2002

Performance of Multi-System Air Conditioner With Variable Frequency Control Based On Units

S. Shao
Tsinghua University

W. Shi
Tsinghua University

X. Li
Tsinghua University

Q. Yan
Tsinghua University

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ABSTRACT

Because there are many indoor units and outdoor units, the measurement and simulation of multiple air conditioning system are very difficult. From the viewpoint of similarity between simple system and multi-system air-conditioner, the refrigeration system is separated into several components by their function and location. By the location there are two types, indoor units and outdoor units. When the room needs to be heated, the indoor unit acts as a condenser. On the other hand, when the room needs to be cooled, the indoor unit acts as an evaporator.

In order to predict the performance of multiple air conditioning system, the components’ mathematical model in air conditioning system are set up such as variable frequency compressor, heat exchanger, electronic expansion valve and connecting pipe by distributed-parameter. The performance of each unit is analyzed by simulation under different conditions. The heating/cooling capacity of each indoor unit is determined by the electronic expansion valve and the variable fan. In the outdoor unit, the compressor meets the total heating/cooling load of the system by adjusting the frequency and the variable speed fan keeps proper heat exchanged in the outdoor heat exchanger.

Generally speaking, the heat exchanged in the heat exchanger is determined by the inlet air temperature, the air volume, the refrigerant mass flow rate and the refrigerant states at inlet. The refrigerant mass flow rate is controlled by the frequency of compressor and the opening rate of electronic expansion valve, and the air volume is controlled by the variable speed fan. Each unit has enough controlling means to keep the performance by itself, so the system can also be controlled at high efficiency based on the independent control of each unit. The opening rate of EEV or
the frequency of compressor regulate the cooling/heating capacity of the unit by adjusting the refrigerant mass flow rate. And the air volume is adopted to keep the refrigerant states, subcooling degree or superheating degree, at the outlet of the heat exchanger in the unit.

**NOMENCLATURE**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>EEV</td>
<td>electronic expansion valve</td>
</tr>
<tr>
<td>FWV</td>
<td>four-way valve</td>
</tr>
<tr>
<td>Ga</td>
<td>air volume ($m^3/h$)</td>
</tr>
<tr>
<td>Gr</td>
<td>mass flow rate of refrigerant (g/s)</td>
</tr>
<tr>
<td>Ha</td>
<td>air enthalpy (KJ/Kg)</td>
</tr>
<tr>
<td>HE</td>
<td>heat exchanger</td>
</tr>
<tr>
<td>HPL</td>
<td>high pressure liquid pipe</td>
</tr>
<tr>
<td>HPG</td>
<td>high pressure gas pipe</td>
</tr>
<tr>
<td>Hr</td>
<td>refrigerant enthalpy (KJ/Kg)</td>
</tr>
<tr>
<td>LPG</td>
<td>low pressure gas pipe</td>
</tr>
<tr>
<td>MVRV</td>
<td>multiple variable refrigerant volume</td>
</tr>
<tr>
<td>PC</td>
<td>condensing pressure (Pa)</td>
</tr>
<tr>
<td>Pe</td>
<td>evaporating pressure (Pa)</td>
</tr>
<tr>
<td>Qe</td>
<td>heat exchanged in evaporator (W)</td>
</tr>
<tr>
<td>SH</td>
<td>superheating degree(°C)</td>
</tr>
<tr>
<td>SL</td>
<td>subcooling degree(°C)</td>
</tr>
<tr>
<td>SVRV</td>
<td>simple variable refrigerant volume</td>
</tr>
<tr>
<td>Tc</td>
<td>condensing temperature(°C)</td>
</tr>
<tr>
<td>Te</td>
<td>evaporating temperature(°C)</td>
</tr>
<tr>
<td>TWV</td>
<td>three-way valve</td>
</tr>
<tr>
<td>VRV</td>
<td>variable refrigerant volume refrigeration system</td>
</tr>
</tbody>
</table>

**Subscripts**

- 1: inlet
- 2: outlet
- o: outdoor unit

**INTRODUCTION**

With the development of national economy and the improvement of living standard, the requirement of air conditioner increases very quickly to make a comfortable environment for living and working. Some multi-system air conditioners have been developed to satisfy the need of several rooms in residential and light commercial buildings (Lijima et al 1991; Masuda et al 1991; Shao et al 2001a). VRV (Variable Refrigerant Volume air conditioning system) is a typical model of multi-system air conditioners from the viewpoint of decreasing the energy consumption and increasing the human comfort.

The multiple VRV system (MVRV) is shown in Figure 1 with several outdoor and indoor units. The simplest VRV system (SVRV) with only one indoor unit and one outdoor unit is shown in

![Figure 1](configuration.png) **Figure 1** Configuration of a multi-system air conditioner
Figure 2. Shi (2000) discussed the similarity of the single-system and multi-system. The SVRV is the abstraction and simplification of MVRV while MVRV is the expansion and extension of SVRV. Both MVRV and SVRV are composed of indoor units and outdoor units. The indoor unit consists of a heat exchanger, an electronic expansion valve and a variable speed fan. The outdoor unit consists of a compressor, a heat exchanger, an electronic expansion valve and a variable fan. When the room needs to be heated, the indoor unit acts as a condenser. On the other hand, when the room needs to be cooled, the indoor unit acts as an evaporator.

The similarity of structure leads to the similarity of function and the performance. So the performance of SVRV based on the units can indicate the performance of MVRV. This will be analyzed in detail by simulation in this paper.

**DESCRIBE OF THE SIMULATION MODELS**

Mathematical simulation method has been developed to study the refrigeration system and heat pump air conditioners (Domanski and Didion 1984, Fisher et al 1988, and Roury 2001). In order to predict the performance of multiple air conditioning system, the mathematical simulation method has been developed based on the models reported before. Chen et al (2001) set up the model of variable frequency compressor with regression analysis from about twenty types compressors. In Chen’s model the parameters that influence the performance of a compressor were taken into account, such as inlet pressure, discharge pressure, density of refrigerant at inlet, ambient temperature, and compressor frequency. Ge (1997) set up the model of evaporator and condenser by distributed-parameter method. And Shi (2000) developed this model by considering the influence of gravity. The connecting pipe model has been built by Hirao et al (1992) to predict the performance of a heat pump system with long pipe and high head. The EEV was modeled as an orifice with a series of suction area by Nakashima et al (1985) and Hirao et al (1992). These models have been modified with experimental data and applied in the performance prediction of refrigeration system or/and the components (Shao 2001b, Shi 2000).

**PERFORMANCE OF INDOOR UNIT AS EVAPORATOR**

When the room needs cooling, the indoor unit acts as an evaporator. The liquid refrigerant from the condenser is depressurized by the EEV and becomes gas-liquid fluid then flows into the evaporator. EEV can regulates the mass flow rate of refrigerant by adjusting its opening rate. The gas-liquid refrigerant in the evaporator turns into gas gradually by absorbing the heat from the air out of the evaporator. The parameters such as Te, Ta, Ga and Gr all influence the performance of the evaporator and the refrigerant state at the outlet of evaporator, but usually Ta and Te are the aims of the system. And Gr is not easy to measure, so the simulation model of EEV is induced to calculate Gr. In order to keep the compressor operating safely, it is necessary to keep the refrigerant superheated at the outlet of the evaporator. The capacity and the refrigerant states are calculated by the simulation model, which is shown in

![Figure 2 Configuration of a simple air conditioner](image-url)
As the increase of the opening rate of EEV, the mass flow rate of refrigerant increases, the superheating degree of refrigerant becomes less and less, the cooling capacity becomes larger and larger. When $SH$ goes down to 0°C, not all the liquid refrigerant evaporates, which indicates that the air volume is too little to give enough heat for evaporating refrigerant, the air temperature at evaporator outlet has reached evaporating temperature which is the lowest value of air temperature. The heat transferred between refrigerant and air can be expressed as

$$Q_e = Ga(H_{a_1} - H_{a_2}) = Gr(H_{r_2} - H_{r_1})$$

When the EEV keeps a constant opening rate, if the air volume is very small, there is much liquid refrigerant at the outlet of evaporator. As the increasing of air volume, the outlet air temperature increases also, more and more liquid refrigerant can evaporate as gas, and the outlet refrigerant enthalpy rises also. When the outlet refrigerant are all in gas phase, the heat transfer leads to the increasing of refrigerant temperature. But the coefficient of heat transfer of single-phase refrigerant in the pipe is much less than that of gas-liquid fluid. So both $H_{r_2}$ and $Q_e$ increase slowly. That is to say when the refrigerant has some superheating degree, the influence of air volume to the $Q_e$ and $SH$ is very small.

Therefor, when the indoor unit acts as an evaporator, it is the EEV’s opening rate and the air volume that control the cooling capacity and the superheating degree. When there is still some liquid refrigerant at the evaporator outlet, decreasing of EEV’s opening rate and increasing of air volume both can increase the superheating degree (or quality). Especially when $SH$ is over 0°C, the EEV’s opening rate and air volume can be used to keep $SH$ and $Q_e$ respectively. If the values of $SH$ and $Q_e$ is given, we can find the optimum point of EEV’s opening rate and air volume in Figure 3 when the indoor units operates different conditions.

**PERFORMANCE OF INDOOR UNIT AS CONDENSER**

When the room needs heating, the indoor unit acts as a condenser. The gas refrigerant of high pressure and high temperature flows from the compressor into the indoor unit, and condenses to liquid gradually, then flows through the EEV. In this condition, especially in the multi-system, the main function of EEV is to regulate the
refrigerant mass flow rate of each unit, so its opening rate is usually very large, and the pressure drop ($\Delta P$) is small, which is assumed as $1.0 \times 10^5$ Pa (1bar). The refrigerant will be depressurized into gas-liquid by the EEV in the outdoor unit when the liquid refrigerant flows back to the outdoor unit. The parameters such as $T_c$, $T_a$, $G_a$ and $G_r$ all influence the performance of the evaporator and the refrigerant state at the outlet of the condenser, but usually $T_a$ and $T_c$ are the aims of the system. And $G_r$ is also represent by the opening rate of EEV. In order to prevent the system from hunting, it is necessary to keep the refrigerant subcooled at the outlet of the condenser. The heating capacity and the refrigerant states are calculated by the simulation model, which is shown in Figure 4.

The heat transferred between refrigerant and air can also be expressed as equation (1). The increase of the opening rate of EEV leads to increase of the mass flow rate of refrigerant, the decrease of the subcooling degree (SL) of refrigerant and the increase of heating capacity. When $SL$ goes down to 0$^\circ$C, not all the gas refrigerant condenses, which indicates that the air volume is too little and the air temperature at evaporator outlet has reached condensing temperature which is the highest value of air temperature.

When the EEV keeps a constant opening rate, as the increasing of air volume, the outlet air temperature decreases, more and more gas refrigerant can condense, and the outlet refrigerant enthalpy decreases. When the outlet refrigerant are all in liquid phase, the heat transfer leads to the decreasing of refrigerant temperature. But the coefficient of heat transfer of single-phase refrigerant in the pipe is much less than that of gas-liquid fluid. So both the decrease of $H_r$ and the increase of $Q_c$ are slowly. That is to say when the refrigerant has some subcooing degree, the influence of air volume to the $Q_c$ and $SL$ is very small.

Therefor, when the indoor unit acts as a condenser, it is the EEV’s opening rate and the air volume that control the heating capacity and the subcooling degree respectively. When there is still some gas refrigerant at the evaporator outlet, decreasing of EEV’s opening rate and increasing of air volume both can increase the subcooling degree. Especially when $SL$ is over 0$^\circ$C, the EEV’s opening rate and air volume can be used to keep $Q_c$ and $SL$
respectively. If the values of $SL$ and $Qc$ are given, we can find the optimum values of EEV’s opening rate and air volume in Figure 4 when the indoor units operates different conditions.

**PERFORMANCE OF OUTDOOR UNIT AS CONDENSER**

When the system operates in the refrigeration model, the outdoor unit acts as a condenser. The gas refrigerant from the indoor evaporators is compressed into high pressure and high temperature gas by the compressor, then flows into the outdoor heat exchanger, and condenses to liquid gradually. In this condition, the parameters such as $Tc$, $Ta$, $Ga$ and $Gr$ all influence the performance of the condenser and the refrigerant state at the outlet of the condenser, but usually $Ta$ and $Tc$ are the aims of the system. And $Gr$ is also represented by the frequency ($Fz$) of compressor. In order to prevent the system from hunting, it is necessary to keep the refrigerant subcooled at the outlet of the condenser. The heating capacity and the refrigerant states are calculated by the simulation model, which is shown in Figure 5.

Similarly as the analysis in the indoor units, the refrigerant mass flow rate and the air volume are the controllable parameters that influence the capacity and the refrigerant states. In the outdoor unit, the refrigerant is controlled by the frequency of compressor. When the subcooling degree has been over 0°C, the compressor can regulate refrigerant mass flow rate to meet the need of the indoor units, and the air volume can control the subcooling degree in an allowable range.

**PERFORMANCE OF OUTDOOR UNIT AS EVAPORATOR**

When the system operates in the heating model, the outdoor unit acts as an evaporator. The refrigerant from the indoor condensers evaporates into gas gradually in the outdoor heat exchanger, then flows into the compressor and is compressed into high pressure and high temperature gas. In this condition, the parameters such as $Tc$, $Ta$, $Ga$ and $Gr$ all influence the performance of the evaporator and the refrigerant state at the outlet of the evaporator, but usually ambient temperature ($Ta$) is uncontrollable and $Te$ is the aim of the system. For the safety of compressor, it is necessary to keep the refrigerant superheated at the outlet of the evaporator. The performance and the refrigerant
Similarly as the analysis above, the refrigerant mass flow rate and the air volume are the controllable parameters that influence the performance and the refrigerant states. In the outdoor unit, the refrigerant is controlled by the frequency of compressor. When the superheating degree has been over 0°C, the compressor can regulate refrigerant mass flow rate to meet the need of the indoor units, and the air volume can control the superheating degree in an allowable range. When the need of indoor unit and the superheating degree are determined, the corresponding values of air volume and the compressor frequency can be found in Figure 6.

**DISCUSSIONS AND CONCLUSIONS**

In order to study the performance of multi-system air conditioner, the system is separated into several components by their function and location, evaporator/condenser and indoor/outdoor unit, from the viewpoint of similarity between simple system and multi-system air-conditioner. The components’ mathematical model in air conditioning system are set up such as variable frequency compressor, heat exchanger, electronic expansion valve and connecting pipe by distributed-parameter.

From the simulation analysis, the heat exchanged in the heat exchanger is determined by the inlet air temperature, the air volume, the refrigerant mass flow rate and the refrigerant states at inlet. The heating/cooling capacity of each indoor unit is determined by the electronic expansion valve and the variable fan. In the outdoor unit, the compressor meets the total heating/cooling load of the system by adjusting the frequency and the variable speed fan keeps proper heat exchanged in the outdoor heat exchanger. The refrigerant mass flow rate is controlled by the frequency of compressor and the opening rate of electronic expansion valve, and the air volume is controlled by the variable speed fan.

Each unit has enough control means to keep the performance by itself, so the system can also be controlled at high efficiency based on the independent control of each unit. The opening rate of EEV or the frequency of compressor can regulate the cooling/heating capacity of the unit by adjusting the refrigerant mass flow rate. And the air volume is adopted to keep the refrigerant states, subcooling degree or superheating degree, at the outlet of the

![Figure 6 Performance of outdoor unit as an...](image)
heat exchanger in the unit. For example, when the indoor act as a evaporator, the variable speed fan controls the room temperature and the electronic expansion valve keep the outlet superheating temperature, the compressor control the state of the system and the outdoor fan keeps the subcooling degree at outlet of heat exchanger.

Although the independent control strategy is feasible to control each unit, the proper control arithmetic will make this strategy more suitable for the control of multi-system air conditioner, which will be studied later and verified by the experimental data.

**ACKNOWLEDGMENT**

This study was supported by the National Natural Science Foundation of China (Grant No. 50176028).

**REFERENCES**


