Applied Thermal Engineering 65 (2014) 24–33

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

A multi-fluid model for non-equilibrium condensation in gaseous carrier flows

Xiaofei Lv, Bofeng Bai*

State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China

HIGHLIGHTS

- A multi-fluid model is developed for condensing flow in the presence of carrier gas.
- Both the inter-phase velocity slip and temperature difference are taken into account.
- Good agreement is observed between CFD and experimental data.
- The effects of the inter-phase slip are remarkable.

ARTICLE INFO

Article history:
Received 13 September 2013
Accepted 24 December 2013
Available online 4 January 2014

Keywords:
Condensation
Multi-fluid model
Carrier gas
Inter-phase slip
Non-equilibrium

ABSTRACT

The inter-phase slip plays an important role in simulating the condensing flow, which is, however, generally neglected in most numerical studies. To address this, a generalized multi-fluid model is newly developed to predict the two-phase condensing flow in the presence of a carrier gas, where both the inter-phase velocity slip and the temperature difference are taken into account. The multi-fluid model is performed to simulate the condensing flow in two types of supersonic nozzles. Also, the traditional no-slip model is employed for comparing with the multi-fluid model. The simulated results obtained from the multi-fluid model are found to agree better with the experimental data. The effects of the inter-phase slip are revealed qualitatively by comparing the results obtained from these two models. The results show that the effects of inter-phase slip should not be neglected in the whole condensation process. At the initial stage of condensation, both the inter-phase velocity slip and temperature difference are noteworthy. When the condensation finishes and the gas–liquid equilibrium achieves, the inter-phase velocity slip and temperature difference become slight and can be neglected.

1. Introduction

Prediction for vapor condensation in gaseous carrier flows is scientifically interesting in various industrial and technological areas [1–4]. It is noted that the presence of carrier gas makes the condensation process much more complex than the wet steam condensation. As one knows, the carrier gas has a potential effect on the equilibrium vapor fugacity and surface tension due to the mutual interactions between the vapor and carrier gas molecules [5], and would affect the nucleation process by being present in the interior of condensing droplets. Generally, such condensation phenomenon is a complex non-equilibrium process in rapidly expanding flow, the characteristics of which strongly depend on the coupling between the flow field and the condensation process itself. In order to accurately predict the two-phase condensing flow, all physical features such as turbulent gas–liquid flow, the effects of carrier gas on condensation, inter-phase heat and mass transfer due to vapor condensation and momentum transfer as a result of inter-phase velocity slip should be accounted for.

The condensing flow has been experimentally [6–11] and numerically [12–17] studied in different fields for centuries. Generally, Eulerian representation is applied for describing the gas phase, while the condensed phase can be modeled by two ways, i.e., Lagrangian particle tracking approach [18–20] and Eulerian schemes [21–23]. And in general, most calculations using above schemes were performed by imposing a no-slip condition between the phases, which is the so-called no-slip model [24]. Actually, the inter-phase slip has a significant effect not only on the accurate prediction of the velocity field but also on the spontaneous condensation process due to the strong inter-phase coupling between the gas and dispersed liquid phases. However, few attempts have been made on the effects of inter-phase slip, which is potentially significant for simulating the condensing flow.

---

* Corresponding author. Tel./fax: +86 29 82665316.
E-mail address: bfbai@mail.xjtu.edu.cn (B. Bai).

1359-4311/$ – see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.12.060

In recent years, only a few studies have been reported to investigate the effects of inter-phase slip on condensing flow. Wu et al. [25] established a two-fluid model for steam condensing flow, taking the velocity slip and the turbulent diffusion into consideration. Gerber et al. [26] developed an Eulerian multiphase model for the prediction of steam condensation in transonic flow. Dykas et al. [24,27] proposed a two-fluid model to predict the wet steam losses in the low-pressure turbine stages and the model was implemented into the in-house CFD code. It should be noted that the above researches mainly focused on the wet steam flow. To the authors' best knowledge, only few published reports took the velocity slip into account for the prediction of condensation in gaseous carrier flows. Jones et al. [28] adopted a multi-phase multi-size group (MUSIG) population balance model to predict droplet size distributions in Laval nozzles. Prast et al. [1]employed the multi-phase mixture model for calculations of multi-component condensation in the Twister separator, and the inter-phase slip was calculated with the Algebraic Slip Model (ASM). However, the effects of velocity slip were still not clarified in the abovementioned work, and it was found difficult to achieve robust convergence for the multi-phase solver [29].

In this paper, we established a tractable multi-fluid model to characterize the vapor condensation in the presence of a carrier gas. In the newly developed model, both the inter-phase velocity slip and temperature difference were taken into account. In order to comprehensively investigate the effects of inter-phase velocity slip, the present model was compared with the no-slip model and performed to simulate the condensing flow in two supersonic nozzles. On the basis of the numerical simulating results, the proposed models were verified carefully with the existing experimental data. Then the effects of the inter-phase slip were qualitatively determined. Finally, the inertial non-equilibrium and thermal non-equilibrium were analyzed in detail to investigate the interactions between the two phases.

2. Mathematical models and numerical implementation

The schematic of condensing system studied in this paper is shown in Fig. 1, which consists of a carrier gas, a condensable vapor and vast amounts of liquid droplets, and the volume fractions of the vapor and droplets are very small. The basic idea of the common multi-fluid model is treating the dispersed phase as pseudo-fluid [30], thus both phases are described as inter-penetrating continua in the gas-droplet two-phase flow. In the newly developed multi-fluid model, the carrier gas and condensable vapor are described as two independent fluids for the condensing system above-mentioned, besides treating the liquid droplets as pseudo-fluid. Therefore, the two-phase condensing flow is considered as a three-fluid flow, where each fluid has individual constitutive equations solved in an Eulerian framework. One assumption is made in this paper: the carrier gas, as a non-condensing constituent, is absent in the interior of liquid droplets.

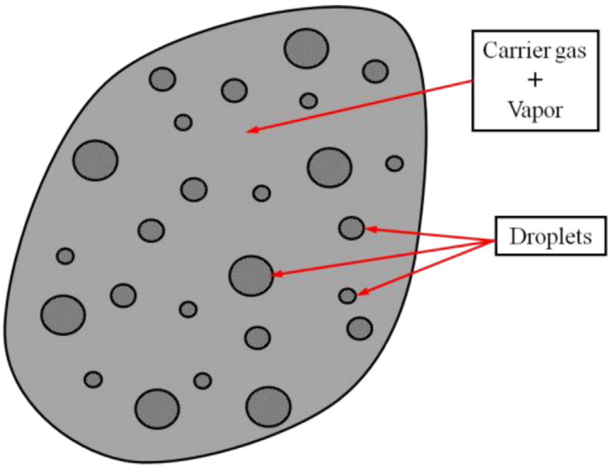

Fig. 1. Schematic of the condensing system.

Since the two gas fluids have the same velocity and temperature, the momentum and energy equations of condensable vapor are unnecessary when the constitutive equations of the carrier gas have been solved. In addition, based on the assumption of no carrier gas existed in the interior of liquid droplets, once the mass conservation equation of liquid phase has been solved, the mass fraction of the condensable vapor can be deduced according to conservation of mass for the whole condensing system, so the continuity equation of vapor can be disregarded. For further simplification, the droplet temperature can be calculated by a high accuracy explicit formula without solving the energy equation of liquid phase. Finally, the multi-fluid model is reduced to the form of separate continuity and momentum equations for carrier gas and liquid droplet phase together with the energy equation for carrier gas. The phase interactions are involved through appropriate source terms of the equations.

As the liquid droplets occupy little volume in the condensing flow and the droplets are sufficiently small (submicron-size and below), it is assumed that the gas phase turbulence remains unaffected by the presence of droplets. However, the gas phase turbulence would affect the dispersion of the droplets. The turbulence effects on the droplet motion are included in the liquid phase equations. Since the methodology of non-equilibrium condensing flow model is independent on the type of turbulence model, the well-established standard $k-\varepsilon$ model is adopted for the condensing flow modeling in present study. For brevity, the equations of the turbulence model are not listed here. Moreover, the no-slip model is depicted in the following section for comparison.

2.1. Multi-fluid model

In the multi-fluid model, both the inter-phase slip and temperature difference are taken into account, so each phase has its own velocity and temperature. Both the gas and liquid phase have individual governing equations, the governing equations for gas phase are as follows:

$$\frac{\partial\left(\rho_{\mathrm{g}}\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho_{\mathrm{g}}u_j\right) = 0 \tag{1}$$

$$\frac{\partial\left(\rho_{\mathrm{g}}u_i\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho_{\mathrm{g}}u_ju_i\right) = -\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}-F_{Di} \tag{2}$$

$$\frac{\partial\left(\rho_{\mathrm{g}}E_{\mathrm{g}}\right)}{\partial t}+\frac{\partial}{\partial x_j}\left(u_j\left(\rho_{\mathrm{g}}E_{\mathrm{g}}+p\right)\right) = -\frac{\partial q_j}{\partial x_j}+\frac{\partial\left(u_i\tau_{ij}\right)}{\partial x_j}+\beta\dot{m}h_{\mathrm{fg}}-u_iF_{Di} \tag{3}$$

where the subscript g denotes carrier gas, p, ρ_{g}, u_i, F_{Di}, τ_{ij}, T_{g} and E_{g} represent the local pressure, gas density, i-wise velocity component, i-wise drag force component, viscous stress tensor, temperature and total energy, respectively. h_{fg} is the latent heat of vapor, $\dot{m}$ is the mass condensation rate, and β is the proportion of the latent heat absorbed by the carrier gas.

To adequately model the liquid phase behavior, the condensation process is described by the Hill's method [31]. Including the