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Hybrid vapor compression refrigeration system with an integrated ejector cooling cycle

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ABSTRACT

A refrigeration system was developed which combines a basic vapor compression refrigeration cycle with an ejector cooling cycle. The ejector cooling cycle is driven by the waste heat from the condenser in the vapor compression refrigeration cycle. The additional cooling capacity from the ejector cycle is directly input into the evaporator of the vapor compression refrigeration cycle. The governing equations are derived based on energy and mass conservation in each component including the compressor, ejector, generator, booster and heat exchangers. The system performance is first analyzed for the on-design conditions. The results show that the COP is improved by 9.1% for R22 system. The system is then compared with a basic refrigeration system for variations of five important variables. The system analysis shows that this refrigeration system can effectively improve the COP by the ejector cycle with the refrigerant which has high compressor discharge temperature.

Système frigorifique à compression de vapeur à cycle de refroidissement à éjecteur intégré

Mots clés : Éjecteur ; Système frigorifique ; Système à compression ; Conception ; Performance

1. Introduction

Refrigeration and air-conditioning systems are widely used in air-handling and cooling applications. Improved system performance will reduce energy consumption as well as reduce CO_2 emissions. Decreases of the condensation temperature and increases of the evaporation temperature or the liquid condensate subcooling will improve the COP of the refrigeration system. These improvements are limited in practice since these temperatures depend on the environmental temperature and operating conditions. However, the refrigerant at the compressor outlet is usually quite warm (usually 80–110 °C for R134a and R22 air-conditioning systems); thus, a large amount of energy must be rejected to the environment in the condenser. This waste heat energy can be utilized to increase the refrigeration system performance.

An ejector cooling system driven by low-grade heat energy can effectively use the waste heat to improve the system COP.

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Nomenclature

A	area (m^2)
h	enthalpy ($kJ\,kg^{-1}$)
m	mass flow rate ($kg\,s^{-1}$)
P	pressure (Pa)
Q	heat load (kW)
R	radius (m)
T	temperature (K)
V	velocity ($m\,s^{-1}$)
W	work (kW)
α_{PP}	pressure ratio, P_{13}/P_8
α_{PS}	pressure lift ratio, P_8/P_7
α_A	area ratio, A_m/A_t
η	efficiency
$\Phi_{ej,m}$	coefficient accounting for friction loss during the mixing process
ρ	density ($kg\,m^{-3}$)
γ	gas specific heat ratio
ω	entrainment ratio, m_7/m_{13}

Subscripts

c	compressor
CA	condenser A
CB	condenser B
B	booster
e	evaporator
ej	ejector
g	generator
m	ejector mixing chamber
p	pump
s	isentropic process
sat	saturation state
t	ejector nozzle throat

An ejector based cooling system offers several advantages, such as no moving parts in the ejector, efficient utilization of the waste heat and low cost. Munday and Bagster (1977) used the "effective area A_e" located some distance downstream of the primary nozzle to develop a theoretical model for an ejector. Huang et al. (1999) developed a 1-D analysis to predict the ejector performance based on the constant-pressure mixing assumption. Zhu et al. (2007) and Zhu and Li (2009) proposed a theoretical model for both dry and wet vapor refrigerants using 2-D exponential expression for the velocity distribution in the ejector.

Ejector cooling system applications are restricted by their low COP that is generally around 0.5. The ejector cooling system performance can be improved in various ways including a good ejector design, system optimization and system designs with solar and absorption cycles. Aphornratana and Eames (1997) studied a small-scale steam jet refrigerator, where the optimal system performance was found by adjusting the nozzle position. Huang et al. (2006) and Srisastra et al. (2008) studied ejector refrigeration cycles which used pressure equilibration and gravity to eliminate the mechanical pump. Chen (1998) studied an ejector–absorber cycle with an elevated absorber pressure using a high-pressure liquid solution from the generator as the ejector's motive fluid. Yu et al. (2006) and Yu and Li (2007) proposed an ejector cooling system with an additional jet pump. Their theoretical analysis showed that the system improved the COP but at the cost of more pump work.

The increase in the secondary flow pressure can increase the ejector entrainment ratio simultaneously with the critical back pressure. The compression enhancement by a booster or a hybrid system with a compression cycle can improve the secondary flow pressure of the ejector cooling cycle. Sokolov and Hershgal (1990a,b, 1991) analyzed a compression enhanced ejector system that improved the ejector cycle by combining the mechanical and thermal energies. Sun (1998) studied a combined ejector–compression refrigeration system in which an inner heat exchanger was used to combine the ejector cycle and the vapor compression cycle. Huang et al. (2001) developed a combined refrigeration system with a vapor compression air-conditioning cycle and an ejector cooling cycle. The ejector cooling cycle was driven thermally by the condenser waste heat from the vapor compression cycle. The cooling capacity obtained from the ejector cycle was used to cool the refrigerant after the condenser. Hernández et al. (2004) developed a theoretical analysis on the thermodynamics of a hybrid ejector–compression refrigeration system. The effects of the working fluid and operation conditions on the hybrid system performance were analyzed.

This paper describes a refrigeration system that combines a basic vapor compression refrigeration cycle with an ejector cooling cycle. The ejector cooling cycle is driven by the waste heat from the condenser of the vapor compression refrigeration cycle. The ejector secondary flow is compressed first by means of a booster to ensure that the ejector works at the right conditions. The obtained cooling capacity from the ejector cycle is directly fed into the evaporator of the vapor compression refrigeration cycle. The entire refrigeration system performance is simulated to analyze the effects of the condensation temperature, the evaporation temperature, the pressure ratio, the pressure lift ratio and the ejector area ratio on the system performance. The results are compared with a basic refrigeration system.

2. System description

Fig. 1 shows the basic vapor compression refrigeration system. A compressor is used to drive the inverse Rankine cycle. The high temperature refrigerant at the compressor outlet rejects heat to the environment in the condenser. This waste heat energy can be utilized by an ejector cycle to increase the refrigeration system COP.

The refrigeration system in this study includes the basic refrigeration cycle and a heat driven ejector cooling cycle. The ejector cooling cycle is connected in parallel with the basic refrigeration cycle as shown in Fig. 2. The ejector cycle consists of an ejector, a condenser, a circulation pump, an expansion device and a booster. The ejector is driven by high