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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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)

B - blockage $(\%)$

c - 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 $(\mathrm{kJ/kg})$

m - amount of refrigerant (kg)

$\dot{m}$ - mass flow rate $(\mathrm{kg/s})$

I - current (A)

I_D - direct solar radiation $(\mathrm{W/m^2})$

I_d - diffuse sky radiation $(\mathrm{W/m^2})$

I_{DN} - direct normal irradiance $(\mathrm{W/m^2})$

I_r - solar radiation reflected from surrounding surfaces $(\mathrm{W/m^2})$

I_t - total short-wavelength irradiance $(\mathrm{W/m^2})$

k - surface conductive heat transfer coefficient $(\mathrm{W/m \cdot K})$

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

W - work done (W)
w - work done per unit refrigerant $(\mathrm{kJ/kg})$
ω - specific air humidity $(\mathrm{kg\,w.v/kg\,d.a})$
δ - thickness (m^2)
x - quality of refrigerant entering evaporator
$\bar{x}$ - average value
z - motor frequency (Hz)
f - surface convective heat transfer coefficient $(\mathrm{W/m^2 \cdot K})$
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
A - type A
bwr - blower
B - type B
c - compressor
C - 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

E - expended

eng - engine

exh - exhaust

f - floor

g - glass

i - inside/inlet

leak - leakage

L - length

LT - latent

m - motor

o - 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.

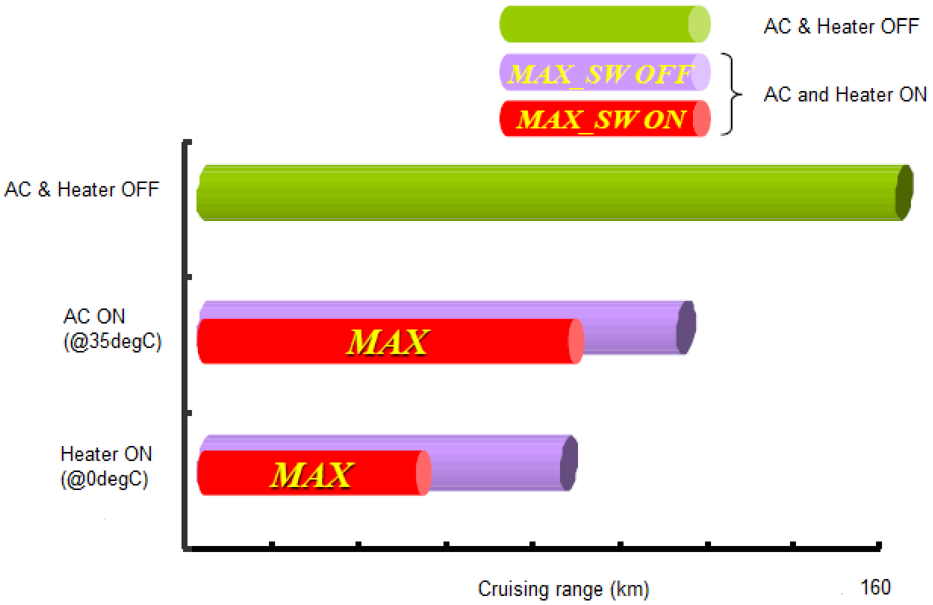

Figure 1.1 Effect of heating, ventilation, and air-conditioning system on cruising range (Kwon *et al*., 2012)

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 energy-efficient 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.

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