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Heat transfer of a cylinder in large-amplitude oscillating wake flows

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Abstract—In order to study the unsteady heat transfer of oscillating wake flows, the heat transfer characteristics of a cylinder in wake flows behind a cylinder located in oscillating flows were investigated experimentally. The amplitudes of surface temperature, hence local heat transfer coefficient of the cylinder in oscillating wake flows are roughly proportional to those of the main flow velocity and inversely proportional to its frequency, although its time-mean is hardly affected by the main flow oscillation. The time-mean and fluctuation of the heat transfer coefficient have a maximum at the reattachment of the shear layer separated from the first cylinder, hence the relative position of two cylinders plays an important role on the unsteady behaviour of the heat transfer of the cylinder in the wake flows.

INTRODUCTION

THE HEAT transfer characteristics of wake flows behind a body are of importance in designing and operating thermo-fluid systems such as gas turbines, heat exchangers, chemical processings, etc. The thermal parts of these systems embedded in wake flows are heated nonuniformly in space and time, and especially unsteady wake flows often cause spontaneous and local hot-spots above the metallurgical allowance. The convective heat transfer of unsteady or oscillating wake flows thus leads to a serious matter in the thermal problems. For example, in gas turbines, turbine nozzles and blades are often exposed locally to temperature disturbances with considerably large amplitudes associated with unsteady wake flows behind struts and blades resulting in overheating failures of their materials. The knowledge of heat transfer of unsteady wake flows is substantial for considering the thermal reliability and safety as well as for estimating the unsteady performance of the systems.

Although much work on unsteady-flow heat transfer has been published, the subjects have been concerned largely with internal flows such as pipe and channel flows. Heat transfer of a body in unsteady wake flows has been little studied because of their complicated flow structures [1, 2]. Unsteady or oscillating wake flows would affect appreciably the fluid-dynamical and thermal behavior of the boundary-layer flow on the surface of the body. Velocity fluctuations may change the process of the turbulent-energy production, hence the structure of turbulence which controls the convective heat transfer. Since the temperature field cannot follow the velocity oscillation at high frequencies due to the thermal inertia, the oscillating flows at relatively low frequencies and high amplitudes may have a substantial effect on the heat transfer behavior.

As a fundamental research of such problems in the present study, the heat transfer characteristics of a cylinder embedded in an oscillating wake flow behind a cylinder are investigated experimentally. Steady problems of such a system have been studied essentially from the standpoint of the heat transfer of tube-array heat exchangers [3–9]. A wind tunnel is equipped to supply airflows with exactly sinusoidal oscillation of velocity at relatively low frequencies and high amplitudes. A cylinder heated electrically is located behind a cylinder unheated in the oscillating flows. The surface temperature of the heated cylinder in the wake flows is measured to obtain the heat transfer characteristics of a cylinder in the oscillating wake flows.

EXPERIMENTAL APPARATUS AND PROCEDURES

Oscillating airflows with large amplitudes are obtained by changing the cross-sectional area of the flow passage as shown in Fig. 1 [2]. Two choked throats geometrically symmetrical are located at the outlets from the air storage tank. The cross-sectional area of the throat is changed alternately in antiphase by a sliding motion of a wedge-shaped piece with the Scotch York link mechanism. High-pressure air with regulated temperature and humidity is introduced from a high-pressure storage tank into the tank containing the throats through pressure regulators. The present equipment can provide exactly sinusoidally oscillating flows of velocities from 0 to 60 m s^{-1} and amplitudes up to 80% at 3 Hz or 10% at 10 Hz. The test section is placed vertically to avoid the influence of natural convection on convective heat transfer. It has a cross-sectional area of 60×100 mm^2 and a length of 300 mm, made of heat-insulating materials 15 mm thick. The flow velocity obtained is uniform throughout above 80% of the test area. The intensity of turbulence is less than 0.6% of the mean velocity, being hardly altered by a change in the frequency, amplitude or time-mean of the flow velocity.

A cylinder is located in the oscillating airflows and another cylinder is located in its wake flow, being heated electrically. The cylinder wall is made of a stainless steel foil 15 μm thick and 43 mm long wrapped around a bakelite pipe as shown in Fig. 1. The foil is heated electrically by an alternating current. On both

NOMENCLATURE

c_w	heat capacity of the heater foil per surface area [kJ m^2 K^{-1}]
d	diameter of cylinder [mm]
f	frequency, $\omega/2\pi$ [Hz]
h	heat transfer coefficient, q/T[W m^{-2} K^{-1}]
Nu	Nusselt number, hd/λ
ΔNu	amplitude of Nusselt number oscillation
q	heat flux per unit surface area [W m^{-2}]
T	wall temperature referred to main-stream temperature [K]
ΔT	amplitude of wall temperature oscillation [K]
t	time [s]
U	main-stream velocity [m s^{-1}]
ΔU	amplitude of main velocity oscillation [m s^{-1}]
X, Y	center position of the second cylinder [mm]
x, y	coordinates.

Greek symbols

δ	phase difference of oscillation referred to main stream [deg.]
θ	circumferential angle [deg.]
λ	heat conductivity of air [W m^{-1} K^{-1}]
ω	angular frequency [rad s^{-1}].

Subscripts

h	heat transfer coefficient
t	temperature
1	first cylinder
2	second cylinder.

Superscript

$\bar{}$	time-mean.

sides of the foil, auxiliary electrical heaters are employed to avoid heat loss due to conduction through the cylinder. The surface temperature of the foil is measured circumferentially by rotating the cylinder with a copper–constantan thermocouple of 18 μm in diameter soldered to the foil. The thermocouple has a sufficient response to follow the temperature oscillations encountered in the present experiment.

The geometrical configuration of the two cylinders and the coordinate system employed are shown in Fig. 2. The x-coordinate is measured in the direction of the main flow and the y-coordinate is perpendicular to it with the origin at the center of the first cylinder. The center of the second cylinder is located at the point, $x = X$ and $y = Y$, which is denoted as (X, Y); $(X, 0)$ means the cylinders stand in a line in the direction of the main flow, and (0, 0) implies the case of a single cylinder.

The oscillating main flows obtained by the present equipment can be expressed within 1% accuracy as

$$U = \bar{U} + \frac{\Delta U}{2} \sin(\omega t) \qquad (1)$$

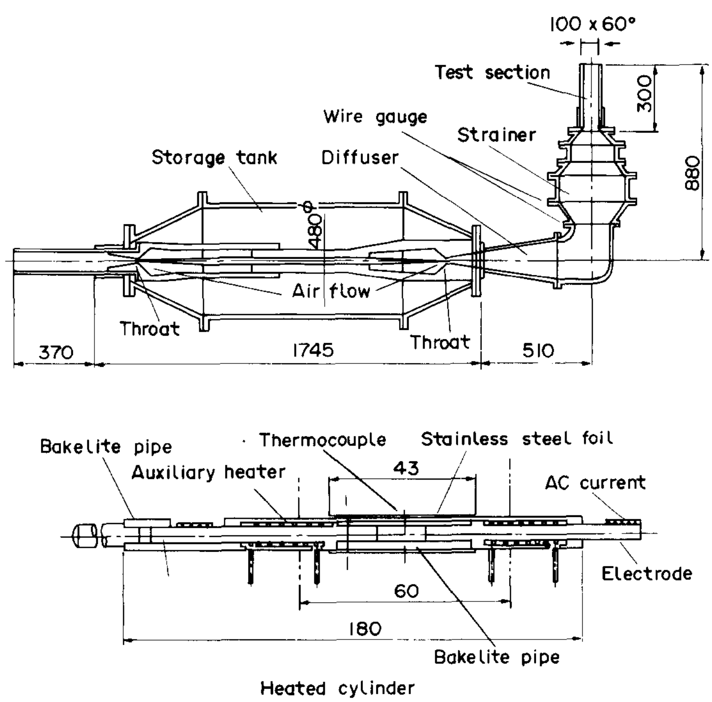


FIG. 1. Wind tunnel of oscillating flows with large amplitudes and a heated cylinder [1, 2].

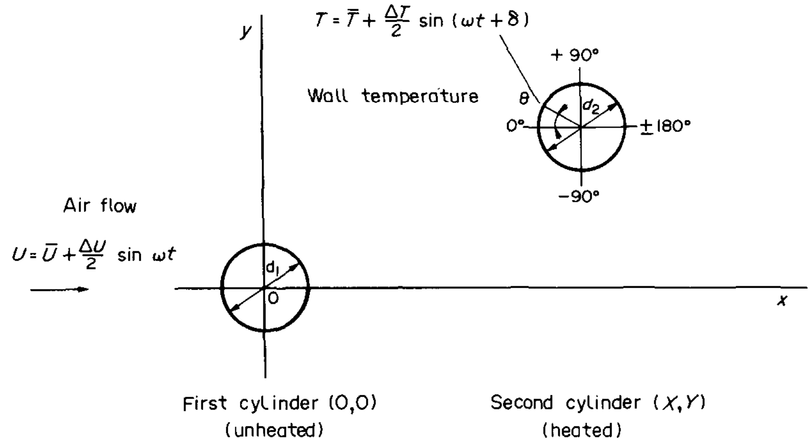


FIG. 2. Cylinder arrangement and coordinates.

where $\bar{U}$ is the time-mean of the main-flow velocity, ΔU the amplitude of its oscillation and ω the angular frequency ($=2\pi f$, where f is the frequency). The surface temperature of the cylinder in oscillating wake flows may not always have a linear response to the main-flow oscillation and may have higher harmonics than the fundamental frequency. The surface temperature measured, however, shows higher harmonics less than 10% of the fundamental and can be approximated as

$$T = \bar{T}+\frac{\Delta T}{2}\sin(\omega t+\delta_t) \quad (2)$$

where the temperature is measured from that of the main flow, $\bar{T}$ the time-mean, ΔT the amplitude and δ_t the phase difference referred to the main-flow oscillation. The amplitude ΔT is defined as

$$\Delta T = T_{max}-T_{min}.$$

With the surface temperature known, the heat transfer coefficient around the cylinder can be calculated. The heat released by electrical heating per unit time and unit area of the surface, q, heats up the foil wall itself as well as the airflow adjacent to it

$$q = hT+c_w\frac{\partial T}{\partial t} \quad (3)$$

where h is the heat transfer coefficient and c_w the heat capacity of the foil wall per unit surface area. The heat transfer coefficient is then given by [2]

$$h = \bar{h}+\frac{\Delta h}{2}\sin(\omega t+\delta_n). \quad (4)$$

The nondimensional form of the heat transfer coefficient, the Nusselt number is then

$$Nu = \bar{N}u+\frac{\Delta Nu}{2}\sin(\omega t+\delta_n), \quad (5)$$

$$\bar{N}u = \frac{\bar{h}d}{\lambda},\quad \Delta Nu = \frac{\Delta hd}{\lambda}$$

where d is the cylinder diameter and λ the heat conductivity of air.

EXPERIMENTAL RESULTS AND DISCUSSIONS

The surface temperature of the cylinder cannot follow the oscillation of the main-flow velocity at higher frequencies to be only in response to its time-mean. Attention is thus paid mainly to the oscillating flows at relatively low frequencies and large amplitudes. The experimental conditions are varied in the range

velocity oscillation: $\bar{U} = 10\text{–}40\ \mathrm{m\,s^{-1}}$
$\Delta U = 0\text{–}20\ \mathrm{m\,s^{-1}}$
$f = 0\text{–}5.0\ \mathrm{Hz}$
heat flux: $q = 10^3\text{–}10^5\ \mathrm{W\,m^{-2}}$
cylinder diameter: $d_1 = 8$ mm, $d_2 = 6, 8, 10$ mm.

In the following illustration of the experimental results, a typical condition is selected unless otherwise stated as follows

$$d_1 = 8\ \mathrm{mm},\quad d_2 = 8\ \mathrm{mm},\quad \bar{U} = 30\ \mathrm{m\,s^{-1}},$$
$$\Delta U = 15\ \mathrm{m\,s^{-1}},\quad f = 1.0\ \mathrm{Hz},\quad q = 17010\ \mathrm{W\,m^{-2}}.$$

The features of the flow fields around the cylinders are illustrated schematically in Fig. 3 to help understand the behavior of the heat transfer [3–9]. The shear layer separated from the first cylinder may reattach onto the surface of the second cylinder. The reattached flow generates a recirculation flow in the wake behind the first cylinder and a boundary-layer flow on the surface of the second cylinder. The reattachment of the shear layer from the first cylinder depends on the relative position of the two cylinders. At certain staggers of the two cylinders ($Y \neq 0$), the surface of the second cylinder is embedded in the inner and outer sides of the wake of the first cylinder, having reattachment only on the latter side. The surface on the former (inner) side is located completely in the wake flow of the first cylinder.

Figure 4 shows a typical example of the surface temperature of the cylinders; (0,0) means the single cylinder, and $(X,0)$ as (12,0) and (16,0) means the second cylinder embedded at $x = X$ and $y = 0$ in the oscillating wake flows behind the first cylinder. In the case of the single cylinder, the time-mean surface

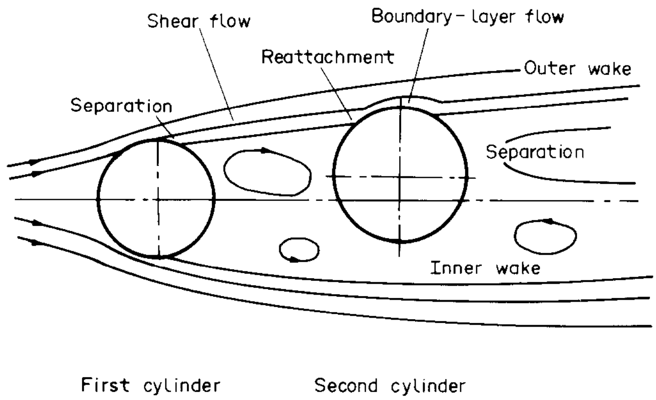


FIG. 3. Flow configuration around cylinders.

temperature takes a minimum at the forward stagnation point ($\theta = 0$), increasing rapidly around the separation point to a maximum and then decreases slightly. The time-mean temperature of the second cylinder takes a minimum at the point $\theta = 60°-80°$ where the shear layer separated from the first cylinder reattaches onto the surface of the second cylinder. Before the reattachment, in the region of the separated wake flow behind the first cylinder, there exists a recirculating flow which increases the surface temperature which has a maximum at the forward stagnation. Around the separation point of the reattached flow ($\theta \simeq 110°$), the temperature also increases rapidly to another maximum. As the distance between the two cylinders decreases, the reattachment tends to be delayed towards larger angles which enlarges the wake flows behind the first cylinder and increases the surface temperature. The separation of the reattached flow is also delayed but the surface temperature in the separated flow of the second cylinder is little affected by the distance between the two cylinders. These features of the time-mean surface temperature are hardly changed by the frequency and amplitude of main-flow oscillation as shown in Figs. 6 and 7, being the same as those of steady flows [3–8].

The amplitude of the surface temperature oscillation, in the case of the single cylinder, is relatively uniform until the separation point after which it increases rapidly to reach a maximum. The amplitude of the second cylinder in the oscillating wake flow has a minimum value at the forward stagnation and reattachment points with a maximum between these two points. After the reattachment, it increases gradually to a maximum around the separation point. As the distance between the two cylinders decreases, the amplitude tends to increase except for the backward surface in the separated region where it is little affected by the distance. The phase lag of the surface temperature oscillation is decreased around the separation point for the single cylinder, whereas it takes a maximum at the reattachment point for the cylinder in wake flows.

The nondimensionalized heat transfer coefficient based on these temperatures is shown in Fig. 5. The features of the time-mean are the reverse of those of the time-mean temperature, taking a maximum value at the reattachment and lower values in forward and backward wakes of the second cylinder. The amplitude of the heat transfer coefficient shows rather different features from that of the surface temperature. The latter has two peaks of amplitude at the forward and backward positions, whereas the former takes only one peak at the reattachment point. Roughly speaking, the amplitude of the heat transfer coefficient seems to be proportional to its time-mean. As shown later in Figs. 9 and 10, however, this holds only for the cases of $Y = 0$ and ∞, and does not for other cases ($Y \neq 0$). Further, it should be noted that the time-mean and amplitude of the heat transfer coefficient are increased by reducing the distance between the two cylinders. The cylinder in the oscillating wake flows is associated with a relatively large heat transfer oscillation compared with the single cylinder.

The effects of the frequency and amplitude of main velocity oscillation on the heat transfer are shown in Figs. 6 and 7, respectively. The time-mean coefficient is hardly affected by the main velocity oscillation, being equal to the value of steady flows ($\Delta U = 0$ or $f = 0$). The amplitude of the coefficient oscillation is increased roughly proportional to the amplitude of the velocity oscillation and decreased with an increase in its frequency. The phase lag of the coefficient oscillation is decreased rapidly with the frequency of the velocity oscillation, although it is not changed by its amplitude.

Figure 8 shows the surface temperature of the second cylinder located in an oscillating wake behind a cylinder with a stagger $Y(\neq 0)$. When the stagger is small ($Y \lesssim 2$ mm, or $2Y/d_1 \lesssim 0.5$) the temperature distribution tends to be shifted towards $\theta < 0$ with appreciable asymmetry. On the inner wake side ($\theta < 0$) of the cylinder surface, the minimum time-mean at the reattachment point is largely diminished, and the maximum amplitude is increased between the forward stagnation and the reattachment point. It implies that one of the recirculations in the wake of the first cylinder

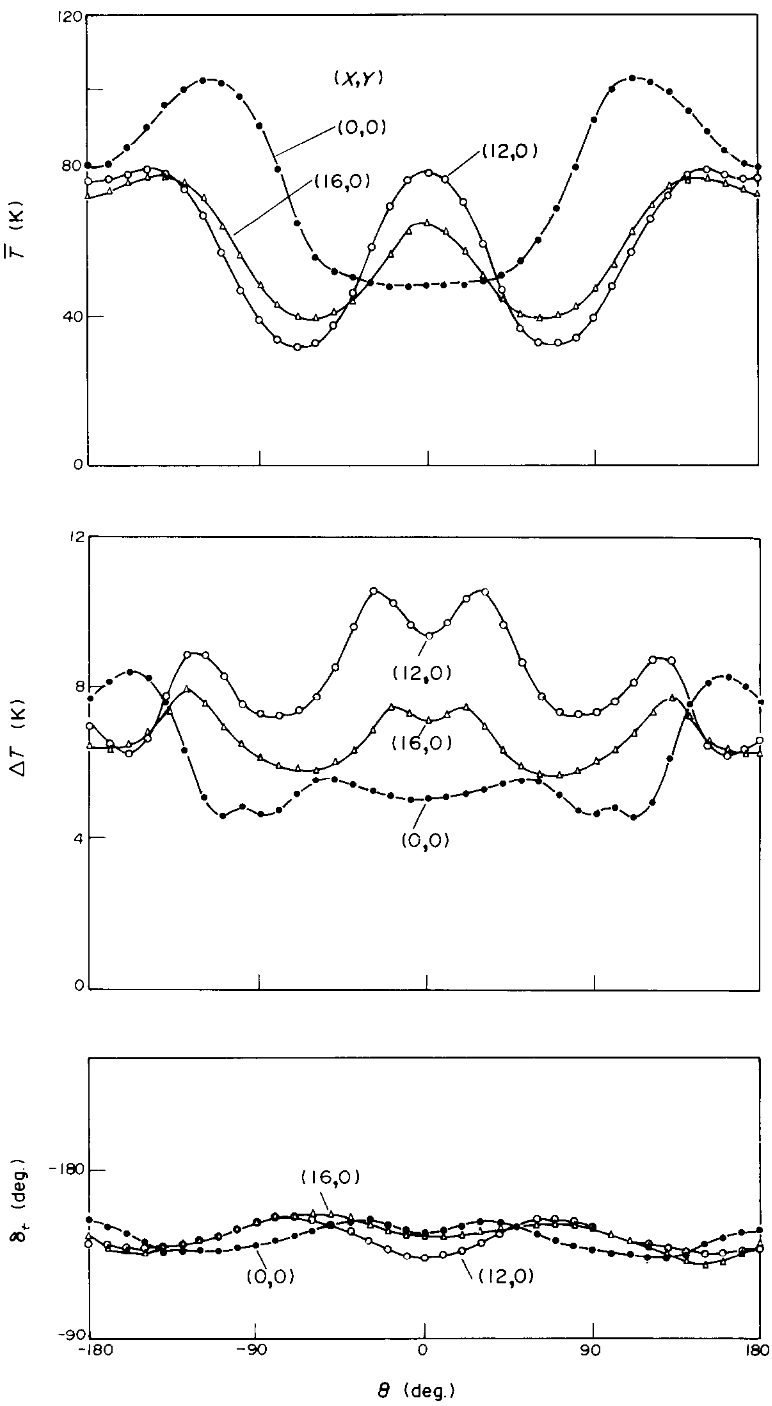


FIG. 4. Surface temperature of the second cylinder located at $x = 0$, 12, 16 mm and $y = 0$, $T(X, 0)$.

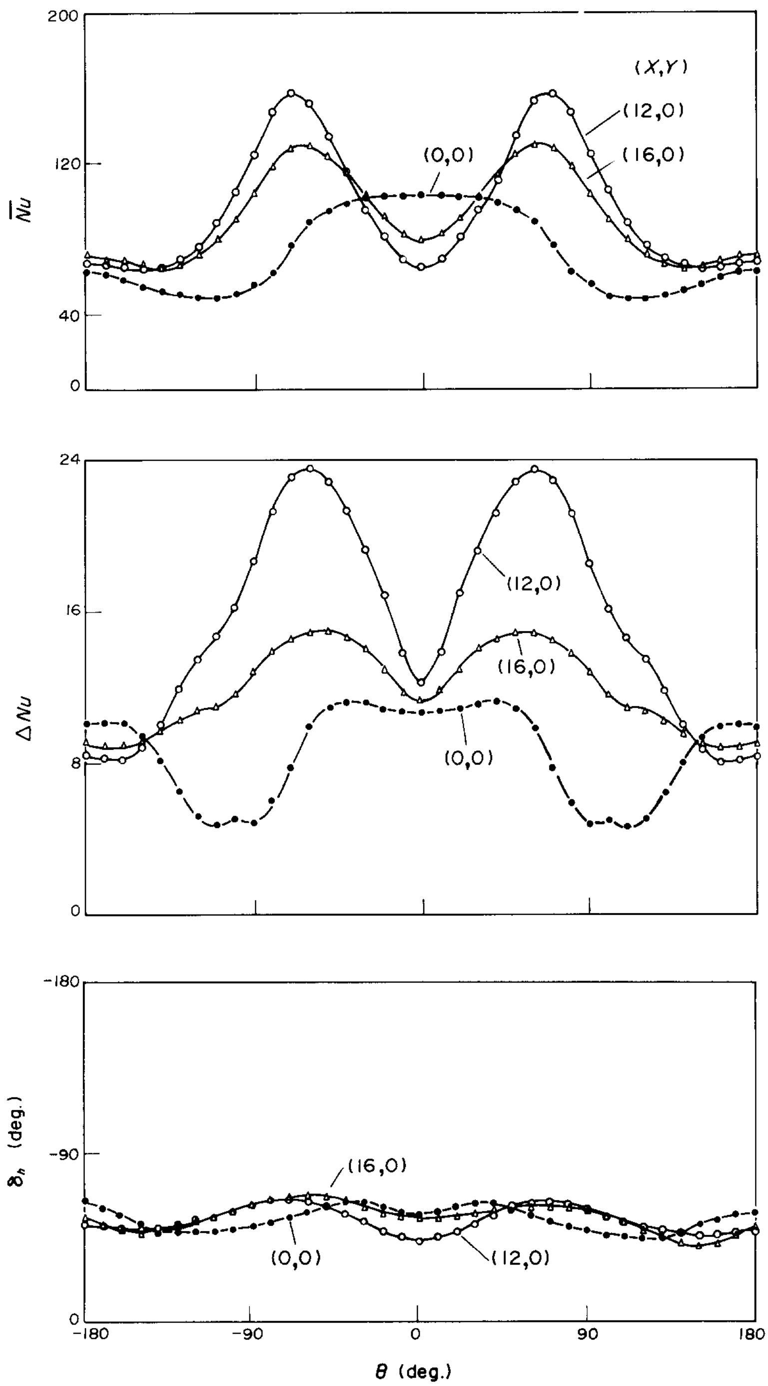


FIG. 5. Nusselt number calculated from the surface temperature shown in Fig. 4, $Nu(X, 0)$.

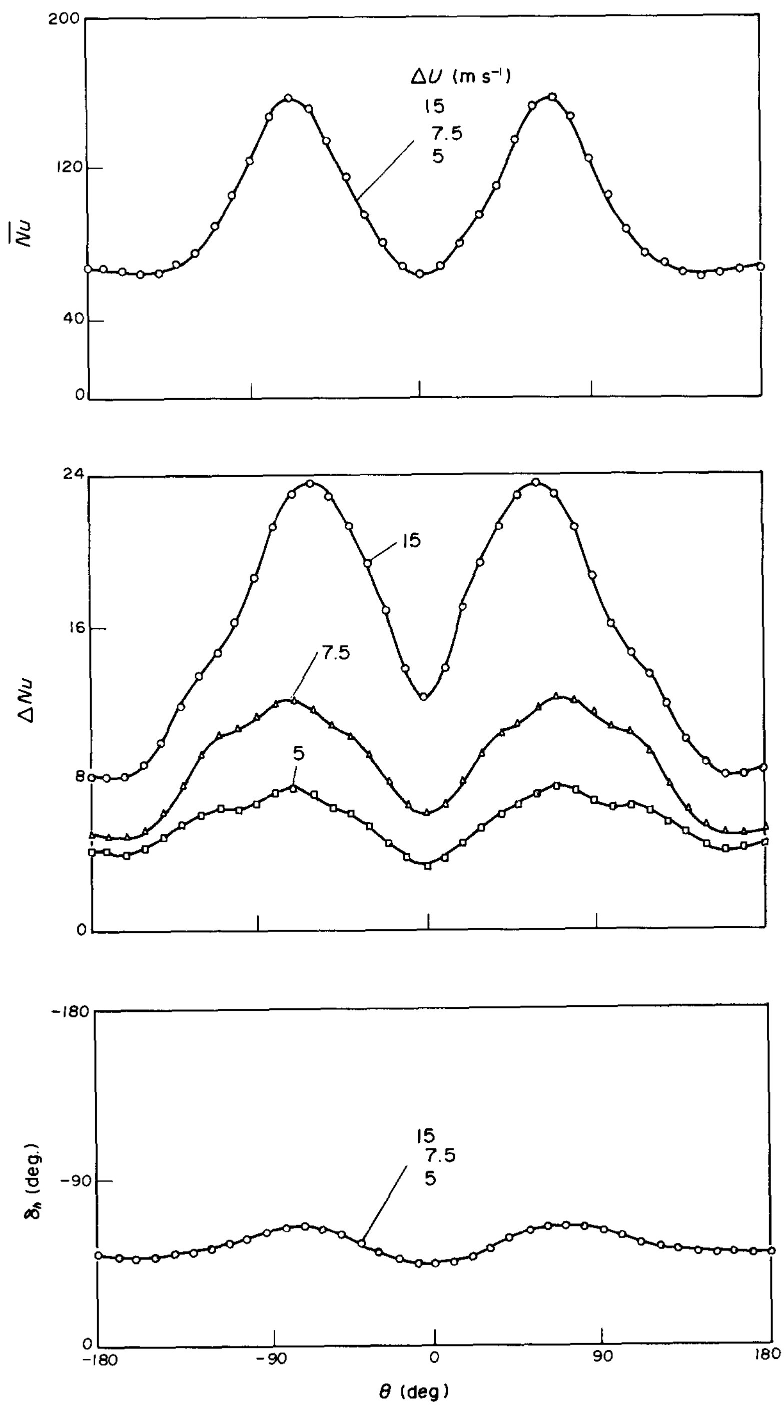


FIG. 6. Effect of the frequency of velocity oscillation on the heat transfer coefficient, $Nu(12, 0; f)$; $\Delta U = 5\,\mathrm{m\,s^{-1}}$.

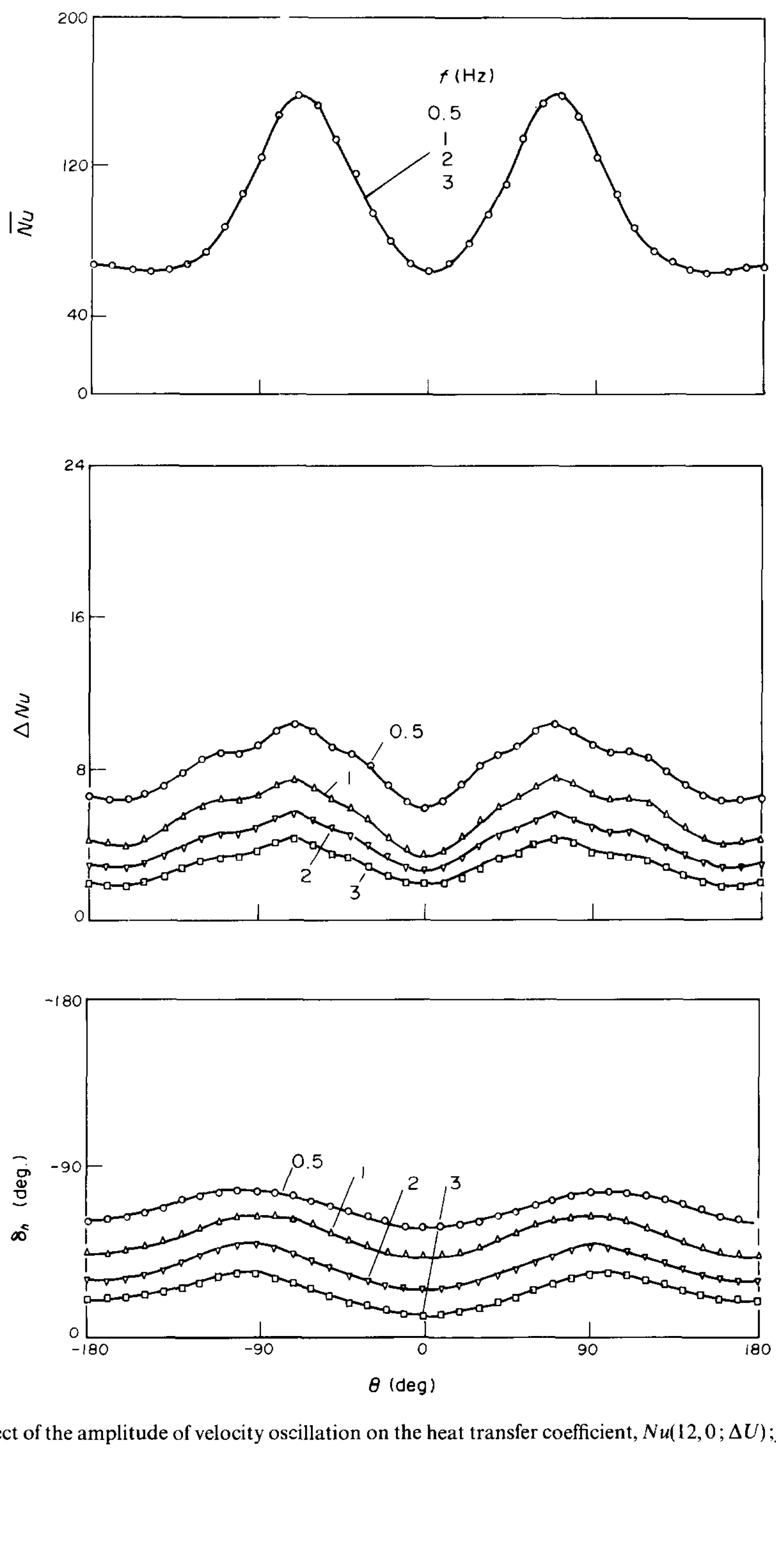


FIG. 7. Effect of the amplitude of velocity oscillation on the heat transfer coefficient, $Nu(12, 0; \Delta U)$; $f = 1$ Hz.

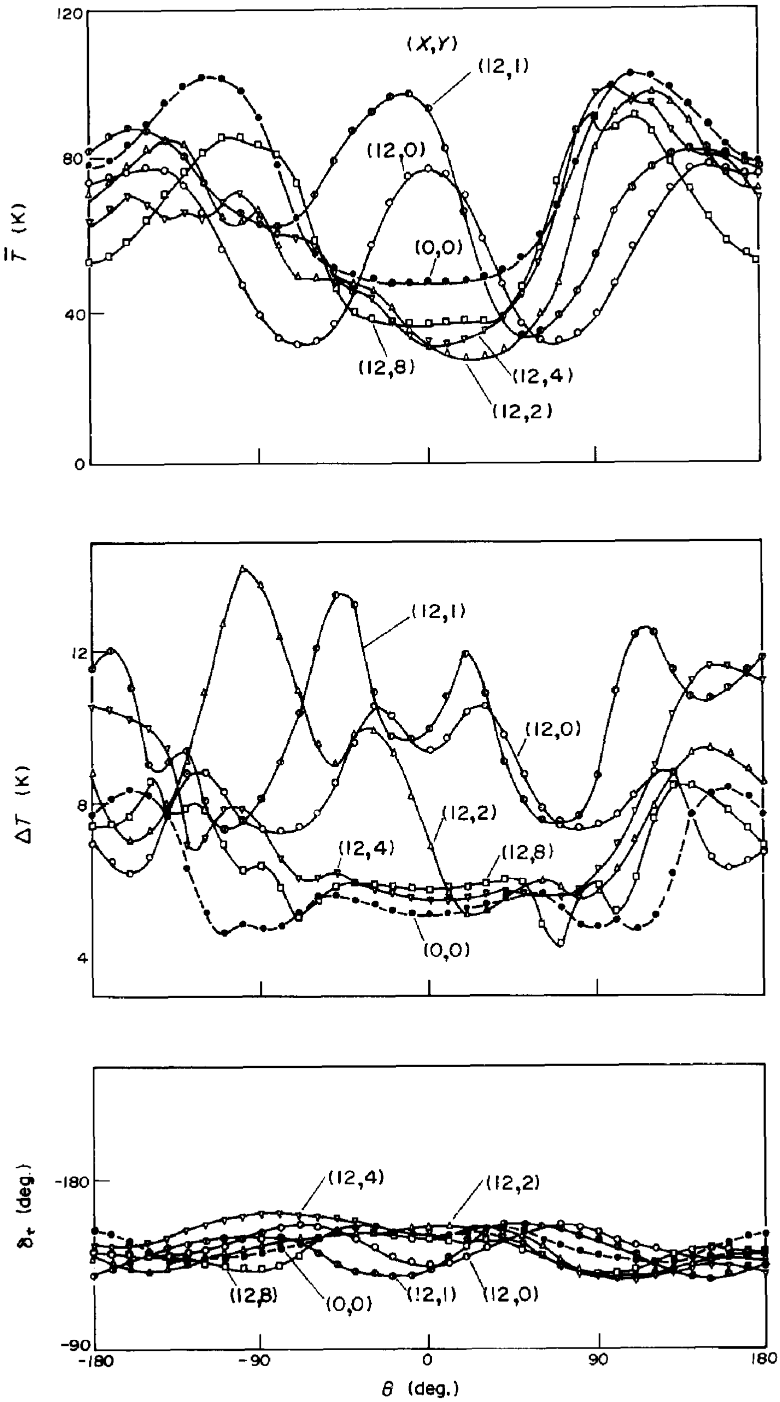


FIG. 8. Effect of the stagger of the second cylinder on the surface temperature, $T(12, Y)$.

may be energized asymmetrically. At larger values of the stagger ($Y = 2$–4 mm, or $2Y/d_1 = 0.5$–1), the temperature on the outer wake side ($\theta > 0$) of the surface tends to approach that of the single cylinder and the reattachment of the shear flow separated from the first cylinder on the second cylinder moves towards $\theta = 0$. On the inner side, the surface of the second cylinder is embedded so completely in the separated wake flow of the first cylinder that are the time-mean and oscillating temperatures are not appreciably varied along the surface of the cylinder. At further large values of the stagger ($Y \gtrsim 4$ mm, or $2Y/d_1 \gtrsim 1$) where the wake of the first cylinder may slip off the second cylinder, the surface temperature behaves like that of the single cylinder.

In Figs. 9(a) and (b), the effect of the stagger on the nondimensionalized heat transfer coefficient is shown for two different axial positions of the second cylinder, $X = 12$ and 16 mm, respectively. From the comparison of Fig. 9(a) with Fig. 8, it is seen that changes in the

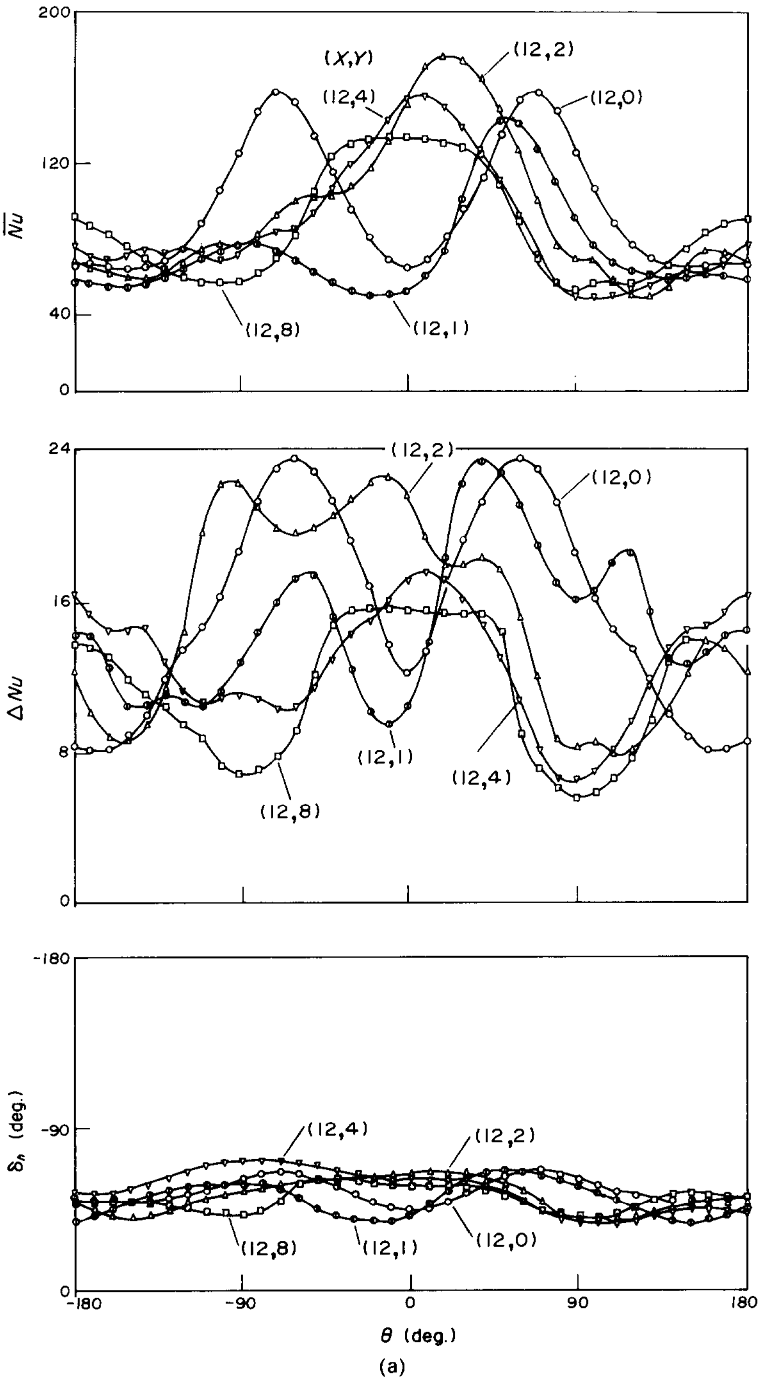


FIG. 9.

coefficient are greatly reduced beyond the reattachment point. The time-mean coefficient takes a maximum value around the reattachment, and its amplitude varies considerably in the forward wake flows before the reattachment. It should be noted that the relation of the amplitude proportional to the time-mean could hold only for cases of $Y = 0$ and $Y/d_1 \gtrsim 1$. At other staggers, the amplitude shows a complicated behavior different from that of the time-mean, being rather similar to that of the surface temperature.

In Figs. 10(a) and (b), the second cylinder has a different diameter from that of the first cylinder (d_1 = 8 mm); d_2 = 6 and 10 mm, respectively. On the outer side ($\theta > 0$), the coefficient of the large cylinder (d_2 = 10 mm) shows the behavior of the boundary layer flow at slightly staggered positions ($Y \gtrsim 2$ mm), whereas that

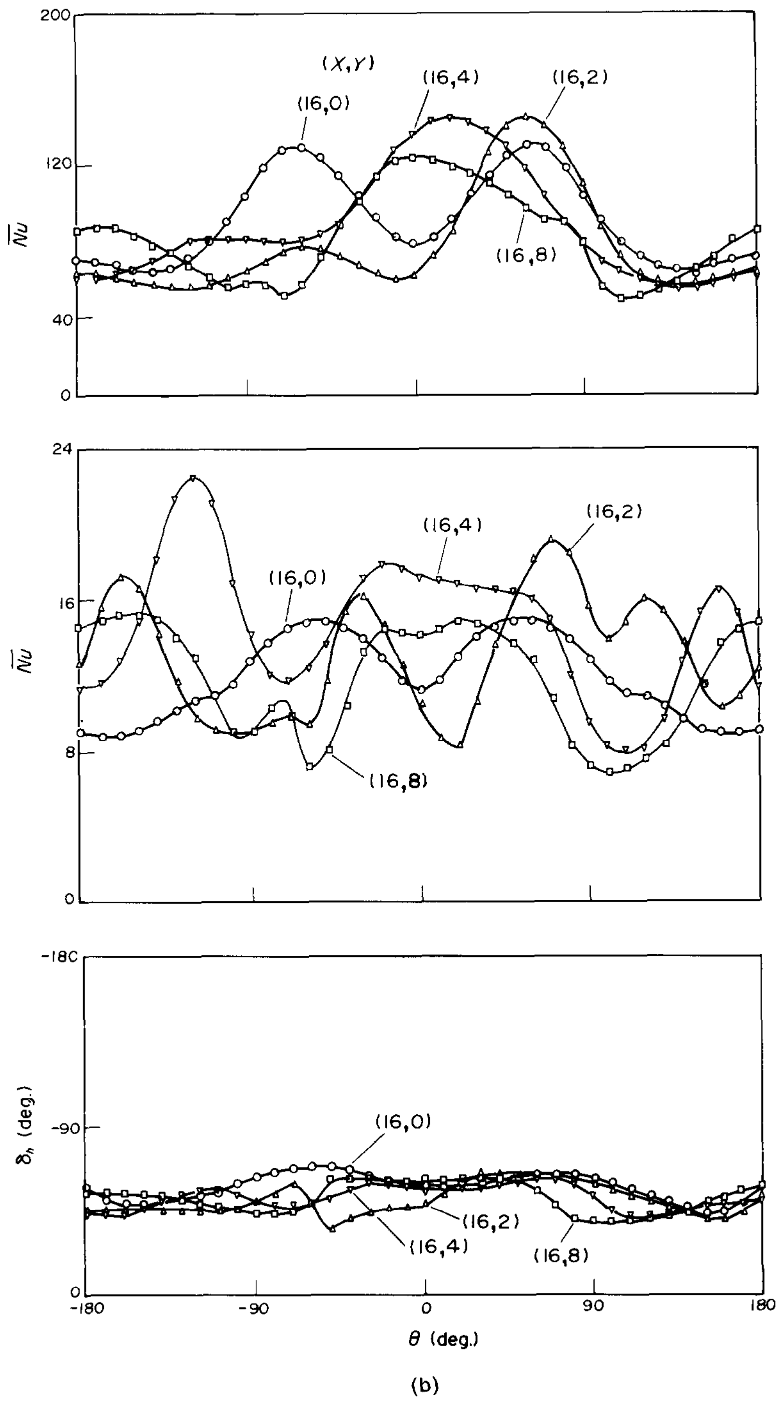
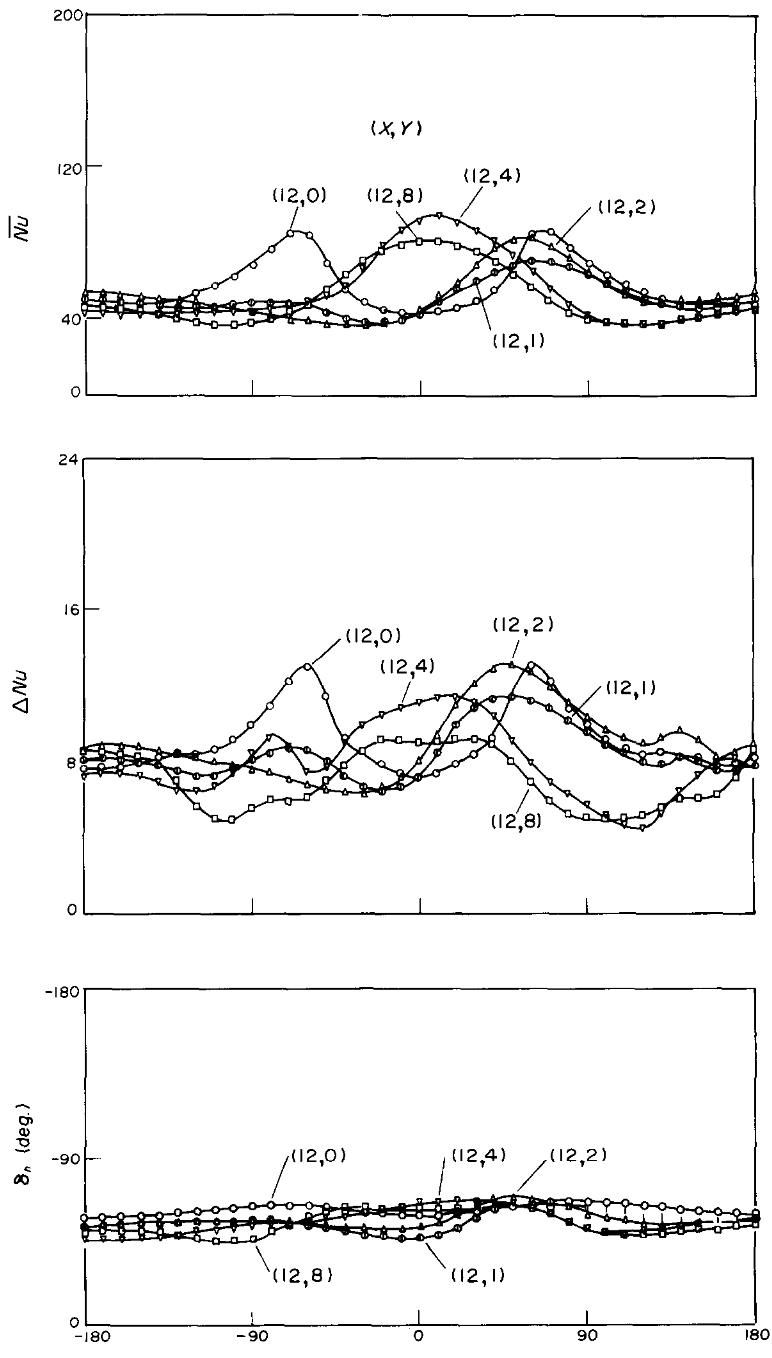


FIG. 9. Effect of the stagger of the second cylinder on the heat transfer coefficient, $Nu(X, Y)$; (a) X = 12 mm, (b) X = 16 mm.

of the small cylinder (d_2 = 6 mm) keeps the tendency of the reattached wake flow until relatively larger staggers (Y = 2–3 mm). On the other hand, the inner side ($\theta < 0$), these are reversed; the large cylinder keeps a reattached wake flow until larger staggers (Y = 3–4 mm) and the small cylinder comes to be embedded thoroughly in the wake flow at small staggers (Y = 2–3 mm). Further, by comparing Figs. 9 and 10, it is noted that both smaller and larger cylinders tend to reduce the oscillation of the heat transfer coefficient.

CONCLUSIONS

Heat transfer characteristics were studied experimentally of a cylinder in wake flows behind a cylinder located in oscillating flows. The velocity of the main

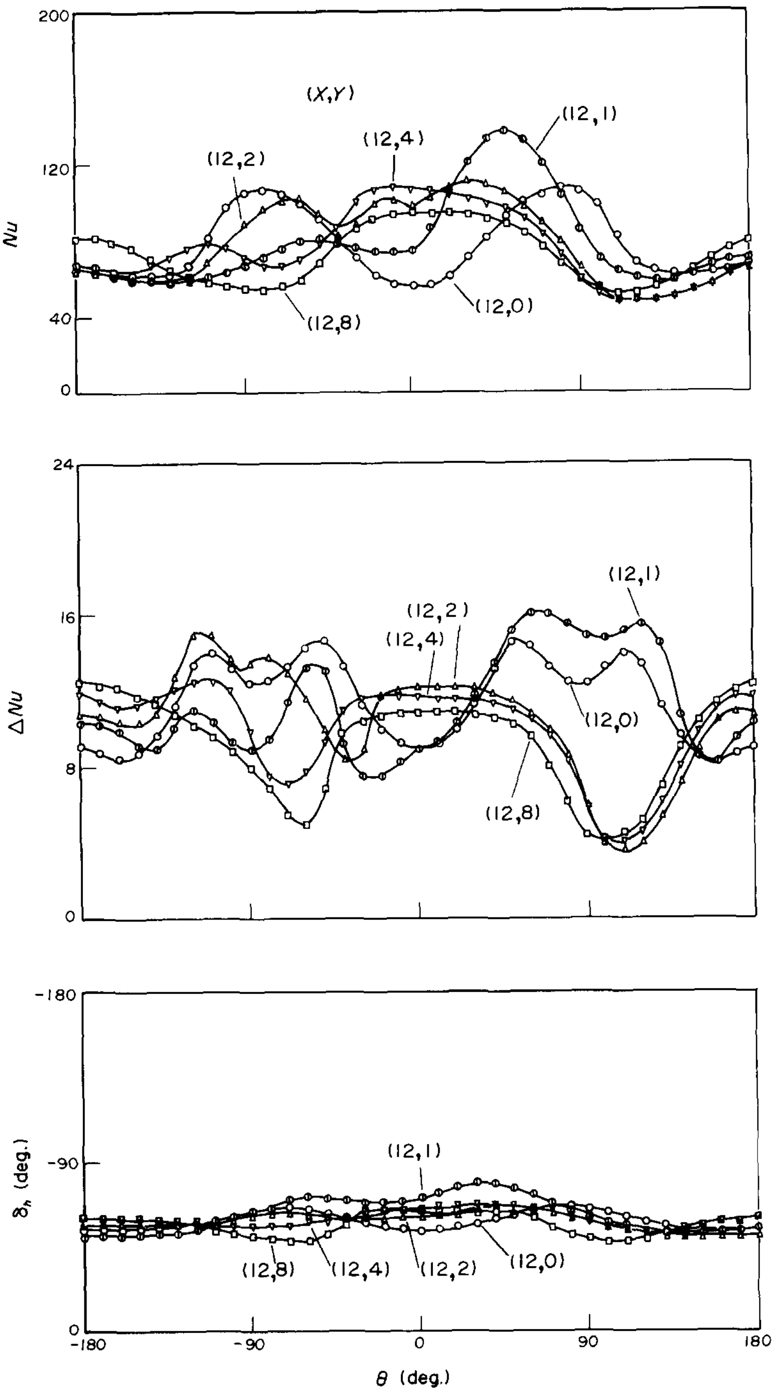


(a)

FIG. 10.

flow oscillated sinusoidally with large amplitudes. The second cylinder in oscillating wake flows behind the first cylinder was heated electrically, and its surface temperature was measured to obtain the unsteady behavior of heat transfer from the surface to the wake flows.

(1) The time-mean surface temperature (heat transfer coefficient) takes a minimum (maximum) value at the reattachment point of the shear flow separated from the first cylinder, and larger (smaller) values at the forward stagnation and rearward separation points, although it is hardly affected by the main flow oscillation.



(b)

FIG. 10. Effect of the diameter of the second cylinder on the heat transfer coefficient, $Nu(12, Y)$; (a) d_2 = 6 mm, (b) d_2 = 10 mm.

(2) The amplitude of the surface temperature oscillation takes also a minimum value at the reattached point and larger values at points in the forward recirculation flow and in the rearward separated flow. The amplitude of the heat transfer coefficient takes a maximum value around the reattachment. The phase lag of the surface temperature is increased slightly in the forward separated flow.

(3) With an increase in the frequency of the main flow oscillation, the amplitude and the phase lag of the surface temperature (heat transfer coefficient) are decreased. As the amplitude of the velocity oscillation increases, the amplitude of the surface temperature (heat transfer coefficient) increases roughly proportional to it, although the phase lag is little affected.

(4) At slightly staggered positions of the second cylinder with respect to the first cylinder, the circumferential distribution of the surface temperature (heat transfer coefficient) shifts to the staggered direction. At staggers of about a half of the cylinder radius, the surface temperature (heat transfer coefficient) shows the features of the boundary-layer flow in the outer surface and of the wake flow in the inner surface, and at further large staggers, it tends to be of the single cylinder.

(5) These effects of the stagger are delayed at the outer side of the second cylinder of small diameter and at the inner side of the cylinder of large diameter. At other sides, these effects arise at smaller staggers.

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TRANSFERT THERMIQUE D'UN CYLINDRE DANS UN SILLAGE OSCILLANT AVEC GRANDE AMPLITUDE

Résumé—Pour étudier le transfert thermique variable de sillages oscillants, on considère expérimentalement les caractéristiques d'un cylindre dans des écoulements de sillage derrière un cylindre placé dans un écoulement oscillant. Les amplitudes de la température de surface et le coefficient de convection thermique du cylindre dans l'écoulement de sillage oscillant sont grossièrement proportionnels à ceux de l'écoulement moyen et inversement proportionels à la fréquence, bien que le temps moyen soit fortement affecté par l'oscillation de l'écoulement principal. Le temps moyen et la fluctuation du coefficient de convection ont un maximum au réattachement de la couche séparée du premier cylindre et par suite la position relative des deux cylindres joue un rôle important sur le comportement instationnaire du transfert thermique du cylindre dans les écoulements de sillage.

WÄRMEÜBERGANG AN EINEM ZYLINDER IN NACHLAUFSTRÖMUNGEN MIT GROSSEN SCHWINGUNGSAMPLITUDEN

Zusammenfassung—Um den instationären Wärmeübergang von oszillierenden Nachlaufströmungen zu studieren, wurde der Wärmeübergang an einem Zylinder im Nachlauf eines zweiten Zylinders, welcher sich in einer oszillierenden Strömung befand, experimentell untersucht. Die Amplituden der Oberflächentemperatur und damit des örtlichen Wärmeübergangskoeffizienten am Zylinder in oszillierenden Nachlaufströmungen sind ungefähr proportional Hauptströmungsgeschwindigkeit und umgekehrt proportional zu ihrer Frequenz, obwohl das zeitliche Mittel kaum von der Hauptstromschwingung beeinflußt wird. Der zeitliche Mittelwert und die Schwankung der Wärmeübergangskoeffizienten haben ein Maximum beim Wiederanlegen der Strömung, die sich am ersten Zylinder abgelöst hat. Infolge dessen spielt der Abstand der beiden Zylinder eine wichtige Rolle beim instationären Verhalten des Wärmeüberganges an dem Zylinder in der Nachlaufströmung.

ТЕПЛОПЕРЕНОС ОТ ЦИЛИНДРА, ОБТЕКАЕМОГО ПУЛЬСИРУЮЩИМИ СПУТНЫМИ ПОТОКАМИ С БОЛЬШОЙ АМПЛИТУДОЙ КОЛЕБАНИЯ

Аннотация—Для изучения нестационарного теплопереноса при течении в пульсирующих спутных потоках проведено экспериментальное исследование характеристик теплообмена цилиндра, находящегося в следе за другим цилиндром, обтекаемым пульсирующим потоком. Амплитуды температуры поверхности и, следовательно, локальный коэффициент теплообмена для цилиндра, обтекаемого пульсирующими спутными потоками, приблизительно пропорциональны амплитудам скорости невозмущенного потока и обратно пропорциональны ее частоте, в то время как среднее время слабо зависит от колебаний невозмущенного потока. Среднее время и колебание коэффициента теплообмена максимальны в точке присоединения пограничного слоя, отделившегося от первого цилиндра, что свидетельствует о той важной роли, которую играет относительное положение обоих цилиндров в нестационарном процессе теплообмена от цилиндра, обтекаемого спутными потоками.