

Thermal Diffusivity Measurement of Ferrofluids by the Laser-induced Thermal Grating Technique

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Abstract: In this report, the experimental thermal diffusivity data are presented for different concentrations of ferrofluids. The thermal diffusivity measurements are conducted using a laser-induced thermal grating technique at room temperature and atmospheric pressure. The ferrofluids studied have volume fractions ranging from 5% to 10%. Because of the small temperature rise in the thin sample during the measurements and the very short measuring time of a few milliseconds, the influence of free convection can be ignored. The results show very good agreement with the experimental data in the openly published literatures, and thereby indicate the feasibility of the technique proposed in this report.

Key words: ferrofluids; thermal diffusivity; laser-induced thermal grating; diffraction

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Most conventional heat transfer fluids, such as water, ethylene glycol and engine oil, have limited capabilities in term of thermal properties, which in turn, may impose severe restrictions in many thermal applications. Fluid containing solid particles may significantly increase its conductivity, the heat transfer coefficient can considerably be augmented. Fluid containing millimetre or micrometer size particles have unfortunately introduced serious drawbacks such as drastic pressure drop, rapid settling of particles, severe clogging as well as premature wear of flow channels and its components. In recent years, modern technologies have permitted the manufacturing of particles down to the nanometre scale, which have created a new class of fluids, called nanofluid^[1].

Ferrofluids (magnetic fluids) are very stable colloidal suspensions of ultrafine single domain

magnetic particles (about 10 nm in size) in a suitable carrier liquid. Because of their unusual physical and magnetic properties, they have an increasing number of commercial and industrial applications, such as sealing, grinding, bearings, machinery processing, heat transferring and so on^[2-5]. In recent years, ferrofluids as a new type of heat transfer medium attracts more and more attention^[6-8]. After adding some ferrofluids, the heat conductivity of the original medium can be remarkably improved, and the natural convection also has been strengthened by the magnetic field. However, because of the fluidity, the thermal diffusivity measurement is very difficult, a few papers reported the thermal diffusivity measurement of ferrofluids^[9-10].

These methods for measuring the thermal diffusivity of liquid include the transient hot-wire method^[11], the laser-induced thermal grating

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method^[12-13], the collinear mirage method^[9-10] and the Angström's method^[14].

This paper describes an experimental investigation of the thermal diffusivity of ferrofluids at room temperature and atmospheric pressure. The measurements were carried out using the laser-induced thermal grating technique.

1 Theory

The theory and the experimental setup of the laser-induced thermal grating technique have been described in detail in [12-13]. Fig.1 shows the principle of this measurement technique. A pulsed laser beam of wavelength λ_h is split into two beams of equal intensity with a beam-splitter. Subsequently, the two beams intersect each other at an angle θ in the sample of thickness d and generate a spatially periodic intensity distribution during a light pulse ($0 < t < t_h$). The period Λ of the interference pattern can be obtained.

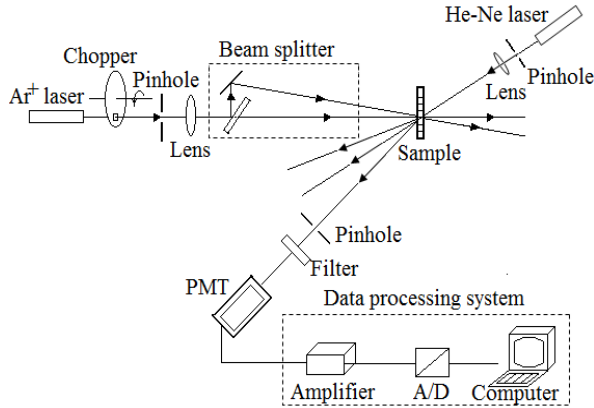


Fig.1 Experimental arrangement for measuring thermal diffusivities of ferrofluids

$$\Lambda = \lambda_h / 2 \sin(\theta / 2). \quad (1)$$

By absorbing the light intensity, a spatially modulated, time-dependent temperature field (i.e., a transient thermal grating) is induced that corresponds to the intensity distribution in the interference region, and a periodic distribution of the refractive index appears due to this temperature distribution. The one-dimensional heat conduction equation of sample can be expressed as follows:

$$\rho C_p \frac{\partial T}{\partial t} - k \frac{\partial^2 T}{\partial y^2} = \beta I_h, \quad (2)$$

where T is temperature, t is time, ρ is the density, C_p is the specific heat, k is the thermal conductivity, y is the direction of heat transfer, β is an absorption coefficient, I_h is the intensity of the incident beam.

After a heating light pulse ($t > t_h$), the thermal grating decays due to heat conduction in the sample. For $t > t_h$, one obtains the temperature fluctuation in the modulation direction of temperature (y direction):

$$T(y, t) = T_0 + \Delta T_0 [1 + \cos(qy) \exp(-t/\tau)], \quad (3)$$

where T_0 is the initial mean temperature, ΔT_0 is the spatial temperature, q is the wave number of the interference pattern, $q = 2\pi/\Lambda$, τ is the relaxation time, which can be expressed as follows:

$$\tau = \Lambda^2 / (4\pi\alpha), \quad (4)$$

where α is the thermal diffusivity, $\alpha = k / (\rho C_p)$.

Because the sample is thin enough, the first-order diffracted probe laser beam intensity, I_1 can be given as follows:

$$I_1 = I_0 \phi_m^2 / 2, \quad (5)$$

$$\phi_m = 2\pi d / \lambda_p (\partial n / \partial T) \Delta T(t), \quad (6)$$

where ϕ_m is the maximum phase variation of grating, I_0 is the incident intensity of the probe beam, d is thickness of sample, λ_p is the wavelength of the probe beam, $\partial n / \partial T$ is the temperature coefficient of the refractive index, $\Delta T(t)$ is the maximum temperature amplitude in Eq.(3), which can be expressed as follows:

$$\Delta T(t) = \Delta T_0 \exp(-t/\tau). \quad (7)$$

Therefore, the time dependence of the normalized first-order diffracted probe laser beam intensity, $I_{\text{norm}}(t)$, is expressed as follows:

$$I_{\text{norm}}(t) = \exp(-2t/\tau). \quad (8)$$

As a result, the relaxation time τ can be evaluated with the least-squared method. The thermal diffusivity α is then determined as

$$\alpha = 1 / (\tau^2 q) \approx \lambda_p / (\tau (2\pi\theta)^2). \quad (9)$$

2 Experiment

Ferrofluids are composed by magnetic particles,

with typical dimensions of about 10 nm, dispersed in water. Each particle is coated with a surfactant to prevent their aggregation. The ferrofluids (Fe_3O_4) are prepared by co-precipitation in our own laboratory. Different concentrations of ferrofluids were used, varying the volume fraction from 5% to 10% in water. The samples were encapsulated in cuvettes 0.5 mm thick on the side and 40 mm diameter. In this study, the samples were not submitted to a magnetic field, keeping its isotropy. The measurements were performed at room temperature ($T=23.0\text{ }^\circ\text{C}$) and atmospheric pressure.

Fig.1 shows the experimental apparatus. As shown in fig.1, an argon ion laser ($\lambda_h = 514.5\text{ nm}$) for generating the thermal grating, and a helium-neon laser ($\lambda_p = 632.8\text{ nm}$) acts as the probe laser being diffracted by the grating. The first-order diffracted probe beam pass through a pinhole of $200\text{ }\mu\text{m}$ diameter and a band pass filter, and detected by a photomultiplier tube.

3 Results and discussion

Using the laser-induced thermal grating technique, the thermal diffusivity of ferrofluids has been measured at room temperature ($23.0\text{ }^\circ\text{C}$) and atmospheric pressure.

Fig.2 shows the diffracted signal (output voltage from the PMT) as function of time recorded by data processing system. The decay data was fitted to single exponential equation with the least-squares method to evaluate the relaxation time τ , which are $745.4\text{ }\mu\text{s}$ and $619.4\text{ }\mu\text{s}$, and the thermal diffusivity calculated from Eq.(9) are $0.221\text{ mm}^2\cdot\text{s}^{-1}$ and $0.266\text{ mm}^2\cdot\text{s}^{-1}$.

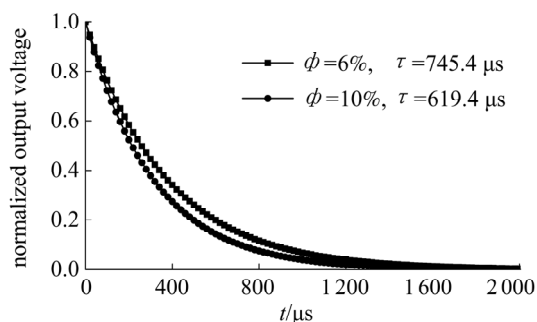


Fig.2 Typical diffracted signals and the fitted curves by the exponential least-squares method

The results of measurements and the comparison between experiments and the open literature are shown in table 1. The errors are separately 0.8% and 0.7%, and are very small.

Table 1 Comparison of thermal diffusivities between experiment and open literatures for two different ferrofluids concentrations

ferrofluids concentration/%	thermal diffusivity/($\text{mm}^2\cdot\text{s}^{-1}$)	
	experiment	literature [9]
6	0.221	0.223
10	0.266	0.268

Fig.3 shows the data of six samples with variable ferrofluids concentrations. The function relationship between the measured thermal diffusivity value and the volume fraction can be approximated by a straight line:

$$\alpha = C_0 + C_1\varphi, \quad (10)$$

where C_0 and C_1 are gotten by the least-square method. When $\varphi = 0$, $\alpha = 0.158\text{ mm}^2\cdot\text{s}^{-1}$, the thermal diffusivity of water derived here, is a few different from the value $0.140\text{ mm}^2\cdot\text{s}^{-1}$ derived from the literature [14], that may be caused by no taking the influence of the surfactant into account. As the ferrofluids concentration increases, the thermal diffusivity increases from $0.212\text{ mm}^2\cdot\text{s}^{-1}$ to $0.266\text{ mm}^2\cdot\text{s}^{-1}$.

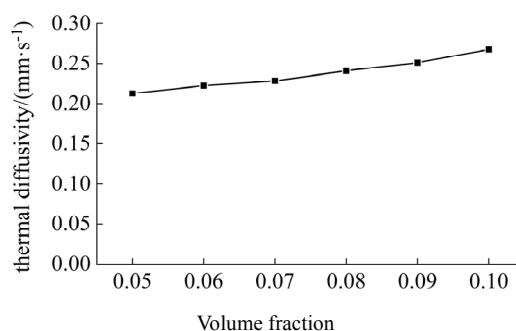


Fig.3 The data of six samples with variable ferrofluid concentrations and the fitted linear line

4 Conclusions

The thermal diffusivity of ferrofluids with different volume concentrations have been measured at room temperature and atmospheric pressure. The experimental results show that the thermal diffusivity of ferrofluids increase relative to that of water.

A comparison between the measured data and those of other investigators shows the errors is very small. They indicates the same trend that the thermal diffusivity of ferrofluids increases along with the increase of the volume fractions.

Using the least-squares linear fitting method to get the function relationship between the measured thermal diffusivity value and the volume fraction, it is found that the thermal diffusivity of water derived is greater than the data of other investigator, which is attributed to the influence of the surfactant.

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激光诱导光栅技术测量磁性液体的热扩散系数

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摘要: 在室温和常压下采用激光诱导光栅技术实验测量不同体积分数的磁性液体的热扩散系数, 体积分 数分别为 5%, 6%, 7%, 8%, 9%和 10%。由于在磁性液体薄片上的升温非常小以及毫秒级的测量时间, 自由 对流所产生的影响可以忽略不计。用激光诱导光栅技术测的数据与已有文献中的实验数据比较吻合, 从 而说明该技术在磁性液体的热扩散测量上是可行的。

关键词: 磁性液体; 热扩散系数; 激光诱导光栅; 衍射

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