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School of Mechanical Engineering

2014

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Experimental Research on Vapor Injection High Temperature Heat Pump with an Economizer

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ABSTRACT

Vapor injection technique is often used in cold regions to increase heat pump's heating capacity and decrease discharge temperature at low evaporation temperature. Injecting refrigerant vapor into port opened at specific position of compressor can increase mass flow rate of compressor and condenser. Vapor injection also changes pressure ratio of compression process and decreases discharge temperature. It's a feasible way to improve heating performance of heat pump at cold regions. High temperature heat pump (HTHP) can provide up to 90-120℃ water for industrial usage regions but there exists some problems on its usage. Total heating capacity decreases and discharge temperature increases with the raise of condensation temperature. Refrigerant temperature before expansion valve is high and may exceed working temperature range of common used electronic expansion valve (EEV). Vapor injection technique with an economizer was adopted to solve these problems. In this paper a new high temperature heat pump cycle was designed based on vapor injection and outlets water temperature of the prototype manufactured was reached to 90℃. Heating capacity, discharge temperature, compressor power consumption of the heat pump system at different amount of injected vapor was conducted by theoretical and experimental research. Adopting vapor injection could increase total heating capacity of a certain heat pump unit worked at high condensation temperature. But coefficient of performance (COP) decreased due to the increment of compressor power consumption caused by mass flow rate increment. Refrigerant temperature before expansion valve was well controlled by the usage of economizer in the experimental research.

1. INTRODUCTION

Vapor injection technique is widely used in heat pumps working in cold regions. To heat room space or supply hot water for household usage at low ambition temperature, heat pump works at a lower evaporation temperature. Reduction of evaporation temperature increases pressure ratio of the heat pump and refrigerant specific volume in suction line. Increased pressure ratio decreases compressor volumetric efficiency reduction and also leads to higher discharge temperature. High discharge temperature weakens the function of lubricating oil in compressor and may cause potential damage to the compressor and running stability of heat pump. The decreased volumetric efficiency and increased refrigerant specific volume of suction line causes a sharp decrease mass flow rate of refrigerant and heating capacity. To keep a reasonable heating supplement and discharge temperature, vapor injection technique is often adopted. By injecting refrigerant into compressor through specific port on compressor, refrigerant mass flow rate of condenser is increased as well as the total heating capacity. Vapor injection changes the pressure distribution in compression chamber and makes the compression process similar to a two-stage compression. Discharge temperature is decreased with the change of pressure ratio and keeps at a safety level for long running of compressor. High temperature heat pump provides much higher temperature water for commercial and industrial heating. Evaporation and condensation temperature of HTHP is much higher than that of regular heat pump. For a specific

HTHP for crude oil heating, its condensation temperature reaches up to 100℃ and total heating capacity reaches to 1700kW. This heat pump could recovery heat from 50-60℃ waste water by-produced with oil and heat the crude oil through a heat exchanger. For high temperature heat pump, heating capacity decreased and discharge temperature increased with the raise of condensation temperature. Refrigerant temperature at the outlet of condenser is high and exceeds the working temperature arrangement of commercial available electric expansion valve. To ensure working safety of common throttling valve, some measures are used to provide big sub-cooling for HTHP. Extra cooling water or water from evaporator is often used to get sub-cooling.

Heo et al. (2010) compared four different refrigerant injection strategies to evaluate the heating performance of air source heat pump. Flash tank cycle and combined flash tank and sub-cooler cycle considered to be the better injection cycle for heating performance. Roh and Kim (2012) did a research on two different ways of refrigerant injection, injecting vapor refrigerant into compressor and accumulator selectively. The research showed that injecting refrigerant into compressor increased heating capacity obviously while injecting refrigerant into accumulator decreased discharge temperature effectively but increased heating capacity and COP slightly. Roh and Kim (2014) applied a vapor injection technique in a cascade heat pump system. The research results showed that two vapor injection cycles of low and high stage increased heating capacity and COP of each stage but the cascade system COP was decreased. In cascade heat pump, vapor injection's advantage of improving system COP was not effective. Some other research focused on using different refrigerants to evaluate the performance of heat pump using vapor injection. R410a, R32 and mixture of R22 and R600a were common used be researchers (Cao *et al.*, 2009, Wang *et al.*, 2009, Roh and Kim, 2011, Xu *et al.*, 2013, Xu *et al.*, 2013).

Heat pumps with economizer, flash tank or vapor injector were common ways to complete vapor injection. The open literature focused on reaching biggest COP of heat pump or getting a reasonable heating capacity at different vapor injection pressure or ratio. Little research was done on the combination of HTHP and vapor injection technique for now. To solve the heating capacity decrement at high condensation temperature and also obtain bigger sub-cooling of refrigerant before throttling valve, high temperature heat pump cycle adopted an economizer was presented. Theoretical and experimental research was done to test vapor injection function in high temperature heat pump.

2. SYSTEM DESCRIPTIONS

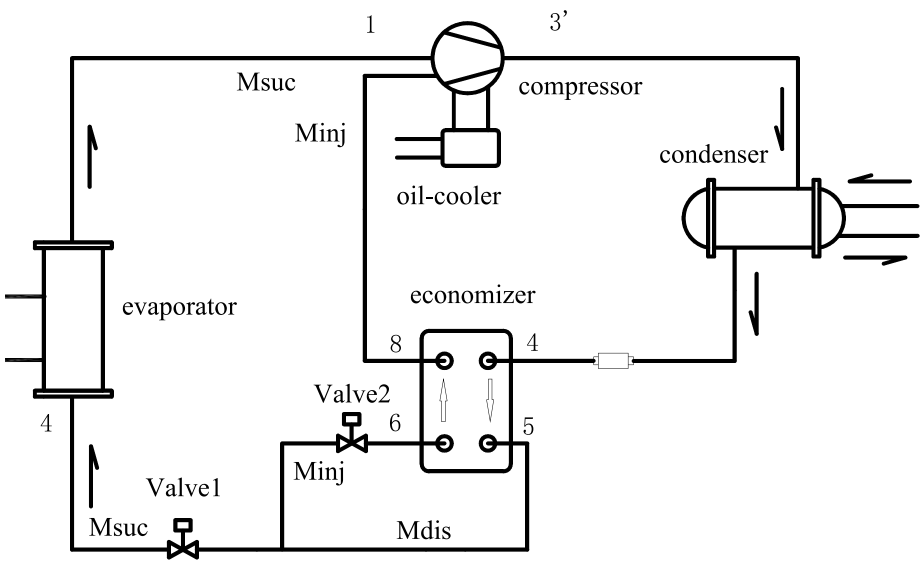

Figure 1: Schematic of HTHP system with economizer

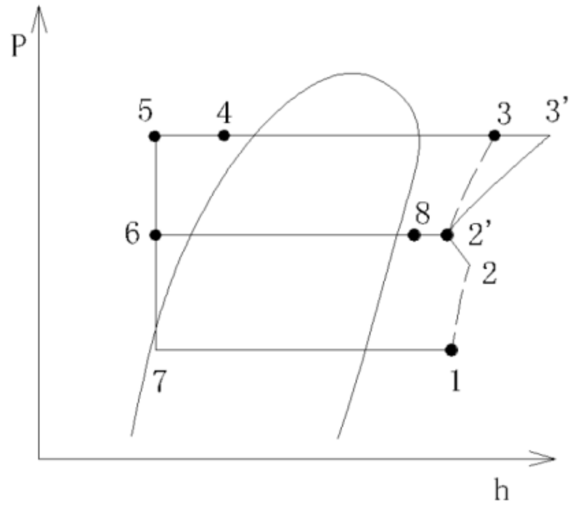

Figure 2: The P-h diagram of HTHP system

Figure 3: Picture of HTHP

Combining the vapor injection technique and high temperature heat pump, a new heat pump cycle was built. The schematic of system is shown in Figure 1 and Pressure-enthalpy diagram of this heat pump system is presented in Figure 2. State point's number on P-h diagram corresponded with the number in Figure.1. Compressor, condenser and evaporator were set same as regular heat pump. An extra economizer was set behind the condenser to complete the vapor injection process. Refrigerant from the condenser flowed through the economizer and then be divided into two parts. One part flowed expansion valve 2 and then flowed back into economizer. Its pressure decreased as well as the temperature after throttling function. This part of refrigerant exchanged heat with refrigerant from the condenser outlet and then the evaporated refrigerant vapor was injected into compressor. The mass flow rate of this refrigerant was defined as M_{inj}. The other part refrigerant flowed through valve1 and then evaporated in evaporator. Mass flow rate of this part refrigerant was defined as M_{suc}. Total refrigerant flowed through condenser was M_{dis} and its value was the sum of M_{inj} and M_{suc}. Figure 3 shows a picture of the tested HTHP.

3. THEORETICAL SIMULATIONS AND ANALYSES

To evaluate the function of vapor injection technique when it was used in high temperature heat pump, a theoretical analysis was made. Theoretical analyses focused on the performance of high temperature heat pump at different vapor injection ratio. During theoretical research, injection pressure was assumed to be a contest value while the vapor injection area was variable. Followed research was all based on this assumption. Common used refrigerant for high temperature heat pump R134a, R124 and R245fa was involved in theoretical comparison.

Considering applications of high temperature heat pump, theoretical heat pump cycle was set as followed: Evaporation temperature and condensation temperature was set to be 35℃ and 100℃ respectively. Indicated efficiency of compressor was 0.65 and the mass flow rate of suction line was set to be 1kg/s for an easier simulation and comparison. State point 4 at the outlet of condenser had a sub-cooling of 5℃. State point 5 at suction line had a super heat of 5℃. Temperature of state point 6 was set to be 55℃ for getting better cooling of refrigerant in the economizer. To maintain the safety running of compressor, refrigerant injected into compressor should be vapor. State point 8 had a super heat of 3℃.

To simplify the theoretical analyses, some assumptions were made as followed. Economizer in the system was isothermal and heat exchanged only between the refrigerant in different flow channels. Steady state heat balance in economizer was calculated by equation (1) and (2).

$$M_{inj}*(h_8-h_6)=M_{dis}*(h_4-h_5) \quad (1)$$

$$M_{inj}+M_{suc}=M_{dis} \quad (2)$$

Refrigerant pressure drop during flowing was ignored and the throttling process was isenthalpic. Compression process in compressor was isentropic and the compressor was adiabatic. Power consumption of the compressor was given in equation (3).

$$W_{comp}=M_{dis}*(h_{3'}-h_{2'})+M_{suc}*(h_2-h_1) \quad (3)$$

Refrigerant injected into the compression chamber under pressure difference and then mixed with that from suction line. Injection port was opened on specific position after calculation. Here used twin screw compressor, the pressure of state point 2 was 1.1 times than that of state point 1. The mixture process in compression chamber was simplified and the energy balance was given by equation (4).

$$M_{inj}*h_8+Msuc*h_2=M_{dis}*h_{2'} \quad (4)$$

In this paper, vapor injection ratio was defined in equation (5).

$$\alpha=M_{inj}/M_{suc} \quad (5)$$

Heating capacity and COP of the HTHP was calculated by equation (6) and (7) in theoretical analyses.

$$Q_{cond}=M_{dis}*(h_{3'}-h_4) \quad (6)$$

$$COP=Q_{cond}/W_{comp} \quad (7)$$

Heating capacity and power consumption of compressor at different vapor injection ratio was shown in Figure 4 and 5. Three refrigerants had the same tendency with the variation of vapor injection ratio. Heating capacity and power consumption increased with the vapor injection ratio. More vapor injection meant more refrigerant flowed through compressor and condenser. Increment of refrigerant mass flow increased the total heating capacity and also power consumption. The R134a heating capacity decrement at the beginning of vapor injection process was caused by the parameter change of state point 3'. Vapor injection decreased the discharge temperature and then decreased the enthalpy difference between the inlet and outlet refrigerant of condenser.

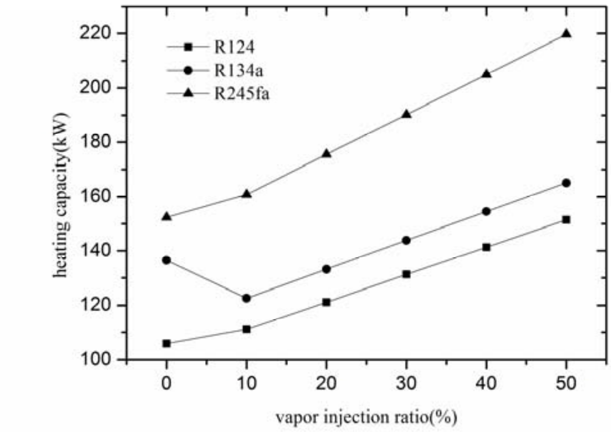

Figure 4: Heating capacity variation versus vapor injection ratio

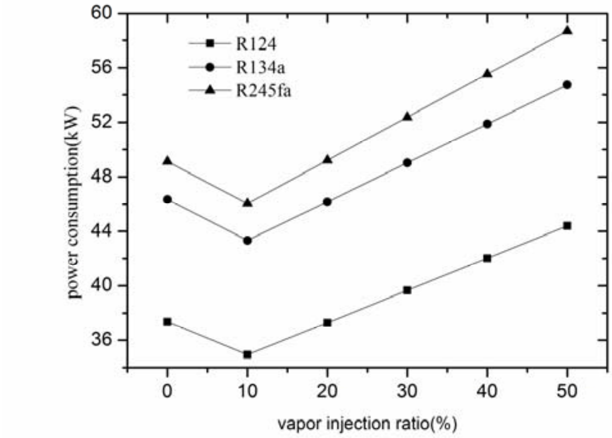

Figure 5: Power consumption variation versus vapor injection ratio

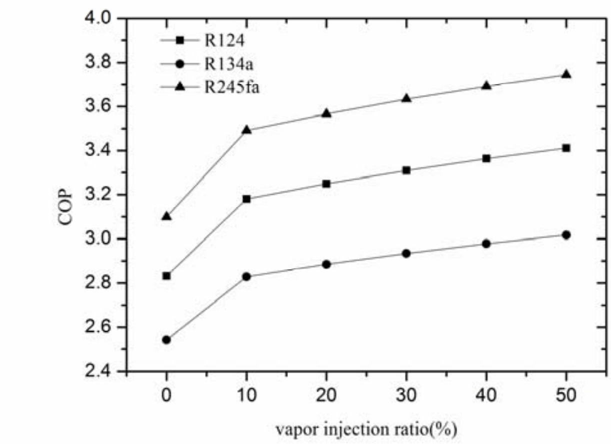

Figure 6: COP variation versus vapor injection ratio

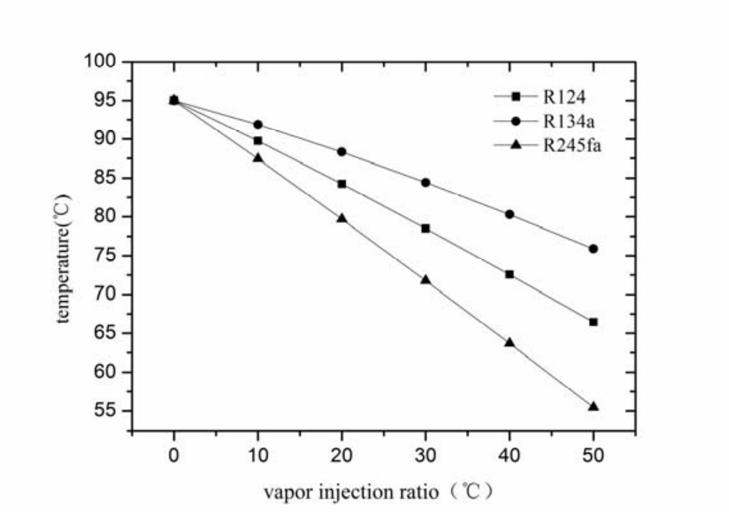

Figure 7: Temperature variation of state point 5 versus vapor injection ratio

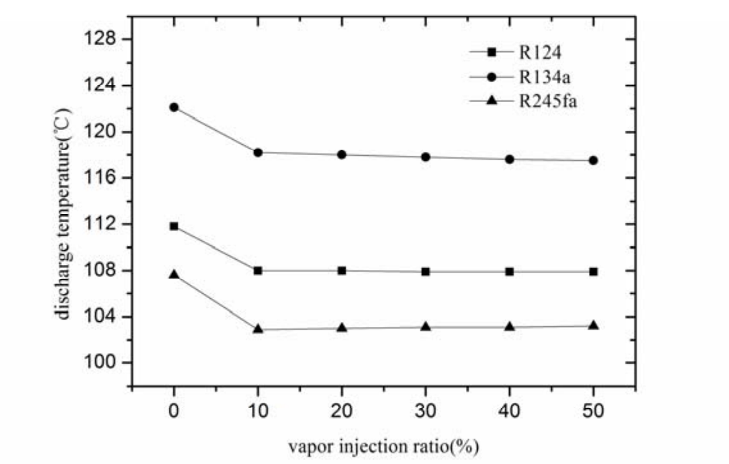

Figure 8: Discharge temperature variation versus vapor injection ratio

COP variation versus vapor injection ratio can be seen in Figure 6. Compared with heat pump without vapor injection, HTHP had a higher COP value. High temperature COP increased with the raise of vapor injection ratio. For R124, 12.3% COP increment was got when the vapor injection ratio reached to 10%.

The COP increment with vapor injection ratio is caused by the increment usage of refrigerant sensible heat. Temperature changes with vapor injection ratio are shown in Figure 7. Value of sensible heat used for economizer was enthalpy difference between enthalpy of state point 4 and 5. With increment of vapor injection ratio, temperature of state point 5 was decreased and more sensible heat was reused and then returned to compressor. State point 5 temperature changed with the vapor injection ratio and its value at different vapor injection was shown in Figure 7. More vapor injection meant lower temperature of state point 5. Lower refrigerant temperature of state point 5 kept the running safety of the EEV.

Discharge temperature variation versus vapor injection ratio is shown in Figure 8. Injecting vapor into compressor decreased the discharge temperature obviously at the beginning of vapor injection. Discharge temperature changed slightly with the variation vapor injection. The function of economizer on controlling compressor discharge temperature at high condensation temperature was proven to be reasonable.

4. EXPERIMENTAL RESULTS AND DISCUSSION

To verify the performance of high temperature heat pump with economizer, an experimental research was done based on the theoretical analyses. After comparison of refrigerant R134a, R245fa and R124 at condensation of 100℃, R124 was chosen as the refrigerant for its thermal properties at the high condensation working condition.

Compressor used here was a modified twin-screw compressor with a vapor injection port specially designed for R124. Condenser and evaporator were shell and tube and the maximum working pressure of condenser was 3.2Mpa. Oil cooler set to control the lubricating oil temperature in compressor and economizer were both plate heat exchangers. Valve 1 was an electronic expansion valve for controlling the mass flow rate of evaporator while valve 2 was a hand-operated valve for controlling the mass flow rate of refrigerant in economizer. For more vapor injection, port on compressor should be designed specially based on the structure of compressor. In testing period, inlet and outlet water temperature of condenser was 82℃and 88℃. Inlet and outlet water temperature of evaporator was 46℃and 43℃. To keep safety running of EEV, the economizer was working all the time and vapor injection ratio we recorded changed from 10% to 22.6% during the whole test.

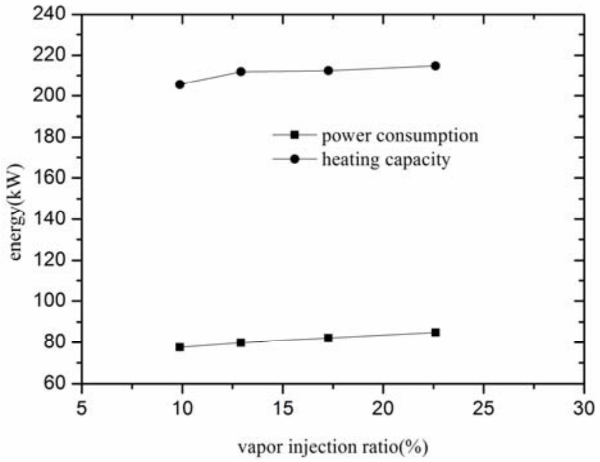

Figure 9: Power consumption and heating capacity of heat pump at different vapor injection ratio

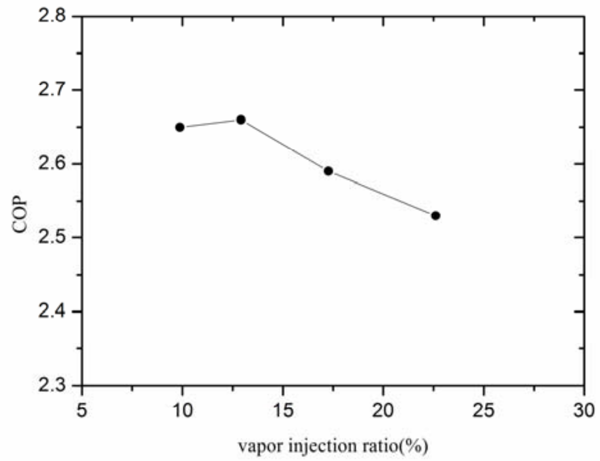

Figure 10: COP variations of heat pump at different vapor injection ratio

Performance of heat pump at different vapor injection ratio is shown in Figure 9 and 10. Heating capacity of heat pump and power consumption both increased with the increments of vapor injection. When the vapor injection ratio changed from 10% to 22.6%, heating capacity and power consumption increased 4.4% and 9.5%, respectively. This tendency agreed the theoretical analyses well and vapor injection did increase the heating capacity. COP increased at the beginning of vapor injection and the decreased with the increment of vapor injection. The biggest COP occurred when the vapor injection ratio was 13%. Here existed a difference between the experimental and theoretical conclusion. This might be caused by the model accuracy of compressor consumption during theoretical analyses.

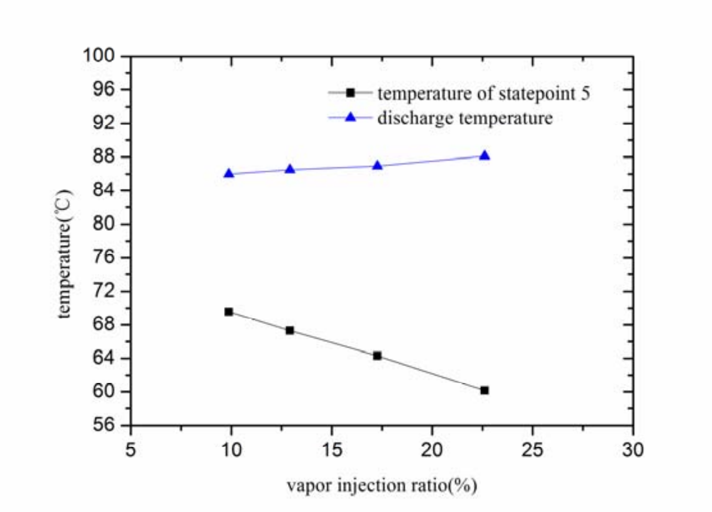

Figure 11: Discharge temperature and temperature of state point 5 variations versus vapor injection ratio

Discharge temperature and temperature before the electronic expansion valve is presented in Figure 11. Discharge temperature rose with the increment of vapor injection. Vapor injection changed from 10%-22.6% while discharge temperature increased only 3℃. Increment on discharge temperature of vapor injection was small and the discharge temperature maintained at a safety value. Bigger vapor injection did not raise the discharge temperature obviously would not cause damage to the compressor.

Refrigerant temperature before the electronic expansion valve (temperature of state point 5) decreased with the ratio of vapor injection. More vapor injection meant a larger enthalpy difference between state point 4 and 5. The refrigerant sensible heat was reused by the economizer to evaporate the injected refrigerant. The lower temperature of state point 5 maintained the stability of electronic expansion valve. The usage of economizer made a great sub-cooling of refrigerant and kept the running of electronic expansion valve.

5. CONCLUSIONS

Adopting vapor injection technique in high temperature heat pump with an economizer was conducted on by theoretical and experimental research. The following conclusion was obtained.

High temperature heat pump could adopt vapor injection technique to increase its heating capacity at higher condensation temperature. The injected vapor increased mass flow rate of condenser and then raised total heating capacity. Adopting vapor injection could increase total heating capacity of a certain heat pump unit worked at high condensation. Power consumption of compressor increased with the vapor injection ratio. Function of vapor injection on COP was slight and also influenced by the characters of refrigerant.

Discharge temperature did not decrease with the increment of vapor injection but increased only 3℃when the vapor injection ratio reached to 22.6%.The use of economizer decreased the refrigerant temperature before electronic expansion valve. This was especially important for the stable working of electronic expansion valve. For high temperature heat pump, an economizer could provide enough sub-cooling of refrigerant and replace other cooling strategy for high temperature heat pump.

NOMENCLATURE

α	vapor injection ratio	
COP	coefficient of performance	
h	enthalpy	($kJkg^{-1}$)
M	mass flow rate	(kgs^{-1})
Q	heating capacity	(kW)
W	power consumption	(kW)
Subscript		
cond	condenser	
comp	compressor	
dis	discharge	
inj	injection	
suc	suction	

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