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Contribution to the modeling of the interaction between a plasma flow and a liquid jet

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ABSTRACT

A numerical simulation of the interaction between a plasma flow and a liquid jet was investigated, leading to the proposal of a compressible model, based on augmented Lagrangian, Large Eddy Simulation (LES) turbulence modeling and Volume of Fluid (VOF) approaches, capable of managing incompressible two-phase flows as well as turbulent compressible motions. The VOF method utilized volume markers to advect the local concentration of gas and liquid in a Eulerian manner. The numerical model was validated on single-phase plasma configurations as well as two-phase cross flow liquid jet interactions. Finally, an example of the first simulations of the interactions between a liquid jet and a plasma is presented. However improvements should be realized as to increase the speed of the VOF-SM algorithm or add specific subgrid models related to jet fragmentation and phase change.

1. Introduction

The plasma spraying process permits the coating production by the metallic or ceramic particle injection. It is commonly used for nanomaterial application developments such as solid oxy fuel cells for instance. The plasma spraying of solid particles does not allow the dense deposit realization with a thickness lower than 50 µm. To decrease the deposit thickness, a solution is to project micronic or submicronic particles. For this, the little particles injection (<5 µm) can be carried out with a liquid precursor. This process is by far more complex because fragmentation and vaporization of the liquid control the coating build-up mechanisms.

Experimental works about plasma spraying using liquid precursors exist. Karthikeyan *et al.* [1–3] finalized an experimental system to inject liquid precursors in a Ar-H2 plasma flow. Siegert *et al.* [4] and Oberste Berghaus *et al.* [5] identified the suspension injection velocity like a dominating parameter. According to Rampon *et al.* [6] and Etchart-Salas [7], the injection of a continuous jet permits a more homogeneous treatment of liquid by plasma. Jordan *et al.* [8] worked about the solution injection by atomization in a plasma in order to decrease the particle numbers which are not totally pyrolysed. Fauchais *et al.* [9] presented some recent developments about parameters quantifying fragmentation and vaporization in the liquid injection.

However the values of the plasma parameters such as the liquid fractions, temperatures or velocities are locally difficult to measure because of the measurement techniques limitations and the particular characteristics of plasma. The modeling and numerical simulation of two-phase flows interacting with a plasma jet can be an alternative to experimental measurements of major importance for the understanding, the characterization and the prediction of the driving physical parameters involved in plasma spraying processes.

The majority of existing works in the literature are based on incompressible statistical continuum approaches for the plasma modeling, since the turbulence is represented through statistical Reynolds Averaged Navier–Stokes equations [10–12]. These approaches are used when the steadiness of the flow, as well as the related physical variables, e.g., the temperature or the concentration of the various species, is verified in average. Few plasma models have been devoted to the introduction of a liquid phase into a plasma jet, and those that exist generally consider the liquid phase to be formed of droplets that are directly inserted into the plasma flow [13].

The aim of the present work was to propose an original model for dealing with three-dimensional and unsteady turbulent interactions between a plasma flow and a liquid water jet. Such a model was designed to tackle the penetration of the liquid jet in the plasma, their interaction in terms of liquid interface deformation, as well as modifications with regard to temperature and concentration. Moreover, the primary fragmentation of the liquid jet should be described by the model. The numerical model must also be able to provide a small scale description of the liquid phase, which contains the solid particles aimed at being coated onto a target material.

There are several main driving actions that need to be modeled in the process:

1. The Mach number of the plasma flow is in the range 0.3 to 0.7. Compressible effects cannot be neglected and must be taken into account in the motion equations. Contrarily, the flow is incompressible

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Nomenclature

t	time
$\boldsymbol{u}$	local velocity
p	pressure
χ_T	adiabatic compressibility
ρ	density
$\boldsymbol{g}$	gravitational acceleration
τ	characteristic time
μ	dynamic viscosity
$\boldsymbol{F_{TS}}$	surface tension force
C	local volume fraction
$\tilde{\varphi}$	phase average of φ
Cp	specific heat
T	temperature
ϕ_{ray}	volume energy density term representative of radiative effects
λ	conductivity
Ψ_i	concentration of species i
D_i	diffusion coefficient of species i
$\Omega_{i,k}(p,t)$	characteristics for plasma
w	water
a	air
p	plasma
C_s	Smagorinsky constant
$\overline{\Delta}$	size of the turbulent filter
S_{ij}	deformation tensor
μ_t	turbulent viscosity
μ_m	molecular viscosity
σ	surface tension coefficient
κ	local curvature of the interface
n_i	normal to the interface
δ_i	a Dirac function indicating the interface
Γ_{ray}	energy flux due to radiative effects in the plasma

in the liquid, under the velocity conditions of the process. A mixed model capable of simultaneously managing compressible and incompressible features of the two-phase flow is required.

2. The unsteady behavior of the interface implies the building of an unsteady and deterministic model for the local thermo-physical variables of the problem, such as the velocity, the temperature and the concentrations. The deformable large scale of the liquid interface must be modeled through a continuum approach not requiring the use of unsteady grids since the deformation, rupture or coalescence of liquid parts are not known *a priori*. A Volume of Fluid method would seem to be an interesting approach in order to achieve this.
3. The Direct Numerical Simulation is not an option due to the large range of time and spatial scales involved in the problem. The larger scale of the process revolves around the decimeter while the smaller turbulent scale is inferior to the micrometer. The same remarks apply to the time characteristics of the problem. A suitable deterministic turbulent approach is the Large Eddy Simulation that solves the larger scales of the problem and models the small dissipative characteristics of the motion.
4. The model is required to manage the small scale modifications of the liquid phase under phase change and secondary droplet rupture. A Lagrangian approach would seem appropriate to achieve this since, from a macroscopic point of view, the smaller liquid parcels behave as evolving markers in the flow.

The points 1, 2, 3 are realized in the present paper. The point 4 is not yet integrated in the model. Now the secondary break-up and the phase change are not taken into account in the model.

The article is organized as follows: Section 2 presents the physical models dedicated to plasma and two-phase flow. The numerical methods are briefly exposed in Section 3. Section 4 is devoted to validation examples and first simulations of water jet interacting with an Ar-H_2 plasma. Conclusions are drawn in Section 5.

2. Physical model

2.1. General equations

The motion equations dedicated to a deterministic description of the compressible two-phase flow are represented by a generalization of the incompressible single fluid or 1-fluid model described by Kataoka [14] and Scardovelli *et al.* [15] in which a new mass conservation equation is derived by developing the partial derivative of the pressure according to time in function of temperature and density and by assuming that the plasma behaves like a perfect gas. The details of this specific aspect of the model will be submitted for publication in the near future. The conservation equation system reads:

$$\frac{\partial p}{\partial t} + \frac{1}{\chi_T}\nabla . u = 0 \tag{1}$$

$$\tilde{\rho}\left(\frac{\partial u}{\partial t} + (u.\nabla)u\right) = \tilde{\rho}\mathbf{g} - \nabla\left(p - \frac{\tau}{\chi_T}\nabla\cdot u\right) + \nabla.\left(\tilde{\mu}\left(\nabla u + \nabla^T u\right)\right) + \mathbf{F_{TS}} \tag{2}$$

$$\frac{\partial C}{\partial t} + (u.\nabla)C = 0 \tag{3}$$

where $\boldsymbol{u}$ is the local velocity, p the pressure, t the time, $\boldsymbol{g}$ the gravitational acceleration, $\chi_T = \frac{1}{\rho}\frac{\partial \rho}{\partial p}$ the adiabatic compressibility, τ a characteristic time of compressible effects linked to inertial time scales of the problem, C the local volume fraction, $\tilde{\rho}$ the density and $\tilde{\mu}$ the dynamic viscosity. In practice, τ is chosen equal to the numerical dynamic time step used in the Navier–Stokes equations. This time step is selected in order to verify a stability criterion, called Courant–Friedrich–Levy CFL, such that the inertial terms do not propagate on more than one grid cell in one calculation step. The $\tilde{\varphi}$ notation is related to the phase average of φ. This point is developed in Section 2.2. The interface between the liquid fluid and the rest of the fluids was defined as $C = 0.5$. Compared to the classic incompressible single fluid model, the mass and momentum conservation equations were modified so as to take into account the compressible features of the flow in terms of dilatation effects. Concerning the mass conservation, it can be noticed that, in the liquid, the compressibility coefficient χ_T was small and the ratio $\frac{1}{\chi_T}$ was large enough to render $\frac{\partial p}{\partial t}$ negligible. In this phase, the incompressible model was recovered. In the plasma, χ_T was larger than in the liquid and Eq. (1) became the standard compressible pressure equation in which the isobaric dilatation term was discarded due to its negligible magnitude. The dilatation term $\frac{\tau}{\chi_T}\nabla\cdot u$ made it possible to take into account the dilatation effects directly in the momentum equations whereas these terms imposed incompressibility when $\frac{1}{\chi_T}$ was large in the liquid. In this case, the pressure acted as a Lagrangian accumulating the incompressibility constraint.

The thermal exchanges were taken into account by employing the energy equation formulated in terms of temperature:

$$\tilde{\rho}\tilde{C}_p\left(\frac{\partial T}{\partial t} + (u.\nabla)T\right) = \nabla\cdot\left[\tilde{\lambda}\nabla T\right] + \Phi_{ray} \tag{4}$$

Here, T is the temperature, $\tilde{C}_p$ the specific heat, $\tilde{\lambda}$ the conductivity and Φ_{ray} a volume energy density term representative of radiative effects.