RESEARCH ON EXPANDER OF CO2 TRANSCRITICAL WATER-TO-WATER HEAT PUMP

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Abstract: To improve the efficiency of CO2 transcritical heat pump system, the fundamental measure is using expander to replace throttle. In the present paper, the internal expansion phase change mechanism of expander has been carried out and the simulation test of the phase transition in expander and the experimental study of CO2 transcritical water to water heat pump system with expander have been conducted. The results revealed that a more reasonable explanation to CO2 expansion phase transition could be obtained with non-equilibrium thermodynamic fluctuation theory. During the process of rapid decompression, the pressure and temperature of the working medium declined into the concave curve. At the same time, the mixture of CO2 and lubricating oil were boiling tempestuously, which caused the obvious bubble growth process. In addition, after analyzing the experimental data, we found that the system flow rate was increased with the increasing of the rotating speed and the inlet conditions of expander, and so was the change of expander recover work.

Key Words: heat pump, CO2 expander, phase transition, rapid decompression, experimental study

1 INTRODUCTION

In CO2 transcritical cycle, supercritical CO2 release heat in gas cooler, and the large temperature slip could make water be heated to higher temperatures(such as 90℃ etc.) without decreasing the system efficiency, which has got certain superiority for CO2 transcritical heat pump system. While in that system, the throttling process caused a great loss of energy and lower 20% to 30% of system efficiency under the equivalent condensation temperature (Ma Yi-tai etc. 2003), which also mean that it is possible to obtain a COP increment of about 25% by using the energy lost by throttle. After calculation, the recoverable work of expansion process could counted for 20% to 25% of compression work (Ma Yi-tai etc. 1998). Considering those above, an expander was used in that system to recover certain expansion work and increase refrigeration capacity to contribute the COP, which was thought to be the foundation measure to contribute that. Same to the compressor study, currently, there are few international publishes which researched the prototype and manufacture of CO2 expander. And that few references revealed that the efficiency of expander is relatively low with the maximum 40% (Zeng Xian-yang 2006).

The research on the expander in CO2 transcritical heat pump and refrigeration system has been carried out in this paper, including the basic introduction of expander using in that system, the theoretical analysis and simulation test on expansion phase change and the test on CO2 transcritical heat pump and refrigeration system with an expander.

2 DESIGNING AND DEVELOPING OF CO2 EXPANDER

Years of research in CO2 transcritical heat pump and refrigeration system have been conducted in Thermal Research Institute of Tianjin University which was led by Professor Ma Yi-tai etc. To the study of CO2 expander, the rolling piston expander was the final choice after considering the advantages and disadvantages of various types of expander and other practical factors, and a prototype was made successfully in 2002 (Wei dong 2002). To solve the leakage, friction and suction control issues under that prototype, the second and third generation of rolling piston expander was developed. An efficiency of more than 45% was got under the test of the third. At the same time, a swing rotor expander was also developed with the leakage and suction control issues solved and got an efficiency of 44% and in 2005 (Guan Hai-qing 2005) a swing rotor compander prototype was made. In addition, taking the irreversible loss caused by expander inlet into account, a new type of rolling piston expander with two-cylinder was designed (Jiang Yun-tao 2009) to replace the suction device with the first cylinder which kept connection with the suction pipe and the second one which connected with the exhaust pipe. As worked out that prototype, it is being tested and improved now. Figure 1 shows the appearance of two-cylinder CO2 rolling piston expander.

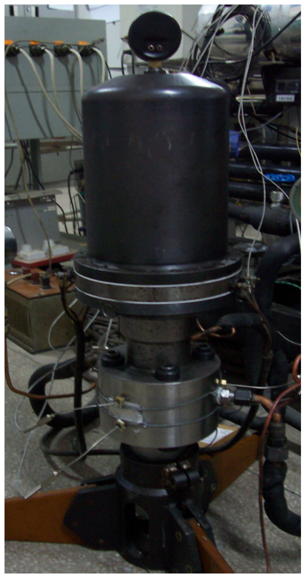

Figure1: the outlook of expander

3 RESEARCH ON PHASE CHANGE OF CO2 IN EXPANDER

3.1 Theoretical Model

The phase transition inside the expander could be simply known as one from the breaking of metastable equilibrium to the forming of two stable which would go through three main process of the overheating of liquid, the forming of evaporation core which is the key to ensure the smoothness of phase change and the growing of bubble. And the following will mainly study on the core formation. After comprehensive analysis, the fluctuation theory of non-equilibrium thermodynamics would be used to explain the loss of stability of metastable equilibrium in the phase transition and other phase change process in a CO2 expander.

At first, let us have a review on some generally accepted theoretical models of the formation of evaporation core. In classical homogeneous nucleation theory model (Pankaj 2006), the low-density critical cores come out of the small holes in liquid which is caused by the local density fluctuations in the liquid resulting from the disordered movement of molecules in the liquid when the saturated liquid become overheating under isothermal decompression or isobaric heating. Figure 2 is expressed this forming process. While in Kwak's molecular interaction model (Tong Jing-shan 2006), which based on the aggregation theory, the high-energy molecules in the overheating liquid get together to form clusters, and phase change generate spontaneously when the clusters reach an unstable state. Kwak's theoretical model of the evaporation core generating process is shown in Figure 3.

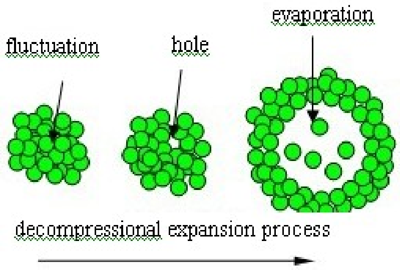

Figure2: classical homogeneous nucleation theory model

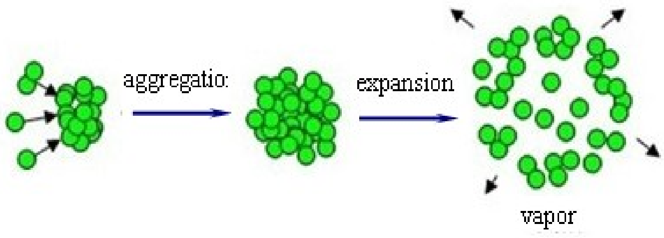

Figure3:formation of evaporation core under Kwak's model

However, the nucleation rate calculated under the classical nucleation theory is far different from the experimental results, and there are many unexplained phenomena in phase change mechanism under that theory. Moreover, in analyzing the dynamics simulation of nucleation process of the vapor-liquid phase change process, only holes have been observed but the expansion process of the critical clusters mentioned in Kwak's model. Therefore, a comprehensive model is proposed in reference (An Qing-song 2008): there are the forming of not only the high molecular clusters but also the holes around the clusters during the temperature rising or the pressure falling.

As has certain rationality of those models, the loss of stability of metastable equilibrium in the phase transition can not be explained smoothly with the equilibrium thermodynamics. While the fluctuation theory of non-equilibrium thermodynamics is a better choice, under which a more reasonable interpretation of the core growth process can be obtained.

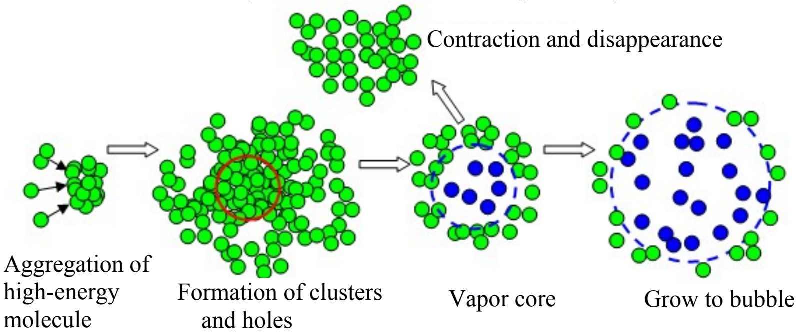

Figure4: the formation of evaporation core under comprehensive analysis

So our opinions are that the formation of the steam nuclear is occurred during the energy fluctuation of superheat liquid under the up of temperature or the down of pressure. The high-energy ones in liquid molecules aggregate to form clusters during the energy fluctuation process and where holes generated due to the absence of liquid molecules causing by the aggregation. The high-energy clusters spontaneously got the phase transition and formed the vapor molecules after reaching the critical state with the continual aggregation of high-energy molecules, while the holes are the low-density nucleus of boiling which will grow with the phase transition of clusters to reach the critical state and grow to the bubble or to become contraction and disappearance then wait for the next formation of a vapor nucleus. Figure 4 is shown the forming process.

3.2 Calculation Methods

According to the fluctuation theory, the energy fluctuation in canonical assemblage and grand canonical ensemble are separately (Zeng Dan-ling 1995):

$$\sigma(E)_c = \left(kT^2 C_v\right)^{1/2}$$

$$\sigma(E)_g = \left(kT^2C_v + \overline{N}\varepsilon^2\right)^{1/2} \tag{1}$$

While, the miniature work for the forming of a bubble in the liquid which is equivalent to the energy fluctuation is:

$$W = \sigma A + p\Delta V = 4\pi\sigma r_c^2 + 4\pi\left(1-\rho^v/\rho^l\right)pr_c^3/3 \tag{2}$$

So, the calculation method of the critical radius of a vapor core is:

$$r_c(c) = \left(kT^2C_v/16\pi^2\sigma^2\right)^{1/4}$$
$$r_c(G) = \left[\left(kT^2C_v + \overline{N}\varepsilon^2\right)/16\pi^2\sigma^2\right]^{1/4} \tag{3}$$

And the limited superheat degree of a liquid could be get from the relationship with the critical radius of a vapor core:

$$r_c = 2\sigma\left\{p_s \exp\left[v^l\left(p^l - p_s\right)/RT\right] - p^l\right\}^{-1} \tag{4}$$

So could obtain the nucleation rate of the superheated liquid under the increaseof temperature or the decrease of pressure:

$$J_{iT} = \frac{\partial N}{\partial \tau} = \frac{\partial N}{\partial T}\frac{\partial T}{\partial \tau}$$
$$J_{dp} = \frac{\partial N}{\partial \tau} = \frac{\partial N}{\partial p}\frac{\partial p}{\partial \tau} \tag{5}$$
$$N = \frac{3}{4\pi r_c^3}\int_{W/\sigma(E)}^{+\infty}\frac{1}{2\pi}e^{-\frac{x^2}{2}}dx$$

Here, k is Boltzmann constant; C_v is heat capacities at constant volume of the system; ε is the average energy of a molecule; N is the vapor core in unit volume of the system; subscript l represent liquid, g gas, and c critical; superscript s represent saturation condition.

Now, the main feature parameters in phase change process, like the critical energy, the critical radius of a vapor nucleus to grow a bubble, the limited superheat degree of a liquid which is the start of phase change and the nucleation rate of bubble, could be obtained one after another under the fluctuation theory of non-equilibrium thermodynamics.

4 VISUALIZATION TEST OF CO2 PHASE TRANSITION

5.1 Test Facility

The whole test facilities include the visualization test specimen of CO2 phase transition process, the test systems and the high-speed photographic equipment. Figure 5 is the basic structure of the test block and the test system, in which the major test instruments contain the pressure gauge, the pressure sensors and thermocouples. Considering the existence of oil mixed with CO2 inside the expander, during the test 3% of the PAG lubricants will be injected in the specimen.

The test is designed to simulate the phase change during the expansion process in expander, to analyze the pressure and temperature changes during the quick decompression, and to analyze the growth of the bubble in phase transition with the photos obtained by the high-speed photography equipment.

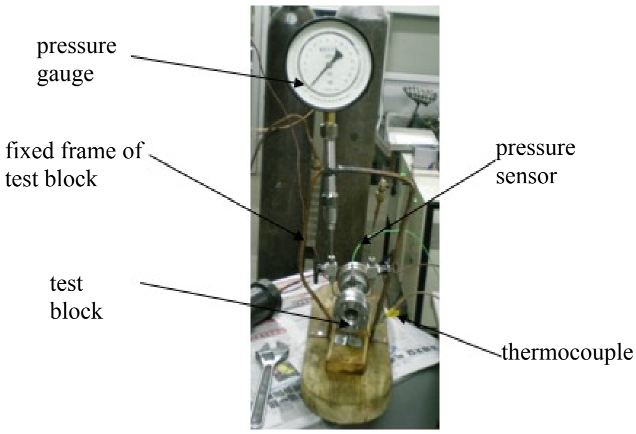

Figure5: the test block and test system

5.2 Results And Analysis

CO2 pressure in the internal of test block was gradually reduced with the marching of deflation process. At the early of that process, the pressure decreased significantly and the drop gradient became little near the end of that when the internal pressure of test block is 0.1MPa. In figure 6, the three curves represent the changes of pressure under different conditions including 8MPa/40ºC (inlet pressure/temperature), 9MPa/40ºC and 10MPa/40ºC and the abscissa is on behalf of the deflation time. From that, we can see, the three showed the same concave curve downward trend and the duration of deflation is longer with the higher initial pressure. And the pressure was gradually close to atmospheric pressure with the end of deflation. So did the variation of temperature.

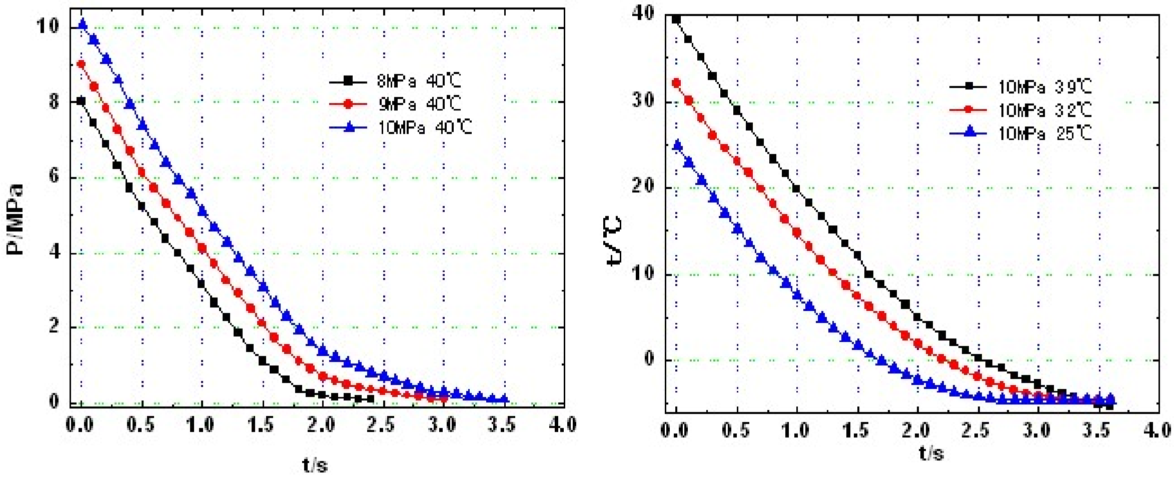

Figure6: the variation curve of pressure and temperature under different inlet conditions

Figure 7 is portion of photos obtained during the deflation process by the high-speed photography equipment. The equipment acquisition frequency is taken as 4000fps and the shooting time is 5s, for which recorded a total of 20,000 images. The photos revealed that, with the deflation process and constant pressure wave transmission, a large number of bubbles with a smaller diameter separated out from the mixture within the specimen, which was along with the severe disturbance of a small number of oil driven by CO2 gas on the right of the test block, and with the disappearance of liquid CO2 and pressure fluctuations and changes in surface tension, the CO2 mixture was boiling which resulted in a large number of bubbles with relatively large radius which was conducive to observation. Those large bubbles moved to reach the border of test clock from the mixture under the density difference and were gradually broken. The yellow circle as shown in Figure 7 is the whole process of a bubble from the formation to fracture.

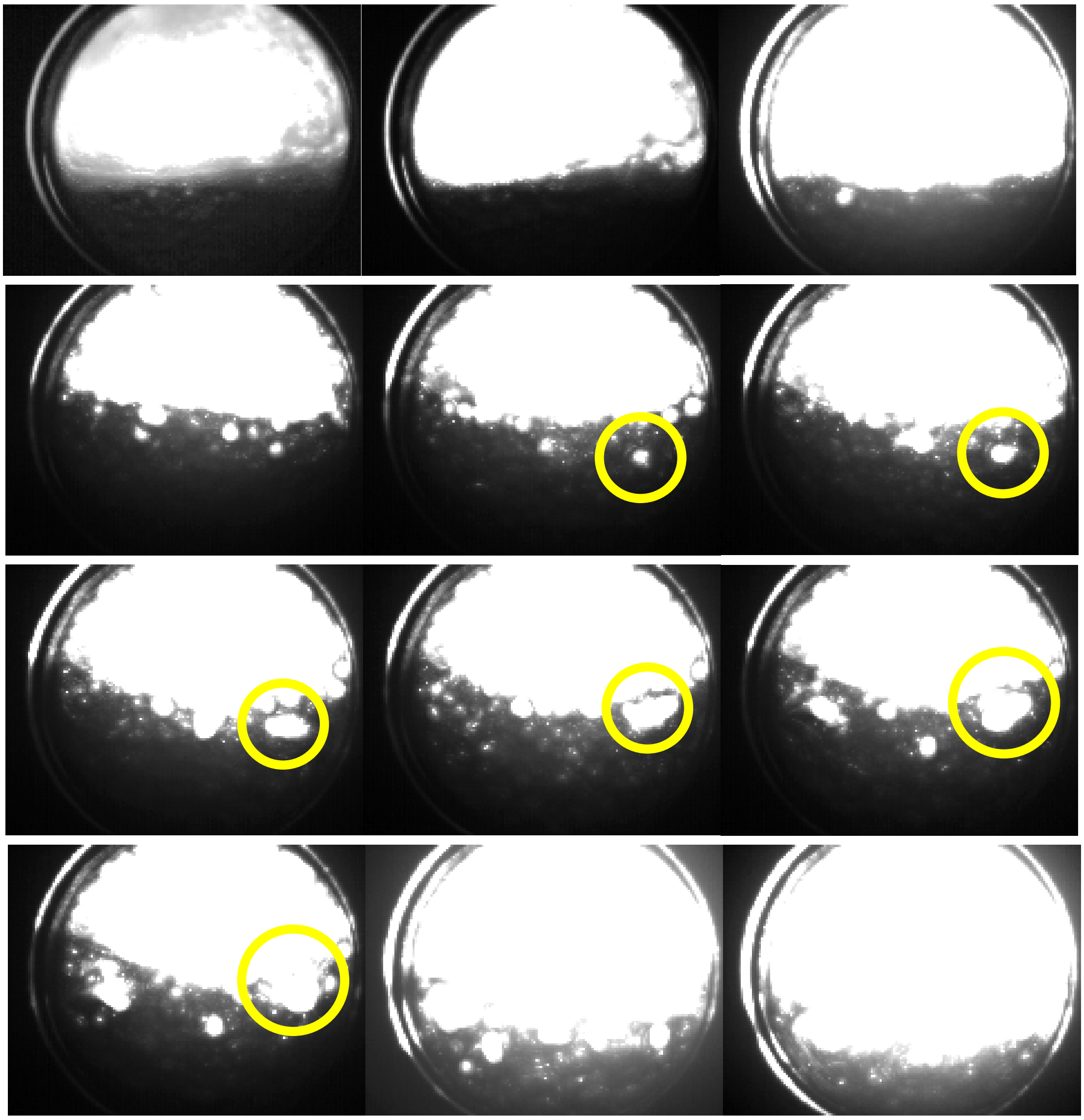

Figure7: the visualization photos of the mixture of CO_2 and oil in deflation process

5 TEST ON CO2 WATER-TO-WATER HEAT PUMP SYSTEM WITH AN EXPANDER

5.1 Test System

The evaporator of the test system is double pipe heat exchanger designed and processed by ourselves, which was made with brass and the working fluid runs in the inside pipe which is three spiral channels with smaller diameter. So does the gas cooler but with adjustable diameter of the inside pipe. The high-pressure refrigerants flow in the inside pipe, and the cooling water in the outer one. The compressor is a piston one which was made in Dorin Italy with a rated input power of 4.0kW. Oil cooler is water-cooled double pipe heat exchanger with the lubricating oil flowing in the inside pipe and changing heat with water which can make the oil temperature maintained in 30°C to 50°C. The oil separator with packed-type structure is installed between the compressor and gas cooler to separate the oil from the compressor discharge. The throttle is the self-made cone-type valve which can be manually continuously adjusted according to conditions. To facilitate the demolition and maintenance, stop valves are installed before and after the throttle valve.

The mainly measured data in the test include refrigerant temperature and pressure, refrigerant flow rate, water temperature and flow rate, compressor power and current, and expander power and rotating speed. Data measurement system is through a variety of

instruments to measure the operating parameters and send to be collected. By using the data monitoring and collection interface, the system operation can be monitored and regulated,
while the value of each parameter can be collected.

5.2 Analysis Of The Test Results

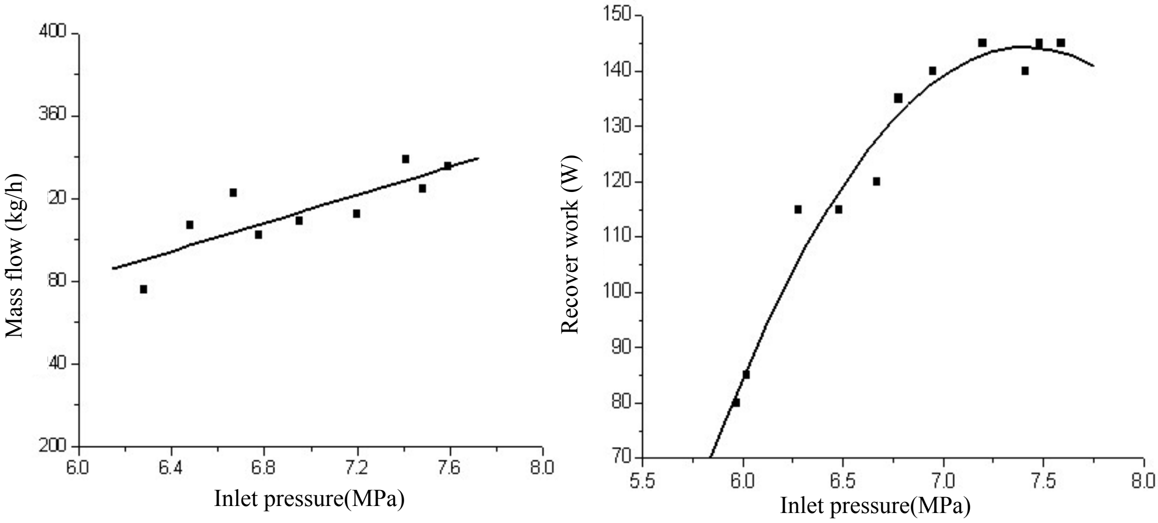

Figure8: the variations of system mass flow and recover power to expander

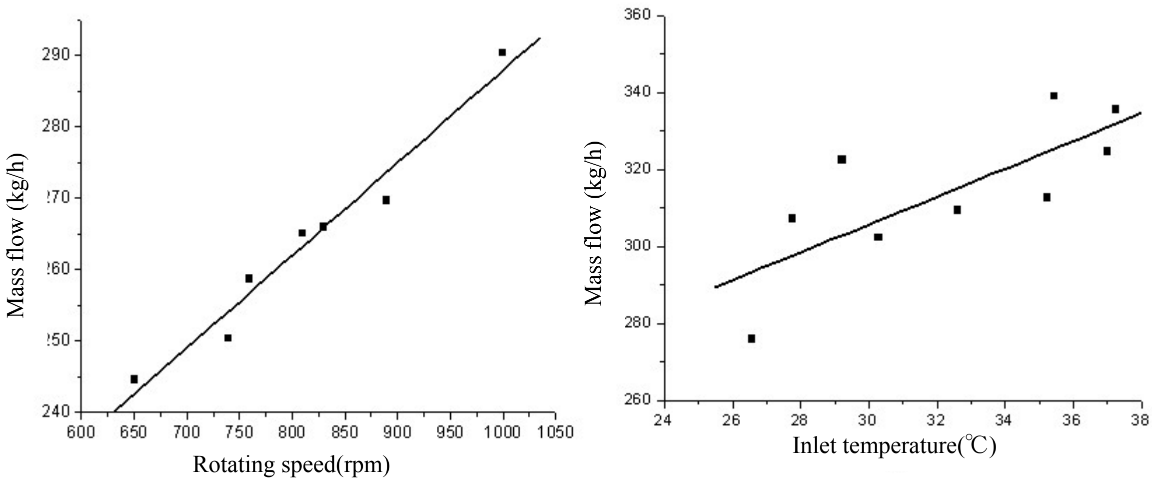

Figure9: the variations of system mass flow to expander rotating speed and inlet temperature

As shown, Figure 8 shows the changes of system working fluid mass flow and expander recover work with the expander inlet pressure. Figure 9 shows the variations of system mass flow with different expander rotating seed and inlet temperature.

The expander inlet temperature and pressure change in synchronization and rely on the adjustment of cooling water flow and temperature. When the expander inlet pressure increases, the density of CO_2 inhaled by expander becomes large and its quality increases. Meanwhile, with the same expander export conditions, the improvement of expander inlet parameters would lead to the increase of enthalpy difference between the import and export, would increase the kinetic moment of expander, which would result in the improvement of expander rotating speed and the increase of system flow rate.

With the inlet pressure increases, the recover power increase gradually and maintain the same when it reaches a certain level. The more recyclable power of expander due to the increment of enthalpy difference between the expander import and export with the inlet pressure rising.

In addition, with the increase of rotating speed, the quantity of working fluid passing expander per minute is increasing. When the expander rotating speed increased from 650rpm to 900rpm, the system's working fluid mass flow increased from 245kg/h rapidly to 270kg/h. Figure 11 indicates the change of expander recover power with inlet pressure.

6 RESULTS

In this paper, efforts have been made to the theoretical analysis on the expansion phase transition and experimental test of expansion model and some character of expander in the CO2 water-water heat pump system, the main results are the following:

(1)The energy fluctuation is the main reason to induce the formation of vapor core in the superheated liquid. The main feature parameters and more reasonable explanations on the main process in phase change process could be obtained under the fluctuation theory of non-equilibrium thermodynamics.

(2)During the quick decompression test, the working fluid temperature and pressure both represent the concave curve downward trend and the change gradient decrease gradually. And the visualization photos show the whole process of a bubble from the formation to fracture. The test results lay some experimental basis for the next step research of expansion phase transition on expander.

(3)In CO2 water-water heat pump system, the system mass flow is related tightly on some character of expander. The former would have an increment with the increase of expander rotating speed and expander inlet pressure and have an existence of maximum increment with the increase of expander inlet temperature. While the expander recover power increases with the increasing of inlet pressure. The test results are significant to optimize the designation of expander and the CO2 heat pump system and to accelerate the application the relative products.

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