4th International Conference on Molten Slags and Fluxes, 1992, Sendai, ISIJ

HEAT TRANSFER IN CONTINUOUS CASTING POWDERS

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Synopsis: The thermal diffusivities of liquid synthetic slags of SiO_2–Al_2O_3–MgO–CaO–Na_2O–CaF_2 system with addition of TiO_2 or ZrO_2 for reference of continuous casting powders have been determined at temperature between 1373K and 1573K using a three layered laser flash method on the differential scheme. The effect of the radiative heat transfer in high temperature melts has also been estimated by two methods of the finite difference and the control volume and it was included for data processing in the laser flash method. The thermal diffusivity values of liquid slags presently investigated are of the order of 4×10^{-7} m^2/s and their temperature dependence is not so explicit. It may be also added that the effect of addition of TiO_2 and ZrO_2 up to 10wt% on the thermal diffusivity of this slag system is insignificant.

Key word: continuous casting, radiation, high temperature, laser flash method, melt, three-layered cell, infrared ray, continuous casting powder, heat transfer

1. Introduction

The heat transfer properties such as thermal conductivity and thermal diffusivity of liquid SiO_2–Al_2O_3–MgO–CaO–Na_2O–CaF_2 system are of interest in connection with the continuous casting process. However, thermal diffusivity measurements of high temperature melts are still far from complete in various cases arising from onset of convective heat flow and mixed contribution of radiative heat component. Thus, the available thermal diffusivity data with sufficient accuracy are limited for only small number of compositions. The laser flash method has currently been a versatile technique for measuring thermal diffusivity of various materials. The front surface of the sample is irradiated by a single pulse laser, and the temperature response of the back surface is measured. This method is also applied to melts samples using two- or three- layered cell consisting of liquid /container [1, 2], of metallic plate / liquid [3, 4] and of metallic plate / liquid / metallic plate [5, 6, 7], in parallel with the recent progresses of data production [8, 9].

A three layered cell by the laser flash method has been successfully employed for determining the thermal diffusivity of molten salts [9]. However, the estimation of a liquid layer thickness is sometimes difficult because of thermal expansion and creep of the cell materials at elevated temperature region. On the other hand, the relative change of thickness of a liquid sample can be accurately measured by up-lifting the upper plate of the three layered cell. The thermal diffusivity can be derived from the difference of two sets of temperature response for different thickness of sample layer. This method allows to determine the thermal diffusivity of a liquid sample without measuring the absolute sample thickness.

The main purpose of this paper is to present the thermal diffusivity values of liquid synthetic slags of SiO_2–Al_2O_3–MgO–CaO–Na_2O–CaF_2 system systematically measured using a three layered laser flash method on the differential scheme. The effect of radiative heat transfer in high temperature melts will also be discussed on the basis of numerical calculation.

2. Theoretical basis and experimental procedure

The temperature response of a three layered cell at the initial time region of the temperature response curve may be given in the following form, analogous to James's approach for a two layered cell [9].

$$\frac{\partial \ln(\theta\sqrt{t})}{\partial(1/t)} = -\frac{(\eta_1+\eta_2+\eta_3)^2}{4} \qquad (1)$$

where η_i is $l_i/\sqrt{\alpha_i}$. Thus, a plot of $\ln(\theta\sqrt{t})$ against $1/t$ for Eq(1). gives a straight line with slope $-(\eta_1+\eta_2+\eta_3)^2/4$. The thermal diffusivity value of α_2 of the second layer (a liquid sample) can readily be determined, when the thermal diffusivity of first and third layers and the thickness of all three layers are known.

Let's consider an infinite slab as shown in Fig.1 consisting of three layers. The thickness and thermal diffusivity of i-th layer are denoted by l_i and α_i, respectively. The upper metallic plate correspond to as the first layer. A liquid sample and the lower metallic plate are considered as the second and third layers. At initial time region, the temperature response of the back surface of the third layer can be described as Eq.(1). Then the following equation may be obtained.

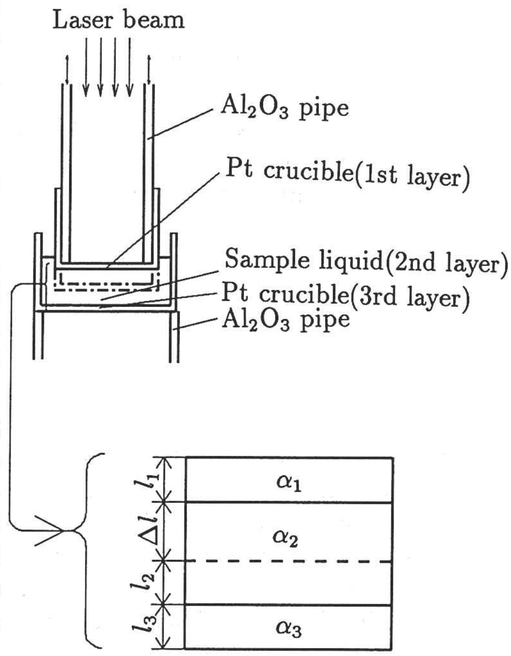

Fig. 1 The schematic diagram of the cell assembly employed in the present differential three-layered laser flash method.

$$l_2/\sqrt{\alpha_2} = 2\sqrt{-\frac{\partial \ln(\theta_{(l_2)}\sqrt{t})}{\partial(1/t)}} - \eta_1 - \eta_3 \qquad (2)$$

$$(l_2+\Delta l)/\sqrt{\alpha_2} = 2\sqrt{-\frac{\partial \ln(\theta_{(l_2+\Delta l)}\sqrt{t})}{\partial(1/t)}} - \eta_1 - \eta_3 \qquad (3)$$

l_2 is the thickness of a liquid sample in the first measurement and Δl is the relative change of thickness of a liquid sample produced by up-lifting the upper plate (the first layer in this case). The relation between the sample thickness l_2 and the sample thermal diffusivity α_2 may be expressed as solid line in Fig.2. For the given Δl, the similar relation between l_2 and α_2 is also obtained as dashed line in Fig.2. The intersection of these two lines provides the thermal diffusivity value of the liquid sample α_2 and its thickness l_2.

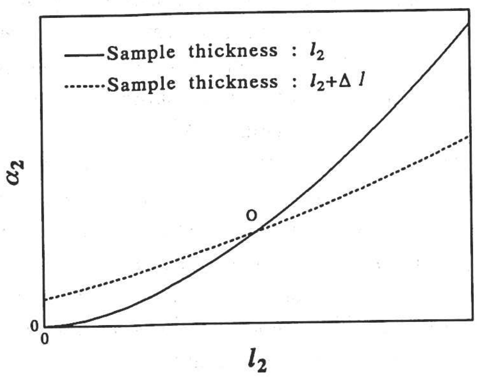

Fig. 2 Thermal diffusivity of α_2 as a function of sample thickness of l_2 estimated from the relations of Eqs.(2) and (3).

The laser flash apparatus for measuring the thermal diffusivity of high temperature melts has been described previously [9, 10] and not duplicated here. Only a few additional details are given below. A platinum crucible corresponding to the third layer contains a small amount of a liquid sample and is placed on the alumina pipe. The size of this crucible is 0.2mm thick, 10mm depth and 19mm diameter. Another smaller platinum crucible of 0.2mm thick, 14mm depth and 14mm diameter is centered to the end of an alumina tube by ceramic cement as the first layer. The tube is connected to a holder on a three axial movable arm and platinum upper crucible is located just right above the lower one to make three layered cell system. The cell system itself was heated in a platinum wounded furnace under the air atmosphere. The inner and outer crucibles were separated for several times during the course of experiments to check no bubble in a liquid sample. Then, a pulsed ruby laser beam is flashed on the top surface of the inner crucible. The temperature response curve was monitored by infrared detector focused on back surface of the outer crucible (third layer). Another temperature response curve was measured after changing the thickness of the liquid sample. The change of the sample thickness can be determined by reading a micrometer scale attached on the holder. The difference of sample thickness Δl in two sets of experiments is fixed to be 0.2mm.

It may be worth mentioning that the validity of this method has been confirmed by measuring the thermal diffusivities of molten $NaNO_3$ at 592–657 K, KNO_3 at 613–698 K and $LiNO_3$ at 539–663 K and by finding good agreement between the results and the literature values [10].

3. The thermal diffusivity values of molten continuous casting powders

The chemical composition of synthetic slags presently investigated are listed in Table 1. The measured thermal diffusivity values of liquid slags are given in Fig.3. using the results of samples containing ZrO_2 as an example. Similar results were obtained for other samples, although there are differences in detail. The scattering observed in the data of Fig.3. is considered the contribution from radiative heat transfer in a liquid sample and such point will be discussed below.

The initial time region of the temperature response curve is known not be severely affected by the radiative heat transfer. However, at higher temperature, the contribution from radiative heat transfer should be included by considering physical properties of cell system. As the first approximation, a liquid layer is considered transparent to the radiative heat transfer, that is, no radiation is absorbed or emitted from the liquid layer, whereas the radiation from a platinum

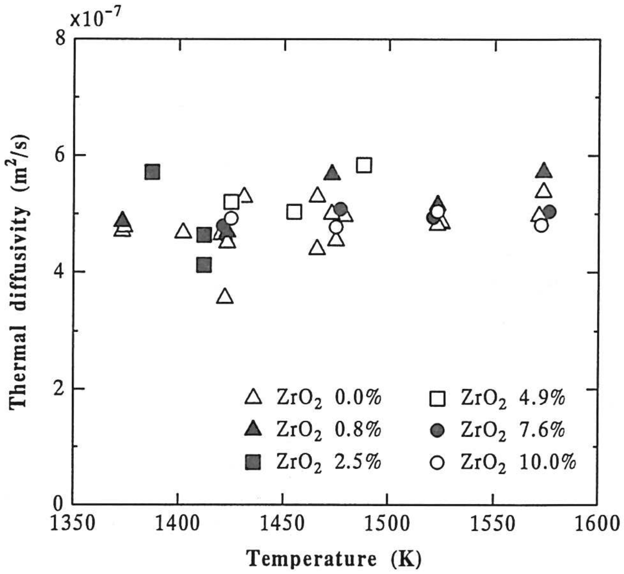

Fig. 3 Apparent thermal diffusivity of molten continuous casting powder containing ZrO_2.

Table 1 The chemical composition of synthetic slags measured in this study(wt%)

	SiO_2	CaO	CaF_2	Na_2O	MgO	Al_2O_3	ZrO_2	TiO_2
Reference	35.6	19.9	17.1	10.1	9.3	7.7		
ZrO_2 0.8%	36.0	21.0	15.8	10.0	9.4	7.5	0.8	
ZrO_2 2.5%	36.0	21.9	13.8	9.4	9.1	7.4	2.5	
ZrO_2 4.9%	35.0	20.3	15.2	9.6	8.8	7.2	4.9	
ZrO_2 7.6%	33.7	20.5	14.0	9.5	8.7	6.9	7.6	
ZrO_2 10.0%	32.8	19.1	14.2	9.1	8.7	6.9	10.0	
TiO_2 0.7%	36.3	21.1	16.4	9.8	7.9	7.5		0.7
TiO_2 2.6%	34.8	21.2	16.0	9.2	9.1	7.2		2.6
TiO_2 4.9%	33.9	21.6	15.0	8.5	8.8	7.7		4.9
TiO_2 7.4%	33.0	20.8	14.6	8.7	8.6	7.6		7.4
TiO_2 9.6%	32.5	19.6	15.0	8.7	8.5	7.5		9.6

plate is dominant. In such case, the boundary condition of heat transfer equations of may be modified so as to include the radiative heat transfer from metal plate. For the outer surface boundary the radiative heat flux F^- is expressed in the following form,

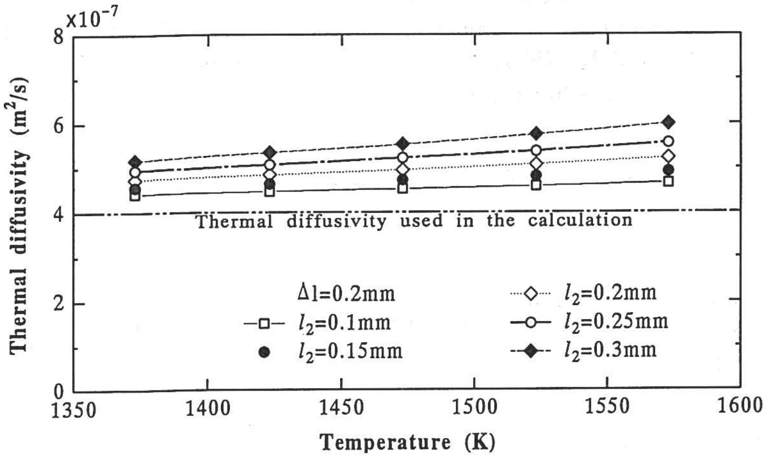

Fig. 4 Apparent thermal diffusivity considering radiative heat flow theoretically calculated on the transparent body approximation for the sample of thermal diffusivity 4 x 10^{-7} m^2/s.

$$F^- = 4\epsilon\sigma T^3\theta \tag{4}$$

where ϵ is emissivity of platinum plate, σ is Stefan-Boltzmann constant, n is the refractivity of a liquid sample and T is the temperature of a sample. For the inner boundary between a liquid sample and the platinum plate the radiative heat flux F^+ is described as follows by considering the multiple reflection of two plates,

$$F^+ = \frac{4\epsilon}{2-\epsilon} n^2\sigma T^3 \Delta\theta_{in.} \tag{5}$$

where $\Delta\theta_{in.}$ is the temperature difference of inner surface of two plates. The heat transfer equations including the radiative heat fluxes given by eqs.(4) and (5) were solved by the finite difference method. The temperature response is calculated with respect to the experimental condition, and from such information the thermal diffusivity value can be estimated by the same procedure as for the measured temperature response. The results are shown in Fig.4 in the case of a sample whose thermal diffusivity of 4 $\times$ 10^{-7} m^2/s. It could be drawn from these results that the contribution from radiative component in the transparent liquid case increase with the increasing the sample thickness and the temperature of a sample.

When the transparent body approximation is not well-accepted as for a sample including iron oxide, the absorption and emission in a liquid layer should be considered. Darby[11] has proposed the basic equations by considering all mode of radiative heat transfer. We made numerical calculation using Darby's equations coupled with the control volume method [13], For simplification, wd also employed the gray body approximation in which the spectral absorption coefficient is reduced to effective absorption coefficient $\kappa_{eff.}$. The temperature response was

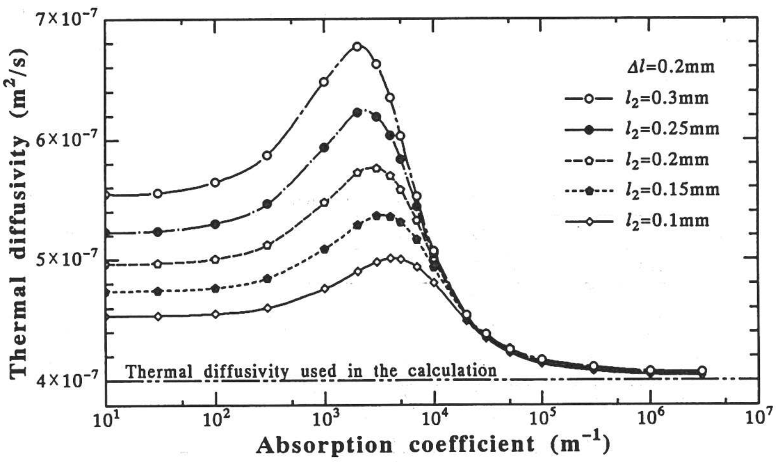

Fig. 5 Apparent thermal diffusivity considering radiative heat flow theoretically calculated on the gray body approximation for the sample of thermal diffusivity 4 x 10^{-7} m^2/s.

calculated as a function of $\kappa_{eff.}$ and then the thermal diffusivity value was estimated by the differential scheme. The results are shown Fig.5. The usefulness of the present calculation may be confirmed by finding good agreement with the value of the Rosseland approximation[12] in the higher absorption region ($l_2\kappa_{eff.} \gg 1$) where the radiative conductivity $\kappa_{eff.}$ expressed by $16n^2\sigma T^3/3\kappa_{eff.}$ is well-accepted. On the other hand, it may also be noted that the present results in the lower absorption region are consistent with those of the transparent body approximation.

The effective absorption coefficient of slag samples were calculated using the gray body approximation from spectral absorption coefficient of corresponding samples in the glassy state. Table 2 shows the effective absorption coefficients for cases where the spectral data are available. The results of Table 3. suggest that with the help of the information of Fig.5. that the transparent approximation is well accepted for slag samples presently investigated.

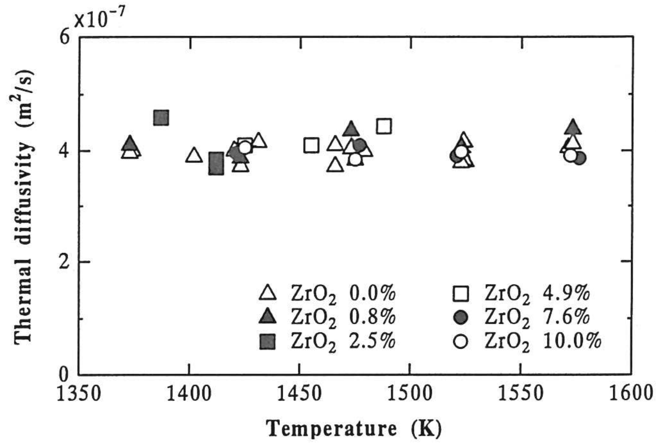

Fig. 6 Thermal diffusivity of molten continuous casting powder containing ZrO_2.

Table 2 Effective absorption coefficient of samples (m^{-1}).

	1373 K	1423 K	1473 K	1523 K	1573 K
Reference	47.2	45.2	43.5	35.5	46.1
ZrO_2 0.8%	127	123	120	117	114
ZrO_2 4.9%	81.1	77.9	75.2	72.7	70.6
TiO_2 2.6%	135	131	127	124	121
TiO_2 9.6%	97.0	93.6	90.7	88.1	85.8

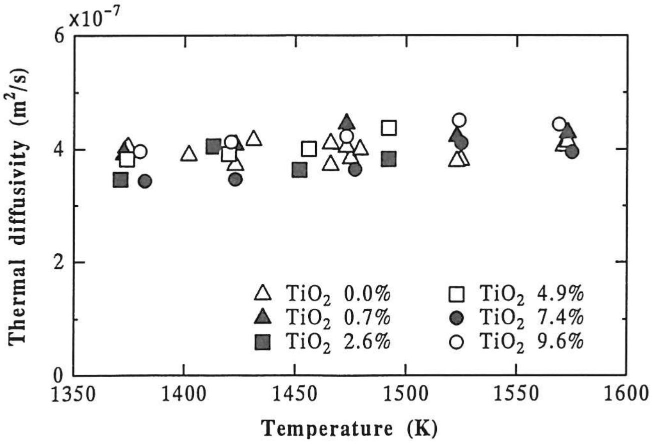

Fig. 7 Thermal diffusivity of molten continuous casting powder containing TiO_2.

On the basis of these results, the contribution from radiative heat transfer was separated from measured thermal diffusivity values of slag samples and the resultant information are summarized in Fig.6 and 7. The thermal diffusivity values of liquid slags presently investigated are of the order of 4×10^{-7} m^2/s and their temperature dependence is not so explicit. It may be also added that the effect of addition of TiO_2 and ZrO_2 up to 10wt% on the thermal diffusivity of this slag system is insignificant.

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