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"Air Conditioning Heat Load Analysis of a Minibus Passenger Cabin Considering Radiation Effect"

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***Abstract* –** The design of minibus is to maintain the thermal comfort under the fluctuating driving conditions like the heavy summer condition and the highway and during the city traffic. The design of bus HVAC duct is to be designed for carrying conditioned air, divide the air so that it gives uniform air temperature distribution inside passenger compartment.

In Indian market the minibus segment is very popular as well as in global market also. due to the unstable global climate change, which means longer hot summer and shorter winter season the HVAC requirement is increases in automotive segment. The customers also need a promising HVAC unit, which not only maintains the thermal comfort efficiently under fluctuating ambient temperature but also helps to get the class-A comfort as per ASHRAE Standard. The thermal comfort of occupant in passenger compartment has become more important due to their increasing mobility leading to more time spent by people inside vehicle.

The authors suggest that the proposed model can be used in early stages of passenger cabin design to reduce CFD modelling effort and time of Cool Down Simulation. This tactic is very effective in designing efficient HVAC for electric buses, since an HVAC directly consumes energy stored in battery results in low travelling range.

INTRODUCTION

A heating, ventilation, and air conditioning (HVAC) system in a vehicle is used to control the internal temperature of the vehicle cabin. It includes three subsystems, namely, heating, cooling, and air conditioning, that work together to provide purified air to the vehicle cabin, ensuring thermal comfort for drivers and passengers. The first challenge to properly size a vehicle A/C system is to define the vehicle air conditioning heat load requirement. Within automotive industry, a model to accurately define vehicle heat load is still under development.

Total Heat load for minibus ranges from 9kw to 14kw depending upon various design factors such as glass area, glass inclination, seating capacity and engine capacity. The summation of all loads encountered by cabin is total heat load of vehicle This total heat load should be taken away by HVAC.

2. MODEL DEVELOPMENT

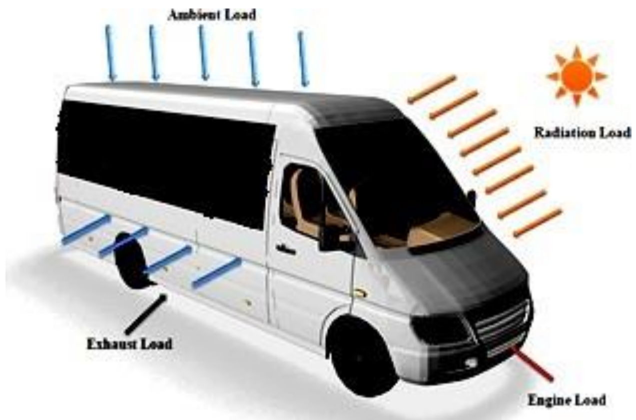

Fig. 1. Schematic illustration of thermal loads in a Minibus Passenger cabin. [8]

The summation of all load encountered by cabin is total heat load of vehicle. The cooling capacity of selected HVAC system should greater than estimated heat load to achieve comfort conditions. Selection of evaporator capacity is highly depends on heat load. Fig 1. Above showsvarious heat loads. The major heat load is due to solar radiations. Radiations falling on vehicle body causing surface temperature to increase. IC engine is prime mover tovarious conventional vehicles; it produces heat depending on operating parameters. Some input values used in thepresent model are based on experiments performed on baseline model under solar load in wind tunnel.

Some components of load pass through the vehicle body panels, while others are sovereign of the geometric parameters of the vehicle cabin. By heat balance the mathematical model of the heat load can thus be summarized as [4]

$$Qtotal = Qocc + Qdir + Qdif + Qref + Qamb + Qexh + Qeng + Qair \quad (1)$$

Heat load is calculated in terms of heat energy / time (Q) in Kw. $QTotal$ is the total heat ingress in vehicle cabin under specified conditions. Qocc is the occupant load. Qdir, Qdif and Qref are the direct, diffuse, and reflected solar radiation loads respectively. Qamb is the ambient load. Qexh and Qeng are the heat ingress in cabin due to due to heat loss by exhaust gases and the engine. Finally Qair is the thermal load to condition cabin air.

A. Occupants Load

Due to metabolic activity inside human body continuously creates heat which passes through the body muscles and tissues and at last to skin. Also due to perspiration latent heat is released in environment. The sum of sensible and latent heat is taken as thermal load due to occupants. The occupant load can be determined by

$$Qmet = Z\,M \times A_{du} \tag{2}$$

Where M is the metabolic heat production rate of occupant. It depends on many factors such as activity level, occupation, age and sex. It is found from ISO 8996 table. , is the DuBois area which is surface area of body depends on height and weight, is determined by [4]

$$A_{du} = 0.202 \times W^{0.425} \times H^{0.725} \tag{3}$$

As per ASHRAE Fundamentals 75 W (sensible heat) and 55 W (latent heat) are the values for a driver and occupant seated and doing light work.

B. Radiation Load

Solar radiation is a most important part of the heat load encountered by cabin. The solar load can be through direct radiation through glasses, and through conduction between

the environment and cabin. Solar radiation has three components direct, diffuse and reflected radiation load.

1) i). Direct Radiation

Direct radiation is that received from sun without scattered by the environment. The direct solar flux (energy per unit area-time) striking a surface is denoted by (I_D). Direct radiations falling on surface of the vehicle body at an angle of incidence (θ), given by

$$Q_D = A \times I_D \times \cos\theta \tag{4}$$

Where ( ) is the direct solar radiations heat load in KW and (θ) is angle of Incidence between the Sun's rays and the surface in deg. For a horizontal surface, the surface normal is the local vertical and the incidence angle is equal to the zenith angle. (A) is the exposed surface area in m^2 . The direct solar radiation heat flux (load per unit area) is given by [6]

$$I_D = \frac{A}{e^{\left(B/\sin\beta\right)}} \tag{5}$$

By ASHRAE Handbook of Fundamentals [1] (A) and (B) constants can be calculated for different months. (β) is the angle between the horizontal plane and a line joining the point under consideration with the Sun.

ii). Diffuse Radiation

The diffuse solar radiation is part of total radiations received from the sun. Due to scattering by clouds in the atmosphere its direction changes. The diffuse solar radiation falling on a surface is denoted by (I_d). Diffuse radiation is short wavelength, since short-wavelength radiation is scattered more by the atmosphere. The diffuse radiation heatload is determined by

$$Q_d = A \times I_d \tag{6}$$

Similarly, is the diffuse radiation flux (heat gain per unit area) which is determined by [5]

$$I_d = C \times I_D \times \frac{1+\cos Z}{2} \tag{7}$$

Where (Σ) is the surface inclination angle measured from the horizontal plane and the values for C.

ii). Reflected Radiation

The reflected solar radiation is that which strikes a surface after the radiation is reflected from surrounding surfaces. The reflected radiation is given by,

$$Q_r = A \times I_r \tag{8}$$

(I_r), the reflected radiation heat flux (load per unit area), is calculated from,

$$I_r = \rho \times (I_D + I_d) \times \frac{1+\cos Z}{2} \tag{9}$$

Where (ρ) is the solar reflectivity coefficient of ground. By reflective capability of particular body surfaces, some part of the incident radiation can be reflected by that surface. In general, the solar radiation reflected upon a surface depends on the solar reflectance, orientation and particular location characteristics of the surrounding surfaces.

c. Load through Sheet Metal

Heat transfer through sheet metal is effect of outside convection, conduction and inside convection. Sheet metal parts such as roof, doors, side wall, floor, firewall, and tail gate. Outside skin temperature of sheet metal is obtained by experimentation. The Overall heat transfer coefficient (U) takes in account for different components consisting of the outside convection, conduction through sheet metal, insulation, and inside convection. [7]

$$\frac{1}{U} = \frac{1}{hi} + \frac{t_s}{k_s} + \frac{1}{ho} + \frac{t_i}{k_i} = R_t \qquad (10)$$

$$Q_s = UA\,\Delta T \qquad (11)$$

Where (hi) and (ho) is Heat transfer coefficient inside and outside respectively in W/m2K, (t_s) is Thickness of sheet metal in m, (k_s) is Thermal conductivity of Sheet metal in W/mk, (t_i) is Thickness of insulation, m, (k_i) is Thermal conductivity of insulation in W/mk, (Q_s) is Heat transfer through sheet metal in W.

Air Conditioning Load

To maintain thermal comfort in-cab air must be conditioned to required temperature and humidity. Load is calculated as given below [7]

$$Q_{air} = m \times C_p \times \Delta T \qquad (12)$$

Where (m) is mass of in-cab air, (Cp) is specific heat if air and ΔT is difference between initial in-cab temperatures and required in cab temperature.

III. RESULTS AND DISCUSSIONS

1) Total Heat Load

The cooling heat load calculation is based on maintaining“in-cabin” conditions of (25°C) average interior temperature and (50%) relative humidity. Table 1. shows inputs for heat load calculations.

The vehicle is assumed to be facing towards south. The solar heat load calculation is done by considering month of July. Heat load is estimated for the total time from morning

06.00 am to evening 06.00 pm. In hot and humid conditions,an opposed cabin load is provided to the cabin in order to decrease its temperature up to comfort level by means of evaporator.

TABLE 1. Inputs for Heat Load Calculations

Specification	Value
Date	21 July
Location	Pune,India
Comfort temperature	25°C
Ambient Teamperature	48°C
Cabin RH	50%
Ground Reflectivity	5%
Front Glass Inclination	45°
Side Glass Inclination	90°
Rear Glass Inclination	90°
No of Passengers	13

The heat load due to passengers is constant as metabolic rate is taken as constant, to avoid model complications. Electrical load is due to heat released by blower motor,lights. The major load is due to solar radiations falling on sheet metal parts, results in higher skin temperature of sheet metal parts.

All above equations are formulated using excel sheet, by entering all boundary conditions and vehicle geometrical details gives total load on vehicle along with heat load distribution. The Table 2 gives the total load acting on the passenger cabin.

TABLE 2. Heat Load Summery

Sources	Value [w]
Total Sheet Metal Heat Load	4001
Glass Conduction Heat Load	725
Glass Radiation Heat Load	1331
Occupant Load	1690
Air Condition Load	231
Electrical Load	500
Other Loads	500
Total	8986
Factor Of Safety	450

Total Load On System	9434

Total load on evaporator is 9.4 KW. Electrical load consists of heat addition due to motor, resister, lights. Factor of safety of 5% of total heat load is considered to avoid overloading of system.

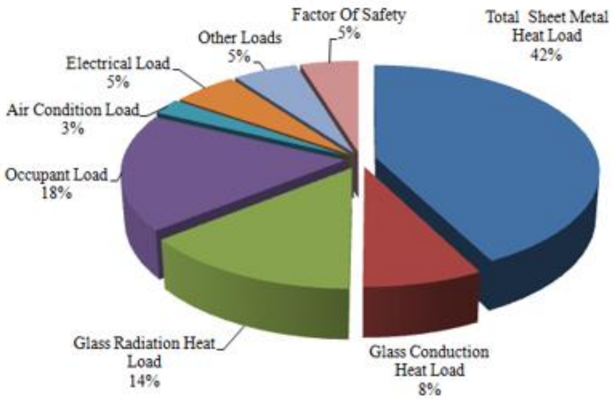

Fig. 2. Solar Heat Load Distribution

2) Variation Of Solar Load With Respect To Time

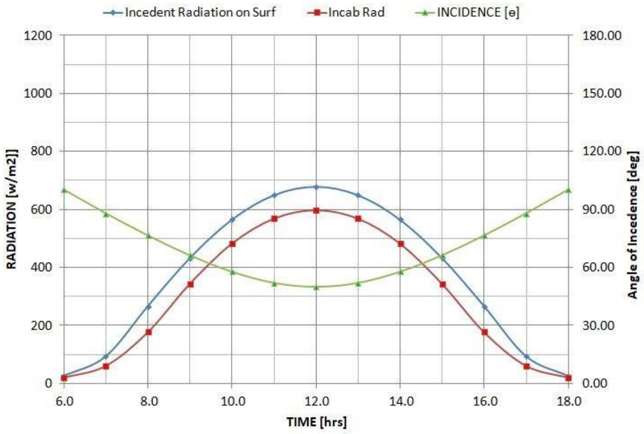

Fig. 3. Solar Radiation Flux on Front Wind Screen

Figure 3 below shows variation of solar radiation on front wind screen with respect to time. It is observed that at 12.00pm radiation falling on front wind screen is maximum, due to lower angle of incidence. The front wind screen is inclined at an angle of 45° with respect to horizontal. Due to increase in solar flux at 12.00 pm the requirement of effective comfort temperature of occupants seating near front window will be increased. But this requirement is varying with variation in solar radiation.

Hence air flow rate coming through front ducts should be adjusted to compensate thermal comfort requirements.

The variation of solar radiation with respect to time may be taken as input parameter for Automatic AC system.

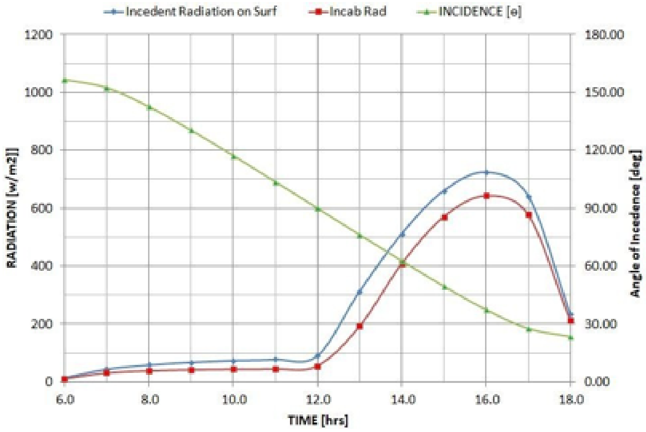

Fig. 4. Solar Radiation Flux on West Side Window

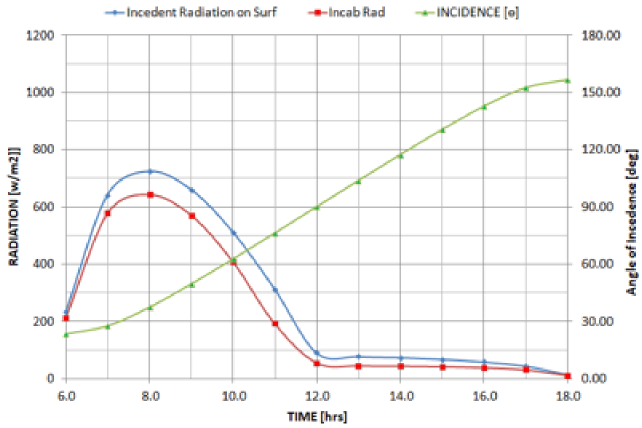

Fig. 5. Solar Radiation Flux on East Side Window

Solar radiation transmitted through west side window is maximum exactly at 04.00PM as solar radiations are exactly perpendicular with respect to glass. Side Glass is exact vertically oriented. The variation of transmissivity of glass with respect to angle of incidence is taken into account. Solar radiation flux on west side window is shown in Fig 4.

By comparing Figure 4 and Figure 5, maximum radiation flux on both side windows is same. It is observed that behaviour of solar flux on side windows is exactly opposite to each other, but exactly at afternoon the value of radiation flux intensity falling on both side windows is same.

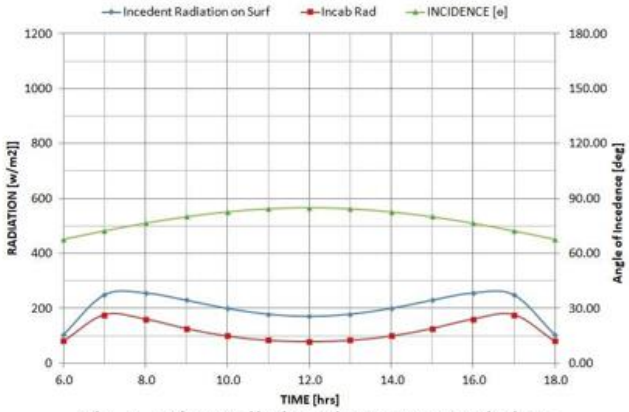

Fig. 6. Solar Radiation Flux on Rear Window

Solar radiation on rear window is very low in comparison to other glasses as it consists of only diffuse and reflected radiation. No effect of direct radiation on rear window is observed.

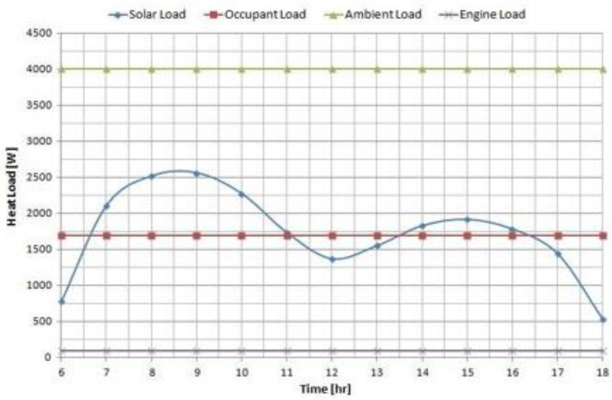

Fig. 7. Heat Load Variation with Respect to Time

Solar load varies with respect to time due to rotation of earth. Figure 6 shows variation of total solar load on passenger cabin with respect to time. The maximum load of 2560 W is observed exactly at 09.00 AM. Major load is due to larger surface area of side glass exposed to radiation at 09.00 AM

Figure 7 shows combined effect of solar radiation through each glass on total solar radiation load through glasses with respect time from sunrise to sunset.

TABLE 3. Solar Radiation flux on windows at 12.00PM

Windows	Solar Heat Gain [W/m²]	Solar Load [W]
Wind Screen (South)	579.2	1001.43
Side, Door Glass (East)	52	163.02
Side, Door Glass (West)	55.5	106.50
Rear Wind Screen (North)	80	59.28

Table 3 shows maximum radiation transmitted inside cabin at 12.00 PM. It is observed that maximum radiation flux of 579.2 W/m^2 at 12.00 PM through glass facing south.

IV. CONCLUSIONS

In this paper, the time saving and accurate methodology is developed to estimate passenger cabin heat load by considering actual variation in solar radiation. In addition to giving a total heat load value, it can also estimate individual contributions of different heat sources and of different body panels and evaluate the impact of changes in their design parameters. Calculated overall heat transfer coefficient values at respective surfaces can be directly applied to CFD domain; hence all sheet metal and insulation domains are not required in simulation, reducing mesh count and simulation time more than 50%. Simplified CFD Simulation is future scope of this study.

It is concluded that maximum radiation flux of 579.2 W/m^2 at 12.00 PM through glass facing South, Which is lower than conventional assumption avoiding over sizing of system.

A cooling load of 9434W is estimated. To design AC refrigeration 2.7 tons of refrigeration is needed. Selectedheat exchangers must able remove 9434W of heat frompassenger cabin to achieve required thermal comfort conditions.

This methodology is very effective for designing efficient HVAC system used in electric and hybrid electric vehicles giving more travelling range. The calculations can also detail the Minibus passenger vehicle heat load distribution.

The solar radiation loads are major loads that give rise to the average in cabin air temperature.

The calculations can be performed in forms of simple, fast and accurate manners by just entering the vehicle geometry and weather conditions. The developed model canbe applied to any kind of vehicle geometry.

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