2014

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Development of an Industrial High Temperature Heat Pump with Twin Screw Compressor

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ABSTRACT

In industrial applications, 90-150℃ hot water needed during production processes is traditionally provided by fuel-fired boilers. The use of fuel-fired boiler has a low efficiency of energy usage and potential danger of explosion. By-produced 30-60℃waste water with large amount of energy is rejected to environment directly, which causes a great energy loss and thermal pollution. Seeking for a high efficiency and safe heating equipment is essential to replace boilers used for now. High temperature heat pump (HTHP) is an ideal solution to reuse the energy in waste water and produces hot water needed. It has a higher efficiency than boilers through the use of energy contained in waste water. Water temperature provided by high temperature heat pump could reach up to 90-120℃. In this paper, an industrial high temperature heat pump with twin screw compressor was developed. For operating at high condensation and evaporation temperature safely, the twin screw compressor used in high temperature heat pump was modified, like the built-in ratio and motor capacity. Moreover, extensive experimental tests were carried out under several working scenarios. In this paper, High temperature heat pump could provide up to 95℃ hot water with coefficient of performance (COP) changed from 3.5-4.3. The 1700kW heating capacity fully met the requirement in industrial heating field. Motor temperature of compressor was lower than 85℃ during the test period and the modified compressor kept work stability of the high temperature heat pump.

1. INTRODUCTION

Heat pumps now are widely used in household and commercial heating for its higher heating efficiency than electrical heating and higher safety level than fuel-fired boilers. This technique can provide 40-60℃ hot water for room heating or directly usage at the ambition temperature lower than -10℃. For now, much research on heat pump made it a mature technology and had been replaced many boilers for its running safety and high heating efficiency. But in industrial regions, like crude oil heating in oil treatment station or yarn dyeing processes, there exists large amounts of requirement for 90-120℃hot water. The hot water needed is commonly provided by fuel-fired boilers with a low heating efficiency and a potential danger of fire or explosion. The use of oil or coal by the boilers in urban area causes air pollution and special skilled staffs are needed for boiler operation.

High temperature heat pump was an ideal solution for the hot water supply. High temperature heat pump could provide 90-120℃ hot water expanded the usage of heat pump into industrial. Considering total heating capacity needed in industrial usage, twin screw compressor was a better choice for its bigger discharge volume. Different form the traditional work condition of heat pump, high temperature heat pump always had a high evaporation temperature for temperature of the waste water. The raise of hot water temperature increased the condensation temperature of heat pump and caused series problems. Discharge temperature increased with condensation temperature and may lead to decomposition of lubricating oil in compressor. For twin screw compressor, higher temperature caused rotor deformation and even broke the compressor rotors. Motor capacity should be modified for the high evaporation temperature and strategy of motor cooling also need to be redesigned. A model to study the flow and thermal behavior of semi-hermitic twin screw compressor was developed by He *et al.* (2013). The validated model could accurately predict the temperature distribution inside the motor. Hsieh *et al.* (2011) proposed a mathematical model and calculation procedure to calculate temperature distributions in the male and female rotor of the oil-injected screw compressor. Some CFD analysis and dynamic simulation was done to improve the accuracy of theoretical analysis. Liu *et al.* (2012) developed a screw compressor model for refrigeration system simulation and the model could be used to optimize the built-in volumetric ratio of screw compressor. Those models provided convinced references for the compressor design (Rane *et al.* 2011, Fu *et al.* 2011, Wu and Chi, 2013).

Much research had been done on the twin screw compressor used in air condition and heat pump. In this paper, a high temperature heat pump with modified twin screw compressor was developed. Modification of compressor for high temperature was given and extensive experimental tests were carried out. Research showed that high temperature heat pump can supply 95℃ hot water with excellent system performance and fully meet the requirement in industrial field.

2. MODIFIED COMPRESSOR

Waste water temperature in industrial regions was always high. High temperature heat pump here had higher evaporation temperature than regular heat pump. Twin screw compressor used should to be modified to accommodate challenges caused by the change of work condition.

2.1 Power Capacity of Motor

Higher evaporation temperature leaded to a small specific volume of refrigerant in suction line and big mass flow rate of refrigerant in compressor. Big mass flow rate raised the power consumption of compressor. Common compressor designed for air conditioning or regular heat pump was failed to work at the high evaporation temperature for its motor capacity. When compressor directly used in high evaporation temperature, the motor would be running in overload condition. Long time overload running increased current of the motor and would raise the motor coil temperature. For a direct usage of compressor on market, evaporation temperature or the superheat of refrigerant should be limited for the safety running of the motor. For twin screw compressor designed for high temperature heat pump, the motor capacity should be enlarged.

2.2 Structure of Motor

For air condition system, refrigerant from evaporator was reheated when flowed through the compressor motor. The compressor motor was cooled down by the refrigerant evaporation and kept at a reasonable temperature level. But for high temperature heat pump, refrigerant came from evaporator had a high temperature and the effect of motor cooling was weakened. Bad cooling caused a temperature raise of the motor. Long time running at high temperature was bad for the compressor motor.

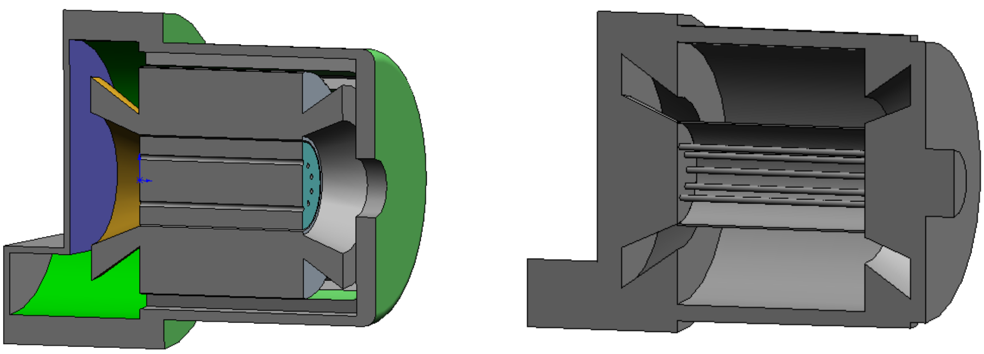

Figure 1: Models of compressor motor and refrigerant flow channel

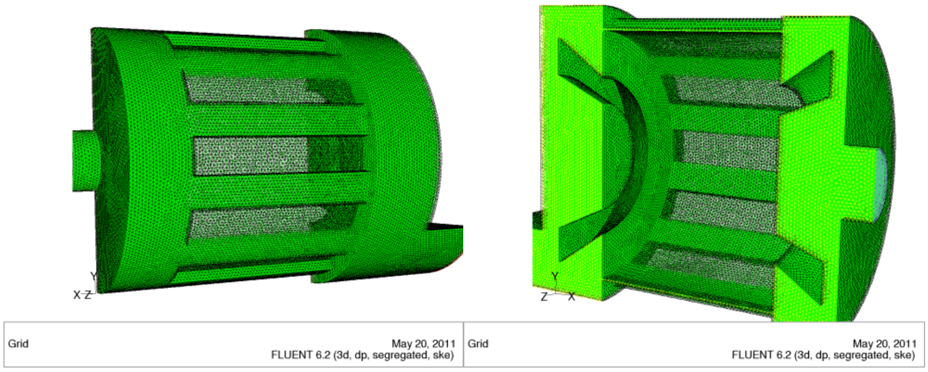

Figure 2: Meshing generation of flow channel

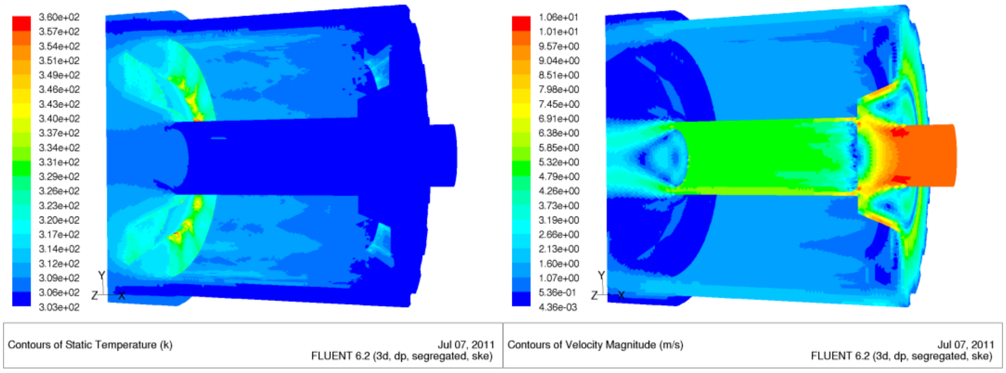

Figure 3: Contours of static temperature and velocity magnitude with inlet temperature of 30℃and power comsumption of 67.8kW

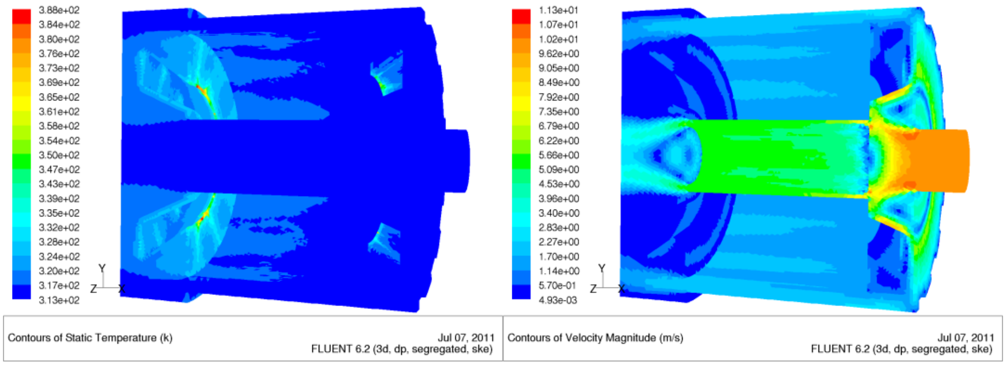

Figure 4: Contours of static temperature and velocity magnitude with inlet temperature of 40℃and power comsumption of 69kW

A CFD-based theoretical analysis was made to show the temperature distribution of compressor and refrigerant velocity in the motor chamber. Refrigerant here was R134a and treated as an ideal gas for simulation. Models of compressor motor and flow channel are presented in Figure.1. A cutaway view was made to show the inner structure of the motor and flow channels for refrigerant. Meshing generation of the model is shown in Figure.2. Mesh element model was tetrahedron and the mesh size was 1mm.

To show the temperature and velocity distribution, a comparison between inlet temperature of 30℃ and 40℃ was made. Contours of static temperature and velocity magnitude at different work conditions can be seen in Figure.3

and 4. In the figures, we could see that temperature of refrigerant in motor chamber was not uniform distribution but gradient distribution. Refrigerant temperature was low at mostly space of the motor chamber but increased sharply around the coil. The closer to the motor coil, the higher temperature of the refrigerant was. Highest temperature even reached to 110℃ some special point. High temperature here badly weakened the heat dissipation of motor coil and may destroyed coil or insulation varnish outside the coil. The much higher temperature around the motor coil can be explained by the difference velocity of refrigerant in the motor chamber. Lower velocity decreased heat convection between motor coil and refrigerant and then leaded to a sharp temperature lift near the coil. Structure of motor chamber affected the refrigerant velocity and should be adjusted to increase the refrigerant velocity at extra high temperature points in motor chamber.

2.3 Built-in Volume Ratio

For now, most twin screw compressor on market was designed for refrigerants of R22, R134a and R404a. Those refrigerants had a good performance when used for regular heat pump or air conditioning. But for high temperature heat pump, those refrigerants had no advantage over other refrigerants like R124 or R245fa. For a new refrigerant, the existing discharge location and area did not match the built-in ratio needed. As shown in Figure.5, under compression process (a)) and over compression process (b)) were two common processes during the compression. The mismatch between design pressure and system back pressure leaded to an energy loss and work increment of compressor. Twin-screw compressor's built-in ratio should be adjusted to maintain high volumetric efficiency of new refrigerant.

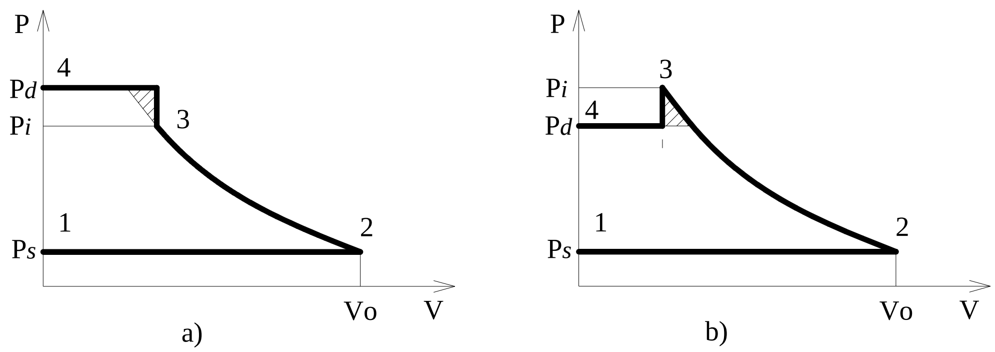

Figure 5: Compression process on P-V diagram

2.4 Bearings

Bearings used in compressor directly influenced the running ability and life of the compressor. When the compressor applied in high temperature, changes of suction and discharge pressure changed the stress distribution on screw rotor and then on the bearings. For a specific twin screw compressor, force analysis should be done to ensure the work stability of bearings.

2.5 Rotor Clearance

Clearance of rotor was an optimal value for the twin screw compressor considering its deformation of heat and gas leakage ratio. But for a higher condensation temperature heat pump, the temperature of screw motor was higher than the regular usage conditions. The deformation of rotor was bigger and might cause interference of twin rotors. Enlarging the clearance of rotor to seek a new balance of rotors deformation and leakage ratio was one choice. While seeking new material was another solution for the heat deformation of rotor.

3. HIGH TEMPERATURE HEAT PUMP

High temperature heat pump designed for industrial heating should provide at least 90℃ hot water and have a big heating capacity. A specific heat pump for providing hot water was designed and its schematic diagram and picture were shown in Figure.6. Whole system was made of two units to increase total heating capacity. Condenser and evaporator were shell and tubes and were shared by those two units. Water flowed in evaporator was waste water during the industrial process and used to be discarded into environment directly. Water in condenser was cycle used to provide heat for user. An oil plate heat exchanger was adopted in heat pump system to cool down lubricating oil temperature of the compressor. Refrigerant temperature before the expansion valve was high and might exceeded the working temperature of common used electrical expansion valves when the heat pump system worked at high condensation temperature. Here in the high temperature heat pump, hand-operated valve was used as the expansion valve. R245fa was used here in the high temperature heat pump.

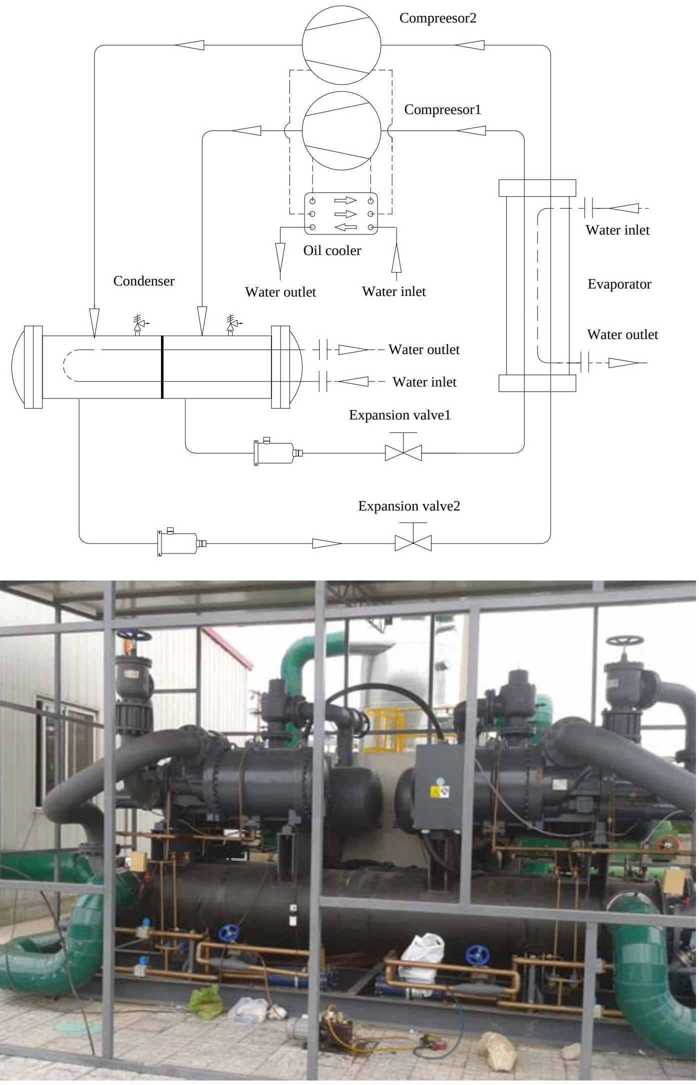

Figure 6: Schematic diagram and picture of high temperature heat pump

4. EXPERIMETAL RESEARCH

Experimental research on high temperature was conducted in an oil treatment station. Water by-product with crude oil was used as heat source in evaporator and its temperature ranged from 55-65℃. Water for crude oil heating was heated in the condenser. The heat pump unit had been running for about 6000h in the oil treatment station and a 72h running period data was used to show its performance. Data used here was acquainted every two hours.

Total heating capacity of the system is calculated by the heat balance in condenser, ignoring the heat loss. The value is calculated by Eq. (1).

$$Q=cm(T_{outlet}-T_{inlet}) \quad (1)$$

where m is the flow rate of water, T_{outlet} and T_{inlet} are the water temperature of outlet and inlet of the condenser. Power consumption of compressor, water pump and the controlling system is recorded by a power analyzer. Power consumption of the heat pump is given by Eq. (2).

$$W_{total}=W_{comp}+W_{pumps}+W_e \quad (2)$$

where W_{comp} is power consumed by compressor, W_{pumps} is consumed by water pumps for condenser and evaporator, W_e is other power consumption of the heat pump unit.

Coefficient of performance (COP) of heat pump is calculated by Eq. (3).

$$COP=Q/W_{total} \quad (3)$$

Figure.7 shows the variation of condenser and evaporator inlet and outlet water temperature. Evaporator outlet water temperature changed from 58℃ to 65℃ with time. The outlet water temperature varied from 90-95 ℃in the test period. 90-95℃ hot water supplied by heat pump met heat requirement of oil treatment station well. The use of high temperature heat pump could directly replace the traditional used boilers with the comparable temperature hot water.

Figure.8 presents the heating capacity and COP changes with time. Heating capacity changed from 1400kW to 1750kW due to the different evaporation temperature. COP of the heat pump had a fluctuant value of 3.5-4.3, which was much higher than the heating efficiency of oil-fired or gas-fired boiler. A common heating boiler used in the treatment station had heating capacity of 1700kW. The reasonable heating capacity and high heating efficiency made high temperature heat pump a competitive replacement of the boilers.

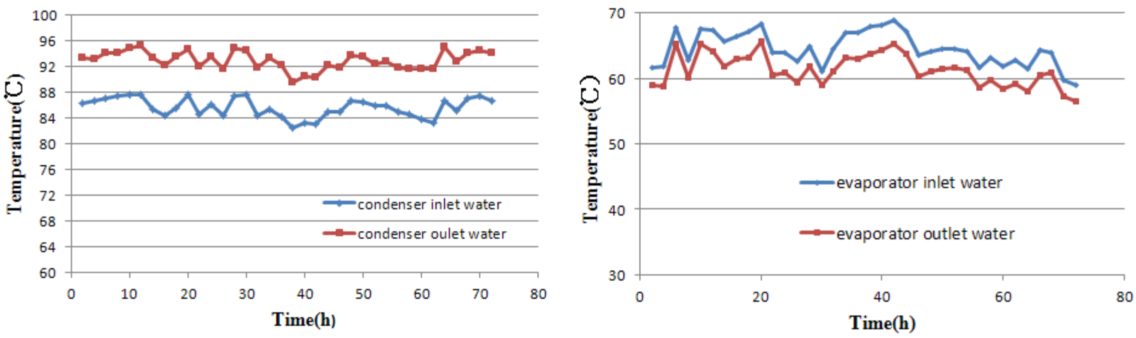

Figure 7: Inlet and outlet water temperature of condenser and evaporator variations with time

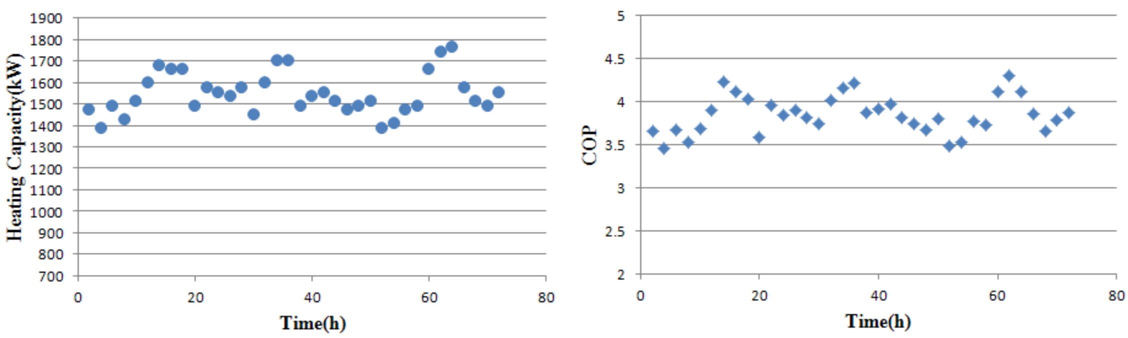

Figure 8: Variations of heating capacity and COP with time

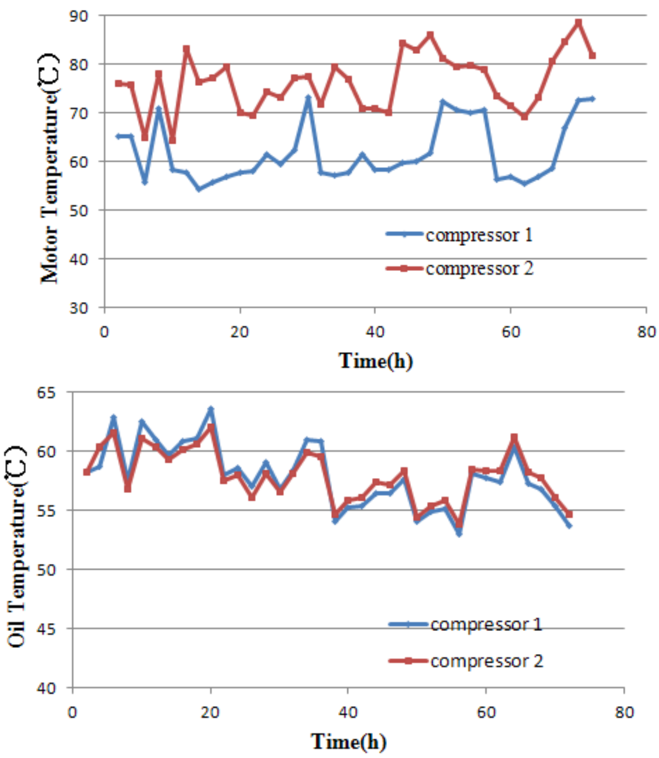

Figure 9: Variations of motor temperature and lubrication temperature with time

As we mentioned before, the work stability of compressor kept the stable running of the heat pump. Motor temperature and oil temperature changes with time are showed in Figure.9. Motor temperature was measured by a PT100 placed near the motor coil. Motor temperature was lower than 85℃ during the test period and reached to 90℃ only once at work period. Lower than 90℃ temperature indicated the function of modifications though we did not measure the temperature details of compressor due to the limitation of equipment. Modification of the compressor could help the compressor working more safely and efficiency. Lubricating oil temperature was well controlled by the use of plate oil cooler. Oil temperature back to compressor maintained between 53℃ and 63℃ during the test.

5. CONCLUSIONS

To expand the usage of heat pump in industrial heating, a new high temperature heat pump with twin screw compressor was presented in this paper. Twin screw compressor was modified to accommodate series changes caused by the work conditions, like high condensation and evaporator temperature. An experimental research was conducted on the performance of compressor and high temperature heat pump. Conclusions were presented as followed.

High temperature could provide up to 95℃ hot water with heating COP of 3.5-4.3, which made high temperature heat pump more competitive heating equipment than other heating equipment. Up to 1700kW heating capacity expanded the usage of heat pump into industrial heating to replace the common used boilers.

Modification twin screw compressor for high temperature was available and kept its performance at the work condition. Enlarged motor capacity and redesigned structure of motor chamber was essential to the compressor. Motor temperature was controlled well at high evaporation temperature of 55-65℃.

NOMENCLATURE

CFD	computational fluid dynamics	
COP	coefficient of performance	
HTHP	high temperature heat pump	
Q	heating capacity	(kW)
V	volume	
W	power consumption	(kW)
P	pressure	(MPa)
T	temperature	(℃)
Subscript		
comp	compressor	
d	discharge	
e	else components	
i	built-in	
s	suction	

REFERRANCES

Fu, L., Ding, GL., Zhang, CL., 2003, Dynamic simulation of air-to-water dual-mode heat pump with screw compressor, Applied Thermal Engineering, vol. 23, no. 13: p. 1629-1645.

Hsieh, S.H., Shih, Y.C., Hsieh, WH., Lin, F.Y., Tsai, M.J., 2011, Calculation of temperature distributions in the rotors of oil-injected screw compressors, International Journal of Thermal Sciences, vol. 50, no. 7: p. 1271-1284.

He, ZL, Xing, ZW., Chen, WQ. , Wang, XL. , 2013, Thermal and hydraulic analysis on the flow around the motor in semi-hermetic twin screw refrigeration compressors, Applied Thermal Engineering, vol. 58, no. 1: p. 114-124.

Liu, JH., Li, QG., Wang, FZ., Zhou, L.,2012,A new model of screw compressor for refrigeration system simulation, *Int. J. Refrig*., vol. 35, no. 4: p. 861-870.

Rane, S., Kovacevic, A., Stosic, N., Kethidi, M., Grid deformation strategies for CFD analysis of screw compressors, *Int. J. Refrig*., vol. 36, no. 7: p. 1883-1893.

Wu, YR., Chi, JW, 2013, A numerical method for the evaluation of the meshing clearance for twin screw rotors with discrete tooth profile points, Mechanism and Machine Theory, vol. 70: p. 62-73.