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Modeling of the heat transfer and flow features of the thermal plasma reactor with counter-flow gas injection

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ABSTRACT

Modeling study is conducted to reveal the heat transfer and flow features of the thermal plasma reactor with a counter-flow gas injection and used for nano-particle synthesis. The modeling results show that a variety of parameters, such as the temperature and flow rate of the carrier gas, the operation conditions of the plasma torch, the distance between the plasma torch exit and the carrier-gas injector exit, the swirling of the plasma jet or the carrier gas, etc., can all affect appreciably the temperature and flow fields and the locations of the stagnation layers formed in the plasma reactor. An appropriate combination of the operation parameters of the reactor is thus required in order to obtain a suitable stagnation layer for the synthesis of nano-scale particles.

1. Introduction

Due to their outstanding features with rather high specific enthalpy and thermal conductivity, thermal plasmas have been used widely in the fields of advanced materials processing, e.g., plasma spraying, particle spheroidization, synthesis of micro- or nano-scale particles, etc., in last decades [1,2]. In the synthesis of micro- or nano-scale particles, the raw materials are usually fed into the plasma region with the help of cold carrier-gas injected laterally (or in the direction perpendicular to the plasma jet axis), then the materials are heated, melted, evaporated, dissociated/decomposed, synthesized in the plasma region, and finally the fine powders with appropriate size distributions are obtained. Compared to the traditional plasma reactors with lateral carrier-gas injection, the plasma reactor with counter injection of the cold fluid (gas or liquid) can improve the reaction environment significantly, such as enhancing the residence time of the reactants in the hot core region, stimulating the intimate mixing of reactants with the plasma, and controlling the particle sizes by reducing particle coagulation or coalescence, etc. In early 1990s, a counter-flow liquid injection plasma reactor for synthesis of advanced ceramic powders was developed in the High Temperature and Plasma Laboratory of the University of Minnesota [3,4]. In recent years, the plasma reactor has been employed for synthesizing aluminum nano-particles with counter-injection of pre-heated carrier-gas (argon) and $AlCl_3$ vapor with temperature in the range of 165–180 °C [5].

In Refs. [3,4], experimental and modeling studies were conducted concerning the characteristics of the laminar thermal plasma reactor with counter-injected liquid feedstock. Those studies showed that many parameters, such as the operation parameters of the plasma torch (e.g., the input power, the working-gas flow rate, etc.), the distance between the plasma torch exit and the injector exit, the swirling of the plasma jet, etc., could appreciably influence the temperature and flow fields in the counter-injection plasma reactor, as well as the particle size distributions. In Ref. [5], an experimental study on the characteristics of nano-scale aluminum particles synthesized within a counter-flow gas-mixture (argon and $AlCl_3$ vapor) plasma reactor were conducted. However, so far no systematic modeling study is performed on the heat transfer and flow features of the plasma reactor with counter-injected carrier gas, as employed in Ref. [5]. In order to obtain a favorable environment for controlling the size distributions of the synthesized particles or optimizing the reactor operation parameters, it is essential to study the heat transfer and flow patterns within the plasma reactor, and to understand the complicated physical/chemical processes occurring in the vicinity of the stagnation layer formed between the plasma torch exit and the injector exit [2,5].

In this paper, a two-dimensional simulation is conducted concerning the influences of reactor operation parameters, such as the input power and working-gas flow rate of the plasma torch, the flow rate and temperature of the carrier gas, the distance between the plasma torch exit and the carrier-gas injector exit and the swirling at the plasma jet side or the carrier gas side, on the heat transfer and flow features of the thermal plasma reactor with counter-flow gas injection, as shown in Fig. 1.

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Nomenclature

c_p	specific heat at constant pressure (J kg^{-1} K^{-1})
c_1, c_2, c_μ, σ_K, σ_ε	turbulence model constants
G	turbulent generation term (W m^{-3})
h	specific enthalpy (J kg^{-1})
K	turbulent kinetic energy (m^2 s^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
L	distance between plasma torch and injector exit (m)
M	momentum of the plasma jet or the carrier gas (kg m s^{-2})
P	torch power (W)
p	gas pressure (Pa)
Pr_t	turbulent Prandtl number
Q	flow rate of the gas (m^3 s^{-1})
R_{in}	inner radius of the torch nozzle or the carrier-gas injector (m)
R_M	momentum ratio
R_{out}	outer radius of the calculation domain (m)
S	swirl number
S_R	radiation power per unit gas volume (W m^{-3})
T	temperature (K)
v_{01}, v_{02}	maximum absolute value of the axial velocity component at the torch exit or the injector inlet (m s^{-1})
$v_{\theta m}$, R_s	maximum value of the tangential velocity component and its radial location (m s^{-1}, m)
v_z, v_r, v_θ	velocity components in z-, r-, and θ-directions (m s^{-1})
z, r, θ	coordinate in axial, radial or tangential direction

Greek symbols

ε	turbulent kinetic-energy dissipation rate (m^2 s^{-3})
η	thermal efficiency of the plasma torch
λ	distance between stagnation point and plasma torch exit (m)
μ	molecular viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	mass density (kg m^{-3})
ξ	dimensionless distance ($\xi = \lambda/L$)
Γ	effective diffusion coefficient

Subscripts

car, 2	carrier gas
in	input or value at the inner side
m, 0	maximum value
M	momentum
out	output or value at the outer side
p, 1	plasma
s	inner point of the solid wall
t	turbulent
w	wall
z, r, θ	components in z-, r-, and θ-directions

2. Modeling approach

2.1. Assumptions

Main assumptions employed in this study include that (1) the flow within the plasma reactor is axi-symmetric, quasi-steady, turbulent and at atmospheric pressure; (2) gas properties are temperature-dependent; (3) the plasma is optically thin and in the local thermodynamic equilibrium (LTE) state; (4) the viscous dissipation and the pressure work terms in the energy equation are negligible; and (5) argon is used as the plasma forming-gas and the carrier gas, i.e., the small amount of $AlCl_3$ vapor in the gas mixture is not considered in this study for simplicity.

2.2. Governing equations

Based on the preceding assumptions, the governing equations used in this modeling can be written in the cylindrical coordinates (r, z, θ) as follows:

Continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r)+\frac{\partial}{\partial z}(\rho v_z)=0 \quad (1)$$

Momentum conservation equation (z-direction):

$$\frac{\partial(\rho v_z v_z)}{\partial z}+\frac{1}{r}\frac{\partial(r\rho v_z v_r)}{\partial r} = -\frac{\partial p}{\partial z}+\frac{1}{r}\frac{\partial}{\partial r}\left[\Gamma_u r\left(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z}\right)\right]+2\frac{\partial}{\partial z}\left(\Gamma_u\frac{\partial v_z}{\partial z}\right) \quad (2)$$

Momentum conservation equation (r-direction):

$$\frac{\partial(\rho v_z v_r)}{\partial z}+\frac{1}{r}\frac{\partial(r\rho v_r v_r)}{\partial r} = -\frac{\partial p}{\partial r}+\frac{2}{r}\frac{\partial}{\partial r}\left(r\Gamma_u\frac{\partial v_r}{\partial r}\right)+\frac{\partial}{\partial z}\left[\Gamma_u\left(\frac{\partial v_r}{\partial z}+\frac{\partial v_z}{\partial r}\right)\right] - 2\Gamma_u\frac{v_r}{r^2}+\rho\frac{(rv_\theta)^2}{r^3} \quad (3)$$

Momentum conservation equation (θ-direction):

$$\frac{\partial(r\rho v_z v_\theta)}{\partial z}+\frac{1}{r}\frac{\partial(r^2\rho v_r v_\theta)}{\partial r}=\frac{\partial}{\partial z}\left[\Gamma_u\frac{\partial(v_\theta r)}{\partial z}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\Gamma_u r\frac{\partial(v_\theta r)}{\partial r}\right] -\frac{2}{r}\frac{\partial(r\Gamma_u v_\theta)}{\partial r} \quad (4)$$

Energy conservation equation:

$$\frac{\partial(\rho v_z h)}{\partial z}+\frac{1}{r}\frac{\partial(r\rho v_r h)}{\partial r}=\frac{\partial}{\partial z}\left(\Gamma_h\frac{\partial h}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_h\frac{\partial h}{\partial r}\right)-S_R \quad (5)$$

In this paper, the standard K–ε two-equation turbulence model is employed to study the influence of turbulence on the heat transfer and flow patterns within the plasma reactor. The corresponding turbulent kinetic energy and its dissipation rate equations are as follows:

$$\frac{\partial}{\partial z}(\rho v_z K)+\frac{1}{r}\frac{\partial}{\partial r}(\rho v_r r K)=\frac{\partial}{\partial z}\left(\Gamma_K\frac{\partial K}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_K\frac{\partial K}{\partial r}\right)+G-\rho\varepsilon \quad (6)$$

$$\frac{\partial}{\partial z}(\rho v_z \varepsilon)+\frac{1}{r}\frac{\partial}{\partial r}(\rho v_r r\varepsilon)=\frac{\partial}{\partial z}\left(\Gamma_\varepsilon\frac{\partial \varepsilon}{\partial z}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\Gamma_\varepsilon\frac{\partial \varepsilon}{\partial r}\right) +\frac{\varepsilon}{K}(c_1 G-c_2\rho\varepsilon) \quad (7)$$

In Eqs. (1)–(7), z, r and θ are the axial, radial and tangential coordinates, while v_z, v_r and v_θ are the velocity components in the z-, r- and θ-directions, respectively. ρ, h and p are the mass density, specific enthalpy and pressure of argon, K and ε are the turbulent kinetic energy and its dissipation rate, and S_R is the temperature-dependent radiation power per unit volume of the argon plasma.

The turbulence generation term, G, appearing in Eqs. (6) and (7) is expressed as

$$G=\mu_t\left\{2\left[\left(\frac{\partial v_z}{\partial z}\right)^2+\left(\frac{\partial v_r}{\partial r}\right)^2+\left(\frac{v_r}{r}\right)^2\right] +\left(\frac{\partial v_z}{\partial r}+\frac{\partial v_r}{\partial z}\right)^2+\left(\frac{\partial v_\theta}{\partial z}\right)^2+\left(\frac{\partial v_\theta}{\partial r}-\frac{v_\theta}{r}\right)^2\right\} \quad (8)$$