and cost effective
   (e) Better HVAC performance
   (f) Improved fuel economy

1.4 Scope of work

Although, significant amount of research in automobile air-conditioning, yet this field is immature. Because of competition between automobile industries to satisfy customer's requirement for thermal comfort and air quality, it is helpful to do some unique research by considering two features say customer satisfaction and fuel economy.

In this study, we divide HVAC system in sub-system, after that we identify and define the parameters affecting the fuel economy then find the relationship between those parameters and fuel economy and at last find relation between all these sub-system. The mathematical model is based on thermodynamic principles of particular sub-system to show its behavior with different input condition.

In early stage of design we have bundle of design option and almost negligible information. after that when information goes on increasing the option will decrease. This relation is shown in figure 1.12. It clearly shows that early stage parameter optimization gives significant effect in process of increasing fuel economy.

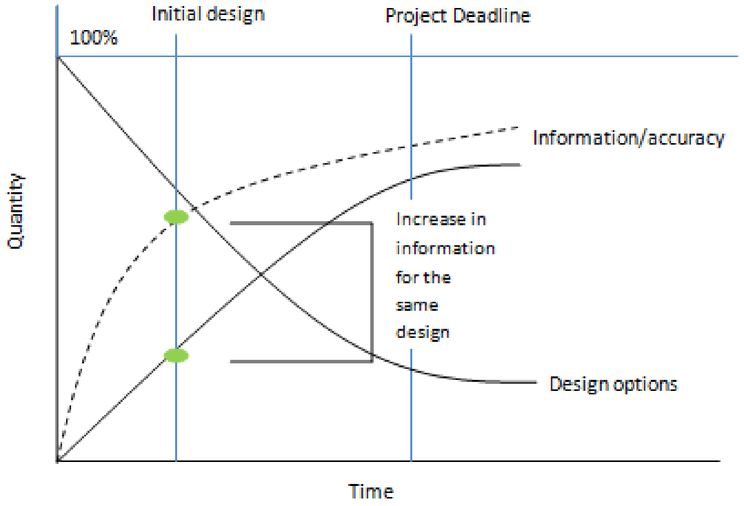


Figure 1.12: Information vs. Design option

Therefore, we will do a detail study of HVAC parameter and it's nature in automobile application and validate model with actual vehicle. The project has been completed in TATA Motors ERC, Pune. There will be good future scope of this project.

1.5 Organization of thesis

The whole thesis is divided in six chapters with bibliography and appendix at the end. This thesis work consists of both numerical results and experimental results for performance of HVAC system.

Chapter 1
The brief scenario of energy and introduction of HVAC system is described in this chapter. Need analysis and scope of work is also discussed. This chapter introduces classification of HVAC system and components of the system.

Chapter 2
This chapter comprises literature review and problem formulation. National and international literature on experimental and mathematical work by various researchers are reviewed. After that, literature gap & problem statement is described and also objectives are introduced.

Chapater 3
This chapter is related to thermal management in automobile HVAC system. The chapter starts with technical approach and mathematical equation to analyze thermal load of the vehicle. The air-conditioning parameter affecting the fuel economy are also identified and based on that mathematical model is formulated. The MATLAB/GUI model is built by using mathematical model in which thermal load is categorized in eight different type of loads. The experimental result is described and GUI model is validated in this chapter.

Chapter 4
This chapter deals with other HVAC parameters affecting the fuel economy. As, Compressor work decreases by increase in sub-cooling temperature as discharge pressure decreases, again it depends on available waste heat which should sufficient for that inter cooler. In this chapter, one of the feasible solution is found to enhance performance of automobile air-conditioning system by varying one parameter. The result are also validated on actual vehicle.

Chapter 5
The summary of present research work, important mathematical and experimental results are demonstrated within this chapter. The scope for future work is also described in this chapter.

Chapter 2

Literature Review and Problem Formulation

2.1 Literature review

Research on improvement of the fuel economy takes great precedence in the automotive industry as it leads to reduction in operating costs of the vehicle and leads to the development of products which are in compliance with emission norms. The present work has done considering demonstrated facts. The literature review is categorized in two broad categories in this chapter:

- Thermal load estimation
- HVAC performance analysis/improvement

2.1.1 Thermal load estimation

Abdulsalam et al. [2] have calculated passenger vehicle heating load for pick condition for different times. The relation between thermal load with respect to time has also shown in this paper. The MATLAB/GUI model has been developed for the same and validated on vehicle Honda Freed and result has been negative heat load of 2867.2 W which is required to maintain cabin comfort. Marcos et al. [3] have proposed simplified and dynamic thermal model for cabin vehicle and validated for hybrid and electric vehicle using MATLAB Simulink. The experiment has performed for different condition; vehicle is stopped and no passenger outside (in solar radiation), vehicle is stopped and no passenger inside (no solar radiation) and vehicle is running with one passenger inside. Experimental results have been achieved by using temperature sensor in cabin. The effect of solar radiation has been focused in this paper, while less focused on heat transfer from ceilings and windows. Singh et al. [4] have studied psychrometric properties and developed mathematical model for calculating vapor pressure. The model has been categorized for three different temperature conditions say, -40 $°C$ to 0 $°C$, 0 $°C$ to 63 $°C$ and 63 $°C$ to 110 $°C$. One can calculate saturated vapor pressure with any of one known pair, those are dry bulb and wet bulb temperature, dry bulb temperature and relative humidity or dry bulb temperature and dew point temperature. The paper is also demonstrated equations to calculate other properties of mixture of air and water.

Pedersen et al. [5] have formulated a procedure to find heat load and the procedure has been formed under ASHARE research project. The procedure is almost conventional and basic; by which it is difficult to develop any mathematical tool. Fayazbakhsh and Bahrami [6] have devised model for calculating heat load using heat balance method with C++. The model was more flexible as it can be applicable on different driving conditions, different cabin configuration and atmospheric conditions. The model is built for eVaro hybrid electric vehicle. The thermal load has been estimated for two driving scenario: 1. cooling load calculation 2. heating load calculation; and compared variation of different load during time of the day. Zheng et al. [7] had developed the simple method to calculate heat load using excel spreadsheet by using cooling load temperature difference method from ASHARE. The results have described that effect of radiation and ventilation load play vital role in thermal management of vehicle. The model has validated by using wind tunnel test. Maximum possible heat gain from one blower motor 0.28 kW and infiltration rate is 3.72 m^3/m and fresh air requirement during recirculation mode is 0.424 $m^3/person$.

Fletcher and Saunders [8] have evaluated infiltration rate with four different passenger vehicles and different ventilation settings. The air change rate has been determined by using tracer gas method with different wind speed and directions. The experiment has performed on stationary vehicle and on a moving vehicle. The infiltration rate has been higher in case of moving vehicle as predicted and concluded that air flow in passenger vehicle increases with vehicle speed linearly. Kilic and Akyol [9] have investigated effect of ventilation mode on thermal comfort and air quality by measuring temperature, humidity and CO_2 level in addition the effect of HVAC setting (i.e. Fresh air mode or re-circulation mode) has been analyzed. The mathematical model has been built for analyze the effect of these modes and also compared with experimental data. They have concluded that CO_2 level can be greater than the threshold value (1200 ppm); therefore cabin air must be replaced periodically. Sweat generation increased in fresh air mode to balance heat exchange between body and environment.

2.1.2 HVAC performance analysis/improvement

Bentrcia et al. [10] have reviewed alternative systems for automobile air-conditioning and divided all alternatives on basis of energy types: waste heat, solar energy, electrical and fuel cell energy. Also, they have demonstrated different cooling system according to work-powered and heat-powered. The comparison between all alternatives has been shown based on their COP, feasibility, technical integrity, etc. The conclusion has been, VCR powered by electric energy and solar energy has achieved advanced stage of development though there are weight, size and packaging issues. Lethwala and Garg [11] have developed solar operated VCR system in vehicle air conditioner and implemented the same in Maruti Suzuki WagonR. The swash plate type mechanical compressor has been used which has been powered by electrical motor. There is a direct relation between solar energy and AC requirement which is the major project strength in their research, because AC is needed when there is high radiation load and at the time of high radiation solar panel can generate high power. Poly-crystalline solar panel and lead acid battery are advised for getting a good compromise between cost and work performance also done cost effective analysis.

Ladke and Choudhari [12] have optimized design of condenser for refrigerant R-290. Environmental characteristic of R-290 has been studied and developed mathematical model for sizing of condenser considering fin efficiency. They have optimized the design parameter with series of experiments by changing outer diameter, fin pitch, number of rows, thickness of fin and come in conclusion that fin with outer diameter of 5.2mm, two row and 12 fins per inch gives better results. The results has been validated with experimental setup in which velocity of air has been varied and temperature at different location has been recorded (i.e. at evaporator inlet, compressor outlet, etc). Cao and Cui [13] have studied condenser with different structure. The CFD analysis has been done for effect of fin width and validated by experimental results. The results shows that 1)the heat transfer resistance is directly proportion to fin width but increase in fin width can't increase overall heat transfer, 2)If fin width increases, unit area heat transfer decreases. The relative error for simulation results has been 5.3%.

Yoo et al. [14] have investigated pressure drop and heat transfer characteristics using different curvature ratio and Reynolds numbers. The variation of curvature radius is a important flow parameter and have found that centrifugal force prompted by curvature radius implies significant effect on heat transfer and pressure drop. They have established pressure drop correlation in terms of Reynolds number. As, centrifugal force enhance heat transfer & pressure drop so, it is higher in case of spiral coiled tube than in case of straight tube. Also, refrigerant mass flow and air velocity plays major role in variation of overall heat transfer coefficient for condenser. Khayyam et al. [15] have applied concept of energy management. They have reduced vehicle energy consumption by controlling mass flow rate of with proper adjustment of blower operation speed. The heat load has been estimated for studying performance of particular AC system. Also, They have compared the performance of vehicle with and without AC system. The intelligent algorithm has been proposed for automatic alteration of recirculation and fresh air mode to maintain cabin air quality.

Rugh et al. [16] have used solar reflective glass which can reduce near infrared radiation. Parallelly, solar reflective paint has been developed which can increase near infrared reflection from vehicle opaque surface. The solar-powered parked car ventilation with general motors data acquisition has been tested along with these two implementation. The consumption of fuel has been evaluated using simulation tool and concluded 30% reduction in AC load, 26% reduction in fuel and also noted CO_2 reduction. Bharathan et al. [17] have shown new technologies, those are able to reduce thermal load and fuel consumption in vehicle due to air-conditioning. The different methods which have been suggested for reducing thermal load are solar-reflective glazing, parked car ventilation and insulation; as these methods produce less impact on cabin temperature though significant reduction in solar load and waste heat coming from engine. The benefit of these methods is mainly at the time of starting the vehicle after soaking when occupant feel discomfort. Thermoacoustics has been also studied which comes not feasible for light duty vehicle but one can get electricity from that and run minor power consuming equipment like blower or condenser fan etc. Some tools have been suggested say, vehicle solar load estimator, integrated climate-control modeling process but they are also not as much cost effective.

Kampf and Schmadl [18] have proposed four different methods for engine independent AC-system: 1) adsorption system, 2) thermal storage, 3) absorption system and 4) Electrically driven compressor. They have concluded that adsorption and absorption have too low power density, in addition the power consumption for charging battery has come significant less compared as power driven out from engine by compressor. In the case of electrically driven compressor and thermal storage system the system gives higher comfort with reduced fuel consumption, less packaging problem for implementing into truck. Heydari and Jani [19] have simulated the performance of HVAC system and optimizing the design of an automobile air-conditioning system .The simulation model has been divided into three distinct components: the mechanical compression air-conditioning system, the air-handling system and the cabin thermal model. The mathematical model of various components has been developed, which can demonstrate entropy generation. Also, the variation of entropy generation with different air flow rate has been studied for evaluating the performance of air-handing system .

2.1.3 Gaps in literature

A detailed study of the literature review shows that researchers are finding alternatives for air-conditioning system as well as they are promoting to utilize value engineering concepts in industries. Some researchers have proposed alternatives like solar powered VCR cycle, vapor absorption, insulation, etc. in above mentioned review. Some have implement the alternatives which gives improvement but still requires significant modification. For early parameter identification, researcher developed model which are still with limitation. For commercial vehicle fuel economy is most important parameter So, industry want remarkable improvement. Therefore, one can find some research gaps from above literature as follows:

- Research work to discover new working fluids and materials.
- Performance of commercial vehicle by implementing electric compressor powered by solar energy.
- Analysis of vehicle by implementing internal heat exchanger with same or different refrigerant.
- Optimization of air-conditioning parameters and validation on actual vehicle.

2.2 Problem formulation

Based on the literature review, it was decided to investigate the effect of HVAC parameter on fuel economy of automobile application and find out critical parameters so that by optimizing them manufacturer can get improved fuel economy. The study is divided into two parts called thermal management, flow management. The comprehensive model is developed for thermal management with considering all parameters. Compressor is selected based on optimum value according to constraint parameters. At last, studying suction and discharge pressure, the fuel economy is improved by some modification in existing design.

2.3 Objectives

The above scope is deliberately analyzed in evolving the following objectives of the present investigation:

- To delineate HVAC parameters affecting fuel economy
- To develop the simple, accurate and fast model for evaluating thermal load
- To validate developed model on actual vehicle
- To ascertain the parameter, optimization of which can give better performance
- To improve fuel economy of the vehicle in existing system

Chapter 3

Thermal Design Calculation

3.1 Thermal load calculation

The first step for designing efficient air-conditioning system is to develop heat load calculation for that particular application.The need of thermal load calculation is to determine size of HVAC component under farthest condition. The information involved for making model is depend upon use of model.

3.1.1 Calculation methods

There are mainly five methodologies to compute heat load.

1. Total equivalent temperature differential method with time averaging (TETD | TA)
2. Transfer function method (TFM)
3. Cooling load temperature differential/solar cooling load/cooling load factor (CLTD/SCL/CLF)
4. Heat balance method (HBM)
5. Radiant time series method (RTS)

3.1.2 Heat balance method

In this method, total load divided into different categories. The total load either positive (i.e. heating up the cabin) or negative (i.e. cooling down the cabin). The assumptions for this model are as follows :

- The temperature distribution in sheet metal is taken as uniform.
- Heat transfer process is solved by lumped capacity assumption.
- One-dimensional heat conduction within surfaces
- Uniform solar radiation

The basic equation for solving thermal load calculation is,

$$\dot{Q}_{total} = \dot{Q}_{grad} + \dot{Q}_{srad} + \dot{Q}_{met} + \dot{Q}_{amb} + \dot{Q}_{eng} + \dot{Q}_{exh} + \dot{Q}_{ven} + \dot{Q}_{ac} \tag{3.1}$$

3.2 Mathematical model

As, total load is divided in eight different loads. Now the analysis of each load is as follows:

Glass radiation load

The solar radiation through glass gives significant amount of heat gain in vehicle, it is categorized as direct, diffuse and reflected radiation. The total glass radiation is given by,

$$\dot{Q}_{grad} = \dot{Q}_{grad(dir)} + \dot{Q}_{grad(dif)} + \dot{Q}_{grad(ref)} \tag{3.2}$$

Direct radiation is also known as beam radiation which directly strikes on glass surface of vehicle and is calculated by,

$$\dot{Q}_{grad(dir)} = \sum_{glasses} S\tau\dot{I}_{dir}\cos\theta \tag{3.3}$$

Where,

τ = Transmissivity of glass
S = Surface area, m^2
$\dot{I}_{dir}$ = Direct incidence radiation per unit area, W/m^2
θ = Incidence angle, degrees

$$\dot{I}_{dir} = A\exp\left(-\frac{B}{\sin\alpha}\right) \tag{3.4}$$

Where,

α = Altitude angle, degrees
A = Apparent direct normal solar flux at the outer edge of the earth's atmosphere, W/m^2
B = Apparent atmospheric extinction coefficient

There is only direct radiation on clear day, but we assumed average clear day so we will consider diffuse radiation also. diffuse radiation is known as indirect radiation. Diffuse radiation from sky that strikes on a horizontal surface,

$$\dot{I}_{h,dif} = C\dot{I}_{dir} \tag{3.5}$$

Where,

$\dot{I}_{h,dif}$ = Diffuse incidence radiation on horizontal surface, W/m^2
C = Constant

Here, A ,B & C are taken from table 3.1.

Table 3.1: Coefficients for average clear day solar radiation

Month	A		B	C	Declination	Equation of time
	Btu/Hr.ft^2	W/m^2	DL ratio		deg	hr
Jan	390	1230	0.142	0.058	-20	-0.19
Feb	385	1215	0.144	0.06	-10.8	-0.23
Mar	376	1186	0.156	0.071	0	-0.13
Apr	360	1136	0.18	0.097	11.6	0.02
May	350	1104	0.196	0.121	20	0.06
Jun	345	1088	0.205	0.134	23.45	-0.02
Jul	344	1085	0.207	0.136	20.6	-0.1
Aug	351	1107	0.201	0.122	12.3	-0.04
Sep	365	1151	0.177	0.092	0	0.13
Oct	378	1192	0.16	0.073	-10.5	0.26
Nov	387	1221	0.149	0.063	-19.8	0.23
Dec	391	1233	0.142	0.057	-23.45	0.03

Now diffuse radiation heat gain,

$$\dot{Q}_{grad(dif)} = \sum_{glasses} S\tau\dot{I}_{dif} \tag{3.6}$$

$$\dot{I}_{dif} = \dot{I}_{h,dif}\left(\frac{1+\cos\beta}{2}\right) \tag{3.7}$$

Where,

$\dot{I}_{dif}$ = Diffuse incidence radiation per unit area, W/m^2
β = Tilt angle measured from horizontal, degrees

Reflected radiation is part of radiation reflected from the ground and strikes the vehicle. Reflected radiation heat gain,

$$\dot{Q}_{grad(ref)} = \sum_{glasses} S\tau\dot{I}_{ref} \tag{3.8}$$

$$\dot{I}_{ref} = \left(\dot{I}_{dir} + \dot{I}_{h,dif}\right)\rho_g\left(\frac{1-\cos\beta}{2}\right) \tag{3.9}$$

Where,

ρ_g = Reflectivity of ground surface

Here, angles are found by,

$$\cos\theta = \cos\theta_z\cos\beta + \sin\theta_z\sin\beta\cos\left(\psi-\gamma\right) \tag{3.10}$$

$$\cos\theta_z = \cos\delta\cos\phi\cos\omega + \sin\delta\sin\phi \tag{3.11}$$

$$\cos\psi = \frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi} \tag{3.12}$$

Sheet metal radiation load

Total sheet metal radiation load is also divided in three categories direct, diffuse and reflected radiation same as glass radiation. The total solar radiation incidence on the sheet metal and absorbed by the sheet metal.It is given by,

$$\dot{Q}_{srad} = \sum_{surfaces} S\alpha_s \left(\dot{I}_{dir}\cos\theta + \dot{I}_{dif} + \dot{I}_{ref}\right) \tag{3.13}$$

Where,

α_s = Absorptivity of surface

Metabolic load

The heat is persistently created by metabolic activity of inside human being (i.e. perspiration). Heat coming out through the human tissues and by which cabin air gains heat is known as metabolic load.

$$\dot{Q}_{met} = \sum_{persons} MA_{Du} \tag{3.14}$$

Where,

M = Metabolic heat production, W/m^2
A_{Du} = Dubois area, m^2

The value of M is estimated 60 W/m^2 and 85 W/m^2 for driver and passenger respectively. The most useful measure of nude body surface area, originally proposed by DuBois (1916), is described by,

$$A_{Du} = 0.202W^{0.425}H^{0.725} \tag{3.15}$$

Where,

W = Weight of person, kg
H = Height of person, m

Ambient load

The heat transfer occurs due to temperature difference between ambient and cabin air is known as ambient load. This load includes exterior convection, conduction through body panel and interior convection.

$$\dot{Q}_{amb} = \left(\sum_{surfaces} SU(T_s - T_c) + \sum_{glass} SU(T_g - T_c) \right) \tag{3.16}$$

Where,

T_s = Average sheet metal surface temperature, $°C$
T_g = Average glass surface temperature, $°C$
T_c = Cabin temperature, $°C$
U = Overall heat transfer coefficient, W/m^2K

Now, overall heat transfer coefficient is given by,

$$U = \frac{1}{\frac{1}{h_i} + \frac{\lambda}{k} + \frac{1}{h_o}} \tag{3.17}$$

Where,

h_i = Inside convection heat transfer coefficient, W/m^2K
h_o = Outside heat transfer coefficient, W/m^2K
λ = Thickness of surface, m
k = Thermal conductivity of surface, W/mK

Convection heat transfer coefficient can be found by following estimation as it is function of velocity [20].

$$h = 0.6 + 6.64\sqrt{V} \tag{3.18}$$

Where,

V = Velocity of air, m/s

The cabin air is assumed stationary and ambient air velocity is taken same as vehicle velocity. Above relation is applicable to all practical automobile applications.

Engine load

Heat transfer occur due to high temperature engine of conventional or hybrid vehicle. Engine load is calculated as,

$$\dot{Q}_{eng} = S_{eng}U\left(T_{eng} - T_c\right) \tag{3.19}$$

Where,

S_{eng} = Surface area of cabin exposed to engine temperature, m^2
T_{eng} = Temperature of engine, $°C$

Here, we assumed no external convection, since the engine temperature is measured the outside of front surface or the bottom face. The engine temperature is estimated in degree Celsius by [15],

$$T_{eng} = -2 \times 10^{-6} RPM^2 + 0.0355 RPM + 77.5 \tag{3.20}$$

Where,

RPM = Engine speed, revolution per minute

Exhaust load

As, we know exhaust gas temperature is very high, some heat will be transferred to cabin through the cabin floor.

$$\dot{Q}_{exh} = S_{exh} U \left(T_{exh} - T_c \right) \tag{3.21}$$

Where,

S_{exh} = Surface area of cabin in contact with exhaust pipe, m^2
T_{exh} = Temperature of exhaust gas, $^\circ C$

We assumed no external convection, since the exhaust temperature is measured at the outer side of the bottom surface. The exhaust gas temperature estimated in degree Celsius by [15],

$$T_{exh} = 0.138 RPM - 17 \tag{3.22}$$

Ventilation load

There is requirement of fresh air to maintain air quality for passengers. As, the passengers breathe, the amount of CO_2 concentration linearly increases over time. Thus, a minimum flow of fresh air should be supplied into cabin to maintain the passenger comfort. On other hand, there is leakage which is function of pressure difference between the cabin and surrounding as well as vehicle velocity. For a small sedan car at a pressure difference of 10 Pa, a leakage of 0.02 m^3/s was reported [8].

$$\dot{Q}_{ven} = \dot{m}_{ven} \left(e_a - e_c \right) \tag{3.23}$$

Where,

$\dot{m}_{ven}$ = Ventilation or infiltration mass flow rate, kg/s
e_a = Ambient air enthalpy, J/kg
e_c = Cabin air enthalpy, J/kg

Now, $\dot{m}_{ven}$ is found by following correlation.

$$\dot{m}_{ven} = \frac{cmm \times \rho}{60} \tag{3.24}$$

$$cmm = \frac{\vee \times ACH}{60} \tag{3.25}$$

Where,

cmm = Volume flow rate, cubic meter per minute
ρ = Density of air, kg/m^3
$\vee$ = Volume of cabiin, m^3
ACH = Air exchange rate, $hour^{-1}$

The Enthalpy of ambient and cabin air depends upon temperature, saturation pressure, relative humidity and atmospheric pressure; it is found by,

$$e = 1006T + \left(2.501 \times 10^6 + 1770T\right) w \tag{3.26}$$

$$w = 0.62198 \frac{\Phi P_s}{100P - \Phi P_s} \tag{3.27}$$

Where,

T = Temperature of ambient or cabin air, $^\circ C$
w = Humidity ratio or specific humidity, mass of water vapor per unit mass of dry air, $kg/kg\ of\ dry\ air$
Φ = Relative humidity, %
P_s = Water saturation pressure at temperature T, kPa
P = Air pressure, kPa

HVAC system load

The role of air conditioning system is to compensate for other thermal loads so that the cabin temperature remains within the acceptable comfort range. HVAC system load is to be considered as vehicle thermal load, it may be positive (heating) or negative (cooling) based on requirements. HVAC load is calculated considering all thermal load as well as two more load that is deep thermal mass of vehicle and cabin air which is required to cool down at comfort temperature. It is given by,

$$\begin{aligned} \dot{Q}_{ac} = & -\left(\dot{Q}_{grad} + \dot{Q}_{srad} + \dot{Q}_{met} + \dot{Q}_{amb} + e\dot{n}g_{ac} + \dot{Q}_{exh} + \dot{Q}_{ven}\right) \\ & - \left(m_a c_a + DTM\right)\left(T_i - T_{comf}\right)/t_c \end{aligned} \tag{3.28}$$

Where,

m_a = Mass of air in cabin, kg
c_a = Specific heat capacity of cabin air, J/kgK
T_i = Present cabin temperature, $^\circ C$
T_{comf} = Target comfort temperature, $^\circ C$
DTM = Deep thermal mass, J/kg
t_c = Pull-down constant, sec

Pull-down time is time required to reach comfort temperature from cabin temperature. Pull-down time is decided by manufacturer as per application and customer's requirement. Pull-down constant can be determined by pull-down time,

$$t_c = \frac{t_p}{\ln |T_o - T_{comf}|} \tag{3.29}$$

Where,

t_p = Pull-down time, *sec*
T_o = Intial cabin temperature, $°C$

3.3 MATLAB/GUI model

The demonstrated methodology is applied in MATLAB/GUI. The code is generated according to methodology and GUI model is built. The all required modification is done on the model and final model is shown in figure 3.2. The variation of thermal load and power consumption by compressor during day hours is depicted in figure 3.1. It also shows variation of ambient temperature during day time for particular location and day. The graph shows only nature of variations because the values is changed vehicle to vehicle and also location specific.

The user friendly features is also added in model with which one can select any vehicle which is already developed, for new vehicle select other vehicle, warning dialogue box, etc. as shown in figure 3.3. The model is validated for number of vehicles and the case study of two vehicles are shown in figure 3.4 & 3.5. The results are verified with experimental value and concluded that it gives 3.4033% error.

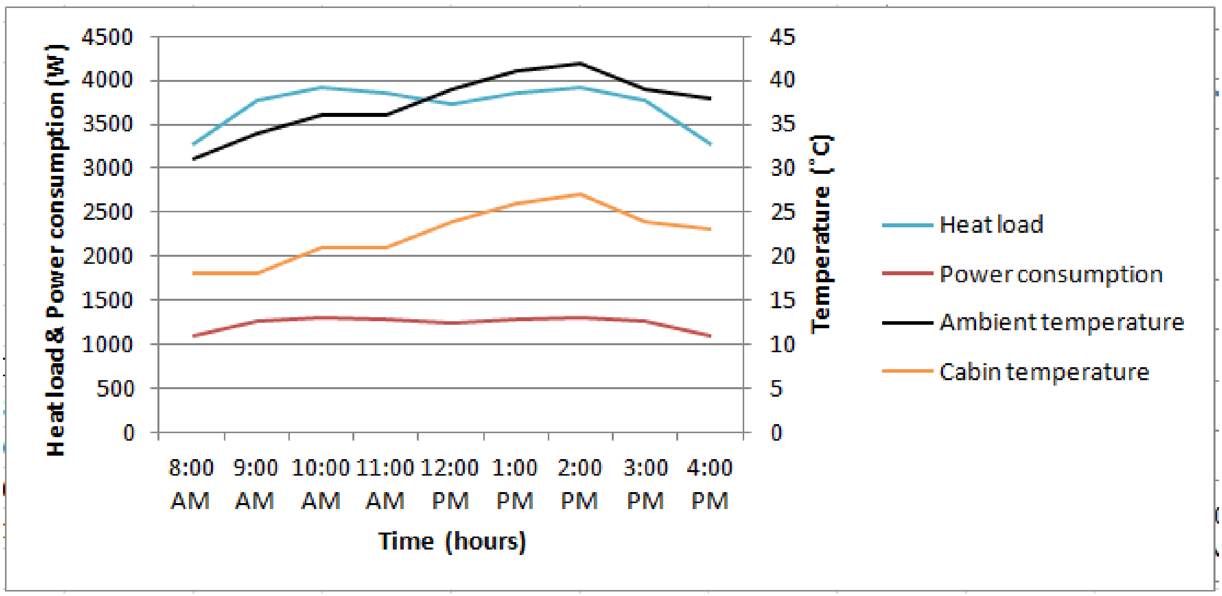


Figure 3.1: Variation of heat load and power consumption with time

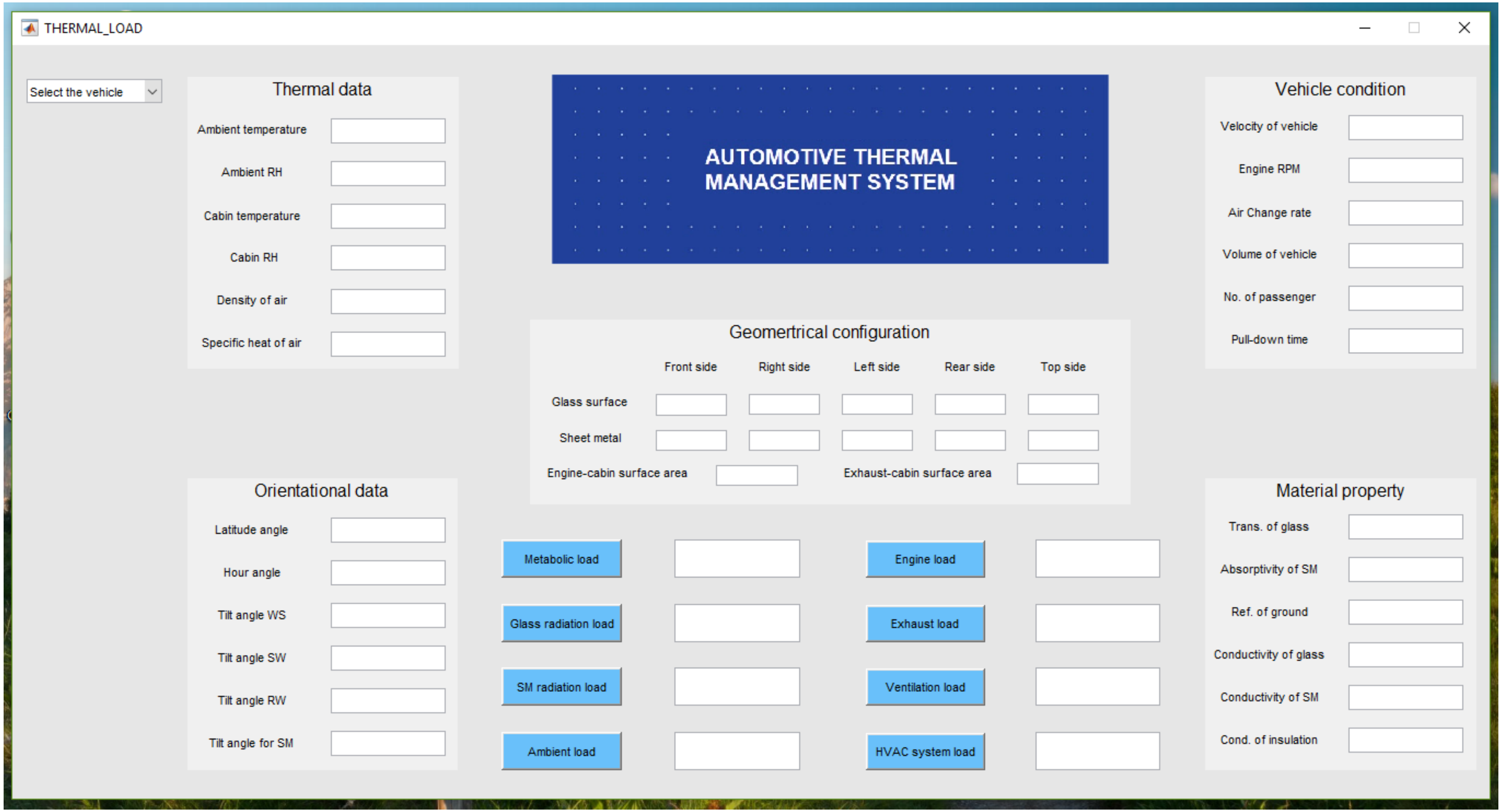
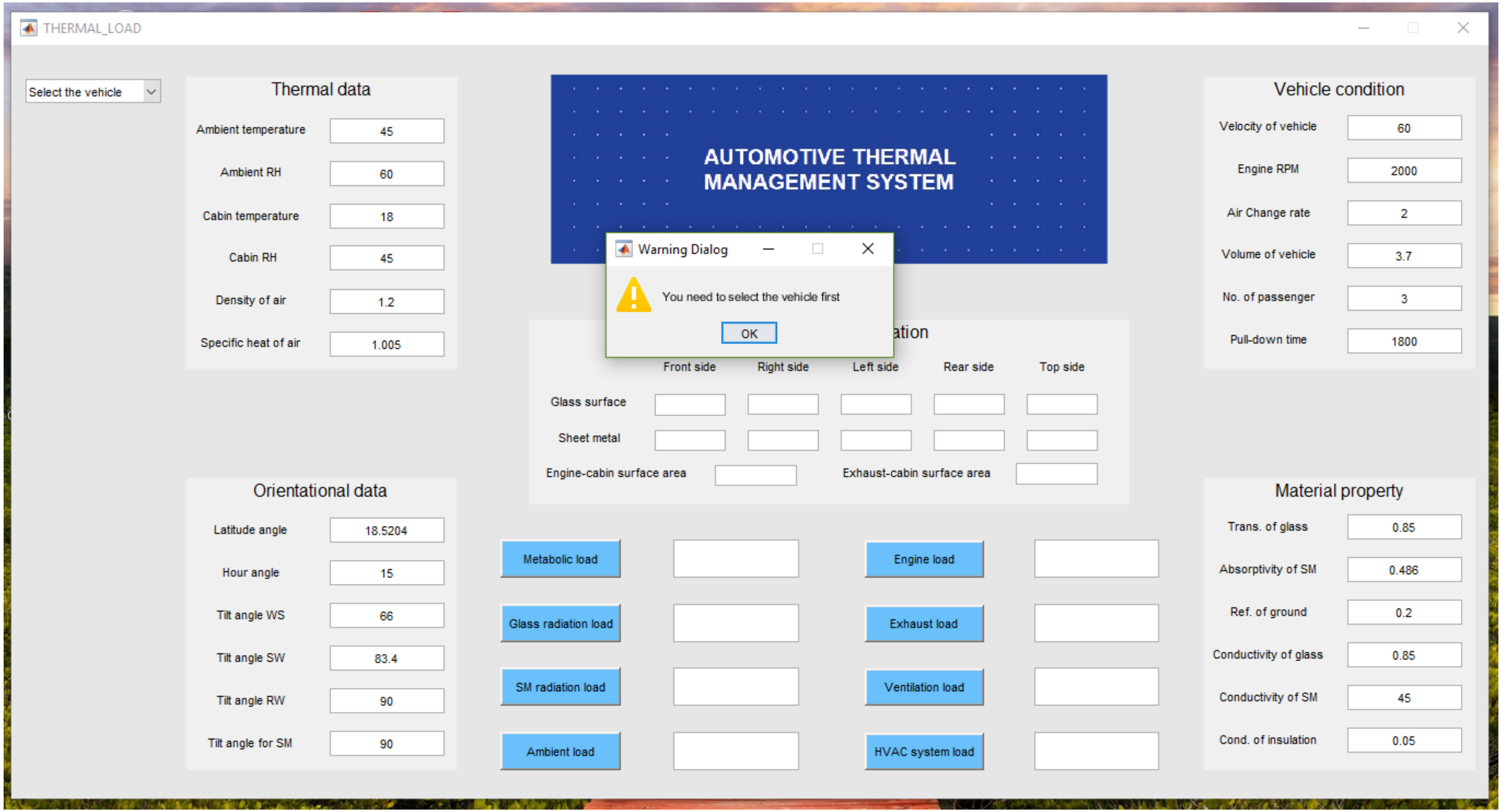


Figure 3.2: GUI Model



You need to select the vehicle first

Thermal data

Ambient temperature 45
Ambient RH 60
Cabin temperature 18
Cabin RH 45
Density of air 1.2
Specific heat of air 1.005

Orientational data

Latitude angle 18.5204
Hour angle 15
Tilt angle WS 66
Tilt angle SW 83.4
Tilt angle RW 90
Tilt angle for SM 90

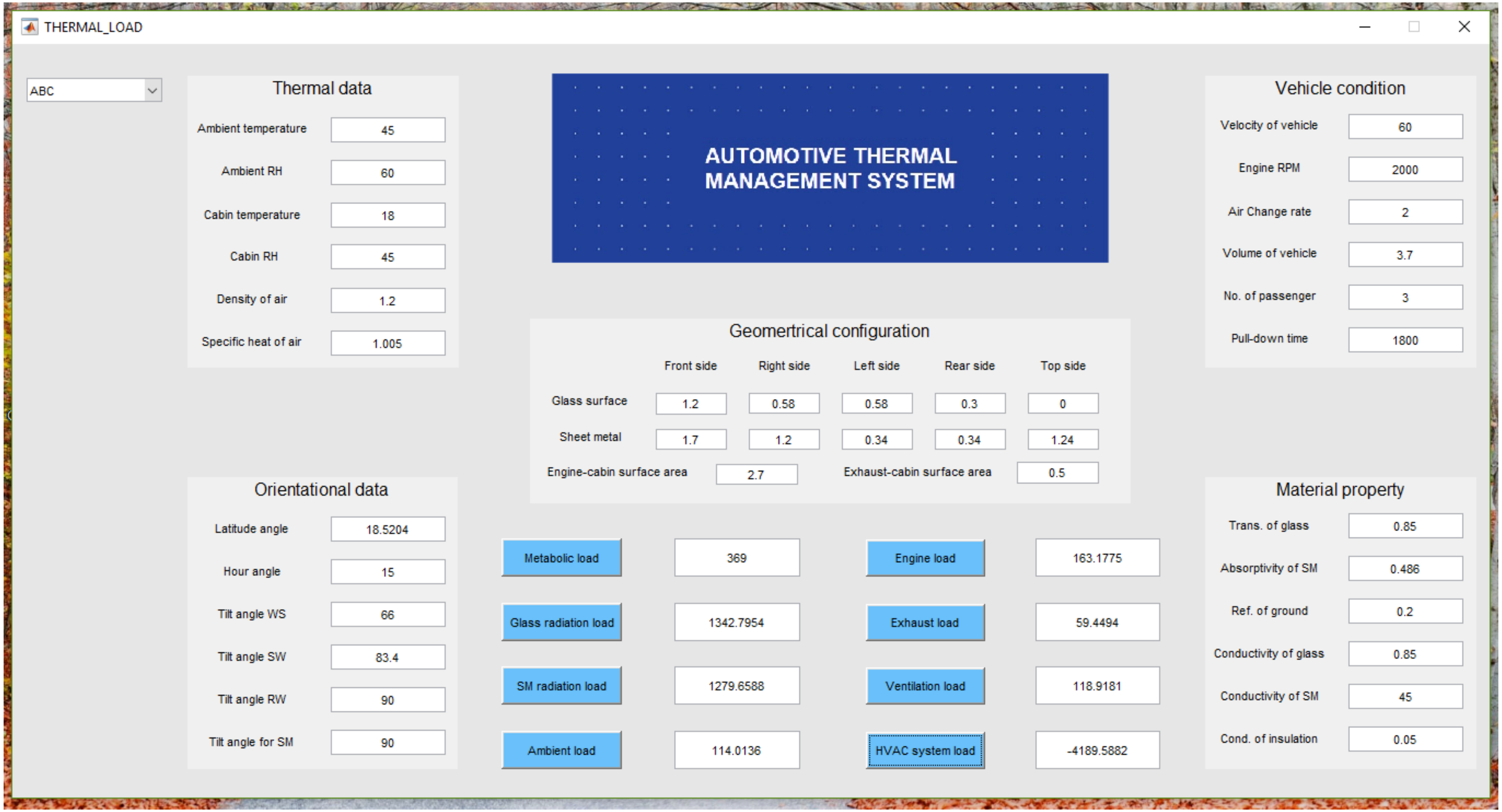
Vehicle condition

Velocity of vehicle 60
Engine RPM 2000
Air Change rate 2
Volume of vehicle 3.7
No. of passenger 3
Pull-down time 1800

Material property

Trans. of glass 0.85
Absorptivity of SM 0.486
Ref. of ground 0.2
Conductivity of glass 0.85
Conductivity of SM 45
Cond. of insulation 0.05

Figure 3.3: Warning dialogue box



Thermal data

Ambient temperature	45
Ambient RH	60
Cabin temperature	18
Cabin RH	45
Density of air	1.2
Specific heat of air	1.005

Orientational data

Latitude angle	18.5204
Hour angle	15
Tilt angle WS	66
Tilt angle SW	83.4
Tilt angle RW	90
Tilt angle for SM	90

Geomertrical configuration

	Front side	Right side	Left side	Rear side	Top side
Glass surface	1.2	0.58	0.58	0.3	0
Sheet metal	1.7	1.2	0.34	0.34	1.24

Engine-cabin surface area 2.7

Exhaust-cabin surface area 0.5

Metabolic load	369	Engine load	163.1775
Glass radiation load	1342.7954	Exhaust load	59.4494
SM radiation load	1279.6588	Ventilation load	118.9181
Ambient load	114.0136	HVAC system load	-4189.5882

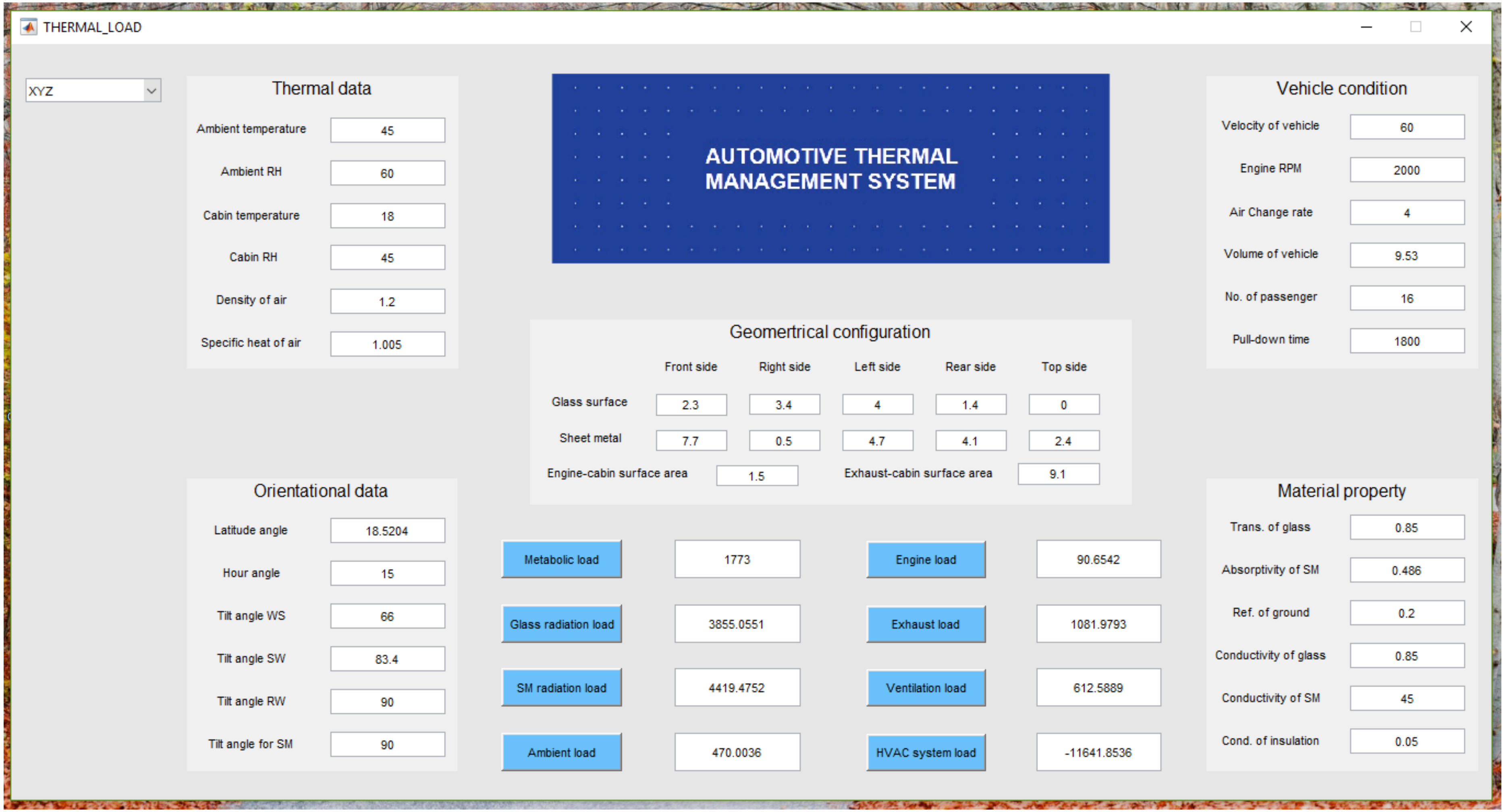
Vehicle condition

Velocity of vehicle	60
Engine RPM	2000
Air Change rate	2
Volume of vehicle	3.7
No. of passenger	3
Pull-down time	1800

Material property

Trans. of glass	0.85
Absorptivity of SM	0.486
Ref. of ground	0.2
Conductivity of glass	0.85
Conductivity of SM	45
Cond. of insulation	0.05

Figure 3.4: Thermal load calculation for vehicle ABC



XYZ

Thermal data

Ambient temperature	45
Ambient RH	60
Cabin temperature	18
Cabin RH	45
Density of air	1.2
Specific heat of air	1.005

Vehicle condition

Velocity of vehicle	60
Engine RPM	2000
Air Change rate	4
Volume of vehicle	9.53
No. of passenger	16
Pull-down time	1800

Geomertrical configuration

	Front side	Right side	Left side	Rear side	Top side
Glass surface	2.3	3.4	4	1.4	0
Sheet metal	7.7	0.5	4.7	4.1	2.4

Engine-cabin surface area 1.5
Exhaust-cabin surface area 9.1

Orientational data

Latitude angle	18.5204
Hour angle	15
Tilt angle WS	66
Tilt angle SW	83.4
Tilt angle RW	90
Tilt angle for SM	90

Metabolic load	1773	Engine load	90.6542
Glass radiation load	3855.0551	Exhaust load	1081.9793
SM radiation load	4419.4752	Ventilation load	612.5889
Ambient load	470.0036	HVAC system load	-11641.8536

Material property

Trans. of glass	0.85
Absorptivity of SM	0.486
Ref. of ground	0.2
Conductivity of glass	0.85
Conductivity of SM	45
Cond. of insulation	0.05

Figure 3.5: Thermal load calculation for vehicle XYZ

Chapter 4

Optimization of HVAC Flow Parameters

4.1 Selection of compressor

The compressor is the nucleus of all refrigeration or air conditioning systems. The function of compressor is to draw cool vaporized refrigerant which takes the heat from evaporator side, to compress it from low pressure to high pressure and pumping it around the air-conditioning loop for heat rejection purpose. Compressor are described as follow:

- Drive speed (constant speed or variable speed)
- Number of stages (single-stage, two-stage, or multi-stage)
- Drive types (motor, engine, belt, or chain, etc.)
- Structure (open type, semi-hermetic and hermetically sealed)
- Cooling method and medium (air-cooled, water-cooled, or oil-cooled)
- Lubricating method (splash lubricated, forced lubricated, or oil-free)

The features required for compressor are thermal shut-off, proper sealing, low noise, light weight, etc. The compressors used in automobile HVAC system are :

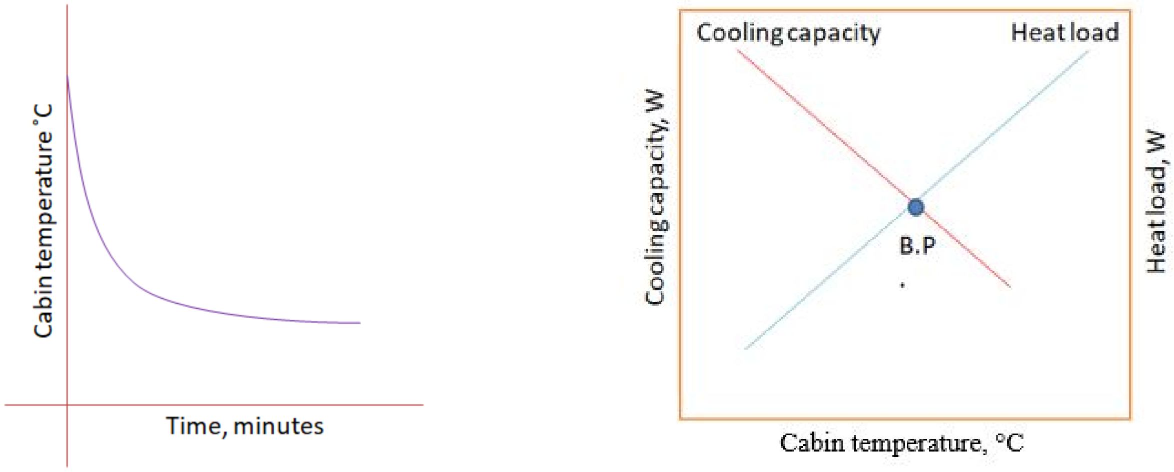
- Swash plate type (fixed displacement) compressor
- Swash plate type (variable displacement) compressor
- Vane type rotary compressor
- Scroll type rotary compressor

4.1.1 Selection procedure

The input parameters, which should be considered for selection of compressor are evaporator and condenser pressure, allowable temperature rise in compressor, temperature and specific volume of vapor at suction flange, etc. The step by step procedure to select compressor for automobile air-conditioning is as follow :

- First heat load calculation conducted on test vehicle environmental chambers where heat loads can be controlled, together with, and based on theoretical calculation.

- With the high heat loads the cooling capacity of the system is inadequate to instantly reduce the cabin temperature down to a desirable level, with the continued operation the progressive reduction in heat load will enable the cooling capacity of the system to increase.
- Any system must be capable of reaching balancing point (see figure 4.1) to ensure adequate cabin cooling and customer satisfaction at predetermined heat loads within an acceptable time frame , this is commonly referred to as the pull down test.



(a) Pull-down performance (b) Cooling capacity vs Thermal load

Figure 4.1: Blancing point estimation

After finding cooling capacity, next step is to find required mass flow rate of refrigerant. It is derived by,

$$\dot{m}_r = \frac{RE}{e_{out} - e_{in}} \tag{4.1}$$

Where,

RE = Refrigerating capacity, kW
e_{in} = enthalpy of refrigerant at the inlet of evaporator, kJ/kg
e_{out} = enthalpy of refrigerant at outlet of evaporator, kJ/kg

We can verify this mass flow rate by finding heat rejection in condenser and after finding this mass flow rate the actual mass flow rate is,

$$\dot{m}_{act} = \dot{m}_r \times duty\ factor \tag{4.2}$$

Where, duty factor is the percentage of amount of time that compressor can be run in full cycle. It includes compressor run time & rest time. It varies compressor to compressor.

The last step is we compare rpm vs. cooling capacity curve of different compressor precisely and select optimum solution.

4.2 Condenser and Evaporator

Condenser and evaporator both are the heat exchanger in air-conditioning system. The main parameter for designing these heat exchangers is pressure. To understand analogy of pressure and effect of pressure on condenser and evaporator, one should know basic vapor compression cycle.

4.2.1 Vapor compression cycle

There are two basic principles in thermodynamics, which are used to understand vapor compression cycle.

1. The first law of thermodynamics which explains that energy can neither be created nor be destroyed, but it can transform from one form to other form
2. The second law of thermodynamic on which refrigeration and air-conditioning systems are derives, explains that heat cannot transfer from low temperature to high temperature without any external effort.

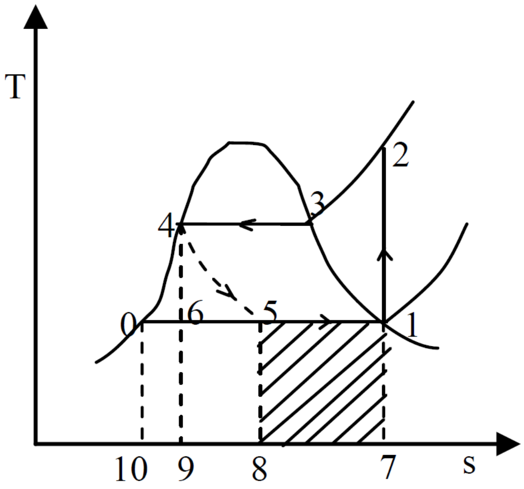


Figure 4.2: Theoretical vapor compression cycle

The standard vapor compression cycle is shown in figure 4.2. The cycle begins with low pressure low temperature vapor from evaporator enters into compressor where pressure and temperature of refrigerant get rise. The high pressure high temperature refrigerant enters into condenser where there are desuperheating, saturation and subcooling zone. The refrigerant passed through all three zones and converted into high temperature high pressure liquid which will enter into orifice tube or expansion valve according to system. The throttling process is highly irreversible process which also know as isenthalpic process. The low temperature and low pressure refrigerant absorbs heat from desired place. Here the process in condenser and evaporator is constant pressure process.

The actual vapor compression cycle is shown in figure 4.3. There are many variations in theoretical and actual vapor compression cycle; some of which are uncontrollable and increase energy losses. The main difference between theoretical and actual cycle are as follows:

1. The process in evaporator and condenser is not constant pressure, i.e. there will be pressure drop
2. The compression process are neither isentropic nor polytropic.
3. The refrigerant leaving from the evaporator is superheated and leaving from the condenser is sub-cooled where, in standard cycle it is assumed as saturated.

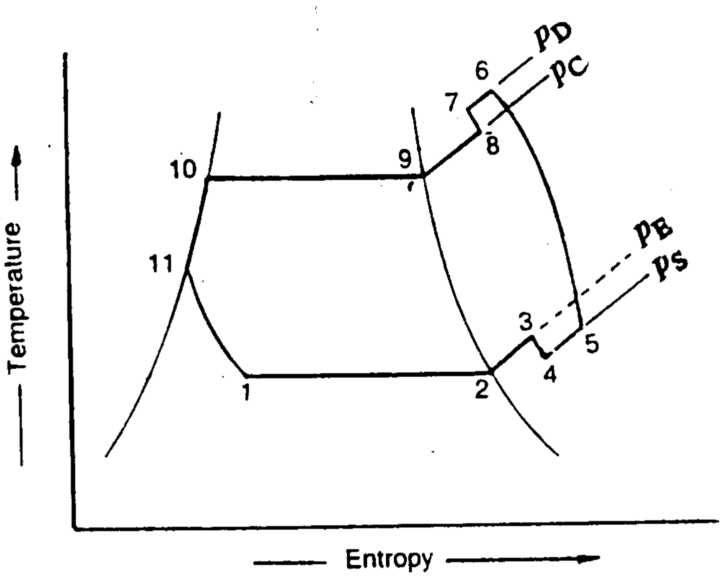
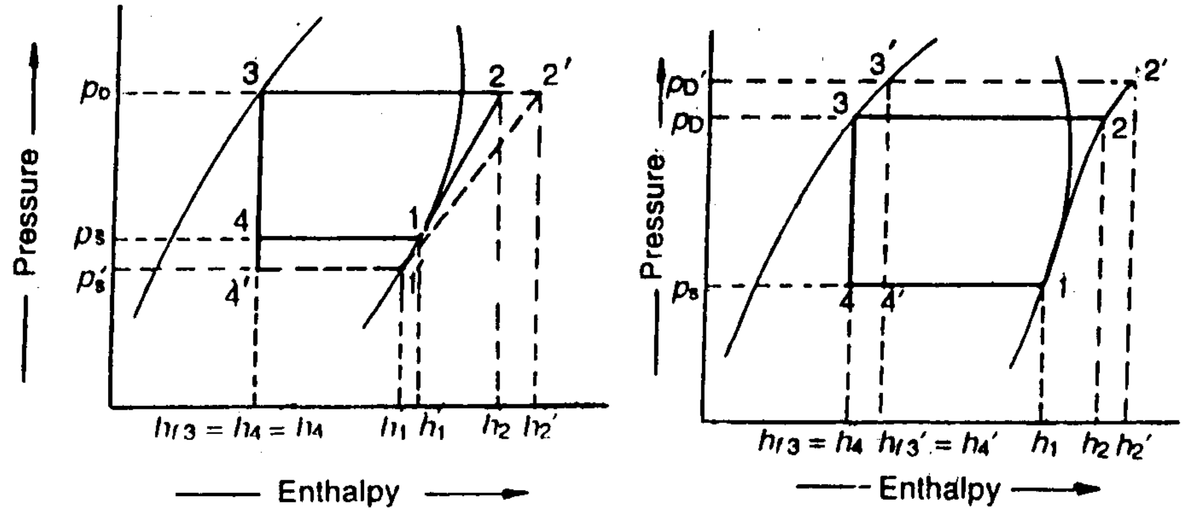


Figure 4.3: Actual vapor compression cycle

4.2.2 Suction & discharge pressure

Suction and discharge pressure are one of the important parameters which significantly affects the power consumption. The suction pressure decreases due to friction loss in evaporator and henceforth compressor work increases. Similarly, discharge pressure increases for retaliating effect of the flow resistance and therefore power consumption is more. The effect of suction pressure and discharge pressure is shown in the figure 4.4. One can examine from the figure 4.4 that if suction pressure is decreased and discharge pressure is increased the compressor work will increase. By reversing this analogy, power consumption will decrease if somehow suction pressure increases and discharge pressure decreases. So, one of the methods for improvement in fuel economy by varying the air-conditioning parameters is subcooling and superheating together.



(a) Effect of suction pressure (b) Effect of discharge pressure

Figure 4.4: Pressure impact on compressor work

4.3 Heat transfer augmentation

Appropriate design of condenser and evaporator is needed for satisfactory working of HVAC system. There are many common things in design of condenser and evaporator, as both are heat exchangers. The basic difference between them is, refrigerant in condenser losses the heat and gains the heat in evaporator. So, condenser works as heat sink while evaporator works as heat source. The one of the constraint while designing evaporator is, no freezing or frosting takes place within the system.

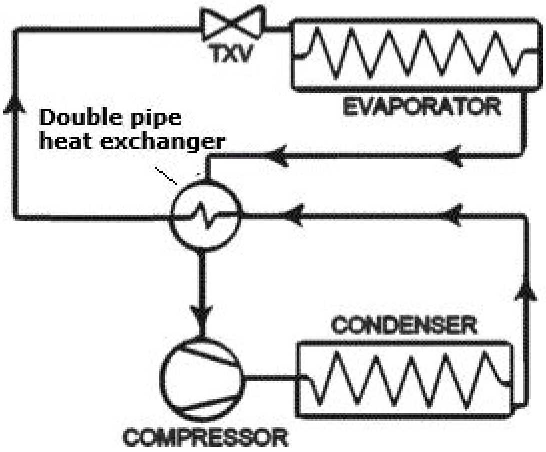


Figure 4.5: Symmetric diagram of modified AC system

Double-pipe heat exchanger (DPHEX)(figure. 4.5) is suggested to achieve the objective of subcooling and superheating together. Copper is used as material for annulus and tube construction. The refrigerant coming out from evaporator is used as the cold fluid in DPHEX. The flow through DPHEX is counter flow as irreversibility of counter flow is low, which means uniform heat transfer between hot and cold fluid. Some calculations are carried out for optimizing the design of DPHEX. The design parameters of DPHEX are refrigerant mass flow rate and length of DPHEX. We have considered design parameters as variable inputs and with some constant input like properties of fluid, material properties, diameter and thickness of DPHEX. The design parameter is selected according to results of experiments. Taguchi's full factorial design has been selected as experimental method. Total 48 experimentations have been carried out for all factors and levels of Taguchi's full factorial design. Factors and levels combination are described in table 4.1.

Table 4.1: Taguchi's Factors and Levels Combination

Factor & Level	1	2	3	4
Mass flow rate (kg/s)	0.17	0.34	0.51	0.68
Ambient temperature ($°C$)	30	35	40	45
Length (m)	1	1.5	2	-

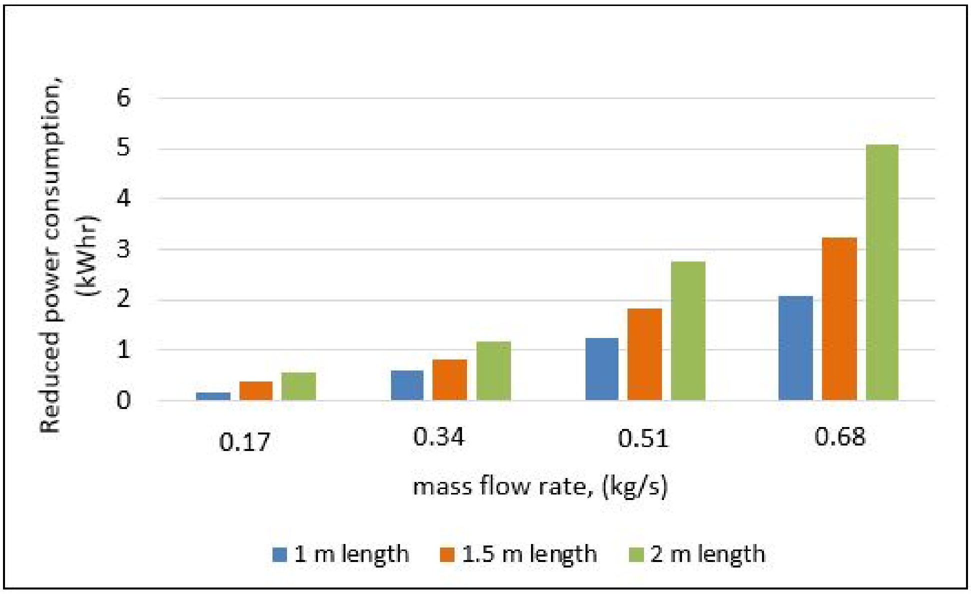


Figure 4.6: Reduced Power Consumption vs Design Parameters

Figure 4.6 shows the results of experiments. The experiments demonstrated that there is negligible effect of ambient temperature. Major parameters are length of heat exchanger and mass flow rate of refrigerant. The specification of DPHEX is shown in table 4.2. The double-pipe heat exchanger is implemented in the vehicle. One reference vehicle is establish as target for manufacturer and tests have been done and compared with reference vehicle. Initial results gives the base point which is without any modification in existing design. Here, we have assumed reference vehicle fuel economy as 100 percentage points and all other readings are in terms of 100. As the fuel economy of base vehicle is 89.44 which is lower than the fuel economy of reference vehicle.

Table 4.2: DPHEX specification

Parameter	**Estimated value**
Material	copper
Mass flow rate of refrigerant (kg/s)	0.68
Annulus inner diameter (mm)	38
Tube outer diameter (mm)	28
Tube inner diameter (mm)	25
Length (m)	2

The result shows that initial compressor on time of vehicle is 99.47% and compressor on time of vehicle after modification is 36.15% (fig 4.7). The power consumption of compressor is reduced to 3.42 $kWhr$ from 8.48 $kWhr$ which shows 59.66% of energy saving. Figure 4.8 shows fuel economy is improved with 16.16%.

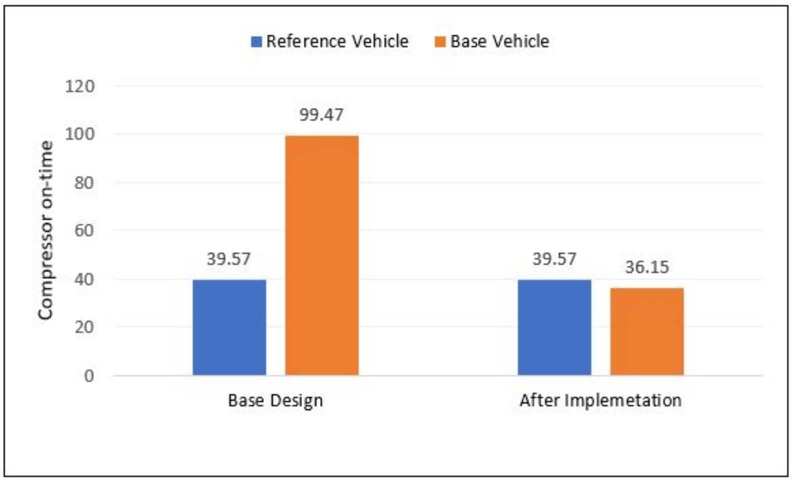


Figure 4.7: Comparison of compressor on-time after implementation

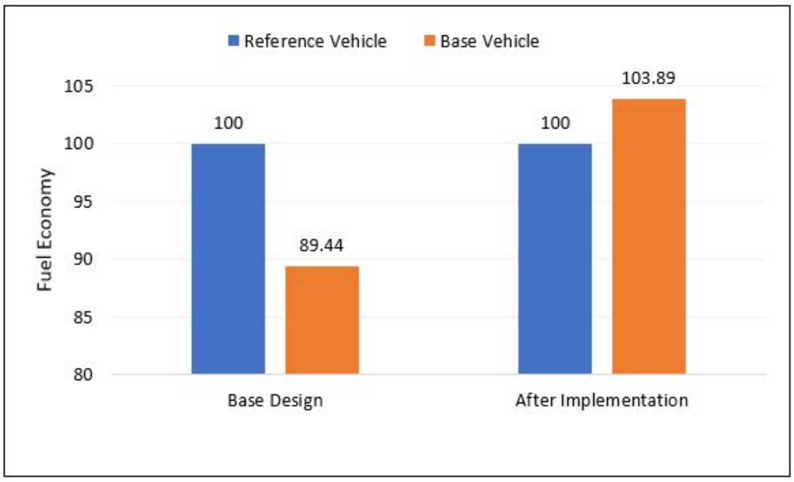


Figure 4.8: Performance of vehicle in terms of fuel economy

Chapter 5

Summary, Conclusion and Scope for Future Work

5.1 Summary

Automobile sector is developing at rapid speed and for commercial vehicle which consumes significant fuel per day, it is necessary to improve fuel economy of commercial vehicle as it directly affect manufacturer to last consumer. The main aim of research work is to reduce fuel consumption which may indirectly balance climate. The thesis work is divided into two parts. In first part, thermal management is adapted and studied all parameter which affect thermally on vehicle while developing new vehicle. The comprehensive model is developed to calculate thermal load of any vehicle. In second part, flow parameter is studied; we found suction and discharge pressure as important parameters. The double-pipe heat exchanger is implemented in existing vehicle. The results shows significant improvement in performance.

5.2 Conclusion & future scope

As, driver fatigue is believed to be one of the main causes of road accidents, the HVAC system becomes a compulsion part for commercial vehicle now-a-days. Precise thermal load calculation is basic requirement for selection and design of the HVAC system. There are many experimental and theoretical methods for estimating thermal load. All industries are applying the value engineering for their product development. One of the aspects of the value engineering is utilization of existing resources effectively and bring out information at early stage of design. The simple, accurate and fast tool for calculating the thermal load and validation of the tool on actual vehicle. Outcome of this research gives a comprehensible tool for estimation and analysis of the HVAC system thermal load which helps automobile industry.

Improvement of air conditioner performance of new vehicle have more options, but for enhancing the performance of existing system we have less options because of so many constraints. In this research, we have modified the existing design with addition of double pipe heat exchanger after condenser. We have used low pressure vapor refrigerant coming out from evaporator to lower temperature of high-pressure liquid refrigerant coming out from condenser and augmented the heat transfer at high pressure side of automobile air-conditioner system. The main outcomes of the proposed work are design optimization of double-pipe heat exchanger, proper fitment of the same and improved air conditioner performance.

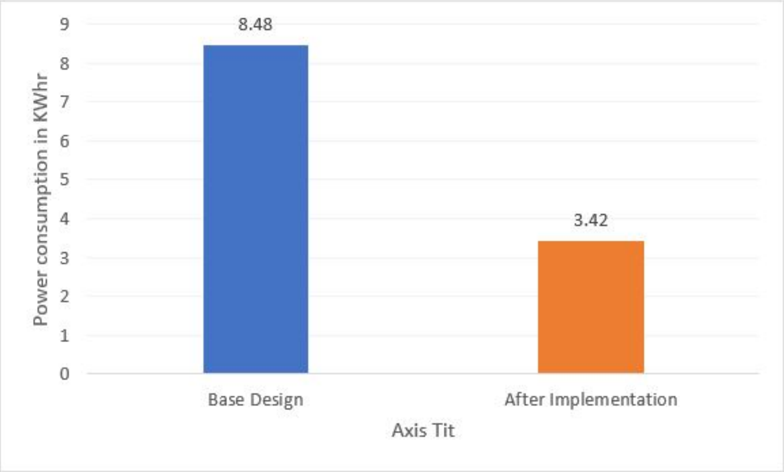


Figure 5.1: Reduced power consumption

The main conclusions extracts from this research work are:

- The automotive thermal management model has been validated on two commercial vehicles. The thermal load for vehicle ABC and XYZ are 4189.5882 W and 11641.8536 W respectively, where for cooling load it will come with negative sign and for heating load it will come with positive sign.
- Real-time case studies have been performed on vehicle and tested on specific route with three trials. The fuel economy is improved by 16.16% and 5.06 $kWhr$ energy is saved. Easy implementation of double-pipe heat exchanger in existing system is supplementary advantage of proposed work.

We can further enhance the performance by using renewable energy like solar to improve fuel economy.

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Publications from The Research Work

1. Y. H. Vaid, S. Apte, D. M. Mani, S. K. Mohapatra, S. Fartade, R. Shah, ”Augmentation in heat transfer by addition of double-pipe heat exchanger in automobile air-conditioning system,” in 4^{th} *International Conference on Recent Multidisciplinary Research*, submitted for publication.
2. Y. H. Vaid, S. Apte, D. M. Mani, S. K. Mohapatra, S. Fartade, ”Prediction of vehicle thermal load using MATLAB GUI model,” in 26^{th} *National Conference on IC Engine and Combustion*, unpublished manuscript.