Monte Carlo Simulation of Radiant Transport Through an Adiabatic Packed Bed or Porous Solid

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Radiant transport in packed beds or porous solids has been examined by a number of investigators (e.g., Chen and Churchill, 1963; Chan and Tien, 1974). However, there appears to be no published work enabling the prediction of the radiant flux transmitted through a bed or porous solid as a function of readily measurable geometric properties such as void fraction or pore size distribution.

Evans et al. (1980) have recently carried out a Monte Carlo simulation of the Knudsen diffusion of a gas within a porous solid. Porous solids were represented, on a computer, as assemblages of spheres of various size distributions, in some cases with a pseudo-random arrangement of the spheres in space and with overlap of spheres. The trajectories of individual gas molecules diffusing through the solid were computed and after a sufficiently large number of trajectory calculations, the Knudsen diffusivity could be related to observable characteristics of the solid such as porosity and mean pore size.

The purpose of this note is to show how these computations can be exploited to yield effective view factors for the transmission of radiation through porous solids or packed beds. The approach is valid only to the extent that there is equivalence between gas molecule behavior in the Knudsen diffusion and photon behavior in the case of radiant transport. This imposes the following restrictions:

(i) The pore size or bed interstices should be sufficiently small that they can be considered optically thin yet much larger than the wavelength of the radiation.

(ii) The pore walls or packing surface must be diffuse surfaces so that reflected or emitted photons leave at random angles to the normal with a cosine probability distribution.

(iii) The pore walls or packing surface must be adiabatic surfaces. [It should be noted that this assumption does *not* imply that the surfaces are perfectly reflecting. A simple heat balance reveals that the assumption is valid for poorly conducting solids, at steady state in the absence of heat sinks (such as chemical reaction).]

(iv) The porous solid is large compared to the pores (or the packed bed large compared to the packing).

While these restrictions impair the generality of the results presented here, it is believed that in a large number of cases, radiant transmission through a poorly conducting solid will satisfy these conditions.

Consider a porous plug, or packed bed, thickness L separating a source of radiation from a perfect sink (Figure 1). The fraction of photons incident on the source side of the plug that are transmitted through to the sink is plotted, as a function of L, for one of the simpler arrangements of spheres in Figure 2. The fraction transmitted is seen to be inversely proportional to plug thicknesses. The slopes of the lines in Figure 2 and in similar plots for more complex solids allow the equation

$$\frac{f_T L}{\bar{d}} = 0.0496 + 0.5333\epsilon - 0.09653\frac{\sigma}{\bar{d}} \tag{1}$$

to be obtained as a best straight line relating the fraction transmitted, f_T, to the plug thickness, the mean pore size, $\bar{d}$, and the standard deviation of pore size, σ. The last two quantities were obtained from the pore wall-pore wall trajectory distances stored during the computation. Figure 3, based on Eq. 1, shows the ability of this equation to fit the "data" from the trajectory calculations

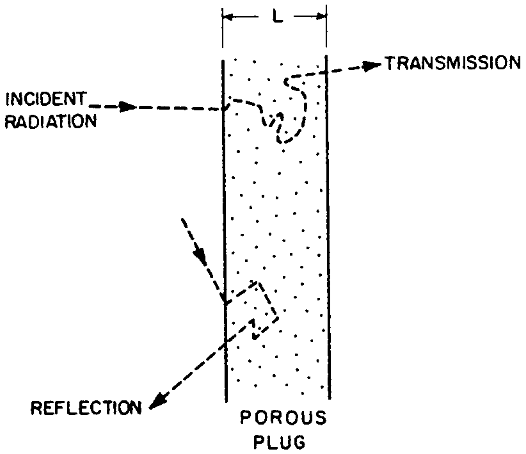
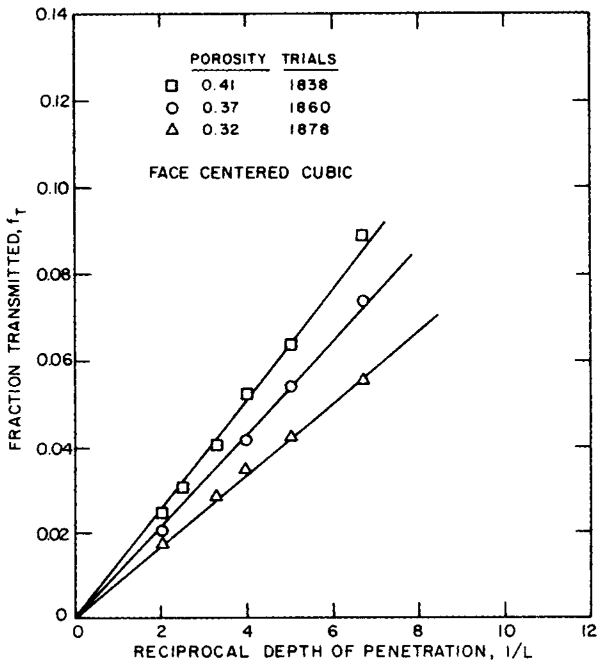


Figure 1. A porous plus (or packed bed) separating a source of radiation from a sink and possible trajectories of incident radiation.



2. Fraction of photons transmitted through the plug as a function of plug thickness.

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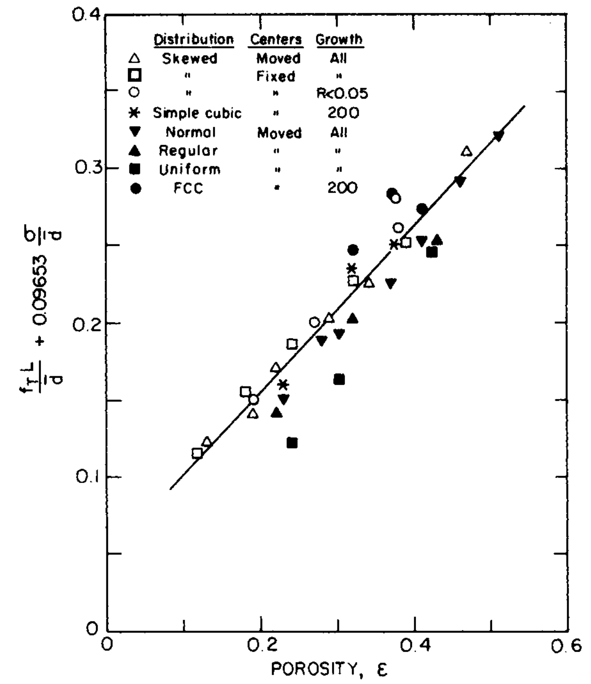

3. Correlation of "data" from the Monte Carlo simulations with the porosity, pore size and standard deviation of pore size for several solids.

performed on each of several solids. The reader is referred to Evans et al. (1980) for a more detailed description of each solid.

The inverse proportionality between fraction transmitted and L, apparent in Figure 2 [and in similar figures for other solids in Evans et al (1980)] enables an approximate calculation of the solid temperature profile in the bed or porous solid. Consider a plane within the slab of solid (or bed) that is parallel to the faces of the solid and a distance x from the face on which a radiant flux Q_{In} is incident. A flux Q_F passes through this plane in the forward direction (increasing x) while a flux Q_B passes in the backward direction. When there is no radiation incident on the face at $x = L$ then

$$Q_F = Q_{In} f_T(x) + Q_B\,(1 - f_T\,(x)) \tag{2}$$

$$Q_B = Q_F\,[1 - f_T\,(L - x)] \tag{3}$$

or rearranging

$$Q_F = \frac{Q_{In} f_T(x)}{[1 - (1 - f_T\,(L - x))\,(1 - f_T\,(x))]} \tag{4}$$

If attention is restricted to values of x that are neither close to zero, nor close to L, to a first approximation,

$$Q_B = Q_F \tag{5}$$

and

$$Q_F = \frac{Q_{In} f_T\,(x)}{[f_T\,(x) + f_T\,(L - x)]} \tag{6}$$

Exploiting the inverse proportionality for f_T

$$Q_F = \frac{Q_{In}}{L}\,(L - x) \tag{7}$$

Equation 5 suggests isotropy of the radiant fluxes and the irradiation, H, of the pore walls (or packing surface) is therefore given by

$$H = \frac{Q_{In}}{L\epsilon}\,(L - x) \tag{8}$$

where ϵ is the porosity or void fraction. Finally, recognizing that for a gray adiabatic surface

$$\sigma_s T^4 = H \tag{9}$$

the following equation results:

$$T = \left[\frac{Q_{In}\,(L - x)}{\sigma_s L \epsilon}\right]^{1/4} \tag{10}$$

It should be stressed that this equation is applicable only to those regions of the solid (bed) that are not adjacent to the outside, i.e., to the regions which can be regarded as separated from the outside by a continuum.

NOTATION

$\bar{d}$ = mean pore size
f_T = franction of photons transmitted through the porous plug or packed bed
H = irradiation of the packing surface
L = porous plug or packed bed thickness
Q_B, Q_F = radiant flux in backward and forward direction respectively
Q_{In} = incident radiant flux
T = temperature of the solid or bed packing
x = distance into the porous solid

Greek Symbols

ϵ = void fraction or porosity
σ = standard deviation of pore size
σ_s = Stefan-Boltzman constant

LITERATURE CITED

Chan, C. K., and C. L. Tien, "Radiative transfer in packed spheres," *Transactions of the ASME*, 52 (Feb., 1974).
Chen, J. C., and S. W. Churchill, "Radiative heat transfer in packed beds," *AIChE J.*, 9(1), 35 (1963).
Evans, J. W., M. H. Abbasi, and A. Sarin, "A Monte Carlo Simulation of the diffusion of gases in porous solids." *J. Chem. Phys.*, 72(5), 2967 (1980).

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