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3D Particle Imaging Thermometry and Velocimetry (PITV) using Liquid Crystal
—2nd Section; Time Response Characteristics of the Micro-capsulated Liquid Crystal—

感温液晶粒子を用いた3次元粒子画像温度・速度計測法
—第2報; マイクロカプセル化された感温液晶粒子の時定数特性—

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1. INTRODUCTION

As stated in the previous section of this paper, the response time of the micro-capsulated liquid crystal particle is another important factor for the application of this particles as a temperature tracer.

The effect that leads to a visible temperature phenomenon is a two-step process. If we cause an instantaneous change in the temperature of a chiral nematic liquid crystal, the medium will have, in general, a new pitch corresponding to a minimum free energy[1]. It has been reported by Fergason[2] that the shift of the peak wavelength in response to a sudden change in temperature level occurs with a time constant of 0.1 second in cholesteryl nonanoate and 0.2 second in cholesteryl oleyl carbonate. McElderry's[3] result reports that the response time of the microcapsulated liquid crystal particle is in the order of 0.1 to 0.2 second. The considered time response was based on the result of thin film tests in which the heat capacity of the capsule of the micro-capsulated liquid crystal itself was not considered. The response of a film of micro-capsulated chiral nematic to a rapidly increasing surface temperature was assessed by Ireland et al.[4]. Rates of increase in temperature of greater than 2000°C/sec were employed and experiments showed the delay between the time at which the surface reaches the steady state color display temperature, and the occurrence

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of the color display in the TLC film to be no more than a few milliseconds. In this case, the film was heated by an aluminum foil exposed to still air. And this compares with values by Fergason[2] for thermal time constants of cholesteric mixtures which are of the order of hundreds of milliseconds. The response times applied in many studies were based on the results of their experiments respectively. In their studies the delay behavior is the traceability of color to the change of temperature of the particle regarding the molecular structure. And most of their results were for the film containing the microcapsulated liquid crystal particles.

For the use of the micro-capsulated liquid crystal particle itself as a temperature sensor in the suspending method, the heat capacity of the capsule itself should be regarded as an important factor in predicting the time response of the micro-capsulated liquid crystal directly injected in a thermal fluid flow. Without a new temperature sensor smaller than the particle, it is very difficult to measure the time response of the microcapsulated liquid crystal itself. And therefore a numerical simulation for the time response is considered in this study.

2. TIME RESPONSE OF THE MICRO-CAPSULATED LIQUID CRYSTAL PARTICLE

Micro-encapsulation[5] is a unique approach to protect the liquid crystal from the environment. In this process minute droplets of crystals are dispersed in an aqueous mixture of gelatin and gum arabic. The liquid crystal is coated with gelatin in a polyvinyl alcohol binder. And since the specific gravity of the micro-capsulated liquid crystal is not equal to

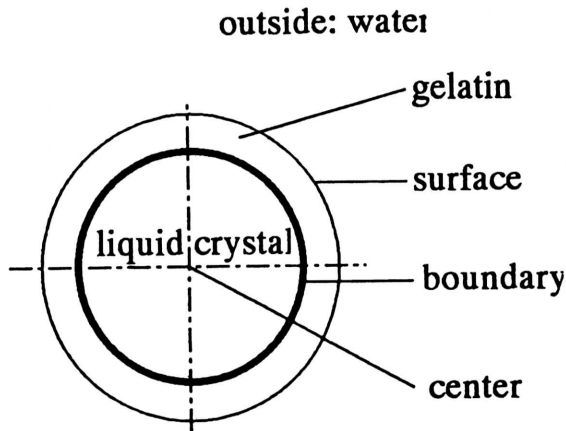||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||

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outside: water

Figure. 1　Structure of micro-capsulated liquid crystal particle.

Table 1　Physical properties of the particle.

properties　　　parts	capsule	liquid crystal
thermal conductivity [J/seccm °C] , λ	0.38	0.14
heat capacity [J/m³ °C , ρ Cp	3.105×10^6	1.50×10^6

that of fluid, a relative velocity may be exist, though small. From these facts, the Reynolds number for the particle is regarded very small, about 1 related to Kolmogrov scale.

$$\rho \, Cp \, \frac{\partial T}{\partial t} = \lambda \, \frac{\partial}{\partial r} \left(\frac{\partial T}{\partial r} \right) \tag{1}$$

Considering the above facts, the heat transfer equation for the micro-capsulated liquid crystal particle in spherical coordinate can be written as the equation (1). Figure 1 shows the schematic picture of the micro-capsulated liquid crystal particle and its physical properties are shown on table 1. Thickness of the micro capsule is based on Parsely's data[6]. The physical properties of gelatin are reported on the monthly report of agricultural and biological chemistry reported by Kong[7] and Sakiyama[8]. Since the particle is spherically symmetric, the equation (1) can be rewritten as an one-dimensional equation. And the linear algebraic equation of the reformed equation can be expressed as the equation (2).

$$\Delta V \frac{\partial T}{\partial t} = \alpha \left[\Delta S_+ \frac{\partial T}{\partial r_+} - \Delta S_- \frac{\partial T}{\partial r_-} \right] \tag{2}$$

Here, r means the radius of the particle and Δ V is equal to

$4/3 \, \pi r^3$, the volume of an element. ΔS_+ and ΔS_- are equal to $4 \pi r^2$, the surface area of an element. The sign + means the left nodal point of the control volume of the calculation grid impliciting the direction of the heat flux is toward the center of the particle and the sign − means the opposite direction, toward the outside of the particle. The boundary conditions of the center of the micro-capsulated liquid crystal particle, the boundary between the liquid crystal and the capsule, and the boundary between the capsule and outside of the capsule are able to be expressed as equations (3), (4), and (5), respectively.

$$\Delta \, V_1 \frac{T_1^{n+1} - T_1^n}{\Delta t}$$
$$= \alpha \left[\Delta \, S_+ \frac{T_2^{n+1} - T_1^{n+1}}{\Delta r_+} - \Delta \, S_- \frac{T_2^{n+1} - T_1^{n+1}}{\Delta r_-} \right] \tag{3}$$

$$\left[(\rho Cp \Delta V)_l + (\rho \, Cp \Delta V)_g \right] \frac{T_{NL}^{n+1} - T_{NL}^n}{\Delta t}$$
$$= \lambda g \Delta \, S_g \left[\frac{T_{NL+1}^{n+1} - T_{NL}^{n+1}}{\Delta r_+} \right] - \pi_l \Delta \, S_l \left[\frac{T_{NL}^{n+1} - T_{NL-1}^{n+1}}{\Delta r_-} \right] \tag{4}$$

$$(\rho \, Cp \Delta V)_{NS} \frac{T_{NS}^{n+1} - T_{NS}^n}{\Delta t} =$$
$$-(\lambda g \Delta S_g)_{NS+1} \left[\frac{T_{NS}^{n+1} - T_{NS-1}^{n+1}}{\Delta r} \right] - \Delta \, S_g \, \alpha (T_{NS}^{n+1} - Tf) \tag{5}$$

In the above equations, the subscript 1 means the center of the particle and the subscript 2 means the next grid point. The λ means the thermal conductivity the subscript g means the gelatin layer, and the l means the layer of liquid crystal. The super letter NL means the grid point on the boundary between the liquid crystal and the gelatin layer. The super letter NS means the grid point on the boundary between the gelatin layer and the surface of the particle. The subscript f means the fluid side containing the particle and α means the thermal diffusivity. At this time, since the time response is dependent upon the flow field and the experimental conditions, namely, Nusselt number, the correct physical interpretation of the liquid crystal's transient behavior can be attained only through knowledge of the time response behavior. In this study, Vliet's data[9], equation (6) is used as the boundary condition between the capsule and the water.

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$$\alpha d / \lambda = (1.2 + 0.53\, Re^{0.54})Pr^{0.30}(\mu / \mu_w)^{0.25}$$

where, $(2 < Pr < 380,\ 1 < Re < 300000)$

(6)

Here, d is the diameter of the liquid crystal particle. Furthermore, μ means the viscosity of liquid crystal and μ_w means that of water.

The highest Lagrangian frequency felt by the particle itself who is moving with the flow is proportional to $u/v \sim Re^{1/4}$ (u is fluctuating velocity and v is the Kolmogorov velocity)[10]. This frequency is related to the response of the frequent change of temperature of the flow.

Consequently, the response time of the liquid crystal particle itself is examined on the condition of the equation (6). Figure 2 shows the step response of the micro-capsulated liquid crystal particle.

The time response resulted through this method was 150 ms on the condition that the response has reached up to 99 percent of the input. Figures 3 shows the response of the micro-capsulated liquid crystal particle for the fluctuating change of the temperature of fluid when the frequency is 1 Hz. The notable response is the dotted line, which means the representative response of the particle.

And the highest lagragian frequency based on this was 20 Hz. For the 20 Hz, the frequency response has been calculated by solving the equation (1) and the result showed about 85 percent traceability for the fluctuating fluid temperature. Another important factor for the time response of the micro-capsulated liquid crystal particle is a thermal inertia problem of the particle. When the particle is moving with the fluid from the upstream of the thermal fluid
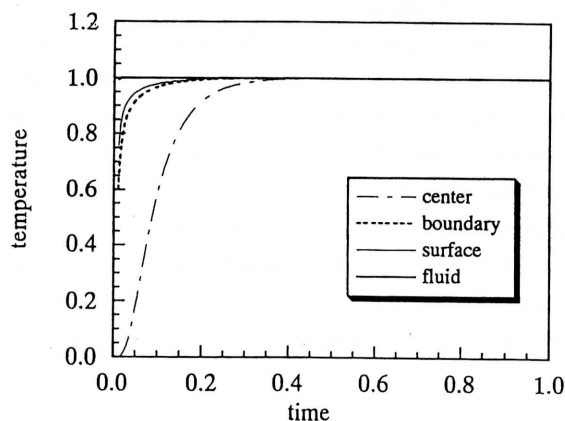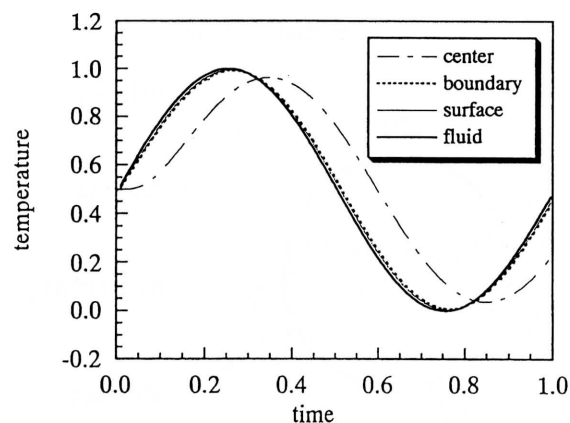

Figure. 3　Frequency response (1 Hz).

flow to downstream, it is possible for the particle to have a past history of the upstream temperature. This can be said as a kind of thermal inertia of the particle moving toward downstream. This thermal inertia should be considered as a bias error for the temperature measurement.

In this study, since the experiment for temperature measurement is undertaken for a turbulent vertical buoyant jet in the self-preservation region, the quantitative analysis for the thermal inertia is considered using the conventional inspection done by Chua[11]. By using the empirical formulas representing the spatial temperature distribution and the spatial velocity distribution, the temporal distribution of temperature in the self-preservation region can be deduced. And then, this temporal distribution of temperature is used as an input for the micro-capsulated liquid crystal particle for predicting the behavior of thermal inertia numerically. Figure 4 shows the result of thermal inertia. The temperature difference tested in this study is from 22.8°C to 30°C to
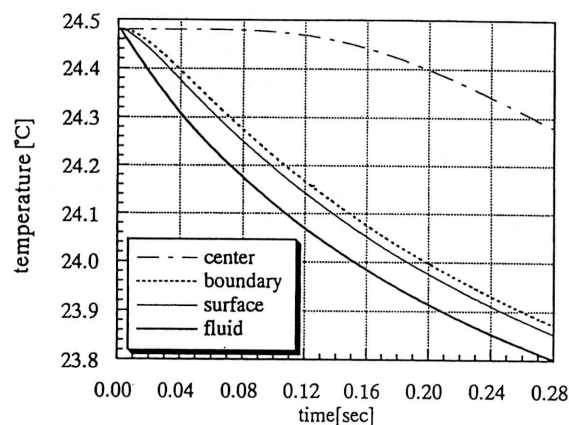

Figure. 2　Step response.

Figure. 4　Response for thermal inertia.

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be the experimental conditions. From this figure, it can be said that the temperature error from the thermal inertia in the jet is about 0.08°C in this case. This error is a kind of bias error for the temperature measurement while the differences of the amplitudes on the frequency response explained in advance is a random error for the temperature fluctuation.

3. CONCLUSIONS

Since the micro-capsulated crystal particle has a heat capacity, there exists a certain time delay for the response of color for the temperature change of the outside of the particle. And also the response characteristic is different according to the conditions of the thermal fluid flow containing the micro-capsulated liquid crystal. This means that for using this microcapsulated liquid crystal particle as a temperature sensor, the experimental conditions such as the highest lagrangian frequency explained in the previous section should be obtained in order to evaluate the traceability of the color change of the particle to the temperature change of the thermal fluid flow quantitatively. From the test of step response, it can be said that the time delay 150 msec is the relaxation time of the particle for an abrupt step change of temperature meaning the physical properties. For the temperature fluctuation of the fluid, the response of the particle is relatively reasonable in a sense that the 85 percent of the fluctuating component of the fluid temperature can be traceable, which is comparable to other temperature measurement methods such as thermo-couples, cold wires, and etc. The maximum error from the thermal inertia of the particle is 0.08°C which is relatively small and this error is a kind of bias error.

Since most of the time delay depend on the thickness and the physical properties of the capsule, for an improvement of the response characteristic of the microcapsulated crystal particle, a counteract for this problem can be adopted considering a new encapsulation technique that reduces the thickness of the capsule and reduces the heat capacity of the capsule itself by selecting another chemical alternative of which heat capacity is smaller than gelatin.

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