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Transient thermal model of passenger car's cabin and implementation to saturation cycle with alternative working fluids

Hoseong Lee [a,*], Yunho Hwang [a], Ilguk Song [b], Kilsang Jang [b]

[a] Center for Environmental Energy Engineering, University of Maryland, 3157 Glenn L. Martin Hall Bldg., College Park, MD 20742, USA
[b] Halla Visteon Climate Control Corp., Daejeon, Republic of Korea

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ABSTRACT

A transient thermal model of a passenger car's cabin is developed to investigate the dynamic behavior of cabin thermal conditions. The model is developed based on a lumped-parameter model and solved using integral methods. Solar radiation, engine heat through the firewall, and engine heat to the air ducts are all considered. Using the thermal model, transient temperature profiles of the interior mass and cabin air are obtained. This model is used to investigate the transient behavior of the cabin under various operating conditions: the recirculation mode in the idling state, the fresh air mode in the idling state, the recirculation mode in the driving state, and fresh air mode in the driving state. The developed model is validated by comparing with experimental data and is within 5% of deviation. The validated model is then applied for evaluating the mobile air conditioning system's design. The study found that a saturation cycle concept (four-stage cycle with two-phase refrigerant injection) could improve the system efficiency by 23.9% and reduce the power consumption by 19.3%. Lastly, several alternative refrigerants are applied and their performance is discussed. When the saturation cycle concept is applied, R1234yf MAC (mobile air conditioning) shows the largest COP (coefficient of performance) improvement and power consumption reduction.

1. Introduction

MAC (mobile air conditioning) systems work under widely changing operating conditions and should satisfy thermal loads for various vehicle designs and sizes. In order to design MACs properly, a transient thermal model of the cabin is essential. Many researchers have developed the cabin model with different approaches: typically either lumped parameter models [1–9] or transient CFD (computational fluid dynamic) models [10,11] as shown in Table 1. First research focus was on developing the lumped parameter model assuming that the temperature difference in the cabin space is negligible. Gado (2006) developed the cabin model to simulate real car cabin conditions and its interaction with the MAC being tested. The cabin model used the following variables, which were measured and fed to the model as inputs: supply air temperature, supply air humidity ratio, and evaporator airflow rate, and various other user inputs, such as cooling loads and physical characteristics of the cabin [1]. Khayym et al. (2011a, 2011b, 2012, 2013) calculated the energy balance of the cabin room based on nine different load parameters: direct solar radiation, diffuse solar radiation, radiation reflected by road, ambient, engine, exhaust, ventilation, cooling, and metabolic. The cabin model was developed by considering solar radiation with zenith angles. This developed model was used to evaluate the MAC. They discussed about an intelligent air conditioning control system that reduces the energy consumption of the vehicle and improves its efficiency. The fuzzy controller made adaptive which operates effectively in different road load. They reported that the adaptive intelligent air conditioning controller provides the comfort temperature [2–5]. Rugh et al. (2001) developed the model with experimental data, and considered heat transfer between the cabin-side and ambient-side. The overall heat transfer coefficient was obtained from the test data, and it was integrated into the energy balance equation [6]. Sanaye and Dehghandokht (2011) and Sanaye et al. (2012) developed the cabin model by considering ventilation, solar radiation and human thermal load and interior mass load [7,8]. Jha et al.

* Corresponding author. Tel.: +1 301 405 5247, +1 301 405 8672; fax: +1 301 405 2025. Center for Environmental Energy Engineering (CEEE), Department of Mechanical Engineering, University of Maryland, 3157 Glenn. L. Martin Hall Building, College Park, MD 20742, USA.
E-mail address: hslee@umd.edu (H. Lee).

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Abbreviations

Symbols

A	area
Cp	specific heat
F	fresh air
h	enthalpy
IP	injection port
LHS	left hand side
m	mass flow rate
Q	heat transfer capacity/heat gain
R	recirculation air
RHS	right hand side
T	temperature
U	overall heat transfer coefficient
V	velocity
W	humidity ratio
x	incident angle
ρ	density

Suffixes

a	absorptance
amb	ambient
c	core (collective mass inside cabin)
e	evaporator
fg	vaporization
fw	firewall
HG1	heat gain from engine to supply air duct
HG2	heat gain from engine to return air duct
iv	infiltration/ventilation
m	mixing (upstream)
o	overall
p	passengers
r	room (cabin)
s	supply
sol	solar
t	transmittance

Acronyms

AC	air conditioner
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	computational fluid dynamics
COP	coefficient of performance
EES	Engineering Equation Solver
GWP	global warming potential
HVAC	heating, ventilation and air conditioning
MAC	mobile air conditioning
PAG	polyalkylene glycol
POD	proper orthogonal decomposition
PR	pressure ratio
TXV	thermal expansion valve
VCC	vapor compression cycle

Table 1
Summary of literature review.

Method	Authors (year)	Load				Validation			Cabin volume [m³]	Application
		Q_{sol}	Q_{ENG}	Q_{duct}	$Q_{int.\ mass}$	Idling mode (ventilation)	Idling mode (recirculation)	Driving mode		
Lumped Capacity Model	Gado (2006) [1]	Yes	No	No	Yes	No	Yes	Yes	8	SUV
	Khayyam et al. (2011) [2–5]	Yes	Yes	No	Yes	No	No	No	2.3	Sedan
	Rugh et al. (2001) [6]	Yes	No	No	No	No	No	Yes	N/A	SUV
	Sanaye and Dehghandokht (2011) [7]	Yes	No	No	Yes	No	No	Yes	3.6	Sedan
	Sanaye et al. (2012) [8]	Yes	No	No	Yes	No	No	Yes	3.6	Sedan
	Jha et al. (2013) [9]	Yes	Yes	No	Yes	No	No	Yes	N/A	Five-door SUV
	Torregrosa-Jaime et al. (2014) [10]	Yes	No	No	Yes	No	Yes	No	24.6	Minibus
	Levinson (2011) [11]	Yes	No	No	Yes	No	Yes	No	2.6	Sedan
	Marcos et al. (2014) [12]	Yes	No	No	No	Yes	No	Yes	N/A	Sedan
	Lee at al. (current study)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	2.8	Sedan
Transient CFD	Jiazhen et al. (2013) [13]	Yes	No	No	Yes	No	No	No	N/A	Sedan
	Ye (2013) [14]	Yes	No	No	Yes	No	No	No	N/A	Sedan

(2013) developed the model by considering solar radiation, air leakage, electrical fittings and the occupants. The model showed a good correspondence with experimental results, with error falling within ±15% of experimental results. In addition, it was noted that the model consistently overpredicted the thermal load acting on the vehicle [9]. Torregrosa-Jaime et al. (2014) developed the lumped-parameter thermal model for the passengers' compartment of the vehicle. Their model was a dynamic model and validated under various ambient conditions [10]. Levinson (2011) developed the lumped-capacity model. They focused on decreasing the soak temperature, reducing the MAC capacity, and improving the fuel economy by using solar reflective shells. They experimentally characterized component temperatures and cooling demands in a pair of dark and light colored vehicles, the former with low solar reflectance and the latter with high solar reflectance [11]. Marcos et al. (2014) proposed a thermal model of a vehicle cabin. This model was tested under three different conditions: stopped and unoccupied while outdoors, stopped and unoccupied while indoors, and running with one person inside the vehicle. The model was validated by considering the cabin of a real car outfitted with a temperature sensor network [12].

Second research focus was on utilizing CFD simulation either to estimate the cabin room temperature directly or to build the meta-model. Jiazhen et al. (2013) introduced a new simulation tool that