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Research paper

Modeling and numerical approach for the design and operation of two-phase ejectors

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HIGHLIGHTS

- A thermodynamic model of two-phase ejector is proposed.
- The design of the nozzle is performed by maximising the mass flow at the throat.
- In the mixing chamber, the wall friction is accounted in the momentum balance equation.
- Results of the model agree with available experimental data.

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ABSTRACT

This paper presents a modeling procedure of liquid–vapour ejectors for refrigeration, heat pumps and several other potential industrial applications.

Fluid flow in the ejector is two-phase and compressible. The modeling relies on a thermodynamic approach where conservation equations and properties of real refrigerants are being used. Refrigerant liquid and vapour phases are assumed to be in homogeneous equilibrium. The design of primary and secondary nozzles is performed by maximising the mass flow rate at their respective throats, thus circumventing the approximate determination of the velocity of sound and the Mach number in a two-phase flow environment. In the mixing chamber, the flow is handled in such a way as to account for the wall friction in the momentum balance equation.

The result of computations by the present model agrees fairly well with experimental data from a dedicated test bench as well as with those found in the available literature. As an example, computations are performed using this model for an ejector in typical conditions of a refrigeration application.

1. Introduction

There are generally three main approaches of numerical methods that can be used to design and analyse ejectors: CFD (Computational Fluid Dynamic), 1-D (one-dimensional) and thermodynamics methods. CFD is a powerful prediction method, capable of generating the flow details. It is however challenging to set such an application, the results of which highly depend on the turbulence models employed [1], as well as the mixing models in the case of two-phase flow, [2,3].

1-D methods are simpler and less costly than CFD techniques since they require no complex meshing and the computations are performed in only one direction, [4]. They are however difficult to implement, in comparison to thermodynamic methods, since the approach remains to be the resolution of partial differential equations. Thermodynamic methods are the most widely used in two-phase ejector modeling as can be observed in the literature and their main advantage is their ability to rapidly generate results.

Kornhauser [5] has developed one of the first thermodynamic models for two-phase ejectors. The approach was based on HEM model (Homogeneous Equilibrium Model) and the assumption of constant pressure mixing, commonly used in ejectors. Isentropic efficiencies were used to account for friction losses in the primary nozzle and the diffuser. Constant pressure was imposed during the mixing process, where no friction or mixing losses were considered. The Kornhauser model has been used by many researchers [6–10], and still remains popular, due to its simplicity. This approach has however a number of weaknesses. For example, selecting isentropic efficiencies of a thermodynamic model may be tricky, particularly when dealing with two-phase flow [6]. As some

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Nomenclature

A	surface area (m^2)
a	velocity of sound ($m\ s^{-1}$)
D, d	diameter (mm)
f	friction coefficient
G	mass flux ($kg\ m^{-2}\ s^{-1}$)
h	specific enthalpy ($kJ\ kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
M	Mach number
P	pressure (Pa)
r	compression ratio ($P_{out-diff}/P_{in-sec}$)
RAM	section ratio inlet-outlet, mixing chamber
RAD	section ratio inlet-outlet, diffuser
Re	Reynolds number
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
T	temperature (°C)
U	velocity ($m\ s^{-1}$)
V	homogeneous velocity ($m\ s^{-1}$)
v	specific volume ($m^3\ kg^{-1}$)
x	quality
α	void fraction
Δl	constant cross section zone length (mm)
ΔP	pressure loss (Pa)
ε	relative uncertainty (%)
η	isentropic efficiency (%)
ρ	density ($kg\ m^{-3}$)
φ	dissipation coefficient
ω	entrainment ratio ($\dot{m}_{sec}/\dot{m}_{prim}$)

Subscripts

diff	diffuser
in	inlet
inter	intermediary
l	liquid
lift	suction to outlet (temperature increase)
m	mixture
max	maximum
min	minimum
noz	nozzle
out	outlet
prim	primary
sec	secondary
s, is	isentropic
th	throat
v	vapour

experimental tests suggest, many authors set these efficiency coefficients lower than they generally are in single phase ejectors. In the paper of Lawrence and Elbel [10] for example, the coefficients selected for the primary nozzle, the secondary nozzle and the diffuser are respectively equal to 0.8, 0.8 and 0.75.

The Kornhauser model, in its primary version does not allow for optimal design of ejectors, since no provision for the primary nozzle critical design was taken and no consideration of shock formation in the mixing chamber was made. A number of researchers have attempted to improve the Kornhauser's model. Nakagawa et al. [11] have proposed a hybrid approach, which consists in a combination of 1-D and thermodynamic considerations. The primary nozzle is modeled on the basis of an isentropic efficiency while 1-D approach is used for the remaining ejector body. In their development, the momentum equation conservation was considered for each phase, where a wall friction coefficient was applied solely on the vapour phase which was assumed to be in contact with the wall. Such an approach allowed the authors to analyse the geometric characteristics of the mixing chamber. A similar approach was adopted by Banasiak and Hafner [12] where the mixing chamber was treated by a simple thermodynamic approach while the remaining ejector was modeled by a 1-D approach. In the process, two-phase flow was assumed to be homogeneous with the phases in thermal non-equilibrium.

In the model developed by Liu and Groll [13], critical flow was considered in the primary nozzle by assuming that the flow at the throat was sonic, according to the relation due to Attou and Seynhaeve [14]. A coefficient for mixing was also included in the momentum equation describing the flow in this zone. Pressure variation in the diffuser was modeled by means of a recovery factor, based on the correlation given by Owen et al. [15].

Using this model, together with experimental results for an ejector working on CO_2 in transcritical conditions as an expander, Liu and Groll [16] have shown that the efficiency coefficients in the nozzles and the mixing chamber, could greatly vary, depending on the ejector geometry and operational conditions.

The proposed model in the present paper also relies on the principles of HEM for the design of two-phase, liquid–gas ejectors. Primary and secondary flows are treated in such a way as to maximise the mass flow rate. This allows circumventing the computation of the two-phase velocity of sound, which generally represents the main criterion for qualifying the flow conditions but its computation in two-phase conditions remains, to the best of our knowledge, still approximate. The features of this model are detailed in the next sections. Validation is partially performed with data obtained on an experimental set-up, built for the purpose, while additional data is gathered from the literature to complete the validation.

2. Ejector modeling

A two-phase ejector integrated in a mechanical refrigeration or heat pumping system, directly interacts with the compressor, which acts as the ejector source of activation. Consequently, the ejector behaves in the system as an expansion agent for the primary stream fed from the condenser, and as a compression agent for the secondary stream, drawn from the evaporator.

The proposed model relies on a thermodynamics approach, where the different parts of the ejector, as represented in Fig. 1, are considered.

2.1. Main assumptions

In the proposed development, the homogeneous model where liquid and vapour phases are in dynamic and thermal equilibrium is assumed to apply. This is reasonable because average velocities are high, ejector dimensions are small, which is expected to enhance good phase mixing. Mass, momentum and energy transfer between phases are assumed to occur instantly. In this way, the fluid is assumed to behave like a single phase fluid with the same temperature, velocity and pressure in steady state conditions. Moreover, the following conditions, relative to ejector operation are retained:

- Adiabatic flow;
- Stagnation conditions, applied at both primary and secondary inlets;