International Journal of Thermal Sciences 50 (2011) 2235–2247

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

1D Computational model of a two-phase R744 ejector for expansion work recovery

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ARTICLE INFO

Article history:
Received 19 December 2010
Received in revised form
30 May 2011
Accepted 8 June 2011
Available online 13 July 2011

Keywords:
Two-phase ejector
Expansion work recovery
Mathematical modelling
Operation curve

ABSTRACT

A one-dimensional mathematical model of the R744 two-phase ejector for expansion work recovery is presented in this paper. Governing equations were formulated for all passages of the ejector based on the differential equations for mass, momentum, and energy balance as well as a differential representation for the equation of state. For two-flow sections (mixer and diffuser) closing equations for mass, momentum and energy transfer between the primary and secondary flow were introduced. This model utilises the Delayed Equilibrium Model along with the Homogeneous Nucleation Theory for the purpose of the metastable state analysis for a transcritical flow with delayed flashing over the motive nozzle. The thermal properties model was based on a real fluid approach, where the REFPROP 8.0 database was used. Based on the results of experimental tests performed at SINTEF Energi Laboratory, the model was validated for a typical range of operating conditions. The range of available simulation output allowed for the creation of 1D profiles of local values for the flow variables and the computation of the overall indicators, such as pressure lift and expansion work recovery efficiency.

1. Introduction

Two-phase ejectors have constituted an attractive alternative for classic expansion devices for several decades. The main advantage of the ejector may be found in the recovery of the expansion work normally wasted in throttling processes at a typical expansion valve. Nevertheless, proper design of a two-phase ejector for the expansion work recovery requires a detailed analysis in terms of both the numerical simulations and the experimental work. Over the last 20 years, significant effort was invested in the development of computational codes capable of assessing the key features of the two-phase ejector performance, i.e., entrainment and pressure ratios along with the profiles of pressure, velocity and density. However, the capabilities of commercially available computational tools for the mathematical modelling of two-phase ejectors are still quite limited.

The vast part of the scientific outcome reported in journal papers concerned steady state, zero-dimensional (0D) or pseudo one-dimensional (1D) models of the ejection cycle. Balamurugan et al. [1] provided and validated a 0D semi-empirical model of a gas-water ejector, taking into account the compressibility of air and the overall pressure losses of a two-phase mixture. Selvaraju and Mani [2] and Nehdi et al. [3] showed a design mode, pseudo 1D (inlet-outlet conditions) theoretical analysis of a two-phase ejector cycle for several chlorofluorocarbons and hydrofluorocarbons. In their work, the real fluid properties were calculated based on data from the REFPROP database. Cizungu et al. [4] performed a pseudo 1D design and off-design numerical analysis for ammonia and ammonia–water two-phase ejectors. In addition, the authors optimised the ejector geometry to achieve maximum values for either the entrainment ratio or the pressure ratio. Lear et al. [5] simulated choking conditions in a two-phase R134a ejector using pseudo 1D equations of the conservation for mass, momentum and energy, and equations of thermodynamic processes for characteristic cross sections of the passage. A brief review of those and other influential articles may be found in the paper of Hemidi et al. [6].

The authors of the aforementioned papers took into account all of the required geometrical parameters of the ejector along with assumed values of the integral coefficients, such as isentropic efficiencies, for all of the passages. As a result, they were able to perform the off-design analysis and to determine the operating characteristics of the ejector in this mode, e.g., Cizungu et al. in [4]. However, the governing algebraic equations for velocity, pressure, density, enthalpy and cross-section area of the duct did not allow for the evaluation of local field quantities.

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doi:10.1016/j.ijthermalsci.2011.06.007

Nomenclature

A	cross-sectional area, m^2
a	coefficient of scale in Eq. (34)
$\mathbf{B}$	vector of constants in Eqs. (5), (8) and (26)
C	drag coefficient
c	speed of sound, m s^{-1}
D	channel diameter, m
F	lateral surface area, m^2
f	friction factor
h	specific enthalpy, J kg^{-1}
I	nucleation rate, m^{-3} s^{-1}
L	length, m
l	axial coordinate, m
m	mass, kg
p	pressure, Pa
r	bubble/droplet radius
Re	Reynolds number
$\dot{Q}$	heat transfer rate, J s^{-1}
s	specific entropy, J kg^{-1} K^{-1}
T	temperature, K
u	uncertainty of a measured variable
W	force, kg m s^{-2}
w	velocity, m s^{-1}
$\mathbf{X}$	vector of unknowns in Eqs. (5), (7) and (25)
x	mass fraction
y	vaporisation index

Greek symbols

α	heat transfer coefficient, W m^{-2} K^{-1}
ε	absolute roughness, m
ϕ	any specific thermodynamic variable
Γ	mass transfer rate, kg s^{-1}
γ	angle of convergence, °
η	dynamic viscosity, kg m^{-1} s^{-1}
Π	momentum transfer rate, kg m s^{-2}
ρ	density, kg m^{-3}
τ	time, s
$\mathbf{\Omega}$	matrix of coefficients in Eqs. (5), (6) and (24)
ψ	number of bubbles/droplets per unit volume, m^{-3}

Subscripts

1F	single-flow passage
2F	double-flow passage
c	condensation
DIF	diffuser
f	friction
g	gas phase
int	interface
l	liquid phase
m	metastable phase
MCH	pre-mixing chamber
MIX	mixer
MN	motive nozzle
p	isobaric
s	isentropic
sat	saturated
SN	suction nozzle
w	wall
α	motive (primary) flow
β	suction (secondary) flow
∞	local equilibrium symbol in $Re_{\beta,\infty}$

Abbreviations

DEM	Delayed Equilibrium Model
HEM	Homogeneous Equilibrium Model
HNT	Homogeneous Nucleation Theory
HRM	Homogeneous Relaxation Model
IHE	Isentropic Homogeneous Equilibrium

In addition, none of the aforementioned works included a computational analysis of the metastable conditions occurring during the phase transitions, which is particularly important for precise evaluation of the critical mass flow rate of the primary fluid for a given geometry of the motive nozzle. Nakagawa et al. [7] experimentally proved that the decompression pressure profiles for a diverging section of the CO_2 motive nozzles may significantly differ from the profiles calculated according to the Isentropic Homogeneous Equilibrium (IHE), which indicates boiling processes started at non-equilibrium supersaturated state. Based on the results by Nakagawa et al. [7], Angielczyk et al. [8] utilised the Homogeneous Relaxation Model (HRM) for the purpose of the ejector motive nozzle 1D modelling. The authors confirmed the homogeneous equilibrium approach is not suitable for the motive nozzle calculations, neither design nor off-design type.

The limitations of the thermodynamic equilibrium assumption can be overcome by applying a multidimensional, transient and heterogeneous fluid analysis to the two-phase flows, namely Computational Fluid Dynamic (CFD). Typically, air-water ejectors were investigated, according to Hemidi et al. [6] and He et al. [9], with the assumption that air obeys the ideal gas law. However, when both fluids are of the same chemical composition, the condensation and evaporation phenomena analysis should be introduced into the simulation tool.

Narabayashi et al. [10] conducted an analytical and experimental study on water-steam injectors, where the authors utilised a 2D, axisymmetrical, steady state formulation for the continuity, momentum and energy equations with both phases treated as separate, homogeneous and immiscible. The sole mechanisms of the interface interactions between the two phases in a coaxial and annular flow were modelled by direct condensation of steam on the surface of the water jet and the momentum exchange at the phase boundary due to velocity gradients. The model was successfully validated by comparison of the temperature and velocity profiles with experimental data.

Städtke [11] formulated general conservation equations for a transient, 2D flow of a heterogeneous two-phase real fluid. The governing equations included four pairs of main partial differential equations for mass, momentum, energy, and entropy defined separately for each phase. The author presented the results of numerous validation tests performed for various cases of transient flows.

Nevertheless, the non-homogenous formulation of a two-phase fluid requires deep knowledge of the nature of flow. Because flow regimes for the R744 two-phase ejectors have not been well analysed and reported previously, each assumption on the heterogeneous flow model is fairly uncertain and may not constitute a realistic approach. Therefore, the authors of this paper believe that in some cases the homogeneous flow model could offer a reasonable substitute, since a general form of governing equations would allow to encompass all potential flow patterns.

Attou and Seynhaeve [12] presented a mathematical formulation for this type of flow problem that was simultaneously sufficiently complex and computationally efficient. The authors' 1D