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# Numerical investigation of mist flow regime in a vertical tube

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ABSTRACT

In this research, the mist flow regime, consisting dispersed water droplets in vapor flow, is simulated numerically in a vertical tube; using a discrete phase model (DPM). In this method, in addition to solving transport equations for continuous phase, a discrete phase is simulated in a Lagrangian approach and the coupling between phases is modeled through interaction terms in the transport equations. The aims of this research are to investigate thermal equilibrium and evaluate the heat transfer coefficient of mist flow regime. The results show, when thermodynamic non-equilibrium takes happen, the rate of heat transfer from the vapor to the droplets is too slow that their presence is ignored, therefore by increasing the water mass flow rate in this case, due to reduction of vapor mass flow rate, the heat transfer coefficient decreases. But when complete thermodynamic equilibrium condition is established, the rate of heat transfer from the vapor to the droplets is too fast that the vapor temperature remains at the saturation temperature until all the droplets have been evaporated and by increasing the water mass flow rate, the heat transfer coefficient will increase. In order to simulate mist flow regime in thermal equilibrium and non-equilibrium conditions, water droplets with two different diameters are injected into steam flow. The numerical results of heat transfer coefficient and wall temperature in four different vapor qualities are investigated in each state, which show good agreement with experimental data and correlations.



## 1. Introduction

Boiling and evaporation in smooth tubes have been employed in water-tube and fire-tube boilers, water cooled nuclear reactors, heat exchangers, petrochemical plants and many other major applications. Therefore in recent years important contributions have been made towards understanding the heat transfer process and particular two-phase flow patterns, involved in progressive vaporization along a tube. An important two-phase regime encountered in a vertical uniformly heated channel is mist flow. The depletion of the liquid film from the wall by entrainment of the liquid in the form of droplets and by droplets evaporation finally causes the film to dryout completely. This transition is known as dryout and is accompanied by a rise in the wall temperature. The area between dryout point and the transition to dry saturated vapor has been termed mist flow regime. Sudden increase of the wall temperature and wall failure as a possible consequence at dryout point, probable thermodynamic non-equilibrium condition between the superheated vapor and the liquid droplets in post-dryout region and heat transfer enhancement by adding mist into the steam flow in some cases, are important reasons that cause to investigate mist flow regime.

Several experimental investigations of evaporation and convective boiling process have been done by various investigators. Due to the cost of experimental studies and their time-consuming aspects to design and optimization of evaporators, heat exchangers and cooling of gas turbines, numerical simulations have been widely used in recent years. An appropriate method for numerical simulation of particulate two-phase flows is discrete phase model (DPM), which is based on the Euler–Lagrangian approach. The method has been employed for a wide range of discrete phase problems including spray drying, liquid fuel combustion, desuperheaters and simulation of mist flow regime.

Li et al. [1] studied mist flow regime in a confined slot jet experimentally in 2001. It was found that the heat transfer performance of steam could be significantly improved by adding mist into the main flow. In the same year, they evaluated their experimental results numerically, by using the Euler–Lagrange approach [2]. To model the heat transfer of mist/steam impinging jet in this study, the interaction between droplets and droplets break up, were ignored. Also it was assumed that the droplets were at saturation temperature before entering the thermal boundary layer.

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Under these assumptions, results showed a good agreement between the numerical simulation and experimental data.

Chrigui et al. [3] analyzed the interaction between evaporating droplets and the turbulent flow of the carrier gas, using a second order turbulence RANS modeling in a Euler–Lagrangian approach. The analysis was performed in a vertical iso-propanol poly dispersed spray issuing into a co-flowing heated air stream. They studied the effect of the droplet evaporation on the mass and heat transfer processes and the influence of the turbulent fluctuations of different quantities (such as velocity, temperature, etc.) on the droplet evaporation rate.

Wojtan et al. [4] studied stratified-wavy and mist flow regimes experimentally for R-22 and R-410A in a horizontal tube. They investigated mist flow regime for these refrigerants which was not covered before and modified the heat transfer correlation of Groeneveld to predict mist flow heat transfer coefficient during evaporation of refrigerates. Kumari et al. [5] studied a two-phase mist consisting of finely dispersed water droplets in an air stream at the inlet of a longitudinally finned heat sink analytically and by numerical simulation. The simulation indicated that significantly higher heat transfer coefficient was obtained with mist flow as compared to air flow.

Post-dryout heat transfer to high pressure water was investigated experimentally in vertical tubes and annuli containing various flow obstacles by Anghel and Anglart [6]. They investigated the net influence of such obstacles on wall temperature distributions and developed correlations for post-dryout heat transfer in these channels. Kouhikamali et al. [7] simulated the heat transfer of water droplets and superheated steam, as a two-phase drop flow in desuperheaters, by using a discrete phase model. They studied the effects of water droplets diameter, vapor velocity and water mass flow rate on water evaporation rate and outlet steam temperature. They validated their numerical results with the experimental data.

Since there is a dearth of numerical simulation and investigation of thermodynamic equilibrium in mist flow two-phase regime, the main purpose of the present work is to study heat transfer characteristics of mist flow in a heated vertical tube numerically and by using a discrete phase model (DPM) approach in thermal equilibrium or non-equilibrium conditions.

## 2. Basis of numerical simulation

### 2.1. Numerical method

For simulation of droplets in steam flow, two main models are now state of the art. The discrete phase model (DPM) and the Eulerian model (EM). The discrete phase model describes single particles on their way through the simulation region whereas the Eulerian model describes the particles as a continuous phase. Both models have their advantages and disadvantages, especially in regions with low and high particle loading. Since the volume fraction of liquid drops is negligible in this study (less than 10%) and the coupling between the phases and its impact on both discrete phase trajectories and the continuous phase flow is considered properly in DPM with less computational cost than EM; the discrete phase model formulation is used to simulate mist flow in a vertical tube in present work. In this method, in addition to solving transport equations for continuous phase, a discrete second phase is simulated in a Lagrangian approach. It should be noted that the discrete phase formulation includes the assumption that the second phase is sufficiently dilute [7].

While the continuous phase always impacts the discrete phase, the impact of the droplets on the continuous phase is considered as source terms to the governing equations of mass, momentum and energy. Two components (water and water vapor) are simulated in this tube flow.

### 2.2. Governing equations

#### 2.2.1. Equations of particle motion

The trajectory of droplets can be formulated by integrating the force balance on the particle which is written in a Lagrangian approach as [7]:

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho - \rho_p)}{\rho_p} + F_x \tag{1}$$

where $F_x$ is an additional acceleration force, $F_D(u - u_p)$ is the drag force per unit particle mass, $u$ is the fluid phase velocity and $u_p$ is the particle velocity.

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re_d}{24} \tag{2}$$

In this relation, $\mathrm{Re}_d$ is the relative Reynolds number which is defined as [7]:

$$\mathrm{Re}_d = \frac{\rho d_p |u_p - u|}{\mu} \tag{3}$$

Also the drag coefficient ($C_D$) for a smooth spherical droplet, defined in Eq. (4) is a function of Reynolds number [7].

$$C_D = a_1 + \frac{a_2}{\mathrm{Re}_d} + \frac{a_3}{\mathrm{Re}_d^2} \tag{4}$$

where $a_1$, $a_2$, and $a_3$ are constant parameters obtained from experimental correlation [8].

As noted earlier, $F_x$ in Eq. (1), incorporates additional forces in the particle force balance that can be important under special circumstances, such as virtual mass, Saffman's lift force and thermophoretic force.

Virtual mass force is required to accelerate the fluid surrounding the particle and is important when $\rho > \rho_p$. It can be written as [7]:

$$F_v = 0.5(\rho/\rho_p)\frac{d}{dt}(u - u_p) \tag{5}$$

Saffman force concerns a sphere moving in a shear field. It's perpendicular to the direction of flow, originating from the inertia effects in the viscous flow around the particle and can be given as [9]:

$$F_{Saff} = 1.615\rho\nu^{0.5}(u - u_p)(du/dn)^{0.5} \tag{6}$$

where $du/dn$ is the gradient of the tangential velocity. It is valid only when $\mathrm{Re}_p << 1$.

Thermophoretic force, $F_T$ is experienced by the particle suspended in a fluid opposite to the temperature gradient. The following equation can be used to model this force [10].

$$F_T = -D_{T,P}\frac{1}{m_p T}\nabla T \tag{7}$$

where $D_{T,P}$ is thermophoretic coefficient and another form is defined as:

$$F_T = -\frac{6\pi d_p \mu^2 C_s(Kr + C_t Kn)}{\rho(1 + 3C_m Kn)(1 + 2K + 2C_t Kn)}\frac{1}{m_p T}\nabla T \tag{8}$$

where $Kn$ is Knudsen number defined as $Kn = 2\lambda/d_p$, $Kr$ is the ratio of thermal conductivity of the fluid to that of particles, $\lambda$ is the mean