Dynamics of porous aerosol particles under thermal gradients

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Porous aerosol particles are very common in many practical applications (as material processing) and environmental problems (as particulate emissions from combustion). On the other hand, larger aggregates can be modelled as pseudo-porous particles. The dynamics of these particles is affected by the flow penetrating through the particle which modifies the gas streamlines and the viscous stresses on the particle surface. In a recent paper (Garcia-Ybarra et al., 2006), a theoretical analysis provided a general framework for solving the velocity field in the gas and the penetration flow inside the particle. The matching of both flow fields at the particle outer surface allows to determine the viscous drag on the porous aerosol particle.

Moreover, aerosol particles under strong temperature gradients are driven by thermophoresis (Rosner et al., 1992) that pushes the aerosol toward the cooler gas regions. Here, a previous work (Perea et al., 2005) is extended to describe the dynamics of a porous aerosol particle under thermal gradients.

In the outer gas, the Stokes equation relates the velocity field ($\mathbf{v}$) and the pressure distribution ($p$)

$$\nabla p = \mu \nabla^2 \mathbf{v}
$$

where $\mu$ is the dynamic viscosity. Inside the particle, a modified Brinkmann equation holds

$$\frac{\mu}{\chi} (\mathbf{v} - \mathbf{v}_{trans}) = \mu \nabla^2 \mathbf{v} - \nabla p$$

$\chi$ is the permeability of the porous aerosol particle and $\mathbf{v}_{trans}$ is the transpiration velocity induced by the gas thermal slip at the walls of the pores

$$\mathbf{v}_{trans} = \frac{1 - \phi}{6\tau} C_S \frac{\mu}{\rho T_0} \nabla T$$

$\phi$ is the solid fraction, $\tau$ the tortuosity, $C_S$ the slip coefficient, $\rho$ the gas density, and $T_0$ the mean particle temperature. These equations are solved together with the equations for the temperature field in both (gas and porous) media and imposing the appropriate boundary conditions.

At the particle surface, the normal component of the velocity should be continuous, but there is a slip in the tangential velocity ($\mathbf{v}_t$), such that

$$v^\text{gas}_t = v^\text{porous}_t + C_S \phi \frac{\mu}{\rho T_0} \nabla S T ; \text{ at } r=R$$

where $V_S$ stands for the surface gradient.

The forces acting on the aerosol particle are the drag (proportional to the aerosol velocity relative to the gas) and the thermophoretic force (proportional to the temperature gradient, $VT$). The balance between both forces provides the value of the particle thermophoretic velocity, which can be written as

$$\mathbf{v}_T = -\alpha v \frac{VT}{T}$$

Where $\alpha$ is the thermophoretic strength factor for a solid particle of the same size, $v$ the gas kinematic viscosity ($v=\mu/\rho$) and $\varepsilon$ the thermophoretic strength correction due to the particle porosity.

The thermophoretic strength factor $\alpha$ depends on the particle-gas interactions (Garcia-Ybarra & Castillo, 1997). In the studied limit, $\alpha$ is given by

$$\alpha = 2 C_S \frac{\lambda}{\lambda + 2 \lambda_p}$$

Here, $\lambda$ and $\lambda_p$ are the gas and particle thermal conductivity, respectively. Moreover, the thermophoretic strength correction due to the aerosol porosity results

$$\varepsilon = \frac{1 - \phi}{4\tau} + \frac{1 - 3k \tanh(1/k)}{1 - k \tanh(1/k)}$$

with the permeability parameter

$$k = \chi^{1/2} / R$$

$k$ provides a dimensionless measurement of the aerosol permeability. As expected, $\varepsilon$ tends to one for low porosity particles (in the limit $\phi \rightarrow 1, \ k \rightarrow 0$).

The first term in $\varepsilon$ (proportional to the void fraction, $1-\phi$) comes from the transpiration flow through the particle, whereas the second term accounts for the reduction of the thermal slip due to the existence of pores at the particle surface.

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