Proceedings of the 4th International Forum on Heat Transfer, IFHT2016
November 2-4, 2016, Sendai, Japan

IFHT2016-1986

HEAT TRANSFER CONTROL BY LIGHT IRRADIATION TO LOW REYNOLDS NUMBER FLOWS USING A PHOTOSENSITIVE MICELLAR SOLUTION

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ABSTRACT

For the improvement in performance of compact heat exchangers, the authors are aiming at controlling heat transfer rates in milli-scale flows, with photo-rheological fluids (PRFs), viscoelasticity of which can be tuned by light. In our previous study, ortho-methoxy cinnamic acid (OMCA) known as a photo-sensitive molecule was added to a wormlike micellar aqueous solution. OMCA irreversibly isomerizes from trans-OMCA to cis-OMCA upon exposure to UV light. This photo-isomerization alters the molecular packing at the micellar interface, shortens wormlike micelles, and structurally weakens the viscoelasticity of the solution. This study demonstrates light irradiation to PRFs flowing in a milli-scale serpentine channel to change mean heat transfer coefficient and pressure loss penalty. We installed a light irradiation part upstream of the heat transfer part, and performed a heat transfer experiment and pressure-drop measurement in the downstream region. As a result, both mean heat transfer coefficient and pressure loss penalty were decreased, which is supposed to be caused by weaker viscoelasticity of the solution that may significantly influence flow structure, as OMCA undergoes a photo-isomerization. This result suggests the possibility that heat transfer performance can be controlled by light.

KEY WORDS: Viscoelasticity, Photo-rheological fluids, Micellar solution, Heat transfer characteristics, Low Reynolds number flow

1. INTRODUCTION

In recent years, the heat rate generated from a unit area of various electric devices increases with downsizing and integration of electronic circuits, which causes problems in reliable operation of these devices. Thus for the development of a high-performance small heat exchanger, various methods to improve working fluids and flow channel geometry have been extensively studied. Since Reynolds number decreases in small ducts, a flow becomes laminar, and heat transfer performance decreases in comparison with the turbulence where a fluid is mixed by unsteady vortices. One of the methods to solve this problem is using viscoelastic fluids as working fluids. In a viscoelastic flow, unsteady secondary flows are generated even at low Reynolds number regime where a laminar flow is normally formed in the case using Newtonian fluids. Tatsumi et al. [1, 2] experimentally and numerically investigated the flow structure and heat transfer characteristics of viscoelastic flows in a millimeter-scale serpentine channel. They showed that both heat transfer coefficients and wall friction factors were increased by utilizing a polymer solution as a working fluid, since the viscoelasticity of the fluid induces flow perturbations and generates unsteady secondary flows. This implies that more pumping energy to supply working fluids is required for the enhanced heat transfer in viscoelastic fluids than in Newtonian fluids.

In order to overcome this trade-off problem related to the viscoelasticity, the authors are trying to develop an energy saving method of heat transfer control by changing degree of viscoelasticity of a working fluid. Photo-rheological fluids (PRFs), whose rheological properties can be controlled by light, have gathered attention and

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been researched in some engineering fields [3, 4], to date. The authors' research group has been also investigating the characteristics of PRF flows and showed that the viscoelasticity of a photo-sensitive wormlike micellar solution, which is one of the PRFs, was decreased by light irradiation. They also showed that by using this pre-irradiated solution as a working fluid, heat transfer rate and pressure drop were decreased in comparison with the case using Newtonian fluids [5, 6].

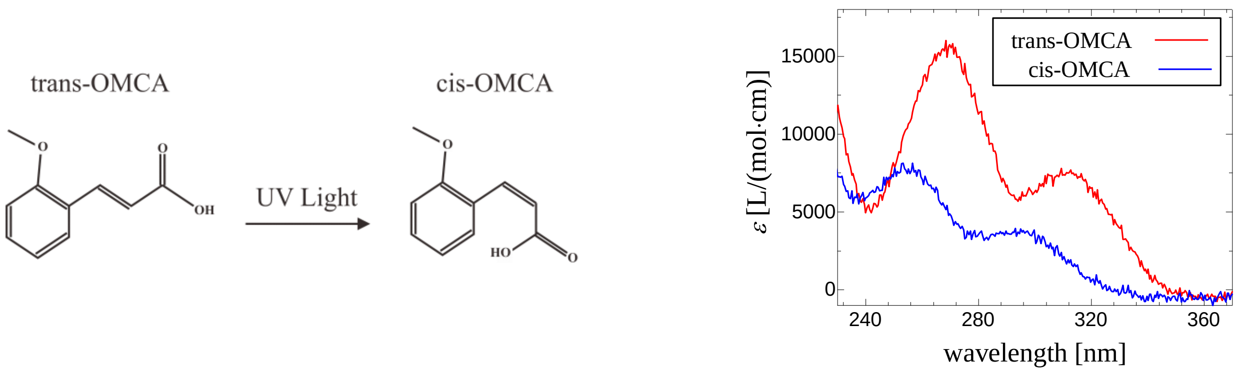
In consideration of the implementation to an actual installation of PRFs to heat transfer devices, this study performs light irradiation to a PRF flowing in a channel upstream of the heat transfer target channel and in-situ switching of viscoelasticity of a photo-sensitive micellar solution. Then, a heat transfer coefficient and a pressure loss in the target channel are measured in order to evaluate the influence of the light irradiation on the heat transfer performance of PRFs.

2. Working Fluids

A working fluid used in the present study was cetyl-tri-methyl-ammonium bromide (CTAB) and sodium salicylate (NaSal) mixture aqueous solutions in which ortho-methoxy cinnamic acid (OMCA) is added. The concentrations of CTAB/NaSal/OMCA solution (CNO solution) were set to be 1.0wt% (CTAB), 0.2wt% (NaSal), and 0.2wt% (OMCA). OMCA is a photo-sensitive molecule which has trans- and cis-arrangements of substituent. Figure 1 (a) and (b) shows the schematic behaviour of OMCA photo-isomerization and molar absorption coefficient, ε [L/(mol·cm)] of trans-OMCA and cis-OMCA, respectively. Figure 1 (b) represents trans-OMCA irreversibly undergoes a photo-isomerization to cis-OMCA upon exposure to UV light, which is attributed to the fact that ε of trans-OMCA is larger than ε of cis-OMCA at wavelength in the range of 250-350nm. In this study, trans-OMCA is added to an aqueous mixture of CTAB and NaSal which are known for inducing the formation of wormlike micelles [7]. When trans-OMCA molecules are taken in micelle-aggregate aqueous solution, they shorten distance between CTAB molecules. Then, long wormlike micelles are formed, the micelles become entwined with each other, and the development of micelle network structure is promoted. The aqueous solution eventually shows viscoelasticity which can be similarly seen in polymer solutions. By contrast, when cis-OMCA molecules are generated by light irradiation and taken in the micelle-aggregate solution, they slightly shorten distance between CTAB. Then, short wormlike micelles are formed and the micelle network development is restrained. As a result, the solution shows less viscoelasticity like a Newtonian fluid. Based on the above mechanism, a viscoelasticity of CNO solutions can be changed by light irradiation and also the concentration of cis- or trans-OMCA in the solution. The concentration ratio of trans-OMCA to cis-OMCA, ϕ [%], which is an important index to evaluate viscoelasticity of CNO solution, is defined below:

$$\phi = \frac{c_{\text{trans}}}{c_{\text{trans}} + c_{\text{cis}}} \times 100 \qquad (1)$$

where c_{trans} and c_{cis} are the mass concentrations [wt%] of trans-OMCA and cis-OMCA, respectively. By UV light irradiation, ϕ is decreased, and therefore the viscoelasticity is decreased. In this study, CNO solution of $\phi = 100\%$ (trans-OMCA only) was prepared to be used in UV irradiation experiment. Besides, $\phi = 50\%$ was prepared by mixing half of trans-OMCA and cis-OMCA to be compared with the solution after UV irradiation.



(a) OMCA photo-isomerization (b) ε of trans-OMCA and cis-OMCA

Fig. 1 Schematics and molar absorption coefficient, ε of OMCA .

3. Apparatus

Figure 2 shows the schematic diagram and dimensions of the experimental setup comprised of a light irradiation section and a heat transfer measurement section. The light irradiation section was installed upstream of the measurement section. CNO solution flowing in the duct was irradiated and (partially) isomerized by UV light before reaching to the measurement section where a heat transfer coefficient and a pressure loss were measured to evaluate the effect of light irradiation in the upstream region.

At the light irradiation section, a 400W mercury lamp (SenLights HL400BH-8) covered by a water cooling jacket was inserted in a cylindrical chamber made by acrylic. CNO solution was fed to an inlet of the section by a pressurized solution-stored tank, and irradiated by the lamp, flowing through the gap between the outer wall of cooling jacket and the inner wall of the chamber. To prevent heat of the lamp from reaching the CNO solution, cooling water at 20 °C was circulated in the cooling jacket.

The measurement section had a square cross section of 5mm × 5mm, and comprised of an entrance duct, a serpentine channel and an exit duct. The serpentine channel consists of 10 semicircle units connected periodically in the streamwise direction. The inner and outer radii of curvature of the semicircle unit were R_i = 5mm and R_o = 10mm, respectively. The length of the serpentine channel along the streamwise direction, L, was ca. 470mm. The entrance and the exit ducts were made of acrylic. The wall of the serpentine channel was made of copper blocks, which was isothermally heated up by water circulation at constant temperature during the experiment. CNO solution was supplied to the serpentine channel via the light irradiation section. The mass of the fluid flowing from the outlet was weighed on an electronic scale in order to measure the mass flow rate, $\dot{m}$ [kg/s]. The mass flow rate was regulated by controlling the pressure in the tank. A K-type thermocouple located at the center of the inlet was used to measure fluid temperature at the inlet, while that at the outlet was measured by five K-type bare thermocouples evenly arranged in the height direction at the center of the channel. Using these temperatures measured at the corresponding locations, the bulk mean temperatures of the fluid at the inlet and outlet of the test section, $T_{b,i}$ [°C] and $T_{b,o}$ [°C], were estimated by weighted average method based on the velocity profile of fully-developed flow in a square channel. The wall temperature, T_w [°C], was obtained by averaging the temperatures measured by four thermocouples placed at the copper wall blocks. Pressure sensors were installed at the entrance and the exit of the serpentine channel to measure a pressure loss, ΔP [Pa]. The average heat transfer coefficient, h_m [J/(m^2·K·s)], and an average Nusselt number, Nu_m, were defined as follows:

$$h_{\mathrm{m}} = \frac{\dot{m}c_{\mathrm{p}}}{A_{\mathrm{s}}} \times \ln \frac{T_{\mathrm{w}} - T_{\mathrm{b,i}}}{T_{\mathrm{w}} - T_{\mathrm{b,o}}} \quad (2)$$

$$Nu_{\mathrm{m}} = h_{\mathrm{m}} D_{\mathrm{h}} / k \quad (3)$$

where A_s [m^2] is the total area of heat transfer and D_h [m] is the hydraulic diameter of the channel. c_p [J/(g·K)] and k [J/(m·K·s)] indicate the specific heat capacity at constant pressure and thermal conductivity of the fluid, respectively. We evaluate pressure loss penalty by Fanning's friction factor, f defined as follows:

$$f = \frac{D_{\mathrm{h}} \Delta P}{2\rho U_{\mathrm{m}}{}^2 L} \quad (4)$$

where ρ [kg/m^3] is the density of CNO solution. The flow rate is represented by modified Reynolds number, Re^*, which is defined as follows:

$$Re^* = \frac{\rho U_{\mathrm{m}}{}^{2-n} D_{\mathrm{h}}{}^{n}}{8^{\mathrm{n-1}} K (B + A/n)^2} \quad (5)$$

where A and B are the geometrical constants, 0.2121 and 0.6766 at the rectangular flow, respectively [8]. The values, n and K, referred to the constants used to express shear viscosity, μ [Pa·s], as a function of shear rate, $\dot{\gamma}$ [1/s] ($\mu = K\dot{\gamma}^{n-1}$). These two values were calculated from the results of static viscosity measurement using the rheometer. Physical properties (c_p, k, ρ) of pure water are used for those of CNO solutions in the above calculations with the consideration of temperature dependence.

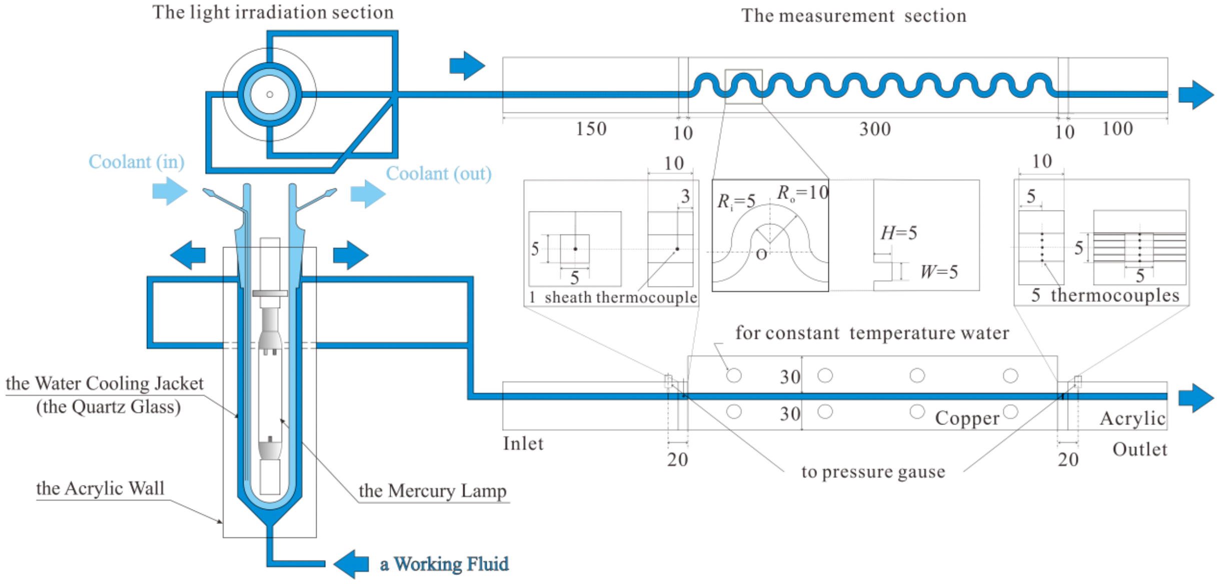


Fig. 2 Apparatus.

4. EXPERIMENTAL CONDITIONS

In this research, viscoelasticity of CNO solution was evaluated by a relaxation time, λ [s], determined using a rheometer (ANTON PAAR, MCR301) equipped with a 50mm diameter cone plate. The measurement was conducted while keeping the temperature of the measurement cell at 30°C.

At Re^*~ O(1) the change in thermal properties by the light irradiation (i.e., isomerization) is considered to be large [5], and thus it is desirable to perform experiments at such Re^* condition. First, the CNO solution (ϕ = 100%) was supplied to the channel with the mercury lamp off. The initial flow rate before the light irradiation was set at Re^* = 1.69 by adjusting a pressure in the tank. After the flow became stable, the lamp was turned on. The light intensity of the lamp gradually increased over 300 seconds and after that maintained a steady state. Also the flow rate increased with the light intensity during the warming-up time of lamp, which resulted in a decrease in viscoelasticity and also pressure loss. This trend corresponds well with the decrease of ϕ implying the trans-to-cis transition, which was reported by the previous study [5, 6]. After the flow became stable again, the measurement of heat transfer coefficient and pressure loss was performed for 100s, which is referred to as Exp.1 hereinafter. After Exp.1, the pressure of the tank was manually increased to obtain a higher flow rate. After the flow became stable, the measurement was performed for 100s again, which is referred to as Exp.2. The solution stably drained from the exit was collected in order to determine λ of each solution using the rheometer. To compare with the above results for the case of in-situ light irradiation, the measurement of heat transfer coefficient and pressure loss was performed for the trans- and cis- concentration adjustment case of CNO solution (ϕ = 50 and 100%) without light irradiation. Note that the experiments for ϕ = 50 and 100% were conducted at various flow rate by changing the tank pressure. The flow rate, Q [mL/s], Re^* of each experiment, and λ of each solution are listed in Table 1.

Table 1 Flow conditions of heat transfer experiments and relaxation times of CNO solutions.

Experiment	Q [mL/s]	Re^*	λ [s]
ϕ = 50%	0.47 ~ 2.07	0.66 ~ 11.00	1.43
ϕ = 100%	0.41 ~ 2.28	0.36 ~ 9.83	4.58
Exp. 1	1.45	4.30	3.10
Exp. 2	2.08	7.80	3.72

5. RESULTS

5.1 Viscoelasticity Figure 3 shows the relaxation time, λ, of CNO solutions plotted against the UV irradiation time per unit volume, t^* [s/mL]. The black squares plotted in Fig. 3 express λ of CNO solutions at various t^* conditions after UV irradiation starts. The CNO solution given initially $\phi = 100\%$ was poured into an open vessel located on a magnetic stirrer and irradiated by the same UV lamp which is used in the measurement apparatus in Fig. 2. In this case, t^* is calculated by $t^* = t / V$, where t [s] is total light irradiation time and V [mL] is volume of a solution in the vessel. The open square indicates $\phi = 50\%$ as a reference. With the increase of t^*, λ of $\phi = 100\%$ decreased and converged to an almost constant value. This trend indicates that a photo-isomerization from trans-OMCA to cis-OMCA progressed markedly in the early periods and the viscoelasticity of solution correspondingly decreased with light irradiation. In this experiment, the photo-isomerization is considered to reach the equilibrium at t^* = 30s/mL.

The red and green squares of Exp.1 and Exp.2 express λ of CNO solutions collected at the channel exit. In this case, t^* is calculated by $t^* = 1/Q$. For both experimental conditions, λ decreased compared to that of the initial solution and the decrement became larger with increasing t^*. This trend indicates that the photo-isomerization was caused by in-situ light irradiation to the flow field using setup in Fig.1, and the viscoelasticity of solutions decreased. Furthermore, this tendency accords well with the case of light irradiation to the solution in the open vessel (the black square plots). This result implies that there is some possibility of predicting the λ of the CNO solutions undergoing in-situ light irradiation at the light irradiation section by using the results of black squares plotted in Fig. 3.

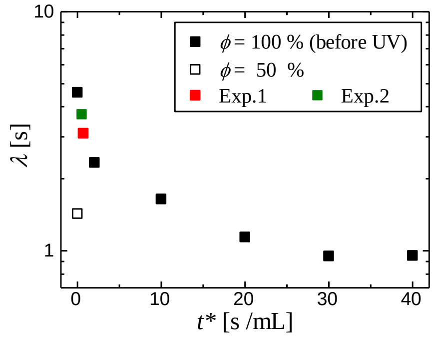


Fig. 3 Relaxation time, λ of CNO solutions depending on the UV irradiation time per unit volume, t^*.

5.2 Heat transfer and pressure drop Figures 4 (a) and (b) show, respectively, the average Nusselt number Nu_m and Fanning's friction factor, f of CNO solution plotted against Re^* in the case of $\phi = 50$, 100%, Exp.1 and Exp.2. The solid line drawn in Fig. 4 (b) indicates the theoretically-obtained friction factor of steady flow in a square duct [8]. In Figs. 4 (a) and (b), Nu_m and f of the case $\phi = 100\%$ (before UV) were totally larger than those of $\phi = 50\%$ in all Re^* region. This indicates that high viscoelasticity caused unsteady flow and enhanced heat transfer in the case $\phi = 100\%$ while the low viscoelasticity caused steady flow and hardly enhanced heat transfer in the case $\phi = 50\%$.

In Exp.1, $Nu_m = 4.79$ and $f = 2.58$ at $Re^* = 4.30$. These values are much smaller than the case of $\phi = 100\%$ and almost consistent with those of $\phi = 50\%$. This indicates that unsteady flow became steady with a decrease in viscoelasticity by light irradiation to the flow field, and as a result heat transfer and pressure loss decreased. In Exp. 2, Nu_m and f at $Re^* = 7.80$ are also much smaller than those of the case $\phi = 100\%$, but, Nu_m is still higher than the case $\phi = 50\%$. This indicates that t^* was decreased by increasing the flow rate compared to the Exp.1 and the decrement of λ became smaller than the case of the Exp. 1, which will lead to the heat transfer control by the degree of in-situ light irradiation. In both experiments, f are slightly lower than the case of $\phi = 50\%$, although, λ of Exp. 1 and Exp. 2 are higher than $\phi = 50\%$ (see Table. 2). These results still leave room for the further inspection about the relation of λ to Nu_m and f. Since there are few samples in this research, we will perform the further experiments and confirm the reproducibility of the results.

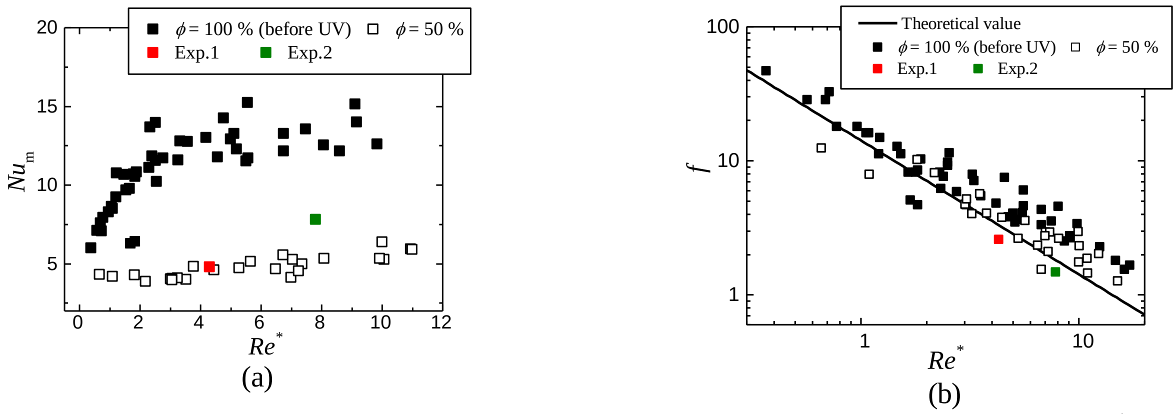


Fig. 4 Nusselt number, Nu_m and Fanning's friction factor, f of CNO solution plotted against Re^*.

6. CONCLUSIONS

Viscoelasticity: By in-situ light irradiation to the flow field, the relaxation time decreased compared to that of the initial solution and the decrement became larger with increasing the light irradiation time.
Heat transfer and pressure drop: The decrease in viscoelasticity by light irradiation to the flow field possibly modifies the flow structure, and as a result heat transfer and pressure loss decreased.

NOMENCLATURE

A_s	total area of heat t ransfer wall	[m^2]
c_{cis}	weight density of cis-OMCA	[wt%]
c_{trans}	weight density of trans-OMCA	[wt%]
D_h	hydraulic diameter of the channel	[m]
f	Fanning's friction factor	[-]
h_m	average heat transfer coefficient	[J/(m^2·K·s)]
k	thermal conductivity	[J/(m·K·s)]
L	length along the serpentine channel	[mm]
$\dot{m}$	mass flow rate	[kg/s]
Nu_m	average Nusselt number	[-]
t^*	UV irradiation time per unit volume	[s/mL]
$T_{b,i}$	bulk mean temperatures at the inlet	[°C]
$T_{b,o}$	bulk mean temperatures at the outlet	[°C]
T_w	wall temperature	[°C]
ΔP	pressure loss	[Pa]
ϕ	cis-trans isomer existence ratio	[%]
λ	a relaxation time	[s]

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