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Analysis by modeling of plasma flow interactions with liquid injection

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ABSTRACT

This paper deals with the modeling of different plasma flows interacting with a liquid jet of pure water. Using only fluid mechanic equations, the goal was to simulate and to understand the first moments of these interactions during suspension plasma spraying of nanomaterials. The obtained simulations were then validated by comparing the results with breakup mechanisms described for the same Weber number in a plasma cross-flow with constant temperature. The global model was applied to various suspension plasma spraying conditions: two plasma gas mixtures (Ar/H_2 and Ar/He) and two types of liquid injections (train of droplets or continuous jet). These simulations demonstrated different trajectories of the liquid and, consequently, different modes of breakup. Droplet size distributions were also calculated in the global modeling field.

1. Introduction

The plasma spraying process is a current and industrial technique for producing coatings to provide protection against high temperatures, corrosion, erosion or wear on manufacturing pieces [1]. By changing the coating's microstructure, one can obtain an improvement of working functions. The use of various scales of materials (from nanometer to micrometer sizes) can contribute to the manufacture of a wide range of specific microstructural coatings. This is one of the reasons why using nanomaterials is deemed interesting.

Since the beginning of the 21th century, all industrial means of deposition have been explored in order to create such specific coatings. In the wide field of surface treatment processes, plasma spraying is a technique that can be employed to deposit high-refractory materials, such as ceramics, which can be used as for instance thermal barriers [2]. As a consequence, large amounts of interesting reviews have been published concerning industrial applications. But prior to this, academic studies have been required to control the process since the fact of spraying nano-sized materials renders it more complex than when using micrometer powders [3,4].

As many authors have explained [5–7], the introduction of a nano-powder in a gas flow at high velocity can only work when the powder's momentum is higher than that of the gas flow. This is why such powders are introduced in the flow as suspensions. Furthermore, the analysis and diagnostics of such systems are complex and difficult. A high-radiation gas at a high velocity but low density (the plasma) interacts with a second fluid (the liquid) with a relatively low velocity but high density. Moreover, the liquid cannot radiate due to its phase changing at low temperature. Nevertheless, several authors have proposed specific diagnostic setups to obtain images of the fluids during their interaction by fast shadowgraphy [7–10].

Another means of analysis is modeling [11–13]. But here too, the action is made difficult because of the lack of specific tools adapted to breakup. The theory of fragmentation is well known and many analytical models have been developed from experiments. The use of such models is however not well accommodated to the field of suspension plasma spraying, which is one of the main conclusions from [12,13] when using analytical models.

In this light, the work detailed in the present paper proposes a new approach based only upon the resolution of Navier Stokes equations. We thus present the results of such modeling applied to suspension plasma spraying.

2. A concentration of complexity

Fig. 1 shows a schematic of the interactions between the plasma flow and a liquid jet. The main points to keep in mind are the following. Different steps of physical phenomena involve very small entities during very short time scales. After injection of the suspension, the first step is the hydrodynamic interaction fragmentation with a time around 1 μs to generate a distribution of droplets smaller than a hundredth of a micron. When the fragmentation is completed, thermal effects can develop with the diminution of the droplet size and of its thermal inertia.

During the step consisting in the vaporization of the carrier liquid, the nanoparticle behavior is not well known: do the particles leave the droplet or stay inside? Pawlowski proposed some explanations in [5]. When the particles are free, they undergo thermal and kinetic effects of the gas flow, such as acceleration, heating, vaporization, in-flight agglomeration or agglomerate explosion, before impacting the substrate to create the coating. This complexity is increased by

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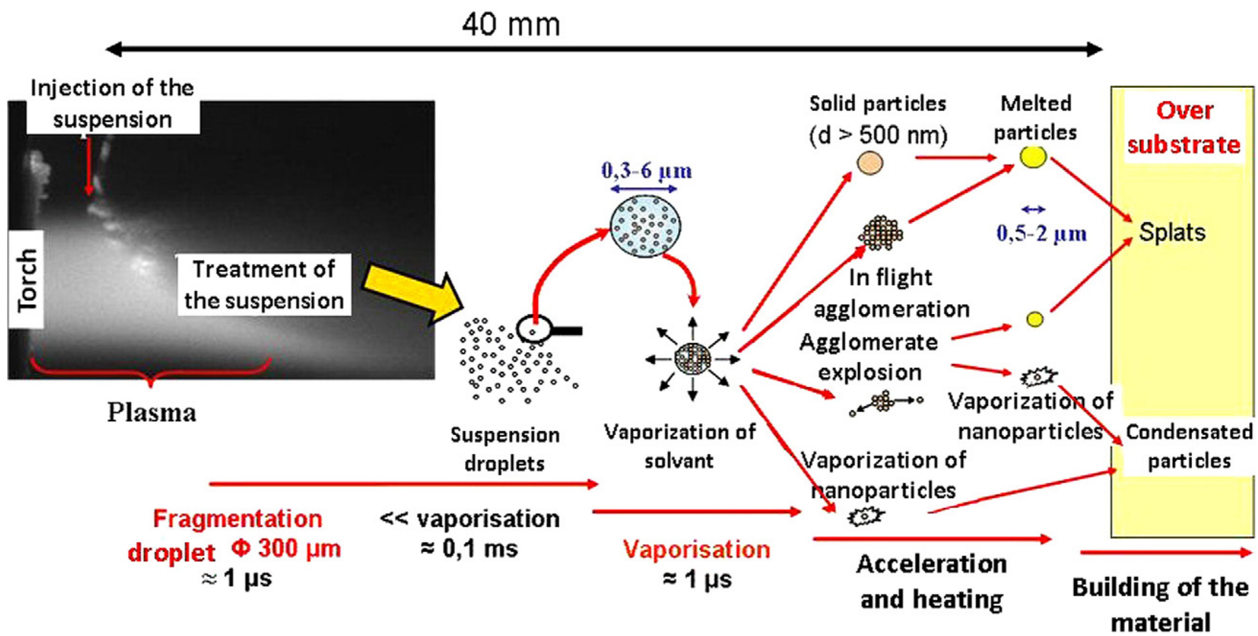

Fig. 1. Schematic of the global suspension plasma spraying process.

the gas flow from the torch exit which presents instabilities due to the motions of the electrical arc inside the torch [14]. These movements depend on the working conditions, one of which is the nature of the gas [15]. For example, a mixture containing a small percentage of hydrogen leads to the restrike mode with a saw tooth voltage signal, as seen in Fig. 2 [16] when monoatomic gas mixtures, such as helium/argon, generate takeover mode, which is much more regular. According to this, the behavior and the atomization of the liquid jet depend on the time during which the interaction takes place in a long or a short plasma jet.

Moreover, although the fragmentation theory is well defined with various breakup modes according to the Weber number [17], these investigations have been carried out in steady modes when the jets do not present high velocity gradients. So another query is: what happens with high-gradient (when it comes to velocity but also temperature and transport property gradients) flows, such as plasma, which give rise to a fast evolution in Weber number during interaction with a liquid? This question was first investigated by Marchand using a Lagrangian particle model with the LES deterministic model [12,13]. The studies showed both the evolution of the Weber number in a large range and the trajectories of the droplet distribution in a one-way coupling dilute regime. No thermal effects in the liquid were integrated in the model. Analytical models such TAB or ETAB have been investigated in such environments and results revealed the non-adaptability of these models due to a too large gap between the initial and present fields of model development.

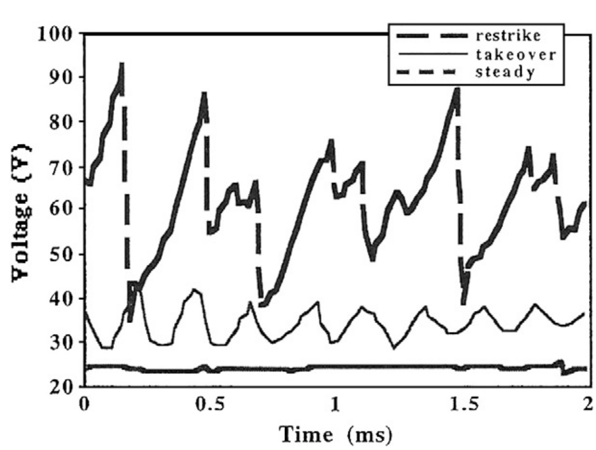

Fig. 2. Evolution of the voltage with time defining the electrical arc behavior modes.

To summarize, the problem to be solved must integrate the 3D geometry, instabilities of the flow, thermal and hydrodynamic effects (with compressible effects because of the MACH number evolving from 0.3 to 0.7), turbulence and unsteadiness between the plasma and the surrounding atmosphere (with the Reynolds number increasing from 1200 at the jet centerline to 6000–9000 at its periphery) and two-phase breakup interactions with the Weber number going from 5 to more than 350.

In this jungle of difficulties, the goal of the present study was to reproduce the global behavior of liquid plasma interaction to determine which physical mechanism had the largest influence during the treatment of nanomaterials. This paper is the first step toward an ambitious goal and is mainly dedicated to hydrodynamic effects between fluids.

3. Modeling strategy

3.1. Eulerian approach and equations

The multifluid problem has been treated by a Eulerian approach in order to solve the classical equations of fluid mechanics:

— mass conservation equation
— momentum conservation equation
— energy equation
— volume of fluid interface tracking equation
— plasma gas concentration equation.

In order to keep this paper simple, all details concerning how to write and to solve these equations can be found in [18,19]. A compressible model [20] is required to take into account the compressible effects in the plasma. The 1-fluid model of Kataoka [21], generalized for plasma conditions, has been employed in this work. Compressibility was taken into account with a new mass conservation equation that has been reformulated as an equation for pressure. For the two-phase flow, a