INTERNATIONAL JOURNAL OF REFRIGERATION 67 (2016) 214–226

Available online at www.sciencedirect.com

ScienceDirect

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

Effects of superheated steam on non-equilibrium condensation in ejector primary nozzle

Chen Wang [a], Lei Wang [a,*], Hongxia Zhao [b,**], Zhongyong Du [a], Zhaoqiu Ding [a]

[a] School of Control Science and Engineering, Shandong University, Jinan, China
[b] School of Energy and Power Engineering, Shandong University, Jinan, China

ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form 22 February 2016
Accepted 28 February 2016
Available online 7 March 2016

Keywords:
Superheated level
Non-equilibrium condensation
Ejector primary nozzle
Wet steam model

ABSTRACT

In order to reduce the non-equilibrium condensation occurring in ejector primary nozzle, wet steam model was adopted to investigate the relationship between steam superheated level and non-equilibrium condensation within ejector primary nozzle. Simulation data of axial static pressure along primary nozzles were validated with experimental data reported in literature. The non-equilibrium condensation process from homogeneous nucleation to droplet growth stage and the resulting products were carefully studied. Moreover, six inlet superheated levels from 5 K to 30 K with the increment of 5 K were compared, and simulation results showed that the increase of superheated level from 5 K to 30 K causes 40.22% delay in the location and 43.92% reduction in the intensity of the condensation shock. Furthermore, there is about 24.30% liquid mass fraction decrease when the superheated level raises to 30 K and total entropy generation increases slowly with the increase of superheated level.

Effets de la vapeur surchauffée sur la condensation en condition de non-équilibre dans une tuyère primaire d’éjecteur

Mots clés : Niveau surchauffé ; Condensation en non-équilibre ; Tuyère primaire d’éjecteur ; Modèle de vapeur humide

---

[*] *Corresponding author.* School of Control Science and Engineering, Shandong University, Jinan, China. Tel.: +86 531 5866 2676; Fax: +86 531 5866 2676.

E-mail address: leiwang@sdu.edu.cn (L. Wang).

[**] *Corresponding author.* School of Energy and Power Engineering, Shandong University, Jinan, China. Tel.: +86 531 8839 9475; Fax: +86 531 8839 9475.

E-mail address: hongxia.zhao@sdu.edu.cn (H. Zhao).

http://dx.doi.org/10.1016/j.ijrefrig.2016.02.022

Nomenclature

u	velocity [m s^{-1}]
P	pressure [Pa]
E	total energy [J]
T	static temperature [K]
B	the second virial coefficients [m^3 kg^{-1}]
Be	Bejan number
C	the third virial coefficients [m^6 kg^{-2}]
ΔG	Gibbs free energy for nuclei formation
R	gas constant for water vapor
r	droplet radius [μm]
S	entropy generation
Sr	supersaturation ratio
V	droplet volume
I	nucleation rate
q_c	evaporation coefficient
k_b	Boltzmann constant
M_m	mass of one molecule
h_{lv}	specific enthalpy of evaporation
ρ	density [kg m^{-3}]
α	thermal conductivity [W m^{-1} k^{-1}]
μ	dynamic viscosity [N s m^{-2}]
δ_{ij}	growth rate of mixing layer
β	liquid mass fraction
η	the number of droplets per unit volume
Γ	mass generation rate [kg m^{-3} s^{-1}]
σ	liquid surface tension
θ	nonisothermal correction factor
ε	dissipation rate of turbulent kinetic
γ	the ratio of specific heat capacities

Abbreviations

SH	the degree of superheat
Df	dryness fraction

Subscripts

v	vapor
in	inlet
l	liquid
eff	effective
m	mixture
*	critical condition
a	average condition
t	turbulent
gen	total
genF	caused from friction and turbulent dissipation
genH	caused by heat transfer irreversibility

1. Introduction

Ejector is widely used in many applications, such as air-conditioning systems (Göktun, 1999; Huang et al., 1999; Majdi, 2016; Wang et al., 2016; Yu et al., 2013; Zhu and Jiang, 2012) and multi-effect desalination systems (Han et al., 2014; Kouhikamali and Sharifi, 2012), for its simple structure, low energy consuming and reliability compared to conventional apparatus. As shown in Fig. 1, ejector consists of five main parts: (1) the primary nozzle; (2) the suction chamber; (3) the constant-pressure mixing chamber; (4) the constant-area mixing chamber; and (5) the diffuser. Primary nozzle converts primarye flow with high pressure and low velocity flow into a supersonic flow with low pressure, which creates a pressure region lower than secondary flow pressure in the suction chamber. So secondary flow is entrained into the constant-pressure mixing chamber and the two flows begin to combine in a very complex form in mixing section. As the flows enter the diffuser, the velocity down to subsonic, secondary flow pressure is compressed to a high pressure.

One interesting phenomena that has been ignored by most ejector investigations is that when steam temperature sharply decreases below the vapor-saturation value under the influence of rapid expansion in the primary nozzle, the non-equilibrium condensation process will take place. Then the steam nucleates to become a two-phase mixture of saturated vapor and tiny liquid droplets, which is known as wet steam. The early experiments on non-equilibrium condensation, where nozzle is the key component, can date back to 1905 by Stodola and Loewenstein (1905). And Gyarmathy (1962) was the first to theoretically explain the influence of Wilson point position on experimental data, which is a milestone in the development of wet steam flow investigation. Furthermore, Moore et al. (1973) conducted an experiment in a wet-steam tunnel and pressure distribution in the nozzle condensation zone was measured. Moses and Stein (1978) conducted a series of experiments on steam condensation in a Laval nozzle over a variety of starting conditions, the homogeneous nucleation and growth of the new phase are documented with both static pressure and laser light scattering. Young (1995) developed the complete set of conservation equations for gas-droplet multiphase flow, which were used regularly in the following investigation of wet steam flow. Dykas and Wróblewski (2011) proposed a two-fluid model to simulate non-equilibrium condensation steam within low-pressure turbine cascade, which can capture the slip velocity between vapor and liquid phases.

One benefit of CFD investigation is the numerical visualization, by which the flow phenomena inside the nozzle can be described from the post processing and used to support the quantitative results. Numerous studies have been conducted to investigate the wet steam flow within nozzles with CFD. White and Young (1993) conducted the first 2D calculations of wet steam flow, which predicted the instantaneous formation of a bimodal distribution within the oscillation mode. Lamanna (2000) conducted a systematic study of condensing flows, mixtures of water vapor in nitrogen, inside supersonic nozzles, which encompasses both theoretical and experimental analysis. White (2000) used a numerical method to predict the condensing flow of steam in boundary layers, and investigated the effects of viscous dissipation and reduced expansion rate on nucleation and droplet growth. Simpson and White (2005) revealed asymmetric modes of oscillation in steam nozzle by unsteady calculation method for viscous flow of condensing steam.

In recent years, numerical studies were conducted to investigate more complex phenomena related to non-equilibrium condensation. Dykas and Wróblewski (2011) proposed a two-fluid model for condensing flow, and droplet radii obtained from the two-fluid model showed a better tendency than calcula-