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Effect of Vibration on the Natural Convection Heat Transfer of a Horizontal Cylinder*

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The local heat transfer rate around a heated, horizontally vibrating cylinder is measured, and the thermal profile, close to the cylinder surface, is obtained by a Mach-Zender interferometer. Moreover, above and below the cylinder, the velocity and thermal profiles of the upward stream of natural convection are measured by a hot-wire anemometer and a unit of temperature-measurement, and then the change in the flow pattern of natural convection is examined by a flow visualization method, using smoke. As a result, the cause of change in the local and the mean heat transfer rate of a heated, horizontally vibrating cylinder is clarified.

Key Words : Convective Heat Transfer, Vibration, Cylinder, Natural Convection, Flow measurement

1. Introduction

It is known that a steady flow, so-called acoustic streaming, is observed near a vibrating body, or near a body set in a sound field.⁽¹⁾ This secondary steady flow improves the transportation rate of heat transfer and diffusion processes, e.g. the coefficient of heat transfer. Therefore the improvement of heat transfer rate in a heated body being vibrated or being set in a sound field is sometimes discussed in relation to the secondary flow. Fand, R.M., et al. revealed the fact that the mean heat transfer rate of a heated cylinder is increased but the local heat transfer rate is not necessarily increased in a sound field, by their detailed experiments on the heat transfer of a heated cylinder.⁽²⁾⁽³⁾⁽⁴⁾⁽⁵⁾

However, in the previously reported papers, the velocity profile and the thermal profile of the secondary flow near a heated cylinder are seldom examined qualitatively, and the relationship between the change in the heat transfer rate and that in the natural convection flow by vibration of a heated cylinder is not clarified yet. In this paper, the measurement of the local heat transfer rate in a heated cylinder and the simultaneous measurement of the velocity and the thermal profiles of natural convection around it are carried out, and thus the effect of the horizontal vibration of cylinder on the heat transfer is qualitatively and experimentally examined.

In this report, at first the angular distribution of the local heat transfer rate of a vibrating heated cylinder is measured by a local heat transfer sensor (Local Sensor). Next the thermal field near the cylinder is visualized by a Mach-Zender interferometer and the thermal profile of the natural convection close to the cylinder surface is obtained. Moreover, the velocity and the thermal profiles and their time-fluctuations of natural convection are simultaneously measured by a hot-wire anemometer and a unit of temperature-measurement. Finally, the convection is visualized by smoke, and the cause of a change in the local heat transfer rate of the heated cylinder in vibration is found out.

Nomenclature

d : diameter of cylinder
 f : vibration frequency of cylinder
 Gr : Grashof number
 Nu : Nusselt number
 $\bar{Nu}$: mean Nusselt number of cylinder
 Pr : Prandtl number
 s : vibration amplitude of cylinder
 T : temperature
 T_{∞} : ambient temperature
 ΔT : temperature difference between the cylinder surface and environment (super-heat)
 U : velocity of natural convection
 U_m : maximum velocity of natural convection
 $\bar{U}$: mean velocity of natural convection at $Y=-10\text{mm}$
 v : vibration velocity amplitude of cylinder
 x : horizontal coordinate from cylinder surface
 y : radial coordinate from cylinder surface
 Y : vertical coordinate from top and bottom cylinder surfaces
 θ : angular coordinate from vertical line (vertical angle)

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2. Experimental Apparatus and Method

2.1 Cylinder

A cylinder tested made of brass is 20 mm in outer diameter and 80 mm in length, and is heated by a temperature-controlled hot water circulated through the cylinder.

The detail of the cylinder tested is shown in Fig.1. Surface temperature of

Fig.1 Detail of cylinder tested

Table 1 Conditions of the present experiment

		Heating		Vibration		
		Super heat ΔT K	Pr Gr	Frequency f Hz	Amplitude s cm	Vibration velocity amplitude πfs cm/s
Local heat transfer rate		19.1	14000	0 60 30	0 0.074 0.250	0 13.9 23.6
		38.1	23000	0 60 30	0 0.074 0.250	0 13.9 23.6
		58.3	27000	0 60 30	0 0.074 0.250	0 13.9 23.6
Visualization	Thermal field	21.3	16000	0 60 30	0 0.074 0.250	0 13.9 23.6
		40.4	24000	0 60 30	0 0.074 0.250	0 13.9 23.6
		61.6	29000	0 60 30	0 0.074 0.250	0 13.9 23.6
	Flow field	20.4	14000	0 60 30	0 0.086 0.236	0 16.2 22.2
		35.7	20000	0 60 30	0 0.086 0.236	0 16.2 22.2
		54.0	24000	0 60 30	0 0.086 0.236	0 16.2 22.2
Velocity profile	Thermal profile	19.8	14000	0 60 30	0 0.071 0.236	0 14.3 23.9
		40.9	24000	0 60 30	0 0.071 0.236	0 14.3 23.9
		58.5	27000	0 60 30	0 0.071 0.236	0 14.3 23.9

cylinder (1) is measured by a Cu-Co thermocouple (4), whose nominal diameter is 0.254 mm, set in the center of the cylinder. On the counter part surface of the cylinder, a local heat transfer sensor (Local Sensor) (2) is set to measure the local heat transfer rate on the cylinder surface. The detail of the Local Sensor is shown in the lower part of Fig.1. The heater made of lead is 25 mm by 3 mm, and it is connected to an electric current source via a rheostat. Surface temperature distribution of the heater is measured by three pieces of Cu-Co thermocouples (4), set 10 mm apart from each other.

Fig.2 Block diagram of apparatus

Fig.3 Setting of the cylinder tested

Fig.4 Measurement of local heat transfer rate

This heater is insulated on the sides and the rear side with epoxy resin to prevent the heat loss by conduction. The cylinder is rotatable around the axis, and so the angular distribution of local heat transfer rate of the cylinder is able to be measured by the Local Sensor. In the experiment, the local heat transfer on the cylinder surface is measured at 5 or 10 degrees intervals. The support (3) of the cylinder is protected by a teflon slide from the water leakage in its rotation.

2.2 Experiment

A block diagram of the experiment is shown in Fig. 2. Surface temperature of the cylinder is kept constant and is controlled by a temperature-controlled hot water circulating the cylinder. The temperature is measured directly by a digital thermometer, or by an oscilloscope, connecting the thermocouples with a cold junction. The cylinder is horizontally set on the driver of an electromagnetic vibrator via rigid support and surrounded with transparent lucite plates in order to protect the natural convection from the outward flow disturbance, as illustrated in Fig. 3.

The vibrating condition of the cylinder is examined by a linear transformer. The vibration amplitude, s , and the frequency, f , are measured by the output of the linear transformer, and the vibration velocity amplitude, v , of the cylinder is used as a parameter of the experiment. The experimental conditions, such as heating and vibrating condition of the cylinder, are summarized in Table 1.

3. Measurements of the Thermal Profile and the Local Heat Transfer Rate

3.1 Experimental procedure

Thermal profile around the heated cylinder is visualized by means of a Mach-Zender interferometer and a He-Ne laser. The laser beam is expanded by a beam expander and is reflected by a concave mirror to the interferometer. The beam is chopped by a rotating disk with a pin-hole, and thus the illumination cycle is synchronized with the vibrating cycle of the cylinder.

In a measurement of the local heat transfer rate, surface temperature of the Local Sensor is made to coincide with that of the cylinder by adjusting the electric current through the lead piece of the Local Sensor by a rheostat. (cf. Fig. 4) The local heat transfer rate of the cylinder is determined by the electric power to the Local Sensor. A similar experimental procedure was carried out by Adachi, T., et al., in their measurement of the heat transfer rate of a cylinder in a forced convection field. (6)

As surface temperature of the lead piece of the Local Sensor is measured and is determined at three points, as previously mentioned, and their deviations from the hot water temperature through the cylinder are within 0.5 percent, the temperature distribution on the heated cylinder surface is regarded as being constant along its axis within the test section.

Fig. 5 Mach-Zender interferometer photographs ($\Delta T = 40.4\text{ K}$, $\text{PrGr} = 24000$)

3.2 Experimental results and discussion

Three series of experiments are carried out as a parameter of the superheat ΔT , shown in Table 1, but their results have the same tendency. So the results of $\Delta T \approx 40$ K are mainly shown in the following sections.

3.2.1 Interferometer photographs

Some of the Mach-Zender interferometer photographs around the vibrating heated cylinder are shown in Fig.5. From the photographs, the change in the natural convection flow field and that in the thermal boundary layer close to the cylinder by heating are clearly understood. However the effect of cylinder vibration on the convection flow field is not clear enough.

3.2.2 Thermal profile near cylinder

From the interferometer photographs, thermal profiles near the cylinder, within about 5 mm from the cylinder surface, are obtained. The results are shown in Fig.6 as a parameter of the vertical angle, taking non-dimensionalized temperature as ordinate and non-dimensionalized radial distance from the cylinder surface as abscissa, where T denotes room temperature.

In Fig.6, owing to the vibration of cylinder, temperature gradient is increased above and below the cylinder ($\theta \approx 0$ and $\theta = 180$ degrees), and is decreased at the sides of the cylinder ($80^\circ < \theta < 120$ degrees). From the results, it is estimated that the heat transfer rate is locally variable, and it increases above and below the cylinder and decreases at the sides of the cylinder, under vibration of the heated cylinder.

3.2.3 Coefficient of heat transfer

The angular distribution of the local heat transfer rate on the heated cylinder, measured by the above mentioned Local Sensor, is shown in Fig.7, taking the non-dimensionalized heat transfer rate $Nu/(PrGr)^{1/4}$ as ordinate and the vertical angles as abscissa.

In Fig.7, regardless of vibration, the local heat transfer rate decreases to the upper part of the cylinder and becomes minimum at its top. With an increase in the vibrating velocity of cylinder, the rate increases around 0 and 180 degrees, but it decreases around 90 degrees of the vertical angle. This tendency agrees with the result of a heated cylinder in a sound field, obtained by Fand, R.M., et al.⁽⁴⁾

Mean Nusselt number ($\bar{Nu}$) of the cylinder tested is calculated from the local heat transfer rate, and is shown in Fig.8. The abscissa in Fig.8 is the vibration velocity of cylinder. According to this result, in the case of small superheat, i.e. small Grashof number, $\bar{Nu}$ increases several percentage points with an increase of vibration velocity. However the rate of increase of $\bar{Nu}$ diminishes with an increase of Grashof number. The main rea-

son is supposed to be that the effect of natural convection is superior to that of vibration in case of large Grashof number.

The mean Nusselt number, obtained in this experiment, is shown in Fig.9, in relation to the product of Prandtl number and Grashof number ($PrGr$).

Fig.7 Local heat transfer rate ($\Delta T=38.1$ K, $PrGr=23000$)

Fig.8 Relations between mean Nusselt number and vibrating velocity

Fig.9 Relations between mean Nusselt number and super-heat

In the figure, solid line shows
 $\bar{Nu}=0.53 (\text{PrGr})^{1/4} (10^3 < \text{PrGr} < 10^8)$

and dashed line shows

$$235 (\bar{Nu}) \exp(-6/\bar{Nu}) = \text{PrGr}$$

They are shown for comparison with the experimental results. (7)(8)

Present experimental results agree well with the empirical formula of Elenbaas, W.

4. Measurements of the Velocity and the Thermal Profiles for Convection Flow Field

4.1 Experimental procedure

A constant-temperature-type hot-wire anemometer is used to measure the velocity profile for convection flow above and below the vibrating heated cylinder. For the measurement, a hot-wire and a cold-wire probe, made of tungsten of 5 micrometers in diameter, are set in parallel. The resistance change in the latter wire is measured by a unit of temperature-measurement in order to determine the thermal profile. It is also used to compensate for the thermal characteristics of the hot-wire probe. The arrangement is shown in Fig.10.

These probes are moved at a speed of 0.03 cm/s by a step-motor, above and below the cylinder. The probe position relative to the cylinder is determined by the output signal of the step-motor. Time-change in the convection flow velocity obtained by the anemometer is analyzed by a signal analyzer in order to examine the special frequency component of the velocity fluctuation for the cylinder vibration.

4.2 Experimental results and discussion

As shown in Table 1, three series of

Fig.10 Setting of a hot- and a cold-wire probe

experiments are carried out for ΔT , but their results have the same tendency. So the results of $\Delta T \approx 40$ K are mainly shown in the following section. Here, the definition of coordinate in the following figures and the frequency-analyzed points are illustrated in Fig.11.

4.2.1 Velocity profile

Measurements are carried out up to 25 mm above and up to 10 mm below the cylinder

Fig.11 Measuring positions and frequency analyzed points

Fig.12 Velocity profiles ($U_m = 38$ cm/s)

der by means of two kinds of probe support, shown in the right side in Fig.10. Some of the results obtained are shown in Fig.12. The ordinate denotes the upward velocity, non-dimensionalized by its maximum value, and the length of the solid lines and the circles show the root-mean-squares of the velocity fluctuation and their mean values, respectively.

The upward velocity has its maximum above the top of the cylinder, so the convection flow is separated from the cylinder surface around the top of it.

With an increase of the vibration velocity, the mean velocity of convection flow below the cylinder and the velocity fluctuation, both above and below the cylinder, increase and the whole natural convection flow field is thought to be disturbed by the vibration of cylinder.

The relations between the mean upward velocity (U) at $Y=-10$ mm and $X=0$ to 20 mm, and the vibration velocity of cylinder (v) are shown in Fig.13(a), as a parameter of $PrGr$. The relations between U and $PrGr$ are also shown in Fig.13(b), as a parameter

Fig.13(a) Relations between mean upward flow velocity and vibrating velocity

Fig.13(b) Relations between mean upward flow velocity and super-heat

ter of v . According to these figures, the upward velocity increases with an increase of vibration velocity and of superheat of the cylinder. Therefore an increase of heat transfer rate, especially below the heated cylinder, results. The rate of increase in mean convection velocity is 8 to 20 percent for v , and 11 to 15 percent for $PrGr$ in the present experiment. An increase of mean convection velocity is supposed to contribute to that of mean Nusselt number, shown in Figs.8 and 9.

4.2.2 Thermal profile

Thermal profile of the convection flow field, obtained from the simultaneous velocity and temperature measurement, mentioned above, is shown in Fig.14. The ordinate of the figure is a non-dimensionalized temperature $(T-T_{\infty})/\Delta T$.

The temperature also has its maximum above the top of the cylinder, and so a heated flow is thought to move upward above the top of it. However, any change in thermal profile through the cylinder vibration is not found clear enough.

4.2.3 Fluctuation of convection flow

Fluctuation of convection flow is analyzed by a signal analyzer and the frequency components obtained are shown in Fig.15. X and Y values in Fig.15 correspond with the coordinates of the analyzed points in Fig.11.

The fluctuation is analyzed in the range up to 200 Hz, and one division of the abscissa of the photographs in Fig.15 is 20 Hz.

In the figure, the fluctuation components of the convection flow are only the fundamental vibration frequency and its higher harmonics, and any special frequency components, which are likely caused by a special vortex as recognized by Fand, et al., are not detected.

5. Flow Visualization by Smoke

In the previous chapter, the flow of the sides of the cylinder and near the cylinder is not clear enough, because its vibration prohibits a measurement. So the flow visualization around the vibrating heated cylinder is carried out by smoke, and the reason why the cylinder vibration changes in the local heat transfer rate is examined.

5.1 Experimental procedure

Smoke for the flow visualization is generated by sticks of incense, which are set in a line 5 mm intervals, and about 100 mm below the cylinder. A He-Ne laser beam is chopped by a rotating disk to synchronize with the cylinder vibration as mentioned in section 3.1. However the beam in the experiment is expanded by a cylindrical lens to a thin plane beam and is radiated toward the center of the test section of cylinder, in order to take photographs, visualizing the convection flow field by smoke.

Fig.14 Thermal profiles ($\Delta T = 40.9 \text{ K}$)

5.2 Experimental results and discussion

Two examples of the results obtained are shown in Fig.16. In case of non-vibrating condition, convection flow separates at about 150 degrees in vertical angle from the cylinder surface after moving upward along its surface. In case of vibrating condition, however, the flow separates from the cylinder surface at about 90 degrees in vertical angle and generates a small vortex-like turbulence.

Therefore, for the vibrating cylinder, boundary layer at about 90 degrees in vertical angle is supposed to be somewhat thicker and the thermal gradient in the flow to be diminished, resulting in a decrease of the local heat transfer rate. A decrease of the thermal gradient in the flow by vibration is obvious in the thermal profile measurement near the cylinder, shown in the third chapter.

Temperature of the incense is measured by an infrared radiation thermometer and is determined to be about 670 K. It is possible for the smoke generation to disturb the natural convection of the heated cylinder, because the temperature of the sticks of incense is rather high and the sticks themselves could be the convection sources in the flow visualization by smoke.

The flow visualized photographs, taken in the smoke-filled measuring duct, however, have not so wide difference from those, taken in the upstreaming smoke, so the effect of the convection flow due to the sticks of incense is ignored in this experiment.

Fig.15 Fluctuation levels of velocity and the frequency analysis ($\Delta T = 40.9 \text{ K}$, $\text{PrGr} = 24000$)

(a) NO VIBRATION (b) WITH VIBRATION
 $f=30\text{Hz}$ $s=0.236\text{ cm}$
 $v=22.2\text{ cm/sec}$.

Fig.16 Visualization photographs of natural convection by smoke
 ($\Delta T = 35.7\text{ K}$, $\text{PrGr} = 20000$)

We should note that the natural convection flow in the smoke-filled measuring duct diminishes and circulation flow is observed in the duct, because the upper part of the duct has to be closed in order to fill it with smoke. Therefore the flow visualization photographs in the smoke-filled measuring duct should not be adopted in this case of natural convection flow.

6. Conclusions

The main results, obtained in the experiments of natural convection heat transfer of a vibrating heated cylinder, are summarized in the following.

- (1) The vibration of a cylinder increases the mean heat transfer rate of the heated cylinder, but it does not necessarily increase the local heat transfer rate in every part on the cylinder surface.
- (2) The local heat transfer rate of a heated cylinder increases in the upper and the lower part of the cylinder and decreases in the sides by its vibration.
- (3) An increase of the heat transfer rate of a heated cylinder by vibration is caused by an increase of mean upward velocity and by that of fluctuating velocity of the whole convection flow.
- (4) The decrease of the local heat transfer rate by the sides of the vibrating cylinder is caused by a diminishing thermal gradient in the convection flow close to the cylinder, because of the separation of the boundary layer and the generation of a small vortex-like turbulence by the cylinder vibration.

Conclusions (1) and (2) have the same tendency with the heated cylinder in the sound field, and conclusions (3) and (4) are understood qualitatively from the secondary flow due to the cylinder vibration. Here, we should note that the vortex-like turbulence, mentioned in the fourth conclusion, is somewhat different from a large-sized vortex, shown by Fand, R.M., et al. in the sound field, and is a very small one.

This experiment is restricted by the performance of an electro-magnetic vibrator, and the available velocity amplitude of the heated cylinder is within 25 cm/s. So the increase rate of the mean upward velocity of the natural convection by cylinder vibration is 8 to 20 percent, as shown in Fig.12(a), and this increase does not affect the natural convection very much. The change in the heat transfer rate by the vibration is interesting from a physical point of view, but from a technological point of view, the secondary flow, i.e. the acoustic streaming velocity should be increased by use of a larger vibration velocity of cylinder.

7. References

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