COMPUTERISED SIMULATION OF AUTOMOTIVE AIR CONDITIONING SYSTEM

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ABSTRACT

This study developed a mathematical model for simulating the thermal and energy performance of an automotive air-conditioning system in passenger vehicles. The research is divided into two parts: experimental work and computer simulation. The experimental work was conducted to generate data to obtain the off-design air-side evaporator sensible and latent heat transfer correlations. The sensible heat transfer correlation relates the evaporator air off dry bulb temperature to inlet air dry bulb temperature, humidity ratio, evaporator air velocity, condenser inlet air dry bulb temperature, condenser air velocity and compressor speed. Another correlation relates the coil air off humidity ratio to the same six independent variables. The experimental rig consists of the original components from the air conditioning system of a compact size passenger vehicle. A mathematical model has been developed based on the elegant z-transfer function method. Cooling load calculations are made using heat gain weighting factors. Heat extraction rate and cabin air dry bulb temperature calculations are made using air temperature weighting factors. The empirical evaporator sensible and latent heat transfer correlations are embedded in the loads calculation program to enable the determination of evaporator inlet and outlet air conditions and the cabin air condition. The semi-empirical computer program performs transient calculations on a minute-by-minute basis. Comparisons with road test data indicated the program is capable of predicting the performance of an automotive air-conditioning system with accuracy of about 95%. Parametric studies were conducted to assess the effects of six parameters, that are, air conditioning volumetric air flow rate, number of occupants, glass thickness, vehicle speed, color of the car and the fractional ventilation air intake on the thermal and energy performance of a 1.6L Proton Wira Aeroback.

ABSTRAK

Kajian ini membangunkan satu model matematik untuk mensimulasi prestasi haba dan tenaga sistem penyamanan udara kereta. Kajian dibahagikan kepada dua bahagian: ujikaji dan simulasi berkomputer. Ujikaji dilakukan bagi menjana data untuk memperolehi korelasi haba deria dan pendam udara keluar penyejat. Korelasi pemindahan haba deria menghubungkan suhu bebuli kering udara keluar penyejat dengan suhu bebuli kering udara masuk penyejat, kelembapan bandingan udara masuk penyejat, halaju udara penyejat, suhu bebuli kering udara masuk pemeluwap, halaju udara pemeluwap dan kelajuan pemampat. Korelasi berikutnya menghubungkan kelembapan nisbi udara keluar penyejat dengan keenam-enam pemboleh ubah yang sama. Pelantar ujikaji terdiri daripada komponen asal sistem penyamanan udara kereta yang bersaiz sederhana. Model matematik telah dibangunkan berdasarkan kepada kaedah rangkap pindah-z. Pengiraan beban penyejukan dikira menggunakan faktor-faktor memberat gandaan haba. Pengiraan kadar haba penyarian dan suhu bebuli kering udara dilakukan menggunakan faktor-faktor memberat suhu udara. Pemindahan haba deria dan pendam penyejat empirik dimasukkan ke dalam program pengiraan bagi menentukan keadaan udara di bahagian masuk dan keluar penyejat juga udara di dalam kabin. Program berkomputer separuh-empirik ini melakukan pengiraan dinamik untuk setiap minit. Perbandingan di antara data simulasi dengan data ujian jalan raya sebenar menunjukkan program ini berkebolehan meramal prestasi sistem penyamanan udara kereta dengan ketepatan 95%. Kajian parametrik dilakukan untuk menilai kesan enam parameter iaitu, kadar alir isipadu udara, bilangan penumpang, ketebalan gelas, kelajuan kereta, warna kereta dan peratusan kemasukan udara luar terhadap prestasi haba dan tenaga Proton Wira Aeroback 1.6L.

TABLE OF CONTENTS

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

Global warming and tropical climate make automotive air conditioning (AAC) a necessary factor for thermal comfort in passenger vehicles. A vehicle is forced to consume more fuel by an AAC system not only for its operation but also for its extra weight to transport. Since additional fuel consumption by the AAC system means more greenhouse gas emissions, enhancement of the AAC's efficiency and evaluation of its performance are both important (Amr Gado et al., 2008). Substantial efforts are required to evaluate the performance of the AAC, since it is subject to highly varying conditions: initial conditions determine air temperatures entering the evaporator and condenser; user choices determine the evaporator volumetric flow rate and ventilation mode; driving patterns determine the compressor revolutions per minute (rpm) and the condenser face velocity; and cabin material, occupancy, and weather determine internal and external thermal loads (Amr Gado e al., 2008).

The air-conditioner compressor is the single largest auxiliary load on an automobile engine (Rugh et. al, 2001). It can add up to 5 to 6 kW peak power draw on a vehicle's engine, which is equivalent to a vehicle being driven down the road at 56 km/hr (Johnson, 2002). Nationally and globally, the extra fuel consumed due to air conditioner use is substantial. A study done by Rugh et al. (2001) indicates air conditioner use reduces fuel economy by about 20% and increases emissions of

nitrogen oxides (NO_x) by about 80% and of carbon dioxide (CO) by about 70%, although the actual numbers depend on the actual driving conditions.

The increase in pollutant emission levels, the parallel development of environmental awareness and reduction of fuel economy have forced the automotive industry to study innovative solutions to improve the quality of the urban environment and the rate of the accumulation of the fuel used for the compressor air conditioner and the climate control system in total. Engineers and researchers collaborate among each other to study means to reduce the fuel used for vehicle climate control while maintaining or improving occupant thermal comfort and safety. Among such approaches are the use of solar reflective glass (Rugh et. al., 2001, Farrington et al., 2000), parking cooling systems for non-idling air-conditioning (Kampf and Schmadl, 2001), demand capacity controlled compressor (Watanabe and Sekita, 2002), air inlet mixture control strategy (Forest and Bhatti, 2002), automatic climate control systems and reduction in weight and size of air conditioning units.

The energy crisis can be avoided by using renewable energy or it can be delayed via efficient utilisation of the existing non-renewable energy reserves. The latter plan is probably the only means of avoiding an impending crisis before a practical and economically viable method of harnessing free energy is found since research efforts on renewable energy (such as solar and wind energy) are still on going. In order to accomplish this goal, an efficient tool for rapid design and prototyping of air-conditioning systems that can interact various factors (such as ambient conditions, vehicle operation, road and traffic conditions etc.) involved in calculating performance and fuel consumption will be necessary. It also must be noted that, increasing the activities of experimentation and prototyping of any air-conditioning system, may also increase the cost and price tag, especially for automotive manufacturers of developing countries like Malaysia. In this respect, computer simulation can be used for rigorous analysis of the cabin thermal load and air conditioner interaction. Simulation is cheap and it does not harm the environment.

Several integrated models for analyzing AAC performance have appeared in the open literature (Kohler et al., 1990; Currle et al., 1997; Huang, 1998; Khamsi and Petitjean, 2000; Ali Heydani and Saeed Jani, 2001; Rugh, 2002). Most of them used (computational fluid dynamic) CFD and lumped parameter approaches. Generally, the CFD scheme is restricted to steady-state cases or very short simulation periods (Hensen et al, 2002) whereas lumped parameter approach involves more analytical efforts and computer time than the original problem (Ingersoll et al., 1992). As a result, in this study, a unique approach is adopted in developing a computerised simulation tool for analysing the thermal and energy performance of air conditioning (A/C) passenger vehicles. The cabin compartment dynamic loads simulation is made on a minute-by-minute basis using the elegant z-transfer function methodology. The methodology has been used by building energy simulation programs on an hour-by-hour time interval, but it has never been used in load simulation of passenger vehicles. By using one-minute time interval, it is possible to capture the dynamics of energy transfer and storage of the vehicles more accurately. The newly developed tool also directly considers the performance of the evaporator coil linking the loads model and actual coil sensible and latent heat transfer performance. As a result, this semi-empirical simulation tool is not only comprehensive but also capable of modelling realistically the actual processes that are very complex.

1.1 Objectives of the Research

The importance to evaluate realistically and accurately the performance of the AAC system, led this research to focus mainly on the methods to develop a comprehensive mathematical model. Accordingly, the objectives of this research are:

1. to develop a mathematical model for realistic simulation of the thermal and energy performance of an automotive air-conditioning system for a wide range of operating conditions;
2. to validate the model using data obtained from actual road test;

3. to perform a parametric study to assess the effects of air conditioning volumetric air flow rate, number of occupants, glass thickness, vehicle speed, colour of the car and the fractional ventilation air intake (XOA) on the thermal and energy performance of a 1.6L Proton Wira Aeroback.

1.2 Thesis Outline

In Chapter 2, a review on thermal load analysis in passenger compartment and methods to link passenger compartment thermal load model and the A/C system are presented.

Chapter 3 presents a background on loads analysis methodologies. This is followed by procedures to perform load analysis using the weighting factor method (WFM). And finally, the methods to calculate hourly heat gains due to conduction through opaque materials, transmission of solar radiation through glass and heat gains due to occupants are presented.

In Chapter 4, the experimental work to derive empirical correlations for the air-side steady-state performance of the evaporator coil in AAC system is presented. Two empirical coil performance correlations are then developed using the experimental data.

Chapter 5 describes the development of the simulation tool. A validation exercise for the new tool is also presented.

In Chapter 6 the results of a parametric study are presented. In this chapter, the effects of selected parameters specifically cabin air temperature, cabin air specific humidity, cabin air relative humidity and total coil loads are discussed. Finally, the main findings and conclusions are presented in Chapter 7.

1.3 Research Methodology

This study was carried out in six phases, as illustrated in Figure 1.1. Phase one involved a literature review, while phase two involved the development of car simulation (CARSIM) program. Phase three comprised the development of empirical equations and in phase four validation of CARSIM program was carried out. Finally phase six involved a parametric study.

1.3.1 Phase One

Phase one aimed to examine the shortcomings in the previous studies, i.e. on a mathematical model to simulate thermal and energy performance of an automotive air-conditioning system for a wide range of operating conditions realistically and accurately. The following shortcomings were realized:

- The z-transfer function methodology has never been used in load simulation for passenger vehicles. This method is an established method used in building energy analysis and has been proven to be economical in terms of computer memory requirements and run time (Mohd Yusoff, 2000).
- No previous research has linked the evaporator coil performance with the thermal load model empirically, which capable of modeling realistically the actual processes of AAC system that are very complex.

1.3.2 Phase Two

Phase two was carried out to establish the best methodology to develop a mathematical model for simulating thermal and energy performance of an AAC system. From phase one, this study has concluded to extend an existing computer program called Building Energy Analysis Package (BEAP) developed by Mohd Yusoff Senawi (2000) to a car cabin analysis. The characteristics of BEAP are as follows:

- BEAP is used to evaluate thermal and energy performance of a building on an hour-by-hour time interval. The program is meant for a stationary space. It has never been used in load simulation of passenger cars.
- The program used the z-transfer function methodology to simulate space dynamic loads.
- Chilled water coil performance data was obtained from a simulation model.

This modified BEAP program is called Car Simulation (CARSIM) program. CARSIM and BEAP programs are similar in term of the method used to model space dynamic loads, i.e., by using the z-transfer function method. However, CARSIM program differs from BEAP program in terms of:

- CARSIM is meant for a moving space such as cars;
- evaporator coil performance data in terms of empirical equations was obtained empirically;
- the program is based on a minute-by-minute time interval.

1.3.3 Phase Three

To develop empirical equations, evaporator coil performance data has been obtained from experimental work. The following activities were performed during the phase:

- The test rig was fabricated in Thermodynamic Laboratory using Denso air conditioning system used by Proton Wira Aeroback (1.6L) model.
- A multi-linear regression of the 273 experimental data has been made to fit two power equations.
- These power equations have been embedded in the loads calculation program to complete the CARSIM program.

1.3.4 Phase Four

In this phase, CARSIM program was validated based on the actual road test to confirm the validity of the proposed model and methodology. The following activities were performed:

- Conducting a road test using 1.6L Proton Wira Aeroback, driven from Skudai to Pagoh and back via the PLUS highway.
- Compare the data obtained from the simulation with actual test data.

1.3.5 Phase Five

Finally, in phase five, the application of CARSIM program as a simulation tool for designers and researchers was demonstrated. The effects of six parameters on the thermal and energy performance of a 1.6L Proton Wira Aeroback were simulated using this program. The selected parameters are air conditioning volumetric air flow rate, number of occupants, glass thickness, vehicle speed, colour of the car and the fractional ventilation air intake (XOA).

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