Simulation Research On Variable Speed Air Conditioner Under Extreme Conditions

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Simulation Analysis on Variable Speed Air Conditioner under Extreme Conditions

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ABSTRACT

It is known that large amount of experiments of variable speed air conditioner are needed under extreme conditions, and the difficulty of these experiments is high. A R410A variable speed air conditioner with the capillary or electronic expansion valve as the throttling element is taken as an example to analyze the large amount of results of simulation under the extreme conditions in this paper. The operation characteristic of the variable speed air conditioner under the extreme condition is obtained, and the difference between the capillary and electronic expansion valve as the throttling element of the air conditioner system is compared. At the same time, the limiting factors affecting the operating range of the variable speed compressor under the extreme conditions are determined. The simulation method of the variable speed air conditioner under the extreme conditions is got in this paper. The operation characteristic of the variable speed air conditioner under the extreme conditions provides reference for the matching of the variable speed air conditioner system and the determination of the operation range of the variable speed compressor.

1. PREFACE

There will be some problems with the reliability of the variable speed air conditioner, when the variable speed air conditioner operates under some extreme working conditions, for example, when the outdoor temperature is very high or ultra-low, or when the operating speed is too low / high. In recent years, for air conditioner manufacturers, except that the compressor must meet the APF performance of air conditioner system, they also began to put forward reliability test requirements for the compressor under the extreme working conditions. Reliability test items are more than APF performance matching tests, and the test conditions are much worse. Once the parameters are not well controlled, the equipment is easy to be damaged. The reliability experiment of air conditioner system under extreme working conditioners is a work that consumes huge experimental resources and experimental cycle. The simulation method of air conditioner system is more efficient than the experimental method, which can save a lot of experimental resources and shorten the product development cycle.

At present, domestic air conditioner manufacturers have hardly used the simulation method to assist the relevant research of air conditioner under extreme working conditions, and the characteristics of the variable speed air conditioner under the extreme conditions is unclear. In addition the reliability matching of variable speed air conditioner involves the cooperation of variable speed air conditioner system, compressor, motor and electrical appliance control. Cross research is difficult, so it is necessary to comprehensively consider the balance of various factors. This paper mainly introduces the simulation method of variable speed air conditioner under extreme conditions, which based on the accumulation of simulation method related to APF performance matching of variable speed air conditioner. This method aims to reduce the test amount of reliability test matching of variable speed air conditioner, and the characteristics of the variable speed air conditioner under the extreme conditions are got through the combination of simulation and test.

2. INTRODUCTION

2.1 Introduction of Simulation Model

The establishment of simulation model is based on the structure and parameters of indoor and outdoor heat exchanger of air conditioner system, the type and specification of throttling equipment, the type and displacement of compressor, the performance parameters of indoor and outdoor fans , the specification of each connecting pipe of air conditioner system, the type of power supply and other relevant physical parameters. The parameterized mathematical model of the variable speed room air conditioner system is built through all the above parameters, which mainly includes the compressor model, heat exchanger model, fan model and throttling equipment model.

- The structure and parameters of indoor and outdoor heat exchanger of air conditioner system includes: pipeline flow, pipe specification, fin type and specification, etc. The structural parameters of the indoor and outdoor heat exchangers of the room air-conditioner are modeled, and the appropriate heat exchange correlations are determined.
  The C.C.Wang model（C.C.Wang et al.1997, 1999, 2001） is used for heat exchange of the air-side. The Shah-Tang model（Shah et al.1979,1982 and Tang et al.1997）is used for the heat exchange of the condensation side. The Kattan-Thome-Favrat mode（Kattan, N., Thome, J.R. and Favrat et al.1998）is used for boiling heat exchange of the evaporation side.
- The mathematical model of compressor is established with 15 coefficient model of AHRI.
  The 15 coefficient model of compressor is expressed as follows:

$$Y = C1 + C2 * Te + C3 * Tc + C4 * f + C5 * Te^2 + C6 * Tc^2 + C7 * f^2 + C8 * Te * Tc + C9 * Te * f + C10 * Tc * f + C11 * Te^2 * f + C12 * Te * f^2 + C13 * Tc^2 * f + C14 * Tc * f^2 + C15 * Te * Tc * f \quad (1)$$

  Y----Performance parameters of compressor (compressor cooling capacity or refrigerant mass flow rate or compressor power consumption or current draw)
  $C_1 \sim C_{15}$----15 coefficient
  T_e---- Condensation Temperature （℃）
  T_c----Evaporation Temperature （℃）
  f----Frequency of compressor （Hz）

- The mathematical model of fan is established, and the fan adopts efficiency model.

$$P_{fan} = {Q * p_{total}}/{(3600 * 1000 * \eta_1 * \eta_2)} \quad (2)$$

  P_{fan}----Required power of fan (KW);
  Q----Volume flow of fan m^3/h;
  p_{total}----Total pressure of fan Pa;
  η_1---- Efficiency of fan;
  η_2----Drive efficiency of fan;
  The parameters 'p_{total}' and' η_1' in equation (2) can be got from the curve of $p_{total} - Q$ and η_1- Q provided by the fan manufacturer.
  The parameter 'η_2' is determined by the type of fan. The drive efficiency of room air conditioner fan is generally 0.95~1.
- The mathematical model of throttling equipment is established. Throttling equipment includes electronic expansion valve and capillary. The simulation results show that the throttling effect of capillary and expansion valve is the same under the rated condition, so the orifice valve model is used for the throttling equipment in this paper. The difference is that the variable speed room air conditioner system with electronic expansion valve adopts the method of suction superheat control, while the suction state of variable speed room air conditioner system with capillary is not controlled.

After the above components are modeled, a steady-state simulation model of variable speed air conditioner system is established. And the air conditioner system model is calibrated according to the experimental results from air conditioning system enthalpy difference laboratory, which ensure the consistency between the simulation results and the experimental results. Therefore, the following system simulation in this paper is based on the steady-state simulation model of the variable speed air conditioner system.

2.2 Definition of Extreme Environmental Conditions

Under the condition of extremely high outdoor temperature under cooling condition or extremely low outdoor temperature under heating condition, it is called the extreme environmental condition of room air conditioner. Referring to the provisions on the working conditions of air conditioners in the Standard 《Room Air Conditioners》(GB7725-

2015), the range of ambient temperature under the working conditions of maximum cooling and ultra-low temperature heating is widened. The specific simulation working conditions are shown in Table 1.

Table 1: Simulation working conditions

working conditions	**Dry / Wet bulb temperature (℃)**	
	Out door	**In door**
maximum cooling condition	52/31	32/23
	50/30	
	48/29	
	46/28	
	44/28	
ultra-low temperature heating condition	-7/-8	20/15
	con	
	-15/-16	

3. DETERMINATION OF LIMITING FACTORS

3.1 Limiting Factors of Compressor

For variable speed compressors, in the process of determining the operating range of the compressor, the limiting factors such as the pressure bearing capacity of the compressor under different speed ranges, the pressure ratio of suction and discharge and the pressure difference between suction and discharge are generally considered. The operating range of a compressor is shown in Figure 1.

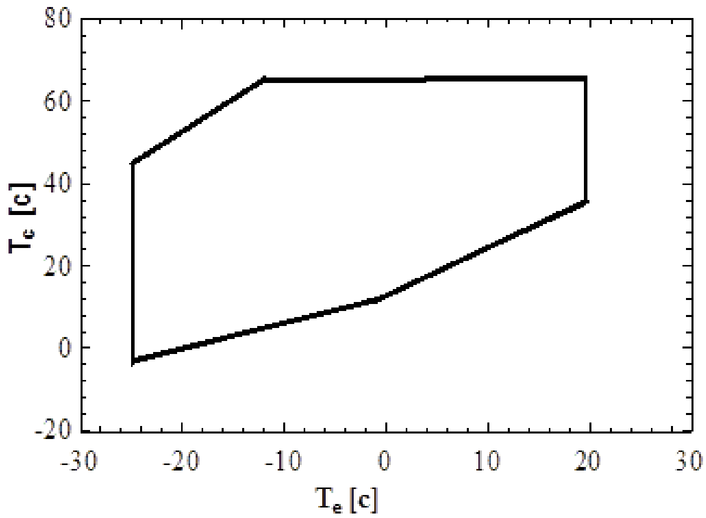

Figure 1: Operation range diagram of variable speed compressor considering only mechanical conditions

In the actual operation of air conditioner, the discharge temperature of compressor, the state of suction with micro amount liquid and limit power of compressor are related to the specific operation of the compressor.

In general, the discharge superheat rises with the increase of frequency. In order to ensure that the discharge superheat during the operation of the compressor is greater than 5 ℃, it is required to control the amount of liquid in suction.

3.2 Limiting Factors of Air Conditioner System

The main limiting factor of the air conditioner system discussed in this paper is the frosting (icing) on the surface of the heat exchanger. Frosting will reduce the heating capacity of the evaporator and damage the refrigeration equipment in serious cases. Frosting is a complex dynamic process. It is hoped that the frosting of evaporator under various working conditions can be obtained by a simulation method of simple steady-state process.

Frosting is generally related to the operating state of the air conditioner system (refrigerant flow), the environmental conditions of the evaporator and the evaporation temperature. The surface temperature of the heat exchanger is estimated by the following equation (3):

$$\tau h_a (t_{amb} - t_w) = h_r (t_w - t_e) \quad (3)$$

τ ——heat exchanger rib coefficient;

h_a ——heat transfer coefficient of air side，$W/(m^2 \cdot K)$;

h_r ——heat transfer coefficient of refrigerant side，$W/(m^2 \cdot K)$;

t_{amb} ——ambient temperature，℃;

t_w ——the surface temperature of the evaporator tube，℃
(The copper tube of the heat exchanger is generally very thin. It is assumed that the internal and external surface temperatures are the same)

t_e ——evaporation temperature，℃;

The relationship between evaporation temperature, heat exchanger tube wall temperature and air dew point temperature with frequency under various working conditions can be estimated, through the simulation calculation results of heat transfer performance under various working conditions (heat rib coefficient, heat transfer coefficient inside and outside the heat exchanger),. When the surface temperature of the heat exchanger is lower than the dew point temperature (DW) of the wet air and higher than 0 ℃, the moisture in the air contacts the surface of the heat exchanger, it is considered that the condensation process occurs and condensed water is produced; When the surface temperature of the heat exchanger is lower than the dew point temperature of wet air (DW) and lower than 0 ℃, it is considered that the wet air on the surface of the heat exchanger begins to freeze / frost.

3.3 Limiting Factors of Electrical Appliance Control

If the operating current and power value of the air conditioner system are abnormally high, the motor coil will generate a lot of heat, which will affect the insulation performance of the compressor motor enameled wire and even burn the motor coil. On the other hand, too high power and current will increase the load of power supply and power line. If it exceeds its bearing range, it may lead to accidents. Based on experience, this study is conducted in the range of 0.8 ~ 1.2 times of power in this paper, that is, 1600 ~ 2400W is used to search for the economic limited power of the compressor.

4. ANALYSIS OF SIMULATION RESULTS

4.1 Error of Simulation Results

Table 2: Error at 46 / 28 ℃ outdoor and 32 / 23 ℃ indoor

f(Hz)	Comparison items	Power (W)	ps (kPa)	pd (kPa)	Td (℃)
69	Experimental results	1447.5	1065	3892	97.7
	Simulation results	1500.6	1077.9	3915.4	97.5
	error(%)	3.67	1.21	0.6	-0.21
74	Experimental results	1665.9	1034	4030	103.3
	Simulation results	1692.2	1077.9	4005.3	98.9
	error(%)	1.58	4.24	-0.61	-4.27
78	Experimental results	1702	1038	4054	103.4
	Simulation results	1733	1070.8	4060.8	100.4
	error(%)	1.82	3.16	0.17	-2.88

Because it is difficult for the actual room air conditioner to reach the limiting factor point set under the extreme condition in the test of extreme environmental condition, and the operation under the extreme condition has a great relationship with the control strategy of the air conditioner system, it is generally difficult to achieve the extreme condition in the test. In order to verify the accuracy of the simulation results, the air conditioner system simulation model calibrated under rated working conditions is used to compare the experimental results with the simulation calculation results under one of the extreme environmental working conditions of maximum cooling (outdoor temperature is 46 / 28 ℃). The specific results are shown in Table 2. It can be seen that the error is within 5%, and it is considered that the simulation calculation results under other working conditions are reliable.

4.2 Distribution of Limiting Factors of Compressor

Figure 2 shows the various limiting factors of compressor change with frequency under different operation working conditions of the air conditioner. Only the white part has no limiting factors within the corresponding frequency range of the air conditioner. It is generally believed that after a limiting factor appears, there is a hidden danger of operation safety.

It can be seen from the Figure2 that the discharge pressure of the air conditioner is the most important limiting factor during operation under the maximum cooling condition, and the second is the limiting factor of power(1600W). The compressor power is the most important limiting factor affecting the safe operation under the ultra-low temperature heating condition. It also can be seen from the Figure2 that the influence of discharge temperature limiting factors and discharge superheat limiting factors on the EEV system is less than that of capillary system.

As for the power limiting factors, there are many working conditions where 1600W power limiting factors appear before other limiting factors, while 2400 power limiting factors generally appear after other limiting factors. Therefore, it is appropriate to set 2000W as the final limiting power of the compressor.

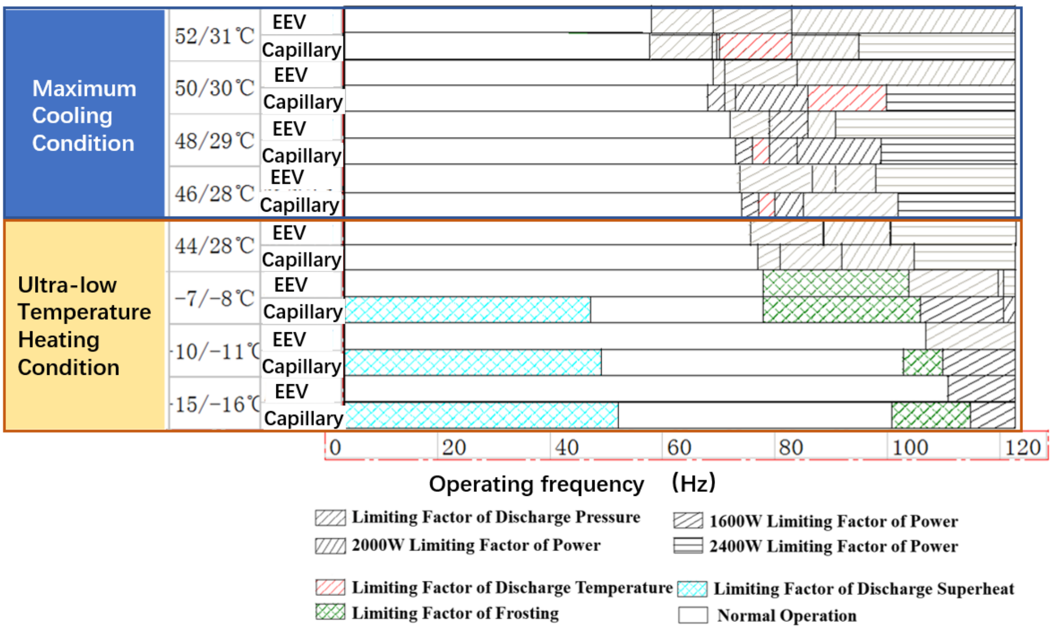

Figure2: Distribution of limiting factors under various conditions of extreme environment with frequency

4.3 Operating Range of Compressor in Air Conditioner

The simulation calculation of all possible working conditions of the air conditioner are obtained, the operation range of the compressor under various working conditions according to the limiting factors of the air conditioner is summarized and sorted out. And the operation range of the compressor itself and the operation range of the compressor in the air conditioner are finally got, as shown in Figure 3. It can be seen from Figure 3 that the operation range involved under the heating condition in the air conditioner is wider than that under the cooling condition.

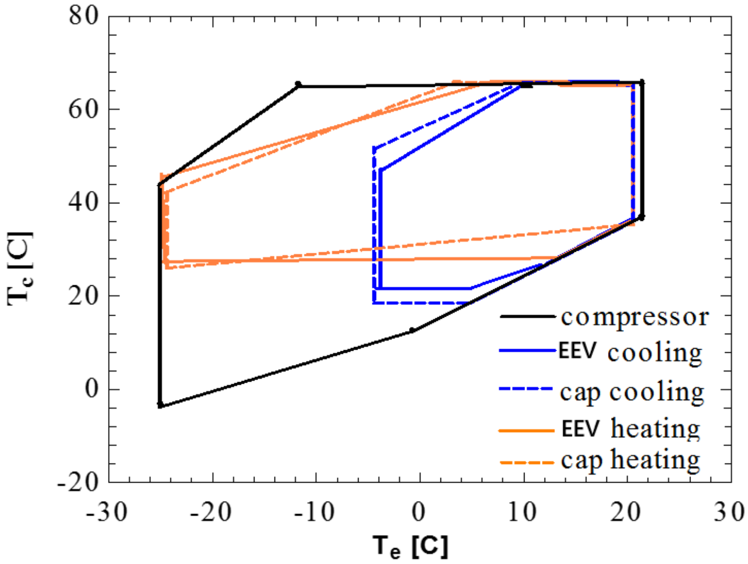

Figure3: Operation range of the compressor itself and the operation range of the compressor in the air conditioner

The throttling equipment has little impact on the overall operation range of the compressor in the air conditioner seen from Figure 3. Under the cooling condition, the EEV system can optimize the operation range of the compressor in the air conditioner and make the compressor operate in a small Te-Tc range. Under heating condition, due to the adjustable throttle opening of the EEV, the EEV system has obvious advantages over the capillary system on discharge temperature control, so that the operation range of the compressor is wider than that of the capillary system.

As shown in Figure 3, the operation range of the compressor in the air conditioner is less than the operation range of the compressor itself. It shows that the studied air conditioner system can improve the potentialities of compressor operation under extreme working conditions through some system optimization means.

5. CONCLUSIONS

A complete limiting condition simulation method is established in this paper, and the limiting frequency and corresponding limiting factors that can be operated under each working condition are obtained through the simulation calculation under the possible operation environment of the air conditioner system. The relationship between the operation range of the compressor in the air conditioner system, with different throttling equipment and under different modes, and the operation range of the compressor itself is obtained. The relevant conclusions are as follows.

- As a throttling component, the EEV can effectively improve the frosting of the evaporator compared with the capillary. In addition, because the performance of the EEV in the control of state discharge (discharge temperature and discharge superheat) is better than the capillary system. Therefore, the EEV as a throttling component has obvious advantages under the extreme working conditions of the air conditioner.
- According to the order of different power limiting factor and other limiting factors of the compressor, as shown in Figure 2, it is recommended to take 2000W as the limit power of the compressor in the process of electric control matching of the compressor.
- The simulation results show that the operation range of the compressor in the air conditioner is less than the operation range of the compressor itself. It shows that the studied air conditioner system can improve the potentialities of compressor operation under extreme working conditions through some system optimization means

NOMENCLATURE

APF	Annual Performance Factor
GWP	Global Warming Potential
EEV	Electronic Expansion Valve
Cap	Capillary
DW	The dew point temperature of wet air

p	Pressure	(Pa)
T	Temperature	(℃)
P	Required power	(KW)
Q	Volume flow	(m^3/h)
η	Efficiency	(−)
f	Frequency of compressor	(Hz)
τ	Heat exchanger rib coefficient	(–)
h	Heat transfer coefficient	($W/(m^2 \cdot K)$)
t	Temperature	(℃)

Subscript

s	suction
d	discharge
c	condensation
e	evaporation
a	air side
r	refrigerant side
amb	ambient
w	the surface of the evaporator tube

REFERENCES

Zhang Lei,(2020). Performance Optimization of Variable Speed Room Air-Conditioner Under Intermediate Speed Working Condition. *International Refrigeration and Compressor Conference, Purdue University, USA*,Paper.2184.

China National Standards Management Committee (2016). *Room Air Conditioner GB7725-2015,* Beijing: Standards Press of China,

Zhang Chunlu(2013). *Simulation Principle and Technology of Refrigeration and Air Conditioner System.* Beijing, Chemical Industry Press,

Huang B, Zhu X Y,Tao H. et al(2014). The Performance Matching of Inverter Room Air Conditioner. *International Refrigeration and Compressor Conference, Purdue University, USA.*

Wang C C,(2001). Parametric study of the air - side performance of slit fin - and – tube heat exchangers in wet conditions[J] . *Journal of Mechanical Engineering Science , 215(9)* ,1111 - 11221

Wang C. C,(1997). Heat transfer and friction characteristics of typical wavy fin-and-tube heat exchangers. *Experimental Thermal and Fluid Science , 14(2),* 174～186.

Wang C. C,(1999). A heat transfer and friction correlation for wavy fin-and-tube heat exchangers. *Int. J. of Heat and Mass Transfer , 42(10)* ,1919～1924.

Wang C. C,(1999). An investigation of the air-side performance of the slit fin-and-tube heat exchangers. *Int. J . of Refrig, 22(18)* ,595～603.

Wang, C.C,(1999). An investigation of wavy fin-and-tube heat exchangers; a contribution to databank. *Experimental Heat Transfer, 12,* 73-89.

Shah, M.M,(1979). A General Correlation for Heat Transfer during Film Condensation inside of Pipes, *Int. J. Heat Mass Transfer, Vol. 22,* 547-556.

Shah, M. M,(1982). Chart Correlation for Saturated Boiling Heat Transfer: Equations and Further Study, *ASHRAE Trans, Vol. 88, Part 1,* 185-196.

Tang,(1997). Empirical Study of New Refrigerant Flow Condensation inside Horizontal Smooth and Micro-Fin Tubes, *Ph.D. Thesis, University of Maryland.*

Kattan, N., Thome, J.R. and Favrat, D,(1998). Flow Boiling in Horizontal Tubes. Part 1:Development of a Diabatic Two-Phase Flow Pattern Map*, J. Heat Transfer, Vol. 120, No. 1,* 140-147.

Kattan, N., Thome, J.R. and Favrat, D,(1998). Flow Boiling in Horizontal Tubes. Part 2: New Heat Transfer Data for Five Refrigerants*, J. Heat Transfer, Vol. 120, No. 1,* 148-155.

Kattan, N., Thome, J.R. and Favrat, D,(1998). Flow Boiling in Horizontal Tubes. Part 3:Development of a New Heat Transfer Model Based on Flow Patterns*, J. Heat Transfer, Vol. 120,No. 1,* 156-165.