Jacketed MVR heat pump evaporating system development and performance research

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Abstract: MVR heat pump evaporating system has many advantages such as no condensator required, no much requirement for feed liquid, simple operation, low energy consumption, no condensate water required and low cost, it's the most efficient and environmental energy saving technology in current evaporation process. To be closer to the actual effect of evaporating system, the jacketed MVR heat pump evaporating system should be applied in industrial production, there for, the jacketed MVR heat pump evaporating system development and performance research are conducted, and also the industrial application is performed to make tremendous contributions to energy conservation and emission reduction of our country.

Keywords: Jacketed; Mechanical vapor recompression; Heat pump; Evaporation; Concentration

1. Introduction

Evaporation and concentration is the basic unit operation in chemical, pharmaceutical, food, desalination, and sewage treatment processes. The multi-effect evaporation is used in traditional evaporation concentration, but due to its large volume, complex system and operation, and high energy consumption, in some cases, it is gradually being replaced by new mechanical vapor recompression (MVR) heat pump evaporation. MVR heat pump evaporating system has the advantages of no condenser required, no much feed liquid requirement, simple operation, low energy consumption, no need of condensing water and low cost [1].

At present, domestic and foreign scholars mainly study the falling film evaporation system, with falling film evaporation system, centrifugal compressors and Roots compressors are mainly used as drive sources. At the same time, the MVR system performance and its optimization direction are studied, but single screw compressor and jacketed MVR heat pump evaporation system have been reported [2]. For some heat-sensitive raw material fluids that are highly corrosive, fouling and a decrease in the heat transfer coefficient may occur during the concentration process, which may cause the concentration of the raw material liquid to be difficult to continue [3]. So jacketed MVR heat pump evaporating system development and performance research are necessary.

2.Jacketed MVR Heat Pump Evaporating System Development

2.1. Jacketed MVR heat pump evaporating system design

The theoretical basis of the MVR system is Boyle's Law, which means the derivative PV/T=K. The concrete meaning of the MVR system is that when the volume of the gas decreases and the pressure increases, the temperature of the gas also increases[4]. The basic principle of MVR is that the temperature of the lean secondary vapor that originally needs to be condensed by the cooling water from the evaporator will increase with the volume compression, thereby realizing the conversion of low temperature, low pressure saturated vapor into high temperature and high pressure saturated vapor. In addition, as heat source, it can be used to reheat the raw material liquid to be evaporated and the purpose of recycling the steam can be further achieved. Single screw compressors use the variable frequency adjustable speed three-phase asynchronous motor to provide power for the MVR system. From the rotate speed formula of three-phase asynchronous motor n=60f (1 一 a)/p, it can be seen that under the condition that the number of pole-pairs P and the slip ratio s of the motor are constant, theoretically, the rotate speed n changes linearly with the power supply frequency f; however, the actual speed is related to load conditions, slip rate, voltage stability and other factors, and no linear change being presented [5]. The singles crew compressor realizes different speeds and torques under the drive of the frequency converter and can adapt to the needs of different working loads. Temperature difference (heat transfer temperature difference between evaporating kettle jacket and inside the kettle), compression ratio, evaporation amount, heat transfer coefficient, COP (heating performance coefficient), SMER (quantitative energy consumption evaporation amount), adiabatic efficiency, volumetric efficiency, etc. each index helps to evaluate the practical performance of the jacketed MVR heat pump concentrating and evaporating system [6]. The simple process and principle of jacketed MVR heat pump concentrating and evaporating system is shown in Figure 1:

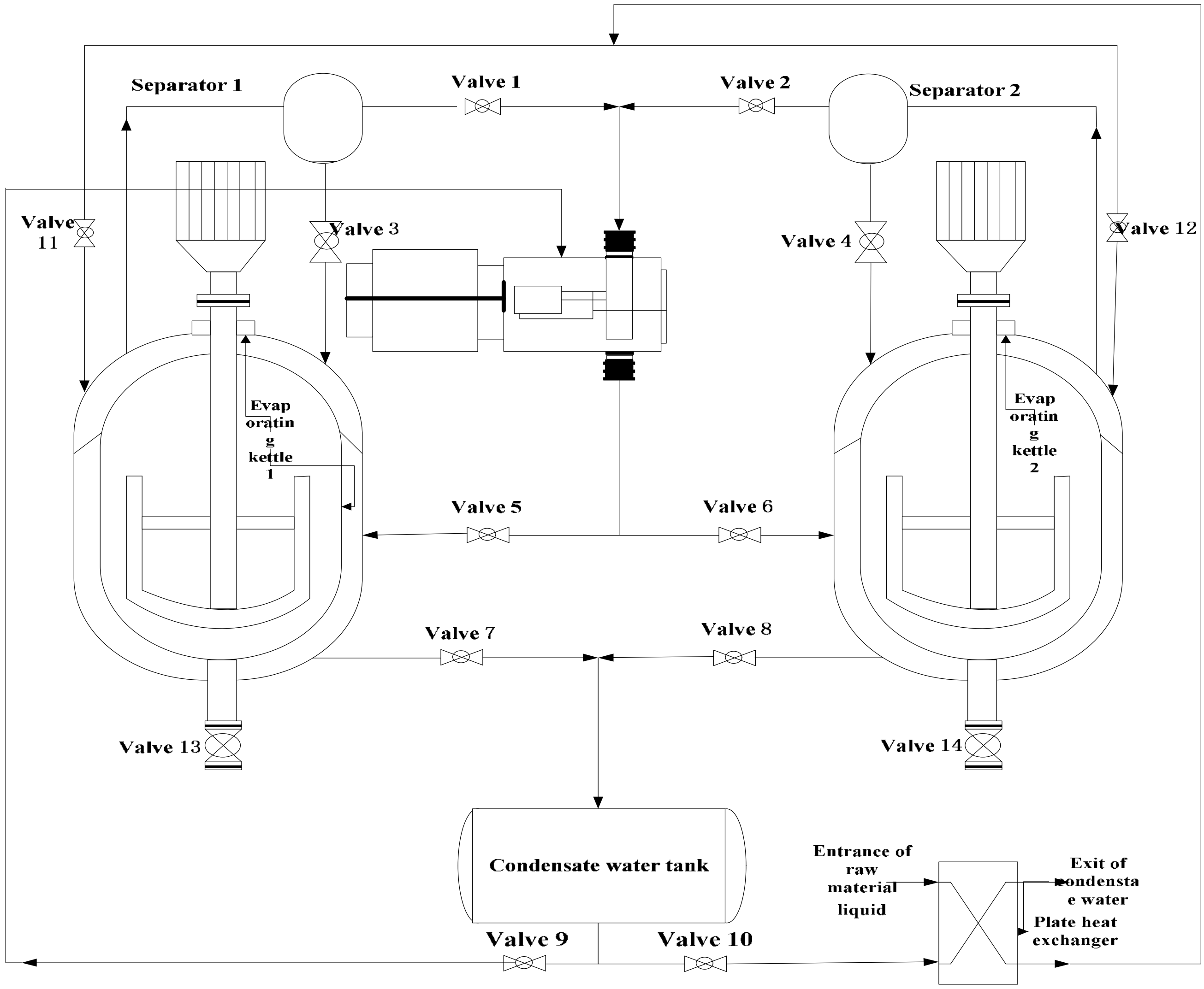

Figure 1. Jacketed MVR heat pump concentrating and evaporating system

The system is mainly composed of the evaporating kettle, separator, single screw compressor, condensate water tank, plate heat exchanger, stirring device, and some accessories. Its working medium can be various corrosive and non-corrosive liquids, it's mainly used in chemical industry (evaporation of aqueous solution), salt industry (salt solution evaporation), environmental protection industry (concentration of wastewater), etc.[7]. System workflow is as follows: the raw material liquid is preheated to the evaporation temperature through the plate heat exchanger and enters the evaporation kettle. The liquid in the kettle is boiled and evaporated at the evaporation temperature. The gas-liquid mixture evaporated is subjected to gas-liquid separation in the separator. The separated liquid re-entering the evaporating kettle, the gas enters the compressor for compressed water to reduce the superheat of the superheated steam while spraying it into the compressor, making it become saturated vapor at high temperature and then the saturated vapor enters into the evaporating kettle jacket. The liquid inside is heated to boil and evaporate. After the saturated vapor condensed, it turns into a liquid and flows into the condensate tank. A part of the liquid is used to spray the compressor, and the other liquid is used to preheat the raw material liquid; after cooling, the condensed water flows from the plate heat exchanger to the storage tank for reuse; and the concentrate liquid in the evaporation kettle is finally discharged through the bottom of the kettle to complete a system circulation. When running a single evaporating kettle, one group of the valves 1, 5, 7, 11 or the valves 2, 6, 8, 12 needs to be closed [8].

To better analyze the system performance, a mathematical physical model of jacketed MVR heat pump evaporation system was established. The following assumptions are made for the jacketed MVR heat pump evaporation system: the operating process of system is taken as a steady-state process, the dynamic changes caused by the parameters measured of instrument are not taken into account, the steady-state value is all replaced by the average measured values of instrument; the leakage of a small amount of material of the system is ignored and the heat radiation loss of the system is not counted; during the operation of the system, there is no non-condensable gas inside the system; the feed in the entrance of evaporating kettle is the saturated liquid feed at the evaporation temperature; the evaporating jacket and the internal heat exchange are uniform; the saturated steam at the outlet of the evaporating kettle is completely separated by the separator; the gases in compressor inlet and outlet are saturated steam at saturated temperature; ignoring the relevant impact of the system's actual water spray conditions on the compressor; the gas entering the jacket side of the evaporating kettle after compression is saturated steam; the saturated steam is completely condensed and become saturated liquid water after heat exchange [9].

The jacketed MVR heat pump concentrating and evaporating system used in the experiment is shown in Figure 2:

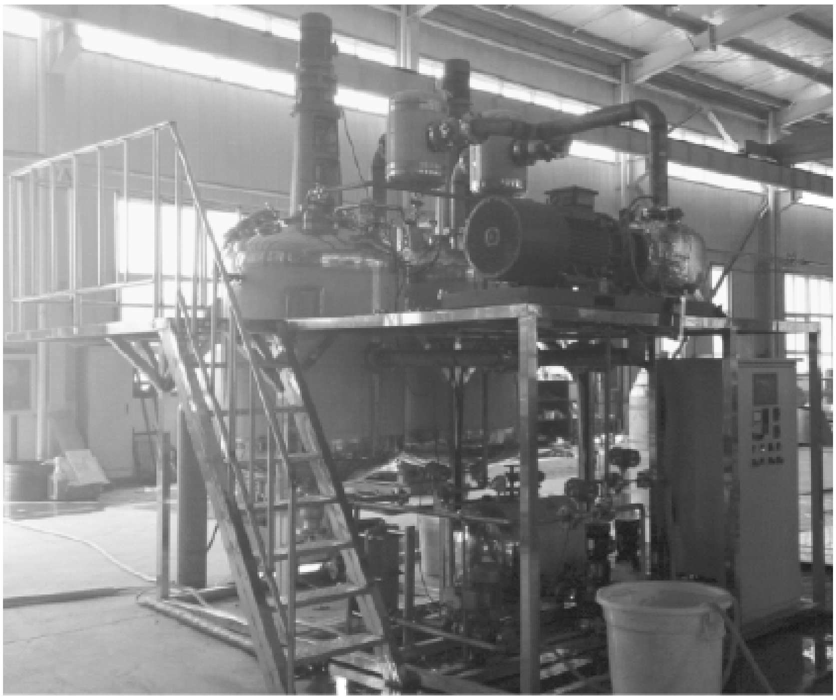

Figure 2. Jacketed MVR heat pump concentrating and evaporating system

The stirring device of the system can accelerate the heat transfer of the raw material liquid and prevent the fouling of heat-sensitive materials [10]. Because the system has good pressure resistance and tightness, no vacuum equipment is required when the evaporation pressure is greater than 50 kPa. The system has the advantages of high evaporation efficiency, simple operation, high corrosion resistance, convenient descaling, and low overall operating cost, and can be operated under normal or negative pressure conditions. Under negative pressure conditions, not only the evaporation temperature of raw material liquid is reduced, but also the material requirements for system-related equipment and piping are reduced while ensuring continuous and stable system production [11].

The entire actual system experiment is based on the pressure (absolute pressure) measured by the pressure sensor, and the experimental process is based on the feed volume (volume flow), while taking the condensate water flow (volume flow) as reference, the liquid level of the evaporating kettle and the condensate water tank are kept basically unchanged. During the experiment, it is necessary to keep the system's stable operation for 2h to eliminate unnecessary experimental interference errors[12]. The main error in the experiment process comes from the parameter error measured by each instrument; the required experimental data collected in real time, and the average value is used instead of the stable value in the data processing. The steady state of liquid level of evaporating kettle and the condensate water tank directly determine the feed volume flow and the condensate water volume flow, which determines the evaporation amount together; the evaporating kettle liquid phase temperature and the evaporating kettle jacket temperature directly affect the calculation of temperature difference; evaporating kettle pressure and evaporating kettle jacket pressure directly affect the calculation of compression ratio[13]; total system power consumption directly affects the calculation of adiabatic efficiency, COP and SMER; evaporation volume directly affects the calculation of compressor volumetric efficiency; the evaporation volume and temperature difference affect the calculation of the heat transfer coefficient. In addition, there are errors caused by electric heaters to compensate for heat in the system.

2.2. Thermodynamics exchange process of jacketed MVR heat pump evaporating

The compressor used in the experimental system is 10m3 single screw compressor. To ensure long-term normal operation of the single screw compressor, it is necessary to spray water to reduce the superheat of superheated steam and make it saturated steam under high temperature conditions. Its temperature after compression is lower than 130°C [14]. The thermodynamic model of the single screw compressor used for the water vapor compression is shown in Figure 3:

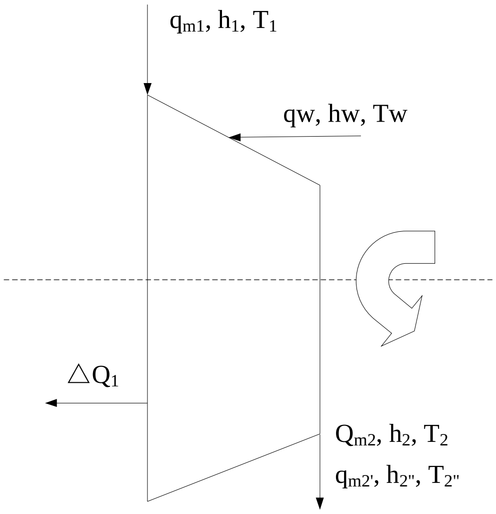

Figure 3. Thermodynamic model of the single screw compressor

Among them, q_{ml} represents the compressor suction mass flow; q_w the compressor spray mass flow; q_{m^2} compressor exhaust mass flow; h_1 the specific enthalphy of compressor suction saturated steam; h_w the specific enthalphy of compressor spray saturated liquid; h_2 the specific enthalphy of compressor exhaust saturated steam; W_D the power consumed by the compressor to compress water vapor; ΔQ_1 the heat loss from the compressor.

The heat exchange area of a single jacketed evaporating kettle was 4.5 m2. The efficiency and mechanical efficiency of the compressor motor were both 0.9. During the experiment, the electric heater was used for preheating and air replenishment. The difference between jacket temperature and evaporation temperature was used as actual system temperature difference, the ratio of jacket pressure and evaporation pressure is taken as the actual system compression ratio; isentropic compression theoretical power of compressor is obtained by isentropic compression simulation by Aspen Plus software, and the adiabatic efficiency of the compressor is calculated [15].

To analyze the system performance, the following assumptions are made for the system: the system is taken as a steady-state process, the dynamic changes in the measured parameters are not taken into account, the mean value is used instead of the steady-state value; the material leakage from the system is ignored, no heat loss is accounted for; no non-condensate gas exists in system; saturated liquid feed is in the inlet of the evaporation kettle; the evaporating kettle heat exchange is uniform; gas and liquid are completely separated in the outlet; the gases in compressor inlet and outlet are all saturated steam. This paper mainly analyzes the single evaporating kettle operation with different evaporation pressure (ie evaporation temperature) and different frequency, and the simultaneous operation of two evaporating kettles with different evaporation pressure (ie evaporation temperature).

In view of the actual conditions of industrial applications, the jacketed MVR heat pump evaporating system selects the jacketed evaporating kettle as the evaporator of the entire system. Since this evaporator has a large vaporization space, there is no need to separately add equipment for vaporization. The thermodynamic model of the jacketed evaporating kettle is shown in Figure 4.

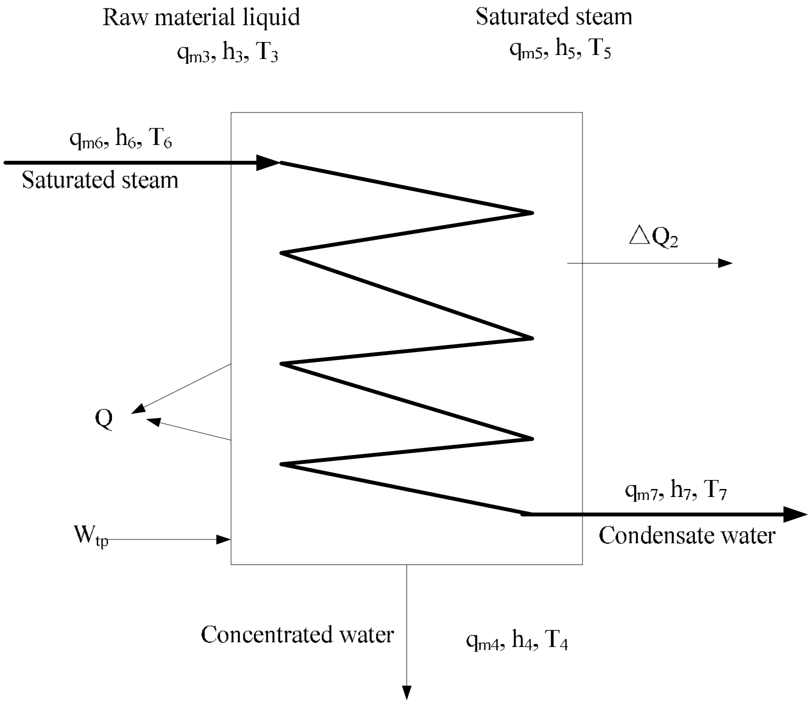

Figure 4. Thermodynamic model of the jacketed evaporating kettle

Where h_3 represents the saturation enthalpy of raw material liquid that entered into kettle; q_{m4} the saturation enthalpy of concentrated solution exhausted after the concentration in kettle; q_{m5} the enthalpy of saturated steam evaporated from the kettle; h_6 the enthalpy of saturated steam that entered into the evaporating kettle jacket after compression; h_7 the saturation enthalpy of condensed water formed after condensation of saturated steam in the jacket; VQ_2 the heat loss of the evaporating kettle; W_{tp} the power consumption of the evaporating kettle stirring device.

The thermodynamic model of the plate preheater is shown in Figure 5.

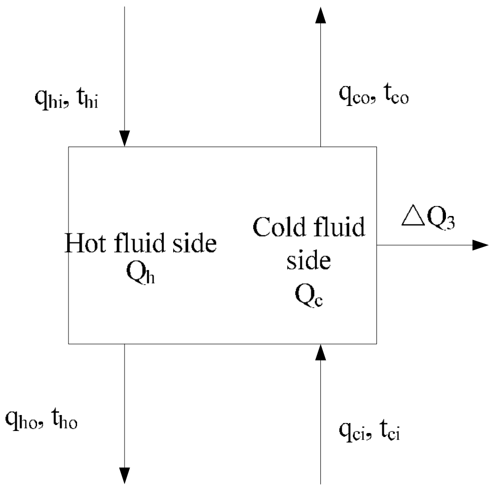

Figure 5. Thermodynamic model of the plate preheater

qhi represents the mass flow of the condensate water inlet on the hot fluid side; qho the mass flow of the condensate water outlet on the hot fluid side; qci the mass flow of the raw material liquid inlet on the cold fluid side; qco the mass flow of the raw material liquid outlet on the cold fluid side; Cph the average specific heat at constant pressure on the hot fluid side; Cpc the average specific heat at constant pressure on the cold fluid side; thi the temperature of condensate water inlet on the hot fluid side; tho the temperature of condensate water outlet on the hot fluid side; t_{ci} the temperature of raw material liquid inlet on the cold fluid side; tco the temperature of raw material liquid outlet on the cold fluid side; $\mathbf{V}Q3$ the heat for plate preheater.

The thermodynamic model of system is shown in Figure 6.

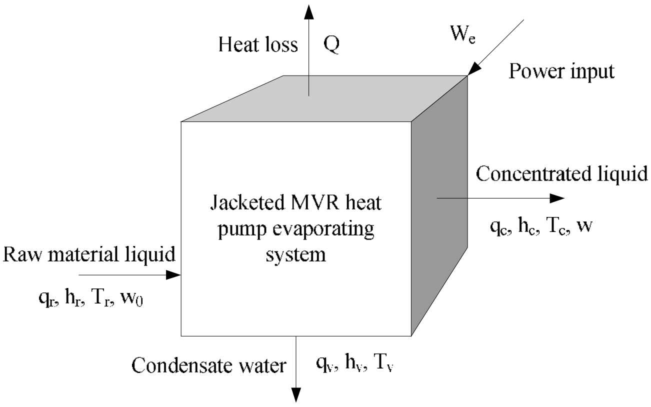

Figure 6. Thermodynamic model of system

q_r represents the raw material liquid mass flow; q_c the concentrated liquid mass flow; q_v the condensate water mass flow; q_r the saturation enthalpy of system raw material liquid; q_c the saturation enthalpy of system concentrated liquid; h_v the saturation enthalpy of system condensate water; w_e the system input power; Q the system heat loss; W_O the raw material liquid solute mass fraction; W the concentrated solute mass fraction.

3. Experiment of Jacketed MVR Heat Pump Evaporating Performance

To meet the needs of different workloads, the system was subjected to variable-frequency evaporating kettle operation experiments to further understand its working performance. When the evaporating pressures were 70, 80, and 90 kPa, the evaporation experiments at the compressor frequencies of 30, 35, 40, 45, and 50 Hz were performed on single evaporating kettle.

3.1. Performance experiment of change frequency of temperature difference

The changes of temperature difference and compression ratio with frequency are shown in Figure 7 and 8:

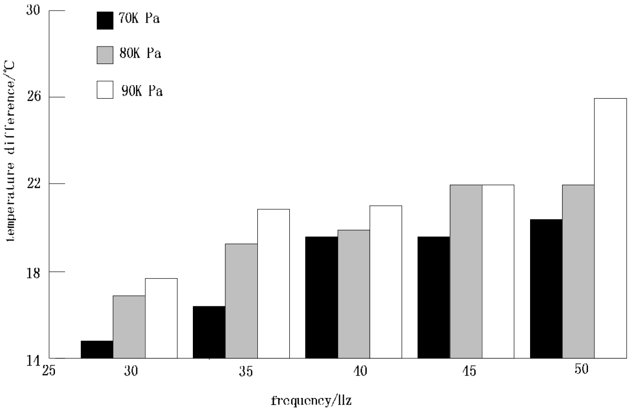

Figure7.Changes of temperature difference with frequency

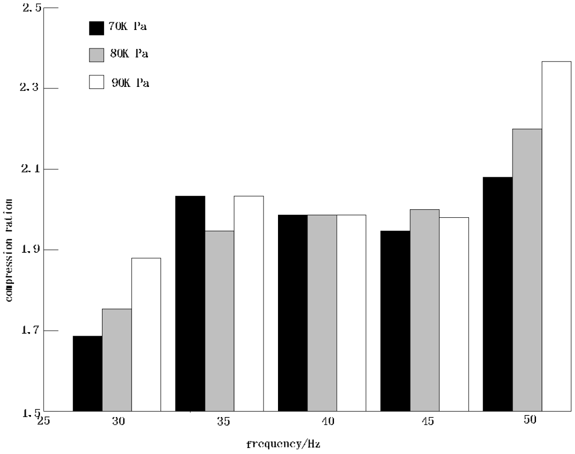

Figure 8. Changes of compression ratio with frequency

With fixed evaporation pressure, as the frequency increases, the rotational speed increases, the energy gained by the gas per unit time increases (gas kinetic energy and pressure energy increase), the compressed gas pressure increases, the compression ratio will increase, corresponding temperature increases, the temperature difference increases.

3.2. Performance experiment of change frequency of evaporation volume

The changes of evaporation volume with frequency are shown in Figure 9:

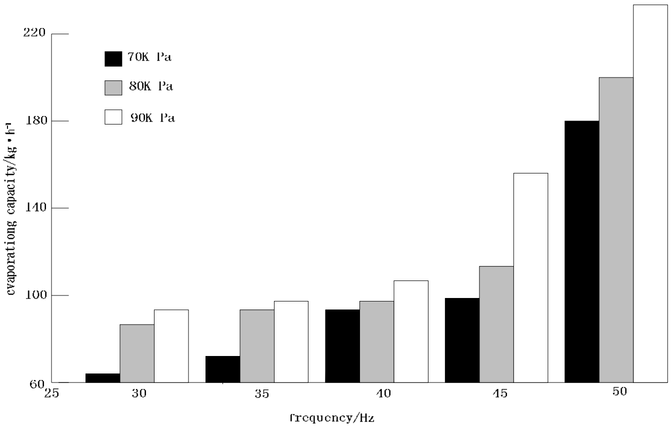

Figure 9. Changes of evaporation volume with frequency

With fixed evaporation pressure, the higher the frequency, the greater the rotational speed, the greater the amount of suction per unit time, the greater the gas displacement, the more heat is used for the system heat transfer; meanwhile, the heat transfer rate (the heat pass by the heat transfer surface within unit time) increases, the evaporation volume increases. However, below 40 Hz, the evaporation volume increases linearly with the frequency. Between 40 and 45 Hz, the curve begins to abruptly change. As the actual rotational speed is affected by various factors such as the workload, it begins to increase nonlinearly, which eventually leads to a non-linear increase in the evaporation volume with the frequency.

3.3. Performance experiment of change frequency of heat transfer coefficient

The changes of heat transfer coefficient with frequency are shown in Figure 10.

With fixed evaporation pressure, the heat transfer coefficient has nothing to do with the temperature difference, the compression ratio, the evaporation volume, but only related to the thermal physical properties of the heat transfer fluid and the heat transfer process. As the frequency increases, the rotational speed increases, the kinetic energy gained by the gas per unit time increases, the gas flow rate increases, the heat transfer process intensifies, and the heat transfer coefficient increases. From Figure 10, it can be seen that when the frequency is 30-40Hz, the heat transfer coefficient is basically unchanged, and when frequency is higher than 40Hz, the rotational speed starts to increase nonlinearly, the flow velocity of the fluid increases sharply, and the heat transfer process is intensified, resulting in a nonlinear increase in the heat transfer coefficient.

3.4. Performance experiment of change frequency of COP, SMER

The changes of COP, SMER with frequency are shown in Figure 11 and 12.

With fixed evaporation pressure, when the frequency is 30-40Hz, the COP and SMER increase with the compressor frequency, the rotational speed increases, the evaporation volume increases, but the increase in the operating power of the system is greater than the evaporation volume, and the heat release of system increases, accordingly, there will be a decrease in COP and SMER. And when frequency is higher than 40Hz, the evaporation volume increases nonlinearly with frequency, and the increases are much greater than the increases of the operating power of system. Therefore, COP and SMER increase nonlinearity.

3.5. Performance experiment of change frequency of adiabatic efficiency

The changes of adiabatic efficiency with frequency are shown in Figure 13.

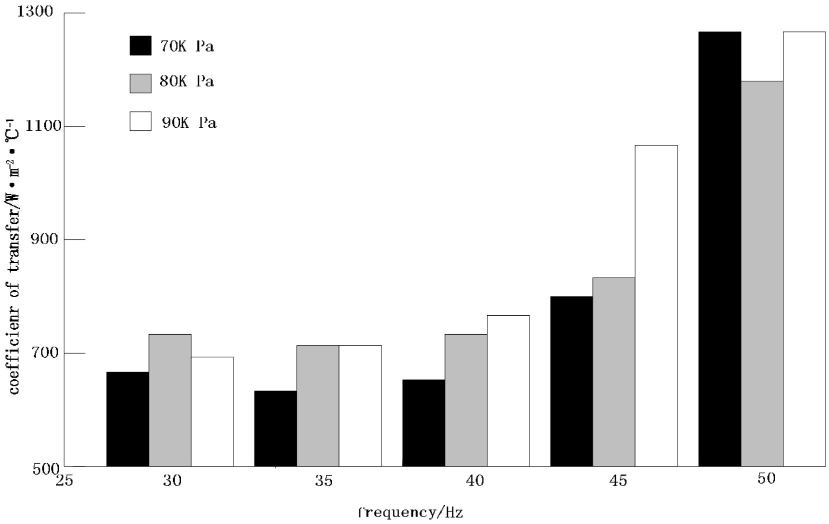

Figure 10. Changes of heat transfer coefficient with frequency

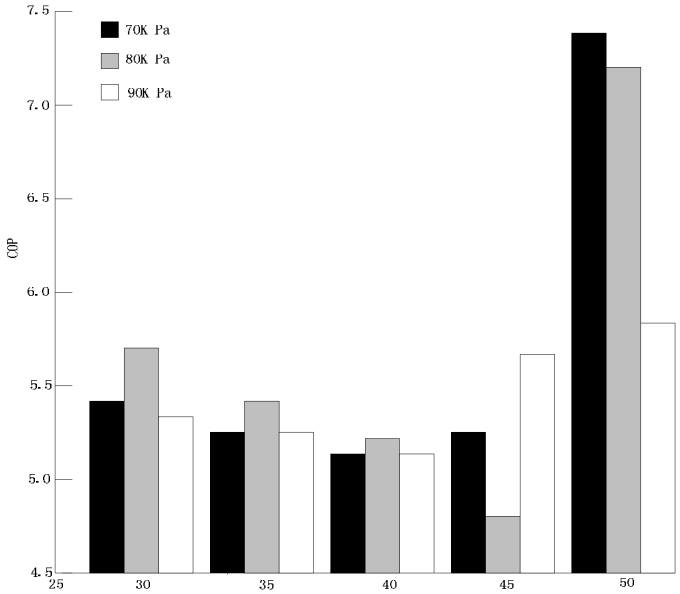

Figure 11. Changes of COP with frequency

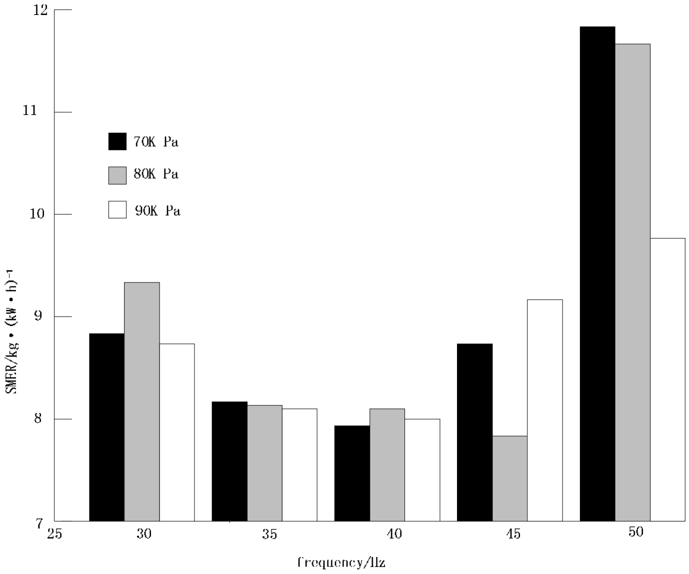

Figure 12. Changes of SMER with frequency

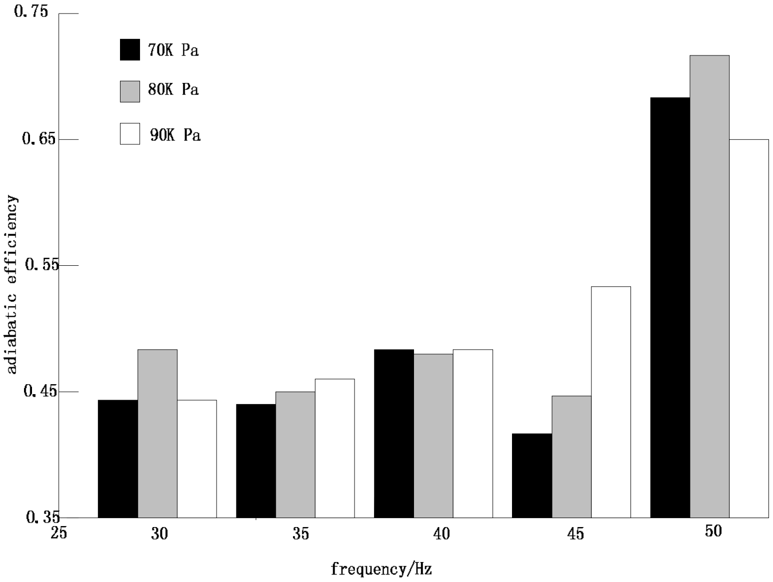

Figure 13. Changes of adiabatic efficiency with frequency

With fixed evaporation pressure, when the frequency is 30-40Hz,the mechanical efficiency of the compressor is low, and the gas flow rate is small. The suction and exhaust resistance is large, causing excess power loss, resulting in large degree of deviation from isentropic compression, so the phenomenon that the adiabatic efficiency is basically unchanged will occur. However, when frequency is higher than 40Hz, as the frequency increases, the rotational speed increases, the mechanical efficiency of the compressor increases, the kinetic energy obtained by the gas per unit time increases, the gas flow rate increases, the suction and exhaust resistances decrease, and the power loss decreases. The reduction in actual power consumption leads to a reduction in the degree of deviation from isentropic compression and thus the sudden increase in adiabatic efficiency.

3.6. Performance experiment of change frequency of volumetric efficiency

The changes of volumetric efficiency with frequency are shown in Figure 14:

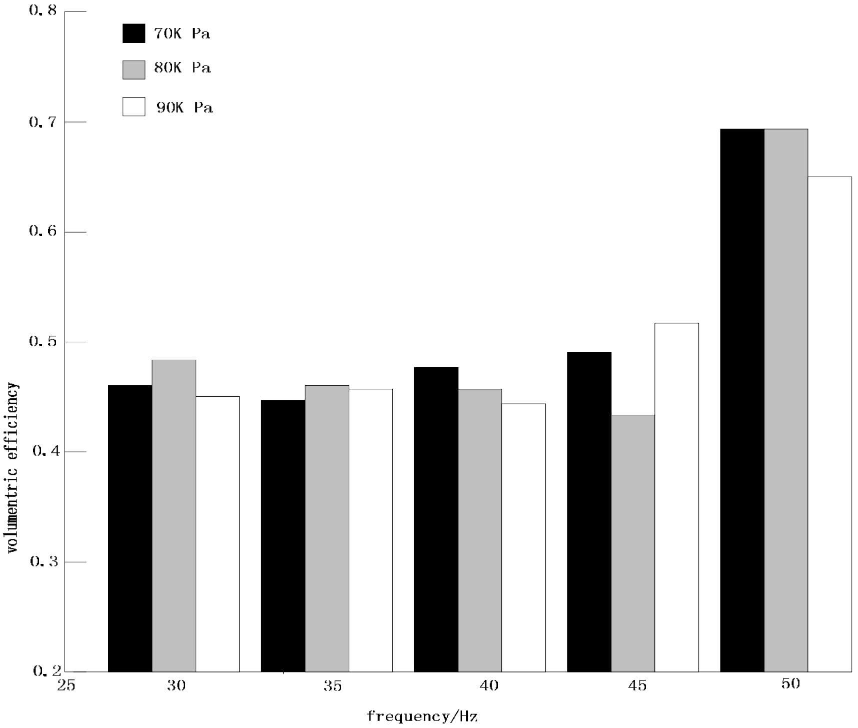

Figure 14. Changes of volumetric efficiency with frequency

With fixed evaporation pressure, when the frequency is lower than 40 Hz, the compressor frequency has little effect on the volumetric efficiency; due to the small gas flow rate at this time, the suction resistance is large and the gas flow loss is large, resulting in decreases in suction pressure. And the volume increases, which reduces the compressor suction, resulting in greater loss of suction pressure, meanwhile, as the external leakage of gas with increased pressure in basic capacity or in basic capacity which is inhaling is relatively large, so the volumetric efficiency will remain basically unchanged. However, when the frequency is higher than 40Hz, due to the nonlinear increase in the rotational speed, the energy gained by the gas per unit time increases rapidly (gas kinetic energy and pressure energy increase). At this time, the gas flow rate is larger, and the increases of the suction flow are far greater than the increase of leakage. There for, the volumetric efficiency will start to increase dramatically.

4. Acknowledgment

As the country gives more importance to environmental protection and energy saving, during the promotion of wide application of MVR heat pump technology, some new problems and opportunities are presented. Once these problems solved, the technology can be better applied not only in evaporating operation, but also in heat pump distillation. But as large difference of temperature is required by heat pump distillation, at present, only single screw compressor can be used to realize the related application of heat pump distillation. There are always large amount of non-condensable gas in MVR heat pump application system, accordingly, the MVR heat pump system with large amount of non-condensable gas is possible to be researched and developed successfully. With successful research and development, the application of MVR heat pump technology in various industries will be promoted, which will make great contributions to energy conservation and emission reduction of our country.

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