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Research Paper

Analysis and validation of transient thermal model for automobile cabin

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HIGHLIGHTS

- Fast calculation dynamical thermal load model based on response factor method.
- Accurate validation with experimental tests in real outdoor conditions.
- Analysis of effects of thermophysical parameters, radiation parameters and driving parameters on thermal load.
- Cutting down thermal conductivity of envelopes will be the most effective method among thermophysical parameters.

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ABSTRACT

As automobile cabin thermal environment is complex and continually varies during its travel on road, a dynamical thermal load model based on response factor method has been presented in this paper. To shorten the calculating time, a fast-response thermal load calculation scheme has been proposed which has optimized iterative error, and the calculating time can be finally reduced to 0.95 s when time step is 50 s. To validate the reliability of this model, several tests have been carried out under ambient conditions. The tests results show that the interior temperature error is within 5% between simulated value and experimental data. Also the simulated conduction thermal load gained through cabin panels except bottom panel closely follows the heat conduction measured by HFM-215 which both value fluctuate around 900 W. In addition, detailed analysis on how to reduce the thermal conduction load is put forward in this paper, which shows that cutting down thermal conductivity of envelopes will be the most effective method among thickness, thermal conductivity and special heat capacity of envelopes. Meanwhile, the influences of solar altitude to solar radiation thermal load, vehicle velocity to interior panel temperature, glazing transmissivity to solar radiation thermal load and total thermal load during the process of driving for a whole day have also been analyzed in detail in this paper.

1. Introduction

Vehicle air conditioning (AC) system is applied in the automobile to change or maintain the temperature, humidity, air-flow velocity, cleanliness and other indexes about the air within the cabin and to create and keep a relatively steady, safety and comfortable thermal environment in the cabin. For the energy consumption of AC system, it accounts for nearly 70% of overall train energy consumption, while 10–15% of automobile oil consumption [1], lots of new energy saving technology of automobile AC are emerging such as variable frequency control technology and Variable Air Volume technology, so how to calculate cabin thermal load accurately has been an important task for transport energy consumption saving at present.

At the early stage, the auto AC compressor was driven by the engine through pulleys and clutches, which rotating speed was uncontrollable. The size of the AC system choosing is just related to the peak thermal load in the cabin. The ways to calculate automobile AC system thermal load for size choosing are mainly based on reference data graph method. Reference data graph can be used in rough approximation [2,3]. Since the automobile design has basically been standardized, the inner volume of cabin are approximately determined which depends on capacity, automobile type and etc., relevant experimental data can be used to estimate the thermal load in the similar situations. This method is easy to approach, but the result is not accurate.

Deal with global energy crisis, automobile lightweight, exhaust emission and oil consumption saving are continual improvement,

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Nomenclature

A	heat transfer area (m^2)
A_{ri}	projected area of shadow falling on equivalent surface (m^2)
Err	iterative error
h	solar altitude
h_r	heat transfer coefficient of cabin ($W/(m^2 \cdot K)$)
h_{v1}, h_{v2}	geometric dimension of automobile (m)
l_{v1}, l_{v2}	geometric dimension of automobile (m)
n	data amount
Q_{ac}	automobile air conditioning thermal load (W)
Q_{cond}	thermal conduction load (W)
Q_{mech}	mechanical thermal load (W)
Q_{met}	thermal metabolic cabin (W)
$Q_{solar,\ window}$	solar thermal load passing through glazing (W)
Q_{vent}	ventilation thermal loads of the automobile cabin (W)
t_{in}	panel interior temperature (°C)
t_r	cabin temperature (°C)
v	driving velocity (m/s)
w_{v2}	geometric dimension of automobile (m)
$Y(j)$	thermal response factor

Greek letters

α	significant level
α_k	negative real root
α_r	relative azimuth angle of solar and driving direction
α_w	heat transfer coefficient of cabin exterior panel ($W/(m^2 \cdot K)$)
θ_B, θ_F, θ_S	geometric angle of automobile
η	measured panel interior temperature (°C)
ξ	simulated panel interior temperature (°C)
ς	absolute difference of ξ and η

Superscript

*	dimensionless

Subscripts

AC	air conditioning
ANNs	Artificial Neural Networks
AR	harmonic method
CEP	circular error probable
CTF	conduction transfer function coefficient method
NL	North Latitude
PDE	partial differential equation
ODE	ordinary differential equation
RF	response factor method

it has become even more important to optimize the performance of automobile AC system. Therefore, the calculation and prediction of cabin thermal load are not only limited to peak value estimation, but also real-time and transient value which will provide algorithm and theoretical basis to the research of automobile AC energy saving and cabin thermal comfort. The calculation of cabin thermal load has developed from static peak value estimation algorithm to real dynamic algorithm. For method of steady-state heat transfer, the calculation will be easy and quick while the accuracy is poor. Hamid Khayyam et al. [4] built up a steady energy balance model in cabin room which takes heat from engine and exhaust into consideration. Sanaye et al. [5] firstly built steady thermal load model and then a fuzzy controller was applied to maintain the thermal comfort, which showed that less time was needed for the cabin to the desired 20 °C. Li et al. [6] also developed a steady heat transfer model of AC unit integrated with passenger compartment where ambient condition, inside condition, car speed, fresh air volume, solar time and number of passengers are taken into consideration as key factors for the numerical simulation and analysis. Ozgur Solmaz et al. [7] implemented Artificial Neural Networks (ANNs) method for prediction hourly cooling load of a vehicle. For ANN model, seven neurons determinated as input signals of latitude, longitude, altitude, day of the year, hour of the day, hourly mean ambient air temperature and hourly solar radiation were used for the input layer of the network. For method of dynamic steady-state, the ambient temperature and driving velocity change over time while the thermal inertia of envelopes is not carefully considered, which finally results of the thermal conduction load through envelopes being inaccuracy. Marcos et al. [8] built a simplified and dynamic steady-state thermal model and validated under three different conditions: stopped and unoccupied while outdoors, stopped and unoccupied while indoors, and running with one person inside the vehicle. The results demonstrated that dynamic steady-state modelling method can be applied for cabin thermal load calculation. Torregrosa-Jaime et al. [9] presented an lumped-parameter transient thermal model for passengers' compartment of a vehicle by means of steady heat transfer method. The mean temperature and relative humidity of air inside the cabin have been obtained. Liu et al. [10] built a mathematic model to simulate dynamic cooling load of an air-conditioned train compartment which has taken the effect of train speed into consideration. For method of dynamic unsteady-state, the thermal inertia of envelopes is well considered which can achieve distinction between heat gain and thermal load. Jan Pokorny et al. [11] presented the development of a mathematical model based on the energy balance between the cabin and the outdoor environment accounting for conduction, convection and shortwave and longwave radiation. Through the experimental validation for a Škoda Felicia Combi car in situations of summer parking and an autumn journey, the model showed a very good agreement with the measured mean air temperature. Also, Jan Pokorny et al. [12] developed a new computational tool called the Virtual Testing Stand software for the transient prediction of the car cabin environment and heat load during real operating conditions using Matlab as a windows standalone application, with a graphical user interface.

However, with the development of automobile energy saving technology, the heat insulation performance and thermal inertia strength have been improved continuously, so that steady heat transfer method cannot meet the accuracy demand of cabin thermal load calculation. On the other hand, unsteady heat transfer method is mainly used in the building AC engineering. Nowadays, there are variable methods to achieve a thermal dynamic heating and cooling loads used unsteady method which can essentially classified into two groups: first group is to solve the approximate solution of the differential equation, furthermore to get the approximation of the loads [13]; second group includes dynamic load calculation methods such as the conduction transfer function coefficient method (CTF) [14], response-factor method (RF) [15], harmonic methods (AR) [16]. As regards first group, Finite Difference Method and Simulation Method can theoretically and numerically provide more accurate solution. However they are not suitable for applying in vehicle load calculation, as the calculation procedure may take a long time which cannot meet the fast