Heat Transfer in Porous Media With Known Pore Structure (Alundum)

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The effective thermal conductivity of synthetic porous materials (sintered Alundum) was measured with the pore volume filled with air or nitrogen. Data were obtained from 14.7 to 2 × 10^{-3} p.s.i.a. This pressure range of gas extended through the region of free-molecule conduction so that the conductivity of the solid could be obtained by extrapolation. Permeability and pore size distribution measurements were also made for the four samples. The pore size range was rather narrow and symmetrical with peak values (diameters of equivalent circular pores) from 21 to 420 microns.

EXPERIMENTAL STUDIES of heat transfer rates in beds of fine particles have been reported by numerous investigators (*1, 3, 4, 8, 10, 13*). The results often include vacuum measurements as well as those for the void volume filled with stagnant gases and liquids. Similar data for consolidated porous media are meager; the only information published is for naturally occurring materials such as limestone samples (*1, 5, 11, 12*). Progress on the theory of heat transfer in porous media has been sufficient to predict the effect of pressure (*8*) and the effects of solid and fluid thermal conductivities (*1, 3, 8, 12*). However, it has not been possible to predict absolute values for the effective thermal conductivity, k_e, because of uncertainties concerning the heat transfer through the solid path in the media. In unconsolidated beds the problem is one of contact resistance and area between adjacent particles. In consolidated materials, the effective area for heat transfer in the solid phase is not yet predictable. As a result, the several quantitative procedures for estimating k_e involve one or more unknown parameters which depend upon the porous material. In consolidated media, part of the difficulty appears to be due to the random distribution of pore sizes and shapes, and uncertainties in chemical composition of the solid phase, that exist in such naturally occurring substances as limestone. The purpose of this present work was to provide carefully taken data wherein these disadvantages were eliminated as much as possible. Such information should be valuable in the development of a more complete quantitative explanation of heat transfer in porous media.

Measurements were made for synthetic samples of porous Alundum. The data obtained included pore size analysis, to verify the narrow pore size range, and permeabilities, as well as k_e values. Alundum is made of electrically fused alumina grains bonded together with an aluminous glass, which results from the high firing temperature (*9*). Optical examination of the structure shows the individual grains to be uniform in shape and size and to be covered with a vitreous coating. Hence the individual grains are not porous, in contrast to alumina used as a catalyst or catalyst carrier. A characteristic of these materials is their homogeneity. Typical chemical analysis is as follows:

	Wt. %.
Al_2O_3	82.0
SiO_2	13.0
Fe_2O_3	1.0
MgO	0.5
CaO	0.8
TiO_2	2.5
Na_2O	0.2

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EXPERIMENTAL

Measurements were made on four samples of Alundum with mean pore diameters from 21 to 420 microns. The pores were filled with dry air or nitrogen and data obtained at pressures from 2.1 × 10^{-3} to 14.7 p.s.i.a. The permeability data were taken with nitrogen at 21° C., and atmospheric pressure on the downstream side of the sample.

The complete heat transfer apparatus is shown in Figure 1 and the details of the test section in Figure 2. A radial flow of heat through the sample of Alundum is obtained by an electric heater, 22 gage nichrome wire wound on a procelain rod and inserted in a ⅝-inch copper tube, inserted along the axis of the sample. The energy is absorbed in a jacket through which cooling water flows, as shown in Figure 2. The samples were cylinders 3-inches long, 2 3/16-inches outside diameter, and with a ¾-inch hole drilled in the center.

The method of evaluating k_e requires negligible transfer of the electrical energy in the axial direction. To approach this condition, the Alundum sample in which temperature measurements were made was placed between two like specimens. The samples were sealed into the steel sections with sauereisen cement. To avoid the penetration of sauereisen into the pores of the Alundum, the lateral suface of the samples were first sealed with a thin coat of epoxy resin. Tests indicated no leakage of gas between the sample and the steel tubes.

The total energy input was measured with a Weston Wattmeter (Model 310) and this quantity varied from 20

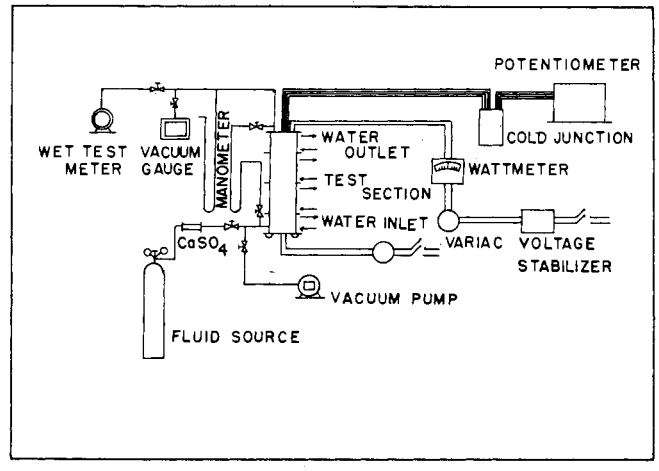

Figure 1. Experimental heat transfer apparatus

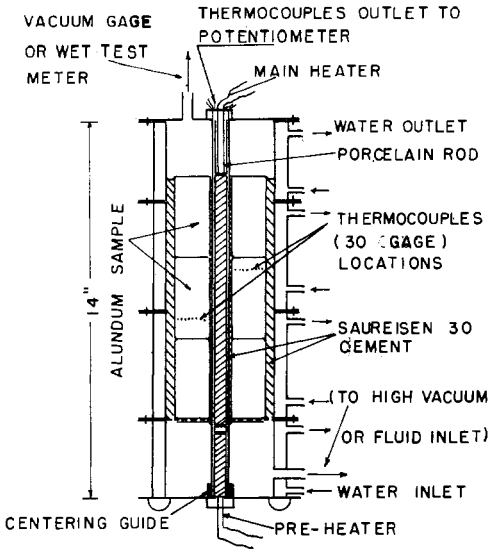

Figure 2. Test section detail

to 50 watts. The energy rate to the central sample of Alundum was determined from the fraction of the electrical resistance in this section of the heater. A voltage stabilizer was used in the power line to maintain a constant input to the heater.

The supposition of no axial heat flow was evaluated by measuring temperature distributions across the center sample at two axial positions as shown in Figure 2. Copper-constantan thermocouples of 30 gage wire were first calibrated at the boiling and freezing points of water. These couples were then inserted at various radial positions in holes drilled around the sample. The holes were made with a number 54 drill, and the void spaces filled with epoxy resin. The radial penetration of the thermocouples into the sample was measured prior to sealing with resin. Seven thermocouples were installed at each axial position. It was necessary to install a separate preheater at the fluid inlet in order to prevent axial heat transfer to the entering fluid. The preheater was wound around the same porcelain rod as the main heater (see Figure 2) but could be separately controlled. With this arrangement, it was possible to eliminate measurable axial temperature gradients in the center sample of alundum. This is illustrated in Figure 5 where the radial temperature distributions at the two axial positions are plotted.

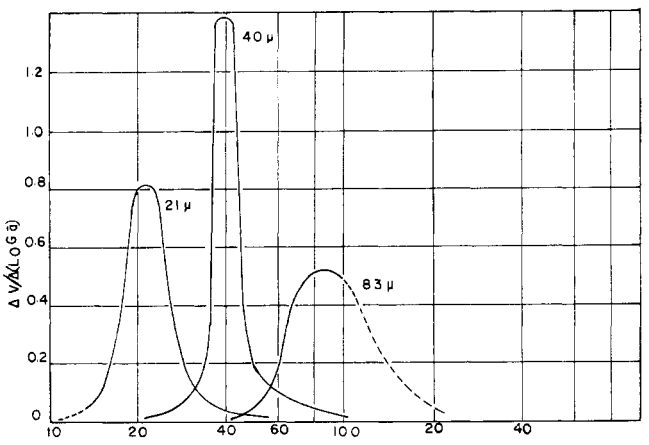

Figure 3. Pore size distribution for Alundum sample

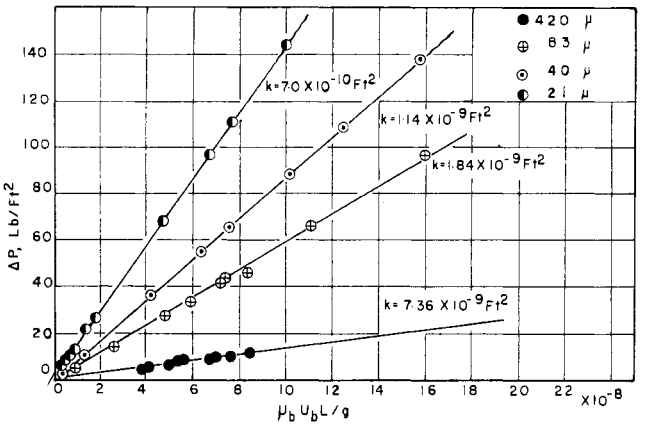

Figure 4. Permeability of Alundum samples
(Nitrogen at 21° C.)

The pore size distributions and porosities were measured in an Aminco-Winslow porosimeter by mercury penetration. The results, shown in Figure 3, indicate both narrow and symmetrical distribution curves. Hence, the mean pore diameter (based upon cylindrical pores) was the same as the peak value, although the nominal values were higher than the measured results (see Table I). It was not possible to test the sample with the largest pores (550-micron nominal size) in the porosimeter because of the low pressures required. The mean diameter was estimated to be 420 microns for this sample in the following manner. From the data for the three other samples, a curve was prepared of mean pore diameter determined from the porosimeter *vs.* the equivalent particle diameter calculated from the permeability using the Kozeny-Carman equation (2). This curve was extrapolated to the equivalent particle size of the 550 micron sample, at which point the porosimeter value was estimated to be 420 microns.

The same apparatus as shown in Figure 1 was used to determine the permeabilities with nitrogen at atmospheric pressure. The permeability curves are given in Figure 4. The measured properties of the samples are summarized in Table I.

Table I. Properties of Alundum Samples

Pore Diameter, microns			Permeability, k	
Nominal	Peak (mean) value	Porosity, ϵ	sq. ft. × 10^9	Darcys
550	420	0.421	7.36	694
124	83	0.396	1.84	174
64	40	0.385	1.14	107
25	21	0.380	0.70	66

Thermal conductivity of solid Alundum (9) at 25° C. = 9.6 B.t.u./(hr.)(ft.)(° F.)

RESULTS AND DISCUSSION

If the effective thermal conductivity of the sample is assumed to be independent of temperature, it can be calculated from the expression

$$k_e = -\frac{Q}{2\pi L}\frac{d(\ln r)}{dt} \qquad (1)$$

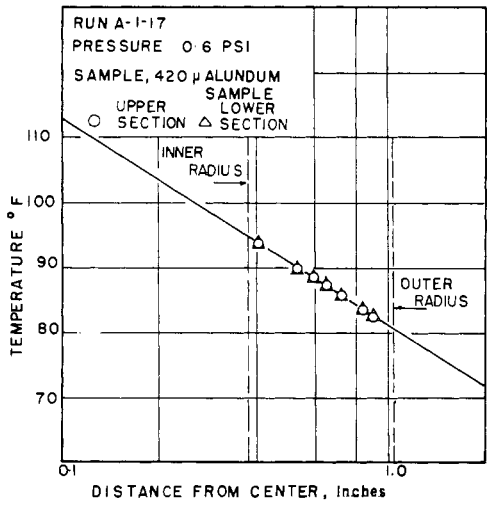

Figure 5. Typical temperature profile data

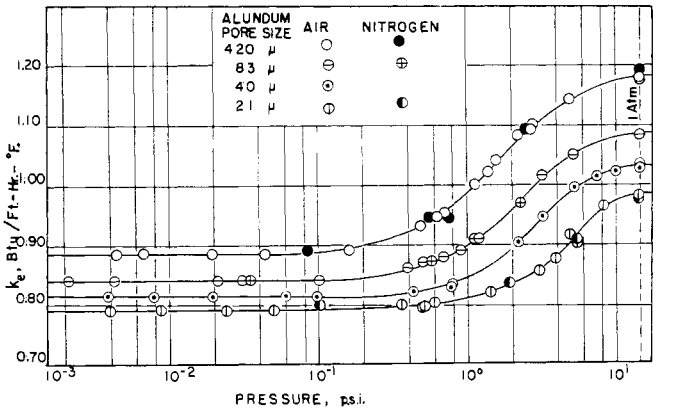

Figure 6. Effect of pressure on stagnant conductivities

The maximum temperature change across the radius of the sample was about 20° F. Hence in using Equation 1 it is assumed that k_e is constant over a temperature change of 20° F. or less. The temperature gradient was evaluated from straight lines through the temperature data as illustrated in Figure 5.

The results are shown in Figure 6 where the values of k_e are plotted *vs.* the absolute pressure. The S-shape curves indicate that free-molecule conduction is important in the pressure range 10^{-1} to 10 p.s.i.a. The flattening of the curves at one atmosphere shows that the heat is transferred in the gas spaces by molecular collisions (normal thermal conductivity) at this pressure. The horizontal nature of the curves at pressures below 0.1 p.s.i.a. indicates that at these pressures the heat transfer is predominantly via the solid in the Alundum samples. The values of k_e at these log pressures is a measure of this solid-path conductivity. There is a small, but definite, increase in thermal conductivity with pore size. An increase of similar magnitude was noted by Willhite (*13*) in unconsolidated beds of spherical glass beads; that is, the effective conductivity increased 10 to 15% as the diameter of the bead increased 10 to 20 fold. Since the average size of the void space increases with particle diameter in beds of spherical particles, the two phenomena are similar. No explanation has yet been advanced to explain this increase either for beds of unconsolidated particles or for consolidated porous media.

Statistical analysis was used to predict the solid path conductivity in consolidated media. This is one of the most difficult parts of the usual gas, solid, and series model (*6, 7, 12*) commonly used to develop a theory for heat transfer in porous media. The end result of this development is a prediction method which involves one arbitrary constant. This method correlates the Alundum data reported here and most other available information somewhat better than other methods (*1, 3, 12*). However, since arbitrary constants are still involved it is not worthwhile to add this procedure, in its present state, to the other similar prediction procedures. Its chief value lies in the application of statistics to predict the solid phase geometry. This might serve as a useful starting point in developing less arbitrary, and hence more widely applicable, correlations of heat transfer in porous media.

ACKNOWLEDGMENT

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NOMENCLATURE

- a = pore diameter, microns; $\bar{a}$ = volume mean diameter
- g_c = conversion factor, 32.2 lb. mass (ft.)/(sec.^{2})(lb. force)
- k = permeability, sq. ft.; defined by equation $k = (u_b \mu_b L)/(\Delta p\, g)$
- k_e = effective thermal conductivity, B.t.u./(hr.)(ft.)(° F.)
- L = length of sample corresponding to measured energy input, ft.
- Δp = pressure drop across length L of samples, lb. force/sq. ft.
- Q = energy input to sample, B.t.u./hr.
- r = radial distance from central axis of sample, ft.
- t = temperature, ° F.
- u_b = mean bulk velocity of nitrogen in samples, ft./sec. (for permeability tests).
- V = pore volume per gram of Alundum sample, cc./g.;
- ΔV = volume in pores from diameter a to $a + \Delta a$.
- ϵ = porosity of sample
- μ_b = viscosity of nitrogen for permeability tests, lb. mass/sec. ft.

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