TEMPERATURE SENSITIVE PARTICLES FOR THE 3-D SIMULTANEOUS MEASUREMENT OF VELOCITY AND TEMPERATURE

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ABSTRACT

Temperature sensitive particles have been developed which enable the three-dimensional simultaneous measurement of velocity and temperature in a fluid flow. Even with the recent advances in experimental techniques in the fluid mechanics and the thermal engineering, the three-dimensional simultaneous measurement of all the three components of velocity and the temperature in the turbulent field could not be performed. As for the velocity field, one can carry out the three-dimensional measurement with the aid of the three-dimensional particle tracking velocimetry (3-D PTV). But, as for the temperature field, the laser-induced fluorescence technique (LIF) can only provide the two-dimensional dense distribution of temperature. Presently, the authors have developed two types of temperature sensitive particles which contain the fluorescence material inside. By using these particles as the tracer for the 3-D PTV, the simultaneous temperature measurement can be carried out within the framework of the 3-D PTV. In this study, the preparation procedures for the temperature sensitive [(W/O)/W] microcapsule and (O/W) microparticle have been demonstrated. The temperature calibrations for these particles have proved the applicability of the present particles to the temperature measurement and the uncertainties at 20:1 odds are found to be 1.18 degree and 0.78 degree respectively. The preliminary experiment in a natural convection layer have shown that the signal to noise ratio of the camera should be improved for the actual measurement.

INTRODUCTION

In order to investigate the mechanism of the turbulent heat transfer, it is crucial to obtain the information about the turbulent statistics by experiments. The accumulation of the experimental data will also contribute to the improvement of mathematical model of turbulence. With recent development in experimental measuring techniques for velocity and temperature with the aid of digital image processing and visualization techniques, two-dimensional or three-dimensional measurement of velocity or temperature can now be carried out. But, it is still impossible to measure the three-dimensional distribution of instantaneous temperature or concentration and all the three components of velocity fluctuation simultaneously.

As for the measurement of the velocity field, the three-dimensional particle tracking velocimetry (3-D PTV), which has been developed by Nishino et al. (1989), can give the three-dimensional distributions of all the three component of velocity vectors simultaneously. While with the particle imaging velocimetry (PIV), which has been developed by Adrian (1991), one can obtain the dense distribution of fluid velocities in a plane of the laser light sheet which is inevitably two-dimensional both in distribution and in components. When we talk about the temperature measurement, the laser-induced fluorescence technique (LIF) enables us to measure the two-dimensional distribution of temperature. As for the simultaneous measurement, Sakakibara et al. (1993) have coupled PIV with LIF to measure the distribution of instantaneous velocity and temperature simultaneously, but the measurement was restricted in a plane of the laser light sheet and the velocity component which is perpendicular to the plane of observation has not been obtained. Under the assumption that the flow is stationary or very slow, these methods can be extended to the three-dimensional field and thus the pseudo three-dimensional measurements can be carried out. For example, Dahm et al. (1991) have scanned the laser light sheet of LIF very fast, and thus obtained a temporal evolution of three-dimensional temperature distribution. While Sato et al. (1996) have scanned the laser light sheet for PIV and LIF and have accumulated the two-dimensional images to reconstruct the three-dimensional distributions of velocity and temperature. Even with this improvement, the third velocity component which is perpendicular to the laser light sheet is still not known. Some trials have been made to carry out the simultaneous measurement of velocity and temperature with thermo-chromic liquid crystal (TLC) but in vain, because the temperature range of its color variation is very narrow and thus its measurement accuracy is limited.

As the first author of this study is one of the contributor to the development of the 3-D PTV, which is a very powerful tool for measuring the three-dimensional velocity field, the present study aims at an improvement of the 3-D PTV that enables the simultaneous temperature measurement. As for the temperature measurement, LIF is very useful. It is non-intrusive and is suitable for image processing, but its observation is restricted to two-dimensional as it uses the laser light sheet for the visualization. In order to overcome these shortcomings, the authors of this study tried to encapsule the fluorescent material inside of the microcapsule or the microparticle, and have succeeded in obtaining the temperature sensitive particles that enable the three-dimensional simultaneous measurement of velocity and temperature. As the 3-D PTV utilizes only the positional information of the particle images, the changes in the brightness of the particle images do not affect the framework of the 3-D PTV. If the microcapsule that contains the fluorescent substance inside is used for the tracer particle for the 3-D PTV, the three-dimensional simultaneous measurement of velocity and temperature can possibly be carried out. Presently, the preparation method of this particle is demonstrated and the accuracy for the temperature measurement by this particle is quantified. Finally, the preliminary experiments for the three-dimensional simultaneous measurement of velocity and temperature in the natural convection layer is carried out and the problems for the actual measurement are made clear.

TEMPERATURE SENSITIVE PARTICLES

In this study, we have developed two types of temperature sensitive particles. First we tried to keep the aqueous solution of the fluorescent dye inside of the microcapsule. Secondly, we have mixed the fluorescent dye directly into the constituent of the microparticle.

Figure 1 shows the SEM photograph of the temperature sensitive microcapsule prepared in this study. This microcapsule contains the aqueous solution of Rhodamine B inside of its thin membrane of polystyrene. As most of this microcapsule is consisted of water, its characteristics, such as specific density and thermal conductivity, are almost same as those of water. Thus the convective and the conductive behaviors of this microcapsule are almost the same as those of water except that its deformation is limited. So if the size of the microcapsule is comparable to or smaller than the turbulent microscale, this microcapsule almost perfectly traces the motion and also the temperature of the fluid. As shown in figure 1, the shape of the microcapsule is nicely spherical and its roundness is approximately 1 micron with the diameter of about 100 microns.

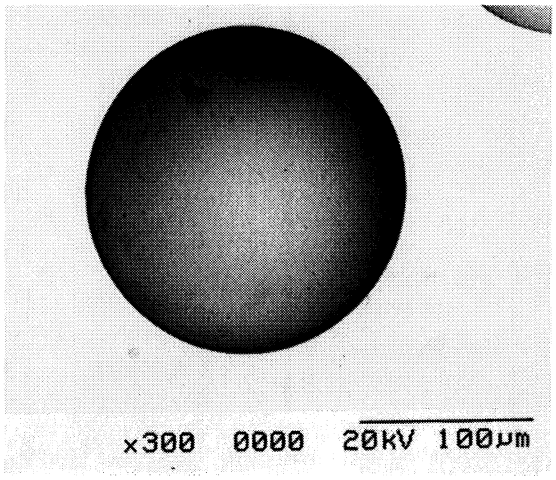
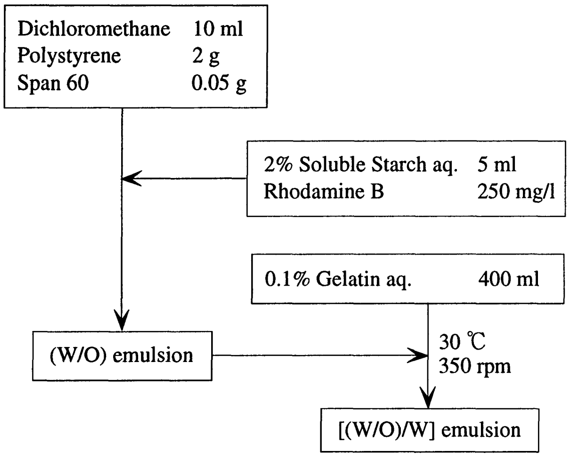


Figure 1. SEM photograph of the microcapsule

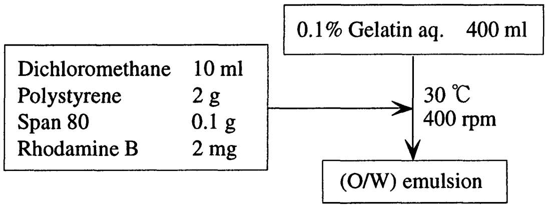
On the other hand, the temperature sensitive microparticle is consisted almost all of polystyrene, whose specific density is about 1.05. Thus it is slightly heavier than water. Moreover, the thermal conductivity of this microparticle may be somewhat smaller than that of water. Nevertheless, this microparticle is much easier to prepare and can contain much higher concentration of the fluorescent dye. Walker (1987) showed that the intensity of the fluorescence is proportional to the concentration of the fluorescent dye. Thus the intensity of the fluorescence of this microparticle is expected to be much higher than those of the aqueous solution. As a result, the characteristics of the former particle is more ideal and that of the latter is more down-to-earth.

PREPARATION METHODS

Microcapsule has been utilized in many applications. It is very useful since many kinds of substance can be kept inside and can be suspended in an environment without being mixed up. In spite of this potential advantage, the solution of Rhodamine B could not be kept inside. As the membrane of the microcapsule is consisted of the polymer chains of polystyrene which is educed from the organic solvent, there are many small holes on the membrane. As the size of the dye molecule is much smaller than the holes of the polymer membrane, the molecules of the fluorescent dye easily penetrate the membrane and soon diffuse into environment. Presently, we have let the



(a) [(W/O)/W] microcapsule



(b) (O/W) microparticle

Figure 2. Flowchart of the preparation procedure

molecules of the fluorescent dye be physically absorbed to other polymer molecule whose size is bigger than the holes of the membrane and have succeeded in keeping the fluorescent dye inside of the microcapsule. As for the absorbing molecule, we used the soluble starch.

The microcapsule is prepared as the [(W/O)/W] type emulsion. The preparation method of the microcapsule in this study is based on the method by Kondoh and Koishi (1987). First, the aqueous solution, the inner water phase W, of the fluorescent dye is dispersed into the polymer solution to the organic solvent, the intermediate oil phase O, with an appropriate type and amount of emulsifier, thus the W/O type, which means that "W"ater is dispersed in "O"il, emulsion is prepared. Second, this W/O type emulsion, which acts as the inner oil phase, is again dispersed into water, which is the outer water phase W, thus we get the so-called [(W/O)/W] type emulsion. Third, the organic solvent is volatilized through the outer water phase and let the polymer be extracted to form the membrane. Figure 2(a) shows the flowchart of the preparation procedure of the [(W/O)/W] emulsion. Finally, by washing out the emulsifier and the excessive Rhodamine B which has not been absorbed to the starch very well, we obtain the temperature sensitive microcapsules. Attention should be paid for the treatment of the exhaust gas and the discharge of the wasted water, because the dichloromethane, which is used as the organic solvent, is toxic and carcinogenic. The details of the preparation procedure is found in Ninomiya et al. (1998).

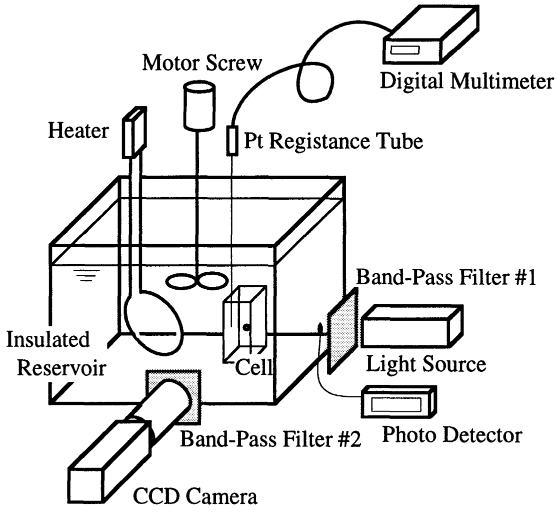


Figure 3. Experimental apparatus for calibration

Here the concentration of Rhodamine B seems extremely high compared to the ordinary LIF measurement in water, but as we have enclosed the fluorescent dye inside of the microcapsules and thus the concentration quenching, which is the result of the absorption of the fluorescence by the surrounding fluid, does not occur. As a result, the present microcapsule emits much brighter fluorescence compared to the aqueous solution of Rhodamine B.

We have also prepared the temperature sensitive microparticle as the (O/W) type emulsion, which is a version of the [(W/O)/W] type emulsion that does not have inner water phase. As Rhodamine B is also soluble to dichloromethane, the solution of the polystyrene and the fluorescent dye to dichloromethane is dispersed into water with adequate emulsifier to obtain the (O/W) type emulsion. Figure 2(b) shows the flowchart of preparation procedure for the (O/W) emulsion. By drying the volatile organic solvent, polystyrene is extracted as the microparticle, with which Rhodamine B is also extracted at the same time. Although this microparticle is solid and is slightly heavier than water, we can put much higher amount of the fluorescent materials inside.

TEMPERATURE CALIBRATION

In order to certify that the present particles have the temperature sensitivity, we have measured the intensity of the fluorescence emitted from the present particles at various temperatures. Figure 3 shows a schematic view of calibration apparatus. A particle was kept in a cell of plexiglass and its temperature is measured by the platinum resistance tube and a digital multimeter. The reservoir is

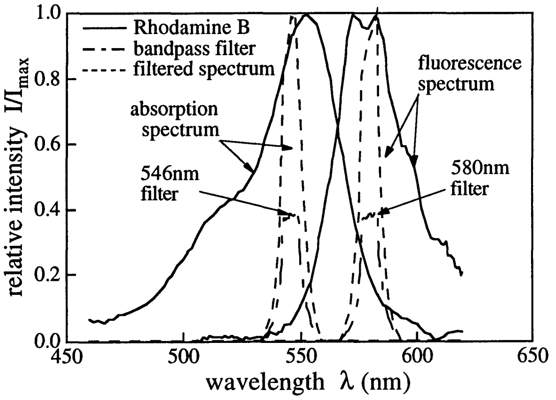


Figure 4. Optical characteristics of Rhodamine B

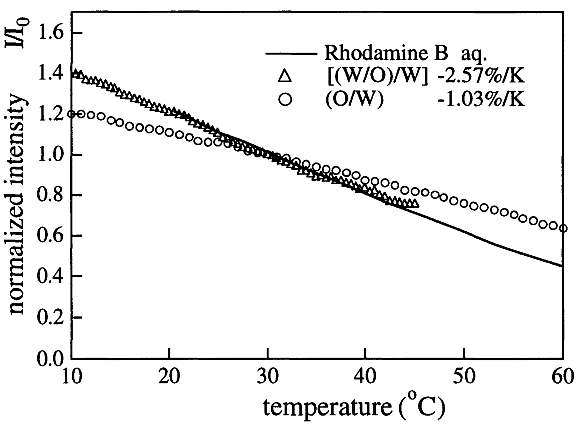


Figure 5. Calibration plot for temperature

insulated by the Styrofoam and has two side windows, one is for the illumination and the other is for the observation. The particle is illuminated by the filtered light from the halogen lamp which is introduced by the fiber optics. The band-pass filter #1 passes the light only around 546 nm. The intensity of the illumination was monitored by the photo detector and that of the fluorescence was measured by the CCD camera (Panasonic WV-MF552), which is equipped with 580 nm band-pass filter #2 to detect only the fluorescence. Figure 4 shows the optical characteristics of Rhodamine B, obtained by Sakakibara (1996), and those of the band-pass filters used in this study. The two filters have no crosstalk and are located around the absorption and the fluorescence maxima. As the intensity of the filtered fluorescence is very weak, we have utilized the video pre-processor (nexus VP-01N) to enhance the CCD camera output before taking into digital image processor (nexus 6810). In order to eliminate the jitter at the A/D converter and the noise of the camera, 16 frames at each temperature and 81 pixels for each particle image were averaged.

Figure 5 shows the calibration plots for the present particles at various temperatures. The plots are normalized by the values at 30.0 degree centigrade. The agreement between the results for the [(W/O)/W] microcapsule and the those for the aqueous solution of Rhodamine B is fairly well. On the contrary, the temperature dependency of the fluorescence of the (O/W) microparticle is rather small. This may be because that the fluorescence molecules are trapped by the polystyrene polymer and thus the mobility of the dye molecules, which contributes to the temperature sensitivity, is somewhat restricted. Although the temperature sensitivity of the normalized intensity of the (O/W) microparticle is smaller, the intensity itself is about 3.7 times higher and the actual sensitivity to temperature is about 1.5 times higher than those of the [(W/O)/W] microcapsule. As Kamei and Kasagi (1994) have pointed out, the uncertainty in the temperature measurement by the LIF technique is mostly come from the uncertainty of the measured intensity of the fluorescence. The higher the intensity of the fluorescence, the less the relative uncertainty in the temperature measurement.

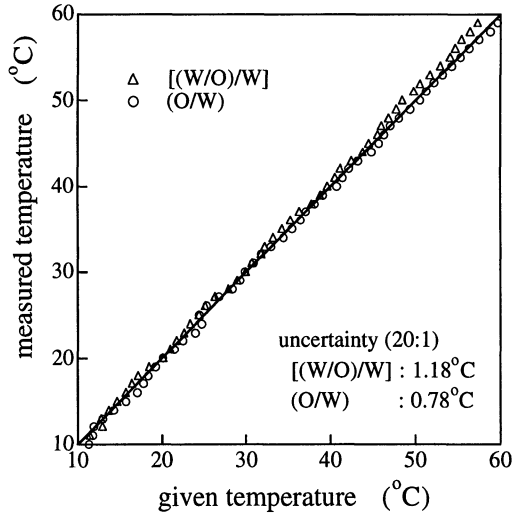


Figure 6. Temperature measurement

Figure 6 demonstrates the results of the temperature measurements by the present particles. The agreements between the measured and given temperatures are very well and the uncertainties at 95% coverage are 1.18 degree and 0.78 degree for the microcapsule and the microparticle respectively.

It has been proved that the present particles have the temperature sensitivity, but in order to carry out the actual three-dimensional simultaneous measurement of velocity and temperature by this particle, there remains many practical problems to be made clear. First of all, the authors have checked whether the calibration curve has

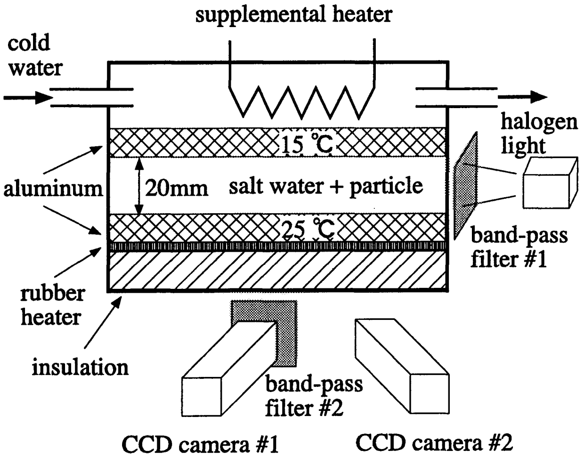


Figure 7. Experimental apparatus for natural convection

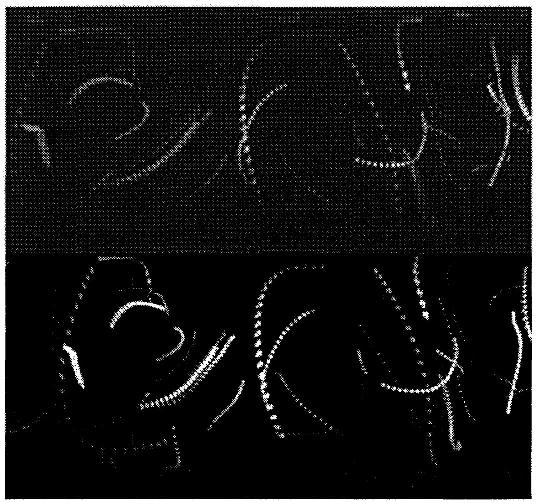


Figure 8. Typical images of natural convection layer

the hysteresis or not. With the repetition of temperature calibration for a single particle, the hysteresis was found during first few heating and cooling. While a pre-heated particle, which has been kept at 60 degree for several hours, did not show this hysteresis and a good coincidence of the calibration curves was found for heating and cooling. As for the torelance to the exposure to the excitation light, there found no distinct change in the calibration plots during the period of our examination with the 150W halogen light. But, the particle that has been exposed to the direct irradiation of 1W Ar-ion laser beam for several hours did not show the temperature sensitivity. This may be because that the fluorescent material have received too much photons and have been changed into non-fluorescent substance, i.e., two-photon excitation (Jones, 1990). As for the difference between individual particles, the normalized calibration plots are almost identical, but there was a small scatter among the intensities of the fluorescence for each particle.

PRELIMINARY EXPERIMENT IN NATURAL CONVECTION LAYER

In order to check the applicability of the present temperature sensitive particles to the practical turbulent phenomena, a preliminary experiment for the three-dimensional simultaneous measurement of velocity and temperature in a horizontal natural convection layer has been carried out. Figure 7 shows the schematic view of the experimental apparatus. The separation between two aluminum plates, which has a 10 mm thickness to prevent the wall temperature variation, is 20 mm. The bottom plate was heated at 25 degree with the PID-controlled electric rubber heater and the temperature of the upper plate was kept constant at 15 degree with the circulating cold water and the supplemental electric heater, which is also PID-controlled. The resulting Rayleigh number is 1.0×10^6. According to Kerr (1996), the Kolmogorov microscale of the present flow field is estimated as 0.76 mm and the thicknesses of velocity and temperature boundary layers are also estimated as 1.80 mm and 1.17 mm respectively. Thus as the present particles of the size of several hundred microns are smaller than these microscales, they may trace the turbulent phenomena very well. The aspect ratio of the horizontal layer to the separation height was set to 14 x 20 to assure the two-dimensionality of the flow domain. The reservoir is insulated by the Styrofoam. As for the tracer particle, the (O/W) type microparticles of nearly equal density were chosen. In order to assure that the particles are neutrally buoyant, the salt water, whose specific density is adjusted to 1.05, was used as the working fluid.

The measuring domain is illuminated by the halogen light from the side window with 546 nm band-pass filter. The observations were made by two CCD cameras, one of which has been equipped with 560 nm band-pass filter to detect only the fluorescence. The positions and angles of the cameras were carefully calibrated before the experiments. Moreover, in order to compensate for the non-uniform distribution of the excitation light intensity, the three-dimensional distributions of the illumination intensity were also calibrated beforehand. As we set our cameras in a stereoscopic arrangement, we can measure the three-dimensional particle positions by the 3-D PTV algorithm and thus the illumination intensity at each particle position can be calculated. The images from the filtered camera are amplified by the video pre-processor and the images from both cameras are combined together by the digital image processor and then successively recorded to the digital video recorder (SONY DCR-TRV1000).

Figure 8 shows the typical images obtained in this study. The 24 consecutive images are superimposed to see the motions of the particles. The above image is taken by the filtered camera and the bottom by the normal one. The time interval between two consecutive images was set to 0.2 seconds. Here the changes in the brightness, which correspond to the changes in the temperature, of the particle in the above images can be observed together with the motion of the particle. Although, we could track the motions of the particles very well, the measured temperature had non-negligible scatter, which may be due to the following reasons. First, the difference of the fluorescence intensities of the individual tracers was not negligible. In order to overcome this shortcoming, the similar idea with Sakakibara and Adrian (1998) may be used. Although the intensities of the fluorescence of each particle are not equal, the relative intensities should be constant. Like they have utilized the second fluorescent dye which is less sensitive to temperature, we can observe the reflection from the particle. We have tried to use the intensity by the non-filtered camera to compensate for this effect, but unfortunately the fluorescence of the present particle was so strong that the reflection could not be separated. The use of another 546 nm filter for the non-filtered camera may solve this problem. Second, the signal was contaminated by the camera noise. Although the intensity distributions of the small particle image was fitted by the polynomial to minimize the noise effect, the random noise have overwhelmed the temperature signal. This may be solved by using the camera of higher fidelity and higher resolution.

With this preliminary experiment, we could make the practical aspects clear for the actual three-dimensional measurement of velocity and temperature in a future study.

CONCLUSION

In order to carry out the three-dimensional simultaneous measurement of velocity and temperature, temperature sensitive particles, which can be used as the tracer for 3-D PTV and LIF simultaneously, has been developed. Followings are the conclusions of this study:

(1) By introducing the soluble starch, which absorbs Rhodamine B, into the inner water phase of the microcapsule, the temperature sensitive microcapsule whose specific density and thermal conductivity are almost the same as water has been prepared.

(2) The microparticle that contains the large amount of Rhodamine B and has the high sensitivity to the temperature has been prepared.

(3) The calibrations and the temperature measurements by the present temperature sensitive particles have proved that they are applicable to the temperature measurement and the uncertainties at 20:1 odds were 1.18 degree and 0.78 degree, respectively.

(4) By the preliminary experiment in a natural convection layer, practical aspects for the actual simultaneous measurement are made clear. The most important thing is to augment the signal to noise ratio of the observed intensity of the fluorescence of the particle.

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