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Effect of mixing on the performance of wet steam ejectors

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ABSTRACT

Steam ejector computational simulations using a wet steam model give higher entrainment ratios and higher critical back pressures for the ejector compared with the ideal gas model. This paper identifies the origin of these differences. Simulation results show that the wet steam model predicts an entrainment ratio for the choked flow ejector operation that is 10% higher than that for the ideal gas model. The wet steam model also gives a higher critical back pressure by about 7% relative to the ideal gas model with a closer agreement to experimental data for the unchoked ejector operation. Enhanced mixing layer growth which arises due to steam condensation in the primary nozzle is identified as the main reason for higher entrainment ratio of the ejector simulations using the wet steam model. The difference in the mixing layer growth rate between ideal gas and wet steam simulations is 21%, indicating enhanced entrainment for the wet steam model. Furthermore, the mixture at the start of the diffuser is shown to have a higher pitot pressure than in the ideal gas simulations and these elevated pitot pressures allow the ejector to operate in a choked mode to a higher critical back pressure.

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1. Introduction

Supersonic steam ejectors are widely used in a large number of industries that require steam for heating or a power generating medium. Ejectors are devices which utilize the energy of a high pressure fluid (the primary stream) to move a low pressure fluid (the secondary stream) and enable it to be compressed to a higher pressure. Their action is similar to a vacuum pump or compressor but ejectors do not use any moving components or electricity for the compression process. They are known for simple construction, easy installation and low capital costs. Steam ejectors essentially consist of four main parts: a primary nozzle, a mixing chamber, a constant area section and a diffuser. Fig. 1(a) shows a schematic of a typical steam ejector illustrating the different parts.

A typical performance curve of an ejector can be categorized into three operating regions as illustrated in Fig. 1(b): choked flow, unchoked flow and reversed flow. Choked flow occurs when the discharge pressure is lower than the critical back pressure. For the unchoked mode, the secondary stream is no longer choked and its mass flow rate decreases rapidly with increasing discharge pressure which reduces the ER (entrainment ratio). Further increase in the discharge pressure causes flow to reverse back to the secondary stream's inlet and ejector malfunction occurs.

There are different parameters affecting the ejector performance including the operating conditions, the geometry of the primary nozzle and its exit position in the mixing chamber, the diameter of the nozzle throat and that of the constant area section. Works from several authors are available in the literature investigating such parameters using CFD (computational fluid dynamics) methods which appear to accurately simulate the flow field inside ejectors [1–6].

Ji et al. [5] and Sreevirakul et al. [7] used CFD methods to investigate the flow structure inside ejectors. They analyzed flow behavior and mixing processes inside steam ejectors and identified the formation of shock waves and how these affect the ejector performance. Yang et al. [8] performed a numerical study on the mixing process in a steam ejector using different nozzle structures. From their investigations, characteristics of the mixing process were explained based on the simulation of streamwise and spanwise vortex distribution in the mixing chamber and their effects on the ejector performance. The ideal gas assumption was employed for these CFD simulations of ejectors, even in the studies which considered water vapor as the working fluid.

The conditions under which water vapor flows begin to condense are already quite well understood and such conditions often occur in steam ejectors. Droplet nucleation and the

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Nomenclature

English letters

a	speed of sound, m/s
b	nozzle throat diameter, m
E	total energy, J
I	nucleation rate, # droplets/m^3.s
k	turbulent kinetic energy, J/kg
M	Mach number
M_c	convective Mach number
M_e	equilibrium Mach number
P	static pressure, Pa
P_0	total pressure, Pa
P_{pitot}	pitot pressure, Pa
r	radial distance, m
S	streamwise distance measured from the nozzle throat, m
T	static temperature, K
T_s	saturation temperature, K
t	time, s
U	velocity, m/s
x	streamwise distance, m

Greek letters

β	liquid mass fraction
Γ	mass generation rate, kg/m^3 s
γ	ratio of specific heats
γ_e	equilibrium specific heat ratio
δ	mixing layer thickness, m
δ'	growth rate of mixing layer thickness
δ_0'	growth rate of equivalent incompressible mixing layer
η	droplet number density, 1/m^3
μ	dynamic viscosity, N s/m^2
μ_t	turbulent viscosity, N s/m^2
Π_c	compressibility parameter
ρ	mixture density, kg/m^3
τ_{ij}	stress tensor
ϕ	velocity ratio
χ	steam quality
Ω	density ratio
ω	specific dissipation rate, 1/s

subsequent development of condensation result in a number of energy transfers which cannot be accurately simulated by assuming that the steam behaves as a perfect gas. Therefore, recent CFD simulations of steam ejector performance have incorporated droplet nucleation and condensation models. Some valuable numerical assessments of ejectors have been completed to study nucleation phenomenon and to investigate condensing steam flow behavior [9–12]. These studies concluded that the wet steam simulation yields a higher entrainment ratio and critical back pressure compared with ideal gas or dry steam simulations.

An important process which affects the performance of ejectors is the mixing of the primary and secondary streams. When two

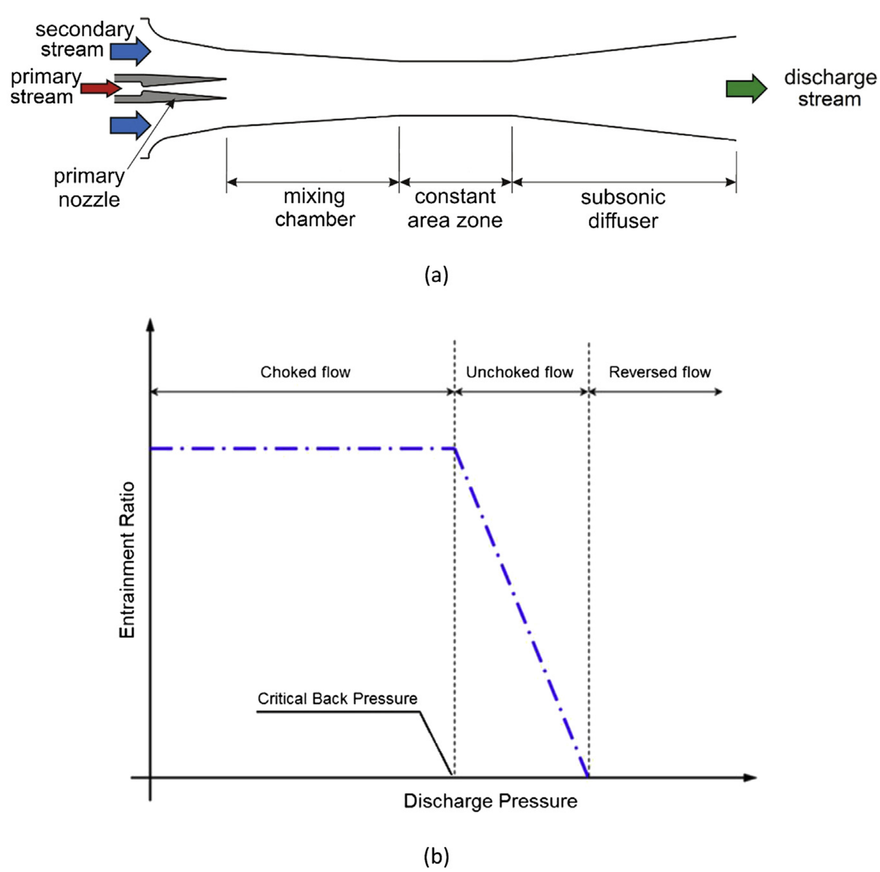

Fig. 1. (a) Schematic showing a typical ejector cross-section illustrating the different zones, (b) Illustrative performance curve of the ejector.

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