A Model for Ultrafine Powder Production in a Plasma Reactor

Pierre Proulx1 and Jean-François Bilodeau1

Received April 9, 1990; revised November 29, 1990

A model is proposed for the analysis of the production of ultrafine particles in thermal plasma reactors. The model initially solves the fluid flow, temperature, and concentration fields using a classical control volume approach. The nucleation and growth of ultrafine particles are then solved along each streamline. The evolution of the particle distribution is described by a statistical approach, using the first moments of the distribution as the dependent variables. Brownian coalescence is considered in the free molecular regime. In the discussion, the model is used to demonstrate the effects of some important parameters, such as the initial concentration of metal vapor, its radial distribution, and the radial injection of a cooling gas, on the particle size distribution.

KEY WORDS: Plasmas; aerosol; modelling; growth; reactor.

1. INTRODUCTION

In the theoretical analysis of ultrafine powder production in an induction plasma reactor, many distinct physical phenomena have to be considered. Firstly, the plasma flow, concentration, and temperature fields have to be determined, coupled to Maxwell's electromagnetic equations. Boulos, Mostaghimi, and Proulx11--31 have given considerable attention to this aspect in the last few years. Secondly, if small particles are to be evaporated in the plasma prior to recondensation, one has to calculate the particle trajectories and thermal histories, and to include the plasma-particle interaction. References 4 and 5 have dealt with such considerations. Lastly, the formation of nuclei and the subsequent aerosol growth have to be considered and have been the subject of two recent papers by Girshick et al.6,7

1 Centre de Recherche en Technologie des Plasmas (CRTP), Département de Génie Chimique, Faculté des Sciences Appliquées, Université de Sherbrooke, Canada J1K-2R1.
In the present paper, an integrated approach is proposed to include the aspects of nucleation and growth in a fluid dynamical model of the plasma reactor. The model is applied to the zone of the plasma reactor where nucleation and growth occurs, i.e., well below the hot plasma core when the gas temperatures have dropped below 3000 K.

2. THE MODEL

2.1. Flow, Temperature, and Concentration Fields of the Reactor

The zone of the plasma reactor where we will focus our attention, which is the actual zone where ultrafine particles (UFP) form, is well below the actual plasma flame, where the gases have cooled considerably and the vapors can supersaturate and condense. Since in this work we concentrate on the nucleation and growth of iron vapor, the plasma flame itself is not included in the analysis. Figure 1 shows the region considered in the model.

The following assumptions are used to write the equations describing the fluid dynamics and heat transfer of the reactor:

—Steady, laminar, axisymmetric flow
—No effect of the ultrafine particles on the flow and temperature fields

The fluid dynamics and heat and mass transfer are then determined by the solution of the continuity, momentum, energy, and species mass conservation equations:

\[ \nabla \cdot (\rho \mathbf{u}) = 0 \]  
\[ \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{u}) \]  
\[ \nabla \cdot (\rho \mathbf{u} C_p T) = \nabla \cdot (k \nabla T) \]  
\[ \nabla \cdot (\rho \mathbf{u} \omega_A) = \nabla \cdot (\rho D_{AB} \mathbf{u} \omega_A) \]

where \( u \) is the velocity, \( P \) the pressure, \( \mu \) the viscosity, \( k \) the thermal conductivity, \( C_p \) the specific heat, \( T \) the temperature, \( D_{AB} \) the diffusivity, and \( \omega_A \) the mass fraction of species A.