1-D Model Extension to Ejector Performance at Secondary Flow Choking

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Abstract

Modeling of ejector performance at secondary flow choking conditions in an ejector refrigeration system (ERS) is presented. This modeling includes two parts. One is the conventional “constant pressure” model of 1-D ejector flow theory by Keenan et al (1). The other is from Chou et al’s model (2), from which the attainable maximum mass flow ratio of an ejector in an ERS due to secondary flow choking can be calculated independently. This model is then utilized to predict the attainable maximum mass flow ratio and the critical discharge pressure of ejector due to secondary flow choking for an ERS at given inlet pressure and temperature conditions of the primary and secondary flows. The results were examined by the existing experimental data of steam ejector (3) and R113 ejector (4) and showed in the good agreement. The current paper presents a simple quantitative analysis procedure for modeling and computing ejector performance characteristics map.

Introduction

Ejector refrigeration system (ERS) is considered to be an alternative mean to the conventional HVAC system. This system can take advantage of low-grade thermal energy such as solar energy and waste heat resources to cool residential and public premises. In such an ERS, the ejector is a thermo-compressor as well as a key component. The schematic ejector is shown in Figure 1. ERS performance is inherently dependent on ejector behavior. Practically, efficient operation of such system is required for the attainable maximum mass flow ratio of the ejector. The mass flow ratio of the ejector is maximized at the secondary flow choking conditions inside the ejector. Modeling of ejector performance under secondary flow choking conditions is necessary.

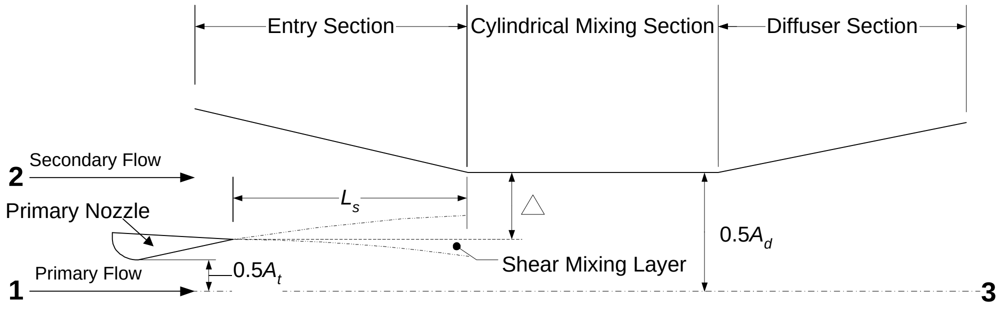

Figure 1 Schematic of ejector configuration

A general ejector performance can be characterized by the relationship between attainable mass flow ratio and the discharge pressure of ejector. This performance analysis can be derived with a 1-D ejector flow model using a control volume approach by Keenan et al (1) who initially laid a firm foundation for ejector analysis. Fluid motion is governed by the conservation laws of mass, momentum and energy. This theory enables a simple analysis of ejector flows and is a useful tool for identifying the significant variables which influences ejector performance, without resorting to complex mathematics input or treatment. When it is applied for ejector design conditions, this relationship has been found to be in good agreement with experiments over a wide range of geometrical and operation variables. When the model is applied for ejector off-design conditions, for a particular ejector geometry, at fixed inlet pressure and temperature conditions of primary and secondary flows, the secondary mass flow through the ejector is affected by the discharge pressure. The lower is the discharge pressure, the greater the secondary mass flow rate. It can be concluded that the mass flow ratio becomes inversely dependent on the discharge pressure of the ejector. This model fails to predict the actual limitation for the mass flow ratio of the ejector at the secondary flow choking conditions. However, experimental results have revealed that the mass flow ratio is independent of the discharge pressure as the secondary flow chokes. In other words, over the range of ejector operating conditions shown, the secondary flow choking acts to significantly limit the mass flow ratio from what would be expected based on the above analysis. Thus the mass flow ratio at the secondary flow choking conditions is a constraint that must be considered in the design and operation of practical ejector systems.

It was found that the multiple-parameter formula (2) works well for the attainable maximum mass flow ratio under the secondary flow choking conditions. The critical discharge pressure is assumed to be low enough, but is not identified thoroughly. This formula fails to account for the effect of the critical discharge pressure. For this reason, when the secondary flow is choking, this formula is incorporated to previous basic ejector theory by Keenan et al (1) and then be extended to analyze such ejector performance that present the whole picture of the ejector performance under secondary flow choking conditions.

The objectives of this paper are to describe the extension of the 1-D ejector model necessary of Keenan et al (1) simply by incorporating Chou et al’s equation (2) to be able to predict the attainable maximum mass flow ratio and the critical discharge pressure of the ejector at secondary flow choking conditions and known inlet pressure and temperature conditions of the ejector primary and secondary flows. This paper also present

Model Extension of Ejector Performance Characteristics in ERS

For one-dimensional analysis of ejector performance, it is assumed that there is steady and adiabatic flow, no flow separation, absence of recirculation flow, and fully mixed of fluids at the inlet of the diffuser. The flow through the primary nozzle is assumed to be isentropic flow under operating conditions, and the influence of shocks due to moisture condensation inside the primary nozzle as the flow expands is assumed to be negligible. By applying the laws of conservation of mass, momentum, and energy to the primary nozzle, secondary flow channel, mixing section and diffuser, a set of governing equations is obtained. For the sake of brevity, the equations are not given here. Extensive details of these equations can be found in Ref. (1). Since a relatively longer entrance inside ejector configuration/layout, the mixing process under constant pressure is next considered.

The operating conditions of primary and secondary flow provide the necessary information to solve the governing equations. Empirical efficiencies for primary nozzle, mixing section and diffuser are used in the calculations. These factors are typically in the range of 0.8~0.9 and 0.7 respectively. For a particular ejector configuration, this theory provides the functional dependence on the discharge pressure and the mass flow ratio for ejector in ERS if the inlet conditions of ejector primary and secondary flows are given.

The attainable maximum mass flow ratio of ejector at secondary flow choking conditions can be solved initially according to the formula presented by Chou et al (2). The attainable maximum mass flow ratio of ejector at the secondary flow choking $(\dot{m}_2 / \dot{m}_1)_{II}$, may be expressed as

$$(\dot{m}_2 / \dot{m}_1)_{II} = \left(\frac{P_2}{P_1}\right) \cdot \frac{1}{\left({}^{T_2}\!/_{T_1}\right)^{1/2}} \cdot \left[-\left(\frac{P_2}{P_1}\right)^2 + w \cdot FP_d \cdot \left(\frac{P_2}{P_1}\right)\right] \cdot \left(m \cdot ff - \frac{A_{pp}}{A_t}\right) \cdot \left({}^{L_s}\!/_{\Delta}\right)^{b-M} \cdot j$$

where:

w = correction constant for the primary nozzle working range,

FP_d = the failure pressure ratio of the primary nozzle,

ff = ejector geometric design area ratio,

A_{pp} = area of primary flow at choking location,

A_t = area of the throat of the primary nozzle,

m = correction constant, 1.35,

L_s/Δ = flow aspect ratio, as shown in Fig. 1,

b = Mach number limitation constant, 4 for freon case and 5.2 for steam case,

M = design exit Mach number of the primary nozzle, and

j is an application specific correction factor which can be applied to an ejector operating with a given refrigerant and system configuration.

It is assumed that the flow process towards reaching ejector secondary flow chocking is isentropic. The computation of the failure pressure ratio, FP_d, is based on the single normal shock effect occurring either at the exit or the throat of the primary nozzle. The correction constant, j , is determined experimentally. As a result, the equation for the mass flow ratio may be used with the basic flow model of the ejector described previously to study the ejector performance characteristics when the secondary flow is choked.

Therefore, for a fixed configuration of the ejector, its performance under secondary flow choking conditions can be calculated from the inlet pressure and temperature conditions of the primary and secondary flows. The attainable maximum mass flow ratio of ejector is first calculated. This is then used to calculate the critical discharge pressure using the 1-D ejector theory of Keenan et al (1).

Results

Overall ejector performance

Figure 2 provides a summary of ejector performance diagram where the mass flow ratio vs. the discharge pressure of ejector is plotted. Since the summarized ejector performances are related to the particular operating conditions, it is beneficial to discuss briefly some basic off-design features of ejector performance under a particular operating condition of an ejector.

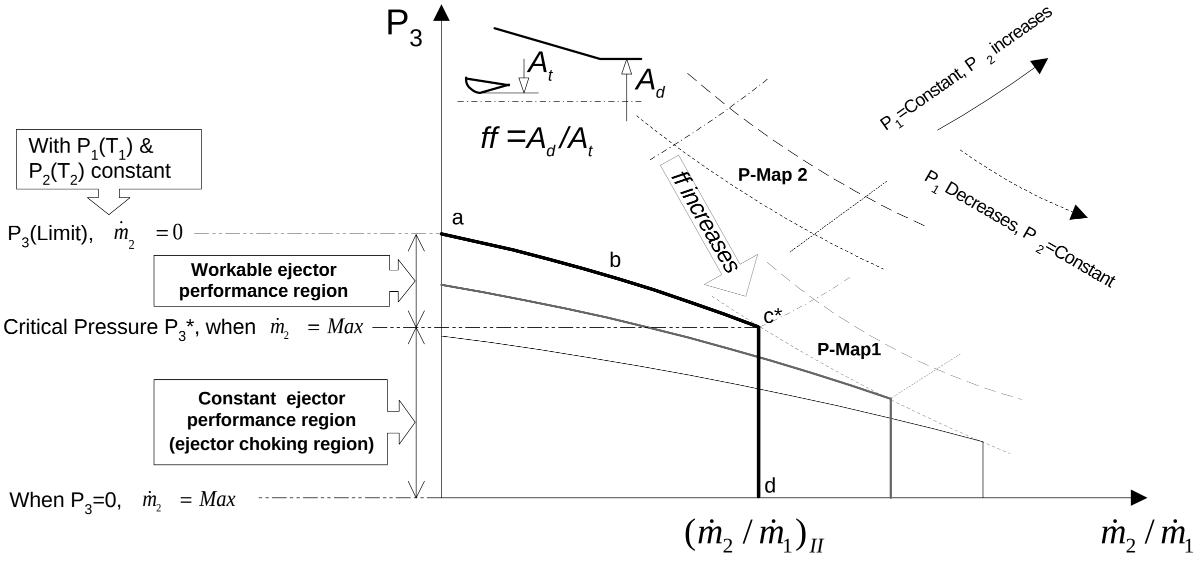

Figure 2 Schematic diagram of overall ejector performance

For a particular operating condition of an ejector, the ejector performance forms an even more pronounced declined curve (a-b-

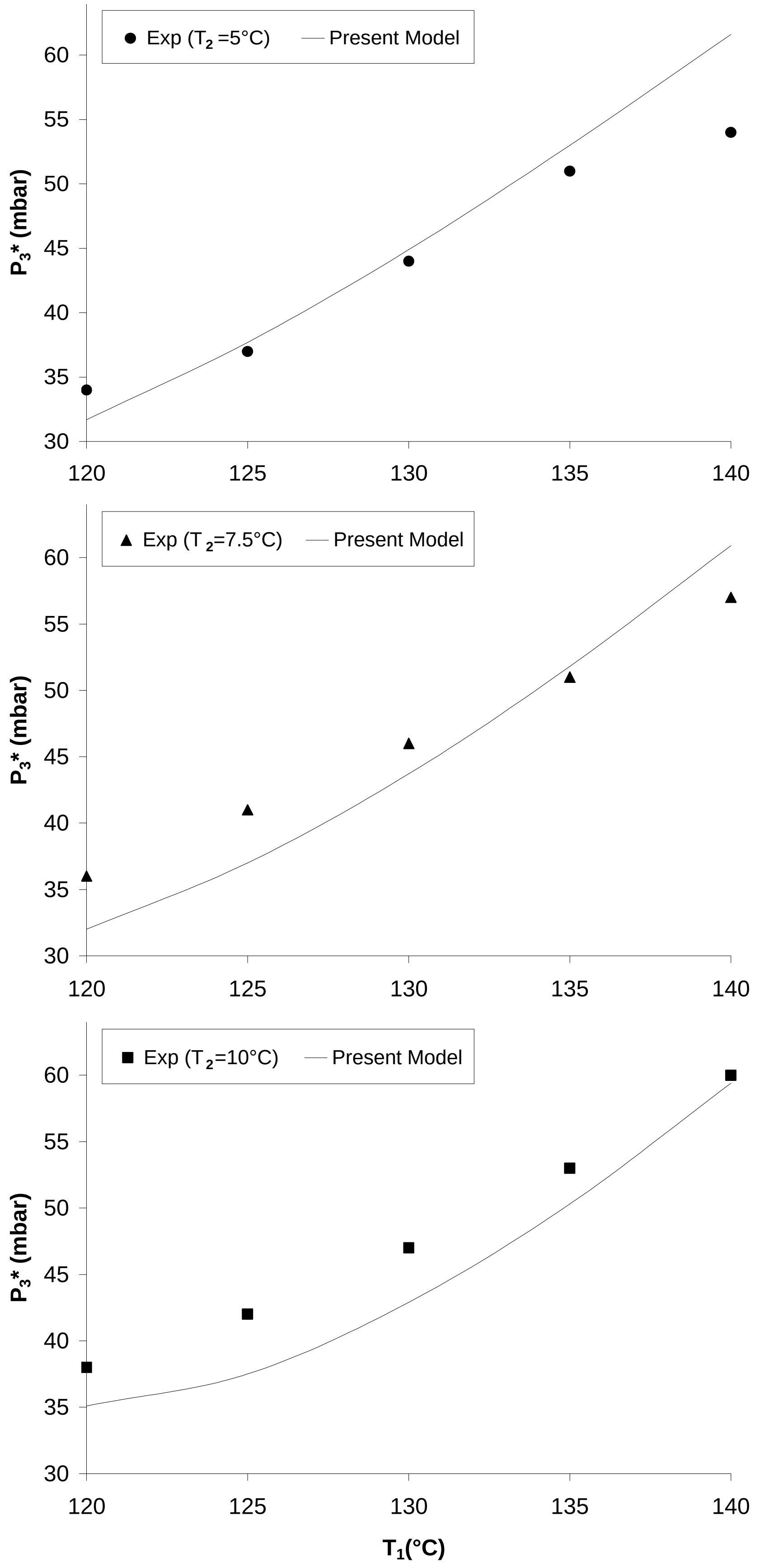

Figure 3 Comparison of present model and experimental date (3) for the critical discharge pressure of ejector (steam ERS)

data of Eames et al (3). For a fixed configuration of ejector, these calculations are in good agreement with the experimental data for the range of operating conditions as shown in Figure 3.

Of particular interest in the application to ejector refrigeration systems is the characteristics performance map. A quantitative relationship of the attainable maximum mass flow ratio against the critical discharge pressure with or without application of the present model is shown in Figure 4. The experimental results were obtained by Huang et al (4). It was reported that the pressure measurement had an uncertainty of ±0.003bar and the accuracy of the measurement of the flow rate was ±5%. When P_2 is fixed, the critical discharge pressure decreases as P_1 increases. So does the attainable maximum mass flow ratio. When P_1 is fixed, the critical discharge pressure decreases as P_2 decreases. So is the attainable maximum mass flow ratio. In Figure 4, the experimental results in terms of both the attainable maximum mass flow ratio and the critical pressure of ejector show good agreement with the corresponding calculations of the present model.

It is of interest to mention other aspects of these results. They are i) when the attainable maximum mass flow ratio becomes smaller, the critical discharge pressure shows a relatively greater discrepancy between the experiments and theoretical calculations; and ii) the trends of both experimental data and theoretical simulation deviate as the attainable maximum mass flow ratio increases under the corresponding operating conditions. In other words, as the attainable maximum mass flow ratio of ejector becomes either smaller or larger, the discrepancies between the experimental data and the

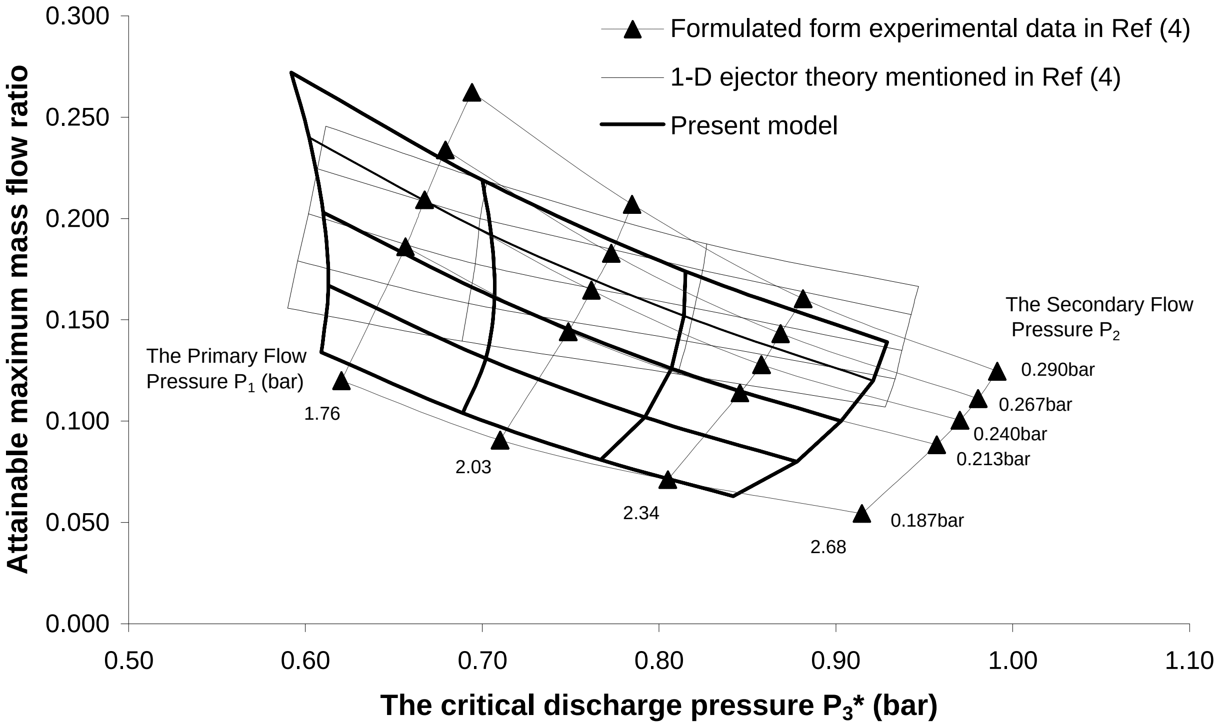

Figure 4 Ejector performance map at choking conditions (Refrigerant R113 ERS)

theoretical calculations increase.

These discrepancies may be due to simplifying assumptions made for the ejector interior flows, i.e. there is a normal shock inside ejector and the mixed flow experiences this normal shock. The pressure recovery thus results from through this normal shock and again in diffuser. Under certain operating conditions, the mixed flow in ejector is supposed to be supersonic but is not expected much to which the assumption could be. Therefore, the discharge pressure computed is overestimated/underestimated as may be seen in Figure 4. With a view of flows inside ejector per se, shock formulation is most likely to be confined in the primary flow region. For the mixed flows in these cases, the formation of a normal shock prior to the inlet of diffuser, in accordance with the assumptions made, is far from reality. Therefore, it is clear that the theoretical calculations are not so accurately conformable to the experimental data under this analysis.

It is also to be emphasized that using such one dimensional ejector flow model, including the assumption of constant pressure mixing inside the ejector, is valid for the case of a relatively fixed operating conditions. If the operating range becomes wider, such simulation does not work well since the constant factors typically in this model cannot provide an acceptance correlation. It is worthwhile to examine and determine the factors that significantly affect the ejector over a wide range of operating conditions.

Conclusions

In the study, a 1-D model for predicting ejector performance at secondary flow choking in ERS has been presented. This is based on the combination of ejector choking formula and the existing conventional 1-D flow model of ejector with constant pressure mixing assumption. The approach is useful for determining ejector performance when the secondary flow choking occurs and the corresponding performance map for an ERS.

Nomenclature

P	Pressure
T	Temperature
A	Area
ff	Ejector geometric design area ratio
$\dot{m}_2 / \dot{m}_1$	Mass flow ratio of ejector

Superscripts

*	the discharge pressure of ejector at secondary flow choking condition

Subscripts

1,2	the status of the inlet of primary and secondary flow respectively
3	the mixed flow at the exit of ejector
II	the status of the secondary flow choking
d	the cylindrical mixing section

References

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