DEVELOPMENT OF FUZZY LOGIC CONTROL FOR VEHICLE AIR CONDITIONING SYSTEM

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Abstract

A vehicle air conditioning system is experimentally investigated. Measurements were taken during the experimental period at a time interval of one minute for a set point temperature of 22, 23 and 24^{o}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. The main objective of the experimental work is to evaluate the energy saving obtained when the fuzzy logic control (FLC) algorithm, through an inverter, continuously regulates the compressor speed. It demonstrates better control of the compressor operation in terms of energy consumption as compared to the control by using a thermostat imposing On/Off cycles on the compressor at the nominal frequency of 50 Hz. The experimental set-up consists of original components from the air conditioning system of a compact passenger vehicle. The experimental results indicate that the proposed technique can save energy and improve indoor comfort significantly for vehicle air conditioning systems compared to the conventional (On/Off) control technique.

Keywords*: Fuzzy logic control, energy saving, vehicle air conditioning*

Abstrak

Telah dilakukan penelitian suatu sistem pendingin kendaraan. Pengukuran dilakukan selama penelitian dengan interval waktu satu menit dengan temperatur ditetapkan sebesar 22, 23 and 24^{o}C dan beban pendingin internal 0, 1 dan 2 kW. Pada penelitian ini dianalisa temperatur kabin and kecepatan kompresor yang divariasikan, unjuk kerja sistem, konsumsi energi dan penghematan energi. Tujuan utama penelitian ini adalah untuk mengevaluasi penghematan energi dengan menggunakan algoritma kendali logika fuzzy (FLC), melalui inverter, secara terus menerus akan diatur kecepatan kompresor. Penelitian menunjukkan operasi kompresor dalam pemakaian energi akan lebih baik menggunakan FLC jika dibandingkan dengan kendali On/Off yang dikesan berdasarkan siklus kompresor pada frekuensi nominal 50 Hz. Peralatan eksperimen dibangun dengan komponen asli suatu sistem pendingin kendaraan penumpang. Hasil penelitian menunjukkan bahwa teknik yang diusulkan untuk sistem pendingin kendaraan dapat menghemat pemakaian energi dan memperbaiki kenyamanan dalam ruangan kabin dibandingkan dengan teknik kendali konvensional (On/Off).

Kata kunci*: Kendali logika fuzzy, penghematan energi, pendingin kendaraan*

1. INTRODUCTION

In general, the vehicle air conditioning (VAC) system presents some peculiarities with respect to its commercial and industrial counterparts. On one hand, its operation is characterized by significant thermal load variations, which depend on several factors such as: opening of a door, changing of sun load through the windshield and side glass windows, and number of passengers on board. On the other hand, the refrigeration system must provide comfort under highly transient conditions and, at the same time, be compact and efficient. This requires a proper design and selection of air conditioning (AC) system [1].

In tropical countries, the peak load which is between 12.00 noon to 3.00 pm drives the AC system to operate at maximum capacity. However, at other times when the system experiences partial load conditions (low sensible heat load), especially at night or when it rains, it still operates at maximum capacity. This leads to an uncomfortable cold condition for passengers. The overcooling is due to the absence of any provision to modulate the system capacity to match the drastic reduction in the imposed cooling load. On the other hand, AC systems are often over-designed: first to ensure a fast response so that the cabin temperature drops quickly when the system is switched on, and second to overcome the irregular and rare conditions of extremely high humidity and high atmospheric temperature. Thus, under normal conditions, a lot of the energy is unnecessarily wasted and results in a higher consumption of fuel. Therefore, attention has been drawn towards designing energy-saving AC systems without sacrificing thermal comfort.

Because VAC is a competitive and technology oriented industry, the literature provides only a limited number of studies concerning the experimental performance of these systems. Davis et al. [2] presented a computer program for performance analyses of separate VAC components as well as that for performance simulation of the integrated AC system. Kyle et al. [3] carried out a performance simulation of a VAC system on the basis of the performance analysis program written for the residential heat pump model. Jung et al. [4] studied the thermodynamic performance of supplementary or retrofit refrigerant mixtures for R12 VAC systems produced before 1995. Lee and Yo [5] conducted performance analyses of the components of a VAC system and developed an integrated model to simulate the entire system. Ratts and Brown [6] experimentally analyzed the effect of refrigerant charge level on the performance of a VAC system. Al-Rabghi and Niyaz [7] retrofitted an R12 VAC system to use R134a and compared the coefficient of performance (COP) for the two refrigerants. Jabardo et al. [8] developed a steady state computer simulation model for a VAC system with variable capacity compressor and investigated its validity on an experimental unit. Joudi et al. [9] developed a computer model simulating the performance of an ideal VAC system working with several refrigerants. Kaynakli and Horuz [10] analyzed the experimental performance of a VAC system using R134a in order to determine the optimum operating conditions. Hosoz and Direk [11] integrated VAC and air-to-air heat pump system using R134a with varying compressor speed to evaluate the effect of the operating conditions on the capacity, COP, compressor discharge temperature and the rate of exergy destroyed by each component of the system for both operating modes. Hosoz and Ertunc [12] predicted various performance parameters of VAC system using an artificial neural network model. Razi et al. [13] presents a neuro-predictive controller for temperature control of VAC system and a numerical model for automotive refrigeration cycle, which includes transient operating conditions employed in simulations.

In this work, an innovative VAC 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 Coefficient of Performance (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]:

$$\mathrm{COP} = \frac{(h_1 - h_4)}{(h_2 - h_1)} = \frac{Q_e}{W_{com}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

and for the Carnot refrigeration cycle [7]:

$$\mathrm{COP}_{\mathrm{carnot}} = \frac{T_1(s_1 - s_4)}{(T_2 - T_1)(s_1 - s_4)} = \frac{T_1}{T_2 - T_1} \quad \ldots\ldots(2)$$

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. FUZZY LOGIC CONTROLLER

The major components of fuzzy logic controller (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].

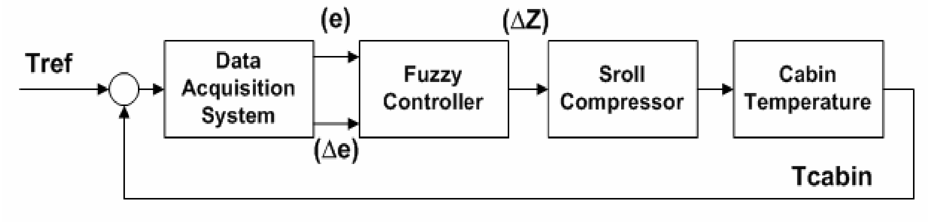


Figure 1. Fuzzy control system

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.

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 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].

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. The rules base from Table 2 are as follows:

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

Table 2. FAM

$e\rightarrow$ $\Delta e\downarrow$	**H**	**N**	**C**
NE	SL	SL	SL
NO	SL	SL	SL
PO	FT	NM	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].

4. PRINCIPLE OF MULTI CIRCUIT

The conventional VAC system consists of two evaporators providing conditioned air to the two rows of the respective passengers' compartment, two stage condensers (connected in series) and one compressor. The principle of the multi-circuit approach is to split the whole system into two small units, each unit is driven by separate a compressor for example one compressor capacity has 0.50 of the total system capacity and the other compressor for the reminder system capacity. Figure 2 shows the schematic diagram of the newly proposed VAC system. The single evaporator is divided equally into separate face-to-face sections, so the half section of one evaporator is connected together with the half section of the other. Therefore, the proposed VAC system is called a multi-circuit AC system with face-to-face evaporator control. The two stage condenser is also divided into two separate condensers where each unit has its own condenser. To make the system respond automatically to the cooling load variation, an organizer or controller should govern how many compressor will be on service (one or two compressors work together).

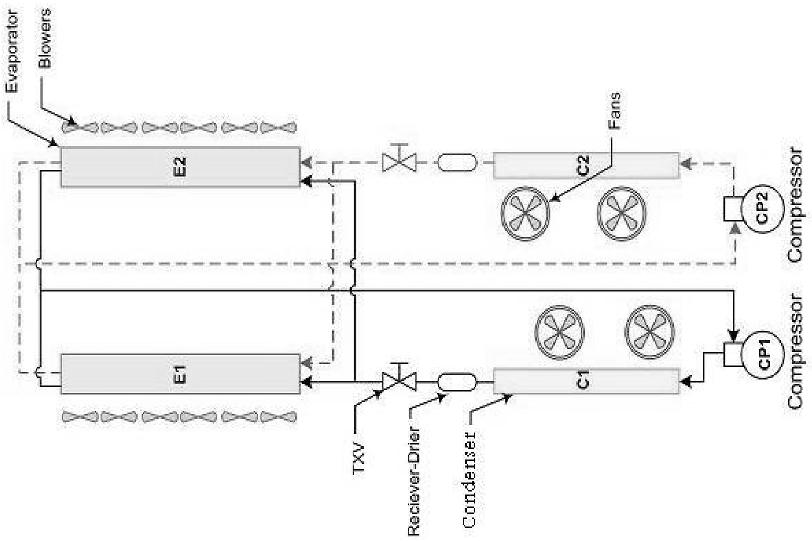


Figure 2. Schematic diagram of the multi circuit VAC

5. EXPERIMENTAL SETUP

The experimental set-up shown in Figure 3 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.

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 3. 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 3. 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.

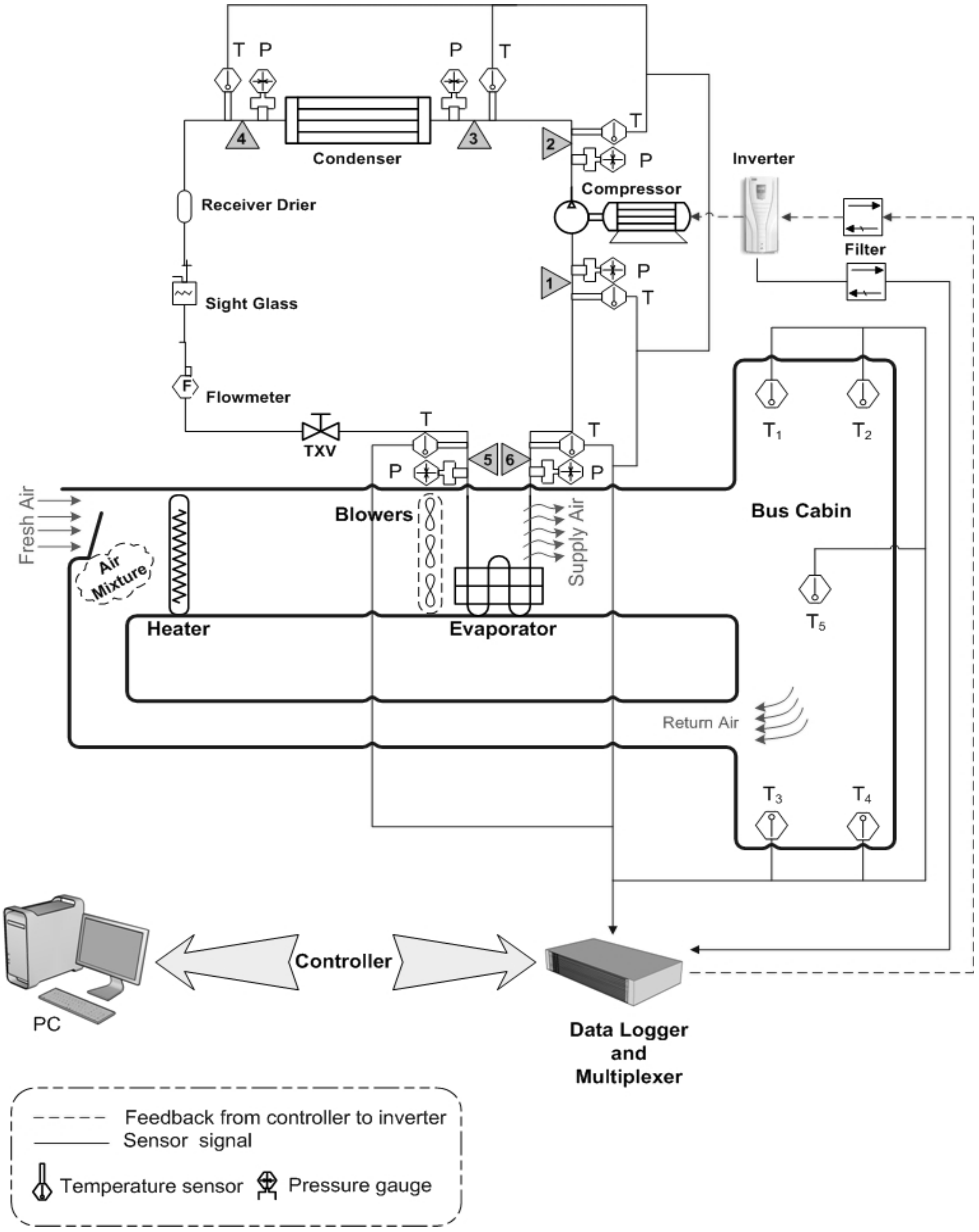


Figure 3. Schematic diagram of the experimental rig

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 set points : 22, 23, and 24°C.
2. Internal heat loads : 0, 1 and 2 kW.

6. RESULTS AND DISCUSSIONS

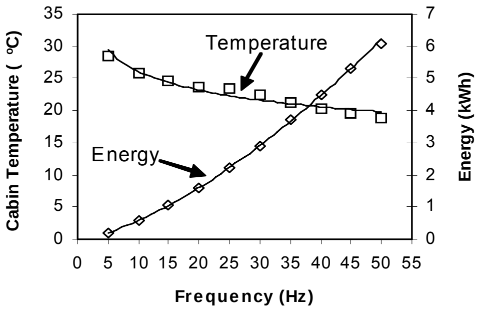
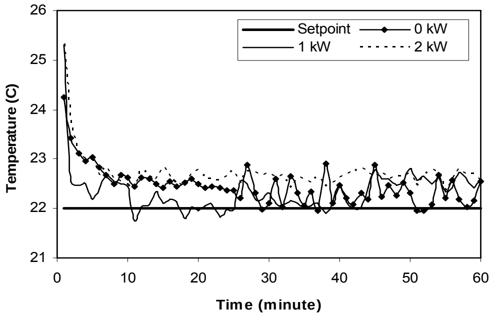
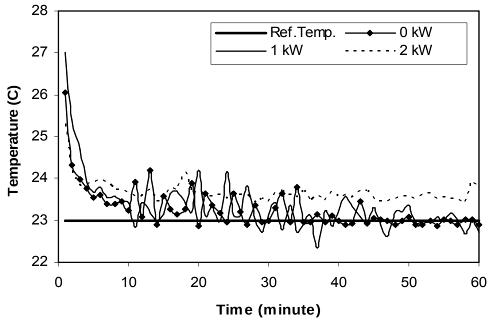


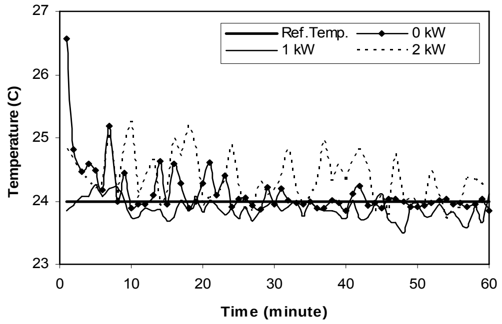
Figure 4. Steady-state cabin temperature and energy consumption at various frequencies



a. FLC (T = 22^{o}C)



b. FLC (T = 23^{o}C)



c. FLC (T = 24^{o}C)

Figure 5. Temperature responses for FLC

Figure 4 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 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.

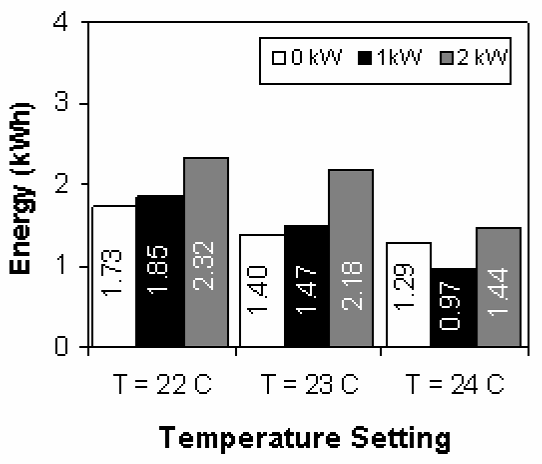


Figure 6. The energy consumption for FLC

Figure 7 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.

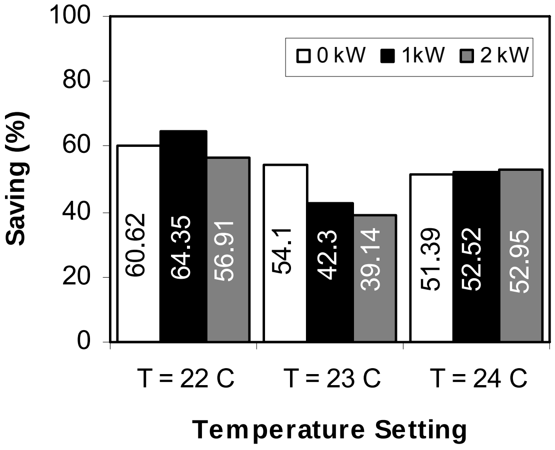


Figure 7. Energy saving: On/Off – FLC

7. CONCLUSION

A series of experiments for a variable speed VAC 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.

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