International Journal of Fluid Machinery and Systems DOI: http://dx.doi.org/10.5293/IJFMS.2015.8.1.013
Vol. 8, No. 1, January-March 2015 ISSN (Online): 1882-9554

Original Paper

Performance Evaluation of a Variable Frequency Heat Pump Air Conditioning System for Electric Bus

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Abstract

This study presents a simulation model of a heat pump air conditioning system with a variable capacity compressor and variable speeds fans for electric bus. An experimental sample has been developed in order to check results from the model. Effects on system performance of such working conditions as compressor speed, evaporator fans speeds and the condenser fans speeds have been simulated by means of developed model. The results show that the three speeds can be adjusted simultaneously according to actual working condition so that the AC system can operate under the optimum state which the control objects want to achieve. It would be a good and simple solution to extend the driving ranges of EVs because of the highest efficiency and the lowest energy consumption of AC system.

Keywords: Air conditioning; Heat pump; Electric bus; EER; Variable frequency

1. Introduction

During the last several decades, the world energy crisis and environmental pollution have been growing with increasing speed. Therefore, the automotive industry is trying to reduce fossil fuel consumption; they are looking for an alternative energy to fossil fuels for a long time. Vehicles using batteries or fuel cells as a power source have been studied and recommended. Especially, electric vehicle (EV) is a good replacement for conventional vehicle with international combustion engines because of the realization of the true "zero emission".

Air conditioning systems are an essential accessory component of vehicles whose utilization provides comfort to vehicle occupants. However the use of battery packs for cooling and heating can seriously impact the already short driving ranges of EVs. Therefore, for reducing the influence of AC system on driving ranges, maximizing efficiency and performance of AC system is very important for zero emission vehicles.

Received September 1 2014; revised October 17, November 8, November 21 2014; accepted for publication November 21 2014: Review conducted by Prof. Yutaka Ohta. (Paper number O14025C)
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In [1], Khayyam et al. reported an intelligent energy management system that is able to reduce the energy consumption of the vehicle AC system and improve its efficiency by using the look-ahead system. The same authors proposed a coordinated energy management system [2]. The simulation results showed the energy consumption can be optimized. Qi et al. [3] studied the performance of mobile AC system using microchannel heat exchangers by experiment. Cooling capacity and coefficient of performance of the enhanced system were increased by about 5% and 8% under high vehicle speed condition. The aforementioned literatures mainly discussed the energy saving for the conventional vehicles with internal combustion engines. Moreover, many studies have investigated, experimentally and numerically, the performance of AC system for electric vehicles under both warm and cold weather conditions.

An electrical AC system using R744 for a fuel cell electric vehicle was developed and tested [4]. The cooling capacity and COP for cooling of the tested system were up to 6.4 kW and 2.5, respectively, by varying the inlet air conditions of heat exchanger and the compressor speed. The developed electrical AC system showed better performance than the conventional AC system in the same operating conditions. Jabardo et al. [5] reported that effects on automobile AC system performance of such operational parameters as compressor speed, return air in the evaporator and condensing air temperatures were experimentally evaluated and simulated by means of developed model. Using the same methods, Hosoz et al. [6] proposed an integrated automotive AC and air-to-air heat pump system.

However, the heat pump operation provides adequate heating only in mild weather conditions, and the heating capacity drops sharply with decreasing outdoor temperature. To solve this problem, many authors proposed multiple source heat pump system. For instance, in [7,8], Lee and Cho studied the performance of a mobile heat pump for an electric bus, which uses the wasted heat from electric devices for a heating and air source for a cooling. They found that heating capacity of over 23.0 kW at all tested outdoor temperatures is sufficient for the heating of general buses. Sun [9] presented an automatic control system of the solar-assisted air-conditioning for pure electric vehicle. The solar cells covered on the bus roof can not only provide heat insulation but also recharge the battery. Liu et al. [10] proposed a new solar air two source heat pump used an air liquid two heat source compound heat exchanger as the core component. They showed the two source heat pump technology is helpful in improving the efficiency of heat pump.

In the references mentioned above, both evaporator and condenser fans are kept at constant speeds. It should be noted that the idea of modulating the fan speed during the control process is relatively unexplored. Among the limited literature, Anton et al. [11] analyzed the influence of the air mass flows and an increase of the area of both evaporator and condenser to maximize the cooling capacity. However, the influence therein is presented only in a given working condition. Yeh et al. [12] proposed two control algorithms, respectively, incorporating the outdoor fan and the indoor fan as the additional control inputs for air-conditioning systems. But the two control algorithms are implemented on a split-type residential air-conditioner not on EVs.

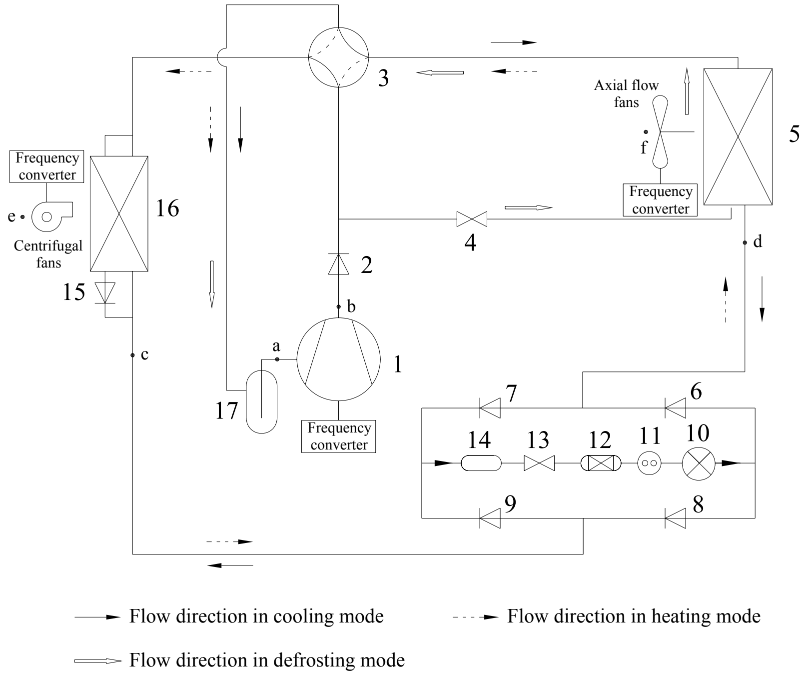
Due to the energy saving, the objective of this paper is to investigate the effects of evaporator and condenser fans speeds as well as compressor speed on AC system performance in different working conditions. Specifically, the performance characteristics of the AC system for electric bus not only are evaluated based on numerical analysis of the steady state model but also are validated experimentally.

2. Experiment

2.1 Experimental setup and design

A conventional vehicle’s AC system warms the interior using heat from the engine and cools it using engine power that drives the A/C compressor directly. On the other hand, electric vehicles have little on-board waste heat, so a heat pump AC system with an electric driven compressor is provided. Fig. 1 shows the schematic representation of the heat pump AC system for electric bus. The heat pump AC system mainly consists of the following components: an electric driven variable-speed scroll compressor, a four-way reversing valve, a fin-tube condenser, a thermostatic expansion valve, a fin-tube evaporator, four indoor fans and two outdoor fans.

The refrigerant flow is switched by the four-way reversing valve, check valves and solenoid valve, so the system can operate in different modes. In the cooling mode, the solenoid valve 4 is closed and the reversing valve 3 is de-energized. The refrigerant circulates in the direction of the solid arrows shown in Fig. 1. In the heating mode, the solenoid valve 4 is still closed, while the reversing valve 3 is energized. The refrigerant circulates in the direction of the dashed arrows shown in Fig. 1. This results in the outdoor and indoor heat exchangers serving as an evaporator and a condenser, respectively. In these two modes, the check valves 6,7,8,9 ensure the refrigerant passes through the thermostatic expansion valve 10 along a single direction. However, in the defrosting mode, the solenoid valve 4 is opened. The hot, high-pressure refrigerant drawn from the compressor enters the outdoor heat exchanger directly, so the frost freezing on the outdoor heat exchanger can be removed quickly.



1-compressor 2,6,7,8,9,15-check valve 3-four way valve 4,13- solenoid valve
5-outdoor heat changer 10- expansion valve 11-slight glass 12-filter/dryer 14-receiver tank
16-indoor heat changer 17-gas-liquid separator

Fig. 1 Schematic representation of the experimental setup

The specifications of the principal system components used in this experiment are listed in Table 1. The electric driven compressor (Emerson Electric Co.) used is a horizontal scroll compressor with R407C refrigerant. An inverter driver (Delta Electronics, Inc.) was used to drive the compressor so that the compressor frequency can be varied from 35Hz to 75Hz, while the rated frequency is 60Hz. The outdoor and indoor coils made in hydrophilic aluminum foil are fin-tube type heat exchangers. They are all designed the left part and the right part which have the same size. The dimensions of each outdoor heat exchanger are shown in Table 1. Given that the required heating capacity is greater than cooling capacity, the number of copper tube along air flow at each indoor heat exchanger is six and eight, respectively, in the cooling mode and heating mode. There are two outdoor fans and four indoor fans which are axial flow fans and centrifugal fans, respectively. As well as the compressor, the outdoor and indoor fans speeds can be varied by the respective inverter. The fan motors frequencies all range from 25Hz to 50Hz, while the rated frequencies are 50Hz. The expansion device used in the experiment is the thermostatic expansion valve (Emerson Electric Co.), which controls the flow of refrigerant into evaporator in exact proportion to the rate of evaporation of the liquid refrigerant in the evaporator.

Table 1 Specification of the principal components

Component	Specifications
Compressor	Electric driven scroll compressor, 98.04cc/rev
Outdoor heat exchanger	Two fin-tube heat exchanger(left and right), 2×1200W×514H mm^2
Outdoor fans	Axial flow fans, 0.75kW, 1400rpm, 4700m^3/h
Indoor heat exchanger	Two fin-tube heat exchanger(left and right), 2×1150W×173H mm^2
Indoor fans	Centrifugal fans, 0.3kW, 2800rpm, 1500m^3/h
Expansion valve	Thermostatic expansion valve(TXV)

2.2 Experimental method and procedure

The experiment is carried out at the environmental chamber with psychrometric calorimeter test facility. The psychrometric calorimeter has an air-handling unit including a cooling coil, a heating coil and a humidifier to maintain suitable testing conditions in both outdoor and indoor chamber [13] and uses the air enthalpy method to determine the unit capacities. In this psychrometric calorimeter, the outdoor and indoor chamber can be set to 5~50℃ and 15~45℃ respectively with an accuracy of ±0.1℃. During the experiments, the major operating parameters are monitored graphically and numerically in real time. In order to calculate and evaluate the performance of the electrical AC system, the temperature and the pressure are measured by thermocouples and pressure transducers, respectively. As shown in Fig.1, the points of a, b, c and d are the measure positions of temperature as well as pressure, while the points of e and f are only the temperature measuring points.

The AC system for electrical bus is tested in the nominal working condition of cooling and heating described in GB/T 7725-2004[14]. In the cooling and heating mode test, one of the frequencies among the compressor, the outdoor fans and the indoor fans is changed at 5Hz interval in their respective range, while the two others are kept constant at maximum value of each. During the cooling and the heating experiments, each test data are measured and recorded after the air temperatures and refrigerant flow rates are completely stable.

3. Mathematical model

In order to calculate and evaluate the energy consumption, cooling/heating capacity and the energy efficiency ratio of the AC system for electric bus, the mathematical model for simulation is provided. Meanwhile, the simulation program developed with the Matlab/Simulink simulation tool is based on steady state mathematical models of the components of the refrigeration cycle including the compressor, heat exchangers, thermostatic expansion valve.

3.1 Compressor

The common methods for compressor modeling [15] are efficiency method and graphical method. The compressor model using efficiency method [16] is adopted in this study, because it is difficult to get performance graphs provided by the manufacturer. The compressor model for simulation includes two performance parameters. The first is the refrigerant mass flow, which is evaluated by the well known correlation:

$$m_r = \eta_v \frac{n_c V_s}{60} \rho_s \tag{1}$$

The second performance parameter is the power consumption of compressor. It can be given by the following equation:

$$P_c = \frac{\eta_v}{\eta_{el}} \frac{n_c V_s}{60} p_s \frac{k}{k-1} [(\frac{p_d}{p_s})^{\frac{k-1}{k}} - 1] \tag{2}$$

where the volumetric efficiency η_v in variable displacement compressors depends upon compressor speed n_c and compression ratio p_d / p_s. The relationship was obtained by curve fitting compressor catalogue data [17]. The electrical efficiency η_{el} is the product of the indicated efficiency, the mechanical efficiency and the motor efficiency.

3.2 Heat exchangers

The evaporator and the condenser are approached in a similar manner from the modeling point of view because they have common characteristics. The heat exchangers models are also based on the steady lumped parameter method. Meanwhile, the flow pressure drop along the heat exchangers is ignored. Therefore, only the energy equations should be considered [18]. In the condenser, the heat rejected by the refrigerant (3), the heat absorbed by the air (4) and the heat transfer within the heat exchanger due to the temperature difference between the refrigerant and the air (5) should match:

$$Q_r = m_r (h_{ri} - h_{ro}) \tag{3}$$

$$Q_a = m_a (h_{ao} - h_{ai}) \tag{4}$$

$$Q = K A_o \theta_m \tag{5}$$

As in the condenser, the energy conservation equation also can apply to the evaporator. The overall heat transfer coefficient *K* is evaluated by assuming that thermal resistance due to wall conduction, contact, and fouling are negligibly small to compare with convection thermal resistance [19]. The resulting correlation can be written as:

$$K = \frac{1}{\frac{1}{\alpha_i}\frac{A_o}{A_i} + \frac{1}{\alpha_o \eta_o}} \tag{6}$$

In view of simplifying the calculation, the refrigerant side heat transfer coefficients α_i for heat exchanges is determined from the Dittus-Boelter correlation [20]. Meanwhile, the single phase refrigerant is assumed at saturated state, on the other hand the refrigerant physical property in two phase region is treated as the mean of saturated liquid property and vapor property.

The correlations (7) and (8) by Wu [21] are used to solve the air side heat transfer coefficients α_o for both evaporator and condenser respectively.

Evaporator:
$$\alpha_o = c\frac{\lambda}{s_f}\mathrm{Re}^{0.65}(\frac{d_o}{s_f})^{-0.54}(\frac{H}{s_f})^{-0.14} \tag{7}$$

Condenser:
$$\alpha_o = c\frac{\lambda}{d_o}\mathrm{Re}^{0.625}(\frac{A_r + A_f}{A_r})^{-0.375}\mathrm{Pr}^{0.33} \tag{8}$$

where the Reynolds number *Re* is related to the air flow rate which changes with the fans speeds. The overall heat transfer coefficient *K* would have some changes because of the variations in fans speeds.

The power consumption of the fans can’t be neglected because sometimes it can exceed 20 percent of overall power consumption for electric bus. In view of the constant torque below the rated frequency the power consumption can be given by:

$$P = \frac{T_N \cdot n}{9550\eta} \tag{9}$$

where the outdoor and indoor fans have their respective speeds and efficiencies [22]. It can be seen that the fans speeds have influence on the fans consumption and the overall heat transfer coefficient *K* which is proportional to the heat transfer *Q*.

3.3 Thermostatic expansion valve

The model works with a thermostatic expansion valve considered as an absolutely ideal process. That is to say, not only it’s an isenthalpic process, but the refrigerant mass flow through expansion valve is same with the compressor displacement at all speed.

3.4 Refrigeration system

The separate models of each aforementioned component constitute the whole system model, coupled by the convergence of the inlet and outlet variables in the refrigeration cycle according to the mass and energy balances.

The cooling capacity is equal to the heat transfer of evaporator, while the heating capacity is equal to the heat transfer of condenser. The total power consumption *P* includes not only the compressor consumption but also the fans consumption. The energy efficiency ratio (EER) of the AC system can be evaluated as:

$$EER = \frac{Q}{P_c + P_i + P_o} \tag{10}$$

Obviously the fans speeds can result in different efficiency.

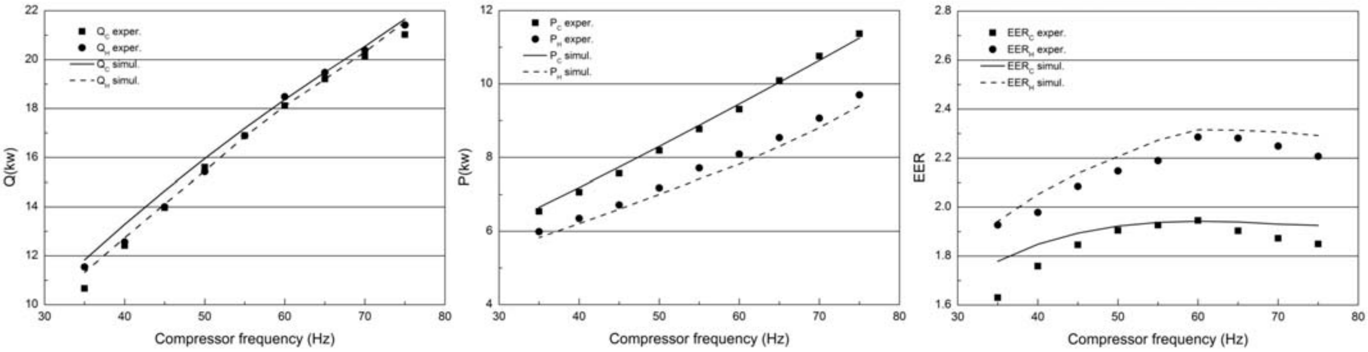
4. Results and discussion

The AC system performance is influenced by such operational parameters as indoor and outdoor air temperatures, compressor speed and fans speeds. They are evaluated by both simulated and experimental results. As shown in Figs. 2, 4 and 6, the simulated results show satisfactory predictions which indicate this model can be used to formulate a control algorithm.

The compressor and fans speeds are modulated by their respective frequency converters, so the frequencies are used to the following analysis instead of the speeds.

4.1 Compressor speed

Fig. 2 shows the variations of EER, cooling/heating capacity and total power consumption with the compressor frequency in the nominal working condition of cooling and heating. It can be seen the compressor frequency has a significant impact on the performance parameters. The graphs in these figures have been obtained at the rated fans speeds. It also shows that results from the simulation model compare very well the experimental ones with deviations mostly within 10% range.

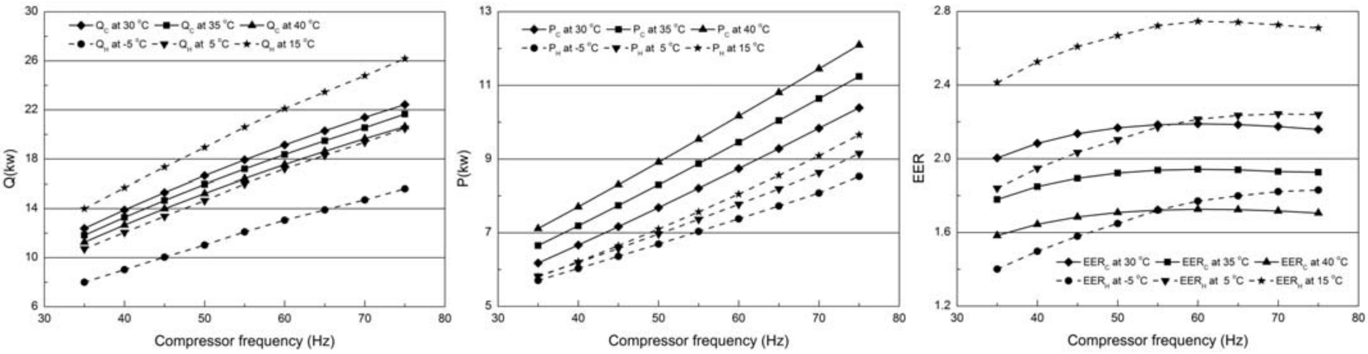


(a) (b) (c)

Fig. 2 Compressor frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in the nominal working condition

The variations in some of the performance parameters of the simulation system with compressor frequency are shown in Fig.3 for various outdoor air temperatures. The indoor temperature sets 27℃ and 20℃, respectively, in the cooling mode and heating mode. The graphs in these figures also have been obtained from the rated fans speeds simulations.

As shown in Fig.3 (a) and (b), at different outdoor temperature the influence of compressor frequency on the cooling/heating capacity and total power consumption are basically identical. They all increase with increasing compressor frequency. The changes in EER for the cooling mode are similar in spite of the various outdoor temperatures as indicated in Fig.3 (c), which the highest EER occur in the compressor rated frequency. However, in the heating mode the variation trends of EER are different at various outdoor temperatures. The optimal compressor frequency increases with decreasing outdoor temperature.



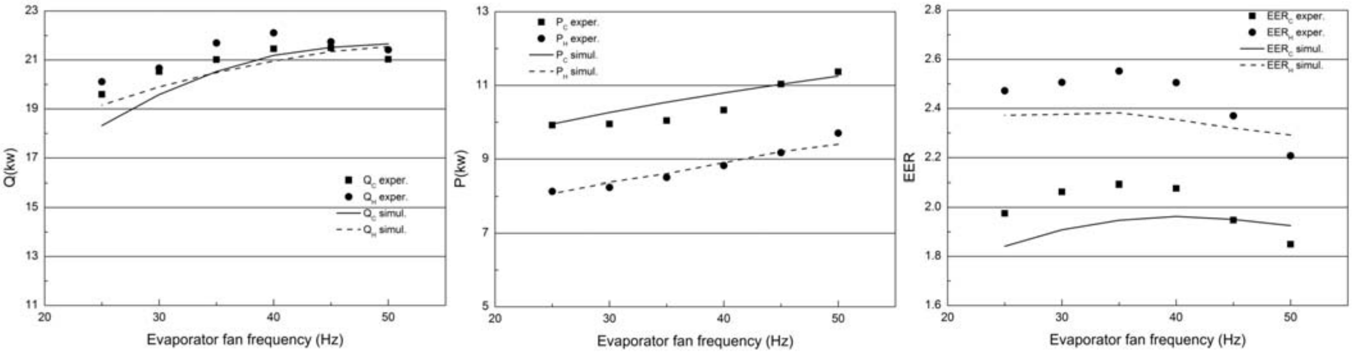
(a) (b) (c)

Fig. 3 Compressor frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in different working conditions

As discussed above, in order to improve the cooling/heating capacity the compressor frequency should be increased, while to reduce the power consumption it should be decreased. In the cooling mode, for the highest EER the compressor should work on the rate frequency in spite of the different outdoor temperature. In the heating mode, it should work on the different frequency according to outdoor temperature in order to obtain the highest EER.

4.2 Evaporator fan speed

The evaporator fan frequency has less influence on the performance parameters than the compressor frequency although the performance parameters are similar variation trends according to Fig.4. The plots of these figures have been obtained at the maximum compressor and condenser fans speeds. Fig.4 also shows that deviations of the simulated results with respect to the experimental ones are within a range with a maximum of 8%.

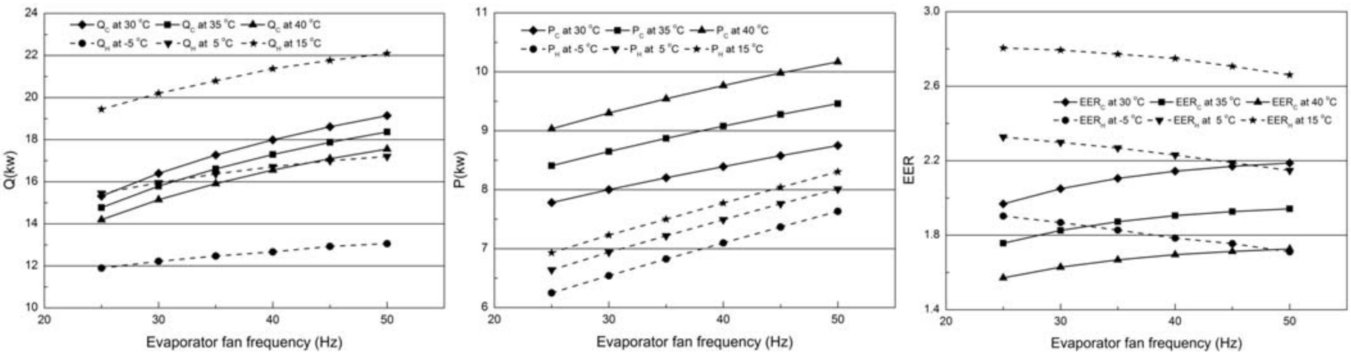


(a) (b) (c)

Fig. 4 Evaporator fan frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in the nominal working condition

Fig.5 shows the variations in some of the performance parameters of the simulation system with evaporator fan frequency in different working conditions which are the same with Fig.3. On the other hand, the graphs have been obtained from the rated both compressor speed and condenser fans speeds simulations.

Whether in the cooling or heating mode, at different outdoor temperature the variations in cooling/heating capacity and total power consumption with evaporator fan frequency are basically identical. They all increase as indicated in Fig.5 (a) and (b). However, with increasing evaporator fan frequency the EER increases in the cooling mode and decreases in the heating mode according to Fig.5 (c). The outdoor temperature doesn't impact on the variation trends of EER.



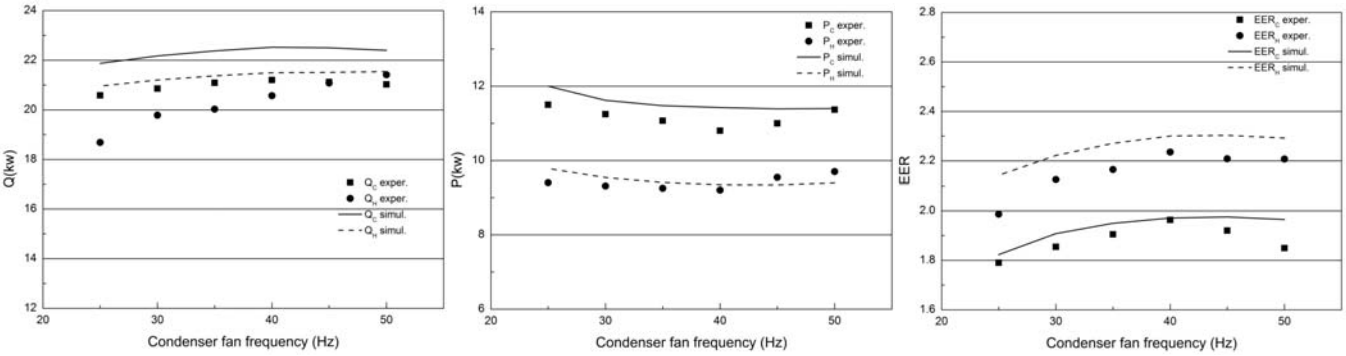
(a) (b) (c)

Fig. 5 Evaporator fan frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in different working conditions

It can be noted that in order to improve the cooling/heating capacity the evaporator fan frequency should be increased, while to reduce the power consumption they should be decreased. In the cooling mode, for the highest EER the evaporator fans should all work on the maximum frequency in spite of the different outdoor temperature. While in the heating mode, it is opposite.

4.3 Condenser fan speed

From Fig.6 it can be seen that the condenser fan frequency has slightly influence on the cooling/heating capacity and the total power consumption. The plots of Fig.6 have been obtained at the maximum compressor and evaporator fans speeds. It also shows that results from the simulation model compare very well the experimental ones with deviations mostly within 11% range.

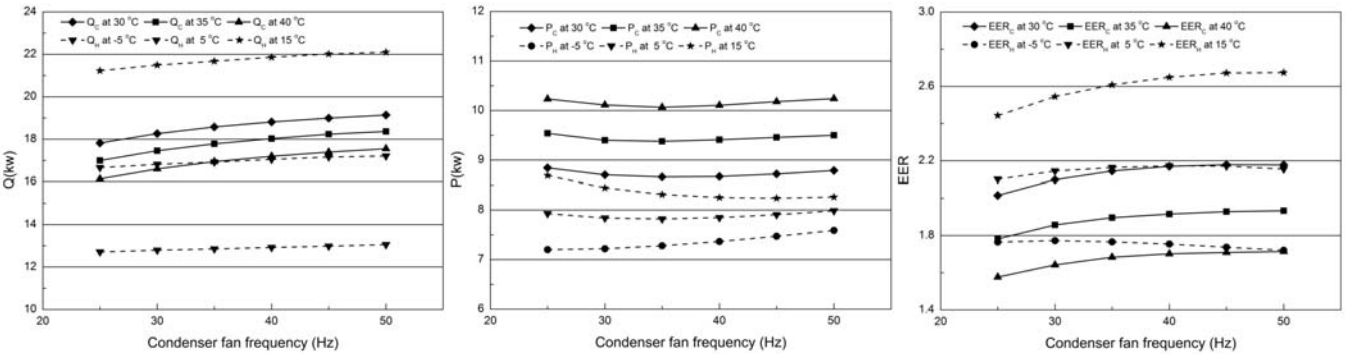


(a) (b) (c)

Fig. 6 Condenser fan frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in the nominal working condition

Fig.7 shows the variations in some of the simulation system with condenser fan frequency in different working conditions which are the same with Fig.3 and Fig.5. Also the graphs have been obtained from the rated both compressor speed and evaporator fans speeds simulations.

According to Fig.7, in the cooling mode there are the same variation trends for each performance parameters in spite of the different outdoor temperature. The cooling capacity increases, while the power consumption decreases firstly and then increases with the increasing condenser fan frequency. They all slightly change. It results that the EER increases firstly and then remains stable. However, in the heating mode the outdoor temperature has a big impact on the variation trends of power consumption as indicated in Fig.7 (b). At 15℃ outdoor temperature the power consumption decreases with the increasing condenser fan frequency, which is opposite at -5℃ outdoor temperature. But it decreases firstly and then increases at 5℃ outdoor temperature. It results that the variation trends of EER are different as shown in Fig.7(c). The condenser fan frequency for the highest EER increases with increasing outdoor temperature.



(a) (b) (c)

Fig. 7 Condenser fan frequency effects on: (a) cooling/heating capacity; (b) total power consumption; (c) EER; in different working conditions

As a result, in order to improve the cooling/heating capacity the condenser fans frequencies should be increased whether in cooling or heating mode. For the minimum power consumption and maximum EER, the condenser fans frequencies are basically same in 35Hz and 50Hz respectively in the cooling mode, while in the heating mode they should be increased with the increasing outdoor temperature.

5. Conclusions

This study has explored the variations in the cooling and heating performances of AC system for electric bus with the compressor and fans frequencies. Based on the experimental and simulated evidences, the final conclusions reached in this study can be summarized as follows.

(1) In both operation modes, in order to obtain the maximum cooling and heating capacities, both the compressor and the fans should work on the respective maximum frequencies.

(2) For the lowest power consumption, the compressor frequency and the evaporator fans frequencies all should be minimum,

while the condenser fans frequencies should be different according to the operation mode. In the heating mode, the best frequency of condenser fan changes with the working condition. It increases with the increasing outdoor temperature. However in the cooling mode the best condenser fans frequencies should be basically same in 35Hz despite the different working condition.

(3) The compressor, evaporator fans and condenser fans all should work on the rated frequency of each to get the highest cooling EER. For the maximum heating EER, the optimal frequencies of compressor and condenser fans vary with the working condition. The best compressor frequency increases while the best condenser fans frequencies decrease with the declining outdoor temperature. Furthermore, the outdoor temperature doesn't impact the optimal evaporator fans frequency which should be the minimum frequency for the highest heating EER.

(4) For cooling/heating capacity and total power consumption, compressor frequency has greater influence than fans frequencies, while condenser fan frequency has less influence than evaporator fan frequency.

Present analysis has shown that the three frequencies can be adjusted according to both actual working condition and operation mode, so that the AC system can operate on the optimum state. It would be helpful to extend the driving ranges of EVs because of the highest efficiency and the lowest energy consumption of AC system.

Acknowledgments

This study is supported by the Industry-University-Research Institute Collaboration Fund of Guangdong Province (No. 2011B090400572), Strategic Emerging Industry Development Fund of Guangdong Province (No.[2011]891), Natural Science Foundation of Guangdong Province (No. S2012010010199), Science and Technology Innovation Fund Project of Foshan City (No. 2013AG100063).

Nomenclature

A: Area (m^2)
d: Diameter (m)
h: Specific enthalpy (J/kg)
H: Height (m)
k: Compression polytropic exponent
K: Overall heat transfer coefficient (W/(m^2·℃))
m: Mass flow rate (kg/s)
n: Rotational speed (rev/min)
p: Pressure (Pa)
P: Power (W)
Q: Heat transfer rate (W)
s_f: Fin spacing (m)
T: Torque (N·m)
V: Volume (m^3)
α: Convective heat transfer coefficient (W/(m^2·℃))
η: Efficiency
θ_m: Logarithmic mean temperature difference (℃)
λ: Thermal conductivity (W/(m·℃))
ρ: Density (kg/ m^3)
Re: Reynolds number
Pr: Prandtl number

Subscripts
a: Air
c: Compressor
C: Cooling mode
d: Discharge(compressor)
el: Electrical
f: Fin
H: Heating mode
i: Inside
N: Rated
o: Outside
r: Refrigerant
s: Suction(compressor)
v: Volume

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