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A proposed subcooling method for vapor compression refrigeration cycle based on expansion power recovery

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ABSTRACT

This study proposes a new subcooling method for vapor compression refrigeration cycle based on expansion power recovery. In a main refrigeration cycle, expander output power is employed to drive a compressor of the auxiliary subcooling cycle, and refrigerant at the outlet of condenser is subcooled by the evaporative cooler, which makes the hybrid system get much higher COP. Various refrigerants, including R12, R134a, R22, R32, R404A, R41, R507A, R717, and R744, are considered. Thermodynamic analysis is made to discuss the effects of operation parameters (expander efficiency and inlet temperature of cooling water) on the system performance. Results show that the proposed hybrid vapor compression refrigeration system achieves much higher COP than the conventional vapor compression refrigeration system, conventional mechanical subcooling system and conventional expansion power recovery system, with maximum COP increments 67.76%, 19.27% and 17.73%, respectively when R744 works as the refrigerant in the main refrigeration cycle. It is most beneficial for R12 and R717 in the auxiliary subcooling cycle and R744, R404A and R507A in the main refrigeration cycle.

Une méthode proposée de sous-refroidissement pour un cycle de compression de vapeur basé sur la récupération de l'énergie de détente

Mots clés : Réfrigération ; Efficacité énergétique ; Sous-refroidissement ; Récupération de l'énergie de détente ; Frigorigène

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Nomenclature

COP	coefficient of performance
h	enthalpy (kJ kg^{-1})
$\dot{m}$	mass flow rate (kg s^{-1})
P	pressure (Pa)
$\dot{Q}$	cooling capacity (W)
s	specific entropy (kJ kg^{-1} K^{-1})
ΔT	temperature difference (°C)
T	temperature (°C)
$\dot{W}$	power consumption (W)
Greek symbol	
η	efficiency
Subscripts	
aux	auxiliary cycle
base	baseline
com	compressor
con	condensing
cw	cooling water
eprs	conventional expansion power recovery system
eva	evaporating
exp	expander
gc	gas cooler
mai	main cycle
mss	conventional mechanical subcooling system
ref	refrigerant
sub	subcooling

1. Introduction

The rapidly growing world energy consumption has already raised concerns over supply difficulties, exhaustion of energy resources and heavy environmental impacts (ozone layer depletion, global warming, climate change, etc.). Refrigeration systems consumed a large amount of energy in maintaining thermal comfort for occupants and suitable climatic conditions for cooling cases, which made up 50% of building energy consumption (Lombard et al., 2008).

Various methods have been proposed to improve the energy efficiency of refrigeration systems. One of the ways is to recover the power loss during expansion. Replacement of the expansion valve by an expander (Lorentzen, 1994; Robinson and Groll, 1998; Nickl et al., 2005; Yang et al., 2009a,b; Subiantoro and Ooi, 2010; Jia et al., 2011; Subiantoro and Oil, 2012; Wang et al., 2012) is a direct measure. The idea was initially proposed to increase the efficiency of the CO_2 refrigeration system (Lorentzen, 1994). An improved structure was suggested by introducing high-pressure gas into the vane slots (Jia et al., 2011). Results showed that the volumetric efficiency was increased from 17% to 35%, and the isentropic efficiency improved from 15% to 45%, resulting in a maximum COP (coefficient of performance) improvement of 27.2%, compared to the throttling cycle under the same working conditions. Subiantoro and Oil (2012) fabricated and tested a revolving vane expander prototype based on the revolving vane mechanism design, where the cylinder was allowed to rotate together with the rotor and the vane, unlike the conventional rotary machines where the cylinders were stationary. The isentropic efficiency was found to be up to 17.5% with the frictional losses caused mainly by the journal bearings. Wang et al. (2012) presented a novel vane-type expander with two internal expansion stages for R-410A system. The study showed that the novel expander obtained built-in volumetric ratio up to 7.6 with the isentropic efficiency of 55.9% at 2000 rpm and theoretically improved the coefficient of performance from 4.0 to 4.56, by 14.2%, under design operating condition. Although replacing the expansion valve with a turbine can significantly improve the performance of CO_2 transcritical cycle, such extensive hardware addition may not be economically feasible for many practical applications, especially for small capacity CO_2 cycle (Sarkar et al., 2005). Subiantoro and Ooi (2013) presented an economic analysis of the installation of expanders on to existing vapor compression cooling systems, particularly medium scale air conditioners. It was found that when the expander efficiency is 50%, the payback periods of most conventional systems are below 3 years in high temperature countries with high electricity tariffs and are above 5 years in other countries. Since basic CO_2 transcritical refrigeration cycle suffers from large expansion loss due to high-pressure difference between gas cooler and evaporator, other measures were proposed include using ejector-expansion device (Li and Groll, 2005; Yari, 2009; Sarkar, 2008; Elbel and Hrnjak, 2008; Yang et al., 2009a,b; Sarkar, 2009; Sun and Ma, 2011; Yari and Mahmoudi, 2011; Cen et al., 2012) to replace the expansion valve. This ejector-expansion device has advantages, such as low cost, no moving parts and ability to handle two-phase flow without damage, making it attractive for the development of high-performance CO_2 refrigeration system (Yari, 2009). Optimization studies along with optimum parameter correlations, using constant area mixing model were presented for ejector-expansion transcritical CO_2 heat pump cycle with both conventional and modified layouts (Sarkar, 2008). He pointed out that the ejector may be the promising alternative expansion device for the transcritical CO_2 heat pump cycle. Elbel and Hrnjak (2008) conducted experimental validation of a prototype ejector designed to reduce throttling losses encountered in the transcritical CO_2 system operation. Their experimental results showed that for the best conditions considered, the cooling capacity and COP were simultaneously improved by up to 8% and 7%, respectively. Sun and Ma (2011) made a comparative study on the transcritical CO_2 refrigeration cycle with ejector and with throttling valve. It was found that ejector instead of throttling valve could reduce more 25% exergy loss and increase COP more 30%. Two new CO_2 cascade refrigeration cycles were proposed and analyzed by Yari and Mahmoudi in 2011. In both these cycles the top cycle was an ejector-expansion transcritical cycle and the bottom cycle was a sub-critical CO_2 cycle. Results exhibited a reasonable value of COP with a much less value of compressor discharge temperature, compared to the conventional cycles. Cen et al. (2012) proposed a novel cycle with two ejectors, and simulation results