COOLING LOAD CALCULATION AND DESIGN OF AIR CONDITIONING SYSTEM IN AUTOMOBILE

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ABSTRACT

Air conditioning system is necessary in automobile to maintain the comfort condition. Therefore it is important to study transient response of vehicle under real driving conditions. The Heat Balance Method (HBM) is used for estimating the heating and cooling loads which develops inside the vehicle cabin. The Load Calculation of Automobile Air Conditioning System is calculated and presented. An hourly cooling load is calculated in Tirunelveli region with respect to its latitude. Tons of refrigeration required is also found out from the cooling load calculation and a review on cooling load calculation is also presented. This study gives overall cooling load and AC power consumption which can be used by HVAC engineers to design more efficient car AC systems. Only by knowing the cooling load and source of thermal load, we can develop intelligent system to reduce AC consumption.

Keywords: Automobile, Automobile air conditioning, Solar radiation load, Cooling load, Tons of refrigeration.

1. INTRODUCTION

Air conditioning operation has direct impact on emission and fuel economy. The cooling system is important for the passenger comfort and thus it is important to study the transient response of vehicle under real day light condition. The cooling load is a calculation that determines the amount energy (heat) that needs to be extracted from the cost with cooling. So after calculating the cooling load we can develop a system and structure with good efficiency to reduce the cost of cooling. Efficient design of mobile air conditioning (AC) has been the center of attention of automotive manufacturers and academic researchers during the last few decades. Reduction of fuel consumption and tailpipe emission are two crucial targets for the auto industry [3]. This paper aims to provide a new and comprehensive model for estimating thermal loads in vehicle cabins. AC operation had a substantial impact on emission and fuel consumption. Operation of vehicle AC system over a range of environmental condition resulted in consisted increase in vehicle emission of nitrogen oxides (NO_x) and carbon monoxide (CO). NO_x increase from 0.1 to 0.6 g/mile, depending on the ambient conditions. CO increased from 0.5 to 12g/mile. NO_x emission increases due to the use of AC range from 15% to 100% of baseline values [1]. The AC power consumption of mid-size cars is estimated to be higher than 12 -17% of the total vehicle power during regular commuting [2]. ASHRAE

Handbook of Fundamentals [4] provides two major thermal load calculation methodologies: Heat Balance Method (HBM) and Weighting Factor Method (WFM). HBM is the most scientifically rigorous available method and can consider more details with less simplifying assumptions. An advantage of HBM is that several fundamental models can be incorporated in the thermal calculations. Although HBM is more accurate than WFM, it is easier to implement WFM for load calculation in a passenger vehicle. However, when more detailed information of the vehicle body and thermal loads is available, HBM is the preferred choice [5]. Curtis O. Pedersen [6] paper has presented a complete formulation of a heat balance procedure for determining cooling loads. From this paper how heat balance is formulated to calculate cooling load is studies. Zheng. Y[7] devised a simple method to calculate vehicle's thermal loads. They calculated the different loads such as the radiation and ambient loads. A case study was performed and the results were validated using wind tunnel climate control tests. The different loads were separately calculated and summed up to give the total heat gain or loss from the cabin. Ergonomics of the Thermal Environment - Determination of Metabolic Heat Production [8] provides passenger metabolic heat production rate based on various criteria such as occupation and activity levels. Huajun Zhang [9] analyze the temperature and air-flow field inside the passenger compartment to ameliorate the amenity and decrease energy consumption.

This paper uses commercial software FLUENT to simulate 3-D temperature distributions and flow field in a compartment with or without passengers. He suggested that the air flow and temperature fields are definitely the most important factors that contribute to thermal comfort. Ozgur Solmaz [10] uses Artificial Neural Networks (ANNs) method for prediction hourly cooling load of a vehicle. He suggested that ANN method can be very effective as it is simpler and does not use so many input parameters like the analytical model. OumSaad Abdulsalam [11] calculated heat occurred in the cabin consists of metabolic, direct, diffuse, reflected, ambient, exhaust, engine, ventilation, and AC loads. The cooling load transient analysis is performed using MATLAB simulation tool. Md Shahid Imam [12] designed a air conditioning system for a Volvo bus. He obtained the final output as 8.25 tons of refrigeration. Ashok Patidar [13] predicted the thermal comfort of the vehicle cabin using computational fluid dynamics. By CFD air flow analysis he determines the soaking analysis gives a realistic distribution of temperature inside the cabin. Alex Alexandrov [14] uses two and three-dimensional computer simulations to address issues of climate control and performance of Heating, Ventilation and Aero-Conditioning (HVAC) system of a generic passenger car. O. Kaynakli [15] investigate the effects of automobile interior conditions resulted by heating and cooling process. The effects of interior environmental conditions on the human physiology and comfort in heating and cooling processes are introduced. Wei and Dage [16] developed an intelligent cabin climate control system based on human-sensory response to comfort factors. Vijayakumar Nachimuthu, Prabhu Mani, Muthukumar. P [17] studied the use of PCM to control the heat generated inside a car cabin due to solar radiation and with the help of CFD, a comparative analysis are executed. Khayyam [18] presents an energy management system to reduce the energy consumption of a vehicle when its Air conditioning system is in use. The system controls the mass flow rate of the air by dynamically adjusting the blower speed and air-gates opening under various heat and loads circumstances. Hamid Khayyam

[19] uses thermal load combine with a fuzzy logic air conditioning enhanced look- ahead system which estimated future road slope within a distance ahead of the vehicle. They showed that 12% energy consumption savings can be achieved using their proposed enhanced fuzzy system.

2. METHODOLOGY AND LOAD CALCULATION

A lumped model of a vehicle cabin was considered for thermal load calculation. Several loads act on the vehicle cabin and they are classified under nine different categories. The summation of all the load types will be the instantaneous cabin overall heat load gain. The mathematical formulation of the model can thus be summarized as

$$\dot{Q}_{Tot} = \dot{Q}_{Met} + \dot{Q}_{Dir} + \dot{Q}_{Dif} + \dot{Q}_{Ref} + \dot{Q}_{Amb} + \dot{Q}_{Exh} + \dot{Q}_{Eng} + \dot{Q}_{Ven} + \dot{Q}_{AC}$$

Figure 1 schematically shows the various thermal load categories encountered in a typical vehicle cabin. Some of the above loads pass across the vehicle body plates/parts,while others are independent of the surface.

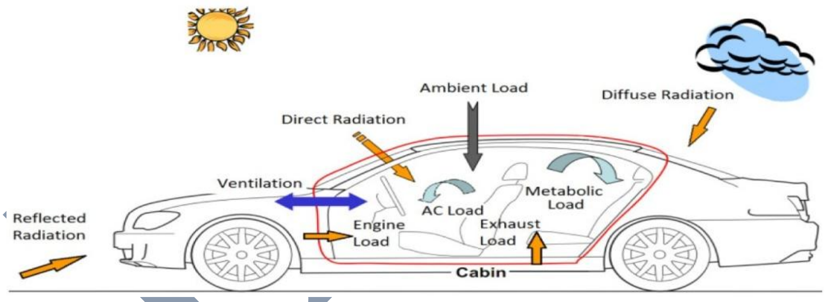

Figure 1: Various thermal load

Metabolic Load:
This amount is considered as a heat gain by the cabin air and is called the metabolic load. The metabolic load can be calculated by

$$\dot{Q}_{Met} = \sum_{Passengers} MA_{Du}$$
$$A_{Du} = 0.202W^{0.425}H^{0.725}$$

SOLAR RADIATION LOAD: Direct radiation is that part of the incident solar radiation which directly strikes a surface of the vehicle body, which is calculated from

$$\dot{Q}_{Dir} = \sum_{Surfaces} S\tau\dot{I}_{Dir}\cos\theta$$

Diffuse radiation is the part of solar radiation which results from indirect radiation of daylight on the surface. During a cloudy day, most of the solar radiation is received from this diffuse radiation. The diffuse radiation heat gain is found by

$$\dot{i}_{Dir} = \frac{A}{\exp\left(\dfrac{B}{\sin\beta}\right)}$$

$$\dot{Q}_{Dif} = \sum_{Surfaces} S\tau\dot{i}_{Dif}$$

$$\dot{i}_{Dif} = C\dot{i}_{Dir}\frac{1+\cos\Sigma}{2}$$

$$\dot{i}_{Ref} = \left(\dot{i}_{Dir} + \dot{i}_{Dif}\right)\rho_g\frac{1-\cos\Sigma}{2}$$

Reflected radiation refers to the part of radiation heat gain that is reflected from the ground and strikes the body surfaces of the vehicle. The reflected radiation is calculated by

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.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.**

$$\dot{Q}_{Ref} = \sum_{Surfaces} S\tau\dot{i}_{Ref}$$

$$\dot{Q}_{Amb} = \sum_{Surfaces} SU\left(T_s - T_i\right)$$

$$U = \frac{1}{R} \quad \text{where} \quad R = \frac{1}{h_o} + \frac{\lambda}{k} + \frac{1}{h_i}$$

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

$$\dot{Q}_{Exh} = S_{Exh}U\left(T_{Exh} - T_i\right)$$

$$T_{Exh} = 0.138RPM - 17$$

ENGINE LOAD: 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.

$$\dot{Q}_{Eng} = S_{Eng}U\left(T_{Eng} - T_i\right)$$

Ventilation Load: It is not efficient to use hot ambient air for ventilation when cooling is required.

$$T_{Eng} = -2\times10^{-6} RPM^2 + 0.0355 RPM + 77.5$$

Qv = □ Vr C ΔT

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

$$\dot{Q}_{AC} = -\begin{pmatrix} \dot{Q}_{Met} + \dot{Q}_{Dir} + \dot{Q}_{Dif} + \dot{Q}_{Ref} + \\ \dot{Q}_{Amb} + \dot{Q}_{Exh} + \dot{Q}_{Eng} + \dot{Q}_{Ven} \end{pmatrix} - \left(m_a c_a + DTM\right)\left(T_i - T_{comf}\right)/t_c$$

$$t_c = \frac{t_p}{\ln\left|T_0 - T_{comf}\right|}$$

3. CABIN GEOMENTRY

In order to perform the energy simulations of the present model, the geometry of the cabin should be known. The simplified vehicle cabin is given below

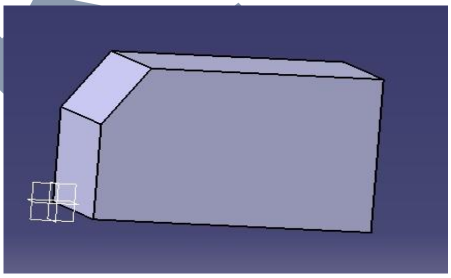

Figure 2: Vehicle Cabin

4. RESULTS AND DISCUSSION

The vehicle is assumed to be driving approximately towards south. It's assumed that cooling load calculation is done in the month of May 15. Cooling load is estimated for the transient period from 10.00 am to 4.00 pm. 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 23° 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. The table below gives the overall load acting on the vehicle cabin.

Time	Qmet	Q direct	Q diffuse	Q ref	Q amb	Q esh	Q eng	Q ven	Q AC	Q total
10.00AM	486.825	992.9154946	140.5925517	0	-119.934236	0	0	-464.14	-3190.52881	-2154.27
10.30AM	486.825	947.1512934	141.7535141	0	-118.8913296	0	0	-460.104	-3151.004478	-2154.27
11.00AM	486.825	777.72285	142.6961809	0	-117.32697	0	0	-454.05	-2990.137061	-2154.27
11.30AM	486.825	852.3522126	143.2917409	0	-116.023337	0	0	-449.005	-3071.710617	-2154.27
12.00PM	486.825	855.8610526	171.541	0	-114.719704	0	0	-443.96	-3109.817349	-2154.27
12.30PM	486.825	852.3522126	143.2917409	0	-113.416071	0	0	-438.915	-3084.407883	-2154.27
13.00PM	486.825	775.6782338	142.6961809	0	-112.112438	0	0	-433.87	-3013.486977	-2154.27
13.30PM	486.825	946.3698154	141.6365558	0	-110.808805	0	0	-428.825	-3189.467566	-2154.27
14.00PM	486.825	987.2555529	139.7911283	0	-112.112438	0	0	-433.87	-3222.159243	-2154.27
14.30PM	486.825	976.6249056	137.5508859	0	-113.416071	0	0	-438.915	-3202.93972	-2154.27
15.00PM	486.825	935.4623115	134.0074204	0	-114.719704	0	0	-443.96	-3151.885028	-2154.27
15.30PM	486.825	866.2195834	129.3620992	0	-116.023337	0	0	-449.005	-3071.648346	-2154.27
16.00PM	486.825	866.1373893	143.7717802	0	-117.32697	0	0	-454.05	-3079.6272	-2154.27

Since cooling is done, the load is negative.

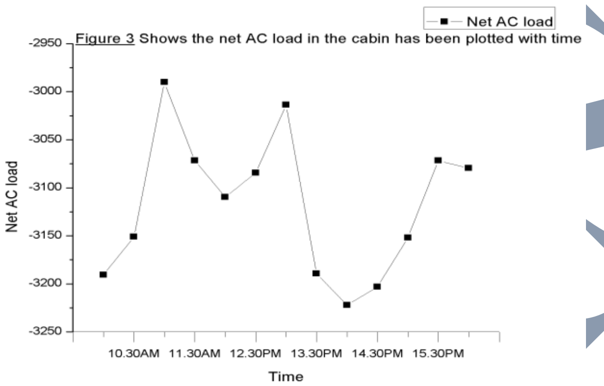

Figure 3 Shows the net AC load in the cabin has been plotted with time

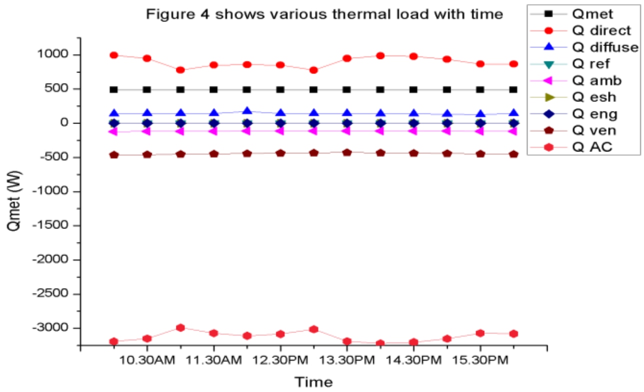

Figure 4 shows various thermal load with time

5. CONCLUSION

Using heat balance method, the heat occurred in the cabin consists of metabolic, direct, diffuse, reflected, ambient, exhaust, engine, ventilation, and AC loads has been calculated. A cooling load of negative value of 2154.27W is estimated. To design AC refrigeration 0.76 tons of refrigeration is needed.

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NOMENCLATURE

A - Apparent Solar Irradiation at Air Mass = 0 (W/m^2)

ADu – DuBois Body Surface Area (m)

B - Atmospheric Extinction Coefficient

c - Specific Heat (J/kg K)

C - Diffuse Radiation Factor

DTM - Deep Thermal Mass (J/K)

e - Enthalpy (J/kg)

h - Convective Heat Transfer Coefficient(W/m^2K)

H - Human Body Height (m)

İ - Radiation Heat Gain per Unit Area (W/m^2)

K - Conductive Heat Transfer Coefficient (W/mK)

M - Mass (kg)

ṁ - Mass Flow Rate (kg/s)

M - Metabolic Rate (W/m^2)

P - Air Pressure (Pa)

Ps - Water Saturation Pressure (Pa)

R - Surface Overall Heat Transfer Resistance (m^2K/W)

RPM - Engine Revolutions per Minute (1/min) **S** - Cabin Surface Element Area (m^2)

Tc - Pull-Down Constant (s)

t - Pull-Down Time (s)

o

T - Temperature (K)

Greek Letters

α - Absorptivity

β - Altitude Angle (°)

Δ*t* - Time Step Size (s)

Δ*T* - Temperature Change (K)

ϕ - Relative Humidity (%)

λ - Surface Element Thickness (m)

θ - Angle between Surface Normal and Sun Position (°)

ρ - Density ($kg/m3$)

ρg - Ground Reflectivity

Σ - Surface Tilt Angle from Horizon (°)

τ - Transmissivity

Subscripts

a - Cabin Air

AC - Air Conditioning

Amb - Ambient

comf - Comfort

Dif - Diffuse Radiation

Dir - Direct Radiation

Eng - Engine

Exh - Exhaust

i - Inside

Met - Metabolic

New - New Time Step

o - Outside

old - Old Time Step

T_0 - Initial Cabin Temperature (K)

U - Surface Overall Heat Transfer Coefficient (W/m^2K)

V - Vehicle Speed (m/s)

W - Human Body Weight (kg)

X - Humidity Ratio (kg water/kg dry air)

Rad - Radiation