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Numerical analysis of flame and particle behavior in an HVOF thermal spray process

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ABSTRACT

In this study, a kerosene-fueled high-velocity thermal spraying model is used to examine the flame and particle behavior in a thermal spray process. The gas flow characteristics (including temperature, velocity, and pressure), mass fraction of the gas components, and the particle characteristics (including the particle temperature, velocity, and in-flight trajectory) are successfully simulated. Besides, the effects of particle diameter, particle shape, and particle injection velocity on the particle behavior in the spraying flame are also investigated. The optimal particle size range is found to be between 20 and 40 μm. In this case, most of the particles are located towards the center of the gun and are in a semi-solid state before impacting the substrate. When the shape factor falls from 1 to 0.6, the non-spherical particles gain more momentum and less heat than spherical particles in the process owing to their higher drag coefficient and shorter dwell time within the flame flow. A comprehensive consideration of the injection velocity on the spray particle dynamics revealed that the optimal particle injection velocity should be greater than 5 m/s but no more than 20 m/s.

1. Introduction

The technology of high velocity oxygen fuel (HVOF) thermal spraying is aimed at forming a coating by the stacking of lamellae resulting from impact, flattening and solidification of impinging molten particles to extend product life, increase performance and reduce maintenance costs. Thermal spraying technology has been widely used in vehicle engineering and aerospace fields [5]. The thermal spraying process is a complex process involving combustion and heat transfer, compressible supersonic flow, turbulent mixing and multiphase interactions. It is necessary to comprehensively understand the flame and particle behavior in thermal spray process.

Most research has been focused on gas-fueled HVOF characteristics, including HV-2000 [6] and Diamond Jet [7, 8]. Recently, great progress has been made in the liquid-fueled HVOF technology. The liquid-fuelled HVOF technology is capable of achieving more momentum output for powder particles and consumes low-cost liquid fuel (for example, kerosene). However, for the JP5000 (Praxair, US), the most widely used liquid-fuel gun, only a few numerical investigations of the gas flow characteristics have been reported [4]. There is thus a lack of systematic studies of liquid-fuel systems including the combusting gas flow and the in-flight particle dynamics.

The numerical technology on thermal spray process has eliminated costly trial and error experimental work to get excellent performance coatings. Much work has been done on the microstructure and performance of the coating regardless of the flame and particle behavior [9, 10]. In fact, the quality of coating is directly related with the particle behavior such as velocity, temperature and in-flight trajectory. Some numerical models have investigated, but have failed to subsequently discuss, the particle behavior in the spray gun [11]. However, these models are only appropriate for spherical particle, while particles such as WC-Co powders made by mechanical milling are not normally spherical. There is also a lack of good understanding of the effect of particle shape on particle in-flight trajectory, temperature and velocity.

In this study, the combustion behavior in a kerosene-fueled thermal spraying gun is calculated using the computational fluid dynamics software Fluent. Fluent incorporates a realizable turbulence model, species transport model, and discrete phase model (DPM) [12]. An investigation is performed to examine the effects of the particle diameter, shape factor, and injection velocity on the particle characteristics in the combusting gas flow. The gas flow characteristics including the temperature, velocity, pressure, and mass fraction of the gas components are successfully simulated. The effects of the particle diameter, particle shape, and particle injection velocity on the particle behavior in the spraying flame are all investigated as part of this research.

2. Mathematical models

Fig. 1 illustrates the schematic diagram of the kerosene-fuelled HVOF thermal spray gun JP5000 made by Praxair company, including

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Nomenclature

A_p	surface area of the particle
C_D	drag coefficient [1]
c_p	specific heat of the particle
d_p	particle diameter
E	enthalpy
F_x	additional acceleration
h	heat transfer coefficient [2]
J_α	mass diffusion flux
k	thermal conductivity
k_{eff}	effective thermal conductivity [3]
m_p	mass of the particle
p	pressure
R_α	species net production rate
R_e	Reynolds number [4]
S_α	generating rate
S_h	chemical reaction source energy
T	temperature
T_g	gas temperature
T_p	particle temperature
T_S	particle solidus temperature
T_L	particle liquidus temperature
u	velocity
u_i	velocity in the i-direction
u_p	particle velocity
x_i	coordinate in the i direction
Y_α	mass fraction of each species

Greek letters

δ	Kronecker symbol
μ	viscosity
μ_t	turbulent viscosity
ρ	density
τ	deviatoric stress tensor

Subscripts

α	species
g	gas
i, j	coordinate indices
p	particle

the fuel–oxygen inlet, the combustion chamber, the convergent–divergent (CD) nozzle, barrel and external domain. 2D simulation domain is adopted in this study to reduce the complexity and computational time. There are several common HVOF systems, like Jet-Kote HVOF systems made by Stellite-Coating Company, Diamond-Jet, Diamond-Jet hybrid and DJ-2000 HVOF system made by Sulzer-Metco Company, and JP-5000 HVOF systems made by Praxair Company. Although spray guns differ in their structure and function, they are all based on the same operating principle. Since thermal spray coatings based on WC-Co offer superior hardness, resilience to fracture, and lower porosity, they provide a very effective means of alleviating losses resulting from surface damage [13]. In this calculation, WC-Co particles are injected from an axial distance of 0.133 m. The length of the combustion chamber and barrel are 92.5 mm and 111.1 mm, respectively. The stand-off distance used in this simulation is 300 mm (300 mm from the gun's exit).

2.1. HVOF thermal spray gun model and boundary

Fig. 2 shows the detailed mesh of the spray gun. Due to the symmetry of the torch, a one-half, 2-D grid is used. The model is radially symmetrical about the centerline. The combustion chamber, CD nozzle, barrel, and external domain consist of 232, 241, 268, and 300 nodes in axial direction, respectively, with a total of 108,318 cells in the whole domain. The grids around the oxygen–fuel inlet, the nozzle, and the free jet region have been successively refined to accurately capture the characteristics of the flame flow.

The oxygen and liquid kerosene are injected into the combustion chamber at the inlet boundary with the mass flow rates of 0.022 kg/s and 0.007 kg/s. Unlike the gas-fuel system where powder is injected into the center of the combustion chamber, the powder particles are introduced downstream of the nozzle using a carrier gas [4]. Subsequently, the spraying particles ranging in size from 5 μm to 60 μm are injected into the nozzle. The particle injection velocity can be varied between 5 and 20 m/s by adjusting the flow rate of the nitrogen carrier gas. The walls of the spray gun are all assumed to maintain at a constant temperature of 300 K. The pressure far field and pressure outlet boundary are applied at the external domain. Finally, the atmospheric pressure is assumed to be 1.01 kPa.

2.2. Gas flow model

In this investigation, an improved version of the standard $k-\varepsilon$ model, called the "realizable $k-\varepsilon$ model," is used extensively in the HVOF simulation. The governing equations for the 2-D model in the Cartesian tensor form are [14]:Mass conservation equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum conservation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(\tau_{ij})_{eff} + \frac{\partial}{\partial x_j}\left(-\rho\overrightarrow{u_i' u_j'}\right) \tag{2}$$

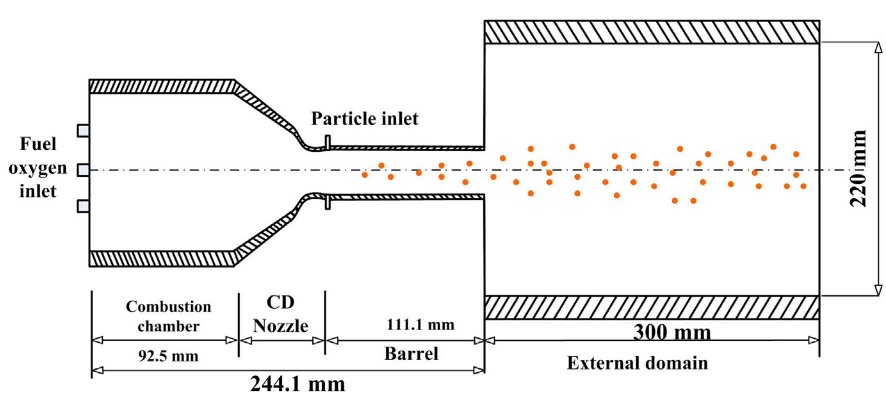

Fig. 1. Schematic diagram of an HVOF spray gun.