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Optimization on ejector key geometries of a two-stage ejector-based multi-evaporator refrigeration system

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ABSTRACT

A three-evaporator and dual-ejector refrigeration system was presented in this paper. By combining two single ejectors as a whole, the authors attempted to discuss the effects of key geometric dimensions of each stage on both stage performances with two-dimensional CFD simulation method. First, the CFD models were validated by experimental data. Then, the primary nozzle diameters of both stages were determined by the cooling load demands of the refrigerating and air-conditioning chambers. Next, the detailed effects of key geometric parameters such as the length of constant-pressure mixing section, the length of constant-area mixing section and area ratio of each stage on two-stage performances were identified with simulations. Finally, the optimum values of the key geometric parameters were obtained, and the results showed that the area ratio had the most significant influences on the entrainment ratio of both stages as compared to other parameters.

1. Introduction

An ejector consists of four main parts: primary nozzle, suction chamber, mixing section and diffuser [1–3]. Due to the characteristics of an ejector like simple structure, no moving parts and low manufacturing cost, it has been widely used in many areas such as refrigeration [4,5], energy recovery [6–8] and chemical industries [9,10]. Ejectors were first used in the refrigeration field by Maurice Leblanc in 1910 [11]. The typical working principle of an ejector utilized in a refrigeration application [12] is as follows:

- the primary flow of high temperature and high pressure through the nozzle to reach a high speed that is supersonic or subsonic, causes a low pressure that forms a negative pressure zone in the suction chamber;
- the secondary flow of low pressure can be entrained into the suction chamber and then mixed with the primary flow in the mixing section;
- the mixed flow leaves the ejector after a pressure recovery process in the diffuser.

Recently, in order to achieve the purpose of energy saving, many studies have been carried out on the application of ejectors in a multi-evaporator refrigeration system (MERS) to partially recover throttling losses in the refrigeration cycle [13–15]. Fig. 1 is the schematic and P-h diagram of an ejector-based multi-evaporator refrigeration system (EMERS). This system consists of a compressor, a condenser, two expansion valves, two evaporators with different evaporating temperatures and an ejector. As shown in the P-h diagram, the low pressure refrigerant vapor enters the compressor and isentropically compressed to a high pressure vapor; then discharged vapor is condensed into liquid refrigerant in the condenser by rejecting heat to surroundings; next, the refrigerant at the condenser outlet is divided into two individual flows that go to the two evaporators after pressure reductions in the two expansion valves; after drawing heat from conditioned space, the refrigerant in each evaporator becomes superheated vapor; the superheated refrigerant vapors from the one evaporator which has higher evaporating temperature and the other with lower evaporating temperature act as the primary and the secondary flows of the ejector; finally, the mixed flow is drawn to the compressor from the outlet of the ejector, and the cycle repeats.

As for the EMERS, some researchers focused on the impact of crucial ejector geometric parameters on the ejector/system performances. Lin et al. [16] used CFD technique to optimize geometric parameters such as nozzle diverging angle, length of the constant-pressure mixing section, nozzle exit position and converging angle of the constant-pressure mixing section, which were used for improvement of the ejector pressure recovery ratio (or PRR: the ratio of the pressure difference between

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Nomenclature

A	length of the constant-pressure mixing section, mm
B	length of the constant-area mixing section, mm
E	total energy, J
$\dot{M}$	mass flow rate, g s^{-1}
P	pressure, kPa
T	temperature, K
u	velocity, m s^{-1}
α_{eff}	effective thermal conductivity, W m^{-1} K^{-1}
μ_{eff}	effective dynamic viscosity, N s m^{-2}
ρ	density, kg m^{-3}
δ_{ij}	kronecker delta function
τ	stress tensor

Abbreviations

AR	area ratio
ER	entrainment ratio, $\dot{M}/\dot{M}_p$
EEV	electronic expansion valve
PND	primary nozzle diameter, mm

Subscripts

p	primary flow
s	secondary flow
o	outflow
1	first-stage
2	second-stage

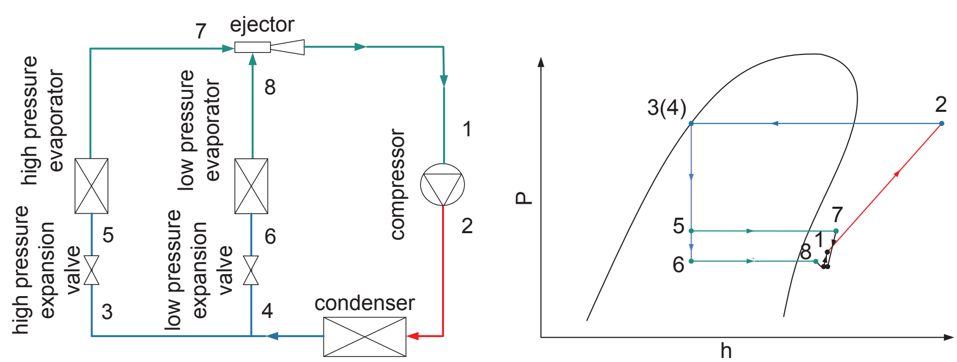

Fig. 1. Schematic and P-h diagram of an EMERS.

the back pressure and the secondary flow inlet pressure over the secondary flow inlet pressure) in an EMERS using R134a as the refrigerant. The results indicated that the pressure recovery ratio was efficiently improved after the geometries optimization. Zhou et al. [17] applied a dual-nozzle ejector to enhance the performances of the two-circuit refrigeration cycle for household refrigerator-freezers. As compared to the conventional ejector-enhanced vapor-compression refrigeration cycle, it was found that the COP improvement of the novel cycle was 10.5–30.8%. Li et al. [18] presented a variable area ratio ejector applied in a MERS and proposed that the critical area ratio of the ejector could be used as an indicator of pressure recovery. The investigation results showed that both the primary and secondary pressure had significant influence on the entrainment ratio, PRR and the critical area ratio. Moreover, Wang et al. [19] experimentally investigated the influences of main geometric parameters such as the nozzle exit position (NXP) and the nozzle throat diameter on two-phase driven ejector performance in an ejector enhanced refrigeration system with using R600a as the working fluid. Hou et al. [20] studied the performance of an adjustable ejector with a spindle employed in a parallel hybrid ejector-based refrigerator-freezer cooling system. It was observed that the effect of the spindle blocking percentage of the primary nozzle on the ejector performance was considerable when the spindle blocking percentage changed from 20% to 40%; moreover, the entrainment ratio obtained was relatively high when the back pressure increment percentage varied from 16.15% to 30%.

However, above-mentioned researches only involved in the effect of crucial ejector geometries in a single ejector based MERS. Recently, the MERS with dual-ejector and dual-evaporator or three-evaporator were proposed and relevant system performances were evaluated. Bai et al. [21] proposed a modified dual-evaporator CO_2 transcritical refrigeration cycle (MDRC) with dual-ejector and theoretically investigated the effects of some key parameters on the thermodynamic performance of the modified cycle by using energetic and exergetic analyses. The simulation results showed that dual-ejector exhibited more effective system performance improvement than the single ejector in the MDRC, and the maximum improvements of the system coefficient of performance (COP) and system exergy efficiency could reach 37.61% and 31.9% over those of the conventional cycle under the given operating conditions. Kairouani et al. [22] utilized a one-dimensional mathematical model of the ejector to study both energy efficiency and performance characteristics of an ejector-based multi-evaporator refrigeration system that consisted of three-evaporator and dual-ejector. The results reflected that the COP of the system had an improvement of 15% as compared with the conventional system. Furthermore, Sarkar et al. [23] proposed four layouts of a MERS with three evaporators and two ejectors and evaluated the system performance by using 1D method. The studies showed that the cooling load distribution had a significant effect on the performance enhancement compared with operating temperature. In addition, Refs. [24–26] provided relevant optimization methods for system performance improvement. However, to the best knowledges of the authors, no attempts have been reported to combine two ejectors as a whole and simultaneously carry out two-dimensional CFD simulations for both of them, and further to identify optimum geometric parameters to provide optimal performances of both stages.

Therefore, a two-stage ejector-based multi-evaporator refrigeration system (TEMERS) used in refrigerated truck is proposed in this paper. For the refrigerated truck with three evaporators (refrigerator, freezer and air-conditioner), three evaporators share a compressor. A two-stage ejector is introduced into the refrigeration cycle to replace PRV, which can partly recover the throttling loss of the pressure regulating valve, so as to improve the suction pressure and reduce the power consumption of compressor. The effects of the two-stage ejector geometric parameters such as the diameters of two primary nozzles, constant-pressure mixing sections, constant-area mixing sections and area ratios on the performances of both stages are evaluated with CFD technique.

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