

A fully meshless method for ‘gas - evaporating droplet’ flow modelling

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A meshless method for modelling two-phase flows with phase transition is described. The method is based on consideration of three systems: viscous-vortex blobs, thermal-blobs and droplets; and can be applied for numerical simulation of 2D non-isothermal flows of ‘gas-evaporating droplets’ in the framework of the one-way coupled two-fluid approach. The carrier phase is viscous incompressible gas. The dispersed phase is presented by a cloud of identical spherical droplets, and, due to evaporation, the radius and mass of droplets are time dependent. The carrier phase parameters are calculated using the viscous-vortex and thermal-blob method; the dispersed phase parameters are calculated using the Lagrangian approach. Two applications have been considered: (i) a standard benchmark – Lamb vortex; (ii) a cold spray injected into a hot quiescent gas. In the latter problem three cases corresponding to three droplet sizes were investigated. The smallest droplets (of the three cases considered) are more readily entrained by the carrier phase and form ring-like structures; the flow shows better mixing. Larger droplets evaporate less intensively. The medium sized droplets collect into two narrow bands stretched along the jet axis. The largest droplets form a two-phase jet, which remains close to the jet axis.

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1 Introduction

Dilute two-phase flows are usually modelled using the Eulerian-Lagrangian approach. However, meshless Lagrangian techniques for fluid flow (gas or liquid without admixture) simulations have been actively developed during the last years [1]. These methods make it possible to develop fully meshless methods for two-phase flows as well. In [2] a method combining the viscous-vortex and the Fully Lagrangian [3, 4] approaches was suggested to simulate particle-laden flows for which accurate calculations of the particle number density are required. In the present study, the viscous-vortex method is developed to model 2D transient, non-isothermal, ‘gas – droplet’ flows. The developed method retains the advantages of the Lagrangian approaches (time efficient, meshless simulations) and makes it possible to simulate phase transitions in two-phase flows. A simplified model of phase transition is used. More advanced evaporation models are discussed in e.g. [5] and will be included in further studies.

2 ‘Gas – evaporating droplet’ model

We consider 2D transient non-isothermal gas-droplet flows. The flows are studied in the framework of a one-way coupled, two-fluid approach [6]. The carrier phase is viscous incompressible gas. The dispersed phase is represented by a cloud of identical spherical evaporating droplets, and, due to evaporation, the radius and mass of droplets are time dependent. In interphase momentum exchange, the aerodynamic drag force is taken into account. The phase transition on the droplet surface is assumed to be quasi-equilibrium. It is assumed that the heat flux on the droplet is consumed by evaporation and that the temperature distribution inside a droplet is uniform. Hence, the droplet temperature remains constant during the simulations. The flow of ‘gas – evaporating droplet’ is defined by six non-dimensional parameters: the flow Reynolds number, the Prandtl number, the specific heat capacities ratio, the droplet inertia parameter, the droplet evaporation parameter, and the initial droplet Reynolds number.

3 Meshless approach to simulate two-phase flows

The 2D vorticity transport and energy balance equations are rewritten in divergence forms after introduction of the corresponding diffusion velocities \mathbf{v}_{dv} and \mathbf{v}_{dT} :

$$\frac{\partial \omega}{\partial t} + \text{div}(\omega(\mathbf{v} + \mathbf{v}_{dv})) = 0, \quad \frac{\partial T}{\partial t} + \text{div}(T(\mathbf{v} + \mathbf{v}_{dT})) = 0, \quad \mathbf{v}_{dv} = -\frac{1}{\text{Re}} \frac{\nabla \omega}{\omega}, \quad \mathbf{v}_{dT} = -\frac{\gamma}{\text{Re Pr}} \frac{\nabla T}{T}. \quad (1)$$

The parameter fields are discretised into two sets of blobs: viscous-vortex and thermal blobs. The strength of a blob (Γ_i and Θ_j) was calculated as the product of the corresponding value of the parameter (vorticity or temperature) and the blob area. As follows from Equation (1), the blob strengths are constant along trajectories described by the velocity $\mathbf{v} + \mathbf{v}_{dv}$ for

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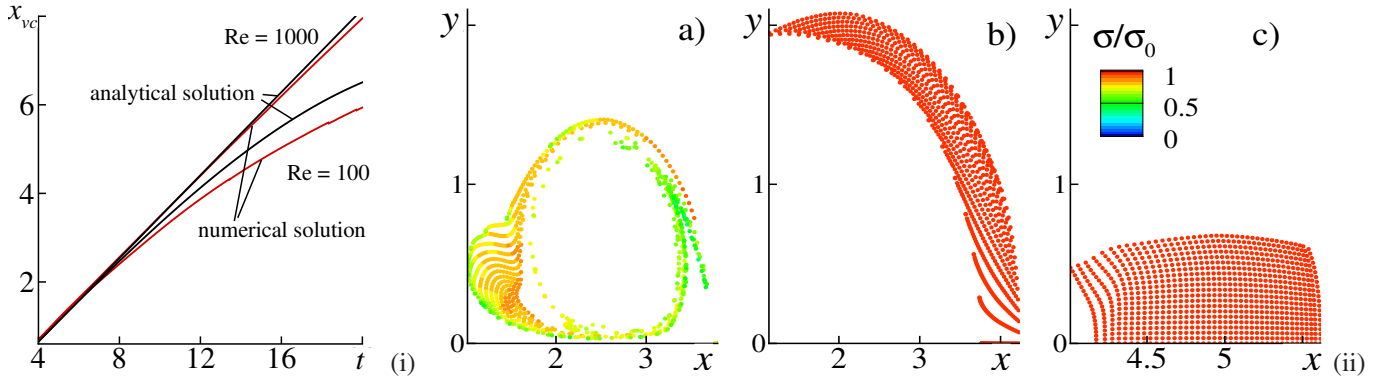


Fig. 1: (i) Vortex centre positions (x_{vc}); $Re = 100$ and $Re = 1000$; predictions of the asymptotic solution (black) and of the numerical simulations (red); and (ii) Droplet distributions, droplet radii σ/σ_0 , where σ_0 is droplet initial radius, at $tU/L = 8$, a) $\beta = 5.5$, b) $\beta = 0.21$, c) $\beta = 0.05$.

viscous-vortex and $\mathbf{v} + \mathbf{v}_{dT}$ for thermal blobs. The vorticity and temperature fields are calculated using interpolation based on cut-off functions of the 4th order [1]: $\zeta_{\varepsilon_i}(\mathbf{r}) = 1/(3\pi\varepsilon_i^2) (4 - \mathbf{r}^2/\varepsilon_i^2) \exp(-\mathbf{r}^2/\varepsilon_i^2)$, where ε_i is a core size for each blob.

The diffusion velocities are calculated using the following formulae [2]:

$$\mathbf{v}_{dv} = -\frac{1}{Re} \frac{\sum_{i=1}^N \Gamma_i \cdot \nabla \zeta_{\varepsilon_i}(\mathbf{r} - \mathbf{r}_{vi}(t))}{\sum_{i=1}^N \Gamma_i \zeta_{\varepsilon_i}(\mathbf{r} - \mathbf{r}_{vi}(t))}, \quad \mathbf{v}_{dT} = -\frac{\gamma}{Re Pr} \frac{\sum_{i=1}^M \Theta_i \cdot \nabla \zeta_{\varepsilon_i}(\mathbf{r} - \mathbf{r}_{Ti}(t))}{\sum_{i=1}^M \Theta_i \zeta_{\varepsilon_i}(\mathbf{r} - \mathbf{r}_{Ti}(t))},$$

where \mathbf{r}_{vi} and \mathbf{r}_{Ti} are positions of viscous-vortex and thermal blobs. The velocity field is reconstructed from the vorticity field using the Biot-Savart law and a mollified kernel of the 4th order [1].

$$\mathbf{v}(\mathbf{r}) = \frac{1}{2\pi} \sum_{i=1}^N \Gamma_i \mathbf{e}_z \times \frac{\mathbf{r} - \mathbf{r}_{vi}}{|\mathbf{r} - \mathbf{r}_{vi}|^2} \approx \frac{1}{2\pi} \sum_{i=1}^N \Gamma_i \mathbf{e}_z \times \mathbf{F}_{\varepsilon_i}(\mathbf{r} - \mathbf{r}_{vi}), \quad \mathbf{F}_{\varepsilon_i}(\mathbf{r}) = \frac{\mathbf{r}}{2\pi \mathbf{r}^2} \left[1 + \left(\frac{\mathbf{r}^2}{\varepsilon_i^2} - 1 \right) \exp\left(-\frac{\mathbf{r}^2}{\varepsilon_i^2}\right) \right].$$

The dispersed phase parameters are calculated using the Lagrangian approach.

4 Two-phase jet injection

A cold water spray injection into a hot water vapour is considered under conditions when a vortex pair is formed. A step-like velocity profile is set at the inlet. After the injection, a vortex pair is formed. The dynamics of the vortex pair were compared with the prediction of the asymptotic analytical solution [7] for $Re = 100$ and $Re = 1000$ (Fig. 1(i)), the Reynolds number is based on the inlet width and injection velocity, $Re = UL/\nu$. The asymptotic solution ($Re \rightarrow \infty$) predicts slightly higher values than the numerical simulations; there is a better agreement between the results for the case of $Re = 1000$; in both cases the agreement between the numerical and analytical results is satisfactory. Three cases corresponding to three droplet sizes have been considered. Different inertia properties of droplets have led to different two-phase flow patterns (both droplet locations and droplet size distributions). See Fig. 1(ii) for droplet and droplet radii distributions at $tU/L = 8$; due to the symmetry only halves of the droplet clouds are presented. Small droplets ($\beta = 5.5$; β is the droplet inertia parameter, inverse Stokes number) show better mixing, form ring-like structures, evaporate faster and collect behind the vortex pair. In the case of the intermediate-sized droplets ($\beta = 0.21$), the two-phase jet is the widest among the flows observed, droplets accumulate in narrow bands. The high-inertia droplets ($\beta = 0.05$) form a two-phase jet that remains close to the jet axis and moves fast. In the latter two cases, droplet sizes have remained almost unchanged (droplet radii change within 10% of their initial size).

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