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Flow and heat transfer around the flat plate installed in a pulsating duct flow with intermittent flow rate fluctuation

Abstract. This study deals with flow behavior and associated heat transfer in a pulsating duct flow. In our previous studies, effect of continuous sinusoidal flow rate fluctuation on heat transfer and flow behavior around the flat plate installed in a duct was experimentally investigated. In these papers the authors concluded that heat transfer enhancement or no impact of pulsation effect on heat transfer depends on the increase or constant of time-averaged local flow rate around the flat plate induced by flow pulsation. Based on this knowledge obtained in the previous studies, heat transfer rate on the flat plate installed in pulsating duct flow can be controlled under combination of several parameters. As the next step, focusing on the pulsation mode, we examined a pulsating duct flow with intermittent flow rate fluctuation. Flow rate change was realized by valve motions inside the flow passage that electronically controlled by a servo motor connected with a ball screw actuator. Combined effects of time averaged flow rate, pulsating amplitude and pulsating frequency on flow and heat transfer around the flat plate in a duct was experimentally investigated. Heat transfer characteristics on the flat plate were evaluated based on both the temperature measurement and visualization of thermal boundary layer. Within the examined conditions, results showed no impact on heat transfer in the case of intermittent flow rate change. In order to make clear what sort of flow behavior attributed to such heat transfer characteristics, flow visualization and PIV analysis were carried out. Time-averaged velocity around the flat plate was approximately to be the same as steady flow even when strong flow instabilities at the inlet of the passage occurred.

1. Introduction

1.1. *Background*

Researches on pulsating flow have been highlighted on its high performance mass transport characteristics in living bodies such as blood flow and respiration [2, 4, 6-8]. Although most of body fluid flows in a living body are pulsating flows, they show various kinds of flow patterns. Such patterns of body fluids flow had been established during a long history of evolution. Therefore pulsating flow seems to be superior to steady flow in term of the controllability of body temperature with negligibly small bad influence on each cell. Focusing on the high performance mass transport characteristics, a lot of researchers in medical and bioengineering fields are interested in pulsating flow. Mechanical engineers also pay an attention to the heat and mass transport mechanisms of pulsating flow for further improvements of various kinds of thermal devices and electric/electronic equipment by providing pulsating flow as their cooling. Present life and industrial activities in our affluent societies depend on hydrocarbon combustion, and global energy and environmental problems such as oil reserve depletion and global warming have been appeared. Although reduction of greenhouse gases is required on a global scale, and the utilization of renewable clean energy such as solar, wind, biofuel energy is promoted, fossil fuel is expected to be the main energy resources in near future due to its huge power density and its supply potential, convenience and economy comparing to any other alternative power resources. Therefore, it is necessary to improve the performance of heat engines and thermal devices with their fine temperature control. However, conventional cooling technologies of heat engines and thermal devices are generally designed under steady operating conditions from the viewpoint of material protection under high temperature operating circumstances, and they are mainly passive temperature control by using convective heat transfer with steady flow. For further improvement of their performance, active temperature control technique must be required. Pulsating flow has higher controllability of flow behaviour comparing to steady flow, therefore, active control of temperature field by pulsating flow can be a breakthrough technology. In recent years, by providing a pulsating flow, researches on pulsating flow aiming at improving heat transfer performance of heat exchangers and heat pipes have been actively carried out. Embaye et al. [1] recommended the employment of pulsating flow for the energy saving in the central heating system of buildings based on their numerical study with its verification with experimental results already reported by other researchers. Persoon et al. [3] investigated the effect of flow pulsation on heat transfer of a mini-channel heat sink, and they reported 40% enhancement in maximum heat transfer by using a pulsating flow instead of steady flow case. The author Saitoh [5] experimentally investigated the flow structure and associated heat transfer on the flat plate installed in a pulsating duct flow. Saitoh [5] reported the controllability of heat transfer rate under several pulsation parameter-combinations based on their visualization results of both the flow and temperature fields.

1.2. *Objectives*
However, flow structure with periodical flow rate change and its effect on heat transfer are still at question. Especially few reports exist focusing on the pulsation mode. Almost all of the published papers deal with the pulsating flow with periodical continuous sinusoidal flow rate fluctuation. This paper focuses on the pulsating flow with intermittent flow rate change based on an idea of higher controllability of flow field. The objective of this study, therefore, is to understand the behaviour of a pulsating duct flow with intermittent flow rate fluctuation and the associated heat transfer characteristics on the flat plate installed in such pulsating duct flow.

2. Heat transfer experiment

2.1. *Experimental apparatus and method on heat transfer evaluation*
Figure 1 shows a schematic of the test section. The test section has 100 mm × 100 mm square cross section, and a heated flat plate is installed in the middle of its cross section. A stainless steel foil was attached on the both sides of the flat plate as heaters. One was used as the heat transfer surface and another one was set as guard heater to realize negligible small heat loss across the flat plate. In the experiments, direct electrical current was supplied to the heater, heat transfer tests were carried out under uniform heat flux condition. Seven K-type thermocouples were attached on the heater along the flow passage for temperature measurement. The test section has one pair of Plexiglass windows to simultaneously conduct the visualization test of thermal boundary layer formed on the heat transfer surface. Thermal boundary layer was visualized by color schlieren method. Visualized thermal boundary layer was recorded with a high speed camera (100fps). Figure 2 shows a schematic diagram of the experimental setup. Operating fluid was air and it was driven by a sirocco fan and flow rate fluctuation (pulsation) was realized by opening/closing control of the valve in front of the test section. After passing through the test section, air was passed through the surge tank and was discharged into the atmosphere via velocity measurement with hot wire anemometer. The pulsation generator consists of a valve head and a ball screw actuator connected with an electronic controlled servomotor. Figure 3 is a photograph of the valve oscillation actuating system. Intermittent flow rate change was realized with valve head motion by the servomotor control. Top dead center of the valve was detected by an infrared sensor connected with a LED lump. LED lump was turned off when the infrared beam was interrupted by the aluminium plate attached with the valve oscillation mechanism. This aluminium plate was set so that the LED lump was turned off when the valve head was placed at its top dead

center. Conceptual figure of the valve oscillation is illustrated also in figure 3. The valve position at an arbitrary time can be calculated from the valve top dead center position and the recording speed.

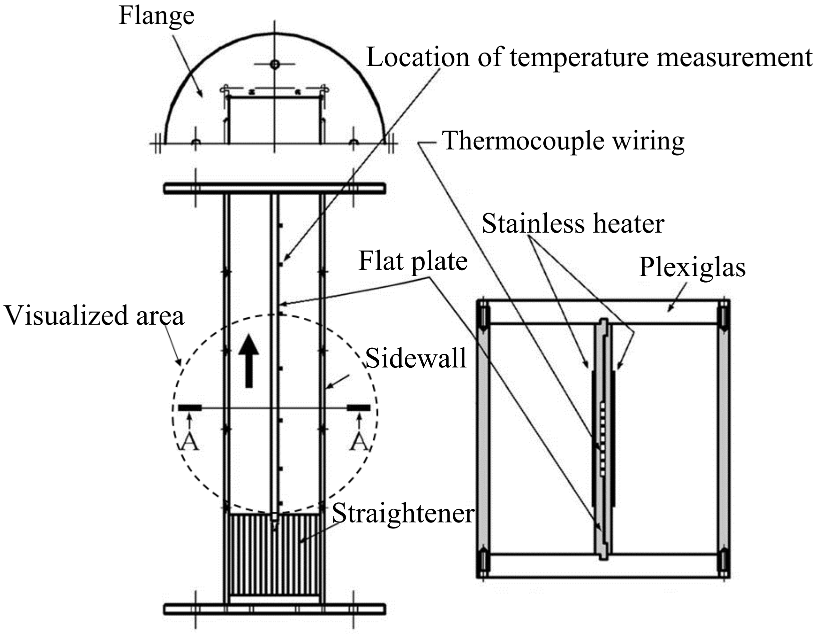


Figure 1. Test section for temp.measurement and schlieren visualization

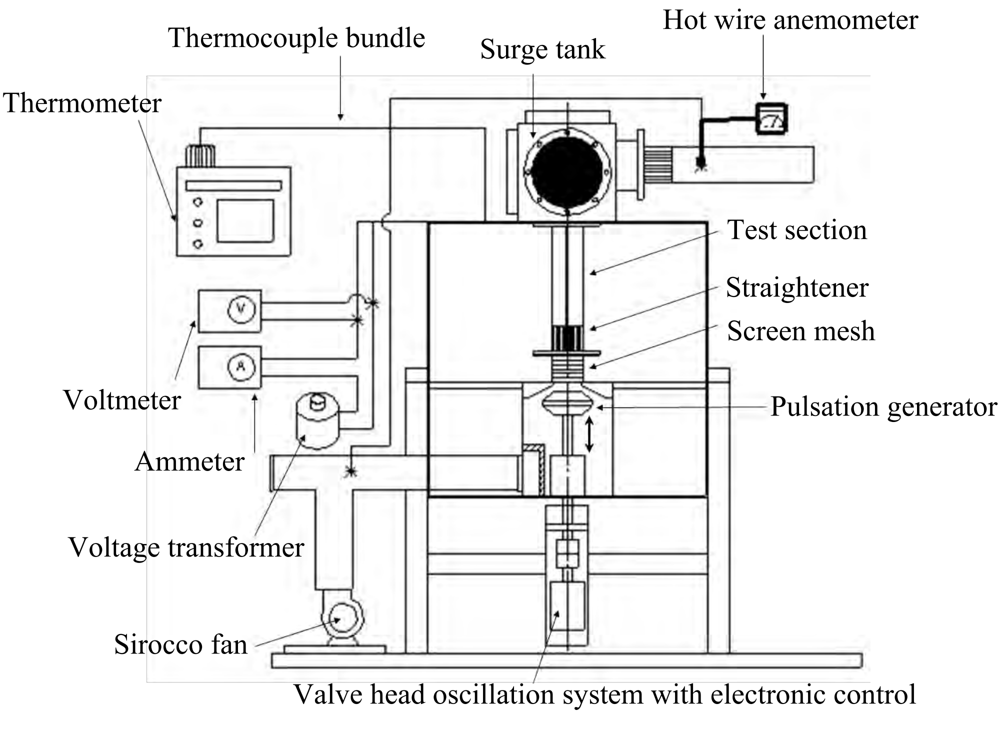


Figure 2. Apparatus for heat transfer experiments

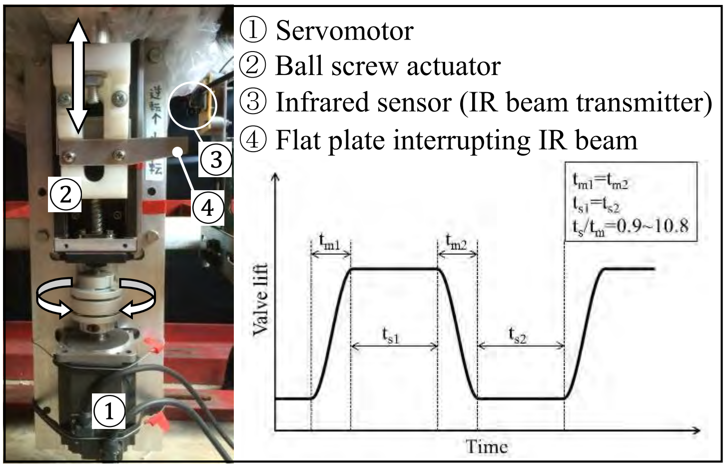


Figure 3. Valve head oscillation mechanism

2.2. *Evaluation method of heat transfer characteristics*

In the experiments, we defined Re_m and Re_f/Re_m as dimensionless time average flow rate and amplitude, respectively. Re_m and Re_f are the Reynolds numbers based on the time average flow velocity u_m and the velocity amplitude u_f in the test section. The respective definition formulas are as equations (1) and (2):

$$Re_m = u_m \cdot d_e / v \tag{1}$$

$$Re_f = u_f \cdot d_e / v \tag{2}$$

The velocity amplitude u_f is expressed by equation (3).

$$u_f = u_{max} - u_m = u_m - u_{min} = \frac{1}{2}(u_{max} - u_{min}) = \frac{A_{max}-A_{min}}{A_{max}+A_{min}} u_m \tag{3}$$

In equation (3), A_{max} and A_{min} represent the cross-sectional areas of the flow passage formed by the valve and contraction part in front of the test section, respectively. Dimensionless pulsating amplitude was defined as the ratio between u_f and u_m. This corresponds to the ratio of two kinds of Reynolds numbers expressed in equations (1) and (2). In order to protect the experimental apparatus, it must be ensured that $A_{\min} \neq 0$. This means that the valve is not fully closed. Pulsating frequency was set by the valve oscillation frequency.

Heat transfer characteristics was evaluated by local heat transfer coefficient expressed by the equation (4) below based on the temperature measurement of the heat transfer surface. T_b represents the bulk temperature of air.

$$h(X) = \frac{\dot{q}}{(T_w(X) - T_b(X))} \tag{4}$$

Local Nusselt number is expressed as equation (5):

$$Nu(X) = \frac{h(X) \cdot d_e}{\lambda} \tag{5}$$

Table 1 shows the experimental conditions. Experiments were carried out for 30 parameter combinations.

Table 1. Experimental conditions

Time averaged flow rate Re_m	920 , 2000 , 3000
Pulsating amplitude Re_f / Re_m	0.56 , 0.72 , 0.85
Pulsating frequency f [Hz]	0(steady flow) , 1 , 2 , 3

2.3. *Experimental results and discussion on heat transfer characteristics*

Figures 4 (a), (b) and (c) show the local Nusselt number distributions along the heat transfer surface under the conditions of Re_m = 920, 2000 and 3000, respectively. Nu (X) monotonically decreases in the flow direction regardless of Re_m condition. In addition, Nu (X) in the cases of pulsating flow coincided with those in the case of steady flow. This tendency is clearly seen in each Re_m condition. This result allows us to conclude that the effect of intermittent flow rate fluctuation on heat transfer is negligibly small. Figure 5 is the visualized image of thermal boundary layer formed on the heated flat plate under the conditions of Re_m = 3000, f = 3 Hz, Re_f/ Re_m = 0.85. The left figure indicates the instantaneous visualization result obtained when the valve was placed at its bottom dead center (BDC), on the contrary, the right figure shows the case when the valve was placed at its top dead center (TDC). As shown in figure 5, regardless of the valve position, thermal boundary layer developed in the flow direction. In comparison with these two images (BDC case and TDC case), it can be seen that the thickness of the thermal boundary layer in the case of BDC is smaller than that in the TDC case. On the movie, it was observed that the thickness of the thermal boundary layer was fluctuated in conjunction with the valve oscillation, and maximum and minimum thickness was indicated at TDC and BDC in valve position, respectively. These characteristics were confirmed under all the examined experimental conditions. Based on the results described above, it is considered that the flow rate becomes the maximum at the valve position of BDC and becomes the minimum at the TDC. It can be recognized from figures 4 and 5 that although the temporal velocity fluctuation rate in the pulsating flow with intermittent flow rate fluctuation is larger than that of the pulsation flow with continuous sinusoidal fluctuation mode, time-averaged local flow rate around the flat plate was approximately the same with that of steady flow case. As the result of such flow behaviour, it seems to show no impact of intermittent flow pulsation on heat transfer around the flat plate. In order to verify the above introduced consideration, flow visualization was conducted.

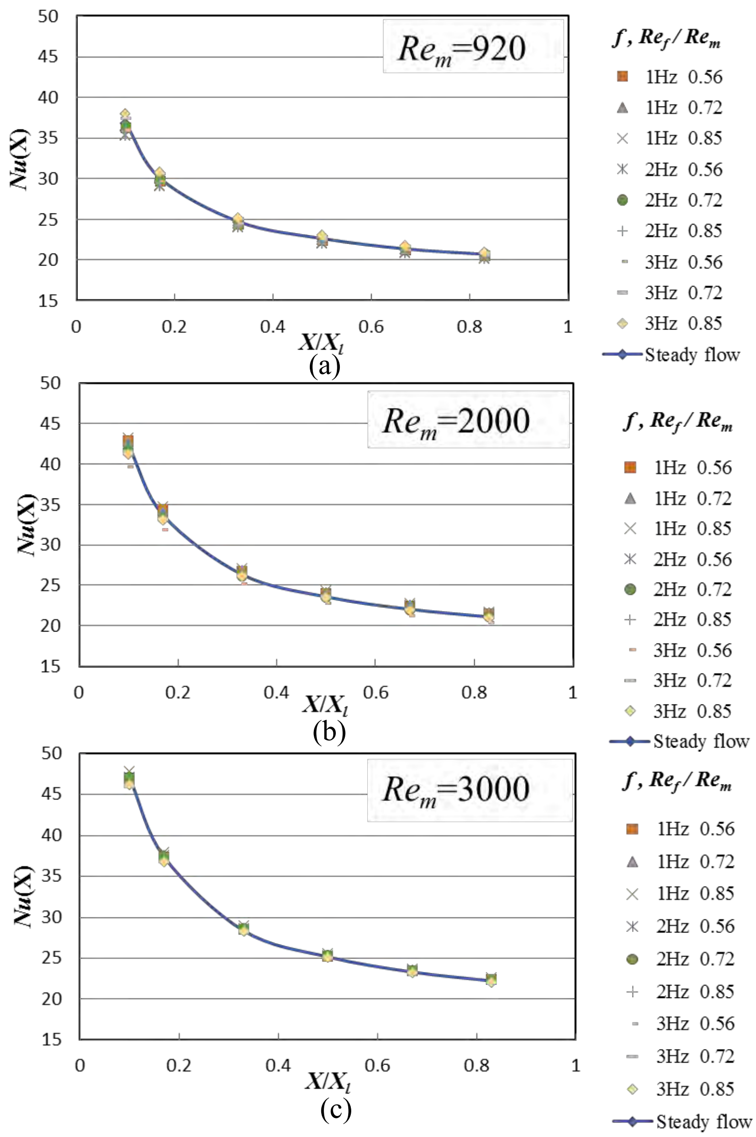
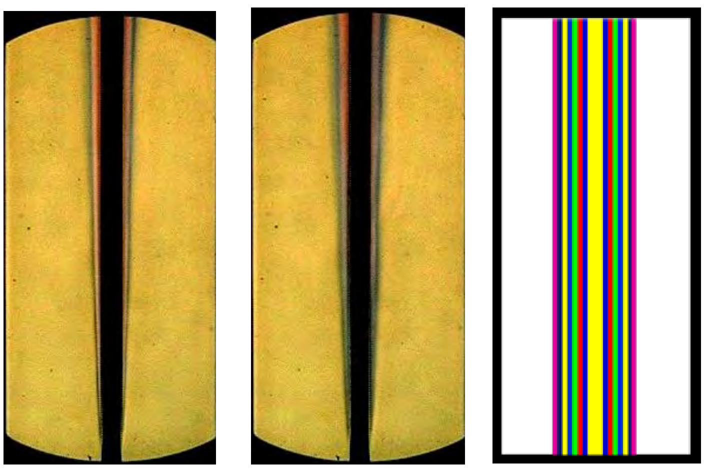


Figure 4. Effects of pulsating frequency, amplitude and time averaged flow rate on local Nusselt number



BDC TDC Color slit

Figure 5. Visualization results of thermal boundary layer at position of the valve head

3. Flow visualization test

3.1. *Experimental apparatus and method for flow visualization*

For quantitative evaluation of pulsating flow field, flow visualization by particle suspension method was carried out and PIV analysis was performed. Figure 6 shows a schematic diagram of flow visualization experimental apparatus. Water was used as the test fluid. Operating fluid, water, was driven by the head difference between the head tank and the overflow tank, and the flow rate was adjusted with the main valve. Temporal flow rate fluctuation was added to the fluid in the pulsation generator placed in front of the test section. Valve oscillation mechanism was the same as that in the heat transfer experiment previously introduced in figure 3. Ion exchange resin (average particle diameter φ 20 μm) adjusted in specific gravity was used as a tracer particle and laser light sheet with its power of 20 mW and 532 nm in its wavelength was employed as a light source. Two-dimensional flow field of the test section was visualized. Software Flownizer 2 D (DETECT Inc.) was used for two dimensional PIV analysis. The experimental conditions were the same as the heat transfer experiments in table 1.

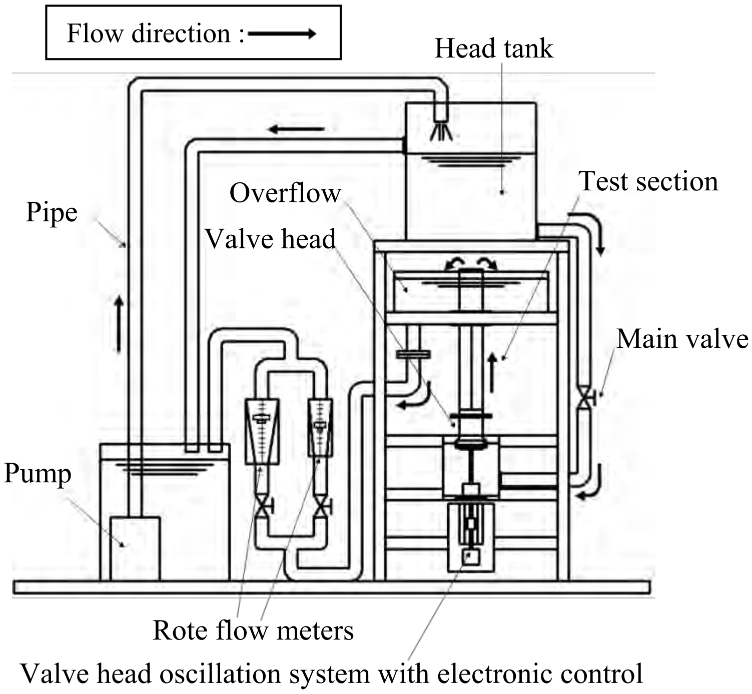


Figure 6. Experimental apparatus for flow visualization

3.2. *Experimental results and discussion on flow behaviour*

Figure 7 is the result of PIV analysis under the conditions of Re_m=3000 and f =3Hz. Each set of nine figures shows the one cycle of flow rate fluctuation. Color contour indicates the scalar value of flow direction velocity component. Velocity vector is recognized by the color contour and the same length arrows represented on the color contour. Numbers described under each figure ①-⑨ correspond to the valve position as shown at the upper part of figure 7. Conceptual image of the valve head speed is also drawn at the upper part of figure 7. Analyzed images of ②-④ correspond to the ascending region of the valve head, and ⑥-⑧ correspond to the descending region. Velocity fluctuation was approximately coincided with valve head motion. When the valve head rose up velocity was increased, on the contrary velocity decreased when the valve head descended. In the case of Re_m=3000, time-averaged velocity calculated from measured flow rate was u_m = 0.060 m/s. At the timing of ②, ⑤ and

⑧, velocity was approximately coincided with the time-averaged velocity (u_m) , and uniform velocity distribution was obtained, although slight flow instability 7 existed near sidewall regions. On the other hand, strong flow instabilities were found at ⑥ and ⑦ timing where negative acceleration was acted on the fluid particle with the valve motion. These characteristics were clearly observed in any other examined pulsating amplitude (Re_f /Re_m) conditions. In the heat transfer experiments where the test fluid was air, valve motion (open/closed) corresponded to (increasing/decreasing) of flow rate. However, in the flow visualization test, test fluid was water, the valve head seemed to be acted on water as a piston. Therefore, reverse flow was obtained at the timing of ⑥ and ⑦ due to negative momentum given to fluid particle by the valve descending motion.

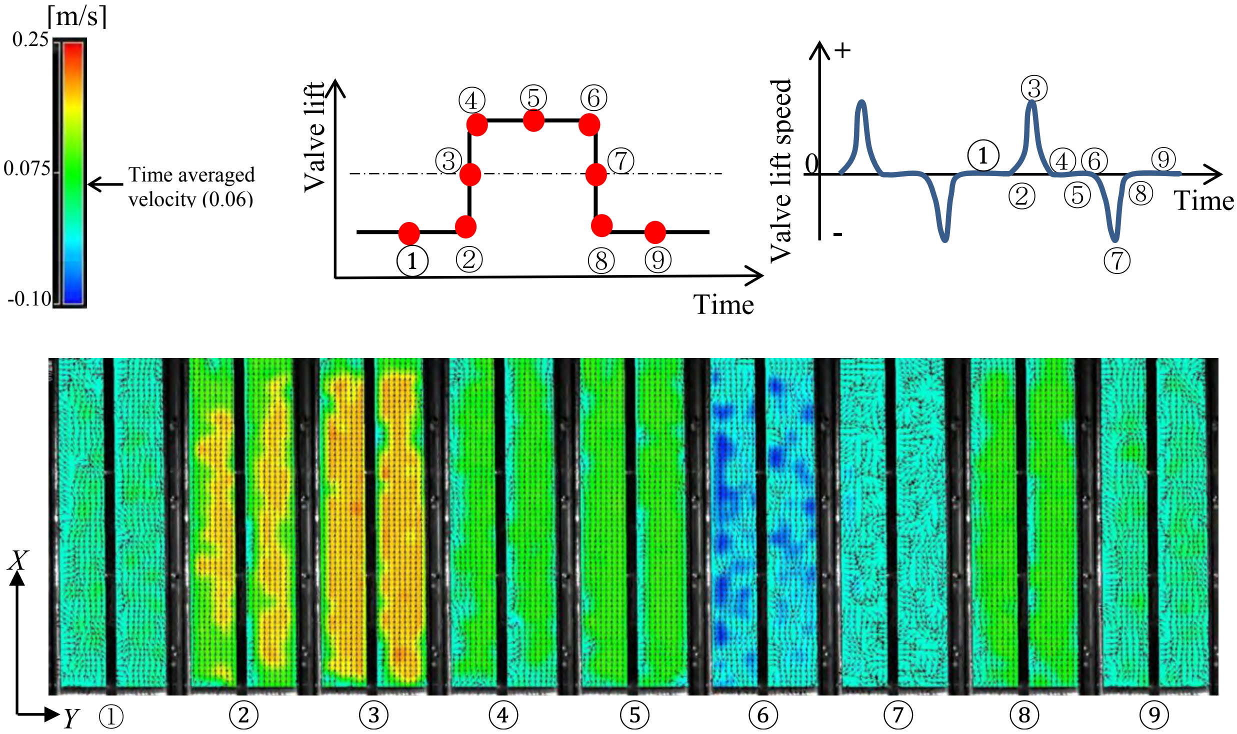


Figure 7. PIV analysis result ($Re_m = 3000, f = 3$Hz , $Re_f/Re_m = 0.85$)

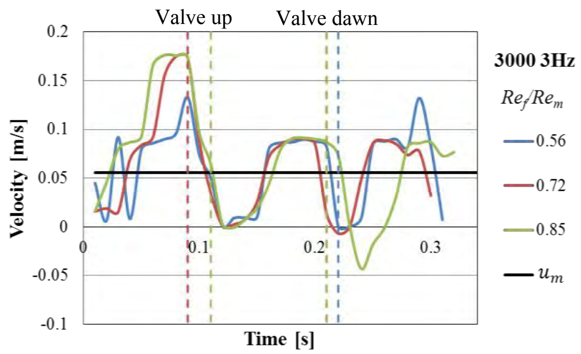


Figure 8. Effect of pulsating amplitude on velocity fluctuation

Figure 8 shows the effect of pulsating amplitude on local velocity fluctuations for one cycle of the pulsating flow under the conditions of Re_m = 3000, f = 3 Hz. Color continuous lines of blue, red and green correspond to the cases of Re_f /Re_m = 0.56, 0.72 and 0.85, respectively. Dashed lines represented as "valve up" and "valve down" indicate the timing of ④ and ⑥ valve head position as illustrated at the upper part of figure 7. Time-averaged velocity as drawn black continuous line was calculated from experimentally measured value of flow rate and that was approximately as the same as the mean value of velocity fluctuation obtained by PIV analysis. Based on this fact the author judged that the PIV analysis data was reliable. When the valve head rises up, which corresponds to the time duration "t_{m1}" as illustrated in figure 3, working fluid can be accelerated due to momentum supply from the valve head; however, at the top dead center of the valve head, velocity seems to decrease drastically due to the stop of momentum supply under the valve almost closed situation. Approximately 0 m/s in velocity was indicated at the top dead center of the valve head (See ⑤ of figure 8). After reaching the top dead center, valve head is maintained its position during "t_{s1}" as illustrated in figure 3. Velocity recovery was seen in "t_{s1}" time duration as ④-⑥ of figure 8. Flow seems to be in a steady state during t_{s1}. On the contrary when the valve head descends ("t_{m2}" duration), strong drag against fluid flow is generated by the valve head negative acceleration, and at the bottom dead center of the valve head velocity seems to increase drastically due to the stop of the negative momentum supply under the valve full-open situation. Flow seems to be steady state again during "t_{s2}". As the result of this flow mechanism, frequency of velocity fluctuation was yielded almost twice of the valve motion frequency. This characteristic of pulsating flow with intermittent flow rate fluctuation is remarkable as completely different from the continuous sinusoidal flow rate change case [5]. Although velocity amplitude was slightly different from each Re_f $/Re_m$ value, temporal velocity fluctuation showed the similar tendency regardless of Re_f $/Re_m$. Therefore, flow seemed to be mainly dominated by time-averaged velocity based Reynolds number (Re_m) and pulsating frequency (f). Due to the test fluid difference, it cannot be compared with the visualized results between temperature field and flow field, heat transfer characteristics as shown in figures 4 and 5 were attributed to the flow behaviour indicated in figures 7 and 8. Namely, flow pulsation with intermittent flow rate fluctuation showed no impact on heat transfer due to constant time-averaged flow rate without strong spatial flow instabilities around the heat transfer surface. However, we obtained one idea of heat transfer enhancement by using pulsating flow with the following flow rate fluctuation; rapid positive momentum supply to the fluid particle corresponding to short "t_{m1}", and slow negative momentum supply corresponding to long "t_{m2}".

4. Conclusions

Focusing on the flow behaviour of a pulsating duct flow with intermittent flow rate fluctuation realized by using a valve oscillation mechanism and associated heat transfer around the flat plate installed in the duct, the authors reached the following conclusions.

1. For pulsating flow with intermittent flow rate fluctuation, time-averaged local heat transfer coefficient (Nusselt number) shows a tendency of monotonous decrease in the flow direction as same as the steady flow case, and the effects of pulsation frequency and the amplitude on heat transfer is negligibly small.

2. Velocity fluctuation is basically followed with valve motion when the test fluid is water. In addition, pulsating frequency of velocity fluctuation is almost twice of the valve oscillation frequency in the cases of 2Hz and 3Hz as experimental pulsating frequency conditions.

3. There is a possibility of active temperature control of an object by using pulsating flow if a combination of parameters such as mechanical structure of pulsation generator, a kind of fluid and pulsation mode is appropriately selected.

5. Nomenclature

A	cross sectional area	[m^2]
d_e	equivalent diameter	[m]
f	pulsating frequency	[Hz]
h	heat transfer coefficient	[$W/(m^2 \cdot K)$]
t	time	[s]
t_b	bulk air temperature	[K]
t_w	wall temperature	[K]
Nu	Nusselt number	[-]
Re_f	velocity amplitude based Reynolds number	[-]
Re_m	mean velocity based Reynolds number	[-]
Re_f/Re_m	dimensionless pulsating amplitude	[-]
u_f	velocity amplitude	[m/s]
u_m	mean velocity	[m/s]
λ	thermal conductivity of air	[$W/(m \cdot K)$]

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