ATMOSPHERIC AXISYMMETRIC PLASMA JET SIMULATION BASED ON LATTICE BOLTZMANN METHOD

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ABSTRACT

We perform a large eddy simulation (LES) of an axisymmetric turbulent argon plasma jet, issuing in surrounding argon, using the lattice Boltzmann (LB) method. The computational technique combines a D2Q9-D2Q4 single relaxation times (SRT) lattice Boltzmann equation (LBE). The Smagorinsky model for the subgrid stress is used. The D2Q9 scheme is implementd for solving the Navier-Stokes equations and the D2Q4 for solving the temperature fields (considered as a passive scalar). We show that the LB equation is more suitable than the classic numerical methods for treating the Reynolds stress tensor. The results of our simulations show agreement with former works in mainly the temperature and velocity fields and their distributions along the centerline. Overall, this work demonstrates that the LB method is a potentially reliable computational tool for complex flows even at high temperature.

RESUME

Nous effectuons une simulation aux grandes échelles de turbulence (Large Energy Scale ou LES) d'un jet plasma d'argon axisymétrique et turbulent, en atmosphère d’argon, en utilisant la méthode de Boltzmann sur réseau. La combinaison D2Q9-D2Q4 est employée comme modèle de l'équation de Boltzmann pour résoudre les équations de Navier-Stokes et l'équation de l'énergie. Le modèle de turbulence de Smagorinsky a été choisi pour représenter la turbulence. La méthode de Boltzmann semble plus appropriée que les méthodes numériques classiques pour traiter le tenseur des contraintes de Reynolds. Les résultats de ces simulations montrent un bon accord avec des travaux de la littérature ainsi pour, les distributions de la température et de la composante horizontale de vitesse ainsi que leur profils sur l’axe. De façon générale, ce travail démontre que la méthode Boltzmann est un outil numérique potentiellement fiable pour des traiter des écoulements complexes y compris pour des forts gradients de températures.

1. INTRODUCTION

Numerous experimental and numerical efforts are conducted on plasma jet and plasma spraying since their interest rule in materials processing [1], for economic needs and to well understand the complex occurring transfer phenomena. However, the first attention must be accorded to the dynamic and thermal fields distributions of the plasma jet. That is because plasma temperature and flow fields, in the flow core, affect absolutely the in-flight particles trajectories, and their temperature histories and then the quality and formability of thermal spray.

For validation, results are always compared to available data or to experimental measurements such as in [2]. In other side, numerical investigations vary between 2D, symmetric, axi symmetric and full 3D treatments, with and without swirling-velocity in both laminar and turbulent state [3-4]. It is worth noting that argon plasma jet is at the head of plasma gas nature investigated, and that most authors used a two-dimension or pseudo three-dimension models [5]. Often the $k-\varepsilon$ turbulent models are used [6], however such models introduce large errors (comparatively to DNS (Direct Numeric Simulation) and LES (Large Energy Scale) that can be damped into the viscosity as it is noticed in [7]. Some others 3D studies are performed by using a commercial computational fluid dynamics package, as FLUENT [8-9]. In other side available modeling works are almost all based on the steady flow assumption in a time-averaged sense [5-6-8]. However G. Delluc et al. show in [10] that the plasma jet is unsteady.

In the last decades, the Lattice Boltzmann (LB) method is considered versus approaches to solve complex problems of heat and fluid flow. Its time-dependent scheme is in accordance with unsteady plasma jet nature. In addition, the LB equation is mainly used to simulating gas flows, which present collision process.

The present paper is an approach to reach a fully LB-understanding of the underlying physical processes and characteristics in argon plasma jet. In our point of view this study gives a new numerical answer to enrich the basis of modeling plasma jet dynamics.

In this work we will perform a numerical simulation of plasma jet in an axisymmetric configuration based on the Jian's model. Furthermore, it is well to mention that plasma jet is laminar in its core but turbulent in its fringes due to the high temperature and velocity gradients (200 K/mm and 10 m/s/mm).

In the present paper, the LBM scheme is employed for simulating the turbulent plasma flow in coupling with the mass conservation, the momentum conservation and the energy conservation equations. For its simplicity, the Smagorinsky turbulence model will be used.

2. NUMERICAL MODEL: BASIC ASSUMPTIONS AND GOVERNING EQUATIONS

The assumptions used in this study include

- the argon plasma jet is issuing into argon surrounding (i.e. Ar-Ar),
- the plasma jet flow is time-dependent during the computation, axisymmetric and turbulent;
- the plasma is in the Local Thermodynamic Equilibrium (LTE) state and the radiation heat loss is neglected;
- all the plasma properties are temperature dependent;
- the swirling velocity component in the plasma jet can be neglected in comparison with the axial velocity;
- the plasma jet flow is incompressible [11], then obeys to the condition low Mach number, hence the compression work and the viscous dissipation can be neglected in the energy equation,
- the gravity effect is neglected.

Based on the above-mentioned assumptions, the continuity, momentum and energy equations in *(r,z)* coordinates are, in tensor form, as follows:

$$\begin{cases} \dfrac{\partial u_j}{\partial x_j} = -\dfrac{u_r}{r} \\ \dfrac{\partial u_i}{\partial t} + u_j \dfrac{\partial u_i}{\partial x_j} = -\dfrac{1}{\rho}\dfrac{\partial p}{\partial x_i} + \upsilon \dfrac{\partial^2 u_i}{\partial x_j^2} + \dfrac{\upsilon}{r}\dfrac{\partial u_i}{\partial r} - \dfrac{\upsilon u_i}{r^2}\delta_{ir} \\ \dfrac{\partial T}{\partial t} + u_j \dfrac{\partial T}{\partial x_j} = \alpha \dfrac{\partial^2 T}{\partial x_j^2} + \dfrac{\alpha}{r}\dfrac{\partial T}{\partial r} \end{cases} \tag{1}$$

Were t the time, u_r and u_z are the radial and axial velocities respectively, ρ is the density, T is the gas temperature, ν is the kinetic viscosity, α is the thermal diffusivity, C_p is specific heat at constant pressure, p is the pressure and δ_{ir} is the Kronecker symbol.

3. THE LBE-LES THERMAL AXISYMMETRIC MODEL IN INCOMPRESSIBLE LIMIT

We have found that the D2Q9-D2Q4 is a suitable model for simulating thermal flows. First it is more stable then the D2Q9-D2Q9 model. Second, it preserves the computation effort, because the collision step takes around 70% of the CPU time.

The standard lattice Boltzmann method is used is Cartesian coordinates. The first intend to representing axisymetric flow was with [12]. However, the temperature field was solved using Finites Difference (FD) method. Recently, some new formulations are available [13,14]. The Jian's model [13] will be used in this work for simplicity among the existing models. Further reading on the model and the LBM technique for computing macroscopic variables, density and velocity, can be found in [13].

For heat transport, the temperature evolution equation in the four-speed (D2Q4) lattice Boltzmann model is given by [15]. Similarly the macroscopic temperature can be obtained from the distribution function (see [15]).

For simplicity we will adopt in what follows the transformation *(x,r)* → *(x,y)*, no changes will be introduced by the transformation.

A common approach of modeling turbulent flows is due to Smagorinsky [16]. See [17] for more explanation on filtering operation and filtered equations.

In the LBM-LES modeling, the value of the collision relaxation time is locally adjusted so that the viscosity is equal to the sum of the physical and the eddy viscosities (ν and νt respectively) as (or D2Q9 model):

$$\upsilon_{tot} = \frac{\tau_{\upsilon\text{-}tot} - 0.5}{3} = \upsilon + \upsilon_t = \upsilon + C\Delta^2 \left|\bar{S}_{ij}\right| \tag{2}$$

Were $\left|\bar{S}_{ij}\right| = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}$ is the magnitude of the large scale strain rate tensor. Fortunately, the strain rate tensor is directly computed from the second kinetic moment of the non-equilibrium part of the distribution function, without taking recourse to the finite-differencing of the velocity field.

$$\bar{S}_{ij} = -\frac{3}{2}\frac{1}{\Delta t\,\rho(x,t)\tau_{\upsilon\text{-}tot}}\sum_k \boldsymbol{e}_{ki}\boldsymbol{e}_{kj}\left(f_k - f_k^{eq}\right) \tag{3}$$

See [17] for details on computing the turbulent viscosity.

Similarly for the thermal field, the relaxation time is readjusted as follows:

$$\alpha_{tot} = \frac{\tau_{\alpha\text{-}tot} - 0.5}{2} = \alpha + \alpha_t = \alpha + \frac{\upsilon_t}{Pr_t} \tag{4}$$

Where Pr_t is the so called turbulent Prandtl number, usually taken between 0.3 and 1.

4. ACCOUNTING FOR TEMPERATURE DEPENDENCE

As mentioned above, argon plasma jet is a high temperature flow. So that, all the physical quantities (viscosity, diffusivity, specific heat, density, sound speed, etc.) are temperature dependent. The discrete data of these quantities are coded in T&TWinner by [18]. To well take account of this behavior, some algebra are needed to transform the real (physical) quantities to its LB values (see [19]).

5. CONFIGURATION MODEL

A half plan is considered as a computational domain for the axisymmetric plasma jet. The graph is mapped in Figure 1. Where W=3R=12mm, L=100mm. The domain is subdivided by a uniform computational mesh resulting in 808x104 node sites. AB is the anode thickness, then, no-slip boundary (**u**=0) condition and a fix temperature (T_{min}=700K) are retained. BC is a fixe temperature (T_{min}=700K) and free bound for the velocity ($\partial\mathbf{u}/\partial\mathbf{n}=0$) are adopted. CD is a free boundary and the classic extrapolation condition is adopted. OD is an axisymmetric boundary (see [12]). OA is governed by the inlet condition of Eq. (5).

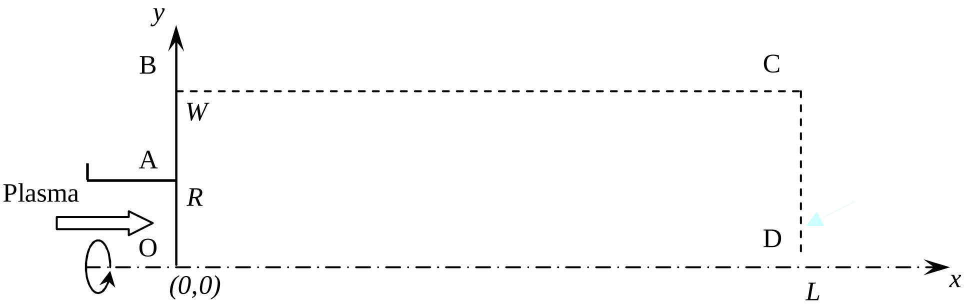


Figure 1. Computational domain

$$\begin{cases} u_{in} = u_{\max}\left[1-\left(\dfrac{y}{R}\right)^3\right] \\ T_{in} = (T_{\max}-T_{\min})\left[1-\left(\dfrac{y}{R}\right)^3\right]+T_{\min} \end{cases} \tag{5}$$

Where u_{max} and $T_{max} = 13500\,K$ are the velocity and temperature of the plasma jet at the torch axis.

6. COMPUTATIONAL RESULTS

To ensure the correctness of our algorithm is performed for $u_{max} = 520\,m/s$ on simulation results of paper [2] and calculated results of codes T&TWinner [18,20] and Jet&Poudres [10] (with conditions $u_{max} = 520\,m/s, T_{max} = 13500\,K$, gaz flow rate=26 l/min, electric power =12500 W and efficiency = 57%). Figure 2 presents the velocity and temperature distributions along the jet centerline. At first it is well noticed that axial temperature gradient near the inlet (interval 0-20 mm) is close to 208 K/mm then high than 200 K/mm and velocity gradient is close to 9 (m/s)/mm, which agree well with former experimental and numerical observations. Our results approach more that of Pfender [2], the outlying of Jet&Poudres [10] results is because ramps are used for the inlet temperature and velocity profiles instead of parabolic ones. The iso-temperature and the iso-axial velocity distributions and the velocity vector traces are shown in Figure 3.

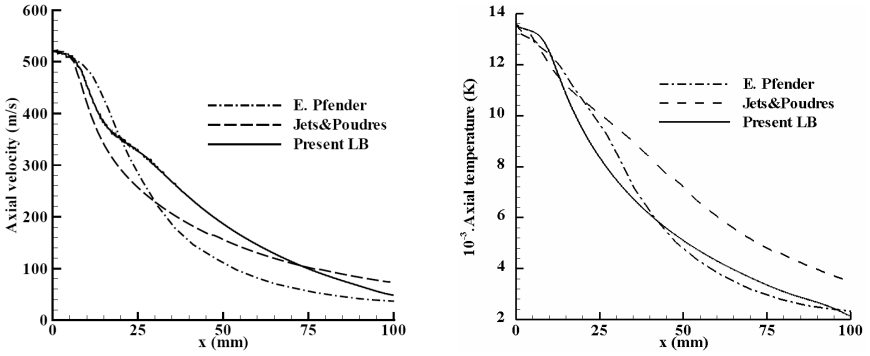
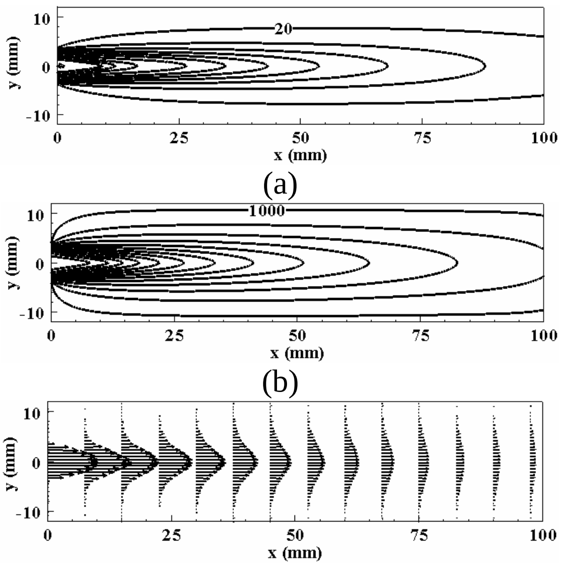


Figure 2. Velocity (left) and temperature (right) distributions along the jet centerline



(a)

(b)

(c)

Figure 3. (a) iso-axial-velocity traces with 50m/s of interval, (b) iso-temperature traces with 1000 K of interval and velocity vector profiles with a skip of 12.5 mm.

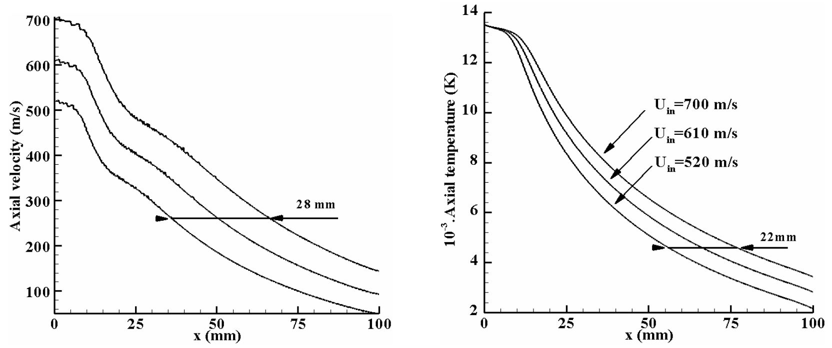


Figure 4. Velocity (left) and temperature (right) distributions along the jet centerline for several inlet velocities

In Figure 4 we present a comparison on the effects of inlet maximum velocity on the centerline temperature and velocity distributions. The chosen values are 520 m/s, 610 m/s and 700 m/s. We have to mention here that we work in the limit of incompressibility; (the Mach number is close to 0.3). The Figure demonstrates that for high inlet velocity the flow is entertained to the downstream region. For low temperature the flow translates about 11 mm/(90 m/s) for the thermal field and about 14 mm/(90 m/s) for the dynamic field.

One can also say that the axial temperature and velocity gradients near high temperature keep the same above mentioned property when increasing.

7. CONCLUSION

A argon plasma jet simulation have been performed in this paper using lattice Boltzmann equation. The axisymmetric, turbulent and unsteady characters are absolutely taken in account during computation. It was found that lattice Boltzmann method is a powerful tool and a serious alternative than classical based discretsation methods for treating these complex flows keeping the good accuracy and computational efforts. We note that all investigations converge in about 40000 time-steps. Our future works will focus on simulating other gazes in presence of flying particles.

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