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ABSTRACT

Some key parameters like system refrigerant charge amount, electronic expansion valve, compressor frequency, indoor and outdoor air-flow rate have been optimized using simulation tools for each matching condition of an inverter room air conditioner in the process of its performance matching. Thus, with the simulation tools and a new work process, the experiments of the performance matching of inverter room conditioner become more efficient, which will greatly shorten the test time, reduce workload and cut the cost.

1. INTRODUCTION

With the improvement of global energy conservation and environmental protection requirements, inverter room air conditioner is becoming increasingly attractive in the market thanks to its high energy saving ratio and flexibility in contrast to traditional constant speed air conditioner.

Along with the growing market, many countries and organizations have announced new rules to standardize the performance of air conditioner. China issued its new APF standards for inverter room air conditioner, which completes the comprehensive evaluation of the performance of a room air conditioner by investigating five different test points.

1.1 The Definition and Difficulties of Air Conditioner`s Performance Matching

The performance matching of air conditioner is to ensure that the system can achieve its best performance under each assessment condition. Under the optimized condition, the system not only can meet the demand of cooling or heating capacity of every condition, but it should also operate with the highest COP value.

Table 1: Comparison of Old and New Standards of China

Item	Old Standards	New Standards
Air conditioner type	Fixed-speed	Various-speed
Assessment points	Rated Cooling Conditions	1) Intermediate Cooling Conditions 2) Rated Cooling Conditions 3) Intermediate Heating Conditions 4) Rated Heating Conditions 5) Low Temperature Heating Conditions
Adjustable parameters	Refrigerant charge amount	1) Refrigerant charge amount 2) Frequency of Compressor 3) Electronic expansion valve 4) Indoor air-flow rate 5) Outdoor air-flow rate
Original Matching method	Air-enthalpy tests	Air-enthalpy tests

In the performance matching of fixed-speed air conditioner, the traditional approach is to use air-enthalpy test matching method. In the case of an inverter room air conditioner with electronic expansion valve, the system performance is supposed to be evaluated under five different conditions which represent the most probable scenarios. The five conditions include intermediate cooling, rated cooling, maximum cooling, intermediate heating and rated heating. Each condition is described by several parameters such as refrigerant charge amount, compressor operating frequency, indoor and outdoor air-flow rate, etc. with the opening of electronic expansion valve directly related to the compressor suction superheat. For instance, each test lasts 2.5 hours, and total 20 tests (actually more) will spend 40 hours, if 8 hours a day, then the total matching test will require about one week, consuming a lot of human resources, experimental resources, and money, etc. Not to mention some other experiment breakdowns.

In this case, both the considerable time consumption and huge investment makes the original air-enthalpy test method unattractive.

1.2 The improvement of the Test Matching Method

In fact, multivariable parameters optimization needs a good mathematical logic, and it is essential and complex to control an array of variable factors. But in the actual air-enthalpy matching experiments, single factor variable control method can make laboratory work faster and efficient. In this method, under each condition, only one variable parameter is investigated and optimized. Consequently, such method failed to take the inter-related influence among several variable parameters on the system at the same time. This paper selects a compromise approach between the actual test methods and mathematical methods. But this approach is really constructive and effective for the performance matching of inverter room air conditioner especially for a company. Some processes and a comparison between this new approach and the traditional air-enthalpy tests are shown in **Table** 2,

Table 2: Comparison of the Air-enthalpy test method and new method

Process of work	
Old method (only air-enthalpy tests)	New method (air-enthalpy test & simulation tools)
1. Test 2. Test 3. Test 4. Test `````` Blindness and require too much time and money.	1. Four diagnostic groups of air-enthalpy tests 2. Calibration according to the four tests 3. Calculation according to the four calibrated points 4. Recommend results 4. Final air-enthalpy test validation

Detail descriptions about the new method are as follow:

Step 1: do four different air-enthalpy tests, whose parameters do not need too much adjustment;

Step 2: calibrate the simulation system with the results of the four air-enthalpy tests, the calibrated simulation accuracy must be maintained at less than 4%;

Step 3: accomplish some calculations in a small-scale range of every parameter blew in the four conditions: intermediate cooling, rated cooling, intermediate heating and rated heating:

1) Refrigerant charge amount
2) Frequency of compressor
3) Suction Superheat
4) Indoor air-flow rate
5) Outdoor air-flow rate

Step 4: recommend value or range of the parameters according to the calculation results

Step 5: final test validation and slight adjustment.

Actually, this new method is based on the actual air-enthalpy tests and a combination of the air-enthalpy test method and simulation approach. Firstly, four diagnostic groups of air-enthalpy tests are performed and their parameters do not need too much adjustment. Secondly, some accurate calibrations to the simulation system are performed just according to the four groups of air-enthalpy tests. After calibration, the simulation accuracy is maintained at less than 4%. Then accomplish some calculations in the vicinity of a small-scale range of the calibrated points. At last, the data is summarized and analyzed partially and globally. Thus every optimal range of the critical parameters is determined and experimenters can quickly complete these matching tasks according to the provided value or range of these parameters. So with the help of simulation tools, the experimental effort and cost can be greatly reduced, which will is definitely economical attractive to a company.

2. SIMULATION AND CALIBRATION OF THE COMPONENTS

2.1 Components Model and Algorithm of Air conditioner

A basic air conditioner consists of four main components: compressor, indoor heat exchanger, outdoor heat exchanger, and throttling device. In simulation tools, each component has a specific model and its own algorithms. When they are combined into a room air conditioning system, a comprehensive method to solve the systemis required.

This paper uses a mathematics model for the simulation of finned tube heat exchanger based on distributed parameter. The inverter compressor model is a semi-empirical model and electronic expansion valve model is also a semi-empirical model.

The simulation is solved by solving multiple equations simultaneously with numerical solvers.

In this paper, an inverter room air conditioner (Rated Cooling Capacity: 3500W, Rated heating Capacity: 4200W) was analyzed and optimized.

2.2 Original Enthalpy Experiment Data

All following tests were done at the air-enthalpy experiment laboratory of Shanghai Hitachi Electrical Appliances Co. Ltd. The performance of the room air conditioner was measured according to certain experimental standard, which is specified in GB21455-2013 of China, and **Table** 3 shows the main experimental conditions.

Table 3: Enthalpy Experiment Conditions

Indoor and outdoor unit \ Indoor conditions	Indoor dry bulb temperature: Tdb (℃)	Indoor wet bulb temperature: Twb (℃)
Outdoor(cooling/heating Test)	35/20	24/15
Indoor(cooling/heating Test)	27/7	19/6

Rated test means the cooling (or heating) capacity of the air conditioner reaches the target value on the nameplate;

Intermediate test means the cooling (or heating) capacity of the air conditioner reaches half of the standard value on the nameplate.

More information about experiment standard, please reference GB 21455-2013 of China.

The original air-enthalpy test results are show in Table 4. All temperatures were measured using platinum resistances, whose measurement error is less than 0.2 ℃; other tested results like power, air-flow rate, capacity, pressure and so on, were all reliable with their relative errors within 2%.

Table 4: Original Enthalpy Experiment Data

Refrigerant		R410A			
Rated capacity		Rated Cooling Capacity:3500W; Rated heating Capacity:4200W			
Tested	unit	Inter-cooling	Rated-cooling	Inter-heating	Rated-heating
Frequency	Hz	30	70	39	79
Tw-air	℃	17.76	14.28	31.61	43.02
Td-air	℃	15.82	13.03	19.1	22.62
Qv_{indoor}	m^3/h	614	591	621	614
$Qv_{outdoor}$	m^3/h	1600	1600	1600	1600
Qc(Qh)	W	1968	3442	2373	4484
Qsen	W	1984	2633	2373	4484
Power	W	460	1159	542	1466
EER/COP		4.28	2.97	4.37	3.06
T_{eva_in}	℃	16.3	12.61	27.76	35.64
T_{eva_out}	℃	14.3	7.47	47.54	80.11
T_{eva_mid}	℃	15.4	10.87	27.94	35.71
Ts	℃	19.5	11.91	3.84	1.16

Td	℃	58	75.56	51.34	81.89
T_{cond_in}	℃	57.6	74.77	2.79	-0.29
T_{cond_mid}	℃	42.1	47.99	3.21	1.07
T_{cond_out}	℃	36	37.29	3.73	3.69
Pd[abs]	MPa	2.54	2.989	2.273	3.401
Ps[abs]	MPa	1.19	0.9	0.85	0.757
θ	/500	405/500	170/500	105/500	140/500
M	g	930	930	930	930

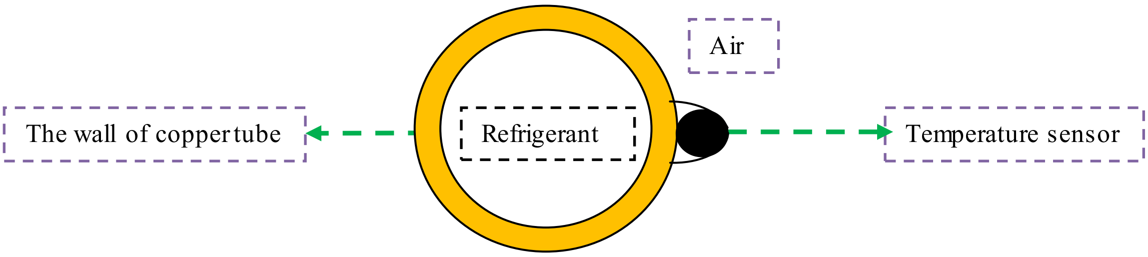

Figure 1 Schematic diagram of temperature sensor measurement point

Since the measured temperature and the real temperature of the refrigerant pipe are not the same, temperature sensors are generally affixed to the outer wall of copper, shown in **Figure 1**, the temperatures measured are actually the combined effects of the refrigerant temperature in the copper tube and the air temperature of the outer copper tube. But as long as the calibration accuracy meets the requirement (within 5%), the accuracy of the calibration can be considered reliable in the simulation.

2.3 Calibration and Accuracy of the Simulation System

In this simulation of air conditioner, simulation will also bring some deviations into the calculations. So there will be some errors between the simulation results and the air-conditioner test results. In order to ensure the accuracy and reliability of the simulation, every simulation model must be calibrated to reduce the calculation errors on the basis of the initial tested data in Table 5.

Table 5: Accuracy of simulation

Test	Location	P_test	P_sim	ABS Residual	T_test	T_sim	ABS Residual
	Unit	[MPa]	[MPa]	[MPa]	[℃]	[℃]	[℃]
Rated Cooling	Compressor suction	0.902	0.900	0.000	11.91	11.51	-0.4
	Compressor outlet	2.989	2.989	0.000	75.56	83.97	8.41
	Condenser outlet	2.989	2.877	-0.122	37.29	40.72	3.43
	Condenser inlet	0.902	1.062	0.160	12.61	9.22	-2.39
Rated Heating	Compressor suction	0.757	0.757	0.00	1.16	-1.53	3.46
	Compressor outlet	3.401	3.401	0.00	81.89	91.36	9.47
	Condenser outlet	3.401	3.382	-0.091	35.64	37.75	2.11
	Condenser inlet	0.757	0.792	0.035	3.69	3.45	-0.24

In Table 5, the pressure values of across the condenser were not obtained from the experiment, but they were predicted according to the pressure at the two ends of the compressor. Although there was slight deviation between the simulation calibration results and the experimental data, it did not affect the overall system simulation accuracy.

The simulation of other conditions are all based on the above four calibrations, from the original four points to multiple points, and then gradually extend to all frequencies and all conditions. At the same time, Some experimental verifications have been made and as a result, the error between tested and calculated is less than 5%, which further indicates that the simulation is reliable.

After the completion of the calibration for all tested points and fulfilling the simulation requirement, calculation can continue in the vicinity of the experimental point calibration.

3. SINGLE VARIABLE LOCAL OPTIMIZATION OF THE PARAMETERS

As discussed above, several parameters affect the performance of inverter room air conditioner. The New APF standard demands the performance of room air conditioner as high as possible even in every test condition, which means each parameter should be set to an optimum value (or within the optimal range) to make the air conditioner achieve overall excellent performance. As a result, the optimization of each factor on the air conditioner system performance becomes very important. The following discusses a single variable local optimization process of this room air conditioner.

3.1 Local Optimization of Refrigerant Charge Amount

In general, the refrigerant charge amount of room air conditioner is the first important impact factor on the performance of the system, and our calculations range from 800g to 1040g. The figures are also with some change of compressor frequency, which will be further discussed in other chapter.

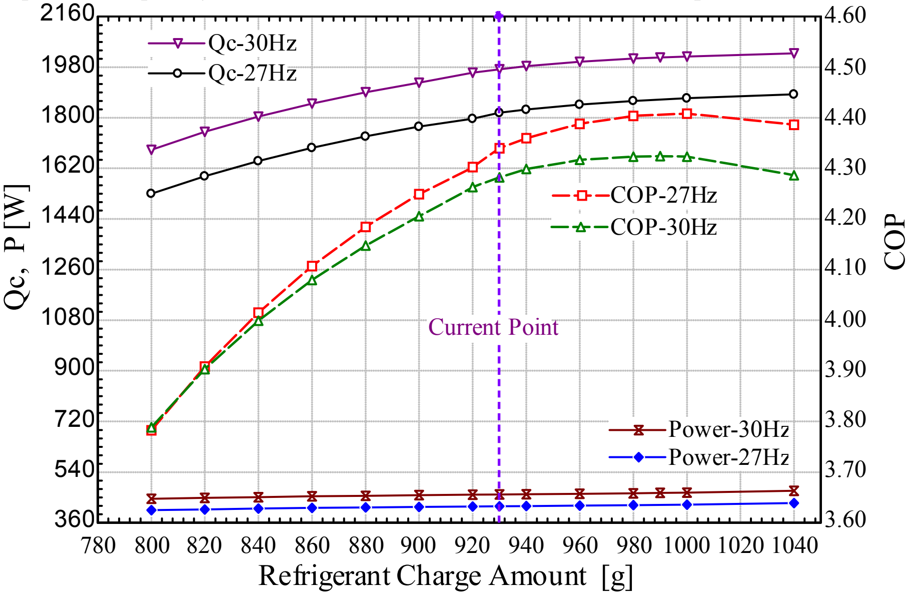

Figure 2 Performance vs. Ref charge amount (inter-cooling)

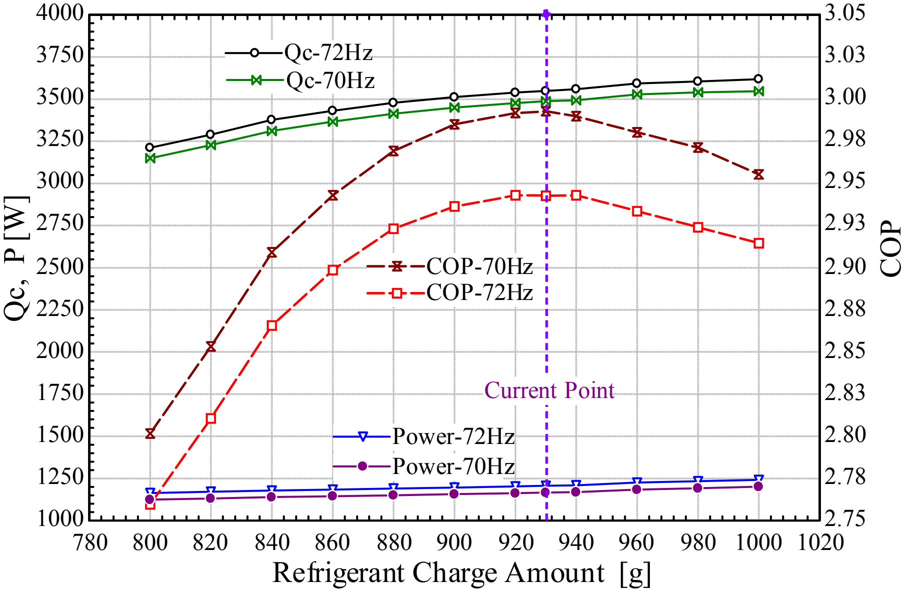

Figure 3 Performance vs. Ref charge amount (rated-cooling)

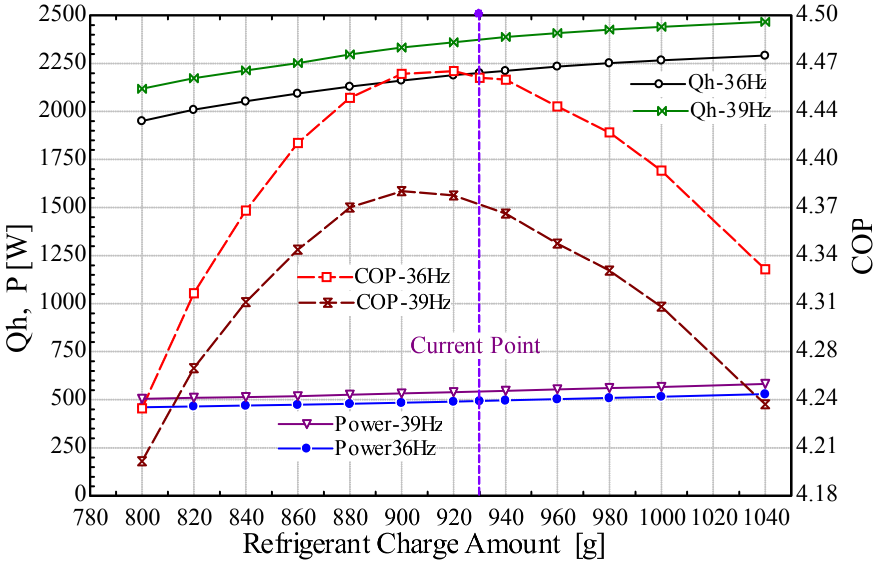

Figure 4 Performance vs. Ref charge (inter-heating)

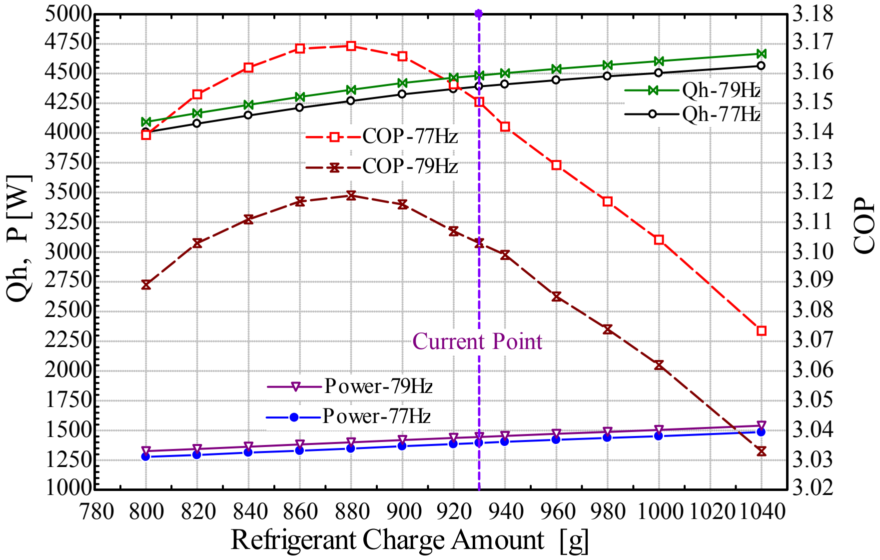

Figure 5 Performance vs. Ref charge (rated-heating)

Qc-30Hz means the cooling capacity of system when the compressor is running at 30Hz;
Qh-79Hz means the heating capacity of system when the compressor is running at 79Hz.
The meanings of other labels are in the same way.

Refrigerant charge amount is an integral factor. As we can see from **Figure 2** to **Figure 5**, the optimum values for each air-enthalpy test conditions are not the same, but on a comprehensive comparison, we can see that the intermediate cooling conditions is more sensitive to refrigerant charge amount compared with other conditions, so refrigerant charge amount can be determined from the intermediate cooling conditions. To this experiment, 930g is just close to the optimal value, so there is no need to do other optimization about refrigerant charge amount any more.

In addition, from the **Figure 2** to **Figure 5**, it also suggests that, when the operation frequency of the compressor is increased, the cooling (heating) capability Qc (or Qh) will increase, as well as system power. But on the contrary, the COP of the system will reduce, which will be particularly discussed in the next chapter.

3.2 Local Optimization of Compressor`s Running Frequency

In the air conditioner system, the operating frequency of compressor is the second important factor that influencing the performance of air conditioner, which directly determines the cooling (heating) capacity and system power. Thus the optimization of the operating frequency of the compressor is particularly important. **Figure 6** and **Figure 7** showcase the frequency influence on the system performance under cooling and heating operation respectively.

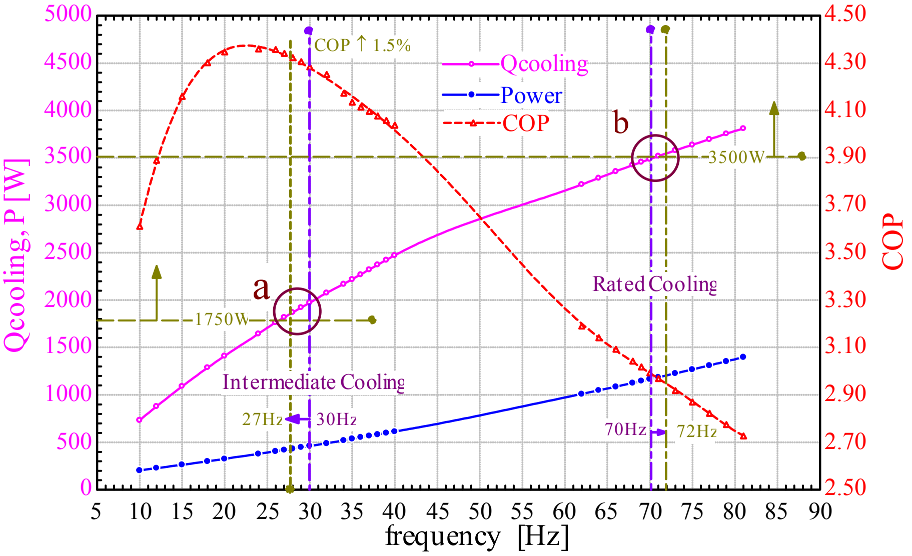

Figure 6 Performance vs. Frequency (Cooling cycle)

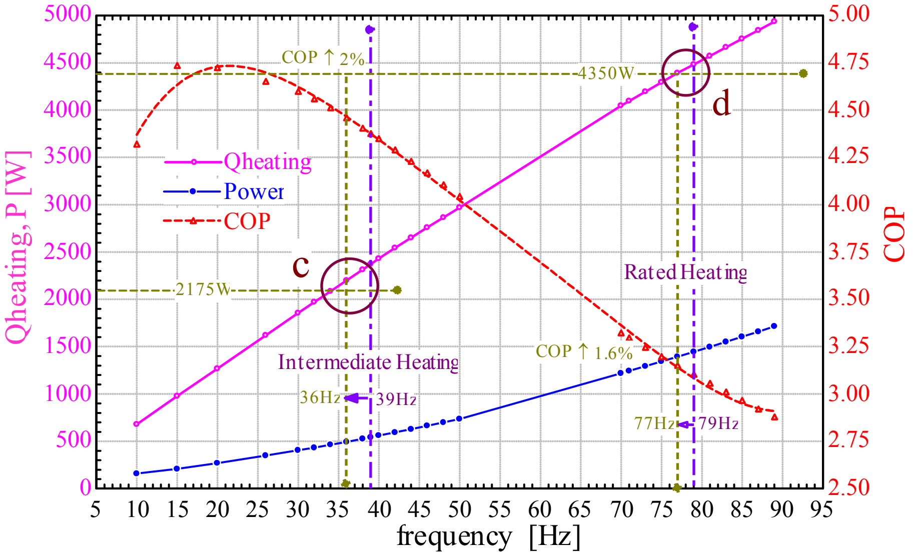

Figure 7 Performance vs. Frequency (Heating cycle)

Cooling and heat capacity and COP are determined to represent the performance as shown in the **Figure 6** and **Figure 7**, a conclusion can be drawn from the two figures: when the compressor frequency rises, the cooling (heating) capacity and power will increases, but the COP of the system has a best compressor frequency range. Additionally, the optimal frequency range is different between cooling and heating conditions. Actually, both of its intermediate conditions and rated conditions are at the right side of the curve peak, the COP of the air conditioner will decrease with the increase of compressor frequency, so the smaller the cooling (heating) capacity, the higher the COP of system. Furthermore, the cooling and heating capacity must meet the requirements of the test, as for this air conditioner, as long as the rated cooling capacity Qc is above 3500W, the intermediate cooling capacity Qc1 is above 1750W, the intermediate heating capacity Qh1 is above 2175W, and the rated heating capacity Qh is above 4350W (if no enough, it will need to increase), it is qualified for the system simulation. So the new suggested frequency is shown in origin color line in the figures.

Table 6 Compressor operating frequency optimization:

Conditions	Original frequency	Suggested frequency	COP effect
Intermediate cooling	30Hz	27Hz	Up 1.5%
Rated cooling	70Hz	72Hz	Up 1.6%
Intermediate heating	39Hz	36Hz	Up 2.0%
Rated Heating	79Hz	77Hz	Up 1.6%

3.3 Local Optimization of electronic expansion valve`s open rate

Capillary or electronic expansion valve play a very important role in air conditioning system. This system uses electronic expansion valve, whose diameter is 0.9mm, and opening of the adjustable range is from 0 to 500. The opening rate of the electronic expansion valve directly affects the compressor suction superheat and finally affects the overall performance of the system. The compressor suction superheat has a negative correlation relationship with the degree of the electronic expansion valve. The impact of superheat on the performance of the air conditioning system is show in **Figure** 8.

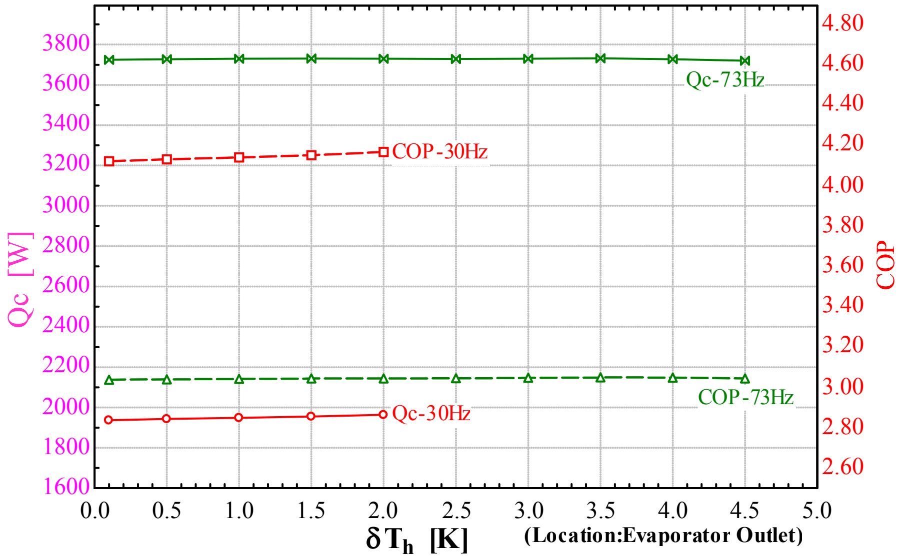

Figure 8 COP vs. Suction Superheat (Cooling Cycle)

There is no need to do other optimization about superheat, i.e. the opening rate of electronic expansion valve will need not too much adjustment according to Figure 8.

Actually, other simulations and tests have been done in at least 5 different room air conditioners, and as a consequence, the best superheat range is 0 ~ 4K for cooling running to an air conditioner. While the superheat range of -1K ~ 2K is determined during heating conditions. Consequently, when the system is running in heating cycle, negative suction defined as small amount of liquid refrigerant at the suction will enhance the system performance.

When suction superheat is negative, it means there is liquid refrigerant in the compressor suction. Other effects (such as "Liquid hammer") will be not considered here, only the impact on system is focused.

Superheat: $$\Delta T_{\text{superheat}} = \frac{h_{suc} - h_0}{Cp_0} \qquad (1)$$

$\Delta T_{\text{superheat}}$, compressor suction superheat, Unit K;

Cp_0, bubble point Cp;

h_0 , enthalpy of bubble point, unit kJ / kg;

h_{suc}, suction enthalpy of compressor, unit kJ / kg.

Under normal circumstances, $h_{suc} > h_0$, suction superheat is positive at this time, known as suction superheat;

When suction with liquid, $h_{suc} < h_0$, superheat is negative at this time, known as negative suction superheat.

In these original tests, the ranges for superheat were accepted, namely the opening of the electronic expansion valve of every condition has already been well adjusted and does not need considerable adjust. In fact, in the four diagnostic groups of air-enthalpy tests, we have made some adjustments according to other simulation conclusion and get the results of other different room air conditioners, ranging from 1HP to 2HP.

3.4 Local Optimization of Indoor and Outdoor Air-Flow Rate

In addition, indoor and outdoor air-flow rates also affect the system performance. When the system is running with a low compressor frequency, the total power of the system is greatly reduced, then the proportion of the indoor and outdoor fan`s power becomes lager. At the same time, like intermediate conditions, the provided air-flow rate may exceed the nominated rate, which will surely lead to extra useless power.

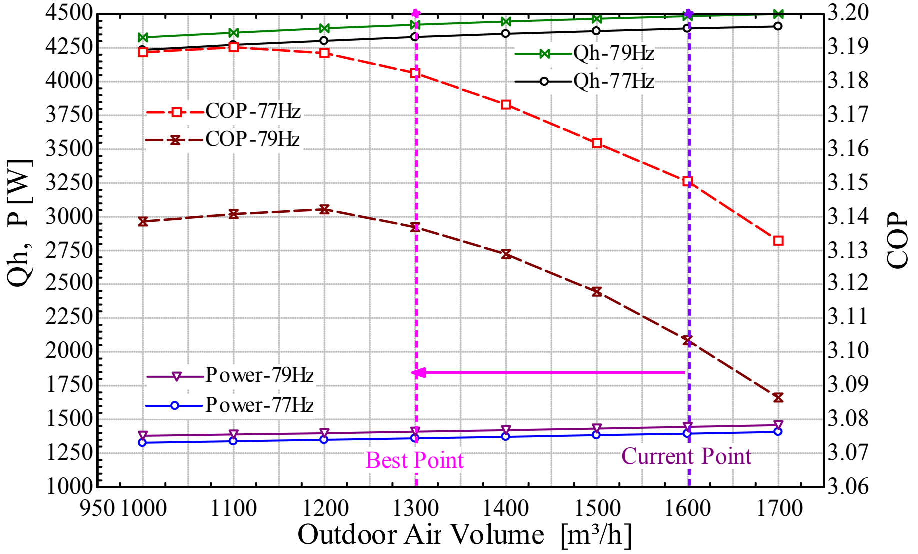

Figure 9 Performance vs. Qv$_{indoor}$ （rated-heating）

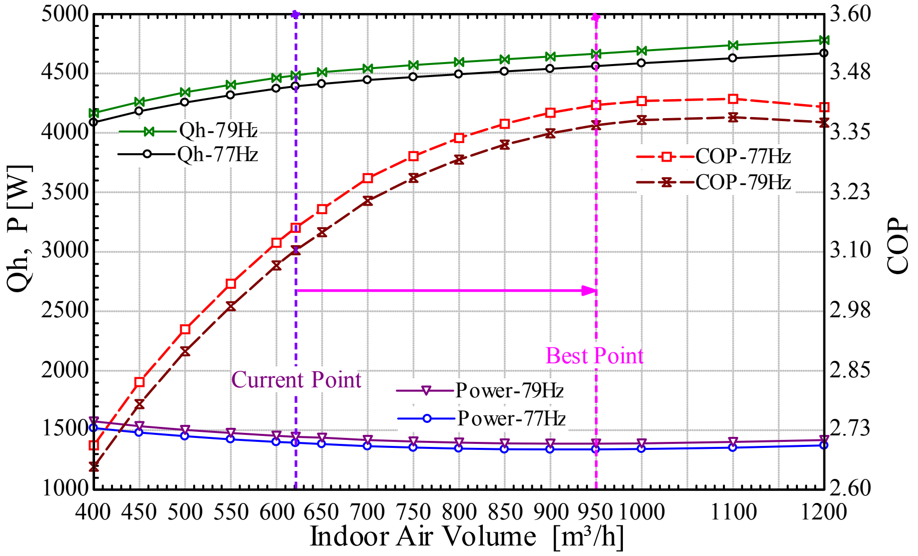

Figure 10 Performance vs. Qv$_{outdoor}$ （rated-heating）

When in the rated heating condition, both of the existing indoor and outdoor air-flow rate have not reached the optimal value, indoor air-flow rate was too small (**Figure 9**) . Therefore, the indoor air –flow rate can be further increased to 950m^3 / h, then system`s COP will significantly improve. While the outdoor air-flow rate was too big according to **Figure 10**, reduce outdoor air-flow rate to 1300m^3 / h, will also benefit the increase of COP, but the effect is not so obvious. Of course, the demand of capacity must be met.

But at the same time, changing indoor and outdoor air-flow rate of rated conditions may generate new problems such as indoor noise, outdoor frost, if these two new issues are solved, the system performance will rise excellently.

The results of intermediate heating are similar to those of rated heating, but there are slightly differences shown in **Figure 11** and **Figure 13**:

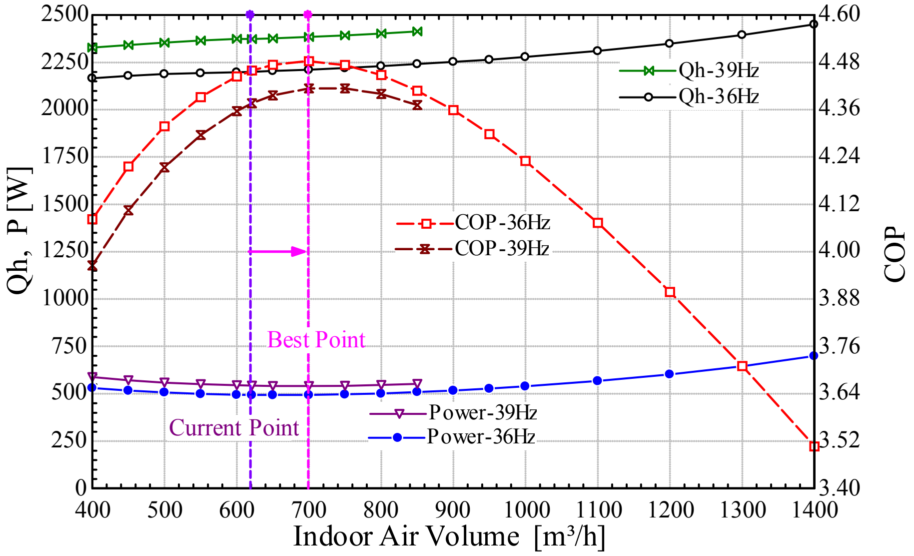

Figure 11 Performance vs. Qv_{indoor} (inter-heating)

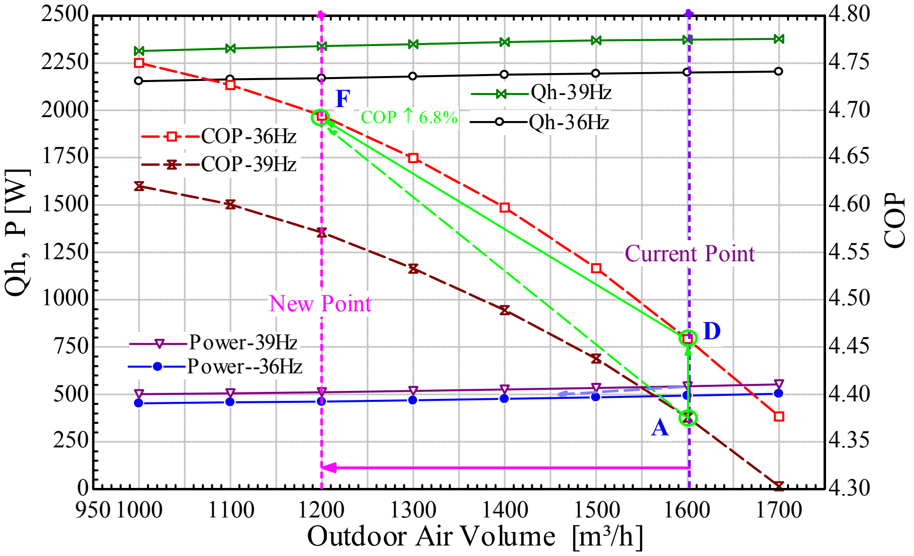

Figure 12 Performance vs. $Qv_{outdoor}$ (inter-heating)

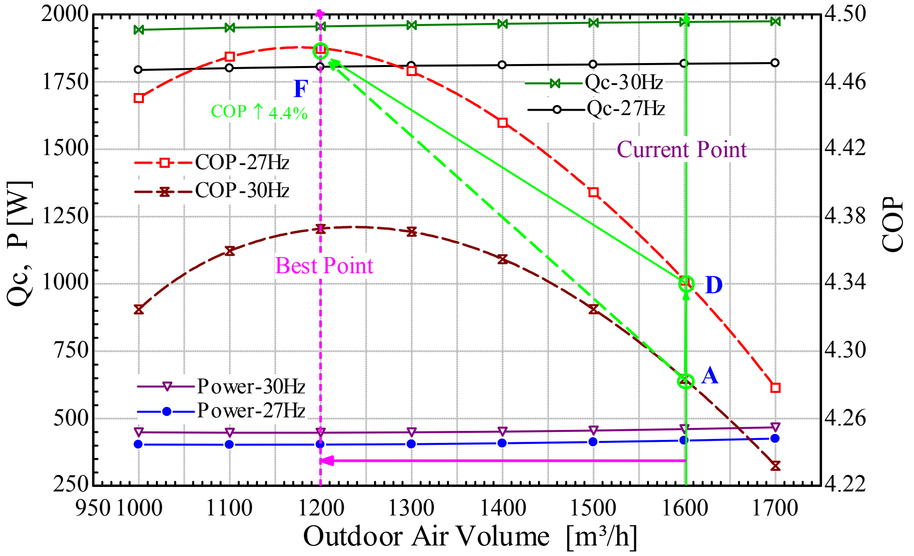

Figure 13 Performance vs. $Qv_{outdoor}$ (inter-cooling)

In intermediate heating conditions, the original indoor air-flow rate 620 m^3 / h is close to the optimal value (**Figure 10**) ,there is no need to optimize anymore. While for the air –flow rate (**Figure 12**) , if it is reduced from the original 1600 m^3 / h down to 1200 m^3 / h, COP will be significantly improved.
Intermediate cooling conditions (**Figure 13**) and the intermediate heating is too much similar, indoor air has reached the vicinity of the optimum value, but its outer air-flow rate is too big. Therefore when the outside air-flow rate is reduced from 1600 m^3 / h to 1200m^3 / h, the system COP will significantly increase .
The following part explains the method to reduce the outside air-flow rate from from1600 m^3 / h to 1200 m^3 / h.
By similarity theorem of fan, air-flow rate can be adjusted by adjusting the amount of wind speed of fan:

$$\frac{Q_b}{Q_a} \propto \frac{n_b}{n_a} \qquad (2)$$

$$\frac{P_b}{P_a} \propto \left(\frac{n_b}{n_a}\right)^3 \qquad (3)$$

Q: the actual rate flow of fan, units: m^3 / h
n: the speed of fan, unit: rpm
D: the diameter of fan impeller, unit: m

So, if the air-flow rate decreases from 1600 m^3 / h down to 1200 m^3 / h, the fan speed is supposed to decrease to 75% of the original value, then the outdoor fan power will drop by about 50%.

3.5 Results and Discussion

After the total process of this optimization, including the refrigerant charge amount, the electronic expansion valve (the compressor suction superheat), the running frequency of compressor, the indoor and outdoor air-flow rate, the overall performance of the compressor will be significantly improved. Final air-enthalpy tests were also carried on according to the optimal parameters. The results are promising, as shown in the following **Table** 7 and **Figure** 14 and **Figure** 15:

Table 7: Optimization Program Summary

Item	Optimal Points	Original Value	New Optimal Value	Predicted Optimal Results	Final Test Validation
Inter cooling	1.Frequency	30Hz	**27Hz**	Qc: 1968W→**1806W** COP: 3.06→**3.15** （↑**4.66%**）	**Qc: 1812W** **COP: 3.16**
	2.Outdoor fan speed	**Down to the 75% of the original value**			
Rated cooling	3. Frequency	70Hz	**72Hz**	Qc: 3442W→3553W **(demand)** COP: 2.97→2.93	**Qc: 3526W** **COP: 2.94**
Inter heating	4. Frequency	39Hz	**36Hz**	Qh: 2373W→2170W COP: 4.37→4.69 （↑**7.00%**）	**Qh: 2153W** **COP: 4.70**
	5. Outdoor fan speed	**Down to the 75% of the original value**			
Rated heating	6. Frequency	79Hz	**77Hz**	Qh: 4484W→4392W COP: 3.06→3.15 （↑**2.96%**）	**Qh: 4401W** **COP: 3.15**

Cooling and heating capacity of basic requirements:
Intermediate cooling capacity must be greater than 1750W;
Rated cooling capacity must be greater than 3500W;
Intermediate heating capacity must be greater than 2175W;
Rated heating capacity must be greater than 4350W;

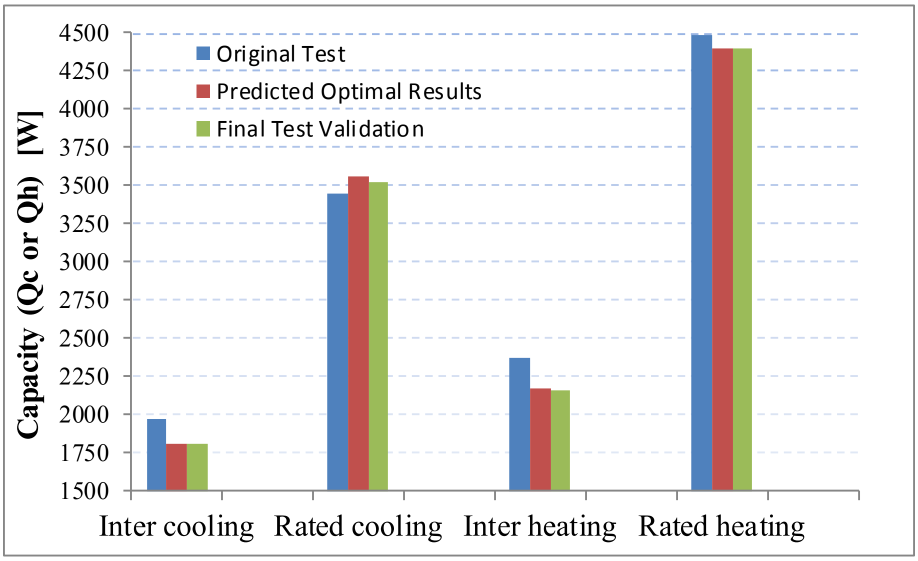

Figure 14: Optimization Program Summary（Cooling or Heating Capacity）

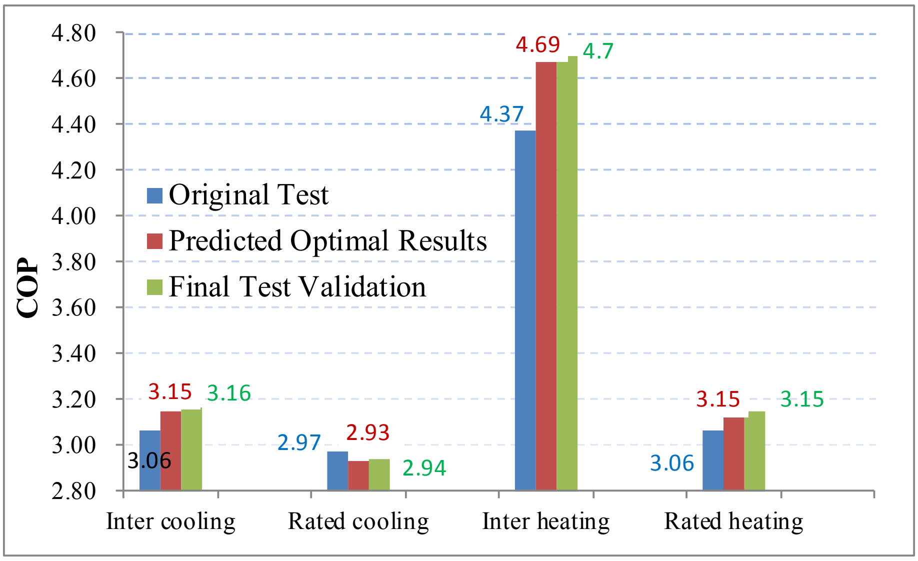

Figure 15: Optimization Program Summary（COP）

The final results of test validation in the Figure 15 indicate that, although this simulation optimal method may be not rigorous enough in the logic of mathematic, but it is practically constructive. The calculations are accurate enough to make the optimization effect remarkable. This method is preferred in practice, the calculation results will significantly reduce the time and cost of the matching experiments.

In fact, some other room air conditioner, their capacity range from 1HP to 1.5Hz, and 2HP, also have been optimized in this new “simulation & air-enthalpy test method”, the results are all decent enough for the performance matching of the inverter room air conditioners. In addition, the results are similar in general as summarized below.

1. Optimum refrigerant charge amount of the four test conditions are not the same, but the ultimate value can be preferentially determined by the intermediate conditions;
2. When the cooling and heating capacity demand is met, the lower the compressor frequency is, the higher the system COP will be, both in intermediate conditions and rated conditions;
3. In rated heating conditions, current indoor air-flow rate increase and current outdoor air-flow rate decrease is both constructive to the performance of the system. But when the air-flow rate changes, new problems like indoor noise and outdoor frost will need to be taken into consideration;

4. Under intermediate conditions, including intermediate cooling and intermediate heating, the original indoor air-flow rate is relatively reasonable, but the outdoor air-flow rate (1600 m^3 / h) is much larger than the optimal value (1200~1300 m^3 / h). With 75% of the rated fan speed, the optimum condition can be achieved.

4. CONCLUSIONS

With the simulation tools and the new work process, the experiments of the performance matching of inverter room conditioner become more efficient. After optimization and final test validation, the COP of intermediate cooling increases by about 4.66%, intermediate heating COP increases by about 7.00%, and as well as rated heating rises about 2.96%. In general, this method will greatly shorten the test time, reduce the workload, and cut the cost.

NOMENCLATURE

Inter-cooling	Intermediate Cooling Conditions	
Rated-cooling	Rated Cooling Conditions	
Inter-heating	Intermediate Heating Conditions	
Rated-heating	Rated Heating Conditions	
f	Frequency of compressor	(Hz)
Tw-air	Indoor Web Bulb Temperature	(℃)
Td-air	Indoor Dry Bulb Temperature	(℃)
Qv_{indoor}	Indoor Air-flow Rate	(m^3/h)
$Qv_{outdoor}$	outdoor Air-flow Rate	(m^3/h)
Qc	Cooling Capacity	(W)
Qh	Heating Capacity	(W)
Qsen	Sensible Capacity	(W)
Power	Input Power of System	(W)
T	Temperature	(℃
Ps	Suction Pressure	(MPa)
Pd	Discharge Pressure	(MPa)
θ	The Opening Ratio of Electronic Expansion Valve	
M	Refrigerant charge amount	(g)
EER/COP	Energy Efficiency Ratio/Coefficient of Performance	

Subscripts

eva_in	Input of indoor heat exchanger
eva_out	Output of indoor heat exchanger
eva_mid	Middle of indoor heat exchanger
cond_mid	Middle of outdoor heat exchanger
cond_in	Input of outdoor heat exchanger
cond_out	Output of outdoor heat exchanger
s	Suction
d	Discharge

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