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ABSTRACT

In this study, the cooling and heating performance of residential air-conditioner system varying with the match of indoor and outdoor heat exchanger were measured and analyzed by changing the indoor unit air flow rate and heat exchanger, and outdoor unit air flow rate. Increase of both indoor unit and outdoor unit were beneficial for the cooling capacity and heating capacity, however, the EER and COP showed a trend of increasing slowly even decreasing after the first rapid increase. The air-conditioner system performance improvement was increased more significantly with increase of indoor unit compared to that of outdoor unit due to constantly smaller indoor unit matched with larger outdoor unit. The heat transfer area of the indoor unit was a more dominant factor affecting system performance than that of air flow rate especially under cooling mode. The maximum increase of cooling capacity, EER, heating capacity and COP with increasing indoor unit including heat transfer area and air flow rate were 35.3%, 24%, 10.4% and 29.9%, respectively. About 40% increase of outdoor unit air flow rate showed only 0.6%, 4.6% and 1.2% improvement for cooling capacity, EER and heating capacity, respectively, while the COP had about 0.7% decrease. Among the systems investigated and compared in this study, the heat transfer area ratio of indoor unit and outdoor unit should not be exceed 0.37, and the average air face velocity should not exceed 1.2m/s for the indoor unit and 1.6m/s for the outdoor unit.

1. INTRODUCTION

Recent years, the HVAC industry continues to develop rapidly and is becoming main part of energy consumption in China. Some Chinese national standards (GB 21455-2008, GB 21455-2013) have been instituted to control the minimum allowable values of the energy efficiency and energy efficiency grades for variable speed residential air conditioners. The newest standard calls for all new air conditioners and heat pumps manufactured for sale in China from October 1 of 2013 onwards must comply with the minimum allowable values of the energy efficiency, which have a minimum SEER (Seasonal Energy Efficiency Ratio) of 4.3 for rated cooling capacity smaller than 4500W, about 43.3% increase over the GB 21455-2008's minimum of 3 SEER for the same cooling capacity. In order to encourage higher efficiency products manufactured, a lot of national or local saving energy allowance policies have provided rebate incentives.

The residential air conditioner and heat pump systems typically consist of two parts: an indoor unit and an outdoor unit. The indoor unit includes evaporator coil and fan, and the outdoor unit includes a compressor, condenser coil, fan, capillary or EEV (Electronic Expansion Valve) and refrigerant. These two parts are specifically designed to work together as a coordinated "team" to provide top performance and maximum efficiency and comfort. So if we install a new high-efficiency outdoor unit, but don't include a new, equally efficient and properly matched indoor unit, the results could be uncomfortable, frustrating and expensive. Therefore, the proper match of indoor and outdoor unit must become an important issue for higher efficiency units.

Literature review reveals that a limited amount of work about match of indoor and outdoor unit has been done for the performance improvement evaluation of residential air conditioners. Wang et al. (2001) studied the design method of the indoor and outdoor heat exchanger heat transfer area ratio for a residential heat pump air conditioner by way of thermodynamic cycle analysis respectively in the cooling mode and heating mode, correlated the heat transfer area ratio to working condition parameters, and indicated the heat transfer area ratio designed as extreme cooling or/and heating work conditions. Shao et al. (2001) evaluated the adjusting performance of variable frequency air conditioning system by system simulation and concluded that increasing the capacity of indoor or/and outdoor heat exchanger were useful for advance system performance, while extending less and less advantage due to reach to extreme of the cooling or heating capacity and system consuming power. Zhang et al. (2005) studied the effect of the indoor and outdoor heat exchanger heat transfer area of heat pump air conditioner on system performance including cooling and heating condition base on system simulation, and found that the EER and COP showed weak sensitivity when the heat transfer area increased to a relatively bigger value and existed optimal heat transfer area for both indoor and outdoor heat exchanger. The optimal indoor and outdoor heat exchanger heat transfer area ratio was 0.315 in Zhang et al. (2005) study.

The revealed studies regarding the match of indoor and outdoor unit were focused on simulation results for the possible performance improvement of residential air conditioner. However, experimental investigation on this issue could not be found in open literature. The purpose of this paper is to investigate the effects of the indoor heat transfer area and air flow rate on the performance, providing information on the parameter design of the indoor and outdoor unit. A residential heat pump air conditioner outdoor unit and three indoor units were chosen as experiment investigation object. The cooling and heating performance were experimentally carried out in steady state under various indoor heat transfer area and both of indoor and outdoor air flow rate.

2. EXPERIMENTAL SETUP AND TEST PROCEDURES

2.1 Experimental Setup

The experimental apparatus as shown in Figure 1 is based on the air enthalpy-difference method proposed based on Chinese national standard GB/T 7725-2004, including indoor and outdoor environmental chambers and air enthalpy-difference and air flow rate measuring apparatus. The cooling capacity and heating capacity were measured as indoor air enthalpy-difference, and the outdoor unit capacity was also measured according to the similar method. Thermocouples and pressure transducers were used to measure the thermodynamic states of refrigerant entering or/and exiting the indoor and outdoor unit. The EER was defined the ratio of cooling capacity and system input power, and the COP was the ratio of heating capacity and system input power.

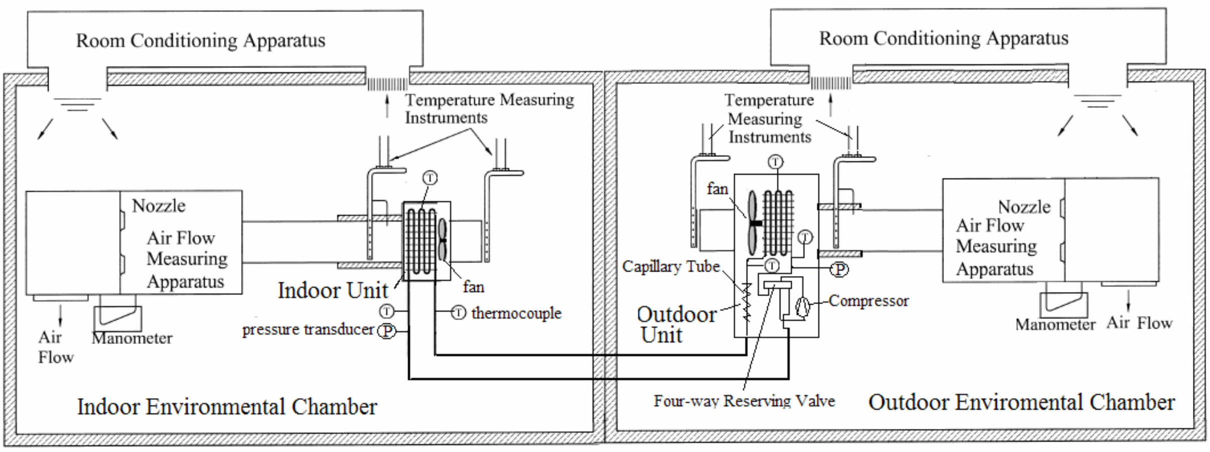

Figure 1: Schematic of experimental setup

The outdoor unit, equipped with a constant speed hermetically-sealed reciprocating compressor, fin-and-tube heat exchanger, fan and capillary tube, was installed in the outdoor environmental chamber, and the indoor unit only contained fin-and-tube heat exchanger and fan was installed in the indoor environmental chamber. The outdoor and indoor environmental chamber can simulate all kinds of air conditions, respectively. In this study, the cooling performance was tested under the air conditions of 35℃ dry-bulb and 24℃ wet-bulb temperatures of outdoor unit and 27℃ dry-bulb and 19℃ wet-bulb temperatures, and the heating performance was tested at 7℃ dry-bulb and 6℃ wet-bulb temperatures of outdoor unit and 27℃ dry-bulb and 19℃ wet-bulb temperatures of indoor unit.

The experimental object was three air conditioner system, which were three different indoor units respectively matched with one outdoor unit. As a matter of convenience, the three indoor units were successively named as A, B and C. The outdoor unit was used in 3500W split-system heat pump air conditioner using R22 as a working fluid, which was named as D. The name and heat transfer area of the four heat exchangers were shown in Table 1 and the heat transfer area was relative value of the outdoor heat exchanger.

Table 1: Name and Heat transfer area of outdoor and indoor unit

Unit	Name	Relative Heat Transfer Area
Indoor	A	0.23
Indoor	B	0.33
Indoor	C	0.37
Outdoor	D	1

2.2 Test Procedures

The optimal refrigerant charge of three indoor units test system was different from each other, so the first step of the experimental procedure was to determine refrigerant charge according charging or discharging the refrigerant of system, which was carried out for the specified indoor unit only in the cooling condition. The system was run at the simulated conditions described above for a 3h period under a quasi-steady operation. During the period, the dry-bulb and wet-bulb temperatures of the two rooms were carefully maintained within ±0.05℃. The optimal refrigerant charge for every indoor unit was determined until the maximize EER was obtained. Then the cooling and heating performance of each indoor unit system were measured under variable indoor unit air flow rate. In order to investigate the effect of increasing outdoor unit on system cooling and heating performance, the test of varying outdoor air flow rate of C indoor unit system was performed.

3. RESULTS AND DISCUSSION

3.1 Effects of indoor unit air flow rate

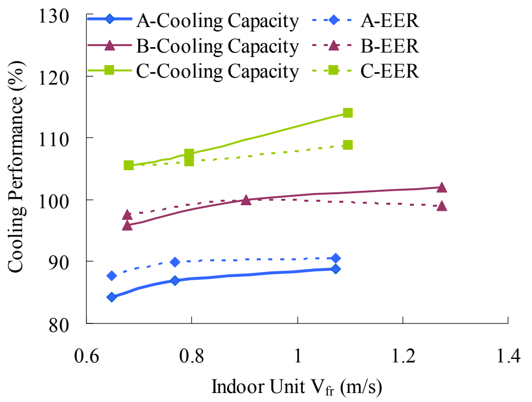

Figure 1: Cooling performance with indoor unit V_{fr}

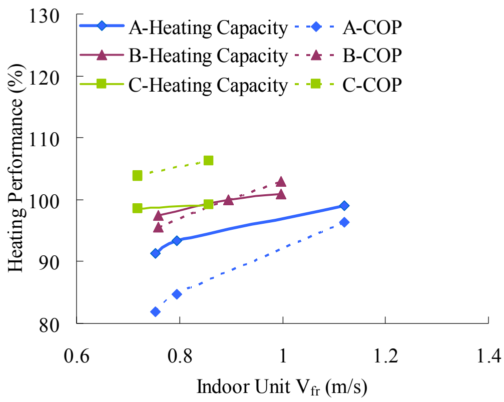

Figure 2: Heating performance with indoor unit V_{fr}

Both the increase of indoor air flow rate and heat exchanger heat transfer area can be considered as increasing the indoor unit. Figure 1, Figure 2, Figure 3, Figure 4 and Figure 5 showed the variations of cooling performance, heating performance, cooling and heating evaporation temperature and condensation temperature, and superheat of the three indoor units matched with the outdoor unit as a function of indoor heat exchanger Vfr (average air face velocity), respectively, in which, the superheat was defined as the difference between refrigerant temperature and refrigerant saturation temperature corresponding to the pressure at the evaporator exit.

It can be seen that the increase of indoor unit was extraordinarily advantageous for both the cooling capacity and heating capacity as shown in Figure 1 and Figure 2. In this study, the maximum increase of cooling capacity, EER, heating capacity and COP with indoor unit were 35.3%, 24%, 10.4% and 29.9%, respectively. However, the cooling capacity, EER, heating capacity and COP tended to increase rapidly only at first, which soon reduced increasing slope even decreasing. The EER of B indoor unit system trended downward when the Vfr exceeded to 1.2m/s in Figure 1, and the heating capacity of C indoor unit system was almost under that of B indoor unit system in Figure 2. In addition, the increase of indoor unit was more beneficial to improve cooling capacity especially for larger indoor heat transfer area system, and improve COP especially for smaller indoor heat transfer area system, and the heat transfer area of the indoor unit heat exchanger was a more dominant factor affecting system performance than that of air flow rate especially under cooling mode.

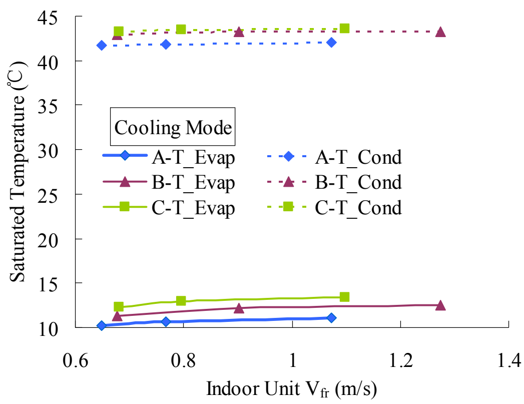

Figure 3: T in cooling mode

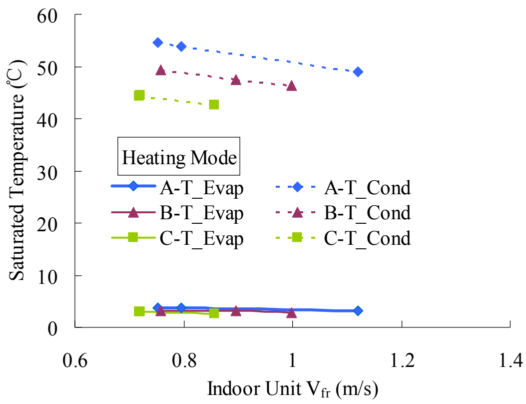

Figure 4: T in Heating Mode

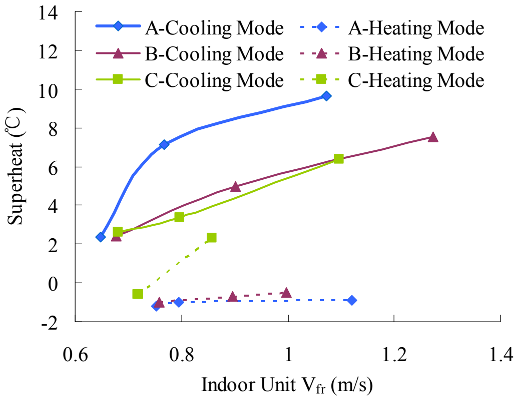

Figure 5: Evaporator exit superheat

The cooling capacity and heating capacity which were equal to indoor unit heat exchanger heat transfer capacity were multiplier of overall heat transfer coefficient, heat transfer area and mean heat transfer temperature difference. On the face of it, the heat transfer area was proportional to the cooling capacity or heating capacity, while the air-side heat transfer coefficient directly related to the overall heat transfer coefficient can be thought as approximately proportional to the $V_{air}^{\ n}$ .Constantly, the power exponent n of $V_{air}^{\ n}$ was less than 1, so although the increase of air flow rate can increase the overall heat transfer coefficient because of reducing the air-side heat resistance, the effect of air flow rate on the system capacity was much less than that of the heat exchanger heat transfer area.

Moreover, as the indoor unit increased, the system evaporation temperature was an increase trend in cooling mode as shown in Figure 3, and the system condensation temperature had a significant decrease in heating mode as shown in Figure 4, such that the heat transfer temperature difference of the indoor heat exchanger was decreasing in both cooling and heating mode, which restricted the continuous increasing heat transfer capacity of indoor unit. From another point of view, the variation of superheat as shown in Figure 5 can also reflect the evaporator heat transfer characteristic and system performance. It can be found that the increase of cooling capacity of A indoor unit system with air flow rate increased so slowly in Figure 1 due to very high superheat in Figure 5, and the heating capacity of C indoor unit system was a little less than that of B indoor unit at the same average air face velocity in Figure 2 also due to high superheat in Figure 5.The higher superheat meant a slight higher enthalpy difference of evaporator and a lower refrigerant mass flow rate. The two factors were opposite, so the heat exchanger heat transfer capacity was not possible to continuous increasing. That's why the cooling capacity and heating capacity showed a trend of increasing slowly after the first rapid increase with the increase of the indoor unit.

In addition, the compressor ratio slowly but continuously decreased with the increase of the indoor unit because evaporation temperature increased more than condensation temperature in cooling mode, and condensation temperature decreased more than evaporation temperature in heating mode. The refrigerant mass flow rate can be derived as decreasing from the trend of superheat. Therefore, the compressor consuming power was decreasing. However, compared to the Figure 3 and Figure 4, it can be found that the variation of compressor pressure ratio was much less in cooling mode than that in heating mode, thus the decrease of compressor consuming power in cooling mode was much less, which was the reason for the increase of EER was less than that of cooling capacity, while the increase of COP was more than that of heating capacity.

The system input power mainly comprised the compressor consuming power, indoor and outdoor fan consuming power. The fan consuming power was proportional to the air flow rate. The larger heat exchanger heat transfer area usually meant larger air flow rate, so no matter increase the heat transfer area or increase the air flow rate of indoor unit, the indoor fan consuming power was increasing. And the portion of the fan consuming power in system power was increasing as the increasing of indoor unit, so that the EER or COP rapidly increased at smaller indoor unit and then the slope gradually decreased with an increase of the indoor unit.

In this experiment, the cooling capacity and EER were respectively from 86.9% to 109.4% and 90.1% to 106.5% of the B indoor unit system when the indoor heat exchanger heat transfer area was changed from 0.23 to 0.37 at the same 0.9m/s air face velocity, while the heating capacity and COP were respectively from 94.2% to 99.1% and 86.6% to 106.1% of the B indoor unit system at the same 0.86m/s air face velocity. The increase range of system cooling and heating performance was trending downwards at larger indoor unit, so the indoor heat transfer area and air flow should not be designed too large for the specified outdoor unit. In addition, with the specified outdoor unit in this study, the matched heat transfer area of indoor unit should not be too high or too low, and the optimal heat transfer area ratio of indoor and outdoor unit was between 0.33 and 0.37, which was better to choose the smaller value for higher indoor unit air flow rate.

The indoor unit air flow rate increased about 19%, for the A indoor unit system, the cooling performance was only about 1% higher in cooling capacity and nearly no increase in EER, however, the heating performance had significant increase with about 2.8% higher in heating capacity and 6.5% higher in COP, respectively; for the C indoor unit system, the cooling performance had a significant increase with about 2.37% higher in cooling capacity and 0.9% higher in EER, and the heating performance had a slight increase with about 0.6% higher in heating capacity and 2.5% higher in COP. The results showed that the small indoor heat exchanger should design higher air flow rate, while the larger indoor unit should design lower air flow, and the optimal air face velocity should not be higher than 1.2m/s.

3.2 Effects of outdoor unit air flow rate

Figure 6, Figure 7 and Figure 8 showed the variation of system cooling and heating performance, evaporation and condensation temperature, and superheat with outdoor unit air flow rate of C indoor unit matched with the outdoor unit system including cooling mode and heating mode, respectively.

It showed that with the raise of outdoor unit air flow rate in Figure 6, the cooling capacity and heating capacity had a very slight increase, and the EER tended to increase rapidly at first and then almost no change, while the COP was decreasing.

The variation of outdoor unit air flow rate mainly changed the system condensation temperature in cooling mode, the evaporation temperature in heating mode, and superheat, while the evaporation temperature in cooling mode and condensation temperature in heating mode related to the indoor heat exchanger heat transfer temperature difference showed a relatively slight variation. The variation of condensation temperature in heating mode was more significant than that of evaporation temperature in cooling mode as shown in Figure 7, so the heating capacity had a relatively significant increase compared to the cooling capacity with the rise of outdoor unit air flow rate.

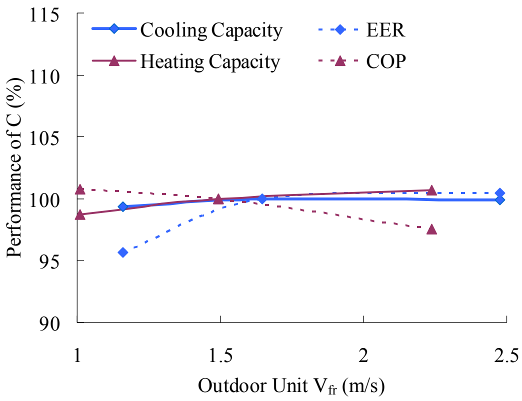

Figure 6: System performance of C

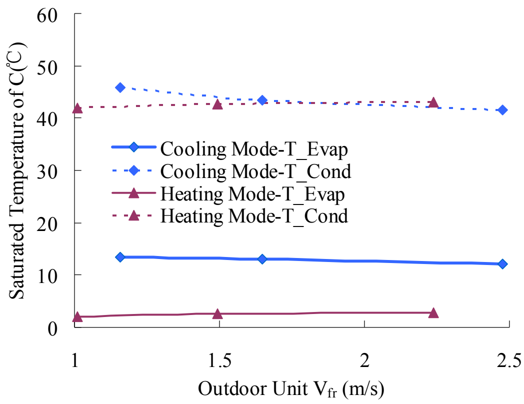

Figure 7: Evaporation and Condensation T of C

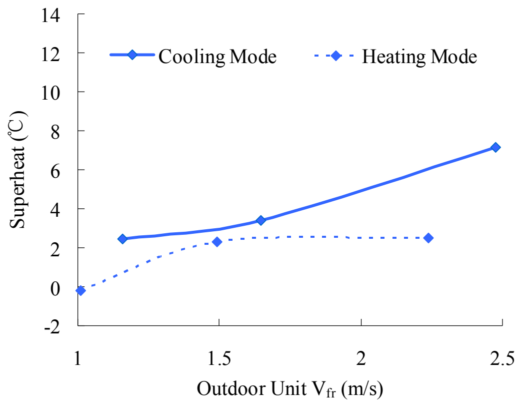

Figure 8: Evaporator exit superheat

The above change of system saturated temperature meant that the compressor pressure ratio in cooling mode had a relatively significant decrease compared to that in heating mode. So the decrease of compressor specific power was more evident in cooling mode than in heating mode. While the refrigerant mass had a slight decrease because of slight variation of evaporation temperature with the variation of outdoor unit air flow rate both in cooling mode and heating mode, so the compressor consuming power was decreasing with the increase of outdoor unit air flow rate and the decrease of compressor consuming power was much more in cooling mode than in heating mode. That's why the EER increased rapidly at first in Figure 6.

Similarly, the system input power mainly comprised the compressor consuming power, indoor and outdoor fan consuming power. The fan consuming power was proportional to the air flow rate. With the rise of outdoor unit air flow rate, the outdoor fan consuming power increased with no doubt. In cooling mode, as the above analysis, the compressor consuming power had a decrease, so the system input power was decreasing at first but with the rapid increase of outdoor fan consuming power, the system input power will be increasing, therefore, the EER will be increase no more. In heating mode, because of a little decrease of compressor consuming power and rapid increase of outdoor fan consuming power, the system input power even increased at first, resulting the COP always decreasing.

Generally, the outdoor air flow rate of a heat pump air conditioner mainly influenced the system EER or COP. In this study, the air flow rate increased about 42%, the cooling performance showed about 0.6% higher in cooling capacity and 4.6% higher in EER, and the heating performance showed about 1.2% higher in heating capacity and 0.7% lower in COP, respectively. It was shown that excessive or insufficient air flow rate can cause the degradation of the system performance. The proposed designed outdoor unit average air velocity should not be higher than 1.6m/s especially under heating condition.

4. CONCLUSIONS

The effects of indoor unit heat transfer area and air flow rate and outdoor unit air flow rate on the system performance of residential air-conditioner were experimentally investigated under rated cooling and heating conditions. Conclusions were shown as follows:

- The system cooling and heating performances had an evident increase with indoor unit, but the increase range was trending downwards. The maximum increase of cooling capacity, EER, heating capacity and COP with increasing indoor unit including heat transfer area and air flow rate were 35.3%, 24%, 10.4% and 29.9%, respectively.
- The average air velocity should be higher for smaller heat transfer area of indoor unit, and that not be higher than 1.2m/s especially under cooling condition. The heat transfer area ratio of indoor unit matched with the specified outdoor unit should not be too high or too low. In this study, the heat transfer area ratio of indoor unit and outdoor unit was between 0.33 and 0.37, which should choose the smaller value for higher indoor unit air flow rate.
- With a rise of indoor unit heat transfer area or/and air flow rate, the increase of cooling capacity was more obvious than EER, while the increase of COP was more obvious than heating capacity. The improvement with indoor unit air flow rate was more significant for smaller heat transfer area indoor unit system especially in the heating mode. For the studied smallest heat transfer area indoor unit, the indoor unit air flow rate increased about 19%, the cooling performance was only about 1% higher for cooling capacity and nearly no increase for EER, however, the heating performance had a significant increase with about 2.8% higher for heating capacity and 6.5% higher for COP, respectively.
- The outdoor unit air flow rate mainly influenced the system EER or COP compared to the capacity, and excessive or insufficient air flow rate can cause the degradation of the system performance. In this study, the air flow rate increased about 42%, the cooling performance showed about 0.6% higher for cooling capacity and 4.6% higher for EER, and the heating performance showed about 1.2% higher for heating capacity and 0.7% lower for COP, respectively. The average air velocity should not be higher than 1.6m/s especially under heating condition.
- The indoor unit heat transfer area and air flow rate should not be too small or too large for specified outdoor unit, and the outdoor unit was the same designed principle for specified indoor unit. Existing a proper match range for the indoor unit and outdoor unit made the system overall performance best.

NOMENCLATURE

COP	coefficient of performance	(–)
Cond	condensation	(–)
EER	energy efficiency ratio	(–)
Evap	evaporation	(–)
Vfr	air face velocity	(m/s)

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