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Research Paper

CFD-based shape optimisation of a CO_2 two-phase ejector mixing section

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HIGHLIGHTS

- The CFD-based shape of the ejector mixing section is presented.
- The efficient computational tool was used for the optimisation.
- The mixer diameter has the most significant influence on the ejector efficiency.
- Presented methodology can be used as the ejector design tool.

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ABSTRACT

In this study, the geometry of a CO_2 ejector mixing section was optimised. Two optimisation algorithms, a genetic algorithm (GA) and an evolutionary algorithm (EA), were used with a validated CFD model based on the homogeneous equilibrium model (HEM). The ejector was designed to increase the Coefficient of Performance (COP) of CO_2 refrigeration systems used in supermarkets. Hence, the objective function (OF) for the optimisation was defined as the ejector efficiency for various refrigeration system loads, which determined the ejector operating conditions (OCs). The optimisation results showed a very strong relation between ejector performance and the mixer diameter. Similar results were obtained with both optimisation algorithms. In each case, the mixer diameter was nearly equal to that of the baseline; however, the length of the mixing section was greater in the optimal design. The ejector efficiency of the optimised design was as much as 2% higher than that of the baseline design.

1. Introduction

In refrigeration systems, particularly those using R744 (CO_2) as the refrigerant, two-phase ejectors reduce throttling losses; thus, these ejectors have recently drawn significant attention from the scientific and refrigeration communities. The use of this type of ejector addresses one of the drawbacks of R744 systems, which is that the throttling loss is greater for carbon dioxide than it is for synthetic refrigerants, particularly at high ambient temperatures. Hence, CO_2 refrigeration units with an ejector can outperform those with an expansion valve (see [1–3]). Furthermore, the principle of the two-phase ejector for CO_2 is relatively simple compared with an expander, and systems with expansion valves can be modified at an affordable cost. However, the COP of an R744 system can be improved only if the ejector is properly designed. Therefore, the design of the ejector is crucial in obtaining high system performance.

The typical measure of ejector performance is ejector efficiency (η_{EJ}) which was introduced by Elbel et al. [4]. This parameter is defined as the ratio of the work rate recovered by the ejector to the maximum possible expansion work rate that can be recovered, as shown in Eq. (1):

$$\eta_{EJ} = \chi \cdot \frac{h|_{s=s_{SN,in}p=p_{DIF,out}} - h_{sn,in}}{h_{MN,in} - h|_{s=s_{MN,in}p=p_{DIF,out}}} \quad (1)$$

The parameter χ in Eq. (1) is the mass entrainment ratio, and it is defined as the ratio of the suction nozzle mass flow rate to the motive nozzle mass flow rate, as shown in Eq (2):

$$\chi = \frac{\dot{m}_{SN}}{\dot{m}_{MN}} \quad (2)$$

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Recently, the χ and η_{EJ} have been used in both experimental and numerical studies to investigate the effect of the geometry on the efficiency of the ejector.

Nakagawa et al. [5] experimentally investigated the influence of the mixer length on ejector performance. That study showed that the overall ejector efficiency was highly sensitive to the mixing section length. The analysis conducted in [5] showed that there is a direct relation between the mixer length and ejector efficiency.

In addition to the dimensions of the mixer section, the motive nozzle position has been the subject of experimental investigations. Liu et al. [6,7] investigated the influence of the distance between the motive nozzle outlet and the mixer inlet. The volume between these parts of the ejector assembly is referred to as the pre-mixing chamber. The studies by Liu et al. showed a strong relation between the ratio of the motive nozzle outlet diameter to the mixer diameter and the ejector efficiency. Moreover, relations between the motive nozzle outlet position and the mixer diameter and between the mixer length and the mixer diameter were established.

Previous studies of ejectors have focused on numerical analyses of the ejector geometry. Hence, mathematical models and computational tools of varying complexity have been used to model the flow of CO_2 in ejectors. Numerical modelling was used to analyse ejector performance and to design prototype ejectors. Banasiak and Hafner [8] introduced the 1-D model which allowed the computations of the crucial ejector performance indicators.

More complex 2-D and 3-D CFD models have been used to provide more accurate flow profiles and flow fields inside an ejector. The range of mathematical approaches used in recent studies is quite broad, including complex approaches, e.g. [9] and [10], and simpler approaches such as in [11] and [12]. For optimisation purposes, the model should be accurate without requiring excessive computation times. The study by Palacz et al. [13] showed that the homogeneous equilibrium model (HEM) can be used for simulating the flow of CO_2 inside an ejector with acceptable accuracy for specific operating conditions. In this regard, the HEM is considered robust and acceptably accurate. Hence, the mathematical formulation in [11] was used in this study. Smolka et al. [11] implemented an enthalpy-based energy equation in the numerical analysis software ANSYS Fluent [14] through a user-defined function. The properties of the fluid were modelled using the NIST REFPROP [15] library with the model.

Banasiak et al. [16] conducted an irreversibility analysis to study the efficiency of an R744 ejector. The mathematical model described by Smolka et al. [11] was used to perform a CFD-based irreversibility analysis. A new, dimensionless quantity called the relative increase in the entropy rate was introduced to determine the influence of each section of the ejector on the overall ejector efficiency. This analysis showed that the mixing section has the greatest effect on performance. Very small changes in the mixer cross-sectional area resulted in significant changes in η_{EJ}, indicating that this part of the ejector should be optimised for the specified operating conditions.

Although the aforementioned mathematical models were successfully used to analyse two-phase ejectors, to the best of the authors' knowledge, none of them was used to optimise the geometry of an ejector mixing section. This study optimises the geometry of the mixing section using the model proposed by Smolka et al. [11]. Moreover, only the operating conditions for which the mathematical model [11] guarantee the accurate computational results were chosen, see Palacz et al. [13]. The authors of that study assumed that the model accuracy is satisfying when the discrepancy between the measured and computed motive nozzle mass flow rate is lower than ± 10%. According to the mentioned study [13], high-quality results from homogeneous equilibrium model are expected for the motive nozzle operating conditions that are in range of 70 bars to 95 bars for the pressure and 25 °C to 38 °C for the temperature [13]. The mathematical model was used with two optimisation algorithms, a genetic algorithm and an evolutionary algorithm. Both types of optimisation algorithms have been used successfully in previous studies [17–21].

2. Ejector geometry

A typical ejector includes four main components: a motive nozzle, a suction nozzle, a mixing section and a diffuser. This typical configuration is presented in Fig. 1. Consequently, fourteen parameters are required to describe the geometry. Moreover, the ejector efficiency depends not only on the geometry of the ejector but also on the operating condition. According to [16], the mixing section is the least efficient part of the device. Hence, to avoid the large computational effort required to optimise the geometry for multiple operating conditions, the authors of this study focused only on the optimisation of that part of the ejector. If the effects of the suction chamber and the radial suction duct are ignored, the ejector geometry can be assumed to be axisymmetric. This simplification is shown in Fig. 2 [8,16].

The ejector geometry considered in this study was designed for a multiple-ejector refrigeration system used in supermarkets and was developed by Hafner et al. [3]. The ejector unit consists of four vapour ejectors that operate in parallel to accommodate a range of refrigeration system loads. Originally, only the vapour ejector with the highest capacity (designated EJ4) was designed using the 1-D model developed by Banasiak and Hafner [8], and the other three ejectors, designated EJ1, EJ2 and EJ3, were scaled-down versions of EJ4. The more detailed description of the designing procedure is presented in the work of Banasiak et al. [22]. The 3-D CFD model introduced in [11] was employed to investigate the performance of the ejectors. Approximately, 100 computational cases were

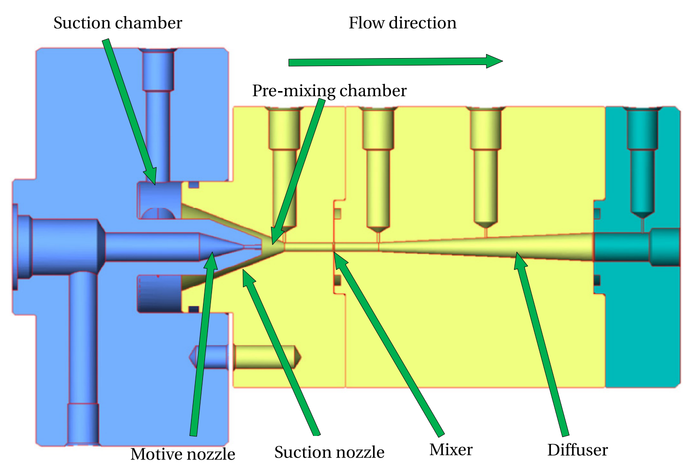

Fig. 1. Typical two-phase CO_2 ejector assembly.

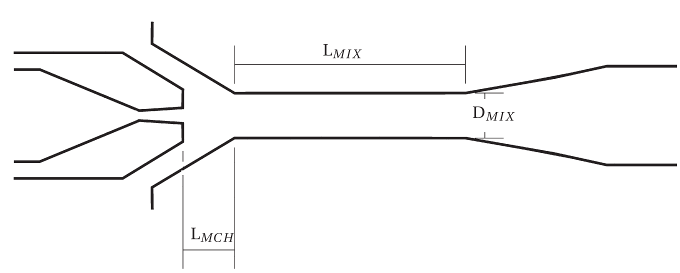

Fig. 2. Basic ejector mixing section geometry and its dimensions.