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ABSTRACT

The mechanical vapor compression (MVC) system is a promising way for energy saving among energy intensive industries such as desalination, food and beverage, chemistry and waste water concentration etc. In practical its application is limited by the vapor compressor technology which is demanded to have high pressure ratio for large saturation temperature difference and low discharge vapor temperature. Due to the ability of wet compression, twin screw compressor can overcome the technical limitation above by the injection of liquid water into the working chamber. In this paper a test rig of a MVC system with water injected twin screw compressor has been designed and built. Compressor performance of power consumption and discharge temperature was measured. Moreover, operation characteristics of the water injected twin screw compressor were studied by the measurement of its working process p-t diagram. The results of the experiment study can provide some design guidance of water injected twin screw water vapor compressor for MVC system.

1. INTRODUCTION

Energy saving has been a target and challenge worldwide for many years due to the crisis of renewable energy sources and sharp increase in fuel prices. One possible and effective way for energy saving among energy-intensive industries is energy recovery. In processes of evaporation, distillation or drying, large volume of boiler generated water vapor is used and very little is recovered after use as its pressure and temperature is too low for recycling. As a result, this 'unusable' water vapor is vented to the environment with its valuable latent heat content. A system which can possibly recover the energy of the once vented water vapor and reduce the energy consumption of boiler is desired. To satisfy the demand, mechanical vapor Compression (MVC) system was induced last century.

The MVC system is operated under the principle of heat pump of which a compressor is used to compressor the low pressure and temperature water vapor from industry processes. Then the pressure, temperature and enthalpy of the vapor are elevated to an appropriate level and return back to the system as a heat source.

According to the feasibility study of water as a refrigerant, it is easily available, inexpensive and presents a high theoretical coefficient of performance (COP) due to its high latent heat of vaporization [1]. Analysis also indicated that heat pump system with water as a refrigerant is competitive for high temperature application. It can be predicted that the utilization of MVC system among industries that consume large boiler generated water vapor to recovery the energy of low temperature vapor and recycle it to replace the boiler generated water vapor is a tendency.

Although the MVR heat pump system has obvious advantages in energy saving, its extension is limited by the technology and economic of the water vapor compressor which is the key component of the MVC system. To meet the demands of practical industrial application, the applied water vapor compressor of MVC system should simultaneously satisfy the requirements below [2]:
(1) High compression ratio corresponding to large saturate temperature difference which could be as high as 40 K;
(2) High volumetric flow capacity with an acceptable compressor dimension;
(3) High isentropic efficiency.

The types of compressor used for water vapor compression include blowers of multi-stage blowers, centrifugal compressors, lobe compressors et al. The blowers can compress a high mass flow rate water vapor, but the saturate temperature difference cannot be higher than 12 K due to its limitation of compression ratios. The temperature difference of lobe compressors can be as high as 20 K with a poor isentropic efficiency and low volume flow rates. Although multi-stage centrifugal compressors can satisfy the requirements above, the machines are expensive with poor reliability. In addition to the requirements above, water vapor compressor should also overcome the technological difficulties below:
(1) How to lower the discharge temperature of the compressor under a high compression ratio, which affects the reliability of compressor;
(2) How to overcome the erosion of compressor;
(3) How to solving the sealing problem as the compressor may working under negative pressure with a suction temperature under 100℃；
(4) How to design or choose the type of shaft sealing as the compressed vapor should be oil free.

Among all types of compressor, twin screw compressor was thought to be more suitable for water vapor compression since it can realize wet compression which means liquid water can be injected into the working chamber for cooling. For the reason of water injection, the discharge vapor temperature can be reduced to saturation ideally. As a result, the pressure ratio or saturate temperature difference of the water vapor compressor can be increased. Moreover the volume flow rate of the compressor will be increased with the evaporation of the injected water. What's more, twin screw compressor has the advantages of less expensive, simple in design and control, reliability of operation etc. The performance evaluation of a water injected twin screw compressor water vapor compressor was analyzed by the author and reported in the 21nd International Compressor Engineering Conference in detail [3].

Till now seldom experimental studies of the water injected twin screw water vapor compressor were reported. A test rig on the base of MVR system is designed and built in this paper to analyze its operation characteristics including power consumption and discharge temperature. Especially the p-t diagram of the working process was measured. Some conclusions or guidance for the design of water injected twin screw vapor compressor and its actual operation were got from the results of the experiment.

2. EXPERIMENTAL SETUP AND PROCEDURES

2.1 Experimental System

Figure 1 shows the schematic of the special designed water injected twin screw water vapor compressor performance testing system which is on the base of MVC heat pump system. The system should be vacuumized before running and water in the water tank must be heated to one set temperature. Once the air in the system is removed by the vacuum pump, the heated water will be sprayed into the evaporator/condenser and then the compressor can be started. Water vapor vaporized from the sprayed water is compressed by the compressor to raise its pressure and temperature. Liquid water is injected to the working chamber of the compressor during the compressing process to lower the discharge temperature. Then the compressed water vapor flow into the condenser tubes of the evaporator/condenser as a heat source to evaporate the sprayed water outside and meanwhile itself is condensed. Due to the reason that the system may work with negative pressure, non-condensable gas can permeate into the system which will be vented by the specially set vent nozzle as shown in Figure 1. The condensed water and the sprayed water which is not evaporated will be circulated by a pump into an air-cooled heat exchanger and then flow back into the water tank. Water in tank will be pumped by another pump and most of it will be sprayed into the outside of the tubes in the evaporator/condenser. The rest part of the water will be injected into the working chamber of the compressor and a by-pass with a small air-cooled heat exchanger is used to regulate the temperature of the injected water.

Figure 2 shows a photograph of the experimental setup. Generally, this test bench consists of four main components: the screw compressor, evaporator/condenser, air-cooled heat exchanger and water tank. A dry screw air compressor was applied and modified as water vapor compressor as seldom special water injected twin screw water vapor compressor is available on the market. Three holes were drilled for the installation of pressure sensors to measure the p-t diagram of the working process. And a special hole was drilled for the water injection which is at an angle that the suction process ends and the compression process begins. A three-phase asynchronous frequency conversion motor combined with a frequency converter is adopted to drive the compressor. The evaporator/condenser in the bench was specially designed by the author and manufactured by a heat exchanger manufacturer. According to the energy balance, an air-cooled heat exchanger is necessary to dissipate the heat that equals to the power of compressor. A water tank is necessary for the circulation and two electric heaters were installed in the water tank for the heat of water before the system start. The details of the components are listed in Table 1.

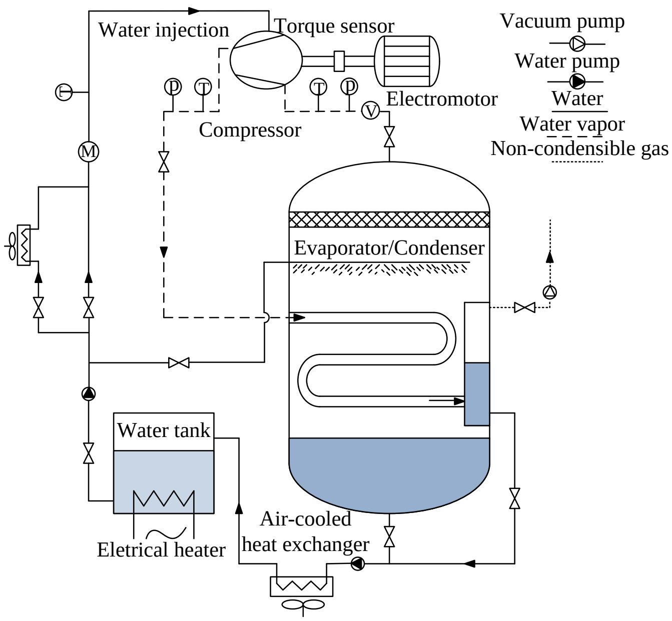

Figure 1: Schematic of the testing system

Figure 2: A photograph of the experimental setup

2.2 Instrumentation system

A set of instruments were mounted on the testing rig as shown in Fig. 1 which consist of pressure meter, thermometer, flow meter and Torque sensor. Moreover, three pressure sensors are installed in the case of compressor for the p-t diagram measurement, which is not shown in Figure 1. Besides a DEWE-1201-All-In-One standard instrument was used to collect the data of pressure sensors. The other experimental data were recorded manually. The major parameters of the instruments are listed in Table 2.

Table 1: Parameters of components in the experimental system

Components	Specifications
Twin-screw compressor	Discharge pressure is 0.25MPa for air compression at a rated speed of 1800 rpm with a speed increasing ratio of 3.72
Eletromotor	Three-phase asynchronous motor, YJTG225S-4/37Kw/380V/5-100HZ
Evaporator/condensor	Carbon steel shell with a inner diameter of 1m and a hight 0f 1.4m, 12 stainless steel tubes inside with a totel heat transfer area of 4.5 m^2
Water tank	Made by carbon steel with a size of 0.5m×0.5m-0.6m
Air-cooled heat exchanger	20kW plate-fin heat exchanger

Table 2: Parameters of instruments

Pressure meter in the suction line	-0.1~0MPa,±0.4%
Pressure meter in the discharge line	-0.1~0.3MPa, ±0.4%
Thermometers	0~200℃, ±1℃
XFV vortex-shedding flow meter	5.5t/h， ±0.15%
DK800-6 glass rotameter	0~60L/h, ±0.4%
JN338-200A torque sensor	0~200Nm, 0~5000r/min,±0.5%
XTL-190M Pressure sensors of Kulite	0~0.35MPa with respective sensitivity for each sensor

2.3 Experimental procedures

The aim of the experimental study is to measure the variation of the working performance of water injected twin screw water vapor compressor which is decided by the temperature or pressure of the suction water vapor, rotate speed of the compressor, mass of the injected water as well as its temperature. During the experimental process, three of them will be kept constant, and change the rest one to record the parameters variation including suction temperature and pressure, discharge temperature and pressure and shaft power. With the recorded parameters above, variation of the pressure ratio is calculated.

Actually the suction volume flow rate was also planned to be recorded. However the volume flow meter failed to work and its reading fluctuated a lot at high rotor speed. What's more the volume flow rate shown in the flow meter failed to increase with the rotor speed. As a result, the variation of volume efficiency and adiabatic efficiency cannot be calculated and not discussed in this paper. It would like to be analyzed in another paper once the problem of volume flow meter is solved.

To analyze the influence of water injection, p-t diagrams of the operation process with and without water injection to the compression chamber can be measured by the data of three pressure sensors. The comparison of p-t diagrams with different mass of water injection would like to be done under the same rotor speed, suction vapor temperature and temperature of injected water.

3. RESULTS AND DISCUSSION

It should be noted that the compressor applied is designed for air compression. The sealing between working chamber and gear case is labyrinth seal with a hole opened to atmosphere. In other words, vacuumizing of the system is impossible. During the experimental process, the compressor was firstly operated at a low speed and the compressed vapor was vented through the non-condensable gas vent nozzle. Meanwhile, the heated water was sprayed into the evaporator/condenser. In this way, the air in the system can be reduced and finally the vented compressed vapor was seen as white mist. Then the compressor speed can be increased. During the operation, part of the compressed vapor was kept venting through the non-condensable gas vent nozzle.
Due to the exist of air and venting of compressed vapor, the suction pressure was a bit higher than the saturation pressure corresponding to the suction temperature and the discharge vapor pressure was always higher than

atmospheric pressure. However the temperature of water inside the evaporator/condenser was the same as the suction temperature and the discharge temperature could be lower than 100℃ the corresponding pressure of which is lower than the discharge vapor pressure. It can be concludes that the partial pressure of the water vapor was still corresponding with its temperature.

3.1 Influence of rotor speed and mass of injected water

To evaluate the influence of rotor speed and mass of injected water, the suction vapor temperature was kept at 60 ℃ with a injected water temperature of 55 ℃. The rotor speed decreased from 1000 rpm to 600 rpm and the mass of injected water varied from 0 to 8 L/h. Due to the reason that mass of injected water should be proportional to the volume flow rate theoretically, high mass of injected water were not tested during the experimental process at low rotor speed conditions. Meanwhile water was injected automatically due to the pressure difference between the water tank and working chamber. The mass regulation was realized by the glass rotameter.

Figure 2 shows the variation of discharge temperature at different operation conditions. It can be found that water injection has obvious effect at discharge temperature reduction. According to the experimental data, the discharge temperature was 166 ℃ and still increased at a rotor speed of 1000 rpm without water injection. With 8 L/h water injected, this temperature reduced to 128 ℃ and this reduction may be continued. Finally the discharge temperature was 117 ℃ at a speed of 606 rpm with 2 L/h water injection. It can also be found from Figure 2 that the discharge temperature increased with rotor speed at the same mass of injected water. This may be a result of the increase of shaft power and pressure ratio.

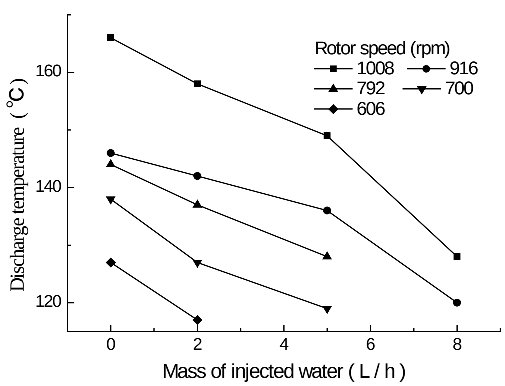

Figure 2: Variation of discharge temperature

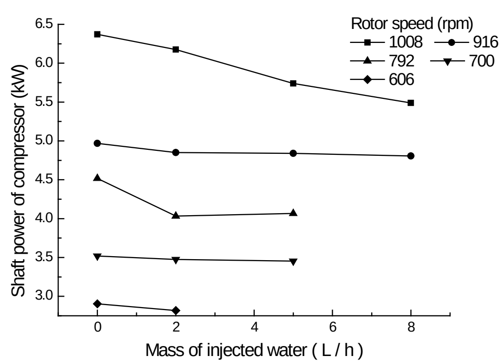

Figure 3: Shaft power variation

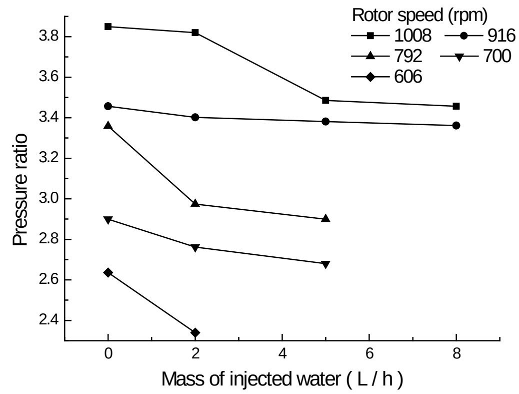

Figure 4: Variation of pressure ratio

The shaft power variation of the compressor is shown in Figure 3. The shaft power was expected to decrease once water was injected as the compression process could be close to isothermal compression theoretically and this reduction can be found in Figure 3. The variation of shaft power at a speed of 792 rpm is quite typical: once water is injected, the shaft power reduces firstly and the shaft power may increase if too much water was injected. As a conclusion the mass of injected water should be just enough for discharge reduction and its calculation is quite important for the design of water injected twin screw compressor. It can also be shown in Fig. 3 that shaft power increased with the rotor speed as the mass flow rates increased.

According to the recorded data, the variation of pressure ratio was calculated and shown as Figure 4. It can be concluded that the pressure ratio increased with rotor speed. It can be explained as follows: the suction pressure ratio decreased a bit once the rotor speed increased as flow resistance increased due to the vapor flow velocity increased; the discharge pressure increased with the rotor speed as the volume flow rate increased and the venting vapor through the vent nozzle was limited. As a result the pressure ratio increased with the rotor speed. Analogously the pressure ratio decreased with the increase of injected water as shown in Figure 4. It may be because of that the injected water increased the partial pressure of the water vapor and then lower the discharge pressure.

3.2 Influence of temperatures of suction vapor and injected water

In order to testing the influence of temperatures of suction vapor and injected water, the rotor speed was kept at 701 rpm with 4 L/h water injection. During the operation process, electric heater inside the water tank kept working to increase the temperatures of sprayed water and injected water. As a result, the temperatures of suction vapor and injected water kept increasing and then the data of performance parameters were recorded. Due to the reason of flowing through long pipe, the temperature of injected water was finally lower than the sprayed temperature. The main parameters were listed in Table 3.

It can be found that the discharge temperature firstly increased and then lowered. This may be explained as: the discharge temperature should be increase with the suction temperature; the injected water cannot all evaporated once injected and some may leaked into the suction chamber where it evaporated to lower the temperature of vapor in the suction chamber; also the evaporated mass fraction of injected water may increase as the discharge temperature increased and the cooling effect can be more obvious.

Except for the variation of discharge temperature, the variations of other parameters were quite small. The abnormal data at a suction temperature of 49 ℃ may be a result of too much air among the compressed vapor during the starting process. Theoretically the shaft power should increase with the suction pressure and the corresponding saturated suction temperature as the specific volume increases and mass of compressed vapor increases.

It can also be concluded from Table 3 that temperature of injected water temperature has small influence to the performance of compressor. This may be because that the cooling effect is mostly a result of the evaporation of the injected water to using its latent heat. And the evaporation temperature of water is decided by the pressure of working chamber. Taking this into account, it is suggested that the temperature of the injected water should be the same as or a bit higher than the suction temperature. In this way the water leaks into the suction chamber may be reduced. At the same time the discharge port of water injected twin screw water vapor compressor should be set downward to reduce the leakage of water if too much water is injected.

Table 3: Parameters at different temperatures of suction vapor and injected water

Suction temperature (℃)	Temperature of injected water (℃)	Discharge temperature (℃)	Shaft power (kW)	Pressure ratio
49	40	75	3.4559	2.730
51	44	87	3.3259	2.594
52	47	101	3.5263	2.425
53	48	100	3.5515	2.438
54	50	89	3.5482	2.438

3.3 Results of p-t diagram measuring

Three XTL-190M pressure sensors of Kulite were installed in the case of the compressor to measure the changes of pressure in the suction chamber, compressing chamber and discharge chamber respectively. The complete vapor pressure change along with the time in the working chamber called p-t diagram can be achieved. Figure 5 shows the recorded data of three pressure sensors in one graph as an example.

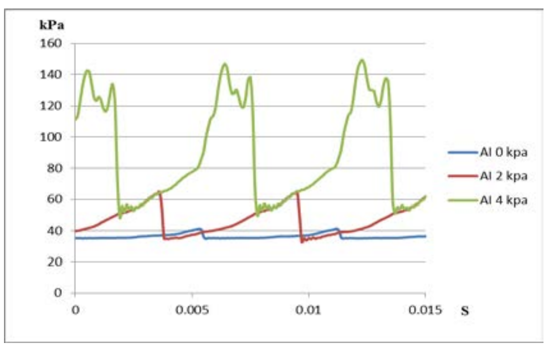

Figure 5: p-t diagrame without water injection

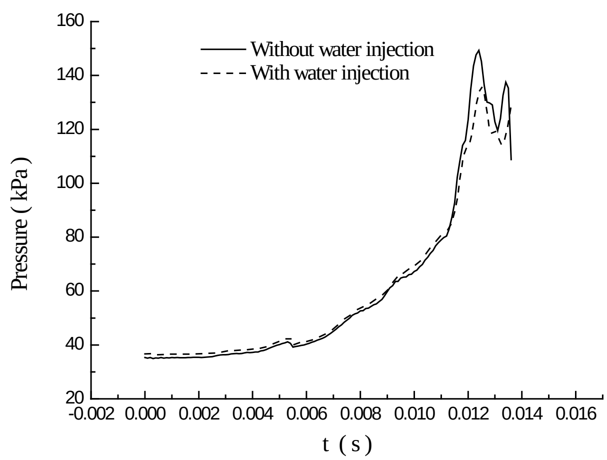

Figure 6: p-t diagram with water injection

Figure 6 shows the combined p-t diagrams without water injection and with 2 L/h water injection at a rotor speed of 916 rpm with a suction temperature of 60 ℃ and injected water temperature of 55℃ in the same graph for comparison. Obvious difference can be found between the two p-t diagrams that suction pressure with water injection was higher than that without water injection and the pressure of the compressed vapor was firstly higher than that without water injection and lower than it at one angle and finally the discharge pressure with water injection was lower than that without water injection. This may because that unevaporated water leaked into the suction chamber and evaporated there and this evaporation continued as water was injected once the compression process started. As a result the pressure increased with a limited working volume of the compressor. Due to the reason that the compressed vapor contained the inleaked air, the discharge pressure was higher than the saturation pressure of water vapor corresponding to the discharge temperature with water injection. The evaporation of water may reduce the partial pressure of air according to its cooling effect. By this way the discharge pressure with water injection was lower than that without water injection. Besides over compressing of vapor can be found in both p-t diagrams which is a result of improper discharge port setting as the compressor is designed for air compressing.

During the experimental process, the suction chamber pressure measuring sensor failed to work once too much water was injected as shown in Figure 7. It can be explained as this: the unevaporated water flowed to the inner wall of the case and leaked into the suction chamber through the clearance between the rotors and inner wall; then the water flowed in the hole for pressure sensor installation and contacted with the sensor; finally the sensor failed to work as it cannot be used for pressure measurement of conductive medium. It can concluded that the volume efficiency of water injected twin screw water vapor compressor may not be increased even though too much water is injected as the main leakage of compressed vapor is through the blow hole and paths of contact line between rotors which may not be sealed by the water. And the spayed water should be atomizing as far as possible once injected into the working chamber.

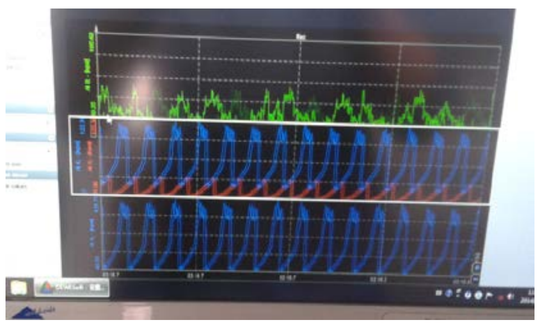

Figure 7: Gragh of the failing suction chamber pressure measurement

4. CONCLUSIONS

A test rig was set up for the experimental study of water injected twin screw water vapor compressor. According to the results, it can be concluded that water injection has obvious effect for the discharge temperature reduction and it can be reduced to the saturation temperature corresponding to the discharge pressure. Besides, the unevaporated water may leak into the suction chamber through the clearance between the rotors and inner wall. And the evaporation of water in the suction chamber may reduce the displacement of compressor and improve the suction pressure. On the other hand, water injection can reduce the power consumption as the compression process gets close to isothermal compression. At the same time the power consumption will increase if too much water is injected. As a result, the mass of injected water should be well calculated.

As for the design of water injected twin screw water vapor compressor, the following suggestions can be made according to results of experimental study: the port location for water injection should be delayed to an angle that the compression process has been undergoing for a while to reduce the mass of water leaked into the suction chamber; the temperature of injected water is suggested to be the same as or a bit higher than the suction temperature as the main cooling effect is by its latent heat of evaporation; the discharge port of water injected twin screw water vapor compressor should be set downward to blow out the unevaporated water if too much water is injected. Specially, appropriate sealing type should be applied to guarantee the vacuumizing of MVC system and proper discharge port should be designed to reduce the energy loss of over compressing.

Finally it should be noted that variation of volume flow rate which is the main performance for compressor was not analyzed in this paper due to its inaccurate measurement by the applied flow meter. It will be the next work of the author. The variation of volume flow rate along with volume efficiency and adiabatic efficiency would like to be reported in another paper.

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