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Numerical study of high-speed two-phase ejector performance with R134a refrigerant

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A B S T R A C T

An ejector is a passive pumping device to increase the flow rate of a motive fluid and to enhance compression of the fluid flow by geometrically induced secondary flows. In particular, the high-speed two-phase ejector has attracted attention as an alternative to the throttling valve, because by compensating the throttling loss that appears in expansion devices it has the potential to improve significantly the performance of refrigeration systems. However, flows inside the ejector are so complex that it is not easy to characterize the relevant flow and thermodynamic behaviors experimentally. In contrast, the numerical approach is relatively favorable to elucidate the relevant physics inside the ejector, and is considered useful to improve the performance of the ejector. However, there have been few relevant numerical studies, because it is challenging to resolve high-speed flows accompanied with phase transitions. In the present study, we present numerical solutions of the high-speed flows inside a two-phase ejector. An evaporation-condensation model is implemented and the real-fluid properties of refrigerant R134a are input in our RANS simulations to resolve phase transitions. Based on the validated predictive ability of our computational apparatus on the baseline model of the ejector, we present a parameter study to identify the effects of geometry variables on the entrainment performance. Our study provides specific guidelines to be considered when designing supersonic two-phase ejectors, and thus, it is expected to contribute to studies associated with supersonic two-phase ejector-equipped refrigeration systems.

1. Introduction

An ejector is a passive pumping device to increase the flow rate at the nozzle exit and to enhance compression of the flow by geometrically induced secondary flows, without loading external energy. Since the initial design of an ejector was proposed by Henri Giffard in 1858, ejectors have been employed in a broad range of engineering applications, e.g., propulsion, cleaning, air-conditioning, and refrigeration [1]. In general, an ejector consists of a driving nozzle, suction channel, suction chamber, mixing tube, and diffuser, as illustrated in Fig. 1(A). In the configuration of an ejector, engineering benefits are driven from the jet flow that results from highly pressurized fluids passing through the driving nozzle. Specifically, when geometrically boosted jet flows pass through a nozzle exit, the pressure inside the suction chamber decreases by a Venturi effect so that a favorable pressure gradient is formed between the inlet of the suction channel and the suction chamber. As a result of the pressure difference, additional mass flows are entrained from the suction channel inlet. A shear mixing also occurs between the jet flows and the entrained flows in the mixing tube of a constant cross-sectional area, and then, the pressure of the mixed stream increases at the end of the diffuser. From the operating principle, it is beneficial to replace an expansion valve (which is a component of the standard refrigeration cycle) by an ejector, because it is able to induce pumping of fluids without external energy, and accordingly compensates the throttling loss that appears in an expansion process and directly unloads the compression work required in a compressor. [2] Hence, the performance of a refrigeration cycle can be improved significantly, as illustrated in Fig. 1(B). A number of studies have been carried out to predict and improve the performance ejector-equipped refrigeration cycles since such an idea was first proposed by Gay in 1931 [3].

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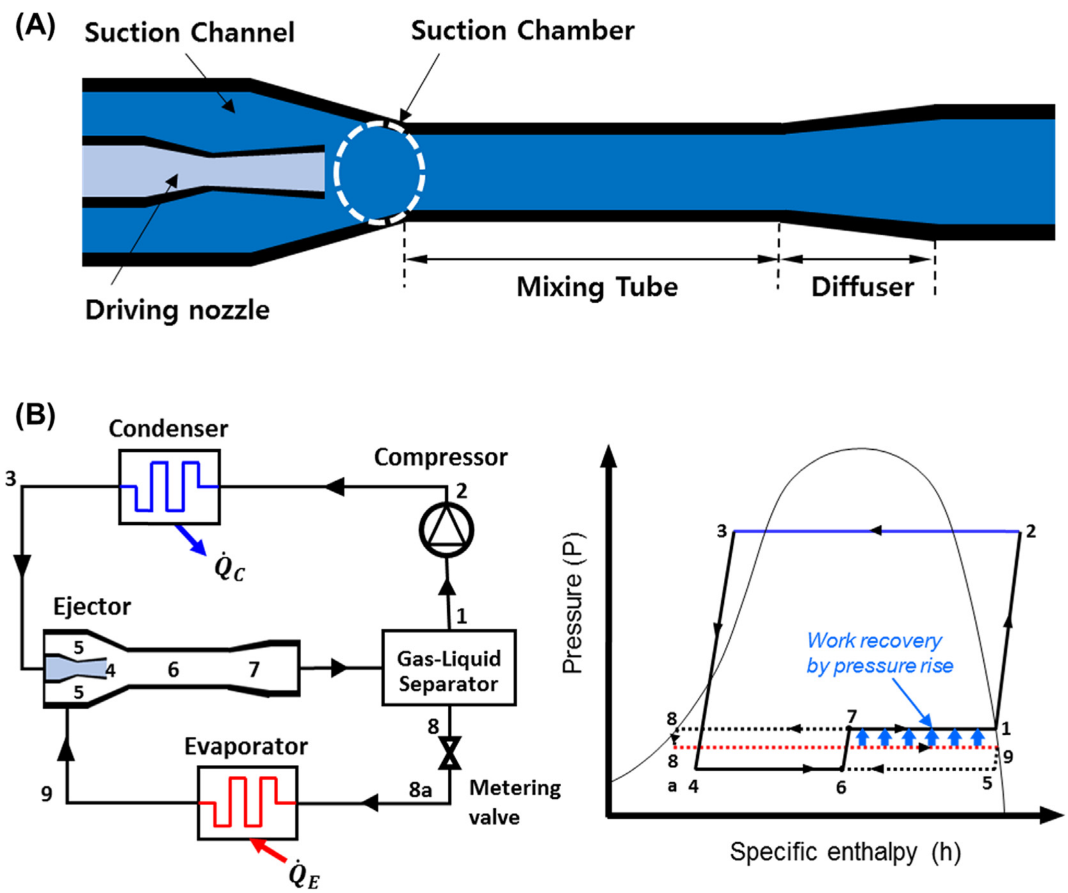

Fig. 1. Schematic diagram of (A) a high-speed two-phase ejector and (B) the work recovery effect of an ejector-equipped refrigeration cycle.

In the early stage, theoretical approaches were used to analyze the ejector performance. The one-dimensional (1D) model proposed by Kornhauser [4] aimed to predict the performance of two-phase ejector-equipped refrigeration systems. In the model, the efficiencies of the four components of the ejector were assumed constant. In addition, it was assumed that the jet flow and an entrained flow were mixed under the condition of constant pressure in the mixing tube. Li and Groll [5] developed a model based on the assumption of constant-area mixing. It is remarkable in those two studies that the momentum and energy conservation equations were considered together to achieve accurate predictive abilities. With such analytical models, it is easy to estimate the flow and thermodynamic properties inside an ejector, but the constant efficiency assumption is not consistent with the real situations in each component. Moreover, the energy transfer at phase interfaces is assumed negligible in most of the analytical models, but this is inconsistent with real flow situations. In order to improve the accuracy of the analytical models, such assumptions were corrected with empirical correlations measured at each component of the ejector [6,7]. Zhang [8] calibrated the efficiencies of each ejector component based on their experimental data for the two types of refrigeration systems such as a diffuser outlet split cycle and a condenser outlet split cycle, respectively, in their 1D simulation. It was shown in their study that the correction is able to improve the prediction accuracy of the previous 1D model [4] for the both cycles. However, such a correction methodology is restricted by the feasibility of experimental measurements. Specifically, the flows inside an ejector involve complex flow behaviors, e.g., phase transition, compressibility effect, and mass and energy transfer between phases; thus, it is challenging to measure the relevant flow and thermodynamic variables accurately.

Recently, the replacement of the expansion valve in the low-pressure refrigeration cycle by an ejector has attracted significant attention. The studies associated with a two-phase ejector have been carried out primarily in conjunction with transcritical CO_2 refrigeration cycles, because the CO_2 refrigerant leads to a large throttling loss in the expansion process, and accordingly, the substitution of the throttling valve by an ejector can yield a remarkable work recovery. On the contrary, the ejector is not expected to yield an amount of work recovery and increase in coefficient of performance (COP) in low-pressure refrigeration cycles as much as in CO_2 refrigeration cycles. However, the low-pressure refrigeration cycles have the wider range of application than the CO_2 cycles; the use of the former is extended to a variety of industrial applications such as air conditioners, chillers, and vehicle refrigeration systems while the latter is restricted to hot water suppliers or large size refrigeration systems. Hence, it is beneficial to exploit an ejector for low-pressure refrigeration cycles, in spite of its relatively low engineering benefits compared with those in CO_2 refrigeration cycles. Recently, it was shown that the performance of low-pressure refrigeration cycles can be improved significantly by the aid of ejectors [9,10]. However, it has not yet been shown how significantly each component of a supersonic two-phase ejector influences its entrainment performance. If this subject is clarified, specific guidelines will be obtained for design optimization of the ejector, and further, the performance of low-pressure refrigeration systems will be improved significantly.

We aim to assess numerically the performance of a supersonic two-phase ejector with refrigerant R134a which is a representative working fluid of those used in low-pressure refrigeration cycles. Specifically, we aim to examine the effects of the dimensional parameters of the ejector on its entrainment performance based