ENERGY SAVING IN ROOF-TOP PASSENGER VEHICLE AIR CONDITIONING SYSTEM

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Abstract

A roof-top passenger vehicle air conditioning system is experimentally investigated. Measurements were taken during the experimental period at a time interval of one minute for a setpoint temperature of 23°C with internal heat loads of 0, 1 and 2 kW. The cabin temperature and the speed of the compressor were varied and the performance of the system, energy consumption and energy saving ware analyzed. This study demonstrated the application of the On/Off and Fuzzy Logic Controllers (FLC) for the reduction of energy consumption and for thermal comfort. The energy analysis indicates that FLC is better than the On/Off mode of control. The results also indicated that the proposed FLC can successfully maintain the cabin temperature at acceptable levels with significant energy saving.

Keyword*: Fuzzy logic control, Energy saving, Vehicle Air Conditioning*

1. Introduction

Automotive air conditioner presents some peculiarities when compared to its commercial and industrial counterparts. Automotive applications are characterized by significant thermal load variations, which depend, among other factors, on the time of the day and the number of passengers in the cabin. Moreover, the refrigeration system must provide comfort under highly transient conditions and, at the same time, be compact and efficient [1]. Since the compressor is belt driven by the engine, the compressor speed is directly proportional to the engine speed, which causes the cooling capacity of the system to vary as a function of the engine speed. Consequently, these systems differ from domestic air conditioning system due to the varying compressor speed and cooling capacities as well as the variable cooling load involved [2].

The roof-top passenger vehicles (buses or trains) have thermostat or On/Off control component in their air conditioning (AC) systems. Usually they allow the compressor to work continuously without any consideration to the energy consumption or thermal discomfort during partial load conditions. Consequently, the passengers are subjected to unnecessary low temperatures and they either have to wear thicker clothing or close the air duct louvers. Certainly, this freezing condition will create discomfort to the passengers [3].

Al-Rabghi and Niyaz [4] retrofitted a CFC12 automotive air conditioning (AAC) system and used HFC134a as a refrigerant. They determined the experimental coefficient of performance (COP) for the system as a function of compressor speed for each refrigerant. They found that the AAC system using CFC12 had a 23% better COP than the system using HFC134a.

Jabardo *et al.* [1] developed a steady state simulation model for an AAC system consisting of a variable capacity compressor, a micro-channel parallel flow condenser, a thermostatic expansion valve and a plate fin tube evaporator. They tested the validity of the model on an experimental unit. They observed that the deviations between the simulated and experimental results for the cooling capacity, COP and refrigerant mass flow rate as a function of compressor speed were within 5%. However, for the same performance parameters, as a function of the evaporator return air temperature, the devitations of the simulated results with respect to the experimental ones were as high as 18%.

Kaynakli and Horuz [5] analysed the experimental performance of an HFC134a AAC system to find the optimum operating conditions. They presented some performance parameters such as cooling capacity, compressor power, total power consumption, refrigerant mass flow rate and COP as a function of condensing temperature, evaporator return air temperature, ambient temperature and compressor speed.

Tian and Li [6] developed a mathematical model for an HFC134a AAC system with variable capacity compressor to simulate its steady-state performance. They use the model to determine the effects of compressor speed, ambient temperature, and evaporator air flow rate on the evaporating pressure, condensing pressure, cooling capacity and indicated compressor power. They validated the model results with an experimental unit, and they found that the deviation between the simulated and measured parameters were within 11%.

Hosoz and Direk [7] studied performance characteristics of an HFC134a AAC system which could operate as an air to air heat pump. For this purpose, they developed an experimental system and tested it for both the air conditioning and heat pump modes. The compressor speed and air temperatures at the inlets of the outdoor and indoor coils were varied. They evaluated the performance of the integrated system in terms of cooling and heating capacities, COP, compressor discharge temperature and the rate of exergy destroyed in each component of the system. They determined that the heat pump operation usually yielded a higher COP and a lower rate of exergy destruction per unit capacity compared to the air conditioning operation, although it provided inadequate heating. However, all the literature on AAC system [1 – 7] has not been tested for energy saving of the air conditioning unit.

In this work, an innovative bus AC system has been proposed to overcome the shortcomings of the existing system using multiple-circuit AC system (MCACS). In such a system more than one unit can be used, each unit shares the evaporator surface area and this is known as face-to-face evaporator control. The main advantages of the MCACS concept are of its simple installation and maintenance together with the potential to conserve energy. Should one compressor fail to function, the other circuit can still supply some cooled air to the passengers until repair work can be performed. However, this research is focused on energy saving using fuzzy logic controller. The main idea of designing the controller is to maximize energy saving and thermal comfort for an air conditioning system application through variable speed drive control. The result of the fuzzy logic controller (FLC) will be compared with the On/Off control.

2. Coefficient Of Performance

The COP of a refrigeration machine is the ratio of the energy removed at the evaporator (refrigerating effect) to the energy supplied to the compressor. The COP follows the following general formula [8]:

$$\text{COP} = \frac{(h_1 - h_4)}{(h_2 - h_1)} = \frac{Q_e}{W_{com}} \quad (1)$$

and for the Carnot refrigeration cycle [7]:

$$\text{COP}_{\text{camot}} = \frac{T_1(s_1 - s_4)}{(T_2 - T_1)(s_1 - s_4)} = \frac{T_1}{T_2 - T_1} \quad (2)$$

where h_1, h_2 (kJ/kg) are the enthalpy at the compressor inlet and outlet respectively, h_4 (kJ/kg) is the enthalpy at the evaporator inlet, Q_e (kJ/kg) is the refrigerating effect, W_{com} (kJ/kg) is the compression work, T_1 (^{o}C) is the evaporating temperature, T_2 (^{o}C) is the condensing temperature, s_1 (kJ/kg.K) is the entropy at the compressor inlet and s_4 (kJ/kg.K) is the entropy at the evaporator inlet.

3. Energy Saving

The energy saving calculated is expressed in terms of saving in percentage unit, based on the difference between energy consumed using On/Off control and energy consumed using FLC [8]. The equation is given as:

$$\text{Energy saving} = \frac{(\text{on/off energy}) - (\text{FLC energy})}{(\text{on/off energy})} \times 100 \quad (3)$$

4. Fuzzy Logic Controller

The major components of FLC are shown in Figure 1. They are the input and output variables, fuzzification, inference mechanism, fuzzy rule base and deffuzification. FLC involves receiving input signal and converting the signal into fuzzy variable (fuzzifier). The fuzzy control rules relate the input fuzzy variables to an output fuzzy variable which is called fuzzy associative memory (FAM), and defuzzifying to obtain crisp values to operate the system (defuzzifier) [8].

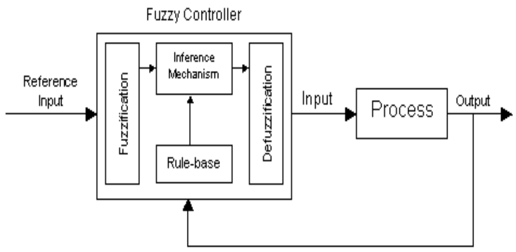

Figure 1. Fuzzy control system

A linguistic variable in the antecedent of a fuzzy control rule forms a fuzzy input space with respect to a certain universe of discourse, while that in the consequent of the rule forms a fuzzy output space. The FLC will have two inputs and one output. The two inputs are the temperature error (e) and temperature rate-of-change-of-error (Δe), and the output is the motor speed change (ΔZ). Table 1 shows the input and output variables, linguistics and labels in the FLC.

The membership functions for fuzzy sets can have many different shapes, depending on definition. Popular fuzzy membership functions used in many applications include triangular, trapezoidal, bell-shaped and sigmoidal membership function. The membership function used in this study is the triangular type. This type is simple and gives good controller performance as well as easy to handle [8].

Table 1. Input and output fuzzy variable

Fuzzy Variable		Linguistic	Labels
Input	e	Hot	H
		Normal	N
		Cool	C
	Δe	Negative	NE
		Normal	NO
		Positive	PO
Output	ΔZ	Slow	SL
		Normal	NM
		Fast	FT

The universe of discourse of e is –2^{o}C to +2^{o}C, the universe of discourse of Δe is –2^{o}C to +2^{o}C, and the universe of discourse of ΔZ is 0 to 5 V_{dc}. The membership functions were chosen to have moderate overlap with a –2, -1, -0.5, 0, 0.5, 1 and 2 distribution for input fuzzy subsets and a 0, 1.25, 2, 2.5, 3, 3.75 and 5 distribution for output fuzzy subsets. In the adjustment process, the shapes of the membership functions were not changed.

A fuzzy logic rule is called a fuzzy association. A fuzzy associative memory (FAM) is formed by partitioning the universe of discourse of each condition variable according to the level of fuzzy resolution chosen for these antecedents, thereby a grid of FAM elements. The entry at each grid element in the FAM corresponds to fuzzy action [8]. The FAM table must be written in order to write the fuzzy rules for the motor speed. The FAM table for the motor speed has two inputs (temperature error and temperature rate-of-change-of-error) and one output (the motor speed change). As the input and the output have three fuzzy variables, the FAM will be three by three, containing nine rules. A FAM of a fuzzy logic controller for the motor speed is shown in the FAM diagram in Table 2.

Table 2. FAM

$e \rightarrow$ / $\Delta e \downarrow$	H	N	C
NE	SL	SL	SL
NO	SL	SL	SL
PO	FT	NM	SL

The rules base from Table 2 are as follows :

1. **If** *e* is H and Δ*e* is NE **Then** Δ*Z* is SL
2. **If** *e* is N and Δ*e* is NE **Then** Δ*Z* is SL
3. **If** *e* is C and Δ*e* is NE **Then** Δ*Z* is SL
4. **If** *e* is H and Δ*e* is NO **Then** Δ*Z* is SL
5. **If** *e* is N and Δ*e* is NO **Then** Δ*Z* is SL
6. **If** *e* is C and Δ*e* is NO **Then** Δ*Z* is SL
7. **If** *e* is H and Δ*e* is PO **Then** Δ*Z* is FT
8. **If** *e* is N and Δ*e* is PO **Then** Δ*Z* is NM
9. **If** *e* is C and Δ*e* is PO **Then** Δ*Z* is SL

The output decision of a fuzzy logic controller is a fuzzy value and is represented by a membership function, to precise or crisp quantity. A defuzzification strategy is aimed at producing a non-fuzzy control action that best represents the possibility distribution of an inferred fuzzy control action. As to defuzzify the fuzzy control output into crisp values, the centroid defuzzification method is used. For practical purposes, the centroid method gives stable steady state result, yield superior results and less computational complexity and the method should work in any situation [8].

5. Experimental Setup And Testing Procedure

The experimental set-up shown in Figure 2 is mainly made up of original components from a bus AC system, arranged in such a way to emulate that of an actual bus. In order to simulate the cooling load imposed on the passengers' compartment, an electric heater was immersed in the main air duct upstream to the evaporators. The evaporator inlet air temperature was attained through the use of the electric heater controller to obtain the sensible cooling load while the latent load was achieved by mixing streams of external air with that of cooled air from the evaporator.

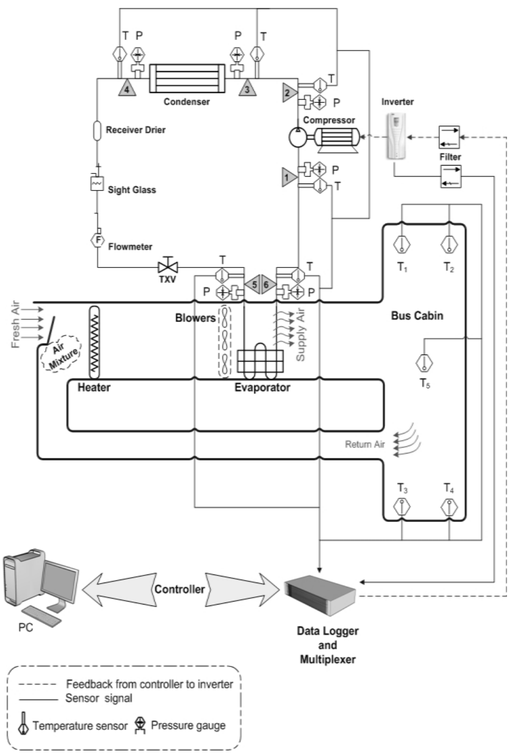

Figure 2. Schematic diagram of the experimental rig

The air ducts were insulated using polyurethane foam with a thickness of 5 cm. The refrigerant lines of the system were made from copper tubing and insulated using an elastomeric material. Temperature, pressure, and mass flow rate were measured at locations indicated in Figure 2. The refrigerant and air temperatures at various points of the system were detected by thermocouples. The thermocouples for the refrigerant temperatures were inserted inside the copper tubes.

The interior surface temperatures of the simulated passenger cabin were measured by attaching five thermocouples to the interior cabin sides as shown in Figure 2. Nine pressures at various points of the refrigerant circuit were measured by pressure gauges. The refrigerant mass flow rate was measured using a refrigerant flow meter for R-134a.

The control system of the compressor speed consists of a thermocouple in the bus cabin, an On/Off and Fuzzy logic subroutine installed on a computer, an inverter and an electric motor. The thermocouple monitors the temperature of the cabin and emits electrical signals proportional to the state of the conditioned space. This signal is filtered before it reaches the controller, thus minimizing noise, which may cause error in the control system. The output signal is supplied to the controller and computer, which sends out a control signal that is a function of the error between the value of the monitored temperature and the required set point temperature. The control signal output is supplied to the inverter, which modulates the electrical frequency supplied to the motor such that it is linearly proportional to the control signal. 50 Hz electricity is supplied to the inverter, which supplies variable-frequency electricity to the motor. The rotational speed of the motor is directly proportional to the frequency of the electricity supplied to the motor. The inverter converts the constant voltage and frequency of a three-phase power supply into a direct voltage and then converts this direct voltage into a new three-phase power supply with variable voltage and frequency. The three-phase asynchronous motor has an infinite speed variation adjustment.

The experiments were conducted at two different conditions:

1. The compressor system with On/Off controller.
2. The variable speed compressor system with FLC.

The experimental settings were:

1. Cabin temperature setpoint : 23^{o}C.
2. Internal heat loads : 0, 1 and 2 kW.

6. Results And Discussions

Figure 3 shows the effect of motor frequencies on the steady state values of the cabin temperature and the energy consumption during the test period of one hour. Energy consumption was calculated from the start of the motor using the motor power multiplied by the time of operation. The result indicates that the energy consumption is dependent on the motor frequency. When the frequency increases the energy consumption increases. It can be observed that the cabin temperature achieved is lower as the frequency is increased.

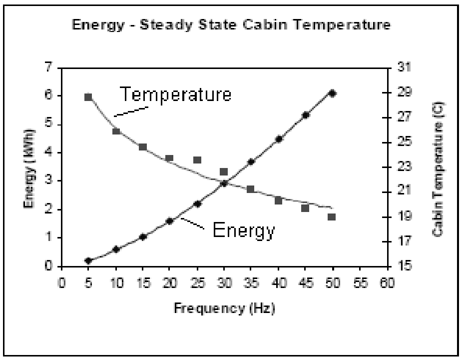

Figure 3. Steady-state cabin temperature and energy consumption at various frequencies

It can also be observed that the higher the frequency, the smaller is the value of COP. A high COP at a lower frequency is mostly due to the small compressor power consumption compared with that at a higher frequency. When the compressor power consumption increases, the COP decreases with the increase of the compressor frequency. Figure 4 shows the steady state COP at various frequencies.

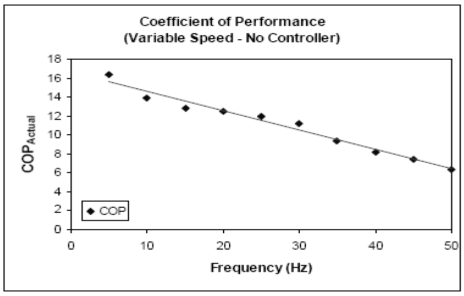

Figure 4. Steady-state COP at various frequencies

Figure 5 shows the temperature responses at various internal heat loads. Initially the motor was set to run at the maximum speed (50 Hz). With the maximum compressor motor speed, the cabin temperature decreases as the time increases. Referring to the set point temperature, the controller will minimize the error between the set point and the cabin temperature. The figures show that the internal heat load affects the room temperature and the speed of the motor. Increasing the internal heat loads results in a longer time to reach the temperature setting, also the motor speed drops from the maximum compressor motor speed as the room temperature reaches the set point. The results indicated that, the higher the internal heat loads the higher is the energy consumption. Figure 6 shows the energy consumption at various internal heat loads.

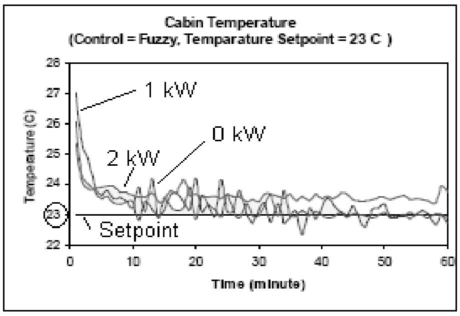

Figure 5. Temperature responses for FLC

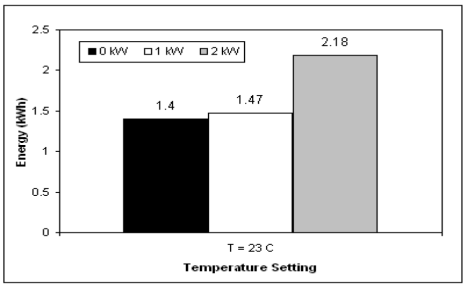

Figure 6. The energy consumption for FLC

Figure 7 shows the coefficient of performance (COP) for the variable speed compressor with FLC. It can be observed that the higher the frequency, the smaller is the value of the COP. The value of the COP is found to be between 5.88 to 19.23. A high COP at the lower frequency is mostly due to smaller compressor power consumption compared with that at the higher frequencies. When the compressor power consumption increases, the COP decreases with the increase of the compressor frequency.

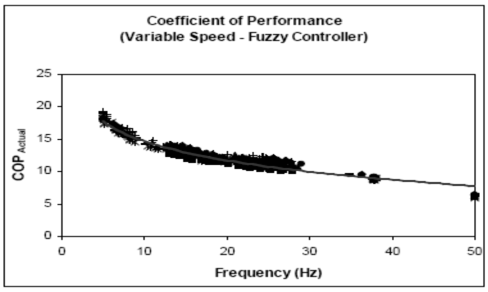

Figure 7. COP for FLC

Figure 8 shows the energy saving for FLC in comparison with the On/Off controller for different internal heat loads. If the internal heat loads is high, the energy consumption is also high. Furthermore, the higher the energy consumption, the smaller is the energy saving.

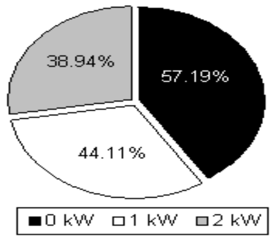

Figure 8. Energy saving : On/Off – FLC

7. Conclusion

A series of experiments for a variable speed AAC system has been conducted at various frequencies from 5 to 50 Hz. The impact of variable speed on the performance of the system, the cabin temperature and energy consumption have been analyzed experimentally. The results indicate that the cabin temperature, the COP and energy consumption is dependent on the frequency of the motor. The temperature of the cabin decreases as the frequency of the motor increases, and vice versa. The inverter allows for more than one temperature setting. For this system, the steady state temperature varies from 18.95°C to 28.54°C. When the frequency increases, the cabin temperature decreases while the energy consumption increases. When the energy consumption increases, the COP decreases with the increase of the compressor's motor frequency. A higher energy saving is achieved when the motor runs at a lower frequency. The high energy saving at a lower frequency is mostly due to the lesser compressor energy consumption.

The FLC was developed to control the motor speed in order to maintain the cabin temperature at or close to the set point temperature. When the cabin was thermally loaded, the controller acted such that the temperature reduction in the cabin is faster until the set point temperature was achieved again. The energy consumption would change with the change in motor speed. When the motor speed increases, the cabin temperature decreases and the COP decreases with the increase in energy consumption. Furthermore, the higher the energy consumption the smaller is the energy saving.

The research has showed that fuzzy logic control gives a higher saving and provides a better control than the On/Off controller. The system's performance in terms of COP is found to follow similar trends for all the internal heat loads.

Acknowledgment

The authors would like to acknowledge the support provided by Universiti Teknologi Malaysia, IRPA grant number 74522 and E-Science fund grant number 79170 from The Ministry of Science, Technology and Innovation (MOSTI) Malaysia, and Universitas Bung Hatta for their cooperation.

References

[1] J. M. S. Jabardo, W. G. Mamani, and M. R. Ianella, "Modeling and Experimental Evaluation Of An Automotive Air Conditioning System With A Variable Capacity Compressor", International Journal of Refrigeration, Vol. 25, pp. 1157 – 1172, Dec 2002.

[2] M. Hosoz and H. M. Ertunc, "Artificial Neural Network Analysis Of An Automobile Air Conditioning System", Energy Conversion & Management, Vol. 47, pp. 1574 – 1587, July 2006.

[3] M. K. Mansour, Design and development of bus air conditioning system responding to a variation in cooling load, PhD progress report, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 2006.

[4] O. M. Al-Rabghi and A. A. Niyaz, "Retrofitting R-12 Car Air Conditioning With R134a Refrigerant", International Journal of Energy Research, Vol. 24, pp. 467 – 474, April 2000.

[5] O. Kaynakli and I. Horuz, "An Experimental Analysis of Automotive Air Conditioning System", Int. Comm. Heat and Mass Transfer, Vol. 30, pp. 273 – 284, March 2003.

[6] C. Tian and X. Li, "Numerical Simulation On Performance Band Of Automotive Air Conditioning System With A Variable Displacement Compressor", Energy Conversion & Management, Vol. 46, pp. 2718 – 2738, Oct 2005.

[7] M. Hosoz and M. Direk, "Performance Evaluation Of An Integrated Automotive Air Conditioning And Heat Pump System", Energy Conversion & Management, Vol. 47, pp. 545 – 559, March 2006.

[8] H. Nasution, "Energy analysis of an air conditioning system using PID and fuzzy logic controllers", PhD Thesis, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 2006.