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Development and testing of a multi-type air conditioner without using AC inverters

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Abstract

This paper reports the results from the development and performance testing of a cost effective, energy efficient, multi-type air conditioner that connected five indoor units (evaporators) to one outdoor unit (condenser) with a digital scroll compressor. Instead of using inverter technology, which has a potential risk of harmonic current emissions, this study used a digital scroll compressor, which provided the variable refrigerant volumes. The measured results for this innovative design showed: (1) The relationship between the degree of opening of the electronic expansion valves (s) and the compressor output ratio (%) could be represented by regression functions, which formed the basic parameters of the system control. (2) The developed system provided true zoning capability because it could run indoor units under part load conditions, therefore wasting little energy. The power consumption of the developed system was reduced from 100% to 25% when the full load was reduced to a partial load of 17%, saving more than 75% of the work required using a conventional un-loading method. (3) The developed system has a broader range of capacity output (from 17% to 100%) than that of an AC variable frequency control system (from 48% to 104%). The developed system cost 20% less than a comparable system with an AC inverter.

Keywords: Electric expansion valve; Scroll compressor; Inverter; Harmonic current emission

1. Introduction

Multi-type air conditioners have been employed in small and medium sized buildings recently due to their several benefits over a conventional air conditioning system, such as the window unit

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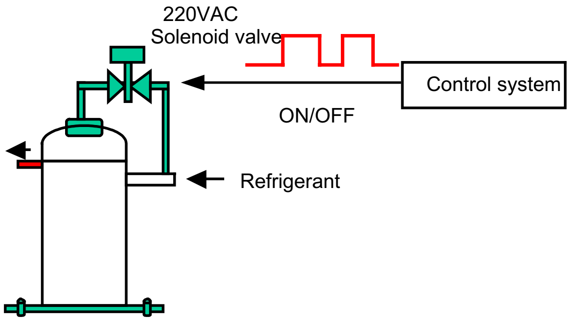

Fig. 1. Capacity control of the screw compressor by on/off switching of solenoid valves to change the position of a static scroll.

type and a duct type system. Their advantages include easier system maintenance, diversification of facility use and, most importantly, precise capacity control, which not only conserves energy but also provides the possibility of an intelligent building control. Multi-type air conditioners have been popular in Asia and much of Europe for many years, and they are gaining popularity in the US recently, primarily in retrofit situations in which ductwork cannot be installed. However, some people think that multi-type systems have high initial costs and harmonic current emissions (hmc) because they use inverter technology, which in some situation, may distort the electric sine wave and emit electronic noise into the electric system, damaging the electronic equipment. Accordingly, the development of a multi-type air conditioner without inverters and, consequently with a reduced cost, is an important goal of manufacturers of air conditioners. Little literature addresses the multi-type air conditioner. Fujita et al. [1] examined the capacity and refrigerant flow control for a multi-type air conditioner that used a twin rotary compressor with two indoor units and EEVs (electronic expansion values). They also reported some means to improve thermal comfort and save energy. Okuzawa [2] reported the optimization of the variation in superheating of a multi-type air conditioner with a horizontally installed twin rotary compressor, which included four to six indoor units. Several papers addressed the performance of an air-conditioner with a variable speed compressor [3–5]. However, none of them elucidated the relationship between the performance of the electronic expansion valve (EEV) and the compressor output. Recently, Park et al. [6] conducted a simulation analysis for a multi-type inverter air conditioner with a linear electronic expansion valve and a variable speed compressor. A further study reported by Choi and Kim [7] focused on the capacity modulation for an inverter driven, multi-type air-conditioner having two indoor units. They suggest that maximum cooling capacity can be achieved when the superheat is maintained at 4 °C. As far as the author is aware, no paper has been published regarding a multi-type air conditioner without the inverter technology. In view of the above issues, this study utilizes a variable refrigerant volume scroll compressor for the multi-type air conditioning system. The compressor is able to operate at 10–100% capacity and at relatively low cost without using the inverter. Fig. 1 depicts the capacity control of the screw compressor by on/off switching of the solenoid valves to change the position of a static scroll, thus providing variable refrigerant output. Fig. 2 shows the tested relationship of the compressor output ratio to frequency.

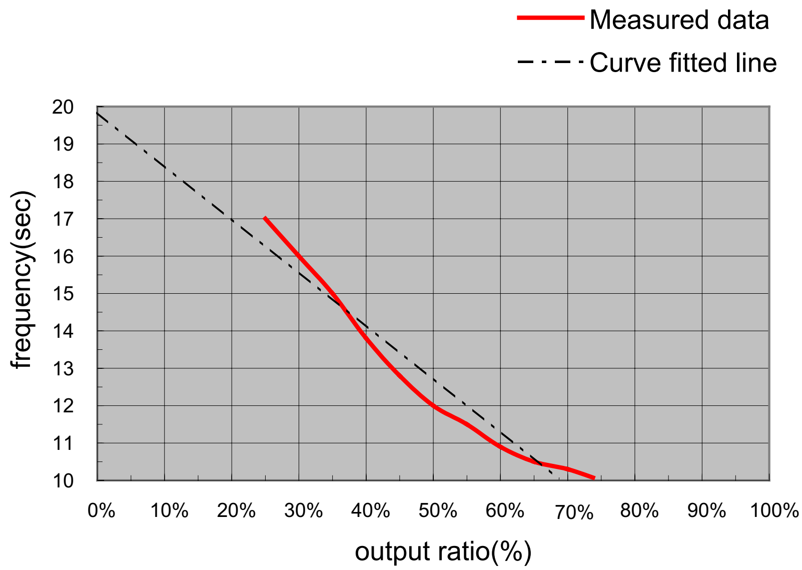

Fig. 2. Measured compressor output ratio to frequency.

2. System development and setup of the test rig

Key works related to the development and setting up of the test rig of the multi-type air conditioner are discussed below.

2.1. System configuration

Fig. 3 shows the system hardware configuration of the developed multi-type air conditioner, which has an outdoor unit (rated capacity is 12,000 kcal/h). The system can connect up to five indoor units, which provides wide ranges of capacity options; including 2000, 2500, 3150, 3550, 4500, and 5000 kcal/h. In the system, the primary pipe of the outdoor unit is connected to a distribution box by check valves. The liquid pipes of the indoor units are connected to the five electronic expansion valves in a distribution box using bell type screw nuts. The indoor unit uses the electric expansion valve to control the required volume of refrigerant and the evaporation temperature. The refrigerant flows from the indoor units to the distribution box and then returns to the compressor through a liquid–gas separator. The refrigerant output and operating point of the compressor are adjusted to meet the required load of the indoor units. Five EEVs are installed individually in the liquid lines of the indoor units, henceforth called EEV1, EEV2, EEV3, EEV4 and EEV5, respectively. The important specifications of the EEVs used are: (1) actuating mechanism: a stepping motor using a 1–2 excitation method with input voltage of 12 V, (2) orifice diameter/length: 1.4 mm/3 mm, and (3) proportional control with maximum degree of opening of 480°.

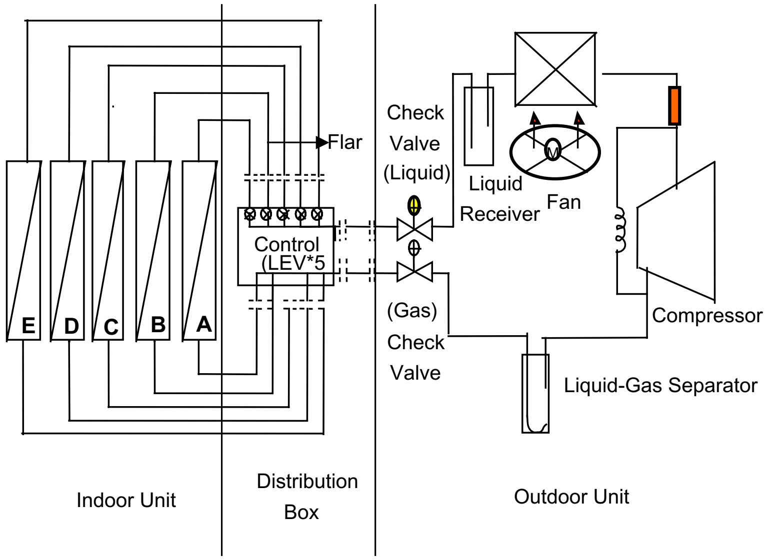

Fig. 3. System hardware configuration.

2.2. Communication of software and hardware

The indoor units receive the user's signals and transmit them to a distribution box through a series of signals (see Fig. 4). The distribution box receives these signals, determines the required load of the indoor units from the difference between the room temperature and the desired temperature, regulates the degrees of opening of the EEVs to control the refrigerant volumes and evaporation temperatures of the indoor units and sends the required signals from the indoor units

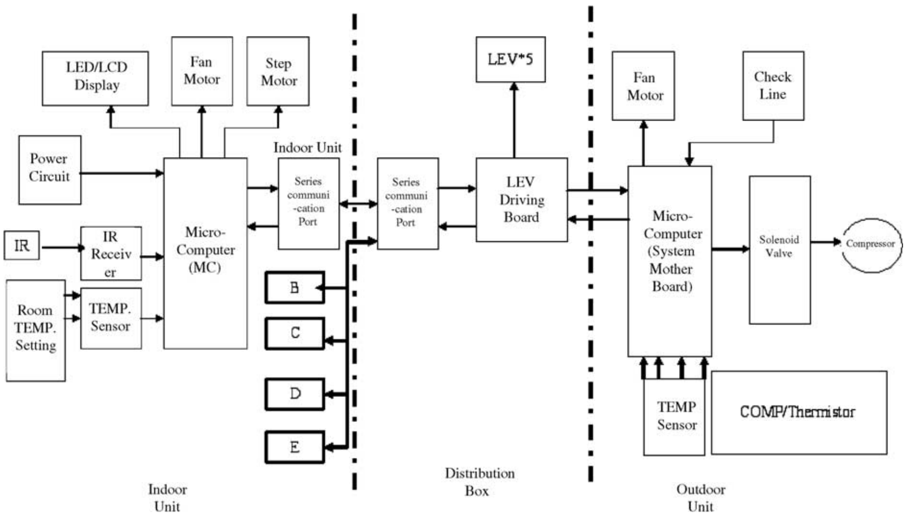

Fig. 4. System software configuration.

to the outdoor unit. The outdoor unit determines the running cycle and output time of the refrigerant in the compressor according to the requirement of the indoor units to control the ON/OFF cycle time of the solenoid valves, which controls the refrigerant volume of the compressor.

In the indoor unit, a LCD indicates the operating conditions, which include air conditioning, dehumidifying and ventilation, and a step motor regulates the outlet guide vanes. A fan motor determines the speed at which air is supplied. The distribution box effectively checks the amount of refrigerant required by each indoor unit by the EEV and governs the speed of the fan of the outdoor unit and the output of the compressor.

2.3. Fan speed control and parameter set up

Fig. 5 shows the relation of the compressor output and the outdoor unit's fan speed, which is relates to the high pressure and sub-cool temperature of the refrigerant system. There are four different fan speeds that control its own range of output ratio. For example, a fan speed of 300 rpm controls the range of output ratio from 30% to 60% and accelerates to 500 rpm if the output ratio is increased to 60%. On the other hand, the fan speed stays at 700 rpm in the output range of 100–70% and slow downs to 500 rpm if the output ratio is decreased to 70%. The fan speed is adjusted by the input cycle time of the wave, which controls the input voltage. Fig. 6 shows the fan speed control of the developed air conditioner when the fan speed is 700 rpm. In the system, the input voltage is controlled by a three cycle ON and one cycle OFF model.

2.4. Measurement rig setup and test procedure

Laboratory measurements were conducted in an environmental chamber based on ASHRAE Standard 116 [8]. Fig. 7 shows the environmental chamber used for sampling the airflow rate and the capacity of the indoor units. The chamber is divided into outdoor and indoor sides, also presented in Fig. 7. The temperature conditions are as follows; outdoors 35 °C DB/24 °CWB and indoors 27 °C DB/19 °C WB. The equipment used was an integrating power meter, (YOKOGAWA WT110 digital power meter), a temperature recorder (YOKOGAWA HR2500E), an electronic expansion valve (FUJIKOKI PF3-48) and a regulator of the output cycle of the compressor (Eagle Signal SX110 timer). The capacity of the, multi-type air conditioner was measured by utilizing both the air flow rate and enthalpy difference across the indoor unit. The airflow rate was measured in the airflow chamber according to ANSI/AMCA 210 [9]. The airflow

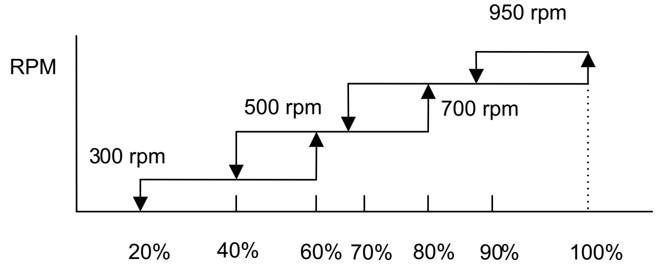

Fig. 5. RPM of outdoor unit's fan vs compressor output ratio.

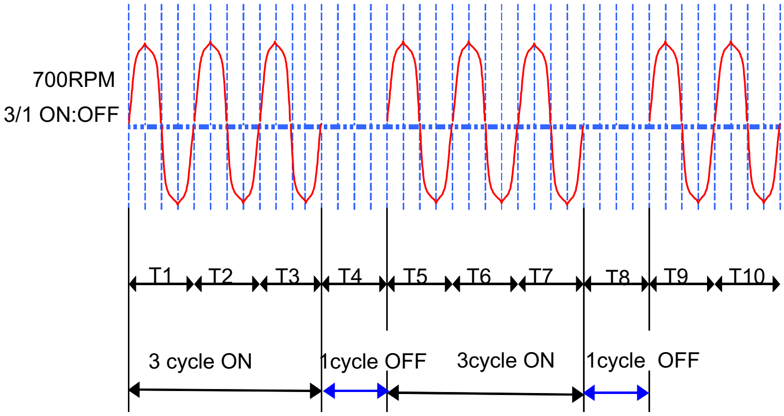

Fig. 6. Input voltage control by 3 cycle ON and 1 cycle OFF when fan speed is 700 rpm.

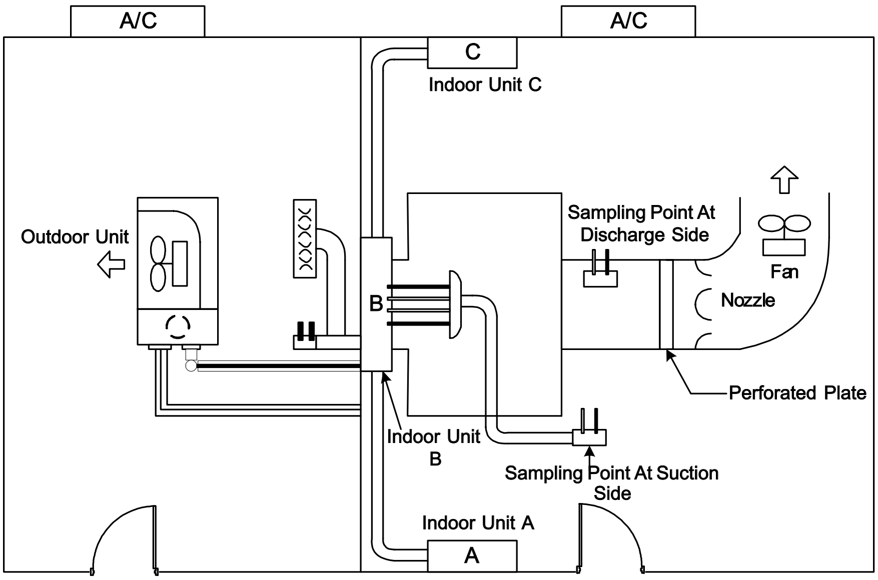

Fig. 7. Arrangement of indoor and outdoor testing chamber.

chamber consisted of a nozzle and a differential pressure transducer, as shown in Fig. 8. Inlet and outlet enthalpies across the indoor coil were calculated by using dry bulb and wet bulb temperatures. Air temperatures were measured using RTDs, which satisfied the accuracy specified by ASHRAE Standard 41.1 [10]. The power input to the system was monitored using a power meter with an uncertainty of 0.01% of full scale. To the outdoor unit (rated capacity = 12,000 kcal/h) and indoor units (six rated capacities available, i.e. 2000, 2500, 3150, 3550, 4500 and 5000 kcal/h), there were 157 combination cases to test (i.e. 6, 21, 53, 55 and 22 combination cases for one indoor unit, two indoor units, three indoor units, four indoor units and five indoor units, respectively.)

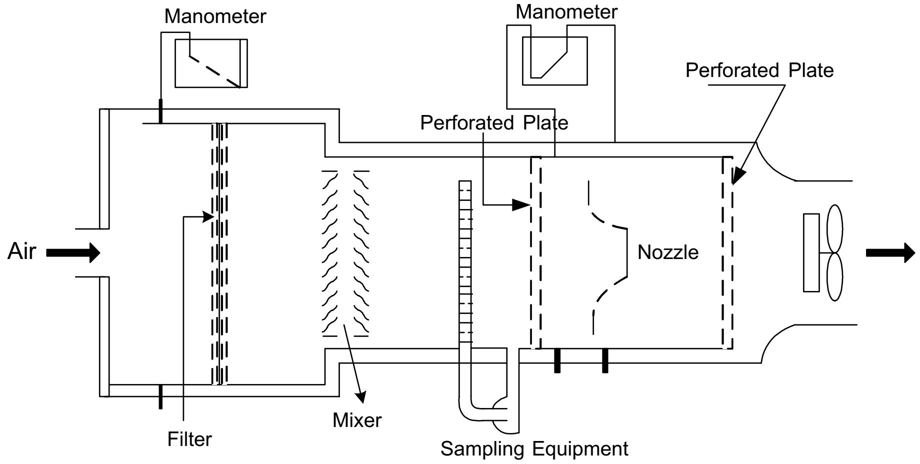

Fig. 8. Airflow volume measurement tunnel.

The relation between the total openings of the EEVs and the output flow rate of refrigerant (m) through the EEVs (kg/h) can be evaluated by

$$m = 5470 \times C_d \times A \times (P_c - P_e)^{1/2} \quad (1)$$

where C_d is a flow coefficient, A is the total open area of the EEVs (m^2), P_c is the EEV inlet refrigerant pressure (Pa) and P_e is the EEV outlet refrigerant pressure (Pa). The output flow rate of refrigerant of a compressor (m_c) can be determined by

$$m_c = v_p/v_g \times \eta_v \quad (2)$$

where v_p is the theoretical piston displacement volume (m^3/h), v_g is the specific volume of the refrigerant in the suction end of the compressor (m^3/kg) and η_v is the volumetric efficiency of the compressor. The specific volume at the inlet of a compressor has the most substantial influence on the flow rate of refrigerant. In this study, the temperature of superheat and sub-cool degree was maintained at 5 °C.

3. Measured results and discussion

3.1. Degree of opening of EEVs and the compressor output ratio

The most important task in developing the system was to identify the relationship between the degree of opening of the EEVs and the compressor output ratio (%). The relationship between the degree of opening of the EEV and the output capacity (%) of a compressor for a particular indoor unit capacity was determined. The outdoor unit has a nominal load of 12,000 kcal/h. The indoor unit has six capacity settings, 2000, 2500, 3150, 3550, 4500 and 5000 kcal/h. An indoor unit with a capacity of 3150 kcal/h was firstly selected as a base for the tested combinations. Tests were conducted to obtain the relationship between the degree of opening of the EEVs and the compressor output capacity (%) for combinations of one, two, three, four and five indoor units. The control parameters included the speed of the outdoor unit fan, the sub-cool temperature and the superheat temperature. The measured degree of opening of the EEVs vs compressor output ratio for the different numbers of indoor units compositions is depicted in Fig. 9. These data are linearly regressed as follows.

$$Y = A_i \exp(B_i X) \qquad X = \ln(Y/A_i)/B_i \quad i = 1\text{–}5 \tag{3}$$

where Y = total degree of opening of the EEVs, X = compressor output capacity ratio (%) and i = number of indoor units. Table 1 presents the factors (A_i and B_i) in the equation that relates the opening of the EEVs to the output of a compressor.

For the different basic indoor unit, we need to obtain its own correction factor (K value) that links to the Y value of the basic unit. For example, in the case of 35% compressor output ratio, the K value of the 2500 kcal/h case to the 3150 kcal/h case (basic indoor unit) was obtained through testing. The testing result is shown in Table 2 and the correction factor K is obtained

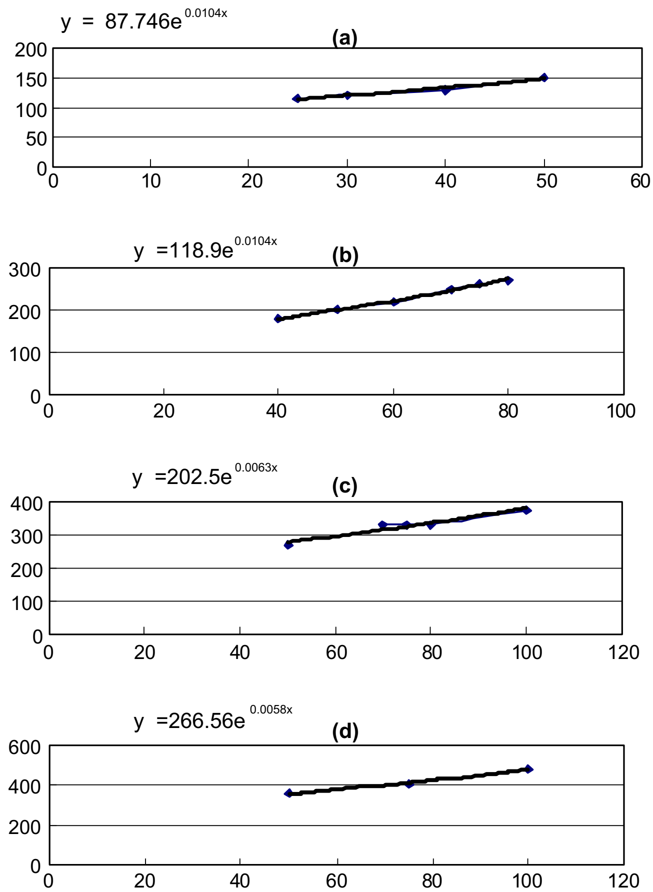

Fig. 9. Degree of opening of EEVs vs compressor output ratio for different number of indoor unit compositions (a) single unit, (b) twin units, (c) triple units, (d) four units.

Table 1
Degree of opening of EEVs vs compressor output ratio (basic unit capacity is 3150 kcal/h)

Number of indoor units	A_i		B_i	
1	A_1	87.746	B_1	0.010
2	A_2	118.9	B_2	0.004
3	A_3	202.500	B_3	0.006
4	A_4	266.560	B_4	0.006
5	A_5	293	B_5	0.004

Table 2
Degree of opening of EEVs for one indoor unit case: 2500 Kcal/h vs 3150 kcal/h

Compressor output ratio (%)	15	16	20	25	30	**35**	40	45	46
Degree of opening when indoor unit capacity is 2500 kcal/h	100	101	104	109	114	**119**	124	130	131
Degree of opening when indoor unit capacity is 3150 kcal/h	105	106	109	114	119	**125**	130	136	137

$$K = 119/125 = 0.95$$

The Y value of 2500 kcal/h unit is therefore obtained by multiplying the Y value of 3150 kcal/h unit by the K value.

3.2. Energy performance tests and comparison with the inverter system

Fig. 10 presents the relationship between the compressor's output (%) and the compressor's power input. Fig. 11 shows the energy performance (in terms of EER) of the developed system.

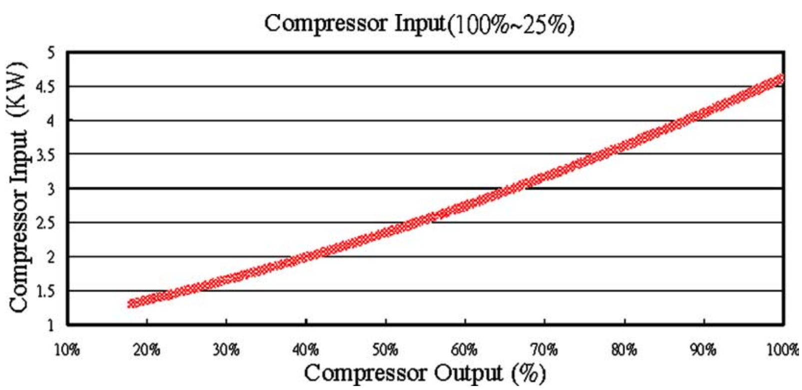

Fig. 10. Compressor input vs output.

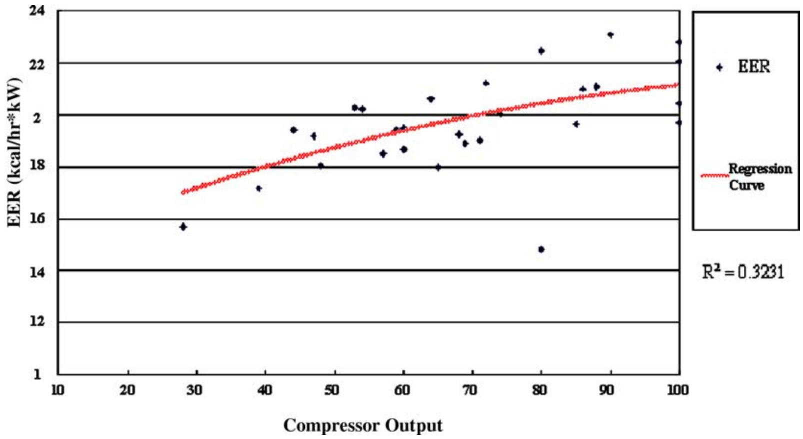

Fig. 11. EER vs compressor output ratio.

From these two figures, we understand that the developed system has true zoning control because it is able to run the indoor units under part load conditions, with the compressor input ratio from 25% to 100% (from part load 1.4 kW to full load 4.7 kW), saving 75% of the electricity used compared with a traditional un-loading method. The maximum EER value (approximately 2.3 kcal/hW) of the developed system occurs at about the full output point (11,000 kcal/h).

Fig. 12 compares the system developed here with a system with an AC inverter, for indoor units with a rated load of 12,500 kcal/h. Two comparisons are considered.

1. For a rated capacity of 100%, the allowable capacity adjustment is 17–100% and the associated power input is 1.3–4.8 kW for the developed system. However, the corresponding data for the inverter system are 48–104% and 2.5–6.1 kW, respectively.

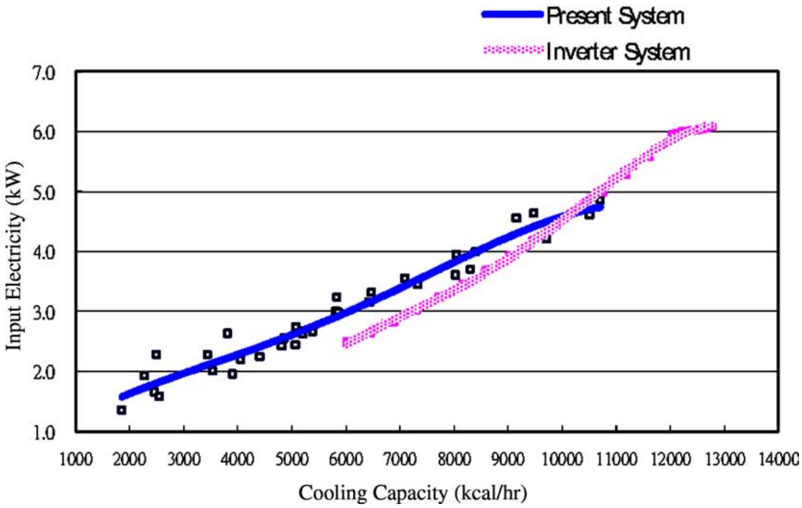

Fig. 12. Energy performance comparison of the present system and inverter system.

2. The greatest EER value (approximately 2.3 kcal/hW) of the developed unit is observed at about 100% (11,000 kcal/h) output point. However, the greatest EER value (approximately 2.5 kcal/hW) of the inverter unit is at the 64% (8000 kcal/h) output point. Notably, the inverter unit with an AC inverter normally costs 20% more than the developed system, and a DC inverter cost even more than the developed system and must overcome several potential problems, including high frequency, vibration and high order harmonic waves.

4. Conclusions

The variable capacity scroll type compressor was successfully applied to the multi-type air conditioner without using inverter technology. Key works related to the development and setting up of the test rig of the multi-type air conditioner are discussed. The developed system with one outdoor unit and the outdoor unit can handle up to five indoor units. This work established a technique for controlling the electronic expansion valve as the load varies, following laboratory tests with various loading combinations. The developed system has true zoning control because it provided the capacity to run the indoor units under part load condition, with compressor input ratios from 25% to 100% (the full-load is 4.7 kW), saving 75% of the electricity used compared with a traditional un-loading method. The developed system has a wider range of operation (17–100%) than that of the variable frequency system (48–104%). The maximum EER value (approximately 2.3 kcal/hW) of the developed system occurred at about the full output point (11,000 kcal/h). However, the maximum EER value (approximately 2.5 kcal/hW) of a variable frequency unit was at the 64% output point (8000 kcal/h). Most notably, a variable frequency unit normally cost 20% more than the system developed here and must overcome several potential problems, including high frequency, vibration, high order harmonic waves etc.

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