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A transient thermal model for full-size vehicle climate chamber

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ABSTRACT

A model for full-size vehicle climate chamber was established based on Matlab/Simulink to study the transient thermal performance and to improve the heating/cooling rate. The model consists of the chilled water system model, chamber air model, building envelope model, and the control system model. Finite difference approach was employed. The model has been verified by experiments conducted in the full-size vehicle climate chamber. Thermal analyses were conducted for both heating and cooling tests, and several main factors that affect energy consumption were considered. It is concluded that the heat loss through building envelope accounted for only 4%, which is much less than the heat loss caused by air tightness and improper control strategy, which accounted for more than 10% and 60%. For zero air leakage case, the average heating and cooling rates improved by 15.1% and 7.7%, respectively compared to the case with air leakage. In the end, a new control strategy was developed for the heating test based on the analysis results and this new control strategy reduced the total heating time by 27%.

1. Introduction

Heating, ventilation and air-conditioning (HVAC) systems are indispensable parts for all kinds of road vehicles to provide thermal comfort for passengers. Great time and effort have been spent on the evaluation and optimization of HVAC systems. Since bench test results are always different from those of actual operation, that is why some tests are performed on the road to get the performance of automobile HVAC systems. However, it is difficult to control road environmental conditions, and tests are always difficult to conduct and unrepeatable in roadway. Furthermore, the data recording is limited and inconvenient [1]. Since the last century, climate wind tunnels were employed to study the door systems, HVAC systems and braking systems under various climatic conditions. However, the climate wind tunnel is a complex test system and has strict requirements regarding uniformity and stability of the flow field and temperature field, which is very expensive to build and operate.

Another test facility, full-size vehicle climate chamber, which is capable of simulating a wide range of weather and road conditions with the advantages of full solar spectrum simulation, humidity control, temperature control, chassis dynamometer and snow generation. It doesn't have that many rigorous requirements as the wind tunnel, so it is easier to build. It has become more and more popular in the automobile industry for vehicle tests, performance analysis and research of the entire vehicle or one part of it.

In order to simulate the weather conditions throughout the year, the climate chamber should have the ability to emulate extreme temperatures over the range of −30 °C to 60 °C and reach the desired test conditions regardless of the ambient weather condition. High power heating and cooling systems improve the heating and cooling rates, which are important performance indicators for climate chamber, but more energy consumption. So an optimum balance should be reached between test efficiency, energy consumption and the cost of cooling and heating facilities.

The transient thermal behavior of the climate chamber strongly depends on the interaction between heating/cooling facilities, thermal insulation of the building envelope, air tightness, control strategies and other factors [2]. Considerable heat loss can be caused by poor insulation of buildings. Proper use of thermal insulation downsizes heating and cooling systems and reduces the energy cost [3]. It is generally accepted that air leakage leads to significant increase in the cooling and heating load. Jokesalo attributed 15–30% of the heating load in both residential and commercial buildings to air leakage [4]. Caffey considered infiltration accounts for 40% of the heating/cooling load in residential houses [5]. The flow of air inside the building causes a wind pressure on the building, which results in inside-outside pressure difference and drives more outdoor air into the building [6]. Furthermore, energy efficient management of building systems plays a major role in minimizing overall energy consumption and costs. So advanced control

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Nomenclature

A	surface area (m^2)
c	specific heat ($J\,kg^{-1}\,K^{-1}$)
c_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
c_v	specific heat at constant volume ($J\,kg^{-1}\,K^{-1}$)
d	hydraulic diameter (m)
E	total energy ($J\,kg^{-1}$)
G	mass flow rate ($kg\,s^{-1}$)
h	heat exchange coefficient ($W\,m^{-2}\,K^{-1}$)
i	air enthalpy ($J\,kg^{-1}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
l	length (m)
m	mass (kg)
T	temperature (°C)
t	time (s)
v	velocity ($m\,s^{-1}$)
y_w	water film thickness (m)

Greek letters

ρ	density ($kg\,m^{-3}$)
λ	resistance coefficient
Δl	length step (m)
ΔP	pressure drop/difference (Pa)
Δt	time step (s)
η	fin efficiency (–)
η_a	surface efficiency (–)

Subscripts

a	air/airside
f	fluid
i	inside
in	inlet
out	outlet
s	saturation
w	water
wet	wet condition

techniques using model predictive control and artificial neural network are widely used to achieve energy saving [7,8].

Thermal modeling of buildings has important applications such as designing control strategies and estimating parameters characterising the system [9], and numerous researchers have investigated the thermal and energy behavior of buildings. Park proposed a generic model to evaluate the thermal load of electrical appliances, which can be adapted to a building model to study their thermal influence on buildings [10]. Gracia studied the dynamic thermal performance of alveolar brick construction system experimentally and theoretically [11]. Jimenez used Matlab System Identification toolbox to estimate thermal properties of building components [9]. A comparison of features and capabilities of twenty major building energy simulation programs was provided by Crawley and Hand [12]. Zhao reviewed recently developed models of building energy evaluation, previous research work and relevant applications were introduced [13]. Privara considered dynamic models are of crucial importance for model predictive control, and he proposed a new approach to obtain a model suitable for the use in a predictive control framework [14]. However, research on the full-size vehicle climate chamber's thermal performance is limited in the open literature. Zhang developed a model to simulate the climate chamber based on Matlab. The model offers a rather high accuracy compared to the experimental results, but only steady state values were validated [15].

In this paper, a simulation model based on Matlab/Simulink is presented to study the transient thermal performance of the full-size automobile climate chamber, which used the method of finite difference to solve the thermal response through time. Computational results were validated with test results and the effect of corresponding factors on system efficiency were analyzed, which provided means to improve heating/cooling rate of the climate chamber.

2. Experimental setup

2.1. Full-size vehicle climate chamber

The full-size vehicle climate chamber is a fully closed air circulation loop. The air tunnel was built vertically for space saving. The dimensions are around 13 m high, 24 m long and 8 m wide. Fig. 1 gives the configuration of the climate chamber. Control room of the test was placed on the first floor, right next to the test section. Researchers can observe the test process through the windows on the control room wall. When under low temperature test conditions, window glasses will be heated by electric heating tape to prevent vapor in the air from condensing. Environmental control facilities are right above the test section.

150 mm thickness insulating panel was used on the surface of the climate chamber. The inside surface of the chamber is relatively smooth in order to reduce air turbulence. The centrifugal fan situated at the bottom left corner with a blade of 2.5 m in diameter is capable of providing air speed from10 $km\,h^{-1}$ to 120 $km\,h^{-1}$. The fan nozzle is 3 m^2 in cross section area, and the length can be adjusted according to the position of the test vehicle. The test section floor is a steel fabrication with a 2-wheel chassis dynamometer accommodates to forward wheel drive or rear wheel drive vehicles. Straightening vanes were installed in the corners downstream the test section to smooth air flow. Humidifier was placed on the top side of the air tunnel. Prior to the humidifier, the airflow will pass four wavy fin-and-tube heat exchangers located upstream, all are 2 m high and 3 m wide, as shown in Fig. 1. There is a 2.8 t full spectrum solar simulation system on the top of the test section. It is 4.7 m above the floor with 28 metal halide lamps. The solar simulation system has the capability to simulate the solar radiation intensity up to 1200 $W\,m^{-2}$ with intensity control. A positioning control system enables it to move vertically and axially according to the size and location of the test vehicle. Rain and snow simulation systems are also equipped.

An exhaust device has been adopted to take away the exhaust created by the test vehicle to prevent air inside from being polluted. There is also a make-up air system providing fresh air at the rate of 2880 $m^3\,h^{-1}$ after dehumidification to provide humidity control and maintain positive pressure in the test section.

2.2. Description of the chilled water system

The chilled water system employed here has the advantages of easy control, high precision and flexibility, so it is widely used for temperature control in the climate chamber. The schematic diagram of the cooling system is shown in Fig. 2. The working fluid used in the cooling system in this study is 50% ethylene glycol solution and it is cooled down in the refrigeration unit. The chilled water temperature out of the refrigeration unit can be adjusted according to the air temperature measured in the test section. The hand valve on the by-pass line is able to adjust the flow rate in the primary chilled water circulation loop. Water tank helps maintain the temperature of inside fluid relatively stable. Two control valves (one larger and the other smaller) are used to regulate the flow rate into the secondary chilled water circulation loop. There are two pumps