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Analysis of the unsteadiness of a plasma jet and the related turbulence

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ABSTRACT

Plasma spraying using liquid feedstock allows realizing thin coatings (<100 μm). In this process, the plasma jet fluctuations play an important role in the behavior of the liquid fragmentation and then in the final deposit characteristics. In this study, numerical simulations of two different plasma jets (argon or argon hydrogen mixture) issuing into air are investigated. The computations are based on a compressible model and a Large Eddy Simulation (LES) modeling for the turbulence. The aim of this work is to analyze the unsteady effects of the plasma jet regarding those of turbulence. In particular, the characterization of the turbulent zone inside the plasma jet is provided. A turbulence analysis is carried out in order to estimate the levels of turbulence and modeling effects.

1. Introduction

Deposition of nanomaterials by suspension thermal spraying is one route to obtain nanostructured coatings with improved properties [1]. Due to the difficulties to observe in operating conditions the interactions between the flow and the suspension, simulations appear as one opportunity to get numerical experiments. But this requires firstly simulating correctly the thermal jet flow. It is the global goal of this work: the simulation of the interaction between a liquid jet and a plasma flow within the framework of the suspension plasma spraying [2–4]. So, a preliminary step consists in studying the plasma alone and to analyze the turbulence and the unsteady character of the plasma (due to the upstream motions of the electrical arc inside the torch [5]) to determine which phenomena can be neglected or not and why as a way to optimize the calculation time.

Several works of plasma flow modeling are based on statistical continuum approaches of Reynolds Averaged Navier–Stokes model type [6–8]. A deterministic turbulent Large Eddy Simulation [9] approach, which solves the larger scales of turbulence and models the smaller dissipative characteristics of the motion, is used in this work as well as a Direct Numerical Simulation (DNS) where all scales in time and space are solved. The LES model, which is rather recent in the plasma field [10–12] allows reaching unstationary information. Different LES sub grid scale models are tested. Few works take into account the unsteady effects [12], which are due to the arc motion in the torch. From [13], this phenomenon is important and has to be introduced in the simulation, in particular for the interaction between a liquid and a plasma flow. In this work, the Ar/H_2 plasma simulation is realized with unsteady boundary conditions. A new compressible model [14] is used to consider the compressible effects of the plasma flow; the following authors treat also the plasma as a compressible flow [6,15,16]. This compressible two-phase model, used in this work, is capable of simultaneously managing compressible and incompressible features of the two-phase flow.

The article is organized as follows: the physical model including the compressible model and the turbulence models are presented in Section 2. Then, numerical methods are briefly exposed in Section 3. After that, two configurations of plasma jet are exposed. The first is the simulation of an argon jet in order to compare with experimental data of Fincke [17] for global validation of the model. In this case, different LES models are compared. Then, the simulation of an argon/hydrogen jet with unsteady boundary conditions is presented through the temperature and velocity fluctuations, Reynolds number and coherent structures. The unsteady character of the plasma ArH_2 is then analyzed. The frequency of the oscillations of plasma temperature and velocity, obtained by the simulation, is compared with the voltage fluctuations frequency. Visualizations with high speed camera of the unsteady behavior of the plasma have been carried out. These experiments are compared to numerical results in order to validate the model and the numerical methods.

2. Physical model

2.1. General equations

To take into account the compressible effects of plasma flow (the Mach number is from 0.3 to 0.6), an original two-phase compressible model [14], which allows taking-into-account the

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compressible effects of the plasma, is built. This model is a generalization of the incompressible 1-fluid model [18,19] with a new mass conservation equation which is reformulated as an equation for the pressure. For Mach number inferior to 1, it is expressed as:

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

$$\tilde{\rho}\left(\frac{\partial u}{\partial t} + (u\cdot\nabla)u\right) = \tilde{\rho}\mathrm{g} - \nabla(p - \lambda\nabla . u) + \nabla\cdot(\tilde{\mu}(\nabla u + \nabla^T u)) \tag{2}$$

$$\tilde{\rho}\widetilde{C}p\left(\frac{\partial T}{\partial t} + (u\cdot\nabla)T\right) = \nabla\cdot\left(\widetilde{\lambda}\nabla T\right) + \phi_{\mathrm{ray}} \tag{3}$$

$$\frac{\partial \psi_i}{\partial t} + (u\cdot\nabla\psi_i) = \nabla\cdot\left(\widetilde{D}_i\nabla\psi_i\right) \tag{4}$$

where $\mathbf{u}$ is the local velocity, p the pressure, t the time, $\mathbf{g}$ the gravitational acceleration, $\chi_T = \frac{1}{\rho}\frac{\partial \rho}{\partial p}$ the adiabatic compressibility, λ is the compression viscosity, $\tilde{\rho}$ the density, T the temperature, $\widetilde{C}_p$ the specific heat, $\tilde{\mu}$ the dynamic viscosity, $\widetilde{\lambda}$ the conductivity, ϕ_{ray} a volume energy density term representative of radiative effects, ψ_i and $\widetilde{D}_i$ are respectively the concentration and the diffusion coefficient of species plasma-forming gas and air.

The evolutions of the plasma characteristics (ρ, μ, λ, and C_p) are tabulated according to the local temperature and pressure [2]. They are obtained thanks to the program "ALEX" developed in the "Chimie des Plasmas" Laboratory at the University of Limoges [20].

The incompressible assumption is only valid when the Mach number is inferior to 0.3. In our case, the Mach number is included between 0.3 and 0.6; it is why a compressible model is developed and used in order to take into account compressible effects. As the Mach numbers are sometimes weak (subsonic regimes) in the limit compressible/incompressible, some works [7,21,22] are carried out with incompressible model and the results are in good agreement with experimental measurements. Then, it depends on the studied plasma jet and its characteristics.

2.2. Turbulence model

The deterministic turbulent approach used is a Large Eddy Simulation (LES), which solves the larger scales of the problem and models the small dissipative characteristics of the motion.

The equivalent dynamic viscosity is obtained as the sum of the molecular and turbulent viscosities as follows: $\tilde{\mu} = \tilde{\mu}_m + \mu_t$ with μ_t which depends on the subgrid-scale models [4]. The turbulence viscosity equations are described in Table 1 for the different sub grid scale models. In order to improve the previously detailed sub grid scale models, a sensor based on local information of the flow is used [27]. This sensor, or selection function, called f, is related to the local angular fluctuations of the vorticity ω such as: $\mu_t^S(x,t) = \mu_t(x,t) \times f(\omega,t)$.

Table 1
Turbulent viscosity for the different sub grid scale models.

Subgrid-scale models	Turbulent viscosity	Reference
Smagorinsky Model	$\mu_{t(SM)} = \rho\left(C_S\ \overline{\Delta}\right)^2\sqrt{2S_{ij}S_{ij}}$ C_S the Smagorinsky constant $\overline{\Delta}$ the size of the turbulence filter S_{ij} the deformation tensor	[23]
Turbulent Kinetic Energy (TKE) model	$\mu_{t(TKE)} = \rho C_{TKE}\overline{\Delta}(q^2_{SGS}(x,t))^{\frac{1}{2}}$ With $q^2_{SGS}(x,t) = \frac{1}{2}\ \overline{u(x,t)'}\ \overline{u(x,t)'}$	[24]
Mixed scale model	$\mu_t = \rho C_M\,\overline{\Delta}^{1+\alpha}(\mid\overline{S}\mid)^{\frac{\alpha}{2}}(q^2_{SGS}(x,t))^{\frac{1-\alpha}{2}}$ $\mu_t = \mu^{\alpha}_{t(SM)}\mu^{1-\alpha}_{t(TKE)} = \rho\nu^{\alpha}_{t(SM)}\nu^{1-\alpha}_{t(TKE)}$	[9]
Dynamic Smagorinsky	$\mu_t = \rho\left(C_S(x,t)\overline{\Delta}\right)^2\sqrt{2S_{ij}S_{ij}}$	[25,26]

The Schmidt and Prandtl numbers [28] are used to determine the turbulence scalar transfers for the energy (Eq. (3)) and transport equations (Eq. (4)).

In a turbulence spectrum, two zones of wave number exist: the dissipative structures and the energy containing range. Energy structures are characterized by the integral scale and dissipative structures by the Kolmogorov scale.

The Kolmogorov scale η_k is the smallest space scale of turbulence $\eta_k = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}$ with ε the viscous dissipation rate and ν the cinematic viscosity. Its value can be compared to the space scale Δx of the grid to know if all scales are solved and if a direct numerical simulation (DNS) is realized. Indeed, the DNS imposes the use of a very fine meshing to be able to capture all the scales of the solution.

Skewness S and flatness F numbers [29] allow determining if a flow is of fully turbulent developed type. These numbers are given by:

$$S = \frac{1}{3}\ \overline{\left(\frac{\partial u_i}{\partial x_i}\right)^3} \Big/ \overline{\left(\frac{\partial u_i}{\partial x_i}\right)^2}^{3/2} \tag{5}$$

$$F = \frac{1}{3}\ \overline{\left(\frac{\partial u_i}{\partial x_i}\right)^4} \Big/ \overline{\left(\frac{\partial u_i}{\partial x_i}\right)^2}^{2} \tag{6}$$

Several studies [30,31] show that the turbulence is fully developed if $-0.5 \le S \le -0.4$ and $3.3 \le F \le 4$.

2.3. Model assumptions

In this study, the model of the plasma jet issuing into ambient air is based on the following assumptions:

- The plasma is continuous and in local thermodynamic equilibrium (LTE).
- The plasma is optically thin.
- The plasma and the ambient air are considered as mono-fluid, their particularities evolving in function of the temperature through the tabulation of their thermodynamic properties and transport coefficients.
- No chemical reactions between the two fluids are taken into account.

3. Numerical methods

The simulation tool is based on the Computational Fluid Dynamic library Thetis, developed at the TREFLE laboratory. The approximations of the conservation equations are based on fixed irregular staggered Cartesian grids and finite volumes. All the numerical methods presented in the following sub-sections have been detailed and validated in [32–34].

3.1. Navier–Stokes approximation

The momentum equation is implicitly discretized. The nonlinear inertial term is linearized as $\tilde{\rho}(u^n\cdot\nabla)u^{n+1}$, where n is the time index. The spatial discretizations employ a first-order upwind scheme for the treatment of the inertial terms and a centered scheme for the viscous terms. In addition, the mass conservation equation is discretized in time with a first-order Euler scheme as $p^{n+1} = p^n - \frac{\Delta t}{\chi_T}\nabla\cdot u^{n+1}$. The pressure gradient in the momentum equation is returned according to the mass equation as $\nabla p^{n+1} = \nabla\left(p^n - \frac{\Delta t}{\chi_T}\nabla\cdot u^{n+1}\right)$. It can be observed that the term $\frac{\Delta t}{\chi_T}\nabla\cdot u^{n+1}$ plays the same role as $\lambda\nabla\cdot u^{n+1}$. In our simulation, λ is assumed to be 0 as its effect is still represented by $\frac{\Delta t}{\chi_T}$ and its molecular value is not known for real gases or liquids.