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Simulation on the performance of ejector in a parallel hybrid ejector-based refrigerator-freezer cooling cycle

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ABSTRACT

In this paper, the simulation is carried out to investigate the performance of ejector used in a parallel hybrid ejector-based refrigerator-freezer cooling cycle. The geometric parameters such as primary nozzle diameter, area ratio and constant-pressure mixing chamber length are studied firstly to achieve a good performance of the fixed area ratio ejector under a certain condition. Based on the obtained ejector geometry, an adjustable ejector with a spindle is used in the system to meet the requirements of variable cooling loads. The results show that the effect of blocking percentage of primary nozzle with a spindle on the ejector performance is considerable. Moreover, the adjustable ejector works well with relatively high entrainment ratio when the back pressure increment percentage as compared to the secondary flow pressure is no less than 16.15%.

1. Introduction

Over the past few years, the concerning on energy saving and environment protecting has become an increasingly predominant topic [1]. As one of the most common household electric appliances, the two-temperature refrigerator-freezer with two separate compartments is extensively used due to its cheap and reliable. However, it contributes considerable energy consumption. Therefore, improving its energy efficiency is of great significance and has been widely studied. Bansal et al. [2] proposed various measures such as advanced insulation, improved heat exchangers and advanced defrost mechanisms to increase the energy efficiency of refrigerator-freezers. Yoon et al. [3] investigated the effects of the capillary tube and the refrigerant charge on the performance of the two-circuit cycle with parallel evaporators. The energy consumption was reduced obviously when the parallel cycle was optimized. Yuan and Cheng [4] proposed a novel multi-objective optimization method and Genetic algorithm NSGA-II to increase overall performance of refrigerator. It is known that the main thermodynamic losses in this refrigerator-freezer refrigeration cycle are throttling process and big temperature difference of heat transfer. In order to solve this issue, the ejector is used in the refrigeration system to partially recover the pressure losses, so that the coefficient of performance (COP) of the system can be improved [5].

The ejector is a simple device which has simple structure, low energy consuming and low maintenance cost as compared to conventional apparatus [6]. The efficiency of the ejector-based refrigeration systems is very sensitive to ejector performance characteristics [7]. The ejector performance is greatly influenced by the geometric dimensions such as primary nozzle diameter and area ratio [8].

Conventional fixed area ratio ejector can only work well at a specific condition, which cannot provide good performance once the load varies. In the real system, variation of loads may be considerable due to the changes of environmental temperature, which means that as the cooling loads vary, a conventional ejector may be inefficient in the system. Ejector with variable area ratio (adjustable ejector) may solve this problem. An adjustable ejector with spindle was deployed by Ma and Zhang et al. [9]. The primary flow of the ejector was controlled by changing the primary nozzle throat cross sectional area using a spindle. The influence of the spindle and operating conditions such as evaporating temperature and generating temperature on the ejector performance was investigated through experiments. Xu and Chen et al. [10] conducted an experimental study on the transcritical CO_2 heat pump system with an adjustable ejector. The needle in the adjustable ejector moved forward or backward to change the throat area. In this way, the high-side pressure could be adjusted and the effects of it on the system performance were analyzed. The results showed

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Nomenclature

D_{ni}	inlet diameter of the primary nozzle, mm
D_n	outlet diameter of the primary nozzle, mm
L_{pm}	length of the constant-pressure mixing chamber, mm
D_{am}	diameter of the constant-area mixing chamber, mm
L_{am}	length of the constant-area mixing chamber, mm
D_d	exit diameter of the diffuser, mm
L_d	length of the diffuser, mm
P_p	primary inlet pressure, kPa
P_s	secondary inlet pressure, kPa
P_b	back pressure, kPa
ρ	density, kg m^{-3}
u	velocity, m s^{-1}
E	total energy, J
P	pressure, kPa
T	static temperature, K
λ	thermal conductivity, W m^{-1} k^{-1}
μ	dynamic viscosity, N s m^{-2}
δ_{ij}	Kronecker delta function
$\dot{m}_p$	mass flow rate of primary flow, g s^{-1}
$\dot{m}_s$	mass flow rate of secondary flow, g s^{-1}
A	cross sectional area of the primary nozzle outlet blocking with spindle, mm^2
A_n	cross sectional area of the primary nozzle outlet, mm^2

Abbreviations

COP	coefficient of performance
ERFCC	ejector-based refrigerator-freezer cooling cycle
EEV	electronic expansion valve
ER	entrainment ratio, $\dot{m}_s/\dot{m}_p$
AR	area ratio

that the adjustable ejector could work with a higher efficiency in a wide range of conditions. The performances of adjustable ejector in a multi-evaporator refrigeration system were studied by Lin et al. through experimental methods [11]. The adaptability of the adjustable ejector was evaluated and the result indicated that it can efficiently deal with the problem of variable cooling loads. Similar applications were found in the research of Li et al. [12]. The key performance indexes such as ejector entrainment ratio and cooling capacity were evaluated. Their results showed that the energy efficiency of the system was improved by using the variable area ratio ejector. The influence of spindle position on the performance of ejector was evident. Vereda et al. [13] presented a numerical model of an ejector-absorption refrigeration cycle and evaluated the feasibility of an adjustable ejector. The results indicated that the variable ejector nozzle geometry was beneficial to optimization and control of the cycle. Elbel et al. [14] used an adjustable ejector in the ejector-based multi-evaporator refrigeration system. The effects of different ejector geometries on performance were studied.

There are two categories of typical connection methods in the ejector-based refrigerator-freezer refrigeration system. One is the series hybrid circulatory system, where the evaporators of the fresh food chamber and freezer chamber are in series; another is in parallel connection of the two evaporators. For the former, Elakdhar et al. [15] analyzed the performance of a compression/ejector cycle with different refrigerants. In this cycle, the liquid refrigerant coming out from the condenser entered the evaporator of the fresh food chamber. The separator was mounted between the refrigerating evaporator and the ejector so that the refrigerant was separated into two tributaries. The vapor refrigerant entered the ejector as primary flow, while the liquid refrigerant entered the evaporator of the freezer chamber and then was entrained into the ejector. The similar system was described and analyzed by Liu et.al. [5] and Sarkar [16]. Wang and Yu [17] proposed another series system which was very similar to the previous one. The difference between the two was that the gas-liquid separator was mounted at the outlet of the ejector. The two-phase refrigerant entered the ejector as primary flow to entrain the vapor refrigerant coming from the freezer evaporator. In this system, however, the manufacture accuracy of two-phase driven nozzle of the ejector was difficult to achieve due to its tiny nozzle diameter. In addition, the freezer chamber cooling speed was relatively slow in the series systems.

For another one, the parallel hybrid ejector-base refrigeration system, where the evaporators of the fresh food chamber and freezer chamber are in parallel, was mentioned by Liu et.al [5] and Wang et al. [18]. To be specific, the liquid refrigerant coming out from the condenser was divided into two flows going through throttling valves. The vapor fluid coming out from the evaporator of refrigerating chamber worked as primary fluid for the ejector. The secondary flow at the exit of the evaporator of the freezer chamber was pumped into the suction chamber of the ejector. The fixed area ratio ejector was employed in the system, therefore, the performance of the system was affected greatly by the operating conditions.

In this work, a parallel hybrid ejector-based refrigeration system for large volume refrigerator-freezer (the volumes of refrigerator and freezer chamber are 350 L and 270 L, respectively) is proposed. The initial geometric parameters of the ejector are next designed according to design guidelines (ESDU [19] and ASHRAE [20]). The optimization of the ejector geometric parameters is simulated with CFD technique. The CFD model is validated by the experimental results. The geometric parameters such as primary nozzle diameter, area ratio and constant-pressure mixing chamber length are optimized. Based on the optimum geometric dimensions obtained, a variable area ratio ejector by using a spindle is proposed to address the requirements of variable cooling loads. Consequently, its performance is identified by varying the area ratio and the back pressure of the ejector.

2. System description

The proposed hybrid ejector-based refrigerator-freezer cooling cycle (ERFCC) in the present study is schematically shown in Fig. 1. The ERFCC mainly consists of the following components: a compressor, an air-cooled condenser, two electronic expansion valves (EEVs), two evaporators (one located in the fresh food chamber and the other located in the freezer chamber), and an ejector. The working process of the ERFCC is as follows:

High pressure superheated vapor that is discharged from the compressor is liquefied into sub-cooled liquid in the condenser. The sub-cooled liquid refrigerant comes out from the condenser, and flows individually across EEV1 and EEV2 before entering the two evaporators. The two flows of refrigerant vaporize entirely in the evaporators and enter the primary nozzle and the secondary flow inlet of the ejector, respectively. The two streams of flow successively go through the processes of mixing, balancing and diffusion, before they finally flow out of the ejector and enter the compressor. The cycle repeats as the vapor of the refrigerant is pumped out from the compressor.