Velocity and temperature evolution of plasma jet with the increasing of SiO$_2$ particles concentration

S. Dresvin$^1$, O. Feygenson$^1$, S. Zverev$^1$, J. Amouroux$^2$

$^1$Technical University, Polytechnic Str. 29, 195251 Saint Petersburg, Russia
$^2$LGPPTS, EMSCP, 11 rue P. & M. Curie, 75005 Paris, France

Abstract

The injection of SiO$_2$ particles in an air RF plasma torch permits a surface treatment by melting or evaporation phenomena. We must remember that SiO$_2$–SiO is a chemical equilibrium between a solid and gas (SiO) at around 4000 K at atmosphere pressure so that, this kind of experimental study is much more complex in air plasma because the first step is to qualify the particles modifications for different trajectories in the RF plasma torch (lateral injection or parabolic injection) which control the residence time in the different thermal zone of the plasma but an increasing of the concentration of the particles produces a cold zone in the plasma gas and the heat transfer phenomena decreases; this process gives the limit of the mass flow treatment.

The modeling of the heat and mass transfer macroscopic phenomena permit to qualify the evolution of the SiO$_2$ particles and their evaporation for increasing of particles concentration from $1/\text{cm}^2$ to $10^4/\text{cm}^2$ or $10^{-7}$ g/s to $2$ g/s by that way we are able to predict the limit of the plasma treatment of high flow of particles.

Key words

Dusted jet, evaporation, optimal degree of loading, RF plasma torch, solid particle.

Symbol list

\begin{itemize}
  \item $T$ [K] – Temperature;
  \item $V$ [m/s] – Velocity;
  \item $c_p$ [J/kg.K] – Specific heat;
  \item $C_d$ – Drag coefficient;
  \item $d$ [m] – Diameter;
  \item $L$ [J/kg] – Specific heat of fusion or evaporation;
  \item $n$ – Number of the particles (particles quantity);
  \item $\alpha$ [W/m$^2$ K] – Convection [heat transfer] coefficient;
  \item $\varepsilon$ – Emissivity factor;
  \item $\lambda$ [W/mK] – Thermal conductance;
  \item $\mu$ [Ns/m$^2$] – Viscosity;
  \item $p$ [kg/m$^3$] – Density;
\end{itemize}

Indexes: \text{«p»} – plasma, \text{«s»} – solid particle, \text{«ml»} – melting, \text{«vp»} – evaporation.
1. Introduction

In experimental investigation and mathematical modeling of evaporation of the powders (for example, SiO₂) the maximum degree of jet loading is the most important. This parameter shows what quantity of powders can be fluxed (evaporated, heated up to the necessary temperature) per a time unit in a plasma jet. Besides that, it is important to consider correctly interaction between a plasma jet and a group of particles placed in it.

The suggested method of investigation of dusted plasma jets is based on a theory of heat exchange between a single particle and plasma. This method is sufficiently simple, demonstrative and besides that, is experimentally confirmed.

2. Investigation of dusted plasma

Conduction convective heat exchange between a particle and a gas flow is usually expressed as a dependence of Nusselt number on Reynolds number and Prandtl number. These dependencies are formed so that in the limit under Re→0 they give Nu=2, which responds to the conductive heat exchange between little spherical particles and a hot gas flow.

The boundary layer theory gives the following formula for the conduction-convective heat exchange between a particle and a plasma flow:

\[ Nu = 2 + A \sqrt{Re} \sqrt{Pr} \]  

Where \( A \) is a semiempirical coefficient of convective heat exchange, which depends on the nature of the plasma jet flow and the streamline conditions of the particle.

Interaction between a group of particles and a plasma jet is expressed, mainly, in transmitting energy from plasma to particles. Particles are heated and accelerated into the plasma jet. The jet, giving energy is cooling and damping. We consider that screening of one layer by another doesn’t happen since particles are on a certain distance from one another and their boundary layers do not cover each other, so thus, we consider that the energy spent on heating and accelerating of particles is equal to the energy transmitted from the plasma jet to single particle multiply by the number of particles. We suppose that a group of particles appears at the outlet cross-section of the plasma torch immediately. The size and initial velocity are the same for all the particles. In other words we do not examine a problem of injection particles into the plasma jet. We consider that a little particle is heated evenly by all its volume like a good heat-conducting body i.e. a temperature in the center of the particle is equal to a temperature on its surface.

The method of calculation involves simultaneous by the following equations:

- Heating equation of a particle in high-temperature flow:

\[ \dot{n}_p \cdot C_p \cdot \frac{dT_p}{dt} = \frac{6 \cdot \dot{a}}{d_i} \cdot (T_p - T_s) - \frac{6 \cdot \dot{a}}{d_i} \cdot \dot{\theta} \cdot T_s^4; \]  

- Energy balance equation of a plasma jet loaded by the group of particles:

\[ \dot{n}_r \cdot C_p \left[ v_r \cdot \frac{\partial T_r}{\partial z} - v_r \cdot \frac{\partial T_r}{\partial r} \right] = \frac{\partial}{\partial z} \left( \rho_r \cdot \frac{\partial T_r}{\partial z} \right) + \frac{1}{r} \frac{\partial}{\partial r} \left( r \cdot \rho_r \cdot \frac{\partial T_r}{\partial r} \right) - U_{in} \cdot \frac{6 \cdot \dot{a}}{d_i} \cdot (T_p - T_s) \cdot n; \]  

(Sources \( \dot{a} \dot{\epsilon} \) is absent in plasma jet outside RF plasma torch)

- Motion equation of a particle in high-temperature flow:

\[ \]