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ABSTRACT

In the process of carbon neutralization, the traditional steam generation methods based on fossil energy (such as coal-fired boilers) will be faded out gradually. It can be predicted that the steam generation method based on electricity with renewable energy will become the main generation method of industrial steam. In this paper, according to the steam demand of pharmaceutical factory, an air source heat pump steam generation system is developed. The cascade air source heat pump is used to produce hot water at the temperature of 80-85°C, then the hot water flash to saturated steam at the temperature of 78-83°C. The saturated steam is extracted to a twin-screw steam compressor, and is pressurized to saturated temperature of 140-160°C. To ensure the purity of steam supplied, water lubricated mechanical seal is developed for the twin-screw steam compressor. When the softened water is used as sealing fluid, zero steam pollution is realized in the generation process. The operation data of the twin screw steam compressor show that the pressure and temperature of the supply steam are stable, the operation of mechanical seals is reliable. It has a good demonstration effect for the further engineering application of air source heat pump steam generation system.

1. INTRODUCTION

Boiler is the key equipment in many industrial fields, the high temperature steam produced by boiler is used to heat or preheat materials in industrial processes. At present, China's boilers mainly rely on fossil fuels and produce a large amount of carbon dioxide (CO_2), resulting in increasing greenhouse gas emissions. The Chinese government has issued a series of policies related to industrial boilers to gradually restrict and eliminate the use of coal-fired boilers to prevent air pollution and reduce CO_2 emissions(MIT,2014). However, the alternatives of coal-fired boilers, such as gas-fired boilers, electric boilers, biomass boilers and solar boilers, have obvious limitations and disadvantages (Yan et al., 2020). High temperature heat pump (HTHP) can extract thermal energy from air or waste heat and produce steam for process heating. It can make full use of renewable energy as energy input, and the heating efficiency is greater than 100%, so it has significant advantages of low-carbon and energy-saving in many application fields.

When the temperature of steam generated by HTHP is relatively low(<125°C), compression heat pump can be used to heat the water to a high temperature in the condenser, and the hot water enters the flash tank to produce low pressure steam after flashing (Bamigbetan et al., 2020). When the temperature of steam generated by HTHP is relatively high (>125°C, i.e. very high temperature heat pump (VHTHP)), steam compressor can be used to further boost the steam pressure to meet the requirements of customers (Wu et al., 2020).

There are four types of compressors for steam compression: centrifugal, roots, single-screw and twin-screw(Pang et al., 2013; Gu et al., 2015; Yang et al., 2016; Chamoun et al., 2013). The twin-screw steam compressor has the characteristics of good stability, large compression ratio and wet compression (Hu et al., 2018). It is especially suitable for conditions with medium volume flow and large compression ratio, such as VHTHP. The coefficient of performance(COP) of this water vapor heat pump is better than the traditional heat pump system under some certain conditions. However, limited by the physical properties of the water refrigerant, and to improve the COP of the VHTHP with steam compressor. The performance improvement of twin-screw steam compressor is urgent and necessary. More specifically, the inlet pressure of steam compressor is usually negative (corresponding to the saturation temperature of 80-90°C), which brings challenges to the seal design of steam compressor.

Multiple restrictive ring type seals or oil lubricated mechanical seals are conventionally used for steam compressors (Kammerer, 1972; Tian et al., 2020). Considering the leakage of non-condensable gas and lubricating oil, the steam will carry a small amount of non-condensable gas or trace lubricating oil, which will affect the purity of steam. To ensure the purity of steam supplied, water lubricated mechanical seal is developed for the twin-screw steam compressor. As the softened water is used as sealing fluid, zero steam pollution is realized.

In this paper, a VHTHP with maximum temperature lift of 180K is proposed first. And then the twin-screw steam compressor adopts water lubricated mechanical seal is developed. It can effectively prevent the leakage of steam and ensures the purity of steam. Next, the water lubricated mechanical seal is considered the best solution for the shaft seal technology of twin-screw steam compressor based on the experimental validation. The last not the least, the results show that the operation of water lubricated mechanical seal is reasonable and reliable.

2. SYSTEM DESCRIPTION

VHTHP is mainly composed of heat pump subsystem and steam pressurization subsystem. For the heat pump subsystem, cascade refrigeration cycle is adopted to provide relatively high temperature lift (60-100K). The cascade heat pump unit absorbs heat from the ambient air or waste heat by the LT evaporator, and heats the hot water in the HT condenser. The hot water is flashed in the flash tank, and the generated steam enters the steam compressor. The flashed steam is compressed to high-temperature and high-pressure state. Due to the use of large pressure ratio steam compressor, the temperature lift of 50-80K can be realized. Combined with the cascade heat pump with temperature lift of 60-100K, the maximum temperature lift of the system can reach 180K. The schematic of VHTHP is shown in Figure 1.

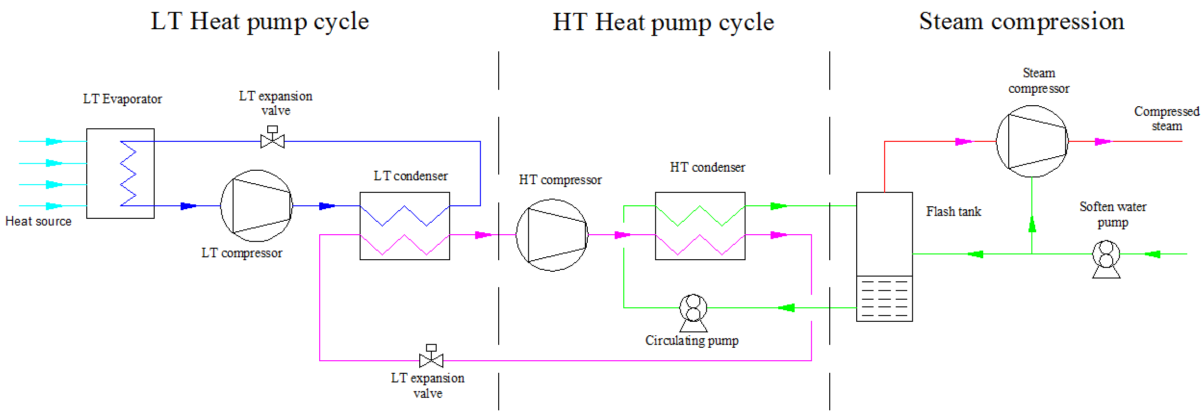

Figure1: Schematic of the proposed VHTHP

3. WATER LUBRICATED MRCHANICAL SEAL

Though the oil free type compressor design method is used for twin-screw steam compressor, the bearings and synchronous gears still need lubrication by pressured lubricating oil. If steam leaks into the lubricating oil, it may emulsify and have the lower viscosity, thus damages the bearing and synchronous gears. Meanwhile, if the lubricating oil leaks to the steam side, it will cause the loss of lubricating oil and affect the quality of steam. This requires that the shaft seals should prevent the contact between steam and lubricating oil.

The technology of twin-screw steam compressor is mostly extended from oil-free twin-screw air compressor and process gas compressor. The sealing types of these two compressors are used for steam compression, but they are subject to many restrictions:

1. The oil-free twin-screw air compressor adopts multiple restrictive ring type seal combined labyrinth oil seal structure (Ingersoll Rand Company, Installation Manual), in which the multiple restrictive ring type seal prevents the leakage of compressed air and the labyrinth oil seal prevents the leakage of lubricating oil. In this structure, a small amount of compressed air may enter the lubricating oil and be vented through the breathing cap set on the compressor casing and lubricating oil tank. However, this structure is obviously not suitable for steam compression, the lubricating oil will be gradually contaminated after the steam condensate even if a small amount of steam enters the lubricating oil, which will affect the safe operation of steam compressor.

2. There are many types of shaft seals for oil-free twin-screw process gas compressors, including:

(1) Multiple restrictive ring type seal: this seal is the conventional structure of the early oil-free twin-screw process gas compressor (Kammerer, 1972). As the process gas is usually flammable and explosive, and sometimes may pollute the lubricating oil, N_2 is injected both in suction side and discharge side, compared with the similar structure of air compressor. Since the process gas component often contains N_2, a small amount of N_2 leaking into the process gas will not have a great impact on the purity of process gas, which can effectively avoid the mutual pollution between process gas and lubricating oil. By using compressed air instead of N_2, this sealing structure has good sealing effect in steam compression (Tian et al., 2020), but compressed air enters steam as non-condensable gas, which may accumulate near the interface and reduce the interface saturation temperature (corresponding to the interface steam partial pressure) (Kuhn et al., 1997). Then it affects the steam condensation and heat transfer effect.

(2) Oil lubricated mechanical seal: because multiple restrictive ring type seal needs to consume a lot of N_2 from the long time. With the increase of operation time, the wear of ring will further increase the N_2 consumption. Therefore, the oil lubricated mechanical seal is used in some applications with small and medium flow rate. The pressured lubricating oil is supplied to the rotating faces of mechanical seal, which can effectively prevent the leakage of process gas (Bowerman et al., 2020). When the mechanical seal works within the reasonable deviation and the process gas allows a small amount of lubricating oil leakage, this seal type has the best economical interest. Because the condensate of the secondary steam generated in MVC device is often reused as reclaimed water or even directly discharged as conventional sewage, and the trace amount of lubricating oil has no effect on its treatment, the oil lubricated mechanical seal is widely used in roots steam compressor and single screw compressor in MVC device. However, for the heat pump steam generation system, some customers are more sensitive to the trace lubricating oil in the steam, which may cause performance degradation and limit its application.

(3) Dry gas seal: with the matured application of dry gas seal in centrifugal process gas compressor, dry gas seal began to expand its application in the field of twin-screw compressor (Cai et al., 2011). Different from the oil lubricated mechanical seal, N_2 is injected into the rotating faces of mechanical seal for dry gas seal. Compared with the oil lubricated mechanical seal, the dry gas seal can operate under high speed and high-pressure conditions for a long time because the interfaces of mechanical seal are not directly contact. There is no risk of pollution by lubricating oil. It is an ideal structure for shaft seal of oil-free twin-screw process gas compressor. However, the biggest challenge of dry gas seal for steam compression is the high cost of seal itself and an auxiliary control system needed, which is often unacceptable to some customers.

The physical properties of water vapor are different from air and process gas, which determines its applicable and favorable sealing types. The steam compressor needs to strictly prevent the leakage of lubricating oil and non-condensable gas. A small amount of softened water enters the compressor, it will not be affected. Therefore, changing the sealing medium of oil lubricated mechanical seal (or dry gas seal) from lubricating oil (or N_2) to water can effectively solve the shaft seal problem of twin-screw steam compressor.

Figure 2 shows the schematic diagram of water lubricated mechanical seal on the exhaust side of deigned steam compressor. A labyrinth seal is set between the mechanical seal and the rotor, and a balance port A is designed in the middle of the labyrinth seal. The high-pressure steam at the exhaust port returns to the suction port through the balance port A and balance pipe. After being pressurized by a water pump, the cooled and filtered seal water is injected into the mechanical seal through the seal water inlet A, and the seal water returns to the seal water tank through the seal water outlet C. An oil seal is set between the mechanical seal and the bearing, so that a cavity is shaped between the mechanical seal and the oil seal. If the mechanical seal and the oil seal are damaged, the leaked sealing water or lubricating oil enters the cavity with a liquid level sensor through the leakage detection port D. A drain port is also set at the bottom of the cavity. Once the liquid level accumulates in the cavity, it can be detected and judged whether the oil seal is damaged or not by opening the drain valve. Due to the existence of the cavity, the steam and lubricating oil do not pollute each other. With the setting of leakage port and cavity, even if the mechanical seal and oil seal are damaged, they can be effectively monitored without stop the normal operation of the compressor. The water lubricated mechanical seal is shown in Figure 3.

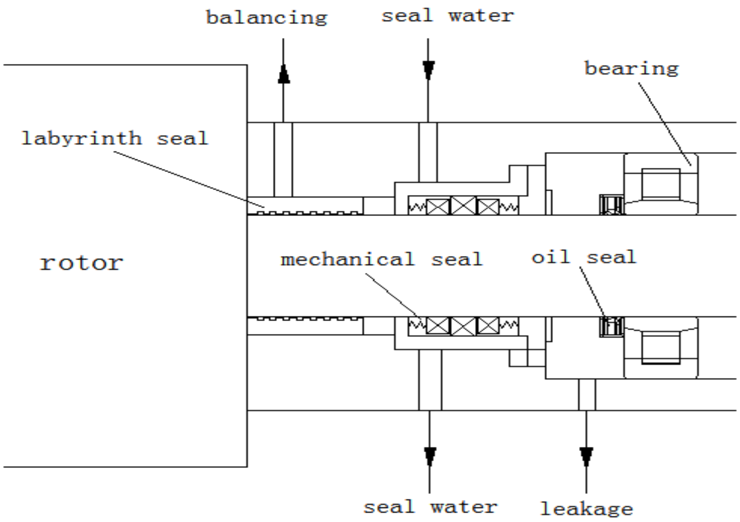

Figure 2: Schematic diagram of water lubricated mechanical seal

Figure 3: Picture of water lubricated mechanical seal

To ensure the good operation of water lubricated mechanical seal, a reasonable water supply parameter is well designed and shown in Table 1. There is detailed information for the design and selection of water lubricated mechanical seals (Fan et al., 2017).

Table 1: Water supply parameters of steam compressor seal

Pressure of water supply (MPaG)	0.4

Pressure of water return (MPaG)	0.1
Temperature of water supply(°C)	<40
Amount of water supply (kg/h)	5000

4. COMPRESSOR MODER

The twin-screw steam compressor with water injected is the significant component for the VHTHP system, as its performance bears significant impact on the system performance. To evaluate the performance of the twin-screw compressor developed, the amount of injected water needs to be determined to ensure the saturated steam discharged at the exhaust port (Wu et al., 2020). To simplify the simulation process, the following assumptions are made to establish the mathematical model:

1. The heat losses to the environment in the compressor are negligible.

2. The change of gravitational and kinetic energy of the steam and water are negligible.

3. In the calculation, the pressure and temperature of steam and water are homogeneous, respectively.

For mass balance.

$$m_{si} + m_{wi} = m_{so} \tag{1}$$

Where m_{si} is the mass flow rate of suction steam, kg·s^{-1}, m_{wi} is the mass flow rate of injected water, kg·s^{-1}, m_{so} is the mass flow rate of supplied steam, kg·s^{-1}.

For energy balance

$$m_{si}h_{si} + m_{wi}h_{wi} + W_{ia} = (m_{si} + m_{wi})h_{so} \tag{2}$$

Where h_{si} is the enthalpy of suction steam, kJ·kg^{-1}, h_{wi} is the enthalpy of injected water, kJ·kg^{-1}, η_i is the indicated efficiency of steam compressor, h_{so} is the enthalpy of supplied steam, kJ·kg^{-1}.
For actual steam compressor

$$W_{ia} = [m_{si}(h_{soa} - h_{si}) + m_{wi}(h_{soa} - h_{wi})\ ]/\eta_i \tag{3}$$

Where h_{soa} is the output enthalpy of adiabatic compression, kJ·kg^{-1}, η_i is the indicated efficiency of steam compressor.

The mass flow rate of injected water(m_{wi}) and suction steam(m_{si}) can be calculated by Eq.(1)~(3).

The calculated operating conditions of steam compressor are shown in Table 2.

Table 2: Designed operating conditions of steam compression

Suction condition	Pressure(kPaA)	47.36
	Temperature(°C)	80
	Mass flow(kg/h)	674
	Water injected(kg/h)	145
Discharge condition	Pressure(kPaA)	476
	Temperature(°C)	150
	Mass flow(kg/h)	819

5. EXPERIMENTAL TEST

The developed VHTHP is used in pharmaceutical factories. To generate 150°C high temperature steam for process heating, the cascade air source heat pump is used to produce hot water at the temperature of 80-85°C, then the hot water flash to saturated steam at the temperature of 78-83°C. The saturated steam is sucked by the developed twin-screw steam compressor, and is pressurized to required high temperature steam. The picture of the developed twin-screw steam compressor is showed in Fig 4. The pharmaceutical industry has high requirements for the quality of steam (BS EN 285,2015). It is required that the quality of steam supplied by the steam generation system is equivalent to that directly generated by the general boiler. It is not allowed to contain any lubricating oil, and the leakage of non-condensable gas is strictly limited (especially the non-condensable gas, such as compressed air, which may contain less lubricating oil). Under such requirements, water lubricated mechanical seal becomes the best solution.

Figure 4: Picture of the developed twin-screw steam compressor

After testing for 168 hours, the VHTHP operates well at the ambient temperature of 0-20°C. The maximum steam supply temperature reaches 155°C, that is to say, the maximum temperature lift of heat source and heat sink is about 150°C. The water lubricated mechanical seal used operates well to ensure the purity of steam supply. The experimental data of part load was recorded in Table 3. It can be seen that the temperature difference between the supply and return water of the mechanical seal recorded in the test is within 6.1°C, which meets the design requirements of mechanical seals. (API STANDARD 682, 2014)

Table 3: Experimental data of steam compressor (part load)

Suction condition	Pressure(kPaA)	44.19
	Temperature(°C)	78.2
Discharge condition	Pressure(kPaA)	474.7
	Temperature(°C)	149.9
	Mass flow(kg/h)	629
Power	Driving motor(kW)	138
Seal water	Mass flow (kg/h)	4760
	Supply temperature(°C)	35.2
	Return temperature(°C)	41.3

6. CONCLUSION

Based on the simulation and on-site test results, the achievements are summarized as follows:

1. Based on the cascade heat pump combined twin-screw steam compressor, a VHTHP with maximum temperature lift of 180K is proposed.

2. The suitable type of shaft seal for twin-screw steam compressor is discussed. By comparison, the water lubricated mechanical seal is considered the best solution for the shaft seal solution of twin-screw steam compressor because it can eliminate the possibility of mutual pollution between steam and lubricating oil.

3. The developed twin-screw steam compressor with water injected has been successfully applied in VHTHP for high temperature steam supply. The test results show that the steam supply pressure and temperature are stable, and the water lubricated mechanical seal is reasonable and reliable.

NOMENCLATURE

h	specific enthalpy,	$kJ \cdot kg^{-1}$
m	mass flow rate	$kg \cdot s^{-1}$
w	power consumption	kW
η_i	indicated efficiency	(–)
Subscript		
si	suction steam	
so	supplied steam	
wi	injected water	

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