Bull. Natn. Sci. Mus., Tokyo, Ser. E, **5**, December 22, 1982

An Interpretation on the Variation among Thermal Diffusivities or Thermal Conductivities of Chondrites

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Abstract

Thermal conductivities of chondrites are calculated as simple four-phase materials to interpret the variation among the thermal diffusivities observed. Results suggest that the thermal diffusivity of chondrites is controlled by two factors; one of these is the metal phase content related to the chemical group; the other is the hardness, for which, however, no quantitative relationship is established at present.

1. Introduction

Observations on thermal diffusivities of chondrites show wide variation, even though the samples belong to the same classification. The thermal diffusivities or the thermal conductivities are in chaos and there seems to be no clear relationship among them (MATSUI and OSAKO, 1979, YOMOGIDA and MATSUI, 1981).

To obtain smoothed values of the thermal diffusivity (a) of a chondrite changing with temperature an empirical equation considering radiation, $a=A+B/T+CT^3$ was used in a previous report (MATSUI and OSAKO, 1979), however, poor fits were observed. Then the thermal diffusivities were plotted versus the reciprocal of the absolute temperature. The graphs were interpreted to mean that the extrapolated thermal diffusivity towards high temperatures was to some extent due to the thermal conduction in the metal phase where thermal conductivity changes more moderately with temperature. It was also suggested that the temperature dependence of thermal diffusivity would be related to the hardness of samples (OSAKO, 1981).

Calculations on the thermal conductivities of model chondrites support this interpretation or suggestion.

2. Calculations

Two expressions are used:

(1) Hashin and Shtrickman's expression, λ_h is a formula for the effective thermal conductivity of multiphase materials from that for magnetic permeability (HASHIN and SHTRICKMAN, 1962, HORAI and BALDRIDGE, 1972). The upper bound (λ_U) and the lower bound (λ_L) for the thermal conductivity are expressed as functions of phase conductivities (λ_i) and volume fractions (v_i).

$$\lambda_U=\lambda_{max}\cdot\left[\frac{1+2S_{max}}{1-S_{max}}\right]$$

Table 1. Thermal conductivity models of chondrites.

Phase	Thermal conductivity $\lambda_i/Wm^{-1}K^{-1}$
1; metal (Fe–Ni)	35[1)]
2; temperature-dependent components such as olivine and pyroxenes	$1300/T$[2)]
3; temperature-independent components such as glass	1.5
4; poor conductivity components such as grain boundary and pores	0.1, 0.03, 0.01

1); estimated from thermal diffusivity of the Shirahagi, iron meteorite (OSAKO, 1981)
2); modeled from the observations on olivines and pyroxenes by HORAI (1971)

$$\lambda_L=\lambda_{min}\cdot\left[\frac{1+2S_{max}}{1-S_{min}}\right]$$

where

$$\lambda_{max}=\max(\lambda_1, \cdots, \lambda_i, \cdots)$$

$$\lambda_{min}=\min(\lambda_1, \cdots, \lambda_i, \cdots)$$

$$S_{max}=\sum_{\lambda_i\neq\lambda_{max}}\left[\frac{\lambda_i-\lambda_{max}}{\lambda_i+2\lambda_{max}}\right]\cdot v_i$$

$$S_{min}=\sum_{\lambda_i\neq\lambda_{min}}\left[\frac{\lambda_i-\lambda_{min}}{\lambda_i+2\lambda_{min}}\right]\cdot v_i\ .$$

λ_h is the average of the upper and the lower bounds,

$$\lambda_h=1/2(\lambda_U+\lambda_L)\ .$$

(2) Geometric mean, λ_g

The geometric mean of the effective thermal conductivity of multiphase material is given by

$$\lambda_g=\lambda_1^{v_1}\cdot\lambda_2^{v_2}\cdots\lambda_i^{v_i}\cdots=\exp\left[\sum(v_i\ln\lambda_i)\right].$$

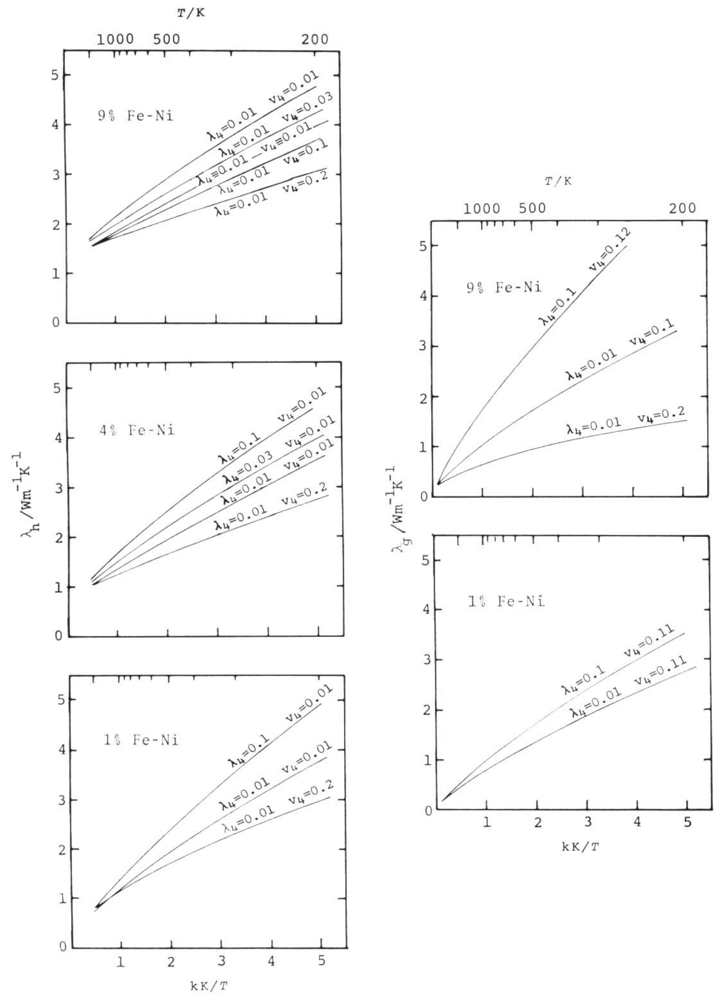
The geomtric mean is bounded between the parallel model and the series one (WOODSIDE and MESSMER, 1961; HORAI and BALDRIDGE, 1972).

Calculations were made for the simplified chondrites as four-phase materials, which have 9%, 4% and 1% of metal phase. The thermal conductivities of the phases were chosen as shown in Table 1.

3. Results and Discussion

Fig. 1 shows the vaiation of thermal conductivities calculated by the formulae for λ_h and λ_g. The model with metal content of 9% corresponds to the H-group chondrite, 4% to the L-group and 1% to the LL-group. In all the cases the thermal conductivities at high temperature, for example imaginary values at 2000 K, depend on the metal content, although the fraction of the poorly chonducting phase changes from 0.01 to 0.2 and the thermal conductivity of the phase changes from 0.01 $Wm^{-1}K^{-1}$ to 0.1 $Wm^{-1}K^{-1}$. The slope of the curves of the thermal conductivities are reduced with increasing fractions of the poorly conducting phase and with decreasing the conductivity of the phase. The thermal conductivity of the chondrite is controlled mainly by the content of metal phase at high temperatures, while the change with temperature is dominated by the poorly conducting phase.

Thermal conductivity is given by the relation, $\lambda = Ca$, where C is specific heat capacity per unit volume and a is thermal diffusivity. As there exists no reliable deter-



(a) (b)

Fig. 1. (a) Calculated thermal conductivities of four-phase chondrites for metal contents of 9%, 4% and 1% using Hashin and Shtrickmah's formula.
(b) Calculated thermal conductivities of four-phase chondrites for metal contents of 9% and 1% using the geometric mean equation.

mination of temperature variation of the specific heat capacity of chondrites, the Debye model is used. The sound wave velocities by YOMOGIDA and MATSUI (1981) and the mean atomic weight of 43 give a Debye temperature of 473 K for H-group chrondrites. The specific heat capacity is 2.1×10^6 $Jm^{-1}K^{-1}$ at high temperatures and is 1.6×10^6 $Jm^{-1}K^{-1}$ at 200 K. The thermal conductivity of an H-group chondrite is estimated from the observed thermal diffusivity (OSAKO, 1981) to be 0.6 $Wm^{-1}K^{-1}$ at high temperatures and to be 1.6 $Wm^{-1}K^{-1}$ at 200 K, which is generally lower than the calculations of λ_h and λ_g for metal content of 9%. The calculations show the trend of the thermal diffusivities of chondrites, but they do not predict the accurate values.

The difference between the upper and the lower bounds of the Hashin and Shtrickman's expression exceeds a factor of ten, when differences among the thermal conductivities of phases contained are large. A more reasonable expression for the thermal conductivity of such multiphase materials is needed, while textural or mechanical properties of chondrites should be investigated. Determinations of thermal conductivity or thermal diffusivity of major constituents of meteorites such as torilite are also important for more detailed discussion as well as measurements of these same parameters on whole samples.

4. Conclusion

The calculations suggest that the thermal diffusivity of chondrite can be expressed as

$$a=\alpha+\beta/T$$

for temperatures ranging from 200 K to room temperature, where α is a function of the metal phase content which is related to the chemical group, E, H, L and LL, and β is a function of the hardness for which a quantitative expression is, however, not established at present.

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