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Research Paper

Performance analysis of a cascade high temperature heat pump using R245fa and BY-3 as working fluid

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HIGHLIGHTS

- A numerical model was set up for HTCHP system performance analysis.
- Experiments were carried out for HTCHP to validate the numerical model.
- Compressor modifications were done to meet high temperature application.
- 100 °C water temperature lift was acquired based on lots of experiments.
- New-zeotropic refrigerant mixture was applied in low-stage cycle.

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ABSTRACT

A high temperature cascade heat pump (HTCHP) using a near-zeotropic mixture named BY-3 as the working fluid in the low-stage refrigerant cycle and R245fa as working fluid in the high-stage refrigerant cycle was proposed in this study. Several experiments were carried out to investigate the performance of the HTCHP at the evaporating temperature from 40 °C to 60 °C and the water outlet temperature on the condensing unit of the high-stage cycle can reach 142 °C with the coefficient of performance (COP) of 1.72. The results showed that BY-3 was feasible to be used in the low-stage cycle. A numerical model of the HTCHP was proposed and validated in this study to evaluate its performance. The comparison between the experimental results and the simulated results showed that the HTCHP system using BY-3 and R245fa can product hot water at 142 °C with good performance and the temperature lift of the HTCHP can reach 100 °C.

1. Introduction

Environmental concerns such as global warming, ozone depletion, global climate change and air population have become worldwide issues in the past several decades mainly due to anthropogenic activities such as vehicle emission, pollutions from power plants, steel mills, and many other industrial sectors [1,2]. The use of substantial fossil fuels contributes this the most, especially the fuel consumption on the industrial aspect. It was reported that the energy was accounted for more than 70% of China's total energy consumption in 2010. In the U.S., the industrial sector accounted for about one third of the total energy consumed and it was estimated that 20–50% of industrial energy input was lost as waste heat in different forms [3]. Consequently, new technologies that can improve energy efficiency and recover waste heat losses provide an attractive challenge for an emission-free and less-costly energy resource.

The cascade refrigeration system composed of two independent refrigerant cycles was first introduced in 1930s to overcome the disadvantage such as high pressure ratio and low COP of single-stage refrigeration in low-temperature refrigeration systems in the range from −30 °C to −100 °C [4,5]. Hae Won Jung et al. drew the conclusion that the cascade heat pump was much more competitive than single-stage heat pump by studying a cascade multifunctional heat pump using R410A and R134a as working fluids experimentally [6].

Many researches have been done to investigate the performance of the cascade heat pump systems. Wang Bingming et al. performed series of experiments to analyze the impact of different operation parameters on the performance of cascade refrigeration and concluded that the NH_3/CO_2 cascade was competitive in low temperature applications [7]. Alberto Dopazo et al. designed and built a cascade refrigeration system

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Nomenclature

COP	coefficient of performance
EEV	electronic expansion valve
HX	heat exchanger
Cp	specific heat (kJ/kg·K)
m	mass flow rate (kg/h)
P	power consumption (kW)
h	enthalpy (kJ/kg)
T	temperature (°C)
Q	capacity (kW)
HTCHP	high temperature cascade heat pump
P_c	critical pressure (bar)
P_{theo}	theoretical power (kW)
P_{in}	input power (kW)
GWP	Global Warming Potential
ODP	Ozone Depleting Potential
r	latent heat (kW/kg)
Ø	EEV opening degree

Subscripts

w	water
v	vapor
l	liquid
L	low-stage refrigerant cycle
H	high-stage refrigerant cycle
cond	condenser
evap	evaporator
ref	refrigerant
t	total
out	outlet
in	inlet

Greek symbols

ρ	density (kg/m^3)
ω	acentric factor
η_s	volumetric efficiency
η_m	friction efficiency
η_e	motor efficiency
1, 2, 3, 4, 5, 6, 7, 8, 9, 10	state point

with NH_3 and CO_2 to study the system performance and the results accords with the trends obtained from the theoretical researches published in technical literature [8]. Qu Minglu et al. presented a control method of air source heat pump and verified it experimentally and the experimental results showed that the control strategy could realize the control of evaporating temperature and intermediate pressure with high accuracy and sensitivity to adjust the system load variation [9]. Han saem Park [10] set up a mathematical model of R134a/R410A cascade heat pump to predict the optimal intermediate temperature to make sure that the system can run with higher COP based on thermodynamic laws and thermodynamic properties of refrigerants. Dong Ho Kim [11] verified the optimal intermediate temperature by experimental investigation conducted on an air to water heat pump, and the numerical model can predict the experimental results with high accuracy. Hansaem Park [12] et al. studied the performance of a cascade heat pump system by quasi-steady state analysis and Cho [13] et al. investigated a two-stage CO_2 system in cooling mode operation.

As a main contributor to productivity and employment in China, the petroleum refining industry consumed approximately 15% [14] of industrial fuel oil and 10% of industrial coal. During recent years, capacity expansion activities had been carried out for lots of petroleum refining companies, but during the design and construction, the heating capacity between the new and old facilities was not integrated well. Accordingly, lots of low temperature waste heating was produced. Take a 10 million-ton refinery, the low temperature waste heat was about 1000×10^4–12000×10^4 kcal/h, the current comprehensive utilization efficiency was only 30–50%, through comprehensive optimization of low temperature heat, the comprehensive utilization rate could increase to about 70%. In general, its energy saving potential accounted for 10–20% of the total energy saving potential of the refinery.

Although a lot of manpower and material resources was invested to carry on the transformation to the low temperature heat system during China's is "Eleventh Five-Year" period, but depending on the energy-intensive characteristic, more cost-effective investments for energy system optimization may be a useful strategy to improve the competitiveness of China's refining industry.

Based on the current situation of the petroleum refining industry, in this study, a water source cascade heat pump system using a new binary near-zeotropic refrigerant named BY-3 [15] and R245fa as working fluid in the low-stage and high-stage refrigeration cycle, respectively, was studied numerically and experimentally. The system was simulated at different water inlet temperature and the simulated results were validated by the experimental results with high accuracy.

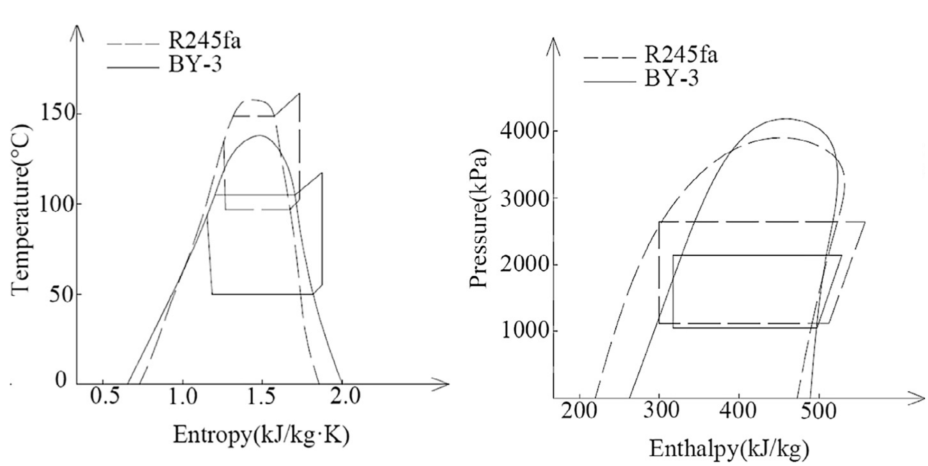

Fig. 1. P-h and T-s diagram of cascade cycle.