Operating Characteristics of Mechanical Vapor Recompression Heat Pump Evaporator System

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Abstract: During the research on operating characteristics of mechanical vapor recompression heat pump evaporator system, taking water as the test medium, such system performance parameters as total moisture extraction rate and system pressure ratio are found to be changed with evaporating temperature. It can be known that the total moisture extraction rate increases with the evaporating temperature, and such increases are obvious; the system pressure ratio decreases as the evaporating temperature rises, but such decreases are not obvious; the volumetric efficiency, adiabatic internal efficiency, Coefficient of Performance and heat transfer coefficient increase with the evaporating temperature. Therefor, mechanical vapor recompression heat pump evaporator system could have a better development in future practical application.

Keywords: Mechanical Vapor Recompression (MVR); Heat Pump System Performance; Evaporator System

1. Introduction

Mechanicalvapor recompression (MVR) is an efficient green energy conservation technology. It's widely applied in solution-evaporation, traditional multi-effect evaporation system and industrial production such as chemical and light industry, food, pharmacy, sea water desalination and sewage treatment [1]. Compared with the traditional multi-effect evaporation system, MVR heat pump doesn't need protogenetic vapor given by steam generator, thus the environmental pollution caused by bunker coal can be reduced. In case that evaporation is needed, the MVR heat pump can be used conveniently only with sufficient electricity. At the same time, the heat of flash steam generated by solution is recycled, which shows its efficient green advantages. As the electricity price decreases, MVR heat pump will be used more widely [2]. Now in some foreign areas with shortage of fresh water, researchers applied the MVR heat pump in sea water desalination with great success. In Chinese salt manufacturing industry, MVR heat pump has its market. Several large salt manufacturing enterprises have introduced MVR heat pump technology from abroad. MVR heat pump system applied in sea water desalination and salt manufacturing is complicated with large scale production. System flow is also characteristic. There are few research on MVR heat pump's application in evaporation technology with small volume. In abroad, MVR heat pump's application in system integration and compressor research began earlier than that in China. Its application in sea water desalination has been widely promoted in abroad [3]. While Chinese research on MVR heat pump started late and focus on theoretical analysis and numerical simulation. Therefor, research on operating characteristics of MVR heat pump evaporator system can promote its better development in future practical application.

2. Performance Analysis of MVR Heat Pump Evaporator System

Main indexes of of MVR heat pump evaporator system include total energy consumption, total moisture extraction rate, specific moisture extraction rate (SMER), Coefficient of Performance (COP), adiabatic efficiency of fan and coefficient of capacity [4]. The perfect modification process of vapor thermodynamic state is as follows: the reversible adiabatic compression, namely isentropic compression, is done to flash steam generated by heating solution, then the flash steam is cooled from superheat state to saturated vapor, and keeps cooling after condensation process to become supercooled state. However, in real compression, because of the influences of various irreversible factors, the compression process is nonisentropic. According to the initial state of flash steam and parameters in end of compression, theoretically, the specific work consumed in isentropic compression is given by:

$$w = h_2^{'} - h_1 \quad (1)$$

In above formula, $h_2^{'}$ is the steam enthalpy in end of isentropic compression; h_1 is the steam enthalpy in initial state.

The specific work consumed in real compression is given by:

$$w_i = h_2 - h_1 \quad (2)$$

In above formula, h_2' is the steam enthalpy in end of real compression.

According to measured electric power Pe, motor efficiency ηe and mechanical efficiency ηm, the specific work actually consumed is also given by:

$$w_i' = \frac{\eta_e \eta_m Pe}{q_m} \quad (3)$$

Where, qmrepresents the working medium mass flow rate.

Adiabatic efficiency indicates the deviated degree of specific work consumed in real irreversible process from perfect reversible adiabatic process, the equation is as follows:

$$\eta_i = \frac{w}{w_i'} = \frac{(h_1 - h_2)\, q_m}{P_e \eta_e \eta_m} \quad (4)$$

Then the SMER of system is given by:

$$Q_{SMER} = \frac{3600\eta_i \eta_m \eta_e}{w} \quad (5)$$

The real COP of system is given by:

$$COP = \eta_i COP_{th} \quad (6)$$

The theoretical COP is given by:

$$COP_{th} = \frac{r}{w} \quad (7)$$

Where, r represents the specific latent heat of condensed steam in the side of evaporator.

Figure 1 is the schematic diagram of MVR heat pump evaporator. It will be explained from the perspectives of material flow process and energy flow process [5].

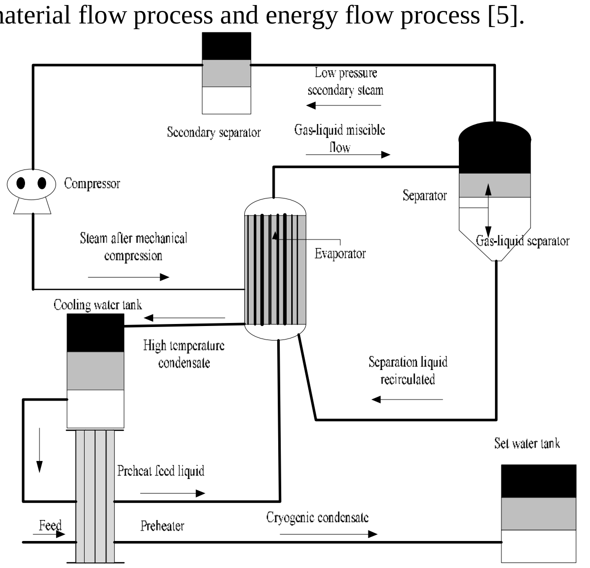

Figure 1. Schematic diagram of system flow

Material flow process: after preheating, the room-temperature materiel is heated to evaporating temperature, then entering into evaporator, absorbing the heat released by vapour condensation; the liquid-vapor mixture is formed by boiling heat transfer and evaporation in evaporator; then in vapor liquid separator, vapor rises and liquid material falls, thus the vapor liquid separation is realized; the declined liquid material returns to evaporator and the second evaporation begins when the risen vapor is exhausted from the top of separator [6]. Then in second separator, the liquid drop is removed; the vapor after second separation enters into the compressor and its power is promoted; the vapor under high temperature and high pressure enters into evaporator to release the heat by condensation, which provides the energy for boiling and evaporation of material; the condensed liquid with high temperature is excluded from the bottom of evaporator to condensed cistern, then exhausted from the cistern; the heat exchange with the room-temperature materiel is done in preheater; a circle is finished after the material is heated to the necessary temperature [7]. Energy flow process is explained with the Figure 2 Modification of vapor thermodynamic state

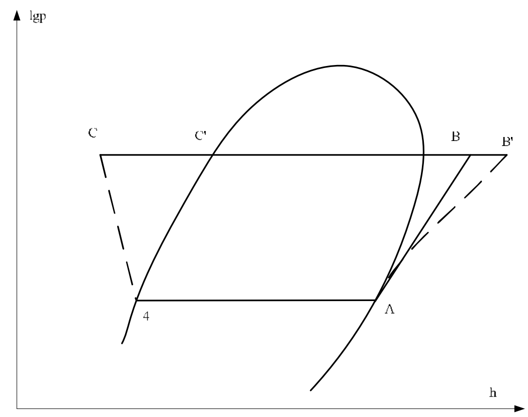

Figure 2. Modification of vapor thermodynamic state

At room temperature, after preheating, the low material's sensible heat is promoted, low material turning into high material; continuous absorption of heat in evaporator further promotes the sensible heat until saturation; then the latent heat keeps increasing and phase-transition starts, which means that hydrone turns into vapour phase from liquid phase; in separator, the declined liquid phase material enters into evaporator after recycle and absorbs heat, latent heat thus increasing and vaporizing constantly; above process is repeated[8]. After second separation, the vapor enters into the compressor to improve the power; such vapor with low enthalpy turns into vapor with high enthalpy through compression; exhausted from the compressor, the vapor with high enthalpy returns to the evaporator, is condensed to release latent heat and to heat material [9]; coagulated condensate water has still high enthalpy; the heat exchange with materiel with low enthalpy is done in the preheater to transfer the heat of condensate water with high enthalpy to material with low enthalpy. With this, the circle of energy is finished [10].

3. Operating Characteristics of MVRheat Pump Evaporator System under Different Conditions

The experimental platform established according to system flow is shown as Figure 3

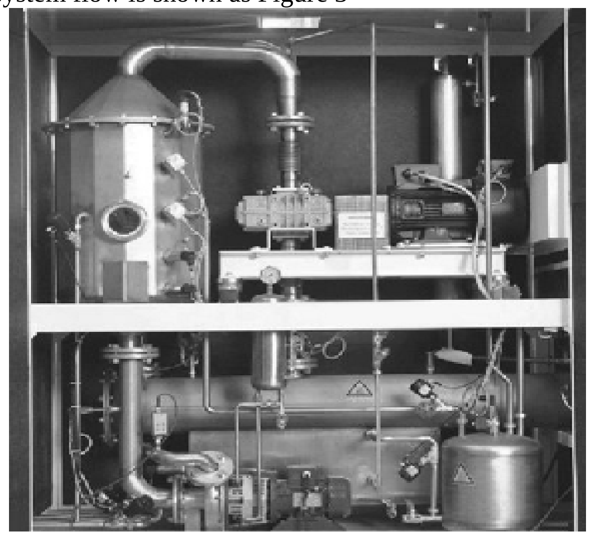

Figure 3. MVR heat pump falling film and evaporation experimental platform

In order to accelerate the system booting process, an electric heating apparatus is set up in addition [11]; when the system operates steadily, this electric heating apparatus is used to supply the heat which is lost outside to maintain the stability of evaporating pressure. The evaporating medium adopted by experiment is water; the measuring parameters during the process include vapor-absorbing pressure and temperature of fan, vapor-exhausting pressure and temperature [12]; shell side temperature and monitor temperature of evaporator; liquid level of separator, liquid level of condensate water; condensate water flow, liquid flow of material enter; power consumption and power of electricity heater of fan. The sensor technology parameters adopted by test are shown as Table. 1:

Table 1. Measuring parameters adopted by experiment

Sensor	Measuring parameters	Accuracy	Scope
PT100thermal resistance	Shell side temperature and monitor temperature of evaporator	0.1	-50~400℃
T-thermocouple	Vapor-absorbing and vapor-exhausting temperature of fan	0.1	-50~200℃
Pressure sensor	Vapor-absorbing and vapor-exhausting pressure of fan	0.5	0~500 kPa
Liquidometer	Liquid level of separator and cistern	1.5	0~300 mm
Liquidometer	Flow of condensate water and liquid flow of material	1.5	0~500 L/h
Power accommodometer	Power of electricity heater	1.0	0~3k W

In the experiment, the criteria to judge the steady operation of system is the evaporating temperature of system, which means that the liquid phase temperature of separator keeps steady in a particular value or has little changes. The evaporation could be steady only when the vapour phase pressure of separator is in accordance with the corresponding saturation pressure of liquid phase temperature [13]. The measuring method of total moisture extraction rate is as follows: maintaining the liquid level of separator, during the steady operation process, the quantity of material entered is equal to that of the evaporation. However, in real operation, it's hard to adjust the quantity of material entered to a particular value to keep the liquid level of separator being constant [14]. A feasible method is to keep the quantity of material entered in a reasonable value, then steady operation for a period is necessary to observe the liquid level modification of separator. The total moisture extraction rate of system can be obtained by subtracting the moisture rate generated by the liquid level modification of separator from the quantity of material entered.

3.1. Moisture extraction rate's change with evaporating temperature

Figure 4 shows the moisture extraction rate's change with evaporating temperature under two different frequencies:

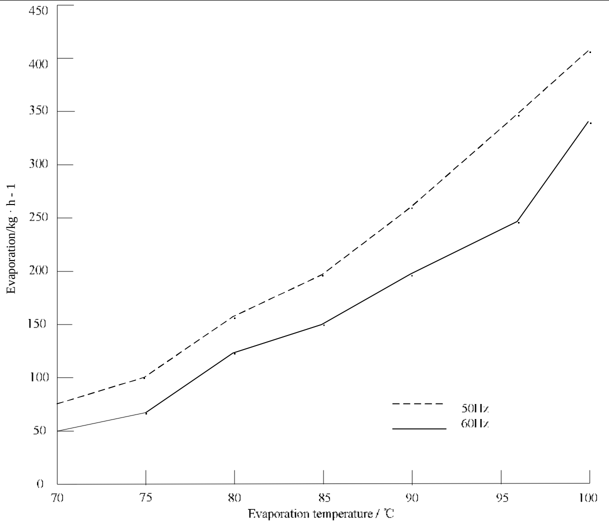

Figure 4. Moisture extraction rate's change with evaporating temperature

It can be seen by analyzing above figure that the higher the evaporating temperature, the greater the moisture extraction rate; the higher the motor frequency, the greater the moisture extraction rate. Because the volumetric efficiency of fan increases constantly as the evaporating temperature rises. When the evaporating pressure rises, both the electric auxiliary heating capacity and power consumption increase with it. As the evaporating pressure of system rises, in case that the leakage loss inside the fan augments and coefficient of capacity decreases, the volume flow rate of vapor will decrease, but the specific volume decreases as the evaporating pressure rises. Thus the mass flow rate of vapor may increase. If the increases of mass flow rate are greater than the decreases of theoretical specific work of compressed vapor, the power consumption will also increase. Change of evaporating pressure is realized through evaporating temperature. Rise of evaporating pressure requires the rise of evaporating temperature, and rise of evaporating temperature needs more electrical heating. Therefor, input of electrical heating increases as the evaporating pressure rises. In addition, as the evaporating temperature rose, the heat leakage loss of system increases, therefor it's necessary to increase the electrical heating to maintain the evaporating temperature. From the perspectives of electrical heating and electric power, after the evaporating pressure rose, the total energy consumed of system increases with it.

3.2. Compression ratio's change with evaporating temperature

Figure 5 shows the change law of compression ratio with evaporating temperature under two different frequencies:

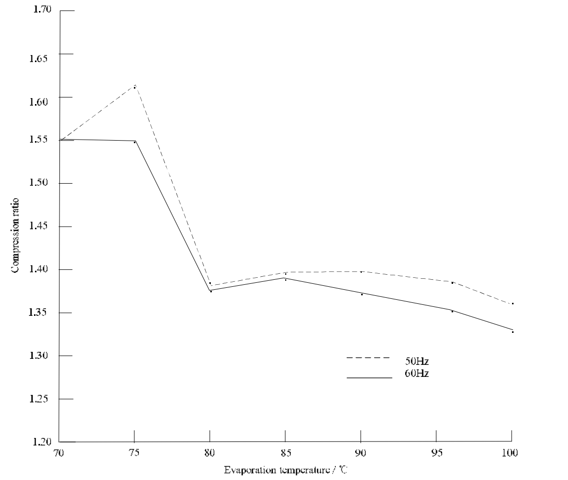

Figure 5. Compression ratio's change with evaporating temperature

The higher the evaporating temperature, the smaller the compression ratio; the higher the motor frequency, the greater the compression ratio. The measured moisture extraction rate is equal to the water volume after the condensate of flash steam. While the theoretical water volume is calculated based on the volume flow rate and vapor-absorbing specific volume of fan in different states. In real compression, absorbed vapor of fan is the wet steam with liquid drops, which increases the mass flow rate of vapor, and at the same time changes the system process as wet compression. The actual power consumption of system is thus increased. MVR heat pump evaporator system rises with the evaporating temperature. Under high temperature and high pressure working conditions, as the evaporating pressure and temperature rise gradually, both the vapor-absorbing and vapor-exhausting pressure of fan increase, the leakage loss inside the fan increases and coefficient of capacity decreases further. It follows that when the system deviates from the rated working conditions, the working performance greatly influences the overall operating efficiency. Within the temperature scope, low evaporating temperature benefits the efficient operation.

3.3. System COP's change with evaporating temperature

Figure 6 shows the change law of system COP with evaporating temperature under two different frequencies:

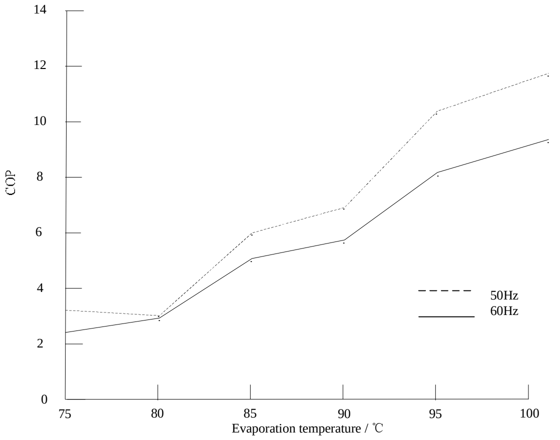

Figure 6. System COP's change with evaporating temperature

From above figure, it can be obtained that the higher the evaporating temperature, the greater the COP; the higher the frequency, the greater the COP; the highest is 11.58, the lowest 2.88. The phenomenon that the higher the evaporating temperature, the greater the COP appears because the increases of moisture extraction rate are much larger than the increases of total power consumption as the evaporating temperature rises. In the theoretical calculation, system COP presents the increasing trend as the evaporating pressure rises, while in real measure, COP presents the decreasing trend as the evaporating pressure rises, which is caused by adiabatic efficiency of fan. As the evaporating pressure and temperature rise, condensate pressure and temperature also increase, adiabatic efficiency of fan decreases gradually and its decreases are larger than the increases of theoretical COP.

3.4. System SMER's change with evaporating temperature

Figure 7 shows the change law of system SMER with evaporating temperature under two different frequencies. From Figure 7, it can be obtained that the higher the evaporating temperature, the greater the SMER; the higher the motor frequency, the greater the SMER; the highest is 18.24, the lowest 4.5. It's reasonable that SMER's change is in accordance with COP. Although the theoretical specific work of MVR heat pump evaporator system decreases as the evaporating pressure rises, the SMER and COP of MVR system of fan decrease as the evaporating pressure rises because the adiabatic efficiency has great degree of attenuation.

3.5. Adiabatic internal efficiency's change with evaporating temperature

Figure 8 shows the change law of adiabatic internal efficiency with evaporating temperature under two different frequencies.

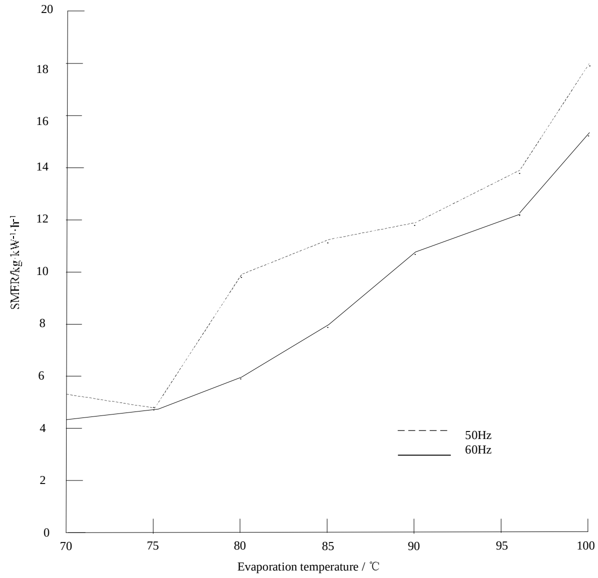

Figure 7. System SMER's change with evaporating temperature

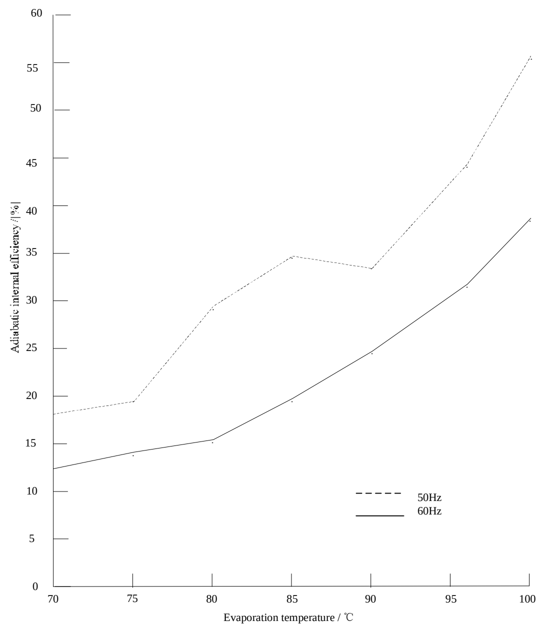

Figure 8. Adiabatic internal efficiency's change with evaporating temperature

The higher the evaporating temperature, the greater the adiabatic internal efficiency; the higher the motor frequency, the greater the adiabatic internal efficiency; the highest is 58.21%, the lowest 11.53%. The reason is that the power consumption of fan has little increases and the moisture extraction rate has much increases as the evaporation temperature rises. As the evaporating pressure rises, the temperature of vapor absorbed by fan rises further, the internal leakage loss of fan increase and the coefficient of capacity decreases. From the formula of adiabatic efficiency, it can be known that the adiabatic efficiency is related with the theoretical flow and measuring flow, which means that it's related with the coefficient of capacity of fan. With the influences of coefficient of capacity, evaporating pressure rises and adiabatic efficiency presents a decreasing trend.

3.6. Volumetric efficiency's change with evaporating temperature

Figure 9 shows the volumetric efficiency's change with evaporating temperature:

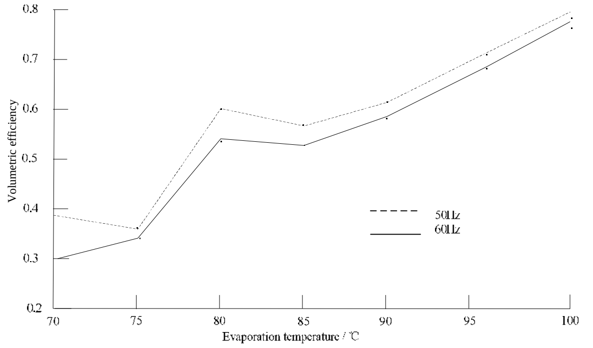

Figure 9. Volumetric efficiency's change with evaporating temperature

The higher the evaporating temperature, the greater the volumetric efficiency; the higher the frequency, the greater the volumetric efficiency. The adiabatic internal efficiency and volumetric efficiency of MVR heat pump evaporator system rise with the evaporating temperature. Under same working conditions, the higher the motor frequency, the greater the adiabatic internal efficiency and volumetric efficiency; the volumetric efficiency rises because the leakage quantity decreases. The adiabatic internal efficiency rises because the potentiation effect of rise of volumetric efficiency to adiabatic internal efficiency is stronger than the attenuation effect of increases of electricity consumption to adiabatic internal efficiency. The adiabatic internal efficiency presents an overall increasing trend and decreases as the evaporating pressure rises because the adiabatic efficiency of system decreases as the evaporating pressure rises. And the decreases of adiabatic efficiency is caused by the decrease of coefficient of capacity of fan.

3.7. Heat transfer coefficient's change with evaporating temperature

Figure 10 shows the change law of heat transfer coefficient with evaporating temperature under two different frequencies:

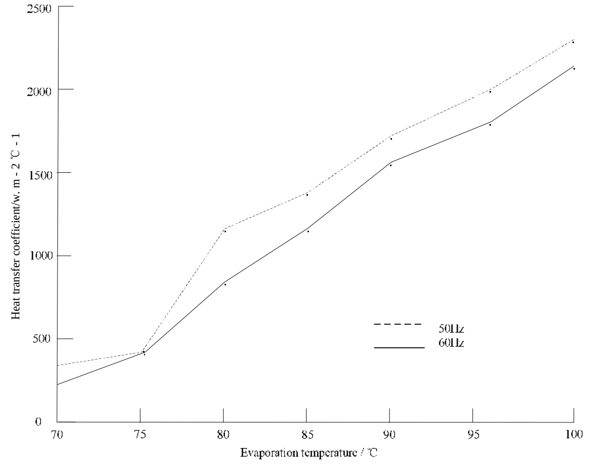

Figure 10. Heat transfer coefficient's change with evaporating temperature

The higher the evaporating temperature, the greater the heat transfer coefficient; the higher the frequency, the greater the heat transfer coefficient. As the evaporating temperature rises, the heat transfer coefficient has great change because the heat transfer is influenced by greater viscosity under low pressure and slight non-condensable gas. The total moisture extraction rate of MVR heat pump evaporator system increases with the evaporating temperature, and the increases are obvious. Under the same working conditions, the higher the motor frequency, the greater the moisture extraction rate; the system pressure ratio decreases as the evaporating temperature rises. The actual moisture extraction rate and power consumption increases with the evaporating pressure, but the actual increases of moisture extraction rate are smaller than the theoretical increases.

4. Conclusion

Through the measure and analysis of practical operating process of researched sample machine, following characteristics can be found: experiment shows that MVR heat pump evaporator system is appropriate for the situation where the moisture extraction rate and temperature rise at boiling point are small; it's quite important for increases of coefficient of capacity of centrifugal fan to improve the MVR system performance of fan; under the same working conditions, the higher the motor frequency, the greater the COP and SMER; the reason is that the adiabatic internal efficiency of fan and volumetric efficiency increase with evaporating pressure; the higher the adiabatic internal efficiency, the smaller the system power consumption, the higher the volumetric efficiency, the greater the moisture extraction rate of system; therefor, while researching on the MVR heat pump evaporator system, the theoretical calculation and experimental analysis should be combined to make the design calculation more reliable.

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