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Research Paper

Numerical study and design of a two-stage ejector for subzero refrigeration

Zhaoqiu Ding [a], Lei Wang [a,*], Hongxia Zhao [b], Hailun Zhang [a], Chen Wang [a]

[a] *School of Control Science and Engineering, Shandong University, Jinan, PR China*
[b] *School of Energy and Power Engineering, Shandong University, Jinan, PR China*

HIGHLIGHTS

- A two-stage ejector applied for subzero refrigeration was designed.
- The performance of the two-stage ejector was studied.
- The effects of operating conditions were investigated.
- The two-stage ejector has an optimum entrainment ratio value with the increase of primary flow pressure.

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ABSTRACT

The supersonic ejector-diffuser systems are usually used for cooling by utilizing low-grade thermal energy, but few can be used in subzero refrigeration applications. In this paper, a methodology was proposed and applied to design a two-stage ejector for subzero refrigeration. The two-stage ejector, using R134a as the working fluid, was operated at 63–74 °C generator temperature and −24 °C to 0 °C evaporator temperature. The performance (entrainment ratio) and flow phenomena of the two-stage ejector were predicted by numerical studies using computational fluid dynamics (CFD) to find the best design parameters for a range of operating conditions. Simulation results showed that (1) when secondary flow pressure is constant, the critical back pressure increases with the increase of primary flow pressure, while the maximum entrainment ratio decreases with the increase of primary flow pressure; (2) when primary flow pressure is constant, both maximum entrainment ratio and critical back pressure increases with the increase of secondary flow pressure; and (3) when secondary flow pressure and outflow pressure are constant, the two-stage ejector has an optimum entrainment ratio value with the increase of primary flow pressure, and that the optimum entrainment ratios of 0.0736, 0.0761 and 0.0813 can be achieved when saturated temperature is at −22 °C, −20 °C, −18 °C, respectively. Numerical study results showed that it is feasible that the proposed two-stage ejector is used for subzero refrigeration applications which can benefit for cold chain logistics systems.

1. Introduction

The low-grade energy is widely available from sources such as solar collectors, industrial processes, and automobiles. Ejector cooling system driven by low-grade thermal energy is a promising way for energy conversation in refrigeration applications [1–3]. This study focuses on exploring the application of ejector in refrigerated and frozen areas.

The ejector cooling system was first proposed by Maurice Leblanc in 1910 [4]. The operating cycle of the ejector cooling system is shown in Fig. 1. The high pressure refrigerant flow, heated in the generator driven by low-grade energy, enters the primary nozzle of the ejector, and through nozzle throat at supersonic speed, then causes a low pressure sucking refrigerant flow from the evaporator. The mixing refrigeration flow is cooled in the condenser, and then pumped back to the generator and partly through the expansion valve entering the evaporator to complete the cycle. Comparing to traditional refrigeration system, it has simple structure and stable operating performance with no other moving parts except circulating pump and small energy consumption.

However, the low Coefficient of Performance (COP) of the ejector system restricts its applications in refrigeration. In view of this disadvantage, lots of improved methods have been proposed.

* Corresponding author.
E-mail address: leiwang@sdu.edu.cn (L. Wang).

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Nomenclature

Ar	area ratio
$\dot{m}_p$	mass flow rate of primary flow (kg/s)
$\dot{m}_s$	mass flow rate of secondary flow (kg/s)
$\dot{m}_o$	mass flow rate of outflow (kg/s)
P	pressure (MPa)
T	temperature (°C)
Er	entrainment ratio
Pc^*	critical back pressure (MPa)
NXP	primary nozzle position (mm)

Abbreviation

COP	Coefficient of Performance

Subscripts

c	condenser
e	evaporator
g	generator
1	the first-stage ejector
2	the second-stage ejector

Sokolov [5,6] developed a booster-enhanced ejector refrigeration cycle and a compression-enhanced ejector refrigeration cycle to improve the system COP. Nguyen et al. [7] designed a gravity pumped ejector cycle, but the huge system size limited its applications in practice. Zhang [8] developed solar bi-ejector refrigeration system, and COP of the system can reach 0.2–0.3. Wang et al. [9] presented a novel MEVRC (modified ejector-expansion vapor-compression refrigeration cycles) which uses a two-phase ejector to enhance the overall system performance. The results showed that the MEVRC can get a bigger pressure lift ratio through the ejector and obtain significant improvement of COP. Ziapour and Abbasy [10] discussed a heat pipe/ejector refrigeration cycle which was proved a compact and high performance system. Their results showed that the second law efficiency of the heat pipe/ejector refrigeration cycle increases with increasing evaporator temperature and decreasing condenser temperature and the maximum heat pipe cooling capacity is obtained for large heat pipe diameters. Wang et al. [11] proposed a hybrid air-conditioning (A/C) system which can operate under three modes: compressor, hybrid and ejector. They studied the performance of the system under different modes by experimental investigation, and found the hybrid A/C system has the potential to be adopted in automobiles for the advantages of low cost, durable operation and better energy efficiency.

As the core component of an ejector cooling system, the performance and stability of ejector directly determine the overall system performance. The mixing process of the fluid in ejector is very complicated and lots of experimental and numerical studies have been reported in literature. Keenan et al. [12] proposed a one-dimensional method for analyzing the performance of jet pumps or ejectors. They compared experimental and analytical results and found that they are consistent within a certain range. Munday and Bagster [13] proposed a new theory of ejector

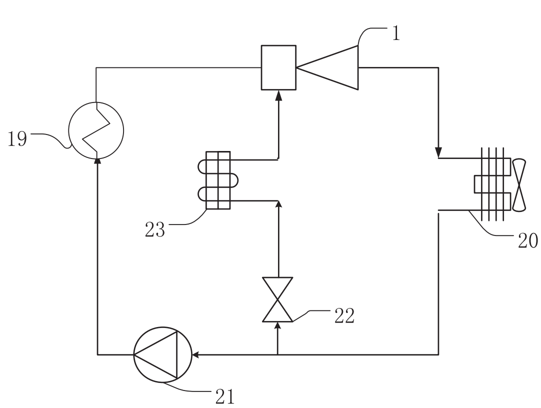

Fig. 1. Schematic diagram of a typical ejector cooling system.

behavior dependent on the assumption of two discrete streams. It is postulated that the secondary vapor reaches sonic velocity and is effectively choked at some cross section of the ejector. Also they thought steam jet refrigeration units should be designed for the most prevailing conditions, rather than the most severe, to achieve greater overall efficiency. Huang et al. [14] built a 1-D analysis model for the prediction of ejector performance at critical-mode operation. It is shown that the1-D analysis using the empirical coefficients can accurately predict the performance of their ejectors. Zhu and Li [15] proposed a novel ejector model and proved it has a good performance for evaluating mass flow rates and the entrainment ratio of ejectors with both dry and wet vapor working fluids at critical operating mode. Khalil et al. [16] developed a mathematical model to design an R134a ejector and to predict the performance of a vapor jet refrigeration system over a wide range of the investigated parameters. It is found that the ejector area ratio at boiling temperature of 85 °C is about double that at boiling temperature of 65 °C for various evaporating and condensing temperatures. Pianthong et al. [17] employed a CFD simulation software to do two-dimensional and three-dimensional simulations of the ejector using water as refrigerant. It is found that the flow pattern does not depend much on the suction zone because the results of axisymmetric and 3D simulation are similar. Also they explored the influence of the working condition and the structure size of the ejector on the ejector performance. Their investigation is helpful for understanding ejector characteristics and provides information for designing the ejector to suit the optimum condition. Yan et al. [18] studied the performance of an ejector with R134a as the refrigerant by both experimental study and CFD simulation. They found that area ratio and NXP are two of the most important and sensitive geometric parameters to the performance of the ejector. They proposed a design method for optimal structure parameters of an ejector. Lin et al. [19] used CFD to investigate the optimum geometry parameters of the adjustable ejector, and the nozzle diverging angle and the length of the constant-pressure mixing section are more important to improve the pressure recovery ratio. Zhu and Jiang [20] proposed a bypass ejector geometry with an annular cavity in the nozzle wall in order to improve the entrainment performance. Also they compared the results with the conventional ejector and found that the bypass ejector has a better entrainment performance (a 31.5% improvement at relatively high primary and secondary flow pressures) than the conventional ejector. Lin et al. [21] investigated the adaptability of an adjustable ejector for changeable cooling loads and the characteristics of ejector pressure recovery in a multi-evaporator refrigeration system. The results showed that it is an efficient solution to keep the primary operating pressure in constant for system stability when the adjustable ejector is using spindle to adjust the throat area of primary nozzle. Selvaraju and Mani [22] investigated the performance of a vapor