Available online at www.sciencedirect.com
ScienceDirect
Surface & Coatings Technology 201 (2006) 886 – 894
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Simulation of powder transport in plasma jet via hybrid Lattice Boltzmann method and probabilistic algorithm

Haiou Zhang [1], Shengde Hu *, Guilan Wang [1]

State Key Lab of Plastic Forming Simulation and Die and Mold Tech. Huazhong University of Sci. and Tech., Wuhan 430074, China

Received 23 March 2005; accepted in revised form 1 January 2006
Available online 21 February 2006

Abstract

When plasma is used to spray coatings on a mould surface, the states of the plasma jet and powder particles have great influence on the quality of the spray layer. In order to find a simple and efficient simulation for the states of the plasma jet and powder particles, an attempt of modeling was made by hexagonal 7-bit Lattice Boltzmann method (LBM) and a probabilistic algorithm in this paper. The velocity and temperature field of the plasma jet and particles are calculated and compared with those obtained by previous models and measurements. The dynamic moving process, accelerating course, maximal speed and distribution of powder particles are calculated by the present model. The optimal spraying distance and deposition efficiency under different spraying conditions are also acquired. It can be concluded that the combined model is competent for numerical simulation of the atmospheric plasma spraying. Simulation by LBM is simpler and faster than that by traditional methods. LBM is also a computational method that offers flexibility and outstanding capacity of parallel computation.

Keywords: Plasma spray; Simulation and modeling; Lattice Boltzmann method; Probabilistic algorithm

1. Introduction

Thermal spray coatings are formed by spraying the melting powdered particles at a high velocity onto a substrate. The quality and formability of thermal spray coatings is directly determined by the velocity, the temperature, and the melt fraction of the sprayed powder particles when the spray coatings are impacting the substrate [1,2]. Therefore, a theoretical modeling is an important tool to understand the plasma process much better.

Theoretical models have been published both on the general characteristics of plasma jets [3–5] and on the behavior of injected particles in a plasma jet [6–14]. Many special effects, due to characteristics of the thermal plasma such as high temperature and temperature gradients, low pressure, strongly varying plasma properties, non-continuum effects, thermophoresis, turbulent dispersion [15–17], evaporation, droplet flattening process, have been discussed in detail by these models in the past 30 years. Of the works on theoretical models, Pfender and his co-workers, the group of Boulos and Proulx has best contributed. Their works have been widely cited in the literature. In addition, some excellent and interesting research, such as droplet collision and flattening by Mostaghimi and coworkers [18–20], air entrainment, coating oxidation and microstructure by Dolatabadi and coworkers [21,22], has been done recently. These well-established models are extraordinarily helpful to improve the understanding of the physical nature of the plasma jet, the relationship between the key process parameters and the effective control of the coating quality. However, to the authors' knowledge, the reported models are mainly at the macroscopic level and based on the finite difference method (FDM) or the finite element method (FEM). Generally speaking, in these models the SIMPLE (or SIMPLER, SIMPLEST, etc.) algorithm and stagger grids are often used to solve the large equations set, where the unsuitable pressure must be eliminated. As a result, the program becomes complex and the simulation speed is slow. So an attempt of studying the plasma by the Lattice Boltzmann method (LBM) at the microscopic level was performed in this paper. There are many advantages in the LB approach, such as the direct physical

* Corresponding author. Tel.: +86 27 87543493; fax: +86 27 87554405.
E-mail addresses: zholab@mail.hust.edu.cn (H. Zhang), adhello@163.com (S. Hu), zholab@mail.hust.edu.cn (G. Wang).
[1] Tel.: +86 27 87543493; fax: +86 27 87554405.

0257-8972/$ - see front matter
doi:10.1016/j.surfcoat.2006.01.006

nature and a simple idea. It also provides easily implemented, fully parallel algorithms and the capability of handling complicated boundaries [23,24]. It can be forecast that the simulation by LBM is faster than that by FDM, for there is no need to solve the large equations and no iterative procedure in the calculation process.

This paper first describes the LB plasma jet model. It also explains the rules the authors propose for adding powder particles on top of the LB plasma fluid, and then presents the results of the simulations and discusses the model, finally gives the conclusions.

2. The LB plasma jet model

Local thermodynamic equilibrium and optical thin are assumed within the plasma jet for the calculation reported here. The calculation domain is the section parallel to the axis, shown in Fig. 1. It consists of a hexagonal 7-bit lattice and shows a calculating model of grid division. The velocity vector of each grid can be expressed as the following form

$$\vec{c_i} = \begin{cases} C(\cos a_i, \sin a_i); & i = 1, \dots 6 \\ 0; & i = 0 \end{cases}$$

Where $a_i = \pi\,(2i-1)/6$, and C is unit velocity of grid.

A multi-speed Lattice Boltzmann model is usually chosen for calculating the temperature change of thermal flow, in which different speeds represent different energy [25,26]. However, it is found that the model does not appropriate for simulating the heat and velocity field of the plasma jet because of the existence of great temperature and velocity gradient. In this paper two sets of Lattice Boltzmann equations with BGK collision operators are selected as the following form [27,28]

$$\begin{aligned} & f_i(\vec{x} + \vec{c_i}\,\boldsymbol{e}, t + \boldsymbol{e}) - f_i(\vec{x}, t) \\ & \quad = \frac{1}{\tau}[f_i(\vec{x}, t) - f_i^{(0)}(\vec{x}, t)], \quad T_i(\vec{x} + \vec{c_i}\,\boldsymbol{\varepsilon}, t + \boldsymbol{\varepsilon}) - T_i(\vec{x}, t) \\ & \quad = -\frac{1}{\tau_{\mathrm{T}}}[T_i(\vec{x}, t) - T_i^{(0)}(\vec{x}, t)] - \frac{\dot{q}\alpha_i}{\rho C_{\mathrm{p}}} \end{aligned} \tag{1}$$

where i is the direction number of particles moving; α_i is the percent of the i direction particles; τ and τ_{T} are relaxation factors; $\vec{x}$, $\vec{c_i}$ and ε are position vector, velocity vector and time step, respectively; $\dot{q}$ is the radiance per unit volume of the plasma jet; ρ is density and C_{p} is specific heat. The key to generating the correct macroscopic hydrodynamic equations is in the choice of the equilibrium distribution functions $f_i^{(0)}$ and $T_i^{(0)}$ [23]. The form can be written as follows:

$$\begin{aligned} & f_i^{(0)} = A_0 - A_1 v^2 + A_2(\vec{c_i}\,\vec{v}) + A_3(\vec{c_i}\,\vec{v})^2, \\ & f_0^{(0)} = D_0 - D_1 v^2, T_i^{(0)} = B_0 + B_1(\vec{c_i}\,\vec{v}), \\ & T_0^{(0)} = E_0, (i = 1, 2, 3, 4, 5, 6) \end{aligned} \tag{2}$$

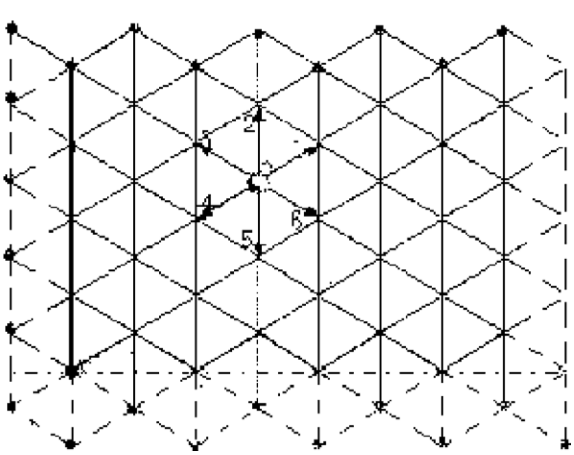

Fig. 1. Lattice grid and velocity of fluid.

The LB equation describes the evolution of the density and the temperature distribution function on a lattice in a manner that the macroscopic fluid dynamical behavior is recovered. For deriving the macro equation of the plasma jet, the coefficients of Eq. (2) must satisfy Eq. (3)

$$\left.\begin{aligned} & \sum_i f_i = \rho, \quad \sum_i f_i c_{ik} = \rho v_{ik}, \quad \sum_i T_i = T, \quad \sum_i T_i c_{i\alpha} = T v_\alpha, \\ & \sum_i f_i c_{im} c_{in} = \rho v_m v_n + p\delta_{mn}, \quad \sum_i f_i c_{il} c_{im} c_{in} = (\rho u_l u_m u_n) + \rho c_{\mathrm{s}}^2 (u_l \delta_{mn} + u_m \delta_{\mathrm{ln}} + u_n \delta_{ml}) \end{aligned}\right\} \tag{3}$$

Where δ_{ij}, p and c_{s} are Kronecker delta, pressure ($p = \rho c_{\mathrm{s}}^2$) and the local sound speed, respectively. Symbol m, n and k are coordinate quantities.

In order to deduce the macro function, the left items of Eq. (1) are expanded by Taylor series and a multi-scale method (Eq. (5)) while the right items are expanded by the Chapman–Enskog method [29] (Eq. (4)). Summations of all direction particles are given on every grid by reference to Eq. (3). The expansion is truncated to ε^2 (about 10^{-12} magnitude). When the simulation field evolves to a steady state, the macro quantities of the same position do not vary with time, and their differential coefficient with time is zero. In addition, the density gradient in the energy conservation equation is neglected because it is too small when compared with the velocity gradient and the temperature gradient. Finally the macro continuity equation, the momentum conservation and energy conservation equation are obtained (Eq. (6)).

$$\begin{aligned} & f_i = f_i^{(0)} + \varepsilon f_i^{(1)} + \varepsilon^2 f_i^{(2)} + \varepsilon^3 f_i^{(3)} + \dots, \\ & T_i = T_i^{(0)} + \varepsilon T_i^{(1)} + \varepsilon^2 T_i^{(2)} + \varepsilon^3 T_i^{(3)} + \dots \end{aligned} \tag{4}$$

$$\frac{\partial}{\partial t} = \frac{\partial}{\partial t_0} + \varepsilon \frac{\partial}{\partial t_1} \tag{5}$$

$$\begin{aligned} & \nabla(\rho\,\vec{v}) = 0, \quad \nabla(\rho\,\vec{v}\,\vec{v} + p\delta_{ij}) = \frac{\partial}{\partial x_j}\left[\mu_{\mathrm{e}}\left[\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}\right]\right], \\ & \nabla[\vec{v}(\rho T)] = \nabla[\Gamma_{\mathrm{e}} \nabla T] - \cdot q / C_{\mathrm{p}} \end{aligned} \tag{6}$$

Where $\mu_{\mathrm{e}} = \mu + \mu_{\mathrm{t}}$, $\Gamma_{\mathrm{e}} = \Gamma + \Gamma_{\mathrm{t}} = \lambda / C_{\mathrm{p}} + \mu_{\mathrm{t}} / P_{\mathrm{rt}}$ is laminar viscosity decided by working gas property and μ_{t} is effective turbulent viscosity decided by gun structure and environment around; λ is thermal conductivity; C_{p} is specific heat and P_{rt} is Prandtl number.