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The feasibility of using vapor expander to recover the expansion work in two-stage heat pumps with a large temperature lift

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ABSTRACT

Vapor expanders are introduced for the first time into heat pumps to recover the expansion work. A two-stage heat pump based on the combination of vapor expander and compressor (TSHP-E) is proposed and its feasibility in cold regions is verified theoretically. Two system configurations are modeled for wet refrigerant like R152a, R134a, R161 and R290, and dry fluids including R227ea, R1234yf and R1234ze. Results indicate that wet refrigerants are more suitable for the TSHP-E system under conditions where the evaporating and condensing temperature is −12.0 °C and 65.0 °C respectively. R152a tops all the candidates with a maximum COP of 2.41 and a COP increment of 15.0%. Using mixtures R152a/R227ea (mass fraction 60/40) will reduce the superheating degree in internal heat exchanger by 4 °C compared with R152a without obvious COP decrease. Thermodynamic and economic performance comparison between the proposed system and other two heat pump systems are conducted.

La faisabilité de l'utilisation de détendeur de vapeur pour récupérer le travail de détente de pompes à chaleur bi-étagées avec un écart de température important

Mots clés : Pompe à chaleur bi-étagée ; Détendeur de vapeur ; Mélange de frigorigène ; Analyse thermodynamique ; Analyse économique

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Nomenclature

CEPCI	chemical engineering's plant cost index
C_t	annual cost of the system (¥)
C_d	annual depreciation (¥)
E_{in}	exergy input (kJ)
E_{loss}	exergy loss (kJ)
h	enthalpy (kJ kg^{-1})
IHE	internal heat exchanger
m_r	mass flow rate (kg s^{-1})
NBP	normal boiling point (°C)
P	pressure (MPa)
P_{BP}	payback period (year)
Q	heating capacity (kW)
T	temperature (°C)
T_{SH}	superheat degree (°C)
T_0	reference temperature (°C)
W	rate of work (kW)
x	vapor quality
X	heat profit of the system (¥)
Y	initial investment of the system (¥)
Z	annual operating cost (¥)

Greek symbols

η	efficiency

Subscripts

1,2,3 et al.	the state points
c	cold side stream
COMP	compressor
COND	condenser, condensation
crit	critical
EVAP	evaporator, evaporation
EXP	expander
h	hot side stream
i	inlet, interest
MIX	mixer
o	outlet
PS	phase separator
sw	supply water
VAL	throttling valve

1. Introduction

Among all the existing end-use heating technologies, only the heat pumps have a coefficient of performance (COP) greater than one, which makes it be the most promising heat-supply systems at the present stage. However, the performance of the heat pump deteriorates markedly as the temperature lift (temperature difference between the condensing temperature and the evaporating temperature) increases, which represents a big obstacle to its application in cold climate regions where the lowest temperature could reach 15° below zero in winter.

As the temperature lift increases, the compression ratio will increase greatly leading to the decrease of compressor efficiency. Besides, the discharge temperature continues to increase with the rising compression ratio, resulting in the destruction of compressor unless the heat pump system is stopped (Ma et al., 2003). To cope with these problems, some methods such as using zeotropic refrigerant mixtures (Hakkaki-Fard et al., 2014), multistage cycles (Bertsch and Groll, 2008; Jung et al., 2000), cascade cycles (Kilicarslan and Hosoz, 2010; Kim and Kim, 2014) and modified compressor with supplementary inlet (Ma and Chai, 2004; Wang et al., 2009) have been proposed over the years.

Using multistage vapor compression cycles may be the most direct way to reduce the compression ratio, while the price is that the power consumption also increases since two compressors are installed. However, the extra power consumption is actually not inevitable, and it could be compensated by recovering the expansion work. Kim et al. (2008) tested on a two-stage transcritical CO_2 cycle in which a scroll expander was installed instead of the throttling valve and designed to drive an auxiliary compressor directly. Experimental results indicated that the system COP was improved by 23.5% by recovering the expansion work. Furthermore, higher energy transfer efficiency could be obtained by coupling the expander and compressor as one unit (Zhang et al., 2007). Theoretically, applying two-phase expanders in subcritical vapor compression cycles is also meaningful in improving system performance, however, very few studies on this topic has been reported by far (Xia et al., 2013). This is attributed to two reasons: firstly, the two-phase expansion volume ratio for organic working fluids is larger than that for CO_2, which brings more difficulties in the design and operational control of expanders; besides, the pressure difference across the two-phase expander in a subcritical cycle is smaller than that in a transcritical cycle, relatively less expansion work could be produced as a result.

The vapor expansion, which has been widely applied in ORC, could produce more power in comparison with the two-phase expansion under the condition of the same condensing and evaporating pressures. This difference is related to the different distribution characteristic of the isenthalpic curves in the two-phase region and the vapor phase region in the temperature–entropy (T–s) diagram. As illustrated in Fig. 1, the isenthalpic lines in the two-phase region are relatively steeper than that in the vapor region. Within the two-phase region, the slope of the isenthalpic line increases rapidly as the vapor quality decreases, and reaches the maximum value around the saturated liquid line. Hence, the two-phase expander will produce less expansion work than vapor expander due to the steeper isenthalpic lines. Besides, the vapor phase expander has advantages over the two-phase expander in the design and control of the device since the refrigerants have much smaller volume ratios during the vapor phase expansion.

Inspired by the character of vapor expander, the authors propose a novel method to recover the expansion work in vapor compression cycles. A two-stage heat pump based on the combination of the vapor expander and compressor (TSHP-E) is presented in the present study. The primary