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Research Paper

Theoretical and experimental investigation of a novel high temperature heat pump system for recovering heat from refrigeration system

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HIGHLIGHTS

- A novel heat recovery system in low temperature refrigeration system.
- Natural refrigerant ammonia is employed and analyzed.
- Specialized semi-empirical model for high pressure twin screw compressor.
- Experimental investigation on compressor and heat pump system performance.

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ABSTRACT

Ammonia has been widely employed as the working media in industrial refrigeration systems including cold chain or pharmaceuticals industry. The condensers of such system are releasing large amount of heat especially in large capacity applications. On the other hand, heating supply at the temperature of 80 °C or even higher is also greatly demanded in related processing systems. High temperature heat pumps, which are capable of recovering heat from condensers of refrigeration systems, could be much more highly efficient compared to boilers or electric heaters. Conventional heat pumps employ heat exchangers on existing refrigeration system condenser, but have much drawback and less efficiency in practical applications. In this paper, a novel system employing higher temperature ammonia twin screw compressors is introduced and analyzed for recovering heat and supplying hot water. A new semi-empirical model is specially developed for high pressure twin screw compressors. Both theoretical and experimental investigations are conducted on such system, while validation of simulation accuracy and efficiency analysis of such system is also given.

1. Introduction

Low temperature refrigeration systems are frequently employed in applications where cooling capacity is required at the temperature lower than −35 °C [1,2]. Natural refrigerant as ammonia, standing out for its excellent thermodynamic, environmentally friendly features and good flowing properties, have been widely applied in large capacity low temperature refrigeration systems [3–5]. On the other hand, in low temperature refrigeration application, heating is also frequently required for processing or manufacturing. In cutting and slicing, distribution or desiccation process, hot water at 80 °C or even higher temperature is greatly demanded. Conventional heat pumps are separately configured with refrigeration systems and the evaporators are heating exchanging with outdoor air. Therefore in winter, the efficiency of heat pump will be quite low. Another option might be combined heat pump and refrigeration systems where the heat pump may recover heat from either condenser, compressor accessories or desuperheater of refrigeration system [6]. Moreover, much heating energy is rejected from the refrigeration system, which is even more than the requirement of supermarkets or cold reservoirs [7]. However, conventional combined system, which combines the refrigeration and heat pump systems using intermediate heat exchangers, has much drawback in recovering heat. The temperature difference in heat exchangers between the heat pump and refrigeration system will inevitably lead to efficiency loss of the whole system, while the energy regulation is also complex to guarantee high efficiency in variable operating conditions. Arias [8] indicated that less than 70% of the necessary heat could be recovered because the heat pump and refrigeration system are coupled through independently controlled heat exchangers. Additionally,

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Nomenclature

AU	heat transfer coefficient (kW/K)
BVR	built-in volume ratio
c_p	specific heat at constant pressure (kJ/(kg·K))
D	diameter (m)
h	specific enthalpy (kJ/kg)
L	length (m)
m	refrigerant mass (kg)
N_u	Nusselt number
n	rotating speed (r/min)
p	pressure (kPa)
P_r	Prandtl number
P	power (kW)
q	fluid flow rate (kg/s)
Q	heat (kJ)
R_e	Reynolds number
s	entropy (kJ/(kg·K))
T	temperature (K)
t	time consumption (s)
u	specific internal energy (kJ/kg)
V_g	control volume (m^3)
V	velocity (m/s)
v	specific volume (m^3/kg)
W	power consumption (kJ)
μ	viscosity (N·m/s^2)
η_v	volumetric efficiency
η_i	isentropic efficiency
λ	heat conductivity efficiency (kW/(m·K))
ρ	density (kg/m^3)

Subscript

in	fluid flow in
out	fluid flow out
H	high-stage
L	low-stage
sh	suction heating
suc	suction
dis	discharge
sp	shaft power
ic	isentropic compressing
sl	simulation
su	supply
nom	nominal
g	gas

the energy equilibrium between heating and cooling remains a big issue for combined systems [9,10].

As a core component of the refrigeration and heat pump system, screw compressors stands out for its excellent efficiency and reliability, while refrigerant injection contributes to a better performance and lower discharge temperature. In CO_2 subcritical refrigeration and NH_3 heat pump systems, the compressor may works at an operating pressure of approximately 5 MPa, so that the performance and stability of its components should be reevaluated. Bingming et al. [11] employ twin screw compressor in NH_3/CO_2 cascade refrigeration system. Experimental results show that its COP is higher than single-stage NH_3 system when the evaporating temperature is below −40 °C. However, limited investigation is made upon natural refrigerant sub-critical high temperature heat pump, especially where screw compressor is employed.

On the other hand, theoretical research on twin screw compressor also attracts much attention. The working process modeling and CFD analysis of twin screw compressor are proved to be significant in analyzing the working process of fluid in compressing chamber and its performance in refrigeration/heat pump systems [12–14]. However, such approaches of performance prediction might be too complex and time consuming for applications in practical engineering. Recently, much investigation has been conducted on developing semi-empirical model for twin screws, Liu et al. [15] developed a new semi-empirical model for semi-hermetic refrigeration twin screw compressor. Either suction preheating, leakage or irreversible efficiency loss is taken into account in predicting the volumetric and isentropic efficiency according to experimental data. Giuffrida [16] proposed a method in developing semi-empirical model for open-type twin screw compressors. With separated stages in working process modeling, more properties of compressor operating conditions could be calculated. However, these models are not specially developed for high pressure twin screw compressors, so that the inter-stage leakage, heat transfer with oil and losses in compressing process are not considered.

In this paper, a novel NH_3 heat pump for heat recovering from low temperature refrigeration system is introduced. A semi-empirical model is proposed to simulate the performance of high pressure NH_3 twin screw compressor employed in the system. The performance of heat pump system is calculated and analyzed under different operating and part-load condition. Experimental facility is also designed and settled to examine the performance of not only heat pump system but also high pressure ammonia screw compressor. The experimental results are applied to prove the accuracy of semi-empirical model, while the change pattern of efficiency and related properties are discussed under different operating conditions.

2. Combined system description

As stated above, conventional heat recovery systems were mainly combination of high temperature heat pumps and refrigeration system through a condensing evaporator. In other words, a series of heat exchangers must be configured to recover heat from the condenser of refrigeration system to supply the evaporation of heat pump system. However, such configuration may lead to not only efficiency loss because of the temperature difference between the condenser and evaporator, but also complexity in energy regulation. An optimized system must be capable of eliminating the temperature difference and efficiently control the heating supply. Therefore, a modified system using NH_3 refrigerant is introduced in this paper for recovering heat from refrigeration system.

Fig. 1 shows how the modified combined system is configured. The NH_3 refrigerant flows though evaporator 6, low pressure compressor 1 and oil separator 2 to be evaporated and compressed. Then it will be divided into two flows. Part of the refrigerant will be condensed in outdoor condenser 3, while the rest is further compressed in high pressure compressor 7 for supplying high temperature heat. In high temperature condenser 9, the high pressure ammonia refrigerant supply heat for the hot water circulation, and is then expanded in expansion valve 10 before mixing with the mid-pressure condensed refrigerant.

The modified system is mainly a two-stage compressing ammonia combined system where mid-temperature condenser is configured for supplementary outdoor condensing. Such system has advantage over the conventional system from several parts.