THERMAL PROPERTY MEASUREMENT OF YAMATO METEORITES

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Abstract: The thermal diffusivity and specific heat of five Yamato meteorites (Yamato-7301, -7308, -74191, -74371 and -74647) were measured. Thermal diffusivity measurement was conducted under vacuum (10^{-3} mmHg or below) over the temperature range 150 to 550 K. The temperature variation of thermal diffusivity is very small at the temperatures 300–500 K. Yamato-7308 (howardite) exhibits a lower diffusivity than other samples (ordinary chondrites). The specific heat of the samples was measured in one atmosphere air over the temperature range 270 to 420 K. The temperature variation of the specific heat is found to be almost identical for all samples.

1. Introduction

Recent progress in photometric observation of the asteroids has revealed the resemblance between meteorites and asteroids (ZELLNER and BOWELL, 1977). According to this observation, asteroids have been classified into C(carbonaceous), S(silicaceous), M(metal-rich) and E(metal-free). It seems that meteorites are mostly related to asteroids and some asteroids are completely differentiated. Differentiation process of the asteroids, however, has not been studied well so far. Deficiency in the thermal property data such as thermal diffusivity, thermal conductivity and specific heat of meteorites possibly makes it difficult to conduct such a study. Therefore, measurement of thermal property of meteorites is considered to be important and very helpful for calculating the thermal history of asteroids, satellites and planets. From this point of view we conducted the measurement of thermal property of meteorites. In this paper we will report several preliminary results of the thermal property measurement on Yamato meteorites obtained to date.

Since meteorites are composed mainly of several rock-forming minerals which are common in terrestrial rocks, it is theoretically possible to calculate approximate values of thermodynamical quantities of such a composite material if those of individual composing minerals were known (HASHIN and SHTRIKMAN, 1962). However, these quantities are affected not only by composition but also by other factors such as density, porosity and texture, which are very different among meteorites even though they belong to the same chemical and petrological class.

Table 1. Modal composition of Yamato-7301, -7308, -74647, -74371 and -74191 (vol %).

	Yamato -7301*	Yamato -7308*	Yamato -74647**	Yamato -74371**	Yamato -74191***
Matrix	87.7	100.0	86.2	88.0	17.9
Chondrule	12.3	—	13.8	12.0	82.1
Total	100.0	100.0	100.0	100.0	100.0
Matrix					
Olivine	51.7	0.4	60.6	59.3	10.0
Orthopyroxene	19.0	69.6	13.0	15.0	1.2
Clinopyroxene	3.2	12.8	0.5	1.0	4.2
Plagioclase	3.7	13.1	0.2	—	—
Cryptocrystalline materials	—	—	1.4	0.8	19.6
Glass	—	0.7	—	—	6.9
Silica mineral	—	0.1	—	—	—
Opaque phase	11.4	2.3	24.2	23.7	58.1
Others	11.0+	1.0++	0.1+++	0.2+++	—
Total	100.0	100.0	100.0	100.0	100.0
Chondrule					
Olivine	56.3	—	43.3	65.6	42.8
Orthopyroxene	30.5	—	47.6	23.4	16.2
Clinopyroxene	6.6	—	2.4	4.4	30.2
Plagioclase	4.2	—	0.7	—	—
Cryptocrystalline materials	—	—	2.7	4.0	1.0
Glass	—	—	—	—	7.1
Opaque phase	2.4	—	3.0	2.6	2.7
Others	—	—	0.3+++	—	—
Total	100.0	—	100.0	100.0	100.0

* after YAGI *et al.* (1978).
** after KIMURA *et al.* (1978).
*** after YABUKI *et al.* (1978).
+ Reddish brown oxidized products of metallic and sulfide phase.
++ Dark-colored undetermined material.
+++ Brown-colored terrestrial weathering products.

Therefore, direct measurement is desirable. In addition, recent development in mineralogical study of achondrites is making it possible to estimate the absolute cooling rate of achondrite by using the width of pyroxene lamellae (MIYAMOTO, 1977). More accurate data on thermal property will be indispensable for calculating

Table 2. Sample descriptions.

Sample	Classification	Size (10^{-2}m)	Volume (10^{-8} m^3)	Weight (10^{-4} kg)	Bulk density (10^3 kg m^{-3})	Metal+Sulfide (wt. %)
Yamato -7301	H4	0.29×0.36×0.31	3.24	1.06	3.3	13.87
-7308	Howardite	0.35×0.38×0.36	4.79	1.05	2.2	1.14
-74647	H4-5	0.34×0.26×0.27	2.39	0.74	3.1	
-74371	H5-6	0.35×0.27×0.36	3.38	1.12	3.3	
-74191	L3	0.42×0.29×0.33	3.98	1.25	3.1	11.55

such a detailed fractional crystallization history of some peculiar asteroids whose surface is similar to the achondritic meteorites such as Vesta.

The samples measured in this experiment are Yamato-7301, -7308, -74191, -74371 and -74647. Yamato-7301, -74191, -74371 and -74647 are classified respectively as H4 (YAGI *et al.*, 1978), L3, H5–6 and H4–5 (YANAI *et al.*, 1978). Yamato-7308 is classified as a howardite (YAGI *et al.*, 1978). The modal composition of samples and sample descriptions are summarized in Tables 1 and 2.

2. Experimental Technique

2.1. Thermal diffusivity

The modified Angstrom method was used for thermal diffusivity measurement (KANAMORI *et al.*, 1969). Schematic diagram of the measurement is illustrated in Fig. 1 (KANAMORI *et al.*, 1968). The thermal diffusivity, k, is determined from the phase lag, $\Delta\phi$, and the amplitude decay with distance, α, of a sinusoidal temperature wave (angular frequency, ω) transmitting through a sample of a finite length, l, by the relation $k=\omega l^2/\Delta\phi$ ln (2α). The accuracy of this method is estimated to be less than ±10%. The measurement was made over the temperature range from 150 to 550 K in the vacuum condition of 10^{-3} mmHg. Although

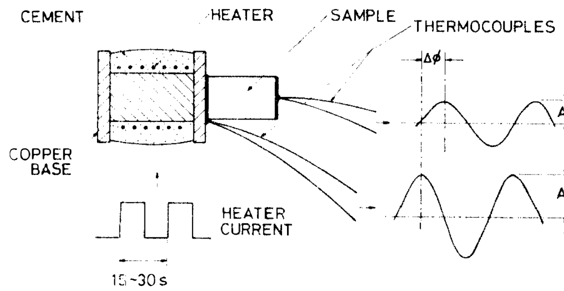

Fig. 1. Schematic diagram of the modified Angstrom method for thermal diffusivity measurement (KANAMORI et al., 1968). Amplitude ratio A_2/A_1 and phase shift $\Delta\phi$ of temperatures at both ends of the sample are measured to determine diffusivity.

heat transfer in porous media is significantly affected by gases in the pores, it is known that thermal diffusivity of porous media does not depend on the ambient gas pressure if pressure is lower than 1 mmHg (FUJII and OSAKO, 1973). Thus the pressure of 10^{-3} mmHg is considered to be low enough to estimate thermal diffusivity in planetary space.

2.2. *Specific heat*

The differential scanning calorimeter (DSC) was used for the specific heat measurement (Rigaku Thermoflex Low Temperature DSC, which is usually used in the measurement of the calorimetric variation associated with phase change). This instrument measures the difference in the power required for heating up between the sample (including the sample pan made of aluminum) and the reference pan (also made of aluminum). If we can measure the heat difference between the sample pan and the reference pan, the specific heat of the sample relative to that of the standard sample could be calculated by comparing them. Using the sample of known specific heat as the standard sample, the absolute value of specific heat can be estimated. In this study we used synthetic sapphire as the standard sample. Samples to be measured in the present study must be powdered. In order to show the reliability of this experimental method we tabulated the specific heat of fayalite measured by this method and that reported by ORR (1953) in Table 3. As is clearly seen, the difference in the values between this study and ORR's is less than 15%. Accuracy of this method is much dependent on the difference in amount between the sample to be measured and the standard sample.

Table 3. Specific heat of fayalite.

Temperature (K)	Specific heat (10^3 J kg^{-1} K^{-1})	
	ORR (1953)	This study
325	0.68	0.67
330	0.68	0.70
340	0.69	0.70
350	0.70	0.67
360	0.71	0.62
370	0.71	0.60
375	0.72	0.64
395	0.73	0.69
400	0.74	0.67
410	0.75	0.67
420	0.75	0.67

3. Results and Discussion

Thermal diffusivity and specific heat of five Yamato meteorites, Yamato-7301, -7308, -74191, -74371 and -74647 were measured. For thermal diffusivity measurement the temperature range was from 150 to 550 K and the measurement was made in the vacuum condition (10^{-3} mmHg or below). On the other hand, specific heat measurement was conducted in one atmosphere air over the temperature range from 270 to 420 K. Using the relation $K=\rho C_p k$, where ρ is bulk density, C_p is specific heat and k is thermal diffusivity, thermal conductivity, K, was

Table 4. Coefficients A, B and C of the empirical equation for thermal diffusivity ($k=A+B/T+CT^3$) and a, b and c of that for specific heat ($C_p=a+bT+c/T^2$).

Sample	A ($10^{-7}m^2s^{-1}$)	B ($10^{-4}m^2Ks^{-1}$)	C ($10^{-15}m^2s^{-1}K^{-3}$)	a ($10^3Jkg^{-1}K^{-1}$)	b (Jkg^{-1})	c (10^7JKkg^{-1})
Yamato -7301	2.53±2.00	2.21 ±0.33	−1.82±2.35	3.69 ±0.36	−5.62 ±0.69	−14.8 ±1.4
-7308	0.12±0.15	0.704±0.023	0.61±0.14	0.484±0.199	0.884±0.377	−1.14±0.79
-74647	−1.28±0.33	2.02 ±0.05	1.68±0.31	0.660±0.156	0.488±0.296	−1.74±0.61
-74371	0.39±0.52	0.964±0.160	0.57±0.15	1.88 ±0.37	−2.06 ±0.704	−6.59±1.43
-74191	3.67±0.81	0.002±0.24	−0.38±0.25	2.31 ±0.22	−2.48 ±0.41	−8.66±0.86

Table 5. Thermal diffusivity (k), specific heat (C_p**) and thermal conductivity (K***) of Yamato meteorites.*

Temperature (K)	Sample														
	Yamato-7301			-7308			-74647			-74371			-74191		
	k	C_p	K	k	C_p	K	k	C_p	K	k	C_p	K	k	C_p	K
100	24.6			7.17			19.0								
150	17.2			4.84			12.3								
200	13.4			3.69			8.97								
250	11.1			3.03			7.08								
300	9.40	0.364	1.13	2.63	0.622	0.360	5.92	0.601	1.10	3.76	0.535	0.66	3.57	0.603	0.67
350	8.06	0.520	1.38	2.39	0.700	0.368	5.22	0.675	1.09	3.39	0.626	0.70	3.51	0.734	0.80
400	6.89	0.522	1.19	2.27	0.766	0.383	4.86	0.731	1.10	3.17	0.650	0.68	3.43	0.776	0.83
450				2.24	0.825	0.407	4.75	0.776	1.14	3.05	0.633	0.64	3.33	0.765	0.79
500				2.29			4.87			3.03			3.20		
550										3.09			3.05		

* k; $10^{-7}m^2s^{-1}$.
** C_p; $10^3Jkg^{-1}K^{-1}$.
*** $K(=\rho C_p k)$; $Wm^{-1}K^{-1}$.

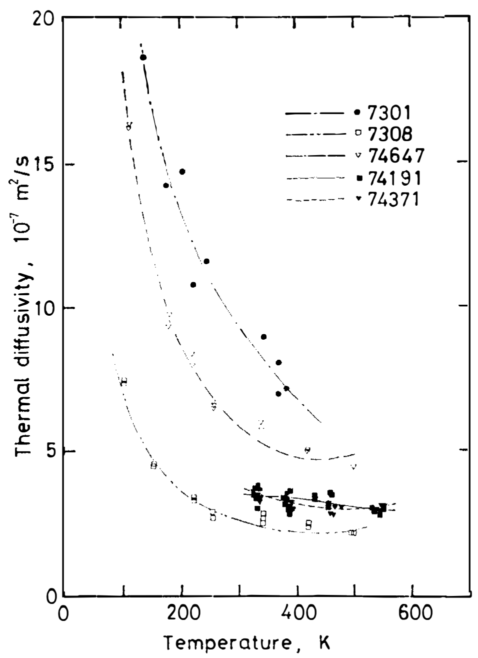

Fig. 2. Thermal diffusivity k versus temperature T for Yamato-7301, -7308, -74191, -74371 and -74647 in the vacuum condition.

calculated. The empirical formulas, $k=A+B/T+CT^3$ and $C_p=a+bT+C/T^2$, were used to obtain smoothed values of the thermal diffusivity and the specific heat (HORAI *et al.*, 1970; FUJII and OSAKO, 1973). Coefficients were determined by least-squares from the data and are listed in Table 4. The corresponding curves are illustrated in Figs. 2 and 3.

The results are shown in Figs. 2 and 3, and are summarized in Table 5. One of the significant features seen in Fig. 2 is that the thermal diffusivity of Yamato-7308 is substantially smaller than those of other samples particularly at the low temperature range. Lower diffusivities and their temperature variation resemble more or less those of the lunar anorthositic gabbro 77017 (Apollo 17) (MIZUTANI and OSAKO, 1974). The low thermal diffusivity of Yamato-7308 might be attributable to a high content of plagioclase since Yamato-7308 is classified as a pyroxene plagioclase achondrite (YAGI *et al.*, 1978). Its higher porosity (~33%) would be another reason for the lower diffusivity: bulk and theoretical (calculated from the modal composition) densities of Yamato-7308 are 2.2 and 3.3 (10^3 kg m^{-3}) respectively. The thermal diffusivity of Yamato-74191 (L3 chondrite) is almost the same as that of Yamato-74371 (H5–6 chondrite) irrespective of the difference in chemical composition and thermal metamorphic grade. Another common feature seen in Fig. 2 is a very small temperature dependence of thermal diffusivity of meteorites at temperatures between 300 and 500 K. Three samples, Yamato-7301,

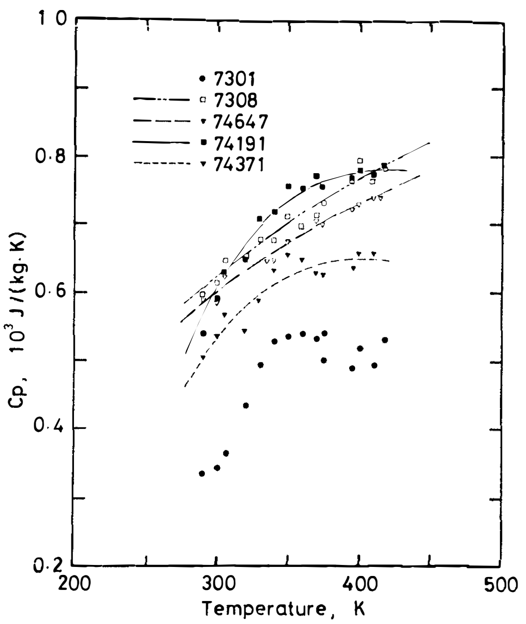

Fig. 3. Specific heat C_p versus temperature T for Yamato-7301, -7308, -74191, -74371 and -74647 in one atmosphere air.

-74371 and -74647, are chemically of the same type (H-group) but petrologically they have different grades of thermal metamorphism (H4–H6). However, the thermal diffusivities of these samples are not identical but are rather scattered as seen in Fig. 2. There seem to be no common features among them although they have almost the same chemical composition. It might mean either that the size of samples (about $0.3 \times 0.3 \times 0.3$ cm^3) is too small to represent thermal diffusivity of the whole meteorite specimen, or that it reflects the difference in petrological metamorphic grade, or that other factors such as pores and micro-cracks affect more significantly the thermal diffusivity than chemical composition. We need more study to form any definite conclusion on systematic variation of temperature variation of the thermal diffusivity of meteorites with chemical and petrological classification. For Yamato-7301, a weathering effect, which causes oxidation and micro-fracturing (increase in porosity) of samples, might be one reason for its deviation from other data since it is highly weathered.

Temperature variation of specific heat of the five Yamato meteorites is shown in Fig. 3. As is seen from the figure, differences in specific heat among measured samples are rather large. However, for Yamato-7308, -74191 and -74647 scattering of the data is within a reliability of the experimental method (~15%). Therefore, the specific heats of these samples are considered to be almost identical, although their temperature dependence (dC_p/dT) is different between Yamato-74191 and Yamato-7308 and -74647. Theoretical specific heats (calculated from the chemical composition) of Yamato-7301, -7308 and -74191 at 300 K are 0.73, 0.77 and 0.75 (10^3 J kg^{-1} K^{-1}) respectively. Cause of the deviation of the Yamato-7301 data from other samples and from the theoretical value may be ascribed to the following reasons: either the amount of the powdered sample, ~10 mg, is too small to represent specific heat of the whole meteorite specimen, or the accuracy of the experimental method is low due to the larger mass difference, ~10 mg, between the Yamato-7301 powdered sample and the standard sample, compared with those of other samples. As was mentioned previously, the accuracy of the experimental method lowers in proportional to the increase in the mass difference between the sample to be measured and the standard sample. Hence the specific heat of Yamato-7301 obtained in this study is less reliable to some extent. Such a significant difference in specific heat in accordance with the chemical classification as observed for the thermal diffusivity cannot be seen for the specific heat as far as these data are concerned. The specific heat of meteorites, however, appears to be slightly lower than that of ordinary terrestrial rocks: the specific heats of granite and basalt at the temperature range from 293 to 373 K are 0.80~0.84 and 0.84~1.00 (10^3 J kg^{-1} K^{-1}) respectively (TOKYO ASTRONOMICAL OBSERVATORY, Rikanenpyo, 1979). It may be due to a higher mean atomic weight of meteorites since meteorites contain more iron.

Measurements of the thermal diffusivity and specific heat of stony meteorites were made under one atmosphere condition by ALEXEYEVA (1958, 1960). The reported values are listed in Tables 6 and 7. The thermal conductivities of stony meteorites obtained by ALEXEYEVA (1960) are, however, significantly higher than those derived in this study. It would be due to the difference in atmospheric condition: one measurement was conducted in one atmosphere air and the other in vacuum. The specific heats reported by ALEXEYEVA (1958) are also slightly higher than our data. Reason for this difference is uncertain. In addition, she found

Table 6. Thermal conductivity of meteorites (ALEXEYEVA, 1960).

Sample	Classification	Metal+FeS* (wt. %)	Temperature	Thermal conductivity (Wm^{-1}K^{-1})
Krymka	Olivine-pigeonite chondrite	22	322.3	1.8
Norton Co.	Aubrite (Enstatite-achondrite)	2	320.7	1.5
Orlovka	Grey olivine -bronzite chondrite	13	320.6	1.8
Zvonkov	Crystalline olivine -bronzite chondrite	12	321.8	2.4

* WOOD (1963).

Table 7. Specific heat of meteorites (ALEXEYEVA, 1958).

Sample	Classification	Metal+FeS (wt. %)	Specific heat ($10^3 Jkg^{-1}K^{-1}$)
Elenovka	Olivine-hypersthene chondrite	9	0.762
Kharkov	Veined white olivine -hypersthene chondrite	17	0.707
Krymka	Olivine-pigeonite chondrite	22	0.695
Kukschin	White olivine -hypersthene chondrite	8	1.00
Misshov	Spherical olivine -bronzite chondrite	23	0.695
Zhovtnevyi	Crystalline olivine -bronzite chondrite	14	0.737

that the specific heat is related to the content of metallic and sulfide minerals. However, such a systematic variation of specific heat with the metal + sulfide content cannot be found in this study. Anyhow, more systematic studies are necessary for reaching any definite conclusion on thermal properties of stony meteorites.

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