Energy Conversion and Management 149 (2017) 168–174

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Influences of area ratio and surface roughness on homogeneous condensation in ejector primary nozzle

Chen Wang [a], Lei Wang [a,*], Tao Zou [b,*], Hailun Zhang [a]

[a] School of Control Science and Engineering, Shandong University, Jinan 250061, China
[b] Shenyang Institute of Automation, Chinese Academy of Sciences, Shenyang 110016, China

ARTICLE INFO

Article history:
Received 16 May 2017
Received in revised form 28 June 2017
Accepted 9 July 2017

Keywords:
Ejector primary nozzle
Area ratio
Surface roughness
Homogeneous condensation

ABSTRACT

Homogeneous condensation inside the ejector has been ignored by numerous researchers. In this paper, the wet steam model was utilized to study the influences of nozzle area ratio and surface roughness on homogeneous condensation in a primary nozzle. A substantial amount of latent heat is released during the homogeneous condensation process to increase static pressure and reduce Mach number. The increase of nozzle area ratio reduces condensation intensity and lowers nozzle pressure but increases liquid mass fraction. Furthermore, with the growth of surface roughness, the slightly increased dryness fraction is almost ineffective for alleviating erosion caused by tiny droplets; the slight decrease in mass flow rate will reduce ejector performance to some extent, while the sharp increase of entropy generation results in more energy wastes. Therefore, nozzle area ratio and surface roughness should be carefully designed to alleviate potential condensation and enhance ejector performance at the same time.

1. Introduction

With the advantages of a concise structure, low energy consumption, and high reliability, the ejector is extensively utilized in a number of industrial applications such as refrigeration systems [1–4], fuel cell systems [5] and multi-effect distillation desalination systems [6,7]. The ejector is formed from five parts: a primary nozzle; a suction chamber; a constant-pressure mixing chamber; a constant-area mixing chamber; and a diffuser (displayed in Fig. 1).

The operating principle of an ejector is described as follows: (1) The primary nozzle converts the low velocity and high pressure flow into a supersonic flow with low pressure. (2) The vacuum region formed from the low pressure draws the secondary flow into the suction chamber. (3) The primary flow and secondary flow commence to combine in a complicated form within the mixing chamber. (4) The mixed flow undergoes shock waves, reducing the velocity to subsonic speed and the pressure reaches the designed back pressure at the outlet of the diffuser.

However, the homogeneous condensation occurred inside the ejector has been neglected by many ejector investigations. Under the rapid expansion of the primary nozzle, steam temperature is sharply decreased to the saturated-vapor line; however, the nucleation core cannot form immediately in the pure steam, which forces the state path to cross the saturated-vapor line and, thus, departs from the equilibrium state. Next, with sufficient Gibbs free energy, the steam nucleates and is converted into wet steam, a mixture of saturated vapor and a mass of tiny droplets.

Inchoate experiments on homogeneous condensation were conducted by Stodola, based on the Laval nozzle [8]. Subsequently, Gyarmathy et al. reached a milestone for wet steam research by theoretically analyzing the effects of the Wilson point position on experimental results for the first time [9]. Furthermore, Moore et al. acquired pressure distribution along a Laval nozzle in a wet-steam tunnel established independently through their research [10], while Young developed a group of conservation equations for wet steam flow and these equations were widely employed in the ensuing studies of wet steam flow [11]. A two-fluid model was developed by Dykas et al to more accurately predict the homogeneous condensation steam and droplet radii attained from the model, which were more precise than that achieved from the single-fluid model [12].

Recently numerical researches were conducted to investigate the homogeneous condensation phenomena. Rad et al. discovered that the volumetric heating of a nozzle's convergent part is beneficial for the enhancement of flow stability by semi-analytical and one-dimensional modeling approaches [13]. Ariafar et al. simulated three primary nozzles in a steam ejector through a wet steam model and determined through empirical observation that after the condensation shock, the value of static pressure and

* Corresponding authors.
E-mail addresses: leiwang@sdu.edu.cn (L. Wang), zoutao@sia.cn (T. Zou).

http://dx.doi.org/10.1016/j.enconman.2017.07.025
0196-8904/

Nomenclature

ρ	density, kg m^{-3}
P	pressure, Pa
E	total energy, J
α_{eff}	effective thermal conductivity, W m^{-1} k^{-1}
T	static temperature
μ_{eff}	effective dynamic viscosity, N s m^{-2}
δ_{ij}	Kronecker delta function
u_p	mean fluid velocity, m s^{-1}
z	von Karman's constant
H	empirical constant
fr	roughness function
β	liquid mass fraction
Γ	mass generation rate, kg m^{-3} s^{-1}
r_*	critical droplet radius, μm
σ	liquid surface tension
η	the number of droplets per unit volume
V_d	average droplet volume
I	nucleation rate
q_c	evaporation coefficient
k_b	Boltzmann constant
M_m	mass of one molecule
θ	nonisothermal correction factor
h_{lv}	specific enthalpy of evaporation
γ	the ratio of specific heat capacities
AR_n	area ratio between nozzle exit and throat
Sr	supersaturation ratio
DF	dryness fraction
S_{gen}	total entropy generation
S_{genF}	entropy generation caused by turbulentdissipation and frictional irreversibility
S_{genH}	entropy generation caused by transfer irreversibility

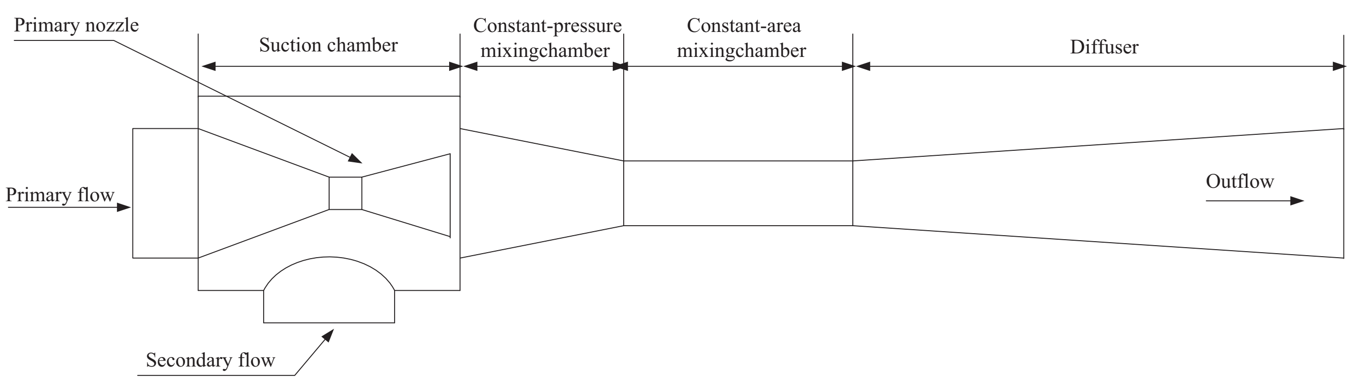

Fig. 1. Configuration of a characteristic ejector.

temperature were increased, as compared to the ideal gas model [14]. A two-phase flow model was proposed by Ding et al. to evaluate the influence of condensation on the mass flow rate of Laval nozzle. Afterwards, they developed an analytical resolution to compute the wet steam flow properties in an efficient way [15,16]. Sharifi et al. [17] and Wang et al. [18] conducted early numerical investigation on the homogeneous condensation inside the ejector. Abadi et al. [19] applied a two-fluid multiphase model for predicting the homogeneous condensation within a high-pressure ejector. Furthermore, volumetric cooling and inlet superheating were explored by Ahmadpour et al. [20] to control the homogeneous condensation within the ejector, which were proved to have the capability of decreasing wetness losses, while enhancing ejector performance. Biferi et al. [21] compared homogeneous equilibrium model and non-equilibrium model for the prediction of condensation inside the ejector.

According to the researches of Luiset et al. [22] and Song et al. [23], tiny droplets will cause erosion in the inner wall of ejector and seriously impact ejector performance. Jia et al. [24–26], Chen et al. [27] and Sag et al. [28] drew the conclusion that the nozzle structure has a significant influence on ejector performance; however, their researches ignored the homogeneous condensation that occurs in the primary nozzle. In this research, the area ratio and surface roughness of the primary nozzle were investigated to abate the effect of the homogeneous condensation on nozzle performance, which is significant for the appropriate design of an ejector. The influences of homogeneous condensation on the ejector nozzle were studied by comparing the variation of the flow parameters and wet steam properties. The concept of dryness fraction was used to evaluate the inner wall erosion caused by the tiny droplets. Entropy generation was obtained, so as to more precisely assess the efficient energy utilization of the primary nozzle.

2. Mathematical model

2.1. Governing equations

A series of primary nozzle models were established to research the influences of the area ratio and surface roughness on the overall nozzle performance. In order to reduce model complexity, assumptions of a stable and dry saturated state inside the ejector nozzle and adiabatic inner wall of ejector nozzle are assumed.

The governing equations can be depicted by the equations of continuity, momentum, and energy:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial(\rho u_j u_i)}{\partial x_j} = \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial P}{\partial x_i} \tag{2}$$

$$\frac{\partial(u_i(\rho E + P))}{\partial x_i} = \vec{\nabla} \cdot \left(\alpha_{eff}\frac{\partial T}{\partial x_i} + u_j(\tau_{ij})\right) \tag{3}$$

where stress tensor τ_{ij} is: