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A CFD-based investigation of the energy performance of two-phase R744 ejectors to recover the expansion work in refrigeration systems: An irreversibility analysis

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ABSTRACT

A CFD-based numerical analysis of the flow irreversibility in R744 ejectors is presented. A validated CFD tool was used to investigate three cases that were differentiated by the mass flow rate per unit area (mass flux) that passed through the mixer, which represented three dissimilar flow patterns. The mixer mass flux was found to significantly affect the ejector performance both locally and globally. An original approach was introduced to assess the contribution of the local irreversibilities to the overall entropy increase. A new factor was proposed to evaluate the ejector performance based on the reference entropy increase in a classic expansion valve. In addition, the influence of the mixer diameter and length on the ejector performance was numerically analysed, which showed that the effects of both geometric parameters may be significant. Namely, in the conditions considered, both enlargement of the mixer cross section area by 17.4% as well as shortening the mixer length by 33.3% resulted in the increase of the overall entropy growth rate by 8.9% and 5.4%, respectively.

Une étude basée sur la mécanique des fluides numérique de la performance énergétique d'éjecteurs diphasiques au R744 pour récupérer le travail de détente dans des systèmes frigorifiques : une analyse de l'irréversibilité

Mots clés : Ejecteur diphasique ; Récupération du travail de détente ; Modélisation en dynamique numérique des fluides ; Analyse de l'irréversibilité

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Nomenclature

A	cross section area, m^2
a	speed of sound, $m\ s^{-1}$
c	specific heat capacity, $J\ kg^{-1}\ K^{-1}$
D	diameter, m
h	specific enthalpy, $J\ kg^{-1}$
k	turbulent kinetic energy, $J\ kg^{-1}$
L	length, m
$\dot{m}$	mass flow rate, $kg\ s^{-1}$
Ma	Mach number
p	pressure, Pa
$\dot{S}$	entropy rate, $J\ s^{-1}\ K^{-1}$
s	specific entropy, $J\ kg^{-1}\ K^{-1}$
T	temperature, K
ΔT	superheat, K
x	mass fraction

Greek symbols

α	volume fraction
β	volumetric expansivity (thermal expansion coefficient), K^{-1}
ε	relative increase of the entropy rate
γ	angle of convergence, °
η	efficiency
κ	isothermal compressibility, Pa^{-1}
ρ	density, $kg\ m^{-3}$
ζ	overall factor of the avoided entropy increase

Subscripts

DIF	diffuser
EJ	ejector
g	gas phase
in	inlet value
l	liquid phase
MCH	mixing chamber
meas	measured value
MIX	mixer
MN	motive nozzle
out	outlet value
p	isobaric
r	reduced parameter
ref	reference value
s	isentropic
sim	simulated value
SN	suction nozzle

1. Introduction

Two-phase ejectors for expansion work recovery have garnered significant attention from the scientific community in recent decades, specifically in the field of R744 refrigeration, where they constitute an attractive alternative for expansion devices in the classic vapour compression systems, primarily due to the possible reduction of the compressor work, Elbel (2011). In addition, the ejector's simplicity (i.e., it has no moving parts) compared to expanders, its low cost and its reasonable efficiency make its use additionally beneficial. Fig. 1 represents the most common option of the ejector cycle used for small capacity refrigeration and heat pumping systems. Nevertheless, the proper design of a two-phase ejector requires a detailed analysis of the flow conditions inside the ejector passages and various parameters of the overall ejector performance.

The overall ejector energy performance is often assessed using a universally accepted approach: a dimensionless factor called the ejector efficiency, η_{EJ}, is commonly used to reflect the total irreversibility of all changes that occur inside the ejector passages, e.g., see Elbel and Hrnjak (2008), Elbel (2011), and Lucas and Koehler (2012).

$$\eta_{EJ} = \frac{\dot{m}_{SN}\left(h|_{\substack{s = s_{SN,in} \\ p = p_{DIF,out}}} - h_{SN,in}\right)}{\dot{m}_{MN}\left(h_{MN,in} - h|_{\substack{s = s_{MN,in} \\ p = p_{DIF,out}}}\right)} \quad (1)$$

This factor, expressing the efficiency of expansion work recovery, is defined as the ratio of the expansion work rate recovered by the ejector to the maximum possible expansion work rate, i.e., the recovery potential that is available in the primary stream. The recovered amount of the expansion work rate is defined as the product of the suction mass flow rate, $\dot{m}_{SN}$, and the specific enthalpy difference $\left(h|_{\substack{s = s_{SN,in} \\ p = p_{DIF,out}}} - h_{SN,in}\right)$, which is identified by the beginning and ending points of an imaginary, isentropic compression from the evaporation pressure to the diffuser outlet pressure. This compression work is assumed to be removed from the compressor's duty and replaced with the ejector operation. Conversely, the maximum possible recovery potential of the expansion work rate is defined as the product of the motive mass flow rate, $\dot{m}_{MN}$, and the specific enthalpy difference $\left(h_{MN,in} - h|_{\substack{s = s_{MN,in} \\ p = p_{DIF,out}}}\right)$, which is identified by the points that end two theoretical, isenthalpic, and isentropic expansion lines from the motive stream to the diffuser outlet pressure.

Unfortunately, the evaluation approach for the separately considered individual sections of the ejector has been a subject of debate. Such analysis is crucial to properly identify and comprehend any encountered flow irreversibility and may suggest potential remedies, particularly in terms of geometric modifications. Although the spectrum of the utilised evaluation parameters is broad, their values often reveal only partial information about the size of the local irreversibility and its contribution to the total ejector efficiency. Furthermore, the underlying methodology is based on numerical simulations instead of experimental work. This approach yields results that depend on the accuracy of the models and are vulnerable to inappropriate assumptions.

Varga et al. (2009) reviewed the available definitions of local ejector efficiencies and numerically determined their values