Observation of Free Surface Flow Behavior Using Laser Tagging Method by Photochromic Dye Tracer

NURRINA BINTI ROSLI

Department of Mechanical Science and Technology
Gunma University
Japan

Under the guidance of
PROFESSOR DR. KENJI AMAGAI, Ph. D. Eng.

Table of Contents

Chapter 4: *Measurement of liquid sheet spray*

Chapter 5: *Measurement of liquid film flow on inclined wall*

Nomenclature

A	area framed by 4-points of dye traces	[mm^2]
b	width of inclined wall in liquid film flow experiment	[m]
B	measured absorbance in Beer-Lambert law	[-]
c	molar concentration of sample liquid in Beer-Lambert law	[mol]
C	closed line connecting dye traces to form plane region S	[-]
d_1	diameter of dye trace parallel to liquid film flow direction	[mm]
d_2	diameter of dye trace perpendicular to liquid film flow direction	[mm]
d_c	diameter or cylinder	[mm]
dl	small linear element on closed line C	[-]
e	molar extinction coefficient in Beer-Lambert law	[$mol^{-1}cm^{-1}$]
f	arbitrary function in calculation formula of flow deformation	[-]
k	range of diode laser irradiation to the test piece in calibration procedure of light absorption method	[mm]
h	diameter of optical flat used in calibration procedure of light absorption method	[mm]
H	known-spacing between optical fiber A and B in liquid film flow experiment	[mm]
I	intensity of light passes through sample liquid in calibration procedure of light absorption method	[a.u.]
I_0	intensity of incident light irradiated to sample liquid in calibration procedure of light absorption method	[a.u.]
l_{ij}	length between dye trace point i and j $(i, j=1, 2, 3,)$	[mm]
L_c	distance between origin points to the center position in between 4-points of dye traces in liquid sheet spray experiment	[mm]
L_i	distance between origin point to the center point of each dye trace in liquid sheet spray experiment	[mm]
L_m	distance travelled by liquid film flow from liquid inlet in inclined wall	[mm]
L_p	distance between center point of dye trace and wave peak	[mm]
L_w	length of wake vortex in creeping flow experiment	[mm]
$\boldsymbol{n}$	outward-pointing normal vector from small line dl	[mm]
n_x	outward-pointing normal vector from small line dl in x direction	[mm]

n_{xij}	x component of normal vector on line between dye trace point i and j $(i, j=1, 2, 3, 4)$	[mm]
n_y	outward-pointing normal vector from small line dl in y direction	[mm]
n_{yij}	y component of normal vector on line between dye trace point i and j $(i, j=1, 2, 3, 4)$	[mm]
Q	flow rate of liquid sheet spray and liquid film flow experiments	[m^3/s]
Re	Reynolds number in creeping flow and liquid film flow experiments	[-]
S	plane region bounded by the closed line C formed by the 4-points of dye traces	[-]
$\boldsymbol{t}$	unit tangent vector from small line dl	[mm]
t_x	unit tangent vector from small line dl in x direction	[mm]
t_y	unit tangent vector from small line dl in y direction	[mm]
T	transmittance of light in Beer-Lambert law	[-]
T_e	room temperature during experiments	[°C]
u	velocity component of dye trace bounding plane region S in x direction	[mm/s]
u_i	velocity component of dye trace point i bounding plane region S in x direction $(i=1, 2, 3, 4)$	[mm/s]
u_j	velocity component of dye trace point j bounding plane region S in x direction $(j=1, 2, 3, 4)$	[mm/s]
$\overline{U_w}$	average velocity of wave calculated by FFT analyzer	[mm/s]
v	velocity component of dye trace bounding plane region S in x direction	[mm/s]
v_i	velocity component of dye trace point i bounding plane region S in y direction $(i=1, 2, 3, 4)$	[mm/s]
v_j	velocity component of dye trace point j bounding plane region S in y direction $(i=1, 2, 3, 4)$	[mm/s]
v_n	normal direction component of velocity vector $\boldsymbol{V}$	[mm/s]
v_t	tangent direction component of velocity vector $\boldsymbol{V}$	[mm/s]
$\boldsymbol{V}$	interpolated velocity vector by velocity of dye trace point i bounding plane region S $(i=1, 2, 3, 4)$	[mm/s]
V_a	velocity of dye trace in creeping flow experiment	[mm/s]
V_c	velocity of moving cylinder in creeping flow experiment	[mm/s]
V_i	velocity of dye trace point i in liquid sheet spray experiment $(i=1, 2, 3, 4)$	[m/s]
$\overline{V_l}$	average velocity of dye trace in liquid film flow experiment	[mm/s]

V_l	velocity of dye trace in liquid film flow experiment	[mm/s]
V_w	velocity of wave in liquid film flow experiment	[mm/s]
$\overline{V_w}$	average velocity of wave passing dye trace calculated by image analysis method	[mm/s]
$\boldsymbol{X}$	distance vector of dye trace bounding plane region S	[mm]
X_l	distance travelled by dye trace in liquid film flow experiment	[mm]
X_w	distance travelled by wave in liquid film flow experiment	[mm]
Θ	divergence of creeping flow	[s^{-1}]
$\overline{\gamma}$	total average shear strain of liquid sheet spray	[-]
γ	shear strain rate of liquid sheet spray	[s^{-1}]
$\overline{\delta}$	average thickness of liquid in liquid film flow experiments	[mm]
δ	thickness of liquid in liquid sheet spray and liquid film flow experiments	[mm]
δ_p	known-thickness of plate used in calibration procedure of light absorption method	[mm]
$\overline{\varepsilon_x}$	total average normal strain of liquid sheet spray in x direction	[-]
ε_x	normal strain rate of liquid sheet spray in x direction	[s^{-1}]
$\overline{\varepsilon_y}$	total average normal strain of liquid sheet spray in y direction	[-]
ε_y	normal strain rate of liquid sheet spray in y direction	[s^{-1}]
$\overline{\varepsilon_z}$	total average normal strain of liquid sheet spray in z direction	[-]
ε_z	normal strain rate of liquid sheet spray in z direction	[s^{-1}]
η	dynamic viscosity of working fluid	[Pa·s]
θ	wall inclination angle in liquid film flow experiment	[deg.]
λ	wavelength of laser light	[nm]
ρ	density of working fluid in liquid film flow experiment	[kg/m^3]
τ	time delay between the two signals cross-correlated by FFT analyzer	[s]
ω	vorticity of creeping flow and liquid sheet spray	[s^{-1}]

Chapter 1

Introduction

1.1 Background and literature review

1.1.1 Free surface flow and the measurement technique

Free surface flows are ubiquitous in our daily life. For instances, the river flow, sea wave, rain droplet, water column flow out from a water tap and water flow in a drain are among the examples of free surface flow that commonly found in our everyday life. Moreover, the free surface flow is also observed in many branches of the industrial fields including the atomization process in automotive engine, wall surface flow related to heat and mass transfer facilities as well as the wave surface flow related two phase flow in thermal exchanger.

In response to the increasing demands to enhance the performance of those industries, study on the liquid flow behavior is fundamentally important. Consequently, the liquid flow visualization has become a significant interest among engineers and researchers to better understand the flow behaviors of free surface flow. Generally, various kinds of measurement were used to estimate the liquid flow behavior such as the hot wire anemometry **[1]**, **[2]**, particle image velocimetry **[3]**, **[4]**, **[5]**, laser Doppler anemometry **[6]**, **[7]**, **[8]** and many more. From our survey, the well-known particle image velocimetry (PIV) has taken very large portion among the techniques applied in the past to measure the flow field structure.

However, the main capital in handling the technique of PIV, i.e. the seeding particles presents limitation and weakness in estimating the liquid flow behavior. For examples, Luo and Wang **[9]** used the 3D-PIV measurement system to investigate bubble flow in between two plates of microchannel. Through their experimental test, the measurement accuracy was slightly affected since the seeding particles stuck around the wall surface. Another limitation was also found by Bress and Dowling **[10]** in their investigation of resins flow. Certain part in the cavity was unable to be visualized due to the uneven brightness of the laser sheet in the flow field. The rapid change of the resins flow also cause the laser sheet to be reflected back the flow behind it and this cause the over-brightness to the region.

Particularly in the free surface flow which presents very large deformation on the liquid surface, the PIV may not become the best choice of method to deal with such flow behavior because it is difficult to detect the flow signal of liquid surface. Therefore, the PIV method is certainly unreliable to be used as the measurement technique for the free surface flow.

Here, a laser tagging method is developed as a new approach to measure the free surface flow behavior. The technique is implemented based on a temporary color change of liquid containing the photochromic dye. Briefly explained, this non-intrusive measurement technique utilizes the color change of the liquid containing the photochromic dye when a laser light source such as ultraviolet (UV) light was irradiated to the liquid. The crucial advantage of this method is that it enables the visualization of flow structure directly without using the seeding particles, and the liquid surface area can be easily traced by the irradiation of UV laser light. An extensive introduction about the laser tagging method using the photochromic dye will be done hereafter.

1.1.2 Laser tagging method using photochromic dye tracer

The laser tagging method was first developed by Popovich and Hummel **[11]** in 1967 to study the viscous sublayer occurred in a turbulent flow in a pipe. **Fig. 1-1** shows the photochromic dye traces images formed in the pipe. Along with the time elapsed, the traces line seen as perpendicular to the pipe and formed the angle from the pipe wall. Thus, the existence of laminar sublayer was successfully proved from their experimental works. The results were also found to meet agreement with Spalding's equation and several results in the past, as shown in **Fig. 1-2**.

Fig. 1-1 Laminar sublayer in pipe flow observed by photochromic dye tracer reported by Popovich and Hummel [11]

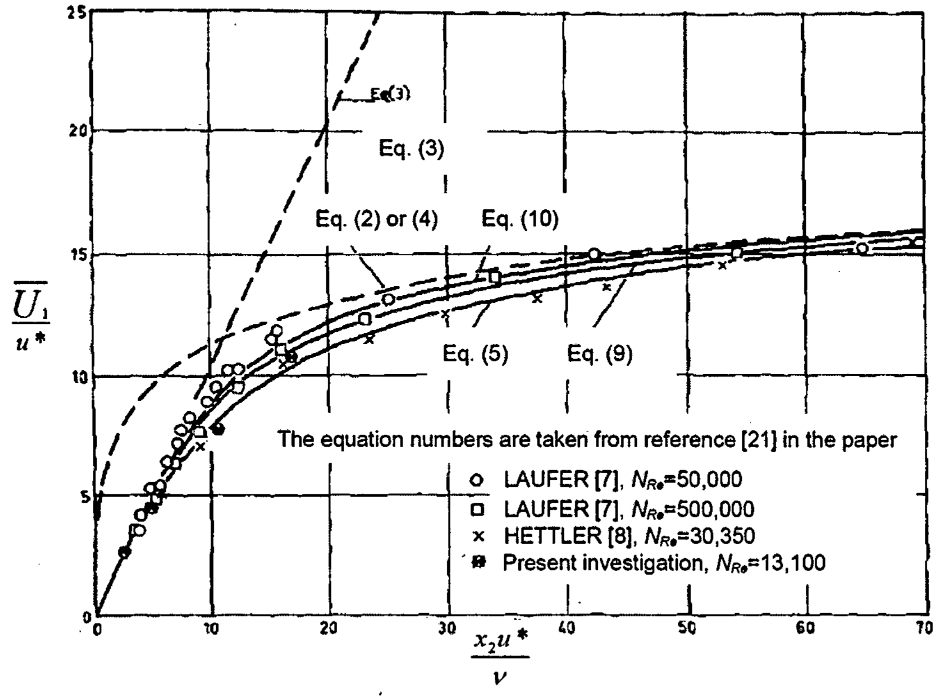

Fig. 1-2 Average velocity distribution near pipe wall compared with several results in the previous literature **[12]**

Since then, its usage has been extensively applied to develop various research fields, especially in the flow field measurements. For instance, Johnson and Marschall [13] used the technique to investigate droplet formation from various kinds of nozzle. The photochromic dye tracer in their experiment was seen clearly as the flow patterns in the droplets as shown in **Fig. 1-3**. The mechanism for the liquid to disperse once discharged from nozzle was clarified by the technique.

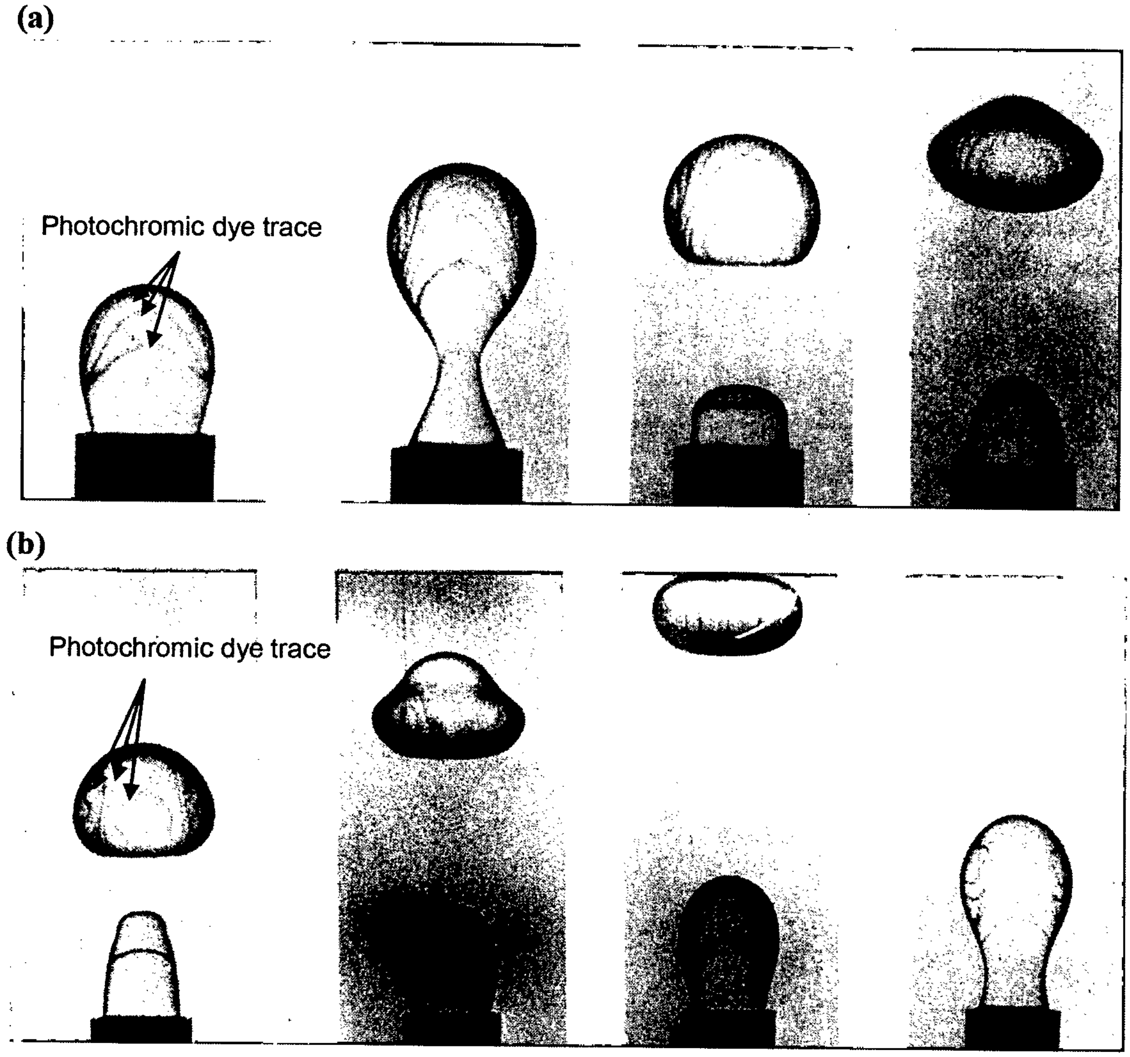

Fig. 1-3 Internal flow visualization of **(a)** slow and **(b)** droplet formation **[13]**

Kawaji **[14]** described several sample experiments conducted by his research team in order to prove the benefit of this technique in visualizing two-phase flow in a pipe. Sample experiments carried out include the wavy-stratified, free falling film, annular and slug flows. Their studies made greater understanding to the flow structures. This time, previous reports in the studies were also confirmed by well-agreements and denials. They successfully observed the vortex motion under large amplitude of disturbance waves in a pipe flow as shown in **Fig. 1-4**.

In the measurement of countercurrent annular flow of falling film, some retardation of velocity was found near the interface as shown in **Fig. 1-5**. This retardation was induced by the countercurrent interfacial shear caused by the gas flow.

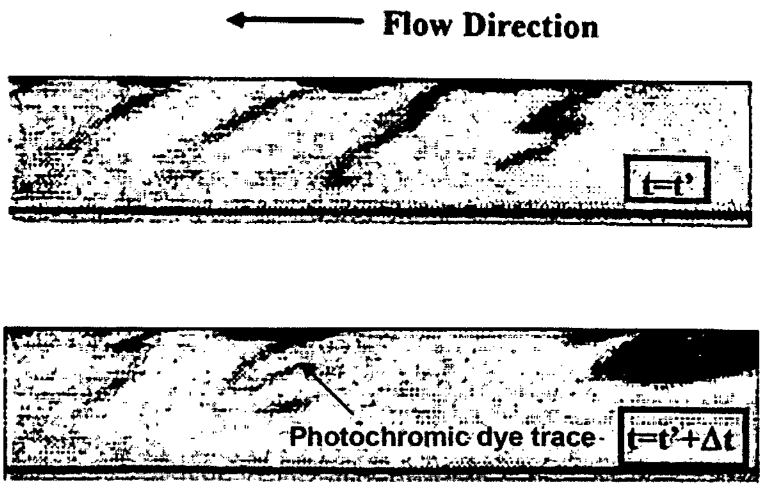

Fig. 1-4 Vortex motion of photochromic dye traces under a disturbance wave in a pipe [14]

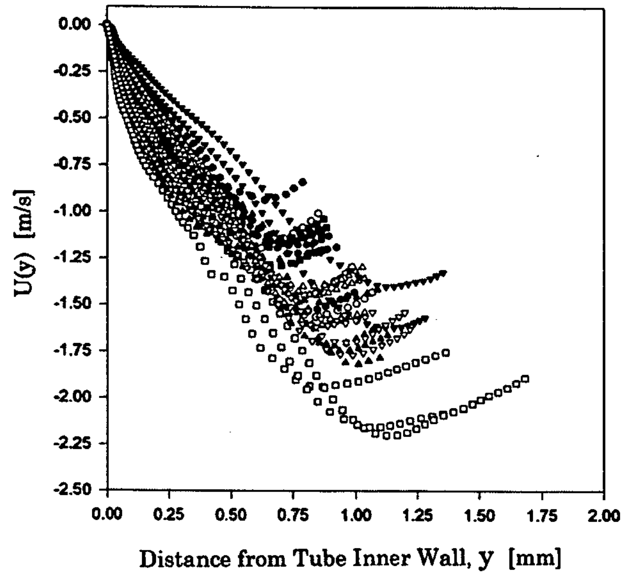

Fig. 1-5 Instantaneous velocity profiles in a falling film at the onset of flooding for countercurrent annular flow [14]

Homescu and Desevaux [15] applied this technique to investigate liquid velocity of curved-surface between groove structures. The dye traces was formed with two consecutive pulsed UV laser as presented in **Fig. 1-6**.

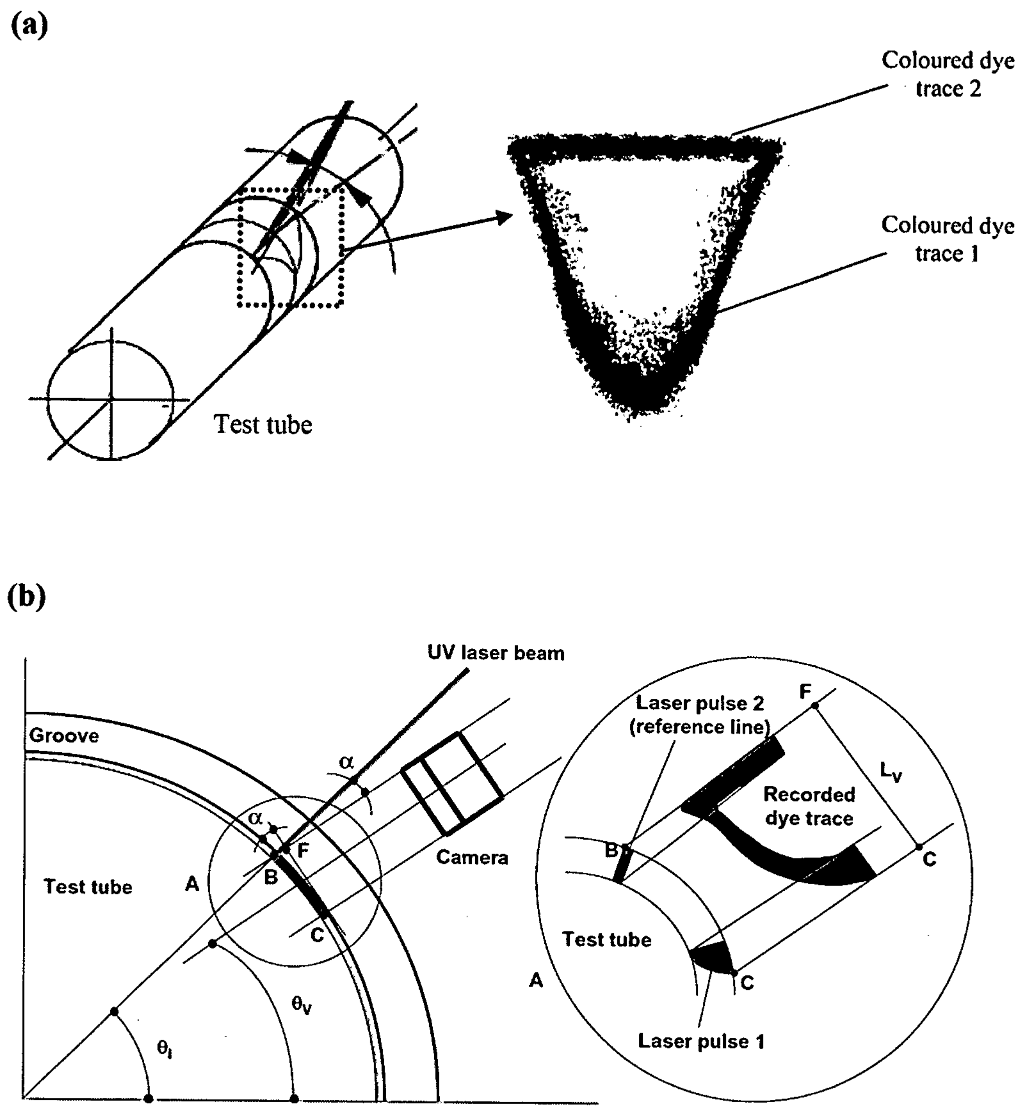

Fig. 1-6 Image of **(a)** photochromic dye traces in the test tube with **(b)** observation method in curved surfaces **[15]**

The advantages as well as limitations of using the photochromic dye marking method were also described. According to them, this technique must be done with suitable optical devices. However, with very little quantity of dye contained in the liquid test, the physical properties are not affected. This is an important point to prove that the technique is trustful and reliable for liquid velocity measurement in various kinds of flow fields which cannot be well-observed by other methods.

Park et al. **[16]** used this technique to measure the flow vorticity occurred in a curved vessel. The photochromic grids as shown in **Fig. 1-7** were formed by using two UV beams sourced from a multi-stage nitrogen laser which were consecutively separated and focused by a pair of lens arrays. In order to ensure the measurements accuracy of the method, the numerical flow field calculations were also performed. The comparison between both results was done and the validity of the laser tagging method was then strengthened from the good agreement of it, as can be seen in **Fig. 1-8**.

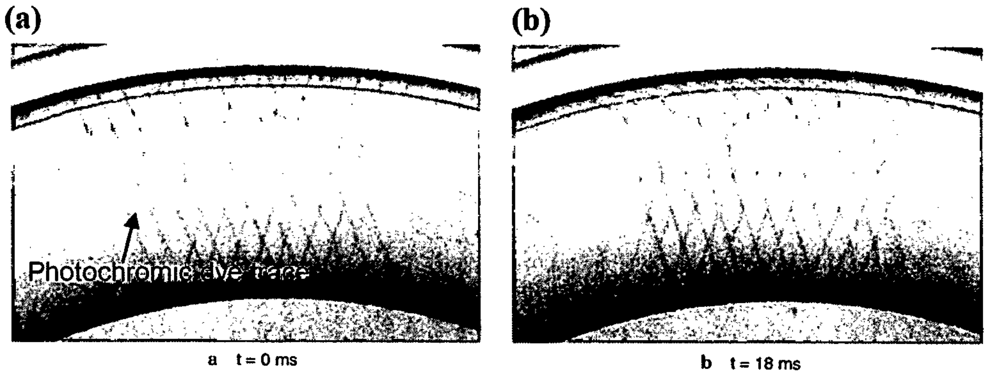

Fig. 1-7 Photochromic grids in curved vessels **(a)** without flash time delay and **(b)** with flash time delay **[16]**

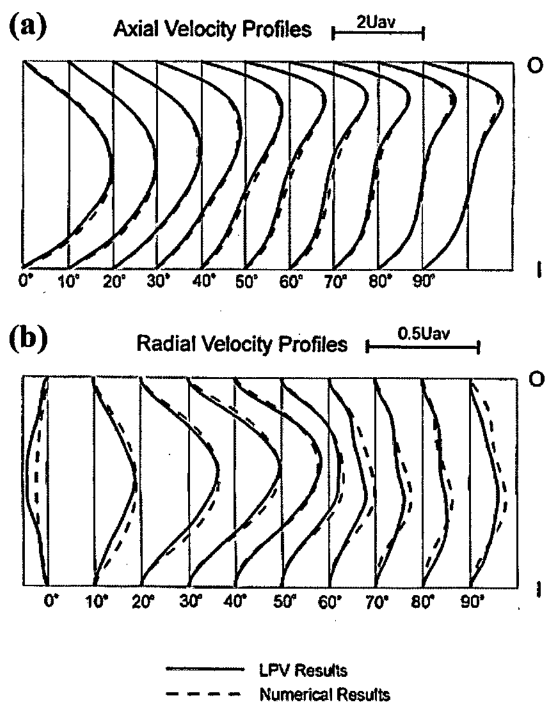

Fig. 1-8 Velocity profiles in **(a)** axial and **(b)** radial components **[16]**

Kai et al. **[17]** proved the successful of using this technique to observe the particle motions in a two-dimensional fluidized catalyst bed. **Fig. 1-9** shows the images of photochromic dye trace motion beside bubble in time interval. The dark areas represent the bubble cavities or activated particles. They enabled to measure the local velocity of emulsion particles around the bubble. As shown in **Fig. 1-10**, the velocity of particles was found to decrease with increasing distance from the bottom of the bubble. The particle velocity at just below the bubble was also found to meet a good agreement with the mean ascending velocity of bubble.

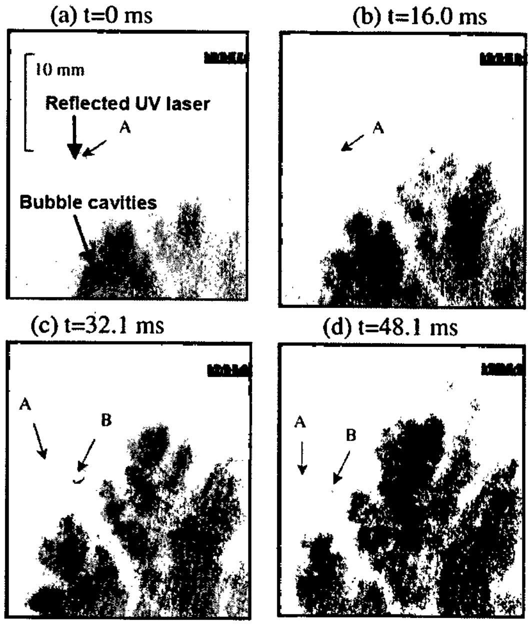

Fig. 1-9 Photochromic dye traces formed beside bubble in fluidized bed [17]

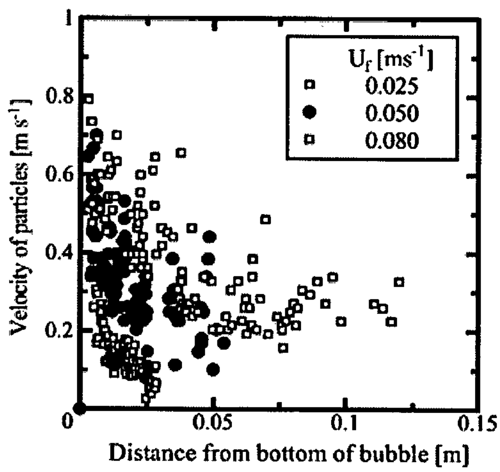

Fig. 1-10 Relationship between distance from bubble and particle ascending velocity [17]

Another experiment of the laser tagging method by photochromic dye associated with bubble flow visualization was done by Sanada et al. **[18]**. They successfully visualized the wake flow structure of bubble moving to higher position from the trajectory of colored liquid in the bubble wake, as shown in **Fig. 1-11**. A single bubble was formed, immediately after UV sheet light illuminated the part of the liquid just above the bubble generation nozzle in order to activate photochromic dye trace.

Once the bubble passed across the colored area of the liquid, the bubble was accompanied by some portion of activated dye tracers and thus the flow structure in the rear of the single rising bubble can be observed. The bubble shape, trajectory, and aspect ratio as bubble rose for 0.1s is shown in **Fig. 1-12**. As can be confirmed, the bubble wake was found to fluctuate several times and moved one periodical zigzag motion.

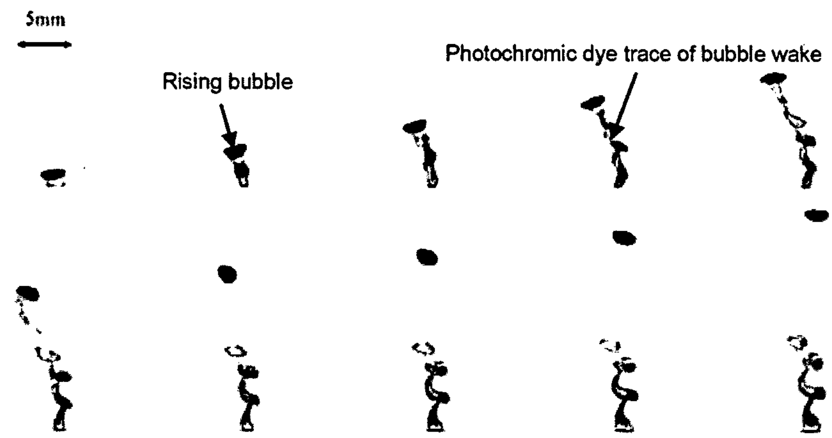

Fig. 1-11 Photochromic dye trace of single rising bubble wake with zigzag motion **[18]**

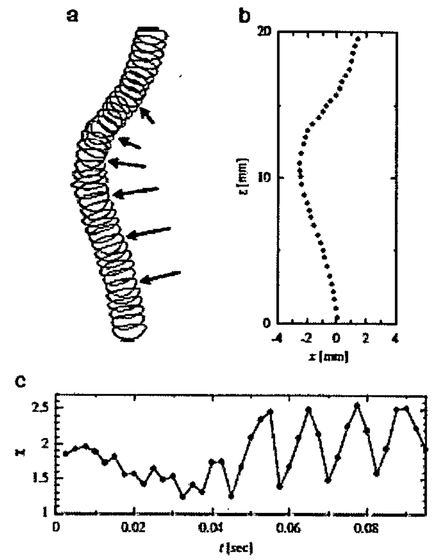

Fig. 1-12 Single rising bubble in **(a)** shape, **(b)** trajectory and **(c)** aspect ratio **[18]**

In regards to the properties of photochromic dye, Fogwell and Hope **[19]** described this matter through their works including the mechanisms and theory of chemical changes presented by many types of photochromic dye. Their investigation especially in describing the dye concentration is greatly beneficial in properly using the photochromic dye for the flow visualization.

From these experimental works reported in the past, the laser tagging method using the photochromic dye tracer is reliable to be used as measurement technique of fluid flow. Especially, since the photochromic dye traces are able to be formed easily with various desired trace patterns in the liquid flow field, the deformation occurred in the flow field thus can be easily observed by using the photochromic dye tracer. Therefore, the technique is applied to our research in order to further study the free surface flow behavior. Here, the research work is conducted to two kinds of free surface flow, i.e. the liquid sheet spray and liquid film flow on inclined wall. Findings and discussion made throughout this research study are described in the respective chapters.

1.2 Objective of this research

The purpose of this research is to investigate the free surface flow behavior using the laser tagging method by photochromic dye tracer. In order to check the applicability of this technique for the free surface flow measurement, this research study was carried out in three different flow fields, i.e. creeping flow of moving cylinder in a channel, liquid sheet spray injected from a nozzle and liquid film flow on inclined wall.

The experiment of creeping flow is carried out as the preliminary experiment to confirm the ability of using the proposed technique for measurement of flow field. Then, the liquid sheet and liquid film flow experiments are conducted to clarify the flow behavior of free surface flow by using the proposed technique.

1.2.1 Measurement of creeping flow around moving cylinder

In the measurement of creeping flow, the laser tagging method by using photochromic dye tracer is applied to assess the ability of the technique to the measurement of flow field. The experiment is carried out to visualize the creeping flow around a moving cylinder in a rectangular cavity. From the movement of the dye traces, the velocity, vorticity and divergence profiles of the creeping flow are estimated. Detailed explanation regarding the experiment of creeping flow is described in chapter 3.

1.2.2 Measurement of liquid sheet spray injected from nozzle

In the measurement of liquid sheet, we focus on the liquid sheet spray as a fundamental study of the atomization phenomena. The laser tagging method using photochromic dye is developed to study the breakup process of liquid sheet in detail, covering from the behavior in the liquid film until disintegrated into ligament and droplets. The motions of the dye traces are analyzed as the liquid surface velocity. By forming a set of 4-points of dye traces on the liquid sheet, the changes of relative position of the set allow the measurement of deformation and rotational motion of liquid film. Moreover, the measurement of average thickness of the liquid sheet is also carried out by using light absorption method. Detailed explanation regarding the experiment of liquid sheet spray is described in chapter 4.

1.2.3 Measurement of liquid film flow on inclined wall

In the measurement of liquid flow on inclined wall, the laser tagging method using photochromic dye tracer is developed to clarify the flow structure of liquid film on inclined wall. Here, the movement of wave is analyzed together with the movement of dye traces. Then, comparison between the wave and liquid velocities is done. The wave velocity is also measured by cross correlating two signals of light intensity from two laser beams spaced in a known distance. The thickness measurement is also conducted to clarify the internal structure of liquid film flow. Furthermore, the diameter change of dye traces is also measured to estimate the internal flow state of the liquid film. Detailed explanation regarding the experiment of liquid film flow is described in chapter 5.

References

[1] Ueda, T. and Tanaka, H.: Measurements of Velocity, Temperature and Velocity Fluctuation Distributions in Falling Liquid Films, *International Journal of Multiphase Flow*, **2**-3 (1975), 261-272.

[2] Zhang, Y.: Experimental Studies of the Turbulence Structures of Impinging Reacting Jets Using Time-Resolved Particle Image Velocimetry Visualisation, Hot Wire Anemometry and Acoustic Signal Processing, *Experiments in Fluids*, **29**-1 Supplement (2000), 282-290.

[3] Jong, A.D. and Spruijt, M.: Particle Image Velocimetry for Quantification of High Pressure CO_2 Release, *Energy Procedia*, **37** (2013), 4682-4691.

[4] Dobrev, I. and Massouh, F.: CFD and PIV Investigation of Unsteady Flow through Savonius Wind Turbine, *Energy Procedia*, **6** (2011), 711-720.

[5] Saleh, S., Thovert, J.F. and Adler, P.M.: Measurement of Two-Dimensional Velocity Fields in Porous Media by Particle Image Displacement Velocimetry, *Experiments in Fluids*, **12**-3 (1992), 210-212.

[6] Yu, L.M., Zeng, A.W. and Yu, K.T.: Effect of Interfacial Velocity Fluctuations on The Enhancement of the Mass-Transfer Process in Falling Film Flow, *Industrial & Engineering Chemistry Research*, **45**-3 (2006), 1201-1210.

[7] Ju, J., Yamagata, Y., Inoue, K. and Higuchi, T.: A Study on Atomization Characteristics of Surface Acoustic Wave Atomizer using Laser Doppler Anemometry, *Service Robotics and Mechatronics*, (2010), 309-312.

[8] Albrecht, H.E., Borys, M. and Fuchs, W.: The Cross Sectional Area Difference Method-A New Technique for Determination of Particle Concentration by Laser Doppler Anemometry, *Experiments in Fluids*, **16**-1 (1993), 61-69.

[9] Luo, R. and Wang, L.: Liquid Flow Pattern around Taylor Bubbles in an Etched Rectangular Microchannel, *Chemical Engineering and Research Design*, **90**-8 (2012), 998-1010.

[10] Bress, T.J. and Dowling, D.R.: Particle Image Velocimetry in Molten Plastics, *Polymer Engineering and Science*, **51**-4 (2011), 730-745.

[11] Popovich, A.T. and Hummel, R.L.: A New Method for Non-Disturbing Turbulent Flow Measurements Very Close to a Wall, *Chemical Engineering Science*, **22**-1 (1967), 21-25.

[12] Popovich, A.T. and Hummel, R.L.: Experimental Study of the Viscous Sublayer in Turbulent Pipe Flow, *AlChE Journal*, **13**-5 (1967), 854-860.

[13] Johnson, G. and Marschall, E.: On the Temperature Jump in Liquid-Liquid Direct-Contact Heat Exchangers, *International Journal of Multiphase Flow*, **12**-1 (1986), 127-133.

[14] Kawaji, M.: Two-Phase Flow Measurements Using a Photochromic Dye Activation Technique, *Nuclear Engineering Design*, **184** (1998), 379-392.

[15] Homescu, D. and Desevaux, P.: Laser Photochromic Dye Activation Technique for the Measurement of Liquid Free Surface Velocity on the Curved Surfaces, *Optics and Lasers in Engineering*, **41** (2004), 879-888.

[16] Park, H., Moore, J.A. Trass, O. and Ojha M.: Laser Photochromic Velocimetry Estimation of the Vorticity and Pressure Field Two-Dimensional Flow in a Curved Vessel, *Experiments in Fluids*, **26** (1999), 55-62.

[17] Kai, T., Kanda, T., Takahashi, T. and Kawaji, M.: Application of Photochromic Dye to the Measurement of Particle Movement in a Fluidized Bed, *Powder Technology*, **129** (2003), 22-29.

[18] Sanada, T., Shirota, M. and Watanabe, M.: Bubble Wake Visualization by Using Photochromic Dye, *Chemical Engineering Science*, **62** (2007), 7264-7273.

[19] Fogwell, T.W. and Hope, C.B.: Photochrome Dye Tracing in Water Flows, *Experimental Heat Transfer*, **1**-2 (1987), 141-154.

Chapter 2

Laser tagging method by photochromic dye

2.1 Principle of the laser tagging method

The main role in implementing the laser tagging method in this study comes from the reversible transformation called as photochromism. Briefly said, photochromism refers to a reverseble color change of transparent liquid containing photochromic dye when exposed to light resource such as UV light.

The photochromism can be described as a reversible transformation of a chemical species between two forms triggered by electromagnetic radiation in the wavelengths area of light resource such as UV light. The color change is resulted from the breakup C-O bonding of the dye molecules once irradiated to the UV light. There are two kinds of photochromic dye widely applied in the research fields, i.e. spirooxazine (SO) and spiropyran (SP) types. As shown in **Fig. 2-1**, the broke up C-O bonding in the chemical structure represents the merocyanine form of the dye in the colored state [1]. The color change is induced by the change of light absorption spectrum in the photochromic dye upon UV light irradiation. As can be seen in **Fig. 2-2**, the absorption band of photochromic dye from invisible ray area (solid curve) was found to appear in the visible ray area (broken curve) under UV exposure [2]. Thus, the dye solution will be seen in a colored state.

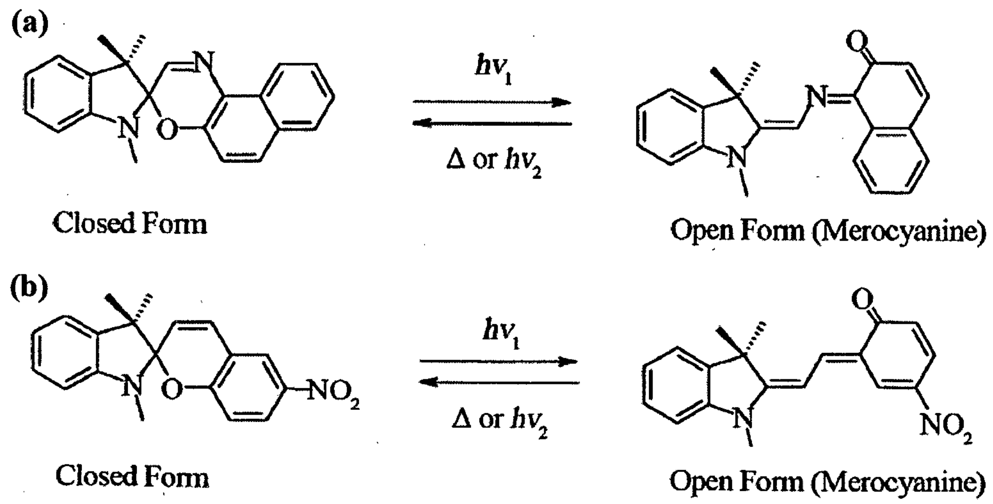

Fig. 2-1 Chemical structure of **(a)** SO type and **(b)** SP type photochromic dye under UV light irradiation **[1]**

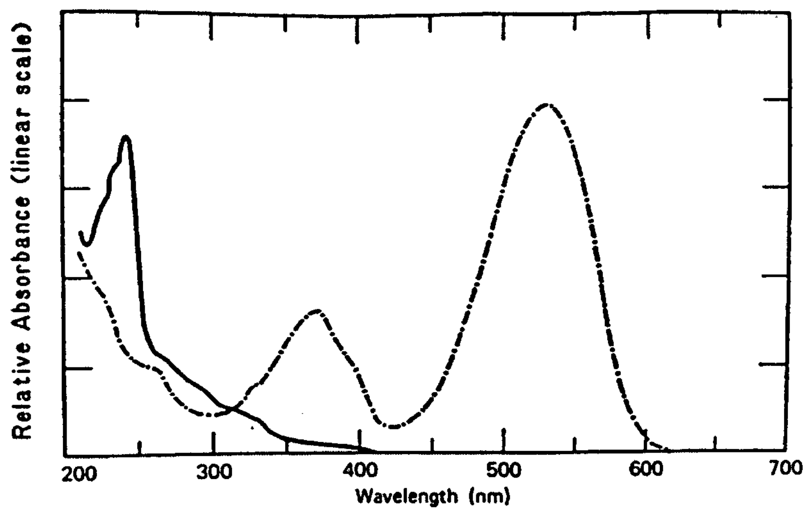

Fig. 2-2 Absorption spectrum of photochromic dye without UV light exposure (solid curve) and with UV light exposure (broken curve) **[2]**

The SP type of photochromic dye was the most preferred by many researchers **[3]**, **[4]**, **[5]**, **[6]**, **[7]**, **[8]**, **[9]**, **[10]**, **[11]**, **[12]**. The superiority of SP dye lies in their high sensitivity to UV light as well as capability of presenting sharp color change. Photochromic dye solution usually takes within less than 3μs **[2]**, **[5]**, **[8]** to change into colored state under UV light exposure and the color will remain in several seconds after the UV light is removed.

2.2 Application in this research

2.2.1 Preparation of working fluid

We used the photochromic dye from SP type of 1'3'3-trimethylindolino-6'-nitrobenzopyryospiran (TNSB) in all experiments of creeping flow, liquid sheet spray and falling liquid film. This type of dye has been selected by several researchers **[4]**, **[6]**, **[9]**, **[10]**, **[11]**, **[12]** due to its wide applicable to various kinds of liquid such as kerosene, toluene, xylene, benzene, acetone and many more. The only demerit of using TNSB dye lies in its inability to be dissolved in the water **[2]**.

In the experiment of creeping flow, the TNSB dye was dissolved in kerosene with concentration of about 0.02wt%. In the experiments of liquid sheet spray and falling liquid film, the TNSB dye was dissolved in kerosene with concentration of about

0.12wt%. This concentration of the dye is sufficient to yield a vivid colored state of working fluid when irradiated by UV light. **Fig. 2-3** shows the photographs of the color change occurred in kerosene when exposed to the UV light. As can be seen, the kerosene obviously turns into dark blue-purple color state from its initial colorless state under the UV light exposure. **Table 2-1** shows the physicochemical property of kerosene oil **[13]**.

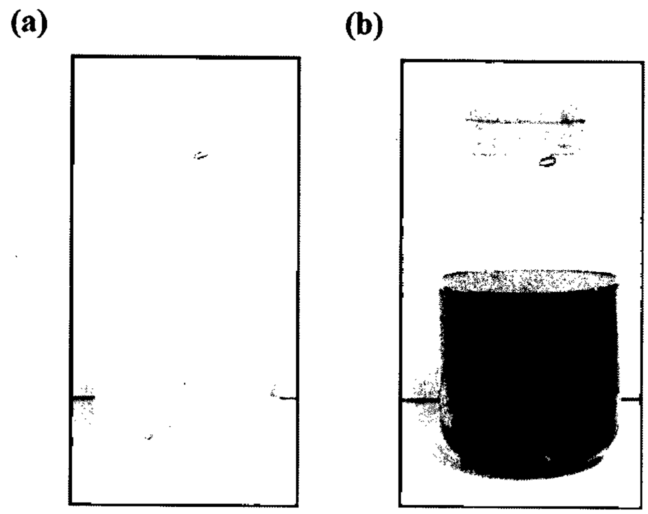

Fig. 2-3 Photochromic dye solution **(a)** before UV light exposure and **(b)** after UV light exposure

Table 2-1 Physicochemical property of kerosene oil **[13]**

Characteristics	**Value**
Specific gravity	0.7879
API gravity	48.091
Kinematic viscosity cSt @ 100 F	2.1808
Aniline point (°C)	58
Flash point (°C)	42
Ash contents (wt%)	0.002
Conradson carbon residue (wt%)	0.13
Total sulfur (wt%)	0.0542

Chapter 1

Introduction

1.1 Background and literature review

1.1.1 Free surface flow and the measurement technique

Free surface flows are ubiquitous in our daily life. For instances, the river flow, sea wave, rain droplet, water column flow out from a water tap and water flow in a drain are among the examples of free surface flow that commonly found in our everyday life. Moreover, the free surface flow is also observed in many branches of the industrial fields including the atomization process in automotive engine, wall surface flow related to heat and mass transfer facilities as well as the wave surface flow related two phase flow in thermal exchanger.

In response to the increasing demands to enhance the performance of those industries, study on the liquid flow behavior is fundamentally important. Consequently, the liquid flow visualization has become a significant interest among engineers and researchers to better understand the flow behaviors of free surface flow. Generally, various kinds of measurement were used to estimate the liquid flow behavior such as the hot wire anemometry **[1]**, **[2]**, particle image velocimetry **[3]**, **[4]**, **[5]**, laser Doppler anemometry **[6]**, **[7]**, **[8]** and many more. From our survey, the well-known particle image velocimetry (PIV) has taken very large portion among the techniques applied in the past to measure the flow field structure.

However, the main capital in handling the technique of PIV, i.e. the seeding particles presents limitation and weakness in estimating the liquid flow behavior. For examples, Luo and Wang **[9]** used the 3D-PIV measurement system to investigate bubble flow in between two plates of microchannel. Through their experimental test, the measurement accuracy was slightly affected since the seeding particles stuck around the wall surface. Another limitation was also found by Bress and Dowling **[10]** in their investigation of resins flow. Certain part in the cavity was unable to be visualized due to the uneven brightness of the laser sheet in the flow field. The rapid change of the resins flow also cause the laser sheet to be reflected back the flow behind it and this cause the over-brightness to the region.

Particularly in the free surface flow which presents very large deformation on the liquid surface, the PIV may not become the best choice of method to deal with such flow behavior because it is difficult to detect the flow signal of liquid surface. Therefore, the PIV method is certainly unreliable to be used as the measurement technique for the free surface flow.

Here, a laser tagging method is developed as a new approach to measure the free surface flow behavior. The technique is implemented based on a temporary color change of liquid containing the photochromic dye. Briefly explained, this non-intrusive measurement technique utilizes the color change of the liquid containing the photochromic dye when a laser light source such as ultraviolet (UV) light was irradiated to the liquid. The crucial advantage of this method is that it enables the visualization of flow structure directly without using the seeding particles, and the liquid surface area can be easily traced by the irradiation of UV laser light. An extensive introduction about the laser tagging method using the photochromic dye will be done hereafter.

1.1.2 Laser tagging method using photochromic dye tracer

The laser tagging method was first developed by Popovich and Hummel **[11]** in 1967 to study the viscous sublayer occurred in a turbulent flow in a pipe. **Fig. 1-1** shows the photochromic dye traces images formed in the pipe. Along with the time elapsed, the traces line seen as perpendicular to the pipe and formed the angle from the pipe wall. Thus, the existence of laminar sublayer was successfully proved from their experimental works. The results were also found to meet agreement with Spalding's equation and several results in the past, as shown in **Fig. 1-2**.

Fig. 1-1 Laminar sublayer in pipe flow observed by photochromic dye tracer reported by Popovich and Hummel [11]

Chapter 3

Application to creeping flow around moving cylinder

3.1 Introductory remarks

A lot of research related to the study of liquid flow behavior has been conducted in the past. In order to enhance the operating performance of machine such as the heat exchanger in largest equipment of energy facilities to the smallest device of micro-reactor, the study of liquid flow behavior has been extensively applied in various industrial fields. Until now, numerous measurement techniques have been developed in order to investigate the flow characteristics in those equipments.

Through our survey, quite quantitative works **[1]**, **[2]**, **[3]**, **[4]**, **[5]**, **[6]** have been dedicated to clarify the liquid flow behavior in micro-channel. For example, Ngoma and Erchiqui **[7]** through their mathematical calculation investigated the effects of slip coefficient and heat flux on the liquid flow in between two plates of micro-channel. They confirmed that the liquid flow behavior in the micro-channel significantly affected by the slip coefficient, pressure difference, heat flux, electro-kinetic separation imposed to the liquid but in various ways of affection.

On the other hand, Kawahara et al. **[8]** conducted their experimental work to investigate the effects of various liquid properties on adiabatic two-phase flows in a micro-channel. Among their findings, bubble in the micro-channel with contraction flow was found to elongate and rapidly flow and thus causing the reduction in the void fraction. Another experiment of bubble in micro-channel was done by Luo and Wang **[9]** through their 3D-PIV system. Through their experimental test, the measurement accuracy was slightly affected since the seeding particles stuck around the walls of the micro-channel.

The measurement method of PIV has been developed time to time to enhance its application in various liquid flow fields not only in relatively large scale of flow, but also in the thin micro-channel and thin liquid film flow. However, the limitations that usually caused by the seeding particles is inevitable. As an alternative technique to clarify the flow behavior of liquid film in various flow fields, laser tagging method using photochromic dye tracer is developed.

In this study, we applied the laser tagging method to study the creeping flow of moving cylinder in a rectangular channel with the aim to evaluate its applicability in the flow field measurement.

3.2 Objective of this experiment

The purpose of this experiment is to assess the applicability of laser tagging method by photochromic dye tracer to the measurement of fluid flow. The experiment is carried out to visualize the creeping flow around a moving cylinder. From the movement of the dye traces, the velocity profiles of the creeping flow in the rectangular cavity are measured. The dye traces are formed in a dot matrix shape to allow vorticity and divergence characteristics of flow field.

3.3 Methodology

3.3.1 Experimental setup and procedure

Figure 3-1 shows the schematic view of the experimental setup for the creeping flow experiment. We generated the flow test by using a circular cylinder with diameter, d_c=10mm placed in a channel (length=190mm, width=50mm, depth=20mm) and connected to a movable stand. The circular cylinder was moved by the movable stand with a constant velocity, V_c=18.8mm/s. The depth of the liquid was approximately 15mm.

Above the channel, UV laser light (λ=248nm) sourced from a KrF Excimer laser was irradiated to the liquid film surface to activate the photochromic dye traces. The laser light was possible to be irradiated around the moving cylinder by using the laser tagging method. However, the irradiation timing must be controlled accurately. In order to achieve the closest visualization of wake flow around the cylinder, we irradiated the laser light around 4mm from the cylinder edge. The laser pulse was 17ns in duration and 450mJ/pulse in energy.

Furthermore, a 20mm×20mm screen plate composed of arrayed holes (diameter= 0.5mm, pitch= 2mm) was placed on the laser light path to form a set of dot matrix dye traces. A cylindrical lens was placed before the screen on the light path to expand the irradiation range of the UV light. Moreover, a halogen lamp was used as the lighting source to assist the visualization of the dye traces movement.

The traces images were then captured by CCD camera and recorded by a video camera recorder (SONY's DCR-TRV20) with 30fps at 3008×2000 pixel resolution. Thus, the spatial resolution of actual space and temporal resolution were respectively, 17μm and 0.03s. The motion pictures were then transferred to a still image data for analysis. The images were changed to the binary images in order to enhance the contrast between liquid and dye traces. The position of the each dye trace was determined by digitizing their coordinates.

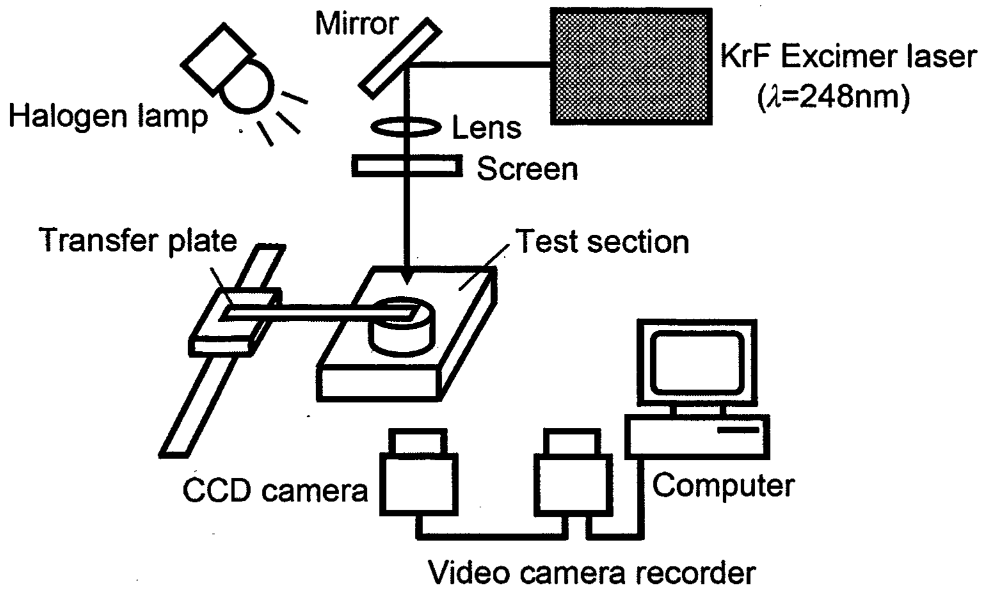

Fig. 3-1 Schematic view of experimental setup for creeping flow experiment

3.3.2 Experimental condition

The Reynolds number, Re is defined by the following equation:

$$Re = \frac{\rho V_c d_c}{\eta} \quad \textbf{(3-1)}$$

where, ρ is the density, V_c is the cylinder velocity, η is the dynamic viscosity of the working fluid and d_c is the cylinder diameter. The experiment was conducted at three positions in x-axis around the cylinder, i.e. $-15\text{mm}<x<10\text{mm}$, $10\text{mm}<x<15\text{mm}$ and $25\text{mm}<x<30\text{mm}$. The cylinder was moved in negative direction of x-axis. The Reynolds number, Re was fixed at 61 (cylinder velocity, V_c=18.8mm/s). The experiment was done at room temperature, T_e= 20~22 °C.