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Thermal Diffusivity Measurements of Chondrites and an Iron Meteorite

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1. Introduction

A classification of meteorites has been established in the light of chemistry and petrology. Analytical data of meteorites provide information on the history of the solar system and petrological research will clarify the thermal and mechanical processes which meteorites have experienced in space. Physical properties of meteorites, such as elastic, thermal and electromagnetic properties have not so far been widely investigated. However, knowlegde of the temperature variation of thermal properties of meteorites is indispensable for studying the thermal processes of planetary bodies, such as the thermal metamorphic history of parent body of meteorites or asteroid and a thermal history of a planetisimal. This knowledge is also important to the study of thermal effects of meteorite magnetism before and after entry into the earth's atmosphere (e.g. NAGATA, 1979).

Thermal conductivity or thermal diffusivity is considerably affected not only by composition but also by other factors such as porosity and texture. ALEXEYEVA (1960) reported the thermal conductivities of chondrites and an achondrite about a temperature 320 K. However, the measurements in one atomosphere air are inadequate to estimate the thermal conductivity of exterrestrial material. MATSUI and OSAKO (1979) recently determined the temperature variation of thermal diffusivities of five Yamato meteorites in vacuum. It was found that the thermal diffusivities were widely different among stony meteorites, even though they belong to the same classification. More measurements are needed to form any definite conclusion on systematic variation of the thermal diffusivity of meteorites with other properties.

2. Samples and Measurement

Table 1 shows the samples used in the experiments. All the samples were in the collection of the National Science Museum, Japan. Kesen, the heavest stony meteorite to ever fall in Japan, is assigned to H-4 group chondrite. Fukutomi, which fell on March 19, 1882 in Saga-ken, Japan, has a peculiar structure recently described by SHIMA *et al.* (1979). Satsuma, which fell on October 26, 1886 in Kagoshima-ken, Kyushu, Japan, is the same meteorite as described as the Kyushu chondrite by MASON

Table 1. Samples.

Sample	Classification	Size[1]	Volume	Weight	Bulk density	Metal phase
		10^{-3}m	10^{-9} m^{-3}	10^{-3} kg	10^3 kg m^{-3}	vol%
Fukutomi	L-4[a]	4.58×3.55×3.59	58.4±0.8	0.2010	3.44±0.51	4[d]
Kesen	H-4[b]	3.14×3.38×3.54	37.6±0.8	0.1408	3.74±0.08	9[e]
Satsuma	L-6[b]	5.99×4.67×3.39	109.9±2.3	0.3573	3.25±0.07	3[f]
Duwun	L-6[c]	2.03×2.8 ×2.1[2]	10.1±0.2	0.0333	3.30±0.06	4[c]
Shirahagi	Octahedrite	9.48×2.51×2.47	58.77	0.4646	7.91	

[1] the first figure of each 'Size' column shows the length used for measurement.
[2] pentagonal prism.
[a] SHIMA, personal communication.
[b] VAN SCHUMUS and WOOD, 1967.
[c] YAKUBI and SHIMA, 1980.
[d] SHIMA *et al.*, 1979.
[e] MIYASHIRO, 1962.
[f] MASON and WIIK, 1961.

and WIIK (1961). Duwun fell on November 23, 1943 in Choemra-Nando, Korea and is assigned to L-6 group (YABUKI and SHIMA, 1980). Shirahagi is classified as a medium octahedrite (MURAYAMA, 1953). Two fragments of this iron meteorite is known, one of which was highly deformed by strong forces probably as a result of terrestrial rock flows in valleys. The sample employed in this investigation was the other undeformed fragment.

The samples were cut and filed with carborundum powder to produce sections parallel to within 0.01 mm for measurement. The bulk density of each sample was obtained merely by dividing the weight by the volume.

To determine thermal diffusivities we used the modified Ångström method (KANAMORI *et al.*, 1969) for which a sample of prism or disc shape is sufficient instead of a long rod required for the ordinary method (HORAI, 1981). The installation of a sample is shown in Fig. 1 in which a schematic diagram of the method is also illustrated. The thermal diffusivity (a) is determined by the equation $a=\omega l^2/\Delta\phi \ln 2(A_1/A_2)$, where $\Delta\phi$ is the phase lag and A_1/A_2 is the amplitude decay with distance of a sinusoidal temperature wave with angular frequency (ω) transmitting through a sample of length l. The accuracy of this method is estimated to be better than 10 per cent. The Measurements were made over the temperature range 100 to 400 K at a reduced pressure of 1 Pa which is considered to be low enough to estimate thermal diffusivity of a rock-like sample in planetary space (FUJII and OSAKO, 1973). Fig. 2 shows the sample assembly in a vacuum tube. This is the same as used in the previous work (FUJII and OSAKO, MATSUI and OSAKO).

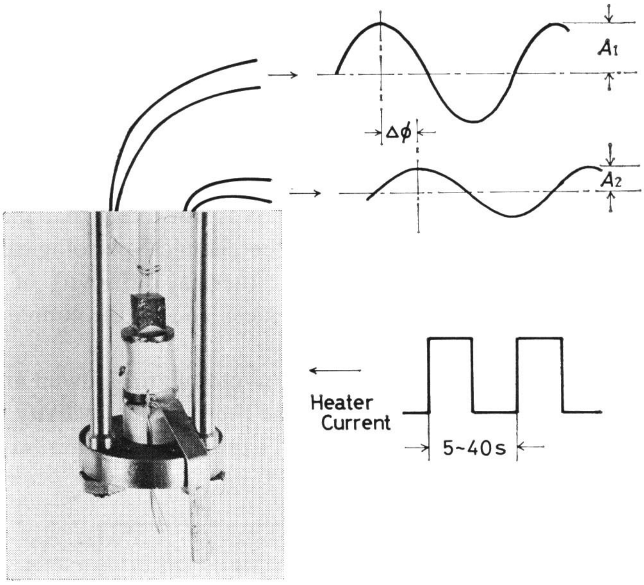

Fig. 1. The installation of a sample and a schematic diagram of the modified Ångström method. The frame and the heater of the sample assembly are made of nickel. A reed on the bottom of the heater is extended to mercury in a glass bute to reduce thermal resistance between the sample and the surface of the tube immersed in liquid nitrogen.

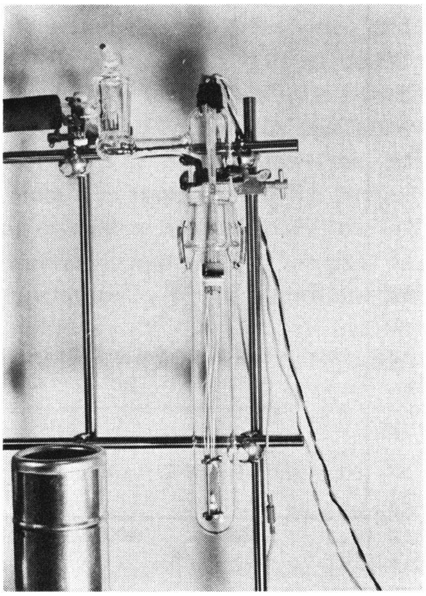

Fig. 2. The sample assembly in a glass vacuum tube.

3. Results and Discussion

Four ordinary chondrites and one iron meteorite were measured over the temperature range 110 to 400 K. Fig. 3 shows the variation of the thermal diffusivities of chondrites with temperature. The values and the temperature variation are all similar and are close to the high value of the previous results (MATSUI and OSAKO). Satsuma (L-6) and Duwun (L-6) have nearly equal thermal diffusivity. Higher diffusivities are seen for Fukutomi (L-4) and for Kesen (H-4). It is not likely that there is a simple correlation between thermal conductivity and the chemical-petrological classification of chondrites. The thermal conductivity or the thermal diffusivity of a meteorite is affected strongly by the presence of pores and cracks and by the content of devitrified or fine-grained materials among crystal grains.

Table 2 shows the model compositions of Fukutomi and Duwun and the thermal conductivities of their constituent minerals. The thermal conductivity of a meteorite could be estimated as that of a simple mineral aggregate, however, lack of data for

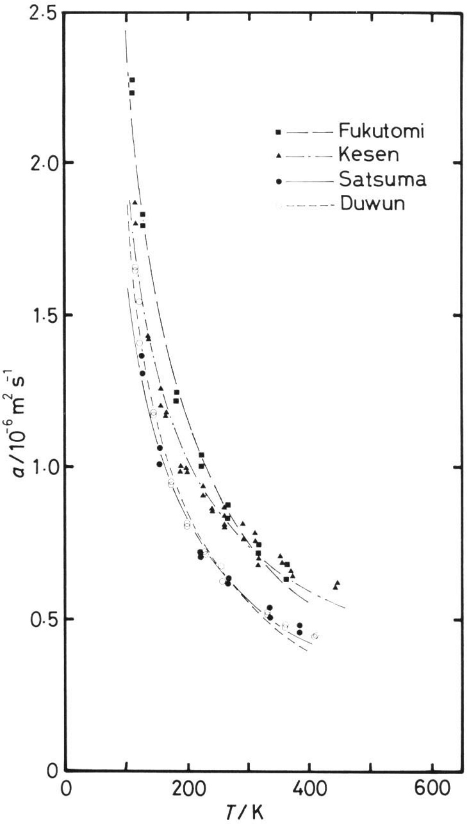

Fig. 3. Thermal diffusivity of four chondrites versus temperature.

Table 2. Modal cpmpositions of Fukutomi and Duwun and thermal conductivities of cpmposite minerals.

	Modal composition, vol%		Thermal conductivity at 25°C
	Fukutomi[a]	Duwun[b]	$Wm^{-1}\ k^{-1}$
Olivine	60	52	4.1[1][c]
Orthopyroxene	13	22	4.2[2][c]
Clinopyroxene	10	7	3.8[3][c]
Plagioclase	—	9	2.0[4][c]
Tridymite	2	—	—
Fe–Ni	4	4	35[5]
Troilite	4	5	—
Chromite	—	1	2.5[c]
Others	7	—	—

[1] Fa_{23}, [2] Fs_{20-22}, [3] augite, [4] Ab_{89}, [5] estimated from thermal diffusivity of Shirahagi.

[a] estimation from SHIMA *et al.*, 1979.

[b] estimation from YABUKI and SHIMA, 1980.

[c] HORAI, 1971.

troilite, which is an important mineral of meteorites, prevents such a calculation. The observed thermal conductivities of Fukutomi (1.5 $Wm^{-1}\ K^{-1}$) and that of Duwun (1.1 $Wm^{-1}\ K^{-1}$) at 25°C are lower than those of the major composite minerals such as olivine, pyroxene and nickel-iron. Thermal conductivity (λ) is obtained by the ralation $\lambda = \rho c a$, where ρ is the density and c is the specific heat capacity reported in MATSUI and OSAKO. Grain boundaries and existence of pores and cracks would reduce the thermal conductivity from that of a simple mixture of minerals. The samples are comparatively compact, therefore thermal diffusivities of $1.0 \times 10^{-6}\ m^2\ s^{-1}$ at 300 K and $2.5 \times 10^{-6}\ m^2\ s^{-1}$ at 100 K would give the upper bound of ordinary chondrite.

To obtain smoothed values of thermal diffusivity a semi-empirical formula $a = A + B/T$ is used. Coefficients A and B obtained by least square fitting and the calculated values are shown in Table 3. Fig. 3 also shows the smoothed curves of thermal diffusivities. In this formula it is assumed that the phonon thermal conduction of a chondrite as an insulating crystalline material obeys the law $a \sim 1/T$ at ordinary temperatures. In Fig. 3, however, it appears that the observed points deviate from the $1/T$-curve at higher temperatures. Fig. 4 shows the thermal diffusivities versus

Table 3. Coefficients A and B of the empirical equation, $a = A + B/T$ and smoothed values of thermal diffusivity (a) of chondrites.

Sample	A	B	$a/10^{-6}\ m^2\ s^{-1}$							
	$10^{-6}\ m^2\ s^{-1}$	$10^{-4}\ m^2\ K\ s^{-1}$	T/K 100	150	200	250	300	350	400	450
Fukutomi	−0.054	2.426	2.37	1.56	1.16	0.917	0.755	0.638	0.553	
Kesen	0.163	1.731	1.89	1.32	1.03	0.856	0.740	0.658	0.596	0.548
Satsuma	0.019	1.627	1.65	1.10	0.833	0.670	0.562	0.484	0.426	0.381
Duwun	−0.059	1.837	1.78	1.17	0.859	0.676	0.553	0.466	0.400	0.349

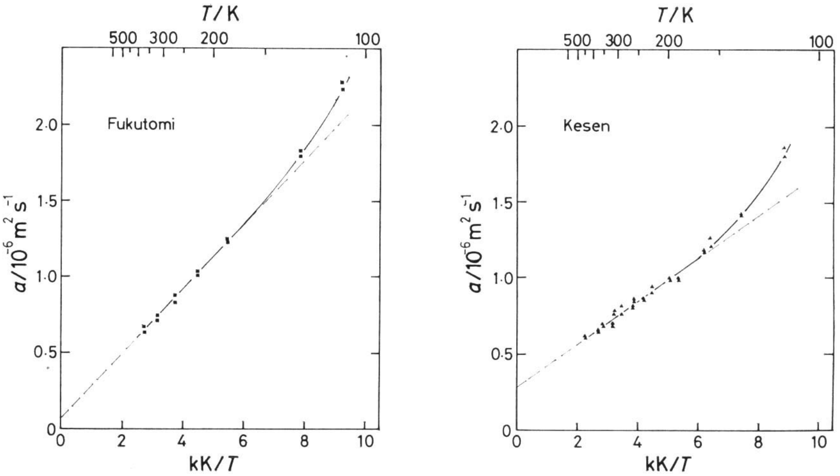

Fig. 4. Thermal diffusivity of Fukutomi and Kesen plotted versus reciprocal of the absolute temperature. The straight lines at higher temperature are not coinside with the curves in Fig. 3.

reciprocal of the absolute temperature for Fukutomi and Kesen, demonstrating this feature more obviously. Theory shows that the thermal diffusivities of a crystalline insulator is expressed as $a \simeq 1/3\bar{v}\Lambda$, where $\bar{v}$ is the mean phonon velocity or sound velocity and Λ is the phonon mean free path, and shows that Λ is inversely proportional to the absolute temperature, $\Lambda \sim 1/T$ at elevated (above the Debye) temperatures, while at lower temperatures it is longer than expressed by this rule(ZIMAN,

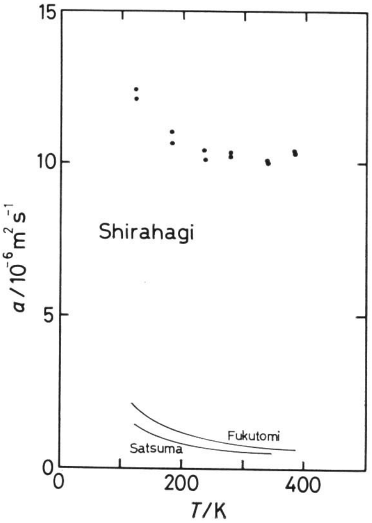

Fig. 5. Thermal diffusivity of Shirahagi iron meteirite, compared with ordinary condrite.

1960). That is, the thermal diffusivity rapidly increases toward low temperature. In Fig. 4 a straight line is drawn to fit the observed points in the high tamperature range and, in consequence, it does not coinside with the curve in Fig. 3. The deviation of the observed points at lower temeratures may be explained by the effect due to the lengthened phonon mean free path. On the other hand it is noticed that Kesen has a higher extrapolated value at infinite temperature than does Fukutomi. This is consistent with the higher metal content of Kesen, because this 'residual' thermal diffusivity is to some extent due to the thermal conduction in the metal phase where temperature variation is more moderate. The quantitative treatment is, however, difficult because the bulk thermal diffusivity of a mixture is not simply expressed as a linear combination of those of its components.

Fig. 5 shows the results of Shirahagi iron meteorite which is composed of 89% Fe and 8% Ni (SHIMA *et al.*, 1978). The thermal diffusivity is more than ten times higher than that of a compact chondrite at ordinary temperatures and even at 100 K more than five times higher, but is lower than that of pure iron or pire nickel. The variation with temperature is more moderate than that of a stony meteorite, a crystalline insulator.

4. Conclusion

The results of these measurements give the upper bound for the thermal diffusivity of compact chondrites. It is impossible to find a correlation between thermal conductivity of thermal diffusivity and the chemical-petrological classification of chondrites at present. We need to find an indicator corresponding to the handness or brittleness of a meteorite which may correlate with thermal conductivity or diffusivity.

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