

International Journal of Innovative Research in Science, Engineering and Technology

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 5, May 2015

Cooling Load Calculation and Thermal Modeling for Vehicle by MATLAB

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ABSTRACT: The heating load calculation is based on peak or near-peak conditions, which normally occur early in the morning before sunrise, in addition, in cold countries, the ambient temperature variation during the winter months is not significant. The development of air conditioning system has been growing rapidly due to people needs of having comfortable condition. The cooling system is one of the important systems, because it is related to passenger comfort and important to study transient response of vehicle under real driving conditions. The procedure of this research is a simulation analysis using MATLAB program that uses mathematic equation, make the cabin model, etc. The heat occurred in the cabin consists of metabolic, direct, diffuse, reflected, ambient, exhaust, engine, ventilation, and AC loads has been calculated with three different time's condition which is performed using cooling load simulation tool of MATLAB/GUI. A negative cabin load is provided to the cabin in order to decrease its temperature to the comfort level.

KEYWORDS: Cooling load, Cabin load, MATLAB, Air Conditioning System.

I. INTRODUCTION

Region in Indonesia, mostly less gives in driving because it is hot (24-28°C), dirty (Dust, smoke) and the wind speed is not erratic. Due to these hot condition; community complains because it can cause disruption of concentration in driving. The heating load calculation is based on peak or near-peak conditions, which normally occur early in the morning before sunrise. In addition, in cold countries the ambient temperature variation during the winter months is not significant. Hence, in conventional heating load calculations, the effects of solar radiation and ambient temperature variation are not considered and heat transfer is assumed to be steady.

The development of air conditioning system has been growing rapidly due to people needs of having comfortable condition. In the automotive field (manufacturer) especially, the air conditioning (AC) was the major attention during the last few decades. The cooling load is a calculation that determines the amount of energy (heat) that needs to be extracted from a structure to maintain the inside temperature. The goal is to create or build a structure with maximum efficiency to reduce the cost with cooling. Cooling load calculation should be conducted before designing the air conditioning system where the amount of cooling load will affect the environment, thus the comfort will be gained.

The cooling system is one of the important systems, because it is related to passenger comfort and important to study transient response of vehicle under real driving conditions. Which meansthat the source of excitation comes from the driver who controls the vehicle itself.The cooling load transient analysis is performed using MATLAB. Kiss et al. [1] described a MATLAB based transient A/C system simulation model is easier to incorporate into MATLAB based vehicle simulation software. Therefore, the availability of a transient A/C system simulation tool developed in the MATLAB/GUI platform is important.

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II. THEORY

Calculation of MATLAB can be reached up to five decimal points. In other word, calculating the percentages of errors indicate that calculation using MATLAB is more accurate than manual calculation. Because of the number of decimal pointsthat's been taking, while manual calculation was three decimal points [2]. Fayazbakhsh et al. [3] estimate the heating and cooling loads encountered in a vehicle cabin using heat Balance Method. Efficient design of mobile air conditioning (AC) has been the center of attention of automotive manufacturers and academic researchers during the last few decades. In order to maintain passenger thermal comfort the air conditioning systems should be designed to compensate for the continuous changes of the cabin thermal loads.

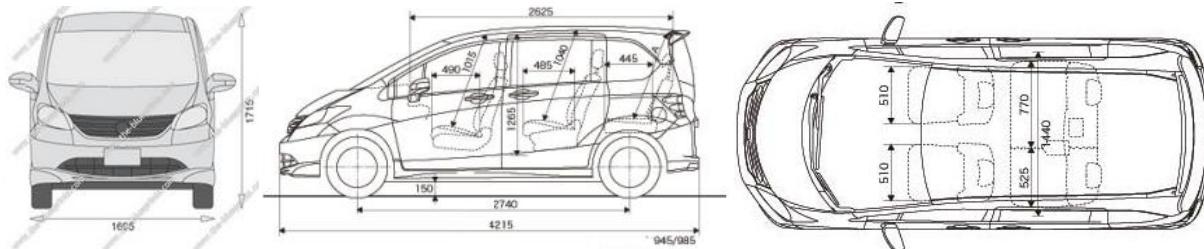


Figure 1.Dimensions of Honda Freed (www.HondafreedIndonesia.com).

The design cooling load (or heat gain) is the amount of heat energy to be removed to maintain the room at indoor design temperature. When worst case outdoor design temperature is being experienced. The mathematical formulation of the model can thus be summarized as follows:

$$Q_{Tot} = Q_{Met} + Q_{Dir} + Q_{Dif} + Q_{Ref} + Q_{Amb} + Q_{Exh} + Q_{Eng} + Q_{Ven} + Q_{AC}$$

Where: Q_{Tot} is net overall thermal load encountered by the cabin, Q_{Met} is metabolic load, Q_{Dir} is direct load, Q_{Dif} is diffuse load, Q_{Ref} is reflected radiation load, Q_{Amb} is ambient load, Q_{Exh} is exhaust load due to high temperature, Q_{Eng} is engine load due to high temperature, Q_{Ven} is load generated due to ventilation, and Q_{AC} is thermal load created by AC cycle.

MATLAB is a high-level language and interactive environment for numerical computation, visualization, and programming. MATLAB has many functions such as can analyze data, develop algorithms, and create models and applications. Develop a graphic user interface(GUI) - To make the programs that will be developed user-friendly type. GUI (graphic user interface) will be developed, so that any person without knowing the detail of the program can run and have the cooling load of a vehicle.

III. METHODOLOGY

The procedure of this research is a simulation analysis using MATLAB program that uses mathematic equation. The steps that should be done in this study area: Modeling platform, Making program by MATLAB, Data input, Result analysis.

The MATLAB/GUI was well suited the simulation modeling platform. The model should be validated for measurement data that has been used. Measurement has to be sufficient for validating the available model, so it can be performed well. Humans need energy to work and produce heat to maintain a body temperature of around 37° C. Environmental conditions and clothing required for comfort will directly depend upon metabolic heat production.

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Table 1 Classification of metabolic rates by activity [4]

Class	Mean metabolic rate Wm ⁻²	Example
Resting	65	Resting
Low	100	Sitting at case/standing
Moderate	165	Sustained hand/arm work
High	230	Intense work
Very high	290	Very intense to maximum activity

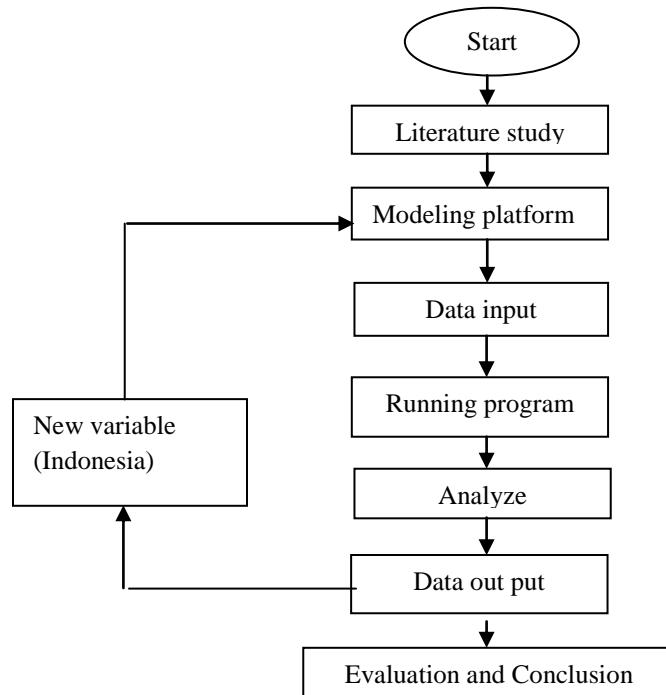


Figure 2. Flowchart of research

IV.RESULT AND DISCUSSION

The cooling load calculation is presented on the basis of some parameters such as metabolic load, direct load, diffuse load, reflected load, ambient load, exhaust load, engine load, ventilation load, and AC load. The cooling load in the car cabin was calculated by the GUI program from MATLAB software.

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Table 2. Specification of cooling load at different condition

Thermal Load	Heat Transfer (W)					
	13:00	13:30	14:00	14:00	15:00	15:30
Q_{Met}	413.05	413.05	413.05	413.05	413.05	413.05
Q_{Dir}	2165.24	1329.94	674.45	-765.94	-870.84	-602.63
Q_{Diff}	351.27	281.39	449.04	167.16	185.45	114.76
Q_{Reff}	0	0	0	0	0	0
Q_{Amb}	210.3	233.4	222.78	220.1	216.09	213.5
Q_{Exh}	0	0	0	0	0	0
Q_{Eng}	0	0	0	0	0	0
Q_{Ven}	310	320	345	360	390	410
Q_{AC}	-3501.4	-2622.88	-2168.38	-440.305	-381.305	-590.475
Q_{TOTAL}	-511.63					

Metabolic Load

The assumption in this study was considered taking into account 1 driver and 3 passengers to calculate the heat in the cabin due to human metabolism. To process the GUI program for metabolic load, the weight and height of the driver and passenger were included to obtain the heat result.

$$Q_{Met} = \sum_{Passenger\ s} MA_{Du} \quad (1)$$

Where M is the passenger metabolic heat production rate. It is found from the tabulated values in ISO 8986 [4]. For a driver and a sitting passenger, the values can be estimated as 85 w/m^2 and 55 w/m^2 , respectively. The Dubois is area A_{Du} which is an estimation of the body surface area as a function of height and weight is calculated by:

$$A_{Du} = 0.202W^{0.425}H^{0.725} \quad (2)$$

Where W and H are the passenger weight and height respectively.

Direct Load

Direct load was one of solar radiation calculation. In this case, mid-summer condition was taken with 1069 W/m^2 for apparent solar irradiation and atmospheric extinction coefficient takes a value of 0.205, where surface element transmissivity was 0.5.

$$Q_{Dir} = \sum_{surface} S \tau I_{Dir} \cos \theta \quad (3)$$

Where I_{Dir} is the direct radiation heat gain per unit area and θ is the angle between the surface normal and the position of sun in the sky. τ is the surface element transmissivity and S is the surface area, respectively. Before local sunrise and after local sunset, simply no radiation loads are considered. The direct radiation heat gain per unit area is found by

$$I_{Dir} = A / \exp(B / \sin(\beta)) \quad (4)$$

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Where A and B are constants tabulated in ASHRAE Handbook of Fundamentals[5] for different months. β is the altitude angle that is calculated based on position and time. The direct radiation loads are important air-conditioning loads that influence the temperature in the cabin. The direct radiation load increases due to the increase in the sun altitude angle which is happening in the simulation.

Diffuse Load

Diffuse radiation is the part of solar radiation, which results from indirect radiation of daylight on the surface. The diffuse radiation factor takes a value of 0.228 with surface element transmissivity of 0.5.

$$Q_{Dif} = \sum_{surface} S \tau i_{Dif} \quad (5)$$

i_{Dif} is the diffuse radiation heat gain per unit area which is calculated from

$$i_{Dif} = C i_{Dir} (1 + \cos(\varepsilon)/2) \quad (6)$$

where ε is the surface tilt angle measured from the horizontal surface and the value for C are tabulated in [5].

Diffuse radiation distribution inside the cabin is independent of the solar angle. For other orientations the effect of latitude is more evident, but not so influential. The diffuse load increases due to the increase in the sun altitude angle.

Reflected Load

The value of reflectivity obviously depends on the surface property on the ground. The reflectivity of the ground or a horizontal surface from where the solar radiation is reflected on to a given surface was 0.02.

$$Q_{Ref} = \sum_{surface} S \tau i_{Ref} \quad (7)$$

i_{Ref} is the reflected radiation heat gain per unit area, is calculated form

$$i_{Ref} = (I_{Dir} + i_{Dif}) \rho g (1 - \cos(\varepsilon)/2) \quad (8)$$

where ρg is the ground reflectivity coefficient. Based on the absorptivity of each particular surface element, a percentage of incident radiation load can be absorbed by that surface, hence increasing its temperature.

Ambient Load

The increasing in the heat indicates that the weather data effect is very important as the change in the ambient temperature affecting the calculation of the external and internal cooling loads. According to these results, the maximum cooling load is above the cooling capacity of the system occurred in high ambient temperature.

$$Q_{Amb} = \sum_{surface} S U (T_s - T_i) \quad (9)$$

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Where U is the overall heat transfer coefficient of the surface element. T_s and T_i are the average temperature and average cabin temperature, respectively. U has different components consisting of the inside convection, conduction through the surface, and outside convection that can be written in the form

$$U=1/R \text{ where } R=1/h_o + \lambda/k + 1/h_i \quad (10)$$

Where R is the net thermal resistance for a unit surface area. h_o and h_i are the outside and inside convection coefficients, k is the surface thermal conductivity, and λ is the thickness of the surface element. The thermal conductivity and thickness of the vehicle surface thermal can be measured rather easily. The convection coefficients h_o and h_i depend on the orientation of the surface and the air velocity. Here, the following estimation is used to estimate the convection heat transfer coefficients as a function of vehicle speed.

$$h = 0.6 + 6.64\sqrt{V} \quad (11)$$

Where h is the convection heat transfer coefficient in $\text{W/m}^2\text{k}$ and V is the vehicle speed in m/s. Despite its simplicity, this correlation is applicable in all practical automotive instances. The cabin air is assumed stationary and the ambient air velocity is considered equal to the vehicle velocity.

Exhaust Load

Vehicles have an internal combustion engine that creates exhaust gases. The high temperature of the exhaust gas can contribute to the thermal gain of the cabin through the cabin floor. In this condition, assumed the overall heat transfer coefficient of the surface element was 0 $\text{W/m}^2\text{k}$.

$$Q_{Exh} = S_{Exh} U (T_{Exh} - T_i) \quad (12)$$

Where U is the overall heat coefficient of the surface element in contact with the exhaust pipe and it should be calculated by Eq. (12) assuming no external convection since the exhaust temperature is measured at the outer side of the bottom surface. S_{Exh} is the surface area exposed to the exhaust pipe temperature and T_{Exh} is the exhaust gas temperature. The temperature of the exhaust gases in Celsius degrees is estimated by

$$T_{Exh} = 0.138 \text{RPM} - 17 \quad (13)$$

Where RPM is the engine speed in revolutions per minute.

Engine load calculation should be considered on severe operating conditions of the engine installation such as high engine output, low vehicle speed, and/or hot ambient temperatures. The heat transfer capacity of the radiator is dependent on the temperature of ambient air.

$$Q_{Eng} = S_{Eng} U (T_{Eng} - T_i) \quad (14)$$

However, under heavy load and/or during high ambient temperature conditions, engine waste heat may exceed the radiator heat dissipation capacity. If the heat load is not reduced, coolant temperature will rise.

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Where U is the overall heat transfer coefficient of the surface element in contact with the engine and S_{Eng} is the surface area exposed to the engine temperate. The overall heat coefficient can be calculated by Eq (10) assuming no external convection. Since the engine temperature is measured at the outside of the front surface. T_{Eng} is the engine temperature and estimated in Celsius degrees

$$T_{Eng} = -2 \times 10^{-6} RPM^2 + 0.0355 RPM + 77.5 \quad (15)$$

Ventilation Load

It is not efficient to use hot ambient air for ventilation when cooling is required. Therefore, a small amount of ventilation flow rate is assumed to account for the minimum fresh air requirement. As shown in Table 2, the ventilation is causing a heat of more than 300 W in the cabin in this condition.

$$Q_{Ven} = m_{Ven} (e_o - e_i) \quad (16)$$

Where m_{Ven} is the ventilation mass flow rate and e_o and e_i are the ambient and cabin enthalpies, respectively. Enthalpies are calculated from

$$e = 1006T + (2.501 \times 10^6 + 1770T)X \quad (17)$$

Where T is air temperature and X is humidity ratio in gram of dry air. Humidity ratio is calculated as a function of relative humidity by

$$X = 0.62198 \times (\emptyset P_s / 100P - \emptyset P_s) \quad (18)$$

Where \emptyset is relative humidity, P is pressure and P_s is the water saturation pressure at temperature T.

AC Load

AC load is used to maintain the comfort in driving condition. Various thermal loads estimations in vehicle cabins can be an assessment of the dynamic changes to the AC loads that occur in the severe condition.

$$Q_{AC} = -(Q_{Met} + Q_{Dir} + Q_{Dif} + Q_{Ref} + Q_{Amb} + Q_{Exh} + Q_{Eng} + Q_{Ven}) - \frac{(m_a c_a + DTM)(T_i - T_{comf})}{t_c} \quad (19)$$

T_{comf} is the target comfort temperature as described and widely used by ASHARE standards [5]. This is the target bulk temperature which is assumed comfortable at the conditions under consideration. t_c is a pull-down constant which determines the overall pull-down time. Pull –down time is defined as the time required for the cabin temperature to reach the comfort temperature within 1k. Using Eq. (19) for the air conditioning load, the pull –down constant can be calculated from

$$t_c = tp / \ln(T_0 - T_{comf}) \quad (20)$$

Where T_0 is the initial cabin temperature.

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Table 3. AC load calculation

Deep Thermal Mass	6500 J/k
Comfort Temp.	23°C
Cabin Air mass	0.08kg
Specific Heat	1008 (J/Kg.k)
t_c	182.04
Q_{AC}	-3501.4W

In warm conditions, negative AC loads of -3501.4W is required for the cabin. This negative AC load is needed for maintaining the comfort conditions.

Discussion

The cooling capacity needed to satisfy the cooling load in the tested vehicles cabin room under warm weather conditions which is not in the comfort level of 24° C. In this hot weather, a negative cabin load is provided to the cabin in order to decrease its temperature to the comfort level. The heat gain in the cabin due to metabolic load is constant due to no change in the number of passengers. The direct and diffuse radiation loads are another positive load. The direct loads have a greater contribution than diffuse or reflected load. The direct and diffuse radiation load increases due to the increase in the sun altitude angle.

As shown in Figure 3, engine load causes a heat gain more than another. While the AC acts a heat loss of more than 2000W from the cabin in hot condition. Thus, a negative AC load of about -3501.4W is required to maintain the comfort level. Therefore, mobile air conditioning system should be designed to compensate for the temperature changes of the cabin thermal loads. With the existence of AC, the cabin thermal can be maintained due to passenger thermal comfort in this condition.

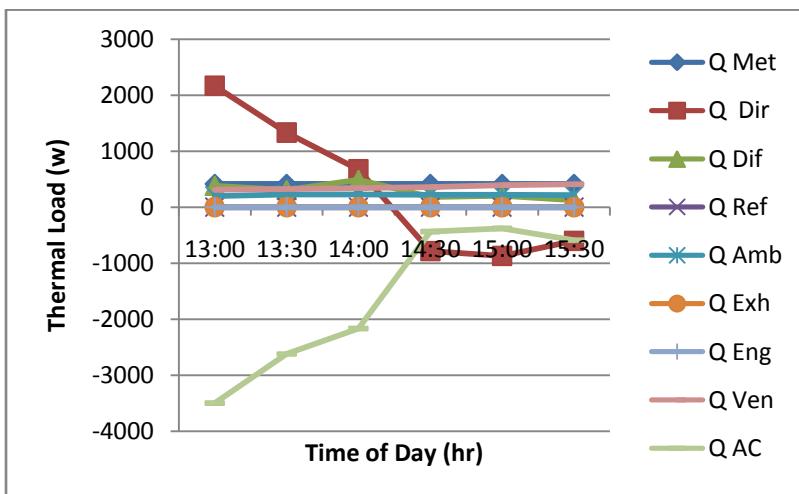


Figure 3Comparison of thermal loads

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Three different times were simulated to find the value of each load categories and standard driving cycle with the comfort level of 24°C is applied in the simulations. The simulation of different times shows that some load categories such as direct, diffuse radiation load are influenced and reflected load is negligible. Metabolic, radiation, ambient, and engine load can play important roles in the variation of cabin temperature.

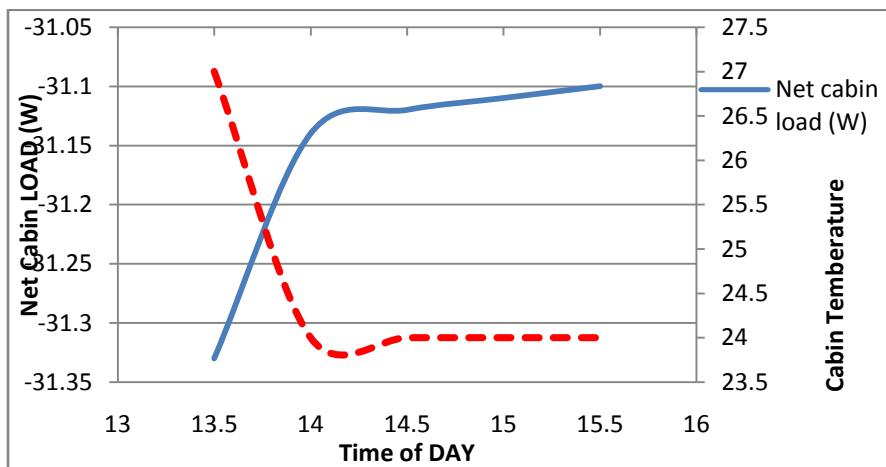


Figure 4 Net cabin load v/s Time v/s Cabin temperature

Figure 4 shows the variation of cabin air temperature with time. The net heat gain in the cabin has been plotted as well. Negative heat values mean heat loss from the cabin, while positive values mean heat gains by the cabin. Figure 4.12 shows that the cabin temperature decreases from a soak temperature of 27°C to the comfort temperature after almost 10 minutes represented by the pull-down time. After the pull-down, a steady-state situation is achieved where the loads are balanced and a zero net load is maintained in the cabin for the rest of the period.

V. CONCLUSION

Based on the research test results, analysis and discussion a conclusion can be as the following:

1. Cooling load simulation tool developer on the MATLAB/GUI has been performed based Honda Freed cabin. The heat occurred in the cabin consists of metabolic, direct, diffuse, reflected, ambient, exhaust, engine, ventilation, and AC loads has been calculated with three different time's condition.
2. In the present study, a negative cabin load is provided to the cabin in order to decrease its temperature to the comfort level. Air-conditioning system has important roles in maintaining the comfort zone in the Honda Freed cabin. A negative AC load of about 2867.2 W is required to maintain the comfort level.

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