Solid–Fluid Systems with Large Specific Interfacial Area

The *interfacial* heat transfer rate for a solid–fluid system with an interfacial area $A_{sf}$ and a local (varying over the surface) surface-convection heat flux $q_{sf} = q_{ku}$ is

$$Q_{sf} = Q_{ku} = A_{sf} q_{sf} D. \quad (5.1)$$

Using the *specific interfacial area* $A_o$ (i.e., the solid–fluid interfacial area per unit volume $V$ of the combined solid and fluid phases), this can be written as

$$\frac{Q_{sf}}{V} = \frac{A_{sf}}{V} q_{sf} D = A_o q_{sf} D. \quad (5.2)$$

For a solid–fluid system with a *fluid volume fraction* $\epsilon$ (i.e., porosity) and for spherical solid particles of diameter $D$, the specific surface area is

$$A_o = \frac{6(1 - \epsilon)}{D}. \quad (5.3)$$

Then as $D$ decreases the specific surface area increases and, for example, for $\epsilon = 0.5$, the specific surface area $A_o$ for particles of $D = 10^2 \mu m$ is $3 \times 10^4 \text{ m}^2/\text{m}^3$, which is rather large. This *large* specific interfacial area of dispersed systems has been used for applications requiring large interfacial heat transfer rates $Q_{sf}$.

The interfacial heat flux $q_{sf}$ depends on the *interphasic* (solid and fluid) heat transfer which is in turn influenced by the fluid- and solid-phase *motions* and their thermophysical properties and on the interparticle convective interactions which itself in turn depends on the average *interparticle clearance distance* $C$. Figure 5.1 shows two elements of a dispersed, solid phase in a flowing, continuous fluid phase. The elements are rendered in a simple geometry with a linear dimension $D$. The average interelemental distance $C$ can be very small (e.g., packed beds) or very large (e.g., dilute suspensions). The solid–fluid interface, where the main heat transfer occurs, can change due to *phase change* (sublimation of solid or condensation (i.e., crystallization) or frosting of gas or melting or solidification). There can be *chemical reactions* occurring on the solid surface and/or in the fluid phase. Here the intrasolid reactions are not addressed by assuming impermeable, internally inert solids. The solid elements can be transparent, semitransparent, or opaque, and the radiation heat transfer in both the solid and fluid phases can be significant.

In this chapter we begin by discussing interfacial convective heat transfer in solid–fluid systems with the solid phase dispersed as elements in a

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continuouss fluid phase. We begin by considering the heat transfer from isolated elements and then address the effect of the interelemental interactions on the interfacial convective heat transfer. Then the case of a continuous stationary solid phase made of the same elements will be considered. This is the thermal nonequilibrium treatment of heat transfer in porous media. Next the more complex case of transport in moving dispersed elements will be examined. This is the thermal nonequilibrium treatment of heat transfer in particulate flows.

5.1 Isolated Dispersed-Phase Elements

The geometry of a dispersed element, in practice, can be complex, and an element may yet be an aggregate of simple elements. Here we refer to an element as the most basic, impermeable solid body which is treatable both by using the continuum treatment and by applying well-defined boundary conditions for its interface with the surrounding continuous fluid. One of the elements most studied for convective heat transfer is the impermeable spherical particle and its two-dimensional counterpart which is the impermeable cylinder. For a steady flow and heat transfer, the convective interfacial heat transfer from these elements has been examined subject to a constant interfacial surface temperature (and in some cases a constant interfacial heat flux). The flow inertia, in fluid flow around an isolated element, and its interaction with the viscous forces and the pressure distribu-