Journal of Natural Gas Science and Engineering 25 (2015) 197–206

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Numerical simulation of binary-gas condensation characteristics in supersonic nozzles

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A R T I C L E I N F O

Article history:
Received 9 February 2015
Received in revised form
2 May 2015
Accepted 4 May 2015
Available online 15 May 2015

Keywords:
Binary-gas
Condensation
Supersonic nozzle
Numerical simulation

A B S T R A C T

Binary-gas condensation characteristics in supersonic nozzles are numerically simulated using the Euler–Euler two-fluid model with the RSM turbulence model. The effects of carrier gas, inlet pressure and inlet temperature on the distribution of the condensation parameters are analyzed. A new Laval nozzle with a central body is designed to study the effects of swirling on the condensation characteristics. The results show that the trends of the condensation parameters are substantially the same for different binary-gas systems with the same condensable gas, while the degree of supercooling, the droplet number density, the droplet radius and humidity in the nozzle are all affected by the specific heat of the carrier gas. Condensation in the nozzle can be further intensified by decreasing the inlet temperature or increasing the inlet pressure in the binary-gas system. The distribution of the condensation parameters no longer presents an axisymmetric phenomenon in Laval nozzles with swirling, and water condensation can be enhanced by increasing the swirling strength.

1. Introduction

Natural gas always contains water when it is exploited from underground, and it is necessary to separate the water from the natural gas. Several traditional methods are employed to do this, and the supersonic swirling separator is a new method utilized to dehydrate the natural gas (Okimoto et al., 2002; Betting et al., 2003; Alfyorov et al., 2005; Wen et al., 2010, 2011(a); Wen et al., 2011(b); Wen et al., 2011(c); Wen et al., 2011(d)). Because of its advantages of compact design, low weight, not requiring chemicals, and unmanned operation, extensive studies have been conducted.

A great deal of recent scientific research has focused on the gas flow characteristics and separation performance of a significant part of the supersonic swirling separator-Laval nozzle (Liu et al., 2005; Jassim et al., 2008; Jiang et al., 2009; Ma et al., 2009, 2010; Malyshkina, 2009; Malyshkina, 2010; Wen et al., 2012(a); Wen et al., 2012(b); Wen et al., 2013), in which the condensation primarily occurs. Some studies on the binary-gas or multi-gas system were also carried out. Young (1993) and Gyarmathy (1982) conducted research on the condensation of a gas system with carrier gas, and a liquid droplet growth rate calculation model was proposed in consideration of the effects of carrier gas. The condensation characteristics of binary-gas and multi-gas systems, such as nonane-methane, octane-methane, amyl alcohol-helium, water-helium, water-nitrogen, nonane-water-methane and so on, were investigated in a nucleation pulse expansion tube and expansion cloud chamber at Eindhoven University (Looijmans et al., 1995; Looijmans and van Dongen, 1997; Luijten et al., 1999(a); Luijten et al., 1999(b); Peeters et al., 2001, 2002, 2004; Lamanna et al., 2002; Luo et al., 2006, 2007). The condensation characteristics of a D_2O–H_2O–N_2 system in the Laval nozzle were studied by Wyslouzil et al. of the Ohio State University (Wyslouzi et al., 1997; Khan et al., 2003; Heath et al., 2002, 2003), and an empirical function for homogeneous water nucleation rates was proposed based on the experimental data, which was acquired using the small angle neutron scattering measurement method.

However, there is a lack of studies on the effects of the type of carrier gas on the binary-gas or multi-gas system flow and condensation characteristics in Laval nozzles. Meanwhile, many present studies focus mainly on the refrigeration effect of the Laval nozzle by optimizing the nozzle structure or separation capacity of the device by unilaterally increasing the swirling capacity. The effects of swirling on the refrigeration or the condensation of the vapor need to be paid more attention. Therefore, in this work, the effects of carrier gas, inlet pressure and inlet temperature on the condensation parameters are discussed. A new Laval nozzle with a central body is designed in order to study the effects of swirling on the flow and condensation characteristics in a binary system.

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http://dx.doi.org/10.1016/j.jngse.2015.05.005
1875-5100/

2. Numerical approach

2.1. Governing equations

The formation diameter of liquid droplets is very small, approximately 1×10^{-9} m, so the slip velocity between the vapor and liquid droplet is ignored in this paper when the governing equations are established. The vapor flow characteristics in the nozzle are depicted by partial differential equations, including a continuity equation, a momentum equation, and an energy equation, defined as Eqs. (1)–(3). A continuity equation, a droplet number density conservation equation, and a relation about droplet radius, droplets number and humidity are employed to describe the flow characteristics of liquid, presented as Eqs. (4)–(6).

$$\frac{\partial \rho_v}{\partial t} + \frac{\partial}{\partial x_j}(\rho_v u_j) = S_m \tag{1}$$

$$\frac{\partial}{\partial t}(\rho_v u_i) + \frac{\partial}{\partial x_j}(\rho_v u_j u_i) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) + S_u \tag{2}$$

$$\frac{\partial}{\partial t}(\rho_v E) + \frac{\partial}{\partial x_j}(\rho_v u_j E + u_j p) = \frac{\partial}{\partial x_j}\left(k_{eff}\frac{\partial T}{\partial x_j} + u_i \tau_{eff}\right) + S_h \tag{3}$$

$$\frac{\partial}{\partial t}(\rho y_d) + \frac{\partial}{\partial x_j}(\rho u_j y_d) = S_y \tag{4}$$

$$\frac{\partial \rho N_d}{\partial t} + \frac{\partial}{\partial x_j}(\rho N_d u_j) = J \tag{5}$$

$$r_d = \sqrt[3]{3y_d/(4\pi\rho_l N_d)} \tag{6}$$

where y_d, J, N_d and r_d are the vapor humidity, and nucleation rate, droplet number density and droplet radius, respectively.

S_m, S_u, S_h, S_y and J are the source terms due to condensation, added to the governing equations.

$$S_m = -\dot{m} \tag{7}$$

$$S_u = -\dot{m}u \tag{8}$$

$$S_h = \dot{m}\left(h_{lg} - h\right) \tag{9}$$

$$S_y = \dot{m} \tag{10}$$

$$\dot{m} = J\rho_l \frac{4\pi r_c^3}{3} + N_d \rho_v \rho_l 4\pi r_d^2 \frac{dr_d}{dt} \tag{11}$$

where $\dot{m}$ is the condensation mass per unit vapor volume per unit time.

2.2. Condensation model

The classic nucleation theory (CNT) model proposed by Zeldovich, 1942 is described as follows:

$$J_{CNT} = \frac{\rho_v^2}{\rho_l}\sqrt{\frac{2\sigma}{\pi m_v^3}}\exp\left(-\frac{16\pi}{3}\frac{\sigma^3}{k_B\rho_l^2 R_v^2 T_v^3 (\ln S)^2}\right) \tag{12}$$

where m_v is the molecular mass; S is the supersaturation of the vapor;$\sigma$is the droplet surface tension.

The studies by Rudek et al. (Rudek et al., 1996; Luijuten, 1998; Lamanna, 2000) show that the internally consistent classical nucleation theory (ICCT) proposed by Girshick et al. (Girshick and Chiu, 1990; Girshick, 1991) is more accurate than the classic nucleation theory model, so an improved ICCT model proposed by Lamanna is applied to calculate the nucleation rate in this work.

$$J_{ICCT} = \varepsilon\frac{1}{S}\frac{\rho_v^2}{\rho_l}\sqrt{\frac{2\sigma}{\pi m_v^3}}\exp\left(-\frac{16\pi}{3}\frac{\sigma^3}{k_B\rho_l^2 R_v^2 T_v^3 (\ln S)^2}\right)\exp(\theta) \tag{13}$$

where θ is the dimensionless surface tension; ε is the correction factor, $\varepsilon = 0.01$ is proposed by Lamanna for the water vapor condensation.

Gyarmathy's model (Gyarmathy, 1962) is employed to calculate the growth rate of droplets.

$$\frac{dr_d}{dt} = \frac{\lambda_v}{\rho_l h_{lg}}\frac{(T_s - T_v)\left(1 - \frac{r_c}{r_d}\right)}{r_d\left(1 + \frac{2\sqrt{8\pi}}{1.5\Pr_v}\frac{\gamma}{1+\gamma}Kn\right)} \tag{14}$$

where Pr_v is the Prandtl number; Kn is the Kundsen number.

2.3. Surface tension model

Lamanna proposed a new water droplet surface tension model called the Lamanna-Dohrmann model (Lamanna, 2000) in 2000, based on the Luijten-Prast model (Luijuten, 1998) and Schnerr-Dohrmann model (Schnerr and Dohrmann, 1990). The Lamanna-Dohrmann model showed high accuracy which was confirmed by the experimental data. Therefore, the Lamanna-Dohrmann model is utilized to calculate the droplet surface tension in this work. The model is described as follows:

When $T \geq 250$K

$$\sigma = 7.61 \times 10^{-2} + 1.55(273.15 - T) \times 10^{-4} \tag{15}$$

When $T < 250$K

$$\sigma = 8.52 \times 10^{-2} - 3.54236T \times 10^{-4} + 3.50835T^2 \times 10^{-6} \tag{16}$$

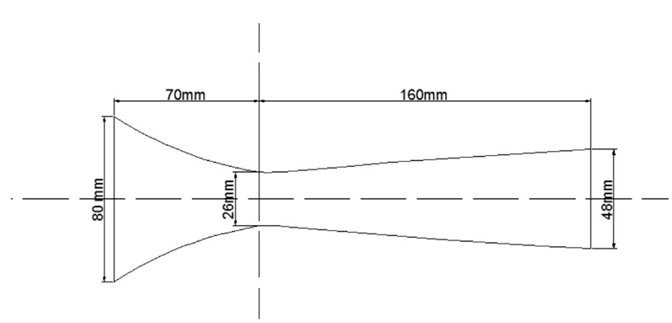

Fig. 1. Structure of Bakhtar's nozzle.