Density, Pressure, and Temperature Effects on Heat Transfer in Apollo 11 Fines

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The thermal conductivity of the Apollo 11 lunar fines is presented as a function of temperature for three values of bulk density corresponding to lightly disturbed, normal surface condition, and packed. The thermal conductivity is also presented as a function of ambient pressure at conditions of normal density and standard temperature. The thermal diffusivity is calculated over the same range of parameters. Average values of the conductivity, diffusivity, and thermal parameter are also presented.

Introduction

A STUDY of energy transfer on the moon, either within the moon or on engineering systems there, requires a complete knowledge of the thermophysical properties of the lunar surface layer. These include both radiative properties of the surface itself as well as the transport properties of the bulk medium.

Previous investigators have determined some of the properties of engineering interest for the Apollo 11 and 12 rocks and fines. Birkebak et al.[1,2] and Hapke et al.[3,4] report measurements of some of the radiation properties of the Apollo 11 and 12 rocks and fines. Robie et al.[5,6] have measured the specific heats of similar samples of rocks and fines, whereas Horai and co-workers[7,8] have measured thermal conductivities and diffusivities of lunar rocks. Cremers and co-workers[9–11] have made some previous measurements of the thermal conductivity of the Apollo 11 and 12 fines at two different densities.

There have also been several pertinent studies of the thermal conductivity for postulated lunar materials. Wechsler and Glaser[12] did a comprehensive search of the literature in regard to the thermal conductivity of powdered minerals whose composition was expected to be close to that of the lunar fines. They also reported a series of their own measurements at several temperatures both under vacuum and at higher pressures. Fountain and West[13] reported the results of measurements of the thermal conductivity of powdered terrestrial basalt as a function of both density and temperature. Measurements were made both under vacuum and under a CO_2 atmosphere.

The measurements reported in the present paper are for the Apollo 11 fines only. If one is concerned with energy transfer on the surface of the moon, either in the surface layer or engineering systems there, then the rocks are not of much importance. The moon, at least in the mare regions so far visited, is covered to a depth of several meters or more with the fine material. Rocks are present but only randomly, and they represent more or less of a perturbation of the fine particulate nature of the surface layer. Consequently, energy transfer there depends for the most part on the properties of the fines.

This paper presents the thermal conductivity as a function of temperature over the approximate range of lunar diurnal temperatures. Densities used correspond to the lowest value attainable under earth gravity, the density corresponding to the Apollo 11 core tube sample, and the highest attainable density. The results are compared with data for terrestrial basalt from the literature. The thermal diffusivity is calculated as a function of temperature for these conductivities and densities using the temperature-dependent specific heat reported by Robie et al.[5] Measurements of the thermal conductivity as a function of atmospheric pressure are also presented and compared with values in the literature, again for basalt. Integrated average values of the thermal conductivity, thermal diffusivity, and thermal parameter, as well as values calculated at the average lunar surface-layer temperature, are presented for use in constant property calculations.

Experiment

The measurement of the thermal conductivity of a particulate medium such as the lunar fines is not straightforward. Any porous material with an internal temperature gradient will transfer heat through a complicated interaction between solid conduction through the particles and their contact surfaces plus radiation which can be scattered in the voids and transmitted or absorbed and re-emitted by the solid material. Under lunar conditions, of course, there is no problem caused by gaseous conduction or convection because of the extremely low pressures on the order of 10^{-12} torr.

One has, then, a heat-transfer problem involving conduction and radiation. If the heat flux is to be considered as an entity, rather than as a two-component flux, then Fourier's law may be used provided that it is recognized that the thermal conductivity so defined is only an effective one rather than a basic property of the material. Elementary theory[14,15] shows that such an effective conductivity of a particulate medium can be represented by the sum of a constant term, representing solid conduction, plus a term proportional to temperature cubed, representing radiation. An experiment to measure the thermal conductivity of the lunar fines must provide a low pressure to suppress gaseous effects, and provision must also be made for ambient temperature control in order to determine the thermal conductivity over the range of lunar temperatures.

Figure 1 shows the test system. The vacuum chamber is pumped to below 10^{-6} torr to provide the pressure environment. An inner chamber with a double wall provides the temperature environment as it can be heated electrically or cooled by circulating liquid nitrogen or boiling freon between the walls. The sample is held in an open cell in the center.

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There are many methods that have been developed to measure the thermal conductivity of a solid substance. A limited number of these are applicable to powdered low-conductivity materials, and just a few of the latter techniques are usable with only small amounts of material to be tested. Sample size was an important consideration in planning the experiment because only a few grams of lunar fines were to be made available, and, using expected densities, this meant only about 2 cm^3 of material. After a great deal of experimenting, it was decided that the line heat-source technique was the best available method. The theoretical treatment of the method is given by Carslaw and Jaeger,[16] and the errors involved in its application are given by Blackwell.[17] The method and its variations have been used previously to determine the thermal conductivities of powdered rocks under vacuum[12,13] and also of other poor conductors.[18]

The mathematical model for the line heat source is an infinitely long constant line heat source imbedded in a homogeneous medium of infinite extent. Solution of the time-dependent differential energy equation for this model, with the initial condition that the medium is at uniform temperature when the heating begins, yields the temperature in the medium as a function of position and time. The solution is in terms of the first-order exponential integral of the inverse Fourier number ($r^2/4\alpha t$) multiplied by a constant that includes the heat-source strength and thermal conductivity; r is the distance from the heat source, α is the thermal diffusivity, and t is time after onset of heating. The integral can be expressed as an infinite series, which is then truncated for the case of small r or large time. This, then, yields the working equation for the method that gives the temperature rise ($T_2 - T_1$) at some point in the medium as a function of the time ratio t_2/t_1, that is,

$$T_2 - T_1 = (q/4\pi k)\ln(t_2/t_1) \tag{1}$$

Here q is the heat source strength and k is the thermal conductivity. Application of Eq. (1) simply requires measurement of $T(t)$ for a given q; k can then be directly calculated. At short times ($r^2/4\alpha t > 0.034$), Eq. (1) does not apply, and at significantly longer times, the errors caused by finite sample size destroy the model.

Normally, the temperature rise is measured with a sensor implanted somewhere in the sample away from the heat source. However, because of the limited sample size in the present case, this approach was not feasible. Rather, the heat source itself, a 32 AWG Nichrome V wire (0.2032 mm diam), was calibrated as a resistance thermometer. Then, with the wire in place in the sample, the voltage change over about 22 mm of the wire was monitored during heating, along with the voltage itself and the current flow. The current through the wire was controlled by a constant-current power supply that provided a current constant to within four significant figures. The voltage change during a run, because of wire resistance change, was 0.25% at the maximum, and so the heat generation rate was constant to within this value as well.

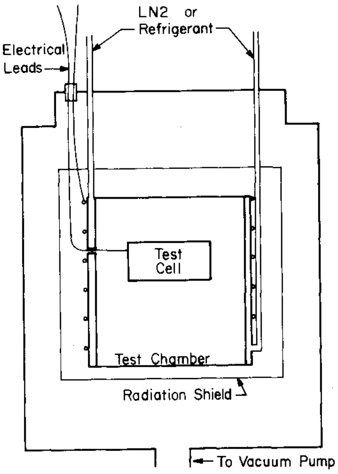

Fig. 1 Test chamber.

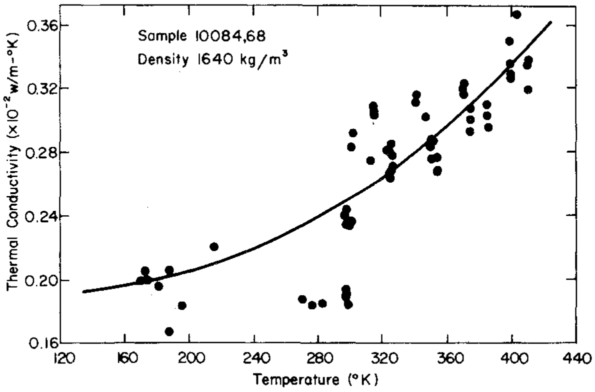

Fig. 2 Thermal conductivity of lunar fines.

The test cell was machined from teflon, and a thermocouple placed in the sample about 2 mm from the heating wire provided a monitor for the sample temperature. With the system as described, the long-time approximation became valid after about 10 sec, and the boundary effects appeared after about 50 sec. Attempts to measure the diffusivity using the temperature response characteristic of the thermocouple at a known distance from the heating wire were not successful.

Results and Discussion

The thermal conductivity as measured for lunar fines sample 10084,68,2 as cataloged by the Lunar Receiving Laboratory at the NASA Manned Spacecraft Center, Houston, is shown in Figs. 2 and 3. These data sets are for sample densities of 1640 and 1950 kg/m^3, respectively. The former is the same as the average density reported for the Apollo 11 core-tube sample[19] and so should represent the true value for the undisturbed lunar surface at Tranquillity Base. The latter value represents the densest packing obtainable in the laboratory. This density was arrived at by vibrating the sample holder for an hour with a Vibrotool etching tool. This density would correspond to that occurring when the lunar soil is packed as might occur during construction of a shelter or equipment base on the lunar surface. Some earlier measurements at the lower density are given in a previous paper.[11] The data in Fig. 2 are considerably more extensive.

In each of Figs. 2 and 3, least-squares curves for a cubic temperature dependence are also shown with the data. These curves are of the form

$$k = a_0 + a_3T^3 \tag{2}$$

in accordance with the elementary theory mentioned previously. The coefficients for Eq. (2) are given in Table 1 for the two densities mentioned plus the coefficients of a similar

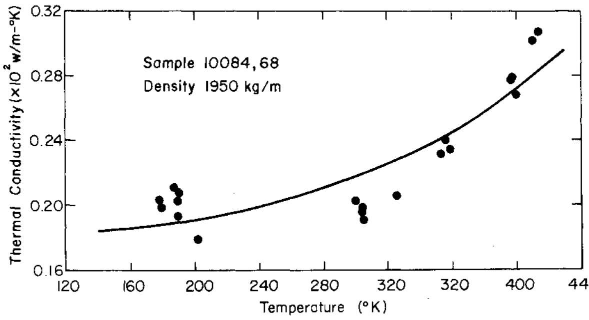

Fig. 3 Thermal conductivity of lunar fines.

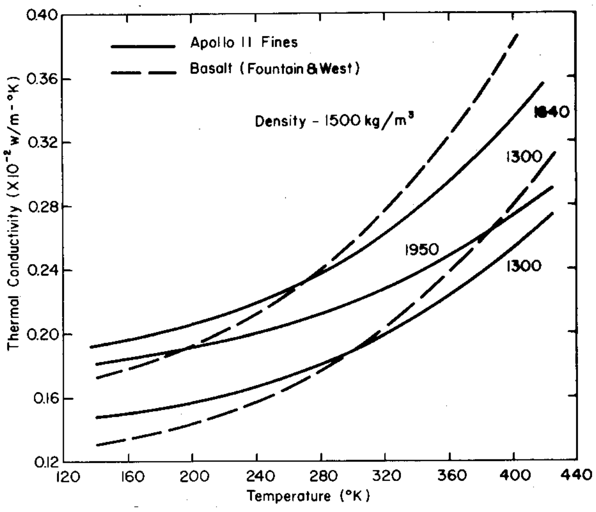

Fig. 4 Comparison of thermal conductivities.

curve fitted through data points for a density of 1300 kg/m^3. The data for this density were reported previously.[9] At that time, because of the limited amount of data available, it was felt that there was not sufficient justification for using an expression of the form of Eq. (2) to fit the data. However, as the project progressed and further data at other densities were taken, it appeared that the cubic temperature dependence was at least close to being correct.

There is a considerable degree of data scatter evident in Figs. 2 and 3. Part of this is because of the usual random errors that occur when data such as these are taken, and part is because several runs over the whole temperature range are included in each plot. Six runs are represented in Fig. 2 and two runs in Fig. 3. No systematic differences seem to occur between different runs with the same sample.

It is felt that most of the scatter is caused by thermal expansion effects either of the heating wire, radially, or of the sample itself. Under vacuum conditions, the lunar fines are extremely cohesive, and the particles readily clod together. Perhaps, as the sample or wire expands or contracts with temperature, the contact resistance between the wire and the sample varies. That is, there may be a local compaction, or, alternatively, small voids may be formed. These effects would not occur if the fines would slide on one another as fine particles usually do.

The cubic temperature fits from the present data and the previous data[10] are shown together in Fig. 4 for purposes of comparison. Also shown are conductivity curves for terrestrial basalt for two densities as given by Fountain and West.[13] In each case, the steeper the slope of the curve, the greater the radiative contribution.

The differences from one curve to another are not too great when the scatter of the data is taken into account. Differences in slope from the basalt to the lunar fines probably represent the effects of different particle sizes and shapes rather than compositional differences. The basalt was sieved to a rather narrow size range of 37–62 m, whereas the lunar fines varied in size from about 100 μm down to less than 1 μm, with most of the particles at the low end of the range.[20]

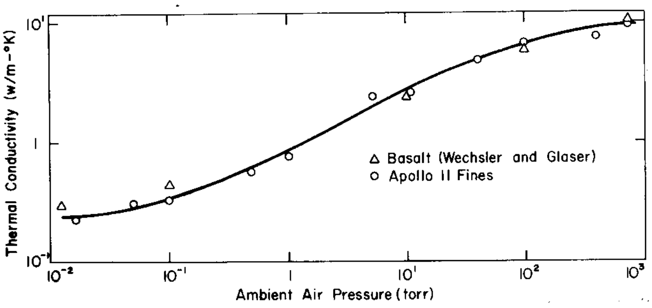

Fig. 5 Pressure effects on conductivity.

Table 1 Thermal conductivity coefficients for Eq. (2)

Density, kg/m^3	$a_0 \times 10^3$	$a_3 \times 10^{11}$
1300	1.425	1.726
1640	1.868	2.299
1950	1.793	1.474

The reasons for the differences between the three curves for different densities of the lunar fines are not clear. Heat transfer in each case is by a complicated process of conduction and radiation. As the fines become more compacted, one would expect the conductive contribution to increase and the radiative contribution to decrease. One would expect the relative magnitude of the curves to increase as the density increases and the slope to decrease as density increases. However, these effects are not apparent from the curves in Fig. 4. Preliminary data on the Apollo 12 fines show similar effects. The data of Fountain and West[13] show increasing conductivity with density, with one exception out of a total of six densities. However, the data of Wechsler and Glaser[12] do not indicate any particular temperature or density dependence of the conductivity. Data of Bernett et al.[21] taken on vacuum samples also do not indicate any particular effect of density. Observation of the present data and comparison with the other studies mentioned previously indicate that the novel method of Fountain and West is perhaps more reliable and accurate than the other techniques, as their data for basalt have much less scatter, and they also more clearly indicate definite trends as the density changes.

The thermal conductivity of the lunar fines as a function of ambient pressure is shown in Fig. 5 for a density of 1640 kg/m^3 and at room temperature. Also, data of Wechsler and Glaser[12] are shown for comparison. The agreement here is good. However, this is somewhat deceiving after considering the previous figures because this is a log-log plot. The increase in conductivity is almost a factor of 100 over the range of pressures given. It appears from these data and the data for simulated lunar solids[12] that the pressure effect is concentrated in the range of 10^{-2}–10^2 torr, with the conductivity having constant values, with respect to pressure, at pressures above and below this range.

The thermal diffusivity calculated from the relation $\alpha = k/\rho c$ is shown in Fig. 6 for the three densities. The specific heats are taken from Robie et al.[5] The curves shown are fourth-degree least-squares fits to the data, that is,

$$\alpha = b_0 + b_1T + b_2T^2 + b_3T^3 + b_4T^4 \tag{3}$$

The fourth degree was chosen simply because it represented the data better than greater or lesser degree polynomials. Nothing can really be said about the relative magnitude of the curves because they follow directly from the conductivities. The coefficients of the polynomial expression for the thermal diffusivity are given in Table 2.

It is frequently of interest to have relevant reference values of thermophysical properties available for computational convenience, because, in many analyses, the constant property assumption will suffice. There are two ways of calculating reference properties in the present case. One way is to calculate the integrated average of the property over the tem-

Table 2 Thermal diffusivity coefficients for Eq. (3)

Density kg/m^3	$b_0 \times 10^8$	$b_1 \times 10^{10}$	$b_2 \times 10^{13}$	$b_3 \times 10^{15}$	$b_4 \times 10^{18}$
1300	1.099	−1.145	5.501	−1.195	0.999
1640	1.142	−1.190	5.714	−1.241	1.037
1950	0.915	−0.945	4.478	−0.960	0.783

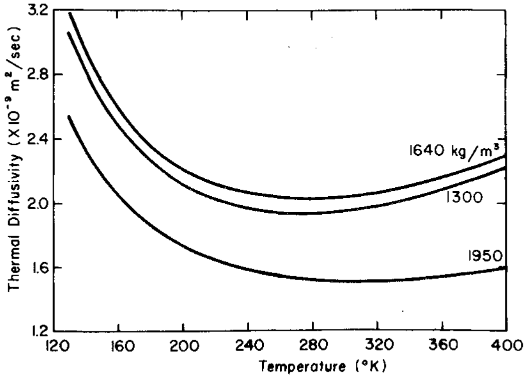

Fig. 6 Thermal diffusivity of lunar fines.

perature range of interest, in this case from 92° to 392°K.[11] A second way is to calculate the property at some average value of temperature, in this case, the constant lunar surface layer temperature far below the surface. This is about 222°K. The calculations have been carried out in the present case for the conductivity and diffusivity and in addition for the thermal parameter $\gamma = (k\rho c)^{-1/2}$, which is frequently of interest in periodic constant property analyses. These average properties are given in Table 3; $\bar{k}$, $\bar{\alpha}$, and $\bar{\gamma}$ are the respective integrated averages, and k^*, α^*, and γ^* are the values calculated for the average temperature of the lunar surface layer.

Table 3 Average values of thermal conductivity, thermal diffusivity, and thermal parameter for several densities

Density, kg/m³	$\bar{k} \times 10^3$, w/m-°K	$k^* \times 10^3$, w/m-°K	$\bar{\alpha} \times 10^9$, m²/sec	$\alpha^* \times 10^9$, m²/sec	$\bar{\gamma} \times 10^2$, m²-°K/w-sec$^{1/2}$	$\gamma^* \times 10^2$, m²-°K/w-sec$^{1/2}$
1300	1.77	1.61	2.34	2.04	2.73	2.81
1640	2.32	2.12	2.42	2.11	2.12	2.17
1950	2.09	1.95	1.85	1.64	2.06	2.08

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