SIMULATION AND ANALYSIS OF A DIRECT CURRENT OPERATED AUTOMOTIVE AIR-CONDITIONING SYSTEM

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Dedicated to my beloved mother, Sinah binti Kasipan wife, Hasimah binti Ahmad

and

children, Nur Insyirah binti Mohamad Firdaus, Umar bin Mohamad Firdaus, Nur Khadeeja binti Mohamad Firdaus, Nur Syamimi binti Mohamad Firdaus

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ABSTRACT

The automotive air-conditioning (AAC) system is the second largest consumer of energy after the power train in a typical passenger vehicle. An improvement on the performance of this system will save a significant amount of energy and significantly improve the vehicle performance. The study was divided into two main sections, namely, experimental work and parametric simulation. The experimental work was conducted to obtain the off-road air-side evaporator heat transfer correlation and refrigerant-side correlations of compressor work, refrigerant mass flow rate, cooling capacity, and heat rejected from the condenser. The experimental rig comprised the original components from the AAC system of a medium-sized passenger car equipped with an appropriately sized electric compressor and electronic expansion valve. Cabin compartment thermal load, air-side evaporator-cabin compartment, and thermal and energy AAC system performance mathematical models had been developed based on models proposed by previous studies. Comparison exercises indicated that the simulation from the cabin compartment thermal load mathematical model and experimental results were within 5% error and were highly consistent with published results. Parametric simulation studies revealed that vehicle surface with darker color, an increment in the number of occupants, vehicle speed and fractional ventilation of air intake, and lower cabin temperature tend to increase the cooling load and require additional cooling capacity up to 144.16 W (5.01%). As a result, compressor work increased, up to 89.12 W (10.82%). Consequently, maximum reduction of COP up to 5.53% was recorded due to dominant increase in compressor work, as opposed to an increase in cooling capacity. In short, the proposed simulation model is able to help designers and/or engineers to understand the best type of vehicles and AAC operating system that can enhance the overall performance of the vehicle, particularly an electric vehicle, in the most efficient way. Consequently, it can reduce the effort, time, and cost to develop AAC systems and vehicles in the future.

ABSTRAK

Dalam operasi sebuah kereta, sistem penyamanan udara kereta (AAC) merupakan pengguna tenaga ke dua terbesar selepas sistem aliran kuasa. Penambahbaikan prestasi sistem tersebut akan menghasilkan satu kesan yang signifikan dalam penjimatan tenaga dan prestasi keseluruhan kereta tersebut. Kajian dibahagikan kepada dua bahagian iaitu kerja ujikaji dan simulasi parametrik. Ujikaji dijalankan bagi mendapatkan kolerasi bahagian-udara, pemindahan haba penyejat dan kolerasi bahagian-bendalir pendingin kerja pemampat, kadar alir jisim bendalir pendingin, kapasiti penyejukan dan haba yang disingkirkan dari pemelwap. Pelantar ujikaji terdiri daripada komponen asal sistem AAC kereta bersaiz sederhana, dilengkapkan dengan pemampat elektrik dan injap pengembangan elektronik yang bersesuaian. Model matematik bagi beban haba ruangan kabin, bahagian-udara penyejat-ruangan kabin, dan prestasi haba dan tenaga sistem AAC telah dibangunkan berdasarkan gabungan model-model yang telah dibangunkan sebelumnya. Perbandingan di antara data simulasi dari model beban haba ruangan kabin dan keputusan ujikaji berada dalam ralat 5% dan sangat konsisten dengan keputusan kajian-kajian yang sudah diterbitkan. Kajian simulasi parametrik mendapati warna luaran kenderaan yang lebih gelap, pertambahan penumpang, kelajuan kenderaan dan peratusan kemasukan udara luar, serta suhu kabin yang lebih rendah cenderung meningkat beban penyejukan dan memerlukan kapasiti penyejukan tambahan sehingga 144.16 W (5.01%). Kesannya, kerja pemampat meningkat sehingga 89.12 W (10.82%). Oleh itu, penurunan COP sehingga maksimum 5.53% direkodkan disebabkan peningkatan kerja pemampat lebih dominan jika dibandingkan dengan peningkatan dalam kapasiti penyejukan. Secara ringkasnya, model simulasi yang dicadangkan mampu membantu pereka-pereka dan/atau jurutera-jurutera dalam memahami jenis kenderaan dan operasi sistem AAC yang terbaik, yang boleh meningkatkan prestasi keseluruhan kenderaan, terutamanya kenderaan elektrik dengan cara yang paling cekap. Dengan itu, ia dapat mengurangkan penggunaan tenaga, masa dan kos dalam membangunkan sistem-sistem AAC dan kenderaan-kenderaan pada masa depan.

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LIST OF ABBREVIATIONS

A/C	-	air-conditioning
AAC	-	automotive air-conditioning
ANN	-	artificial neural network
ASHRAE	-	American Society of Heating, Refrigerating, and Air-
		Conditioning Engineers
COP	-	coefficient of performance
DC	-	direct current
EER	-	energy efficiency ratio
EEV	-	electronic expansion valve
EVAC	-	electric vehicle air-conditioning
EVs	-	electric vehicles
FCC	-	fixed capacity compressor
GHG	-	greenhouse gas
HBM	-	heat balance method
HVAC	-	heating, ventilation, and air conditioning
ICE	-	internal combustion engine
OD	-	opening degree
SAE	-	Society of Automotive Engineers
TFM	-	transfer function method
TXV	-	thermostatic expansion valve
VCBLDC	-	variable capacity brushless direct current
VCC	-	variable capacity compressor
VCREVAC	-	vapor compression refrigerant electric vehicle air-conditioning
VCRC	-	vapor compression refrigeration cycle
XOA	-	fractional ventilation air intake

LIST OF SYMBOLS

A	-	surface area (m^2)
В	-	blockage (%)
С	-	percentage of energy input (%)
CG	-	heat transmitted due to the difference between outside and
		inside temperature (W)
CL	-	cooling load (W)
CR	-	compression ratio
CLS	-	sensible cooling load (W)
D	-	day number of the year
EOT	-	equation of time
ER	-	heat extraction rate (W)
EX	-	exergy destroyed (W)
Gr	-	Grashof Number
h	-	specific enthalpy (kJ/kg)
т	-	amount of refrigerant (kg)
m	-	mass flow rate (kg/s)
Ι	-	current (A)
I_D	-	direct solar radiation (W/m^2)
I_d	-	diffuse sky radiation (W/m^2)
I_{DN}	-	direct normal irradiance (W/m^2)
I_r	-	solar radiation reflected from surrounding surfaces $\left(W/m^2\right)$
I_t	-	total short-wavelength irradiance (W/m^2)
k	-	surface conductive heat transfer coefficient $\left(W/m \cdot K ight)$

LI	-	light intensity (W/m^2)
Ν	-	rotational speed (rpm)
NL	-	number of lights
Р	-	power consumption (W)
Pr	-	Prandtl number
р	-	pressure (bar)
Q	-	heat transfer (W)
q	-	heat transfer per unit refrigerant (kJ/kg)
R	-	resistance $(m^2 \cdot K/W)$
Ra	-	Rayleigh number
Re	-	Reynolds number
RF	-	air recirculated fraction
RPM	-	engine rotational speed (rpm)
SGHa	-	absorbed radiation that travels to air-conditioned space $\left(W \right)$
SGHt	-	transmitted radiation through glass (W)
SC	-	refrigerant sub-cooling (K)
SCHE	-	ratio of average wattage in use between hour t and maximum
		used wattage in space
SCHI	-	ratio of ventilation load at hour <i>t</i> to maximum ventilation
		load
SCHL	-	ratio of equipment heat load at hour <i>t</i> to maximum
sh	_	refrigerant super-heating (K)
T	_	temperature (°C)
t	_	time (s)
1		value (y)
V	-	velocity (iii/s)
v_{afc}	-	condenser air face velocity (m/s)
V_{vhc}	-	vehicle speed (km/h)
$\overset{\cdot}{V}$	-	volumetric flow rate (m^3/h)
V	-	voltage (Volt)

W	-	work done (W)
W	-	work done per unit refrigerant (kJ/kg)
ω	-	specific air humidity (kg w.v/kg d.a)
δ	-	thickness (m^2)
x	-	quality of refrigerant entering evaporator
\overline{x}	-	average value
Z.	-	motor frequency (Hz)
f	-	surface convective heat transfer coefficient $\left(W/m^2\cdot K\right)$
λ	-	compressor expansion coefficient
η	-	efficiency
θ	-	angle of incidence between incoming solar rays and line
		normal to surface (°)
ϕ	-	air relative humidity (%)
μ	-	experimental uncertainty (%)
σ	-	standard deviation
$\varepsilon - \mathrm{NTU}$	-	effectiveness number of transfer units

Subcript

1,2,, n	-	measurement points
a	-	air
Α	-	type A
bwr	-	blower
В	-	type B
С	-	compressor
С	-	combined
cab	-	cabin
cd	-	condenser / condensing
CL	-	coil latent

cpt	-	component
CS	-	coil sensible
CT	-	coil total
d	-	discharge
db	-	dry bulb
dvr	-	driver
e	-	evaporator/evaporating
Ε	-	expended
eng	-	engine
exh	-	exhaust
f	-	floor
g	-	glass
i	-	inside/inlet
leak	-	leakage
L	-	length
LT	-	latent
т	-	motor
0	-	outside / outlet
ocp	-	occupant
pgr	-	passenger
r	-	refrigerant
S	-	suction
SO	-	sol-air
S	-	sensible
sp	-	sampling
sys	-	system
t	-	total
vnt	-	ventilation
wb	-	air wet-bulb
wi	-	inside wall
wo	_	outside wall

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Transport activity is a key component of economic development and human welfare, and this activity is increasing around the world as economies grow (Kahn Ribeiro *et al.*, 2007). Sand and Fischer (1997) found that automobiles are used approximately 249 h on average every year. Automobile air-conditioning (A/C) is also used at nearly 107–121 h per year, which accounts for 43%–49% of vehicle consumption (Fischer, 1995). Therefore, an automotive A/C (AAC) system as a standard accessory is vital to provide thermal comfort to passengers and drivers. Comfort is not the only reason for using AAC systems; another reason is road safety, which improves with the comfort of drivers because a pleasant environment reduces driver fatigue (Konz, 2007).

Many land transport vehicles in the world are powered by internal combustion engines (ICEs), and 95% of worldwide total energy is derived from petroleum (Kahn Ribeiro *et al.*, 2007), thereby resulting in energy-related greenhouse gas (GHG) emissions. In 2004, the transport sector was responsible for 23% of the total GHG emissions in the world, with nearly three-fourths coming from ground vehicles (Kahn Ribeiro *et al.*, 2007). The continuing annual growth of human populations and economies around the world will lead to a higher volume of GHG emissions in the future. Therefore, electric vehicles (EVs) are important to realize a sustainable transport system (Strömberg *et al.*, 2011).

The driving range of an EV is around 140–160 km on a single charge; however, with the application of heating, ventilation, and air-conditioning (HVAC) systems, the driving range decreases by 20%–30% (Kwon *et al.*, 2012). Farrington and Rugh (2000) showed that an increase of the accessory load from 500 W to 3500 W would decrease the EV range by 7%–38%. Chen *et al.* (2011) observed that the total mileage of an EV decreases by 50% when the A/C system is applied, thereby making the vehicle infeasible for long-distance transportation. Figure 1.1 shows the effect of the HVAC system on the cruising range of EVs.



Figure 1.1 Effect of heating, ventilation, and air-conditioning system on cruising range (Kwon *et al.*, 2012)

The usage of the HVAC system varies considerably depending on factors such as climate, time of day, time of year, type of vehicle (including vehicle color), outdoor/indoor parking, occupant clothing, recent occupant activity levels, length of trip, vehicle speed, and personal preference (Farrington and Rugh, 2000). Thus, the usage is expected to be higher than that reported in hot humid countries. An energyefficient air conditioner is significant for EV to achieve vehicular thermal comfort in the cabin compartments and to extend the traveling range as far as possible. Therefore, an improved understanding of the AAC system behavior interacting with various factors mentioned by Farrington and Rugh (2000) is needed to obtain an efficient AAC system for future vehicles.

1.2 Problem Statement

One of the major factors for the success of future EVs is the capability to meet consumer needs, such as city driving and long-distance driving, during various occasions. Another type of consumer need is thermal comfort, which can be provided by the AAC systems that run on battery. AAC cooling loads are the most significant auxiliary loads (Zhang *et al.*, 2009; Kaushik *et al.*, 2011), and AAC systems consume the second largest amount of energy after powertrains (Roscher *et al.*, 2012). Thus, its operation becomes critical for full EVs because of limited battery storage capacity, limited battery charging station, and longer time required to charge the battery compared with conventional fuel-driven ICE-powered vehicles. The battery is used not only to operate the electric motor to run the EV, but also to run the A/C system as well as other accessories. Accordingly, the driving range of the EV is reduced. Therefore, an energy-efficient A/C of EV (EVAC) system is significant.

As highlighted in Section 1.1, an in-depth understanding of the AAC system behavior interacting with various factors, such as ambient conditions and vehicle operation, is necessary to obtain an efficient AAC system for future vehicles. To accomplish this goal, an efficient tool for rapid design and prototyping of the AAC system that can interact with the aforementioned factors is necessary. Consequently, the overall performance of the vehicle, especially that of the AAC system, can be investigated and confirmed before mass production. Given that the increase of experimental and prototyping procedures for any AAC system increases development time, workforce, and cost, a simulation program can be used to carefully analyze the AAC system. Thus, the simulation program of an EVAC system is proposed to predict the AAC system performance under the influence of the aforementioned factors. Through this simulation program, the performance of the A/C system can be simulated to improve or optimize the system. As a result, the energy efficiency of the EVAC system can be enhanced, thereby improving the overall performance of the EVs.

A thermal environment in a passenger car compartment is created according to the performance of its A/C system (Mohamed Kamar, 2008). Therefore, two main aspects need to be considered to develop a comprehensive AAC simulation program: analysis of thermal load in the cabin compartment, and analysis of thermal and energy performance of the AAC system. By connecting the analysis of cabin compartment thermal load to the analysis of thermal and energy performance of the AAC system in both, air and refrigerant sides via the evaporator, we can describe the thermal behavior in the passenger compartment, as well as the thermal and energy performance of the AAC system under the influence of outside environment and various operating conditions. Therefore, the complete simulation program consists of three mathematical models: mathematical model of cabin compartment thermal load, mathematical model of refrigerant-side thermal and energy performance of the AAC system, and mathematical model of air-side evaporator that links the first two models.

In this case, experimental investigation can be conducted to obtain the required empirical correlations of each model. An experimental test rig for the EVAC system can be developed by modifying the existing AAC system available in the market, that is, the AAC system of a 1.6-L Proton Wira Aeroback passenger car with original components of heat exchangers and internal and external fans. Modification of the EVAC system can be performed in the compressor and expansion valve sections. In particular, an appropriate variable capacity brushless direct current motor–compressor and an electronic expansion valve (EEV) for valve opening control can be used. In this study, a complete simulation program of direct current-operated AAC system is developed. Without requiring complicated experimental work, this simulation program significantly reduces the effort and cost in determining the performance characteristics of the AAC system. Thus, planning toward enhanced overall performance of vehicles through an energy-efficient AAC system is possible in the future.

1.3 Objectives of Study

The importance of a complete simulation program to evaluate realistically and accurately the thermal and energy performance of the AAC system, led this study to focus mainly on the development of comprehensive predictive model. Accordingly, the objectives of this study are as follows:

- a. to predict the thermal load characteristics in the cabin compartment for the AAC system,
- b. to develop empirical correlations in order to link cabin compartment thermal load characteristic to the air and refrigerant sides of the AAC system, and
- c. to perform a parametric study to assess the thermal and energy performance of the AAC system.

1.4 Scope of Research

The research scope is divided into three categories: coverage (limiting of the variables covered), method used (preferred method), and validity of results (range of applicability of results).

The independent operational variables of the complete AAC system modeling are restricted to ambient air dry and wet bulb temperatures, desired cabin air dry bulb temperature and humidity, evaporator air volumetric flow rate, condenser air face velocity, number of passengers, vehicle thermophysical properties, and vehicle speed. The AAC system performance is confirmed by evaluating the performance dependent variables including cabin cooling load, refrigerant mass flow rate, evaporating capacity and temperature, compressor work, coefficient of performance (COP), and condensing temperature.

The parametric study for the case of predicting the thermal load characteristics in the cabin compartment are only focused on the changing effect of weather, vehicle surface color, number of passengers, desired cabin air-dry bulb temperature and vehicle speed. Meanwhile, parametric study for the case of assessing the thermal and energy performance of the AAC system in the cabin compartment are only focused on the changing effect of vehicle surface color, vehicle speed, fractional ventilation air intake and evaporator air volumetric flowrate. Both parametric studies cover changing effect of weather from 11.00 am to 3.00 pm.

Only analytical and experimental approaches are used in this study. Compressor and EEV are selected based on the predicted maximum cooling capacity that will be supplied to the cabin compartment. For thermal and energy performance analysis of the AAC system, an analytical method is proposed based on a mathematical model developed from experimental data. The cabin compartment thermal load model and the experimental data used for modeling are validated through available results published in the open literature.

The results collected from this study are considered for steady-state condition with few assumptions. The air velocity, humidity, and temperature measured at the coils are considered uniform along the cross-sectional area of the duct/coils. The heat loss at the EEV and at the wall of the coils where the temperature is measured is assumed to be negligible by considering proper insulation of expansion valve and proper insulation between temperature sensors and coils, respectively. Heat loss from the surface of the compressor is also assumed negligible. The evaporating and condensing temperatures are measured on the surface of the refrigerant pipeline at the inlet of the evaporator and at the outlet of the condenser, respectively.

The air-side evaporator heat transfer correlation, and refrigerant-side correlations of compressor work, refrigerant mass flow rate, cooling capacity, and heat rejected from the condenser are model specific. Thus, the simulation model is only valid for application on an AAC system as in the experimental test rig in which the EEV is fixed at 100% opening degree (OD).

1.5 Thesis Outline

This thesis is composed of six chapters. Chapter 1 introduces the importance of the study.

Chapter 2 presents the literature review. First, the basic concept of an actual vapor compression refrigeration cycle (VCRC) system is presented. Then, the analysis of thermal load in the passenger compartment is comprehensively reviewed, as well as the analysis of the thermal and energy performance of the AAC system. The methods for linking the model of thermal load in the passenger compartment with that of thermal and energy performance of the AAC system are also presented.

In Chapter 3, a complete research approach is outlined. Next, the novel procedures to perform cabin compartment thermal load analysis and energy performance analysis of an AAC system are presented. Then, procedures to integrate the mathematical model of the cabin compartment thermal load with that of energy performance of the AAC system for the complete system simulation are presented. Finally, the method of selecting components to fabricate the experimental test rig; the

purpose of the experimental work; and the method for data mining, data analysis, and data accuracy check are briefly described.

Chapter 4 presents the experimental set up of this study. It consists of two main sub-sections. The first sub-section presents the method of equipment selection (EEV and electric compressor) to develop the experimental test rig using the mathematical model of cabin compartment thermal load. This sub-section starts with the verification process of the model, followed by analysis of maximum cooling capacity estimation. Finally, based on the maximum cooling capacity estimation, the selection procedures of possible electric compressor and EEV are presented.

Then, the experimental work to obtain empirical correlations for the performances of the air-side steady-state evaporator heat transfer and refrigerant-side steady-state AAC system is presented in the following sub-section. One empirical evaporator coil performance correlation and three empirical AAC performance correlations are then developed using the experimental data. The development of the experimental test rig, the test conditions, and the procedures of collecting data are also explained. A validation exercise of the experimental data is also presented before the data are utilized for the complete simulation of the AAC system.

In Chapter 5, the simulation results through parametric study are presented. This chapter discusses the effects of selected parameters including vehicle surface color, number of occupants, desired cabin air-dry bulb temperature, vehicle speed, fractional ventilation air intake and evaporator air volumetric flow rate on the cabin cooling load profile, and thermal and energy performance of the AAC system.

Finally, the main findings, conclusions, contributions to the field of knowledge and recommendations for future works are presented in Chapter 6.

REFERENCES

- Alkan, A. and Hosoz, M. (2010). Comparative Performance of an Automotive Air Conditioning System using Fixed Variable Capacity Compressors. *International Journal of Refrigeration*. 33, 487-495.
- Arora, C. P. (2009). *Refrigeration and Air Conditioning*. (3rd ed.). Singapore: McGraw Hill.
- ASHRAE (1985). ASHRAE Handbook 1985 Fundamentals. Atlanta, GA: ASHRAE, Inc.
- ASHRAE (1993). Handbook of Fundamentals. Atlanta, GA: ASRHAE, Inc.
- ASHRAE (1997). Handbook of Fundamentals. Atlanta, GA: ASRHAE, Inc.
- ASHRAE (2005). Handbook of Fundamentals. Atlanta, GA: ASRHAE, Inc.
- ASHRAE (2009). Handbook of Fundamentals. Atlanta, GA: ASRHAE, Inc.
- Atik, K., Aktas, A. and Deniz, E. (2010). Performance Parameters Estimation of MAC by using Artificial Neural Network. *Expert Systems with Applications*. 37, 5436–5442.

British Standard Institution (1975). B.S. 5141-1. London: British Standard Institution.

- British Standard Institution (1997). B.S. 306. London: British Standard Institution.
- Chang, Y. J. and Wang, C. C. (1997). A Generalized Heat Transfer Correlation for Louver Fin Geometry. *International Journal of Heat and Mass Transfer*. 40(3), 533–544.
- Chen, J. C. (1966). Correlation for Boiling Heat Transfer to Saturated Fluids in Convective Flow. *Industrial & Engineering Chemistry Process Design and Development*. 5(3), 322–329.
- Chen, J., Zhao, Y. and Qi, Z. (2011). New Developments in Mobile Air Conditioning Systems in China. *Front Energy*. 5(1), 53–58.

- Cho, H., Lee, H. and Park, C. (2013). Performance Characteristics of an Automobile Air Conditioning System with Internal Heat Exchanger using Refrigerant R1234yf. Applied Thermal Engineering. 61(2), 563–569.
- Cipollone, R. and Di Battista, D. (2016). High Efficiency Air Conditioning Model Based Analysis for the Automotive Sector. *International Journal of Refrigeration*. In Press.
- Danfoss Group (2014, August). Data sheet: Electric expansion valves Type ETS 6. Refrigeration and A/C: Electrically Operated Valves: ETS electric expansion valve, for fluorinated refrigerants: ETS 6. Retrieved September 13, 2014, from http://www.ra.danfoss.com/TechnicalInfo/Literature/Manuals/01/DKRCC.PD .VD1.D3.02_ETS6_vs.pdf
- Datta, S. P., Das, P. K. and Mukhopadhyay, S. (2014). Obstructed Airflow through the Condenser of an Automotive Air Conditioner - Effects on the Condenser and the Overall Performance of the System. *Applied Thermal Engineering*. 70, 925-934.
- Denso Corporation. (2012). Refrigeration cycle of car air conditioning. *Car Air Conditioners Refrigeration Cycle*. Retrieved February 17, 2017, from http://www.denso.com.sg/products/car-air-conditioner/refrigerationcycle
- Desai, A. D., Sapali, S. N., Parthasarathi, V. and Garikipati, V. (2011). Development of Energy Efficient R-134a Automotive Air Conditioning System using Internal Heat Exchanger. *Proceedings of the World Congress on Engineering* (WCE 2011) Vol. III. 6–8 July. London.
- Diaz, N. F. (2009). Methodology for Uncertainty Calculation of Net Total Cooling Effect Estimation for Rating Room Air Conditioners and Packaged Terminal Air Conditioners. *International Journal of Refrigeration*. 32(6): 1472-1477.
- Duffie, J. A., Bechman, W.A. (2006). *Solar Engineering of Thermal Processes*. (3rd ed.). USA: John Wiley & Sons Inc.
- Dullinger, C., Struckl, W., Kozek, K. (2015). A Modular Thermal Simulation Tool for Computing Energy Consumption of HVAC Units in Rail Vehicles. *Applied Thermal Engineering*. 78, 616-629.
- Fayazbakhsh, M. A. and Bahrami, M. (2013). Comprehensive Modeling of Vehicle Air Conditioning Loads Using Heat Balance Method. SAE Technical Paper Series. Paper No. 2013-01-1507.

- Farrington, R. and Rugh, J. (2000). Impact of Vehicle Air-Conditioning on Fuel Economy, Tailpipe Emissions, and Electric Vehicle Range. *Earth Technologies Forum*. 31 October. Washington, D.C., 1-10.
- Fischer, S. K. (1995). Comparison of Global Warming Impacts of Automobile Air-Conditioning Concepts. 1995 International CFC and Halons Alternative Conference. 23-25 October. Washington, D.C., 1-8.
- Han, X. H., Li, P., Xu, Y. J., Zhang, Y. J., Wang, Q. and Chen, G. M. (2013). Cycle Performances of the Mixture of HFC-161 + HFC-134a as Substitution of HFC-134a in Automotive Air Conditioning System. *International Journal of Refrigeration*. 36, 913–920.
- Hosoz, M. and Direk, M. (2006). Performance Evaluation of an Integrated Automotive Air Conditioning and Heat Pump System. *Energy Conversion and Management*. 47, 545-559.
- Hosoz, M. and Ertunc, H. M. (2006). Artificial Neural Network Analysis of an Automobile Air Conditioning System. *Energy Conversion and Management*. 47, 1574–1587.
- Huang, D., Wallis, M., Oker, E., and Lepper, S. (2007). Design of Vehicle Air Conditioning Systems Using Heat Load Analysis. SAE Technical Paper Series. Paper No. 2007-01-1196.
- Jha, K. K., Bhanot, V. and Ryali, V. (2013). A Simple Model for Calculating Vehicle Thermal Loads. SAE Technical Paper Series. Paper No. 2013-01-0855.
- Joudi, K. A., Abdul Sattar, K. M. and Mohammed, K. A. (2003). Experimental and Computer Performance Study of an Automotive Air Conditioning System with Alternative Refrigerants. *Energy Conversion and Management*. 44, 2959-2976.
- Kaneko, A., Katsuta, M., Oshiro, T., Bae, S., Komatsu, S. and Ohno, Y. (2011). The Development of Performance Prediction Methods for anAautomotive CO₂ A/C Cycle. *Journal of Thermal Science and Engineering Application*. 3, 1-8.
- Kaushik, S., Chen, K. H., Han, T. and Khalighi, B. (2011). Microcooling/heating Strategy for Energy Efficient HVAC System. SAE Technical Paper Series. Paper No. 2011–04–12.
- Kaynakli, Ö. and Horuz, I. (2003). An Experimental Analysis of Automotive Air Conditioning System. International Communications in Heat and Mass Transfer. 30(2), 273-284.

- Kahn Ribeiro, S., Kobayashi, S., Beuthe, M., Gasca, J., Greene, D. Lee, D. S., Muromachi, Y., Newton, P. J., Plotkin, S., Sperling, D., Wit, R. and Zhou, P. J. (2007). Transport and Its Infrastructure. In Climate Change 2007: Mitigation. In Metz, B., Davidson, O.R., Bosch, P. R., Dave, R., and Meyer, L. A. (Eds) *Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge, United Kingdom and New York, USA: Cambridge University Press.
- Kiatsiriroat, T. and Euakit, T. (1997). Performance Analyses of an Automobile Air-Conditioning System with R22/R124/R152a Refrigerant. *Applied Thermal Engineering*. 17(11), 1085-1097.
- Kim, S. G., Kim, M. S., Ro, S. T. (2002). Experimental investigation of the performance of R22, R407C and R410A in several capillary tubes for airconditioners. *International Journal of Refrigeration*. 25, 521-531.
- Konz, M. (2007). A Generic Simulation of Energy Consumption of Automobile Air Conditioning Systems. M Tech Eng Thesis. Nelson Mandela Metropolitan University.
- Kwon, C., Lee, C., Foster, L. and Kwon, J. (2012). Development of an Energy-Saving Occupied-Zone HVAC System (OZ HVAC). SAE Technical Paper Series. Paper No. 2012-01-0320.
- Lee, G. H. and Yoo. J. Y. (2000). Performance Analysis and Simulation of Automobile Air Conditioning System. *International Journal of Refrigeration*. 23, 243-254.
- Lemmon, E. W., Huber, M. L., McLinden, M. O. (2013). NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.1. Gaithersburg: National Institute of Standards and Technology, Standard Reference Data Program.
- Li, W. and Sun, J. (2013). Numerical Simulation and Analysis of Transport Air Conditioning System Integrated with Passenger Compartment. *Applied Thermal Engineering*. 50, 37-45.
- Li, X., Chen, J., Chen, Z., Liu, W., Hu, W. and Liu, X. (2004). A New Method for Controlling Flow in Automobile Air Conditioning. *Applied Thermal Engineering*. 24(7), 1073–1085.
- Liu, W., Deng, O., Huang, W. and Liu, R. (2011). Variation in Cooling Load of a Moving Air-Conditioned Train Compartment under the Effects of Ambient

Conditions and Body Thermal Storage. *Applied Thermal Engineering*. 31, 1150-1162.

- Malaysian Standard Department (2007). *M.S. 1525:2007*. Kuala Lumpur: Malaysian Standard Department.
- Marcos, D., Pino, F. J., Bordons, C. and Guerra, J. J. (2014). The Development and Validation of a Thermal Model for the Cabin of a Vehicle. *Applied Thermal Engineering*. 66, 646-656.
- Masterflux (2013a). SIERRA06-0982Y3. *Masterflux Products: Sierra*. Retrieved July 24, 2013 from http://www.masterflux.com/products/sierra/?pid=51
- Masterflux (2013b, May 31). Compressor Data Sheet. Masterflux Products: Sierra: SIERRA06-0982Y3. Retrieved July 24, 2013 from http://www. masterflux. com/userimages/SIERRA06-0982Y3_DATA_SHEET.pdf
- Mohamed Kamar, H. (2008). Computerised Simulation of Automotive Air Conditioning System. Doctor Philosophy. Universiti Teknologi Malaysia, Skudai.
- Mohamed Kamar, H., Ahmad, R., Kamsah, N. B., Mohamad Mustafa, A. F. (2013). Artificial Neural Networks for Automotive Air-Conditioning Systems Performance Prediction. *Applied Thermal Engineering*. 50, 63-70.
- Mohamed Mansor, M. K. (2007). Development of Roof-Top Bus Air Conditioning System that Responds to Cooling Load Variations in Tropical Countries. Doctor Philosophy. Universiti Teknologi Malaysia, Skudai.
- Nagaya, K., Senbongi, T., Li, Y., Zheng, J. and Murakami, I. (2006). High Energy Efficiency Desiccant Assisted Automobile Air-Conditioner and Its Temperature and Humidity Control System. *Applied Thermal Engineering*. 26, 1545–1551.
- Navarro-Esbrí, J., Ginestar, D., Belman, J. M., Milián, V. and Verdú, G. (2010). Application of a Lumped Model for Predicting Energy Performance of a Variable-Speed Vapour Compression System. *Applied Thermal Engineering*. 30, 286–294.
- National Environment Agency (2013), Weather Statistic. *Weather and Climate: Climate Information*. Retrieved March 25, 2013, from http://appz.nea.gov.sg/weather_statistic.aspx
- Park, S. K., Kim, H., Ahn, H. and Park, H. S. (2006). Study on the Reduction of Fuel Consumption in the A/C System, used Variable Displacement Swash-Plate

Compressor and the Performance Improvement by Field Test. *SAE Technical Paper Series*. Paper No. 2006-01-0164.

- Qi, Z. (2013). Experimental Study on Evaporator Performance in Mobile Air Conditioning System using HFO-1234yf as Working Fluid. *Applied Thermal Engineering*. 53, 124–130.
- Qi, Z., Chen, J. Chen, Z., Hu, W. and He, B. (2007). Experimental Study of an Auto-Controlled Automobile Air Conditioning System with an Externally-Controlled Variable Displacement Compressor. *Applied Thermal Engineering*. 27, 927–933.
- Qi, Z., Zhao, Y. and Chen, J. (2010). Performance Enhancement Study of Mobile Air Conditioning System using Microchannel Heat Exchangers. *International Journal of Refrigeration*. 33, 301-312.
- Rao, S. S. (2002). Applied Numerical Methods for Engineers and Scientists. United States of America: Perentice Hall.
- Ravikumar, T. S. and Mohan Lal, D. (2009). On-Road Performance Analysis of R134a/R600a/R290 Refrigerant Mixture in an Automobile Air-Conditioning System with Mineral Oil as Lubricant. *Energy Conversion and Management*. 50, 1891–1901.
- Roscher, M. A., Leidholdt, W. and Trepte, J. (2012). High Efficiency Energy Management in BEV Applications. *Electrical Power and Energy Systems*. 37, 126-130.
- Saiz Jabardo, J. M., Gonzales Mamani, W. and Ianella, M. R. (2002). Modeling and Experimental Evaluation of an Automotive Air Conditioning System with a Variable Capacity Compressor. *International Journal of Refrigerant*. 25, 1157-1172.
- Sand, J. R. and Fischer, S. K. (1997). Total Environmental Warming Impact (TEWI) Calculations for Alternative Automotive Air Conditioning Systems. 1997 SAE International Congress. 24-27 February. Detroit, Michigan.
- Senawi, M. Y. (1998). Development of a Building Energy Analysis Package (BEAP) and Its Application to the Analysis of Cool Thermal Energy Storage System. Doctor Philosophy. Universiti Teknologi Malaysia, Skudai.
- Shahril, K., Mohd Kasim, N. and Sabri, M. (2013). Heat Transfer Simulation of Motorcycle Fins under Varying Velocity using CFD Method. 2nd International

Conference on Mechanical Engineering Research (ICMER2013). 1-4 July. Kuantan, Pahang.

- Shao, S., Shi, W., Li, X. and Chen, H. (2004). Performance Representation of Variable-Speed Compressor for Inverter Air Conditioners Based on Experimental Data. *International Journal of Refrigeration*. 27, 805–815.
- Society of Automotive Engineers (2008). *J2765*. United States of America: Society of Automotive Engineers.
- Solmaz, O., Ozgoren, M. and Aksoy, M. H. (2014). Hourly Cooling Load Prediction of a Vehicle in the Southern Region of Turkey by Artificial Neural Network. *Energy Conversion and Management*. 82, 177–187.
- Stancato, F., Onusic, H., Antonelli, R. A. and Avila, P. U. (1992) Experimental and Numerical Analysis of Cooling Loads in a Road Bus. SAE Technical Paper Series. Paper No. 921474.
- Stancato, F. and Onusic, H., 1997, Road Bus Heat Loads Numerical and Experimental Evaluation, *SAE Technical Paper Series*. Paper No. 971825.
- Strömberg, H., Ericsson, J., Andersson, P., Karlsson, M., Almgren, S. and Nåbo, A. (2011). Driver Interfaces for Electric Vehicles. *Automotive UI'11*, 29 November - 2 December. Salzburg, Austria.
- Sumeru, K. (2005). Design and Analysis of Ejector as an Expansion Device in a Split-Type Air Conditioner. Doctor Philosophy. Universiti Teknologi Malaysia, Skudai.
- Sukri, M. F., Salim, M. A., Mohd Rosli, M. A., Azraai, S. and Mat Dan, R. (2012). An Analytical Investigation of Overall Thermal Transfer Value on Commercial Building in Malaysia. *International Review of Mechanical Engineering*. 6(5), 1050–1056.
- Tamura, T., Yakumaru, Y. and Nishiwaki, F. (2005). Experimental Study on Automotive Cooling and Heating Air Conditioning System using CO₂ as a Refrigerant. *International Journal of Refrigeration*. 28, 1302–1307.
- Tian, Z., Qian, Ch., Gu, B., Yang, L. and Liu, F. (2015). Electric Vehicle Air Conditioning System Performance Prediction Based on Artificial Neural Network. *Applied Thermal Engineering*. 89, 101–114.
- Umezu, K. and Noyama, H. (2010). Air-Conditioning System for Electric Vehicles (i-MiEV). SAE Automotive Refrigerant & System Efficiency Symposium, 13 - 15 July. Scottsdale, Arizona USA.

- Wang S., Gu, J., Dickson, T., Dexter, J. and McGregor, I. (2005) Vapour Quality and Performance of an Automotive Air Conditioning System. *Experimental Thermal and Fluid Science*. 30, 59–66.
- Wongwises, S, Kamboon, A. and Orachon, B. (2006). Experimental Investigation of Hydrocarbon Mixture to Replace HFC-134a in an Automotive Air Conditioning System. *Energy Conversion and Management*. 47, 1644–1659.
- Wu, M., Yuan, X. R., Xu, Y. J., Qiao, X. G., Han, X. H., and Chen, G. M. (2014). Cycle Performance Study of Ethyl Fluoride in the Refrigerant System of HFC-134a. *Applied Energy*. 136, 1004–1009.
- Zheng, Y., Mark, B. and Youmans, H. (2011). A Simple Method to Calculate Vehicle Heat Load. SAE Technical Paper Series. Paper No. 2011-01-0127.
- Zhang, H., Dai, L., Xu, G., Li, Y., Chen, W. and Tao, W. (2009). Studies of Air-Flow and Temperature Fields Inside a Passenger Compartment for Improving Thermal Comfort and Energy Saving. Part 1: Test/Numerical Model and Validation. *Applied Thermal Engineering*. 29, 2022-2027.
- Zhou, Z. and Zhang, Y. (2010). Performance of a Split-Type Air Conditioner Matched with Coiled Adiabatic Capillary Tubes using HCFC22 and HC290. *Applied Energy*. 87, 1522–1528.
- Zhu, Y., Jin, X., Du, Z., Fan, B. and Fu, S. (2013). Generic Simulation Model of Multi-Evaporator Variable Refrigerant Flow Air Conditioning System for Control Analysis. *International Journal of Refrigeration*. 36, 1602–1615.