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Correlation Between Wall Heat Transfer And Characteristics Of Pulsating Flow In A Rectangular Tube Toward An Automobile Exhaust System

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Abstract - The objective of this study is to investigate experimentally the effect of pulsation frequency on the heat transfer characteristics and the mechanism of the pulsation flow, which is representative of the operating conditions of the engine exhaust flow. The experimental apparatus consists of a rotating disk with holes that converts steady hot air flow rate into a pulsating flow to exchange heat energy with external air. The fluid temperature is measured by thermocouples, and the wall temperature is measured by thermography. It is found that heat transfer enhancement due to pulsation does not occur at frequencies below 25 Hz, even though the velocity amplitude is large. In order to investigate the cause of this phenomenon, the flow field is measured by PIV(Particle Image Velocimetry) and the turbulent kinetic energy is evaluated. It is clarified that the turbulent kinetic energy near the wall is small at frequencies below 30 Hz, despite the large velocity amplitude. From the time series of velocity data, it was observed that the turbulence is extremely small during the acceleration phase of the fluid. As a result, the turbulent mixing during the acceleration phase is suppressed, and the time-averaged turbulent kinetic energy becomes small, which is thought to have suppressed heat transfer enhancement. This is the first attempt to experimentally link heat transfer and flow structure fluctuations in a pulsating flow, which is achieved by unsteady measurement of the flow field using PIV and calculation of the turbulent kinetic energy.

***Keywords*:** Turbulent pulsating flow, Experimental investigation, Heat transfer, PIV.

1. Introduction

Heat transfer in pulsating flows is found in a wide range of engineering applications such as cooling electronics, pulse jet engines, and heat exchangers. In automobiles, the intake and exhaust manifolds flow are typical pulsating flows. The exhaust manifold's flow and heat transfer characteristics are directly related to the catalyst's performance since the efficiency of the catalyst installed downstream is largely dependent on the exhaust temperature. Host et al. [1] used CAE(Computer Aided Engineering) to evaluate operating a catalyst with high efficiency and suggested reducing exhaust heat during cold start. Thus, it is necessary to understand the heat transfer characteristics in pulsating flow in order to optimize the design of automotive exhaust systems and comply with emission regulations.

Fundamental research on heat transfer in pulsating flow in tubes has been widely conducted. Numerical simulation of laminar pulsating flow were investigated by Guo and Sung [2]. They showed that heat transfer enhancement due to pulsation always occurs when the velocity amplitude is larger than the mean flow velocity. Wang and Zhang [3] performed numerical simulation for turbulent pulsating flows ($8000 \leq Re \leq 80000$, $10 \leq Wo \leq 60$) and showed that the heat transfer enhancement is mainly affected by the Womersley number and velocity amplitude. It is also shown that the heat transfer is strongly enhanced when the velocity amplitude exceeds a specific value. In an experimental study, Habib et al. [4] generated a pulsating flow (8462 ≤ Re ≤ 48540, 1 Hz ≤ f_p ≤ 29.5 Hz) by opening and closing the valve, and evaluated the heat transfer characteristics experimentally. The results showed that the Nusselt number was strongly influenced by the pulsation frequency and the Reynolds number, with a maximum improvement of 44.4% in the heat transfer coefficient at a pulsation frequency of 3.33 Hz. Simonetti et al. [5] created a pulsating flow (10000 ≤ Re ≤ 50000, 10 Hz ≤ f_p ≤ 95 Hz) by opening and closing the valves of a single-cylinder engine and experimentally evaluated the heat transfer characteristics. As a result, it was found that the Nusselt number increased under conditions of large velocity amplitude. In particular, the velocity amplitude and Nusselt number increased at the pulsation frequency where the air column resonance occurred. Shiibara[6] et al. generated a pulsating flow with a constant velocity amplitude (0≤Re≤8000, 4≤Wo≤16) by opening and closing a solenoid valve. Then, they measured the wall temperature fluctuation using infrared thermography and the flow field using hot-wire velocimetry. As a result, it was observed that turbulence was suppressed in the acceleration phase of the flow due to the re-laminarization phenomenon, and a state with high velocity but low heat transfer coefficient appeared. This heat transfer enhancement vary with frequency, with the greatest enhancement effect at Wo=11. As described above, the pulsating flow in a tube has been studied extensively. However, there are few studies under the conditions where the Reynolds number is several tens of thousands and the pulsation frequency is several tens of Hz, corresponding to the exhaust flow of a real engine.

Different mechanisms of heat transfer enhancement by pulsation have been shown depending on the flow conditions, such as reverse flow [3][5], thinning of the boundary layer in a moment under conditions of large velocity amplitude [3], a resonance between Bursting and pulsation [4], re-laminarization [6], and air column resonance [5]. However, all of these studies are estimates based on either experimentally obtained local velocity variations [4], [5], [6] or on numerical calculations [3], [5]. There are also no experimental studies that link the dynamic flow characteristics of a pulsating engine exhaust stream to heat transfer. Therefore, the objectives of this study were set as follows

- To clarify the effect of pulsation frequency on heat transfer characteristics under the engine exhaust flow conditions.
- To obtain dynamic flow characteristics by experiments and clarify the heat transfer mechanism.

In this study, the experimental apparatus was designed to reproduce the pulsating flow in a tube in the range of Re = 66000, 15 Hz ≤ f_p ≤ 90 Hz. A hot-wire anemometer was used to measure the velocity fluctuation at the center of the tube. The magnitude of the velocity amplitude was evaluated. Thermocouples were used to measure the fluid temperature, and infrared thermography was used to measure the wall temperature. The heat transfer characteristics were evaluated by calculating the Nusselt number from these two measurements. The flow field was measured by PIV to evaluate the dynamic flow characteristics in the pulsating flow and the effect of flow structure on the enhancement of heat transfer.

2. Experimental Setup

2.1. Experimental apparatus

In order to investigate the effect of the pulsating flow in the tube on the wall heat transfer, the experimental apparatus shown in Fig. 1 was designed. The working fluid, air, is heated by a hot air generator (HAP 3100, Hakko Electric, Tokyo, Japan) and discharged through a test section into a tank at the outlet. As shown in the lower left of Fig. 1, the flow path was opened and closed by rotating a disk with holes to create a pulsating flow. The pulsation frequency was changed by controlling the disk rotation speed with a motor. The rectangular test tube was made of aluminum with a length of 2 m. The inner and outer diameters were D = 32 mm and D_o = 40 mm, respectively. In order to investigate the thermal-hydraulic characteristics in the developed flow, measurement sections for temperature and velocity were located at 34D, 44D, 54D, and 63D from the pulsation generator. The time variation of the central flow velocity in each cross-section was measured by inserting a hot wire anemometer (0251R-T5, Kanomax, New Jersey, USA) through the hole at the bottom of the tube, as shown in Fig. 2 (a). The time-averaged temperature of each cross-section was measured by inserting a K-type thermocouple (T34, Okazaki, Kobe, Japan) through the hole in the upper part of the tube, as shown in Fig. 2 (a). As shown on the right side of Fig. 2, 36 temperatures were measured per section. The wall temperature was measured using infrared thermography (890, Testo K.K., Japan), as shown in Fig. 1. Table 1 shows the experimental conditions. Experiments were conducted at a wide range of frequencies to simulate an actual engine.

Table 1: Experimental conditions.

Reynolds number : Re [-]	Pulsation Frequency : f_p [Hz]	Womersley number : Wo [-]	Inlet temperature [K]	Heat conductivity of air : λ_f [W/m K]	Heat conductivity of alminium : λ_s [W/m K]
66000	15 – 90	31 - 76	398	0.033	236

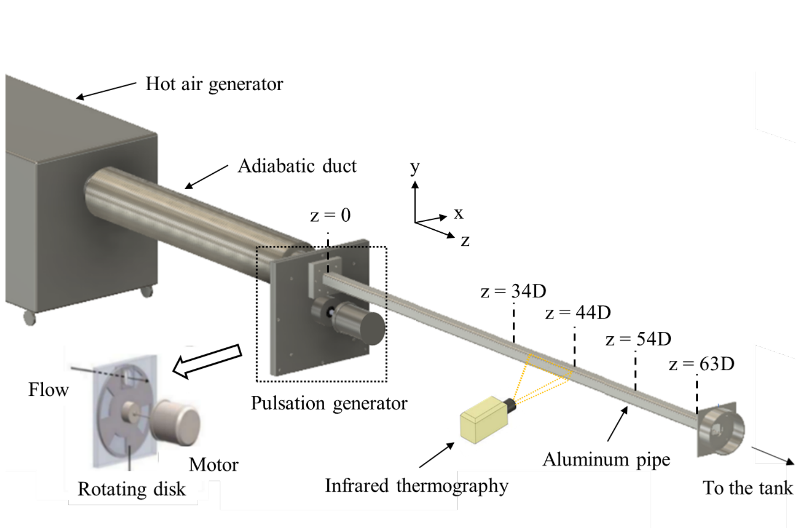

Fig. 1: Experimental apparatus.

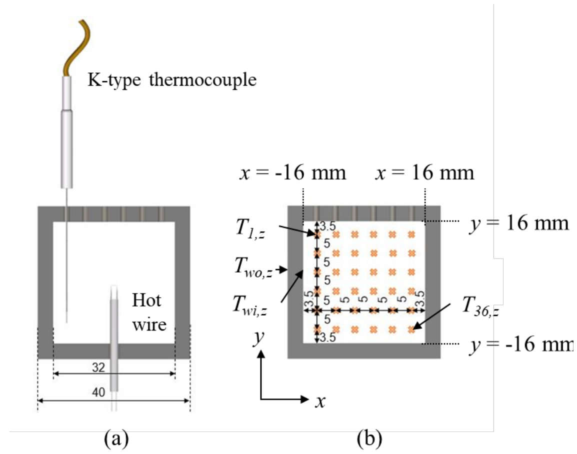

Fig. 2: Measurement methods
(a) How to insert K-type thermocouple and hot wire,
(b) Measurement point of time-averaged temperature

2.2. Data Reduction

Heat was transferred from the hot air inside the tube to the ambient fluid through the tube wall. In this process, the heat flux transferred from the fluid to the inner wall was assumed to be constant. In the inspection area, z/D=34~54, the heat flux $q_{c,z}$ flowing outward is as follows

$$q_{c,z} = mC_p \Delta T / A_{wi,34D-54D} = \rho D^2 \overline{w} C_p \left(T_{fb,34D} - T_{fb,54D} \right) / 80\mathrm{D}^2 \tag{1}$$

where ρ is the density of air, $\overline{w}$ is the time-averaged velocity measured by a hot-wire anemometer, C_p is the specific heat at constant pressure, and $A_{wi,\,34D\text{-}54D}$ is the inner wall area. $T_{fb,z}$ is the space-averaged temperature at z, obtained by ensemble averaging 36 points from $T_{1,z} \sim T_{36,z}$. The local inner wall temperature ($T_{wi,z}$) can be calculated using the following heat conduction equation:

$$T_{wi,z} = \frac{Q_{c,z} \Delta x}{\lambda_s A_{w,z}} + T_{wo,z} = \frac{q_{c,z} A_{wi,z} \left(\mathrm{D_o} - \mathrm{D} \right) / 2}{\lambda_s \left(A_{wo,z} + A_{wi,z} \right) / 2} + T_{wo,z} = \frac{q_{c,z} D \left(\mathrm{D_o} - \mathrm{D} \right)}{\lambda_s \left(D_o + D \right)} + T_{wo,z} \tag{2}$$

where $\triangle x$ is the thickness of the tube, $Q_{c,z}$ is the amount of heat released outside the pipe, λ_s is the thermal conductivity of the tube, $A_{w,z}$ is the local outer wall area, which is the average of outer wall area ($A_{wo,z}$) and the inner wall area ($A_{wi,z}$). Using Eqs. (1) and (2), the local Nusselt number can be defined by the following equation

$$Nu_{i,z} = h_{i,z} \frac{\mathrm{D}}{\lambda_f} = \frac{q_{c,z}}{\left(T_{fb,z} - T_{wi,z} \right)} \frac{\mathrm{D}}{\lambda_f} \tag{3}$$

where λ_f is the thermal conductivity of the fluid in the tube, D is the characteristic length and the inner tube diameter in this system. The heat transfer characteristics in the pulsating flow were evaluated by calculating the local Nu number inside the tube.

2.3. Flow field measurement

In order to visualize the flow field, the optical system shown in Fig. 3 was constructed, and PIV was performed on the xz plane. The origin of the xy coordinates is the center of the tube. The flow velocities u and w were measured in the xz plane at -16 mm < x < 16 mm, y = 0 mm, 44D mm < z < 44D+32mm as shown in Fig. 3(b). The flow velocity u and w in the xz plane were measured as shown in Fig. 3 (b). Oil mist with a small particle size (2-3 μm) was used as a tracer particle to ensure fluid tracking for flow. A Nd:YAG laser (Continuum, Mesa PIV) was used as the light source, and the particle images were taken at a speed of 10000 fps. PIV was performed by making pairs from these particle images, so the time interval of the flow velocity was 5000 Hz. The flow velocity was calculated by direct cross-correlation method. The PIV conditions are shown in Table 2. The inspection window is 27 pix x 27 pix (70% overlap). The flow channel is made of acrylic for visualization purposes, so high-temperature fluid cannot be used. Therefore, the working fluid was air at room temperature, and the Re number was set to the same as the heat transfer experiment. In addition, due to the refraction of the laser by the lid, the particles around x = -16 mm were not observed well. So the data for 0 mm < x < 16 mm was used for the evaluation of the flow field. The data processing of the flow field was performed as follows. First, as proposed by Reynolds et al [7], in the case of turbulent pulsating flow, flow characteristic can be decomposed into three terms, as shown in the following equation.

$$u(x,z,t)=\bar{u}(x,z)+\hat{u}(x,z,t)+u'(x,z,t) \tag{4}$$

where $\bar{u}\ (x,z)$ is the time-averaged term, $\hat{u}\ (x,z,t)$ is the oscillation term, and $u'\ (x,z,t)$ is the fluctuation term of the turbulence. The time-averaged term was obtained by taking the ensemble average of 10 cycles. The oscillatory term can be calculated by taking the phase-averaged process <>.

$$\hat{u}(x,z,t)=\langle u(x,z,t)\rangle-\bar{u}(x,z) \tag{5}$$

The phase average was calculated by taking the ensemble average of 10 points with the same phase for 10 cycles of data. By using phase averaging, background turbulence can be removed, and only organized motion can be extracted from the total instantaneous profile. Equations (4) and (5) were used to calculate the fluctuation components $u'\ (x,z,t)$ and $w'\ (x,z,t)$' of the turbulence, respectively. The mean turbulent kineticenergy $\bar{k}$ was calculated for each inspection window using the following equation. N is the value for 10 cycles, which is 10×fs/2 × f_p.

$$\bar{k}(x,z)=\frac{1}{2}\left\{\overline{u'(x,z,t)^2}+\overline{w'(x,z,t)^2}\right\} \tag{6}$$

$$\overline{u'(x,z,t)^2}=\frac{1}{N}\sum\left(u(x,z,t)-\langle u(x,z,t)\rangle\right)^2 \tag{7}$$

Table 2: PIV condition.

Frame speed :fs [fps]	Resolution [mm/pixel]	Time interval between laser pulses [μs]	Grid size [pixel]	Interrogation window size [pixel]
10000	0.1	100	8	27 × 27

3. Results and Discussion

3.1. Velocity fluctuations in Pulsating Flow

In order to investigate the strength of the pulsation at each frequency, velocity measurements were conducted using a a hot-wire velocimetry. Figure 4 shows the flow velocity waveform for two cycles at z/D = 34. The horizontal axis is the the number of cycles and the vertical axis is the flow velocity. It can be also found that the flow velocity oscillates at the pulsation frequency in all conditions and that there is no or a slight reverse flow. It also can be found that the magnitude of the velocity fluctuation becomes small as the frequency increases. The velocity amplitude was calculated from the difference between the maximum and minimum velocities in the phase-averaged velocity waveform. Figure 5 indicates the values at measurement positions 34D, 44D and 54D, and their spatial averages of three positions. The amplitude of the velocity decreased as the frequency increased, although it varied depending on the measurement position. This can be considered to be due to the fact that the pulsation is generated by opening and closing the flow channel under the condition of constant flow rate, and the larger the frequency, the lower the flow rate that flows out with one opening and closing. In addition, since there is no peak at a specific frequency, the effect of air column resonance is not considered to be significant.

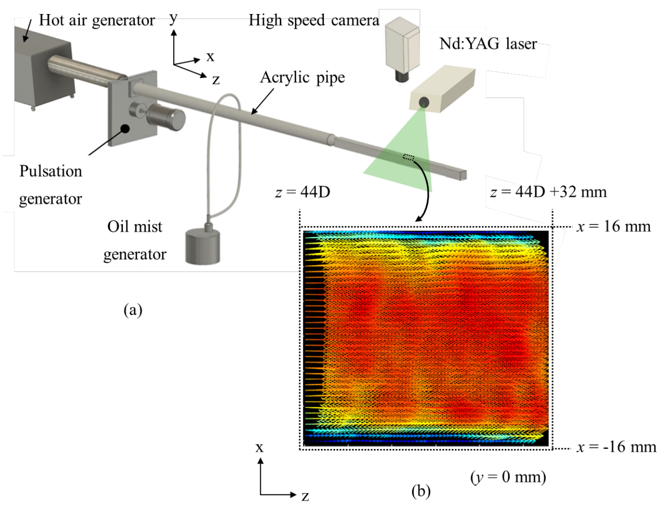

Fig. 3: Experimental apparatus for PIV. (a) Arrangement of experimental apparatus, (b) Velocity vector obtained by PIV.

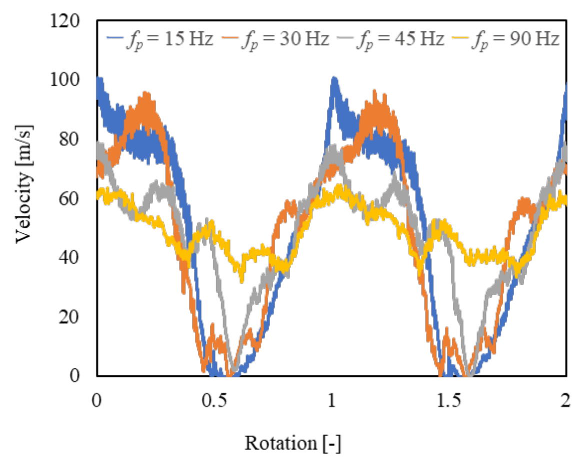

Fig. 4: Velocity at the tube center (z/D = 34).

3.2. Streamwise Temperature Variation and Heat transfer coefficient

The streamwise variation of bulk fluid temperature is shown in Fig.6. It can be observed that the bulk fluid temperature decreases almost linearly as it moves downstream. This tendency was also observed in each condition of pulsating flow. Figure 6 also plots the outer wall temperature obtained by infrared thermography. It can be shown that the outer wall temperature also decreases linearly downstream until z = 54D. However, the outer wall temperature becomes extremely low at 63D. This may be because the flange at z = 63D acts as a heat sink and lowers the wall temperature. Therefore, in this study, the section from z = 34D to 54D was selected for the evaluation of heat transfer characteristics.

Using Eq. (1), the heat flux at z = 34 to 54 was calculated to be about $q_{c,z} \approx 1263$ W/m^2 under all pulsation conditions. The standard deviation is $\sigma = 28$ W/m^2 , with small variation among different frequencies. This may be because the difference between the wall temperature and the ambient air temperature (=25°C) did not differ much, since the wall temperature differed only 1-2 degrees per frequency. However, since the difference between the internal fluid temperature and the wall temperature is small, about 10 degrees, the internal heat transfer coefficient is likely to have a frequency characteristic. Therefore, the Nu number was calculated using Eq. (3). Figure 7 shows dependence of the local Nu numbers at three sections z= 34D, 44D, 54D, and average Nu numbers of the sections on pulsation frequencies. It can be found that the variation by measurement position is not large except at 90 Hz. It can be seen that the variation by measurement position is not very large except at 90 Hz. If we focus on the mean value, we can see that it has a peak at 25-30 Hz. The mechanisms proposed to enhance heat transfer by pulsation include reverse flow, resonance with bursting, gas column resonance, and increase in velocity amplitude. Since the frequency of bursting in the body system calculated from the existing correlation equation is one order of magnitude higher than the pulsation frequency, the influence of bursting is negligible. As discussed in 3.1, it was confirmed that the reverse flow was also negligible at all frequencies, the effect of air column resonance was small, and the velocity amplitude decreased as the pulsation frequency increased. Therefore, similar to the results of Wang et al.,[3] it can be assumed that at low frequencies, the boundary layer became instantaneously thinner due to the increase in velocity amplitude, and heat transfer was enhanced. However, under the pulsation frequency of 15 Hz, no enhancement of heat transfer by the pulsation occurs despite the large velocity amplitude. Therefore, the heat transfer mechanism is expected to be different in this frequency. In order to investigate this issue, the flow structure was evaluated by PIV.

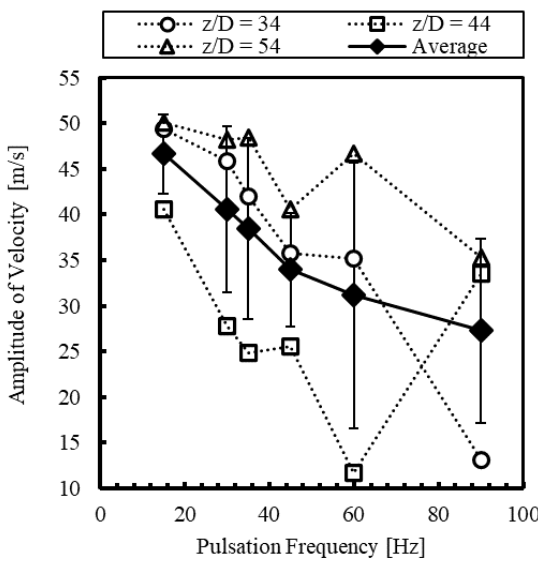

Fig. 5: Frequency characteristic of velocity amplitude

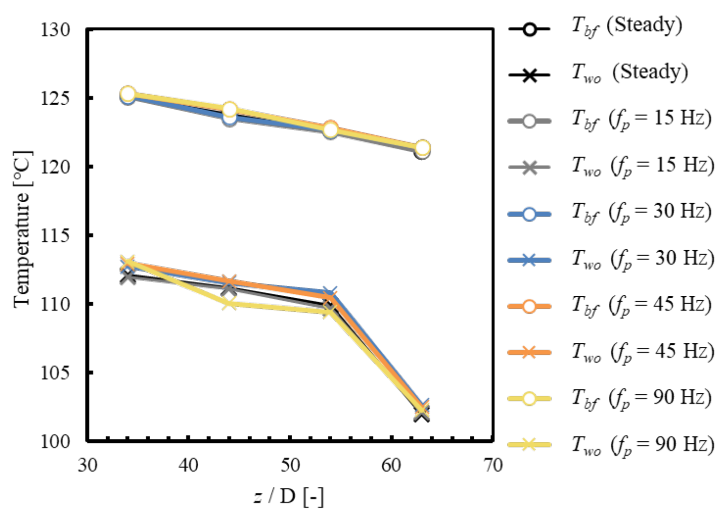

Fig. 6: Bulk fluid temperature and outside wall temperature in streamwise direction.

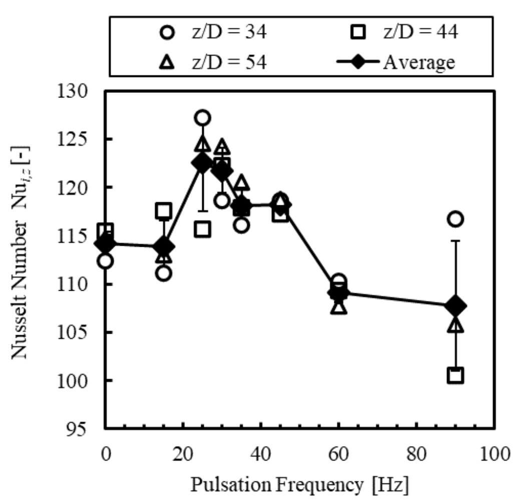

Fig. 7: Frequency characteristic of Nusselt number.

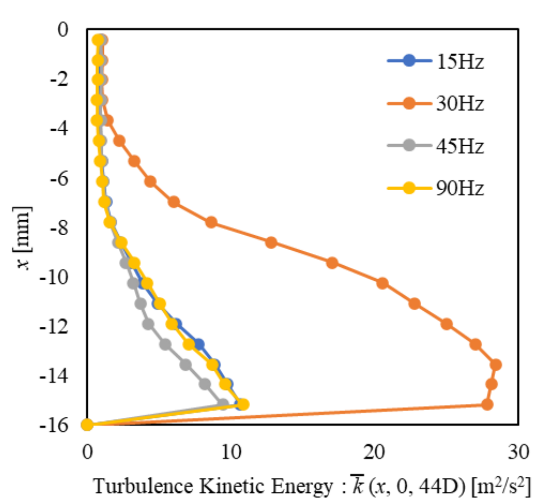

Fig. 8 : Time averaged turbulence kinetic energy at z = 44D

3.4. Flow Structure

In order to investigate the flow structure in the pulsating flow, the velocity field was measured by PIV at a position around z / D = 44. The turbulent kinetic energy calculated using Eq. (6) is shown in Fig. 8 for frequencies 15, 30, 45 and and 90Hz. It can be recognized that the turbulence energy increases near the wall at 30 Hz when the velocity amplitude is is large. Heat transfer enhancement is thought to be due to the increase in turbulent energy. The turbulence energy at 15Hz 15Hz is similar to that at 45Hz and 90Hz. This suggests that heat transfer enhancement did not occur in the pulsating flow below 30 Hz, despite the large velocity amplitude. Next, the velocity fluctuations near the wall were evaluated to investigate why the turbulent energy at 30 Hz was larger and that at 15 Hz was smaller. Figure 9 shows the instantaneous value of the velocity w at x = -15.2 mm, the phase mean value$\langle w\ (x, z, t)\rangle$ and the fluctuation value of the turbulence obtained by Eqs. (4) and (5), repeatedly plotted for two cycles. In analyzing this graph, (1) is the minimum phase, (2) is the acceleration phase, (3) is the maximum phase, and (4) is the deceleration phase. It can be seen in Fig. 9(b)-(d) that turbulence always takes place in all pahses above 30Hz. However, the turbulence is reduced from the minimum phase to the acceleration phase at 15 Hz. The reduction of turbulence is similar to the re-laminarization observed by Shiibara et al. [6], and also makes the turbulent kinetic energy small from the minimum phase to the acceleration phase. The reason for the lack of heat transfer enhancement due to pulsation at 15Hz is considered to be because turbulence is reduced due to re-laminarization in the phase where the fluid accelerates. The reason for the re-laminarization only at 15 Hz is thought to be because the minimum flow velocity became smaller due to the larger velocity amplitude, or that the time until the turbulence became smaller increased due to the smaller pulsation frequency. However, since both the pulsation frequency and velocity amplitude changed in this experiment, it is not easy to separate the two primary factors. To confirm this, it is necessary to conduct experiments in which the pulsation frequency is changed under a constant velocity amplitude and the velocity amplitude is changed under a constant pulsation frequency.

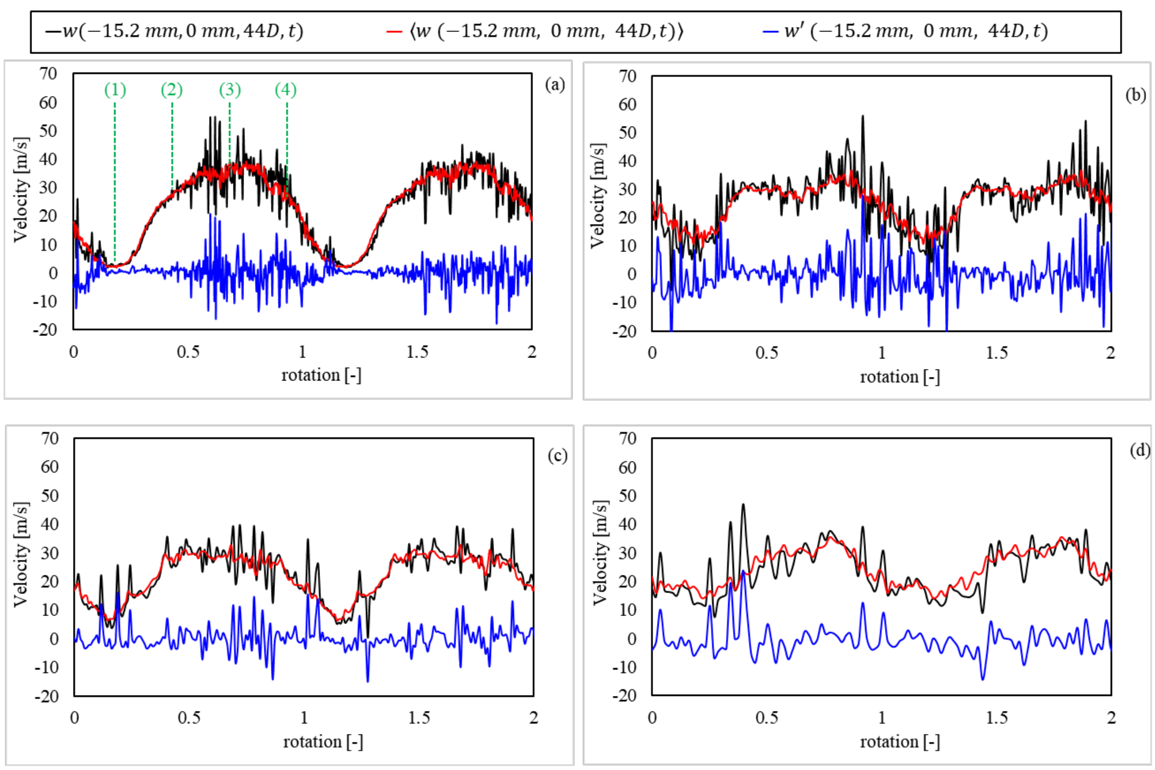

Fig. 9: Variation of Axial velocity w near the wall (x = -15.2 mm, y = 0mm, z = 44D).
(a) f_p = 15Hz, (b) f_p = 30Hz, (c) f_p = 45Hz, (d) f_p = 90Hz.
(1) minimum, (2) acceleration, (3) maximum, (4) deceleration.

4. Conclusion

The convective heat transfer of a pulsating flow under engine exhaust flow conditions was experimentally In order to investigate the effect of the pulsation frequency on the heat transfer, the fluid temperature was measured by thermocouples and the wall temperature was measured by infrared thermography, and the evaluation by Nu number was carried out. In this experiment, the relative Nu number was the highest at 25-30 Hz. Based on the findings of existing studies, the mechanism of the heat transfer enhancement due to pulsation in the region above 25 Hz was estimated to be the thinning of the boundary layer at a certain moment due to the increase in velocity amplitude. However, since the cause of the lack of heat transfer enhancement by pulsation at 15 Hz could not be estimated, the time-averaged turbulent kinetic energy was obtained by measuring the flow field using PIV. As a result, it was observed that the turbulent kinetic energy near the wall became large at 30 Hz. This suggests that the heat transfer coefficient increased at 30 Hz because larger velocity amplitudes temporarily thinned the boundary layer and promoted turbulent mixing near the wall surface. The reason why the turbulent kinetic energy near the wall did not increase at 15 Hz, where the velocity amplitude was as large as 30 Hz, was analyzed from the velocity fluctuation data near the wall. It was confirmed that the turbulent kinetic energy did not increase under the 15 Hz condition, which has the same large velocity amplitude as the 30 Hz condition, because the re-laminarization reduced the turbulence during the acceleration of the flow.

As described above, the influence of the pulsation frequency on the heat transfer in the engine exhaust flow condition was clarified under condition that has not been done in the past. In addition, the heat transfer mechanism was experimentally linked to the variation of the flow structure. This is the first attempt to do so, and it was achieved by unsteady measurement of the flow field using PIV and calculation of turbulent kinetic energy in pulsating flow using phase averaging. It is expected that the use of PIV and phase averaging to estimate the turbulence intensity will be effective in clarifying the thermal-hydraulic characteristics of pulsating flows experimentally.

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