Thin Solid Films 518 (2009) 952–956

Contents lists available at ScienceDirect

Thin Solid Films

journal homepage: www.elsevier.com/locate/tsf

Simulating effects of gas flow on arc plasma to anode heat transfer during incinerator ash treatment

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ARTICLE INFO

Available online 6 August 2009

Keywords:
Hollow cathode
Incineration ash
Simulation
Plasma

ABSTRACT

The conventional method for converting incineration ash to slag employs a plasma type furnace. An analysis of ash melting characteristics was undertaken by changing the inner shield N_2 gas flow rate, assuming a hollow cathode and the ash anode. Results show that heat input intensity characteristics on the ash depend strongly on the gas flow rate through the central hall of the tube cathode arc (TCA). The maximum temperature of the ash surface becomes about 3000–4000 K in a melting state. For a gas flow rate greater than 2 L/min, the shape of the heat input intensity on the ash is annular because of the gas flow. By adjustment of the inner shield gas flow rate, more practical melting of a wider area of the ash can be achieved with the intense annular heat input on the ash.

1. Introduction

In recent years, the quantity of urban garbage has become a severe problem, reaching approximately 50,000,000 t/year in Japan. Of all garbage there, 70% is incinerated, with the remaining incineration ash constituting 6,000,000 t/year. At present, the ash is landfilled in Japan. However, the disposal of incinerator ash in landfills is becoming increasingly more difficult. Therefore, a means to decrease the volume of incineration ash is necessary to use remaining landfills. One notable technique is conversion of incineration ash into slag, which has half the volume of incineration ash. Slag can also be used effectively as a recycled material [1]. The method for the production of slag by ash melting employs a plasma type furnace. A plasma type furnace has the advantage of easily reaching a high temperature, which is a highly controllable process compared to burning type furnaces. Plasma type furnaces also break down more than 99% of the dioxin generated by incineration. Although ash melting with a plasma type furnace is very effective, some problems exist. Few theoretical analyses of ideal ash melting furnaces have been made. Most data are dependent on experimental analysis. Therefore, the design of ash melting furnaces based on theoretical investigation is difficult.

Although a few reports describe simulations conducted for a plasma-type ash melting furnaces [2], these simulation models were incomplete. One factor that must be considered is the cathode shape of the plasma type furnace. Hollow-cathode type cathodes are used frequently in the incineration industry. However, many incineration ash simulation models reported to date have incorporated non-hollow cathodes.

As the first step for modeling of an ash melting furnace, analysis of the ash melting characteristics with the change in the shield gas was conducted assuming the use of a hollow cathode and the ash as anode. Actually, N_2 was selected as the shield gas because this gas is conventionally used; graphite was selected as the cathode material. For a comparative analysis of these conditions, investigations were also conducted using Ar as the shield gas.

2. Simulation model

The cathode, arc plasma, and the ash anode are described using a frame of cylindrical coordinates with axial symmetry around the arc axis. The calculated domain is presented in Fig. 1. Details of the cathode for a tube cathode arc (TCA) are presented in Fig. 2. The respective outer and inner diameters for TCA are 3.2 and 1.6 mm. The electrode gap is set to 10 mm, and the arc current to 100 A. The outer shield gas is introduced at a constant flow rate of 10 L/min from the outside of the cathode on the upper boundary. The inner shield gas at a flow rate of 1, 2, and 3 L/min is additionally introduced through the hole of the hollow cathode. The flow is assumed to be laminar, and the arc plasma is assumed to be under local thermal equilibrium (LTE). Other boundary conditions are presented in Table 1. The following assumptions were made. (1) LTE is adopted, meaning that all temperatures, such as electron and heavy particle temperatures, are equal. (2) An

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doi:10.1016/j.tsf.2009.07.165

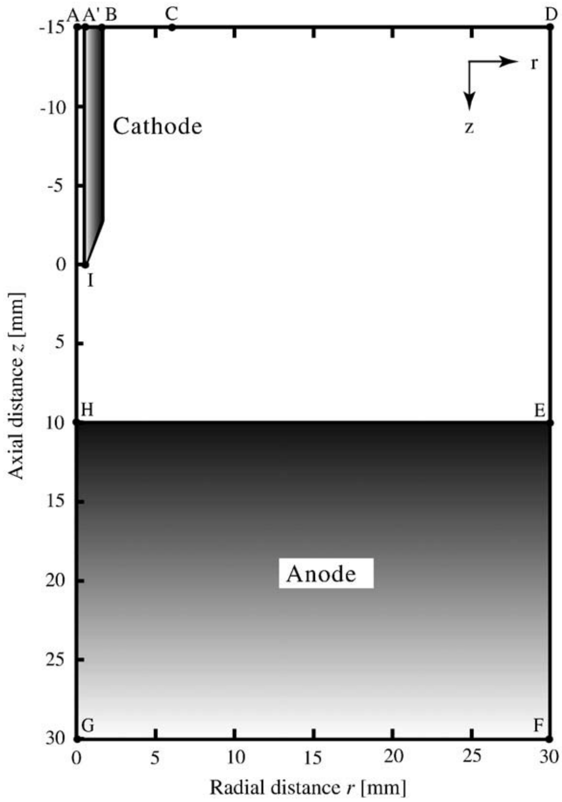

Fig. 1. Schematic illustration of the simulation domain.

optically thin assumption is used, whereby light absorption is neglected. This assumption might engender a plasma temperature lower than 20,000 K. (3) No vapor from the cathode or anode material is present. (4) The turbulence effect of gas flow is neglected.

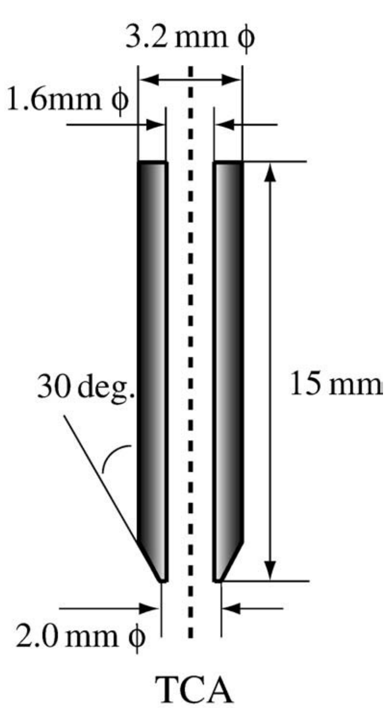

Fig. 2. Schematic illustration of TCA cathode.

Table 1
Simulation boundary conditions.

	T [K]	V [V]	v_z [m/s]	v_r [m/s]
A–A′ (inner inflow)	300	$dV/dz=0$	Inflow	0
A′–B (cathode top)	300	–	0	0
B–C (outer inflow)	300	$dV/dz=0$	Inflow	0
C–D (nozzle top)	300	$dV/dz=0$	0	0
D–E (outflow)	300	$(1/r)d(rV)/dr=0$	0	$(1/r)d(r\rho v_r)/dr=0$
E–F (anode side)	300	$(1/r)d(rV)/dr=0$	0	0
H–E (anode surface)	–	–	0	0
G–F (anode bottom)	300	0	0	0
G–A (axis)	$dT/dr=0$	$dV/dr=0$	$dv_z/dr=0$	0

In accordance with assumptions presented above, the steady plasma characteristics are simulated in the following two-dimensional model:

Mass conservation equation:

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

Momentum conservation equation (radial direction):

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r^2) + \frac{\partial}{\partial z}(\rho v_r v_z)\\ &\quad = -\frac{\partial P}{\partial r} - j_z B_\theta + \frac{1}{r}\frac{\partial}{\partial r}\left(2r\eta\frac{\partial v_r}{\partial r}\right) + \frac{\partial}{\partial z}\left(\eta\frac{\partial v_r}{\partial z} + \eta\frac{\partial v_z}{\partial r}\right) - 2\eta\frac{v_r}{r^2}\end{aligned} \tag{2}$$

Momentum conservation equation (axial direction):

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r v_z) + \frac{\partial}{\partial z}(\rho v_z^2)\\ &\quad = -\frac{\partial P}{\partial z} + j_r B_\theta + \frac{\partial}{\partial z}\left(2\eta\frac{\partial v_z}{\partial z}\right) + \frac{1}{r}\frac{\partial}{\partial r}\left(r\eta\frac{\partial v_r}{\partial z} + r\eta\frac{\partial v_z}{\partial r}\right) + \rho g\end{aligned} \tag{3}$$

Energy conservation equation:

$$\begin{aligned}&\frac{1}{r}\frac{\partial}{\partial r}(r\rho v_r h) + \frac{\partial}{\partial z}(\rho v_z h)\\ &\quad = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{r\kappa}{C_p}\frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial z}\left(\frac{\kappa}{C_p}\frac{\partial h}{\partial z}\right) + j_r E_r + j_z E_z - R\end{aligned} \tag{4}$$

Current continuity equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(r j_r) + \frac{\partial}{\partial z}(j_z) = 0 \tag{5}$$

Ohm's law:

$$j_r = -\sigma E_r, j_z = -\sigma E_z, \tag{6}$$

where z and r respectively represent the position coordinates for the axis and radial directions, T [K] is temperature, v [m/s] is velocity, P [Pa] is pressure, ρ [kg/m^3] is mass density, h [J/kg] is enthalpy, C_p [J/(kg K)] is specific heat, κ [W/(m K)] is thermal conductivity, σ [S/m] is electrical conductivity, η [Pa s] is viscosity, j [A/m^2] is current density, R [W/m^3] is the net radiative emission coefficient from plasma, and E_r and E_z respectively signify the radial and axial components of the electric field intensity defined as $E_r = -dV/dr$ and $E_z = -dV/dz$, where V [V] is the electric potential. The azimuthal magnetic flux density B_θ [Wb/m^2] induced by the arc current is evaluated using the following Maxwell equation:

$$\frac{1}{r}\frac{\partial}{\partial r}(rB_\theta) = \mu_0 j_z, \tag{7}$$