Int. J. Heat Mass Transfer. Vol. 18, pp. 583–587. Pergamon Press 1975. Printed in Great Britain

SHORTER COMMUNICATION

INTERFEROMETRIC FLOW VISUALIZATION OF FREE CONVECTION FROM A HORIZONTALLY VIBRATING ISOTHERMAL CYLINDER*

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(*Received* 31 *January* 1974 *and in revised form* 1 *July* 1974)

NOMENCLATURE

A, amplitude of oscillation from center position to extreme position of oscillation;
D, cylinder diameter;
f, frequency of oscillation;
Gr, Grashof number;
Nu, Nusselt number;
Pr, Prandtl number;
Re_A, average Reynolds number;
ν, kinematic viscosity of air;
ψ, angular position of cylinder measured from left extreme position.

INTRODUCTION

THIS paper is concerned with the effect of horizontal, transverse vibration of an isothermal cylinder on the flow structure of the heated air surrounding a cylinder. It is primarily a flow visualization study that has been carried out to explain the heat-transfer results presented in [5]. Observations of the flow of heated air around a vibratory cylinder are made in an attempt to explain the effect of vibration on the heat transfer from the cylinder and to provide further insight into the mechanisms that affect the heat transfer in oscillatory flow.

Over the past fifteen years or so, there have been many investigations of the effect of vibration on the heat-transfer rate from wires and cylinders in free convection. The vibration is usually achieved by mechanically vibrating the cylinder in a stationary bulk fluid or by vibrating the fluid acoustically while the cylinder remains stationary. Most of the investigations have been limited to the measurement of overall average heat-transfer rates, but there have been a few investigations of local time-averaged heat-transfer rates that were measured by using a segmentally heated cylinder [1] or by using optical methods [2–4]. The measurement of instantaneous local heat-transfer coefficients obtained using a differential interferometer [5] has been previously reported. These measurements were made for free convection from an isothermal cylinder vibrating sinusoidally in a horizontal plane. The results show that the heat-transfer coefficient is strongly dependent upon the ratio of amplitude of vibration to cylinder diameter, A/D. For values of A/D less than approximately $\frac{1}{4}$, a critical vibration intensity was observed below which vibration caused only small increases in the heat-transfer rate; however, at A/D greater than $\frac{1}{4}$, the critical vibrational intensity did not appear to exist because the heat transfer from the cylinder increased gradually as the vibrational speed increased from zero.

*Based, in part, on the doctoral dissertation of W. W. Carr [6].

APPARATUS

A gold plated copper cylinder having a diameter of 2·5 cm and a length of 30·3 cm was used in this investigation. The cylinder was heated electrically by a tubular heating element located along the axis of the cylinder. Copper constantan thermocouples were used to measure the temperature of both the cylinder and the ambient air. Horizontal sinusoidal motion of the cylinder was produced by a Scotch yoke mechanism.

A differential interferometer that is discussed in detail in [6–8] was used to provide a flow visualization of the heated air surrounding the cylinder. With this instrument, a component of the gradient of density can be measured in any arbitrary direction. The differential interferometer can be adjusted to produce an infinite fringe pattern which provides an excellent flow visualization for qualitative observations of thermal boundary layers. A high speed camera was used to photograph interferograms throughout the cycle of oscillation so that information about the instantaneous thermal structure of the heated air surrounding the cylinder could be obtained.

DISCUSSION OF FLOW VISUALIZATION

For oscillatory flow imposed upon free convection, the Nusselt number is considered to be a function of the Reynolds number, Prandtl number, Grashof number, and the ratio of amplitude of vibration to cylinder diameter. The ranges of the parameters of the tests conducted and the percentage increase in the heat-transfer rate above the free convective rates are shown in Table 1. These values also appear in [5], but are repeated here for convenience. The percentage changes indicate the effect of vibration on the overall average heat-transfer rate and are referred to in this discussion.

Table 1. Percent increase in average Nusselt number above free convective value

($Pr = 0{\cdot}72$, values from [5])

A/D	$Re_A = \frac{4Af}{\nu}$	$Gr \times 10^{-4}$ 2·5	4·5	7·5
0	Stationary	0	0	0
$\frac{1}{8}$	150	4	3	1
$\frac{1}{4}$	150	6	8	8
	300	14	8	10
$\frac{3}{8}$	150	24		
	300	39		
	600	170		
$\frac{1}{2}$	150	33	33	25
	300	55	48	46
	600	170	140	
1	150	43	29	19
	300	79	88	49
	600	170	160	
$\frac{7}{4}$	150	38	26	15
	300	92	81	42
	600	200	150	

High speed motion pictures of interferograms corresponding to both the horizontal and vertical components of the temperature gradient were made while the cylinder executed sinusoidal motion. The comments made here are based on careful observations of a large number of 16 mm frames. Those figures, each consisting of eight photographs of interferograms, are included to facilitate the discussion of the flow around the cylinder. Seven of the photographs correspond to seven different cylinder positions in a half cycle of oscillation, and the eighth photograph is an interferogram of a freely convecting, stationary cylinder. Interferograms of the vertical component of the temperature gradient are shown in Figs. 1–3 because for these cases they contain the most information concerning the overall flow. The symbol ψ is used to denote the position (in degrees) of the cylinder on the cycle of oscillation referenced to the left extreme position ($\psi = 0°$). Interferograms for only one half cycle of oscillation is shown since the flow around the cylinder for motion of the cylinder from $\psi = 180°$ to $\psi = 360°$ is the mirror image of that for motion of the cylinder from $\psi = 0°$ to $\psi = 180°$.

The interferograms show that the flow patterns are not symmetric with respect to $\psi = 90°$. This is because the cylinder is accelerating for $0° < \psi < 90°$ and is decelerating for $90° < \psi < 180°$. Also, the air heated in a previous half cycle of oscillation has less time to rise out of the cylinder's path for $0 < \psi < 90°$ than for $90° < \psi < 180°$, and therefore, the heat transfer from the cylinder for $0 < \psi < 90°$ is more affected by the previous half cycle of oscillation.

The results of the flow visualization study are discussed in the order of increasing values of A/D. For the range of Grashof numbers studied, the influence of the Grashof number on the flow patterns was small and will not be discussed here.

Small A/D ($\frac{1}{8}$ *and* $\frac{1}{4}$)

For A/D of $\frac{1}{8}$ and $\frac{1}{4}$, the values of Re_A studied were limited due to the type of vibrational equipment used. Measurements at the critical vibrational level, below which the influence of vibration on the average heat-transfer rate is negligible, reported in [1, 9, 10] were unattainable. Although only small increases in the Nusselt number above the free convective values were obtained as can be seen in Table 1, the flow visualization study revealed changes in the flow from

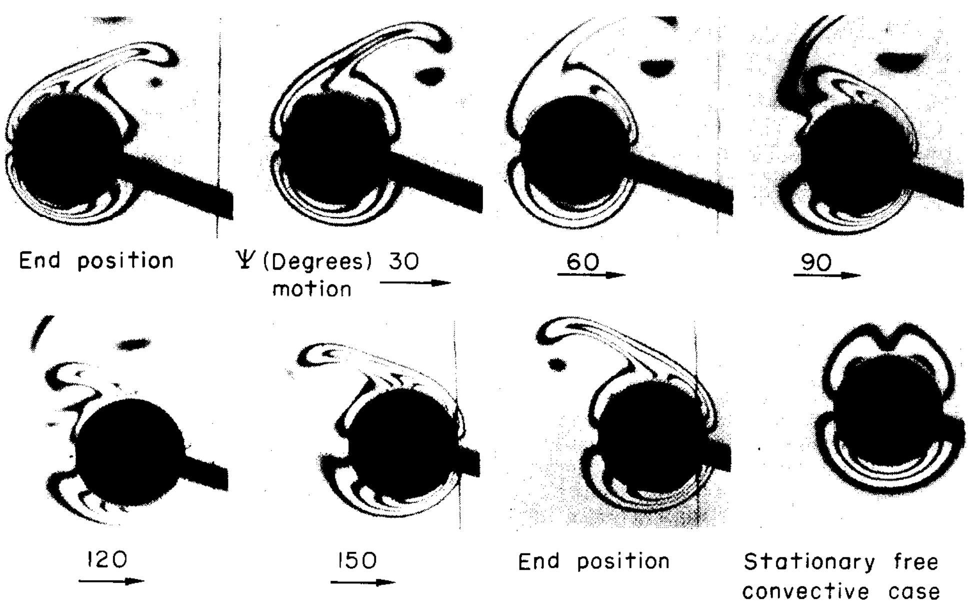

FIG. 1. Vertical infinite fringe interferograms for $A/D = \frac{1}{2}$, $Re_A \cong 150$ and $Gr \cong 4{\cdot}5 \times 10^4$.

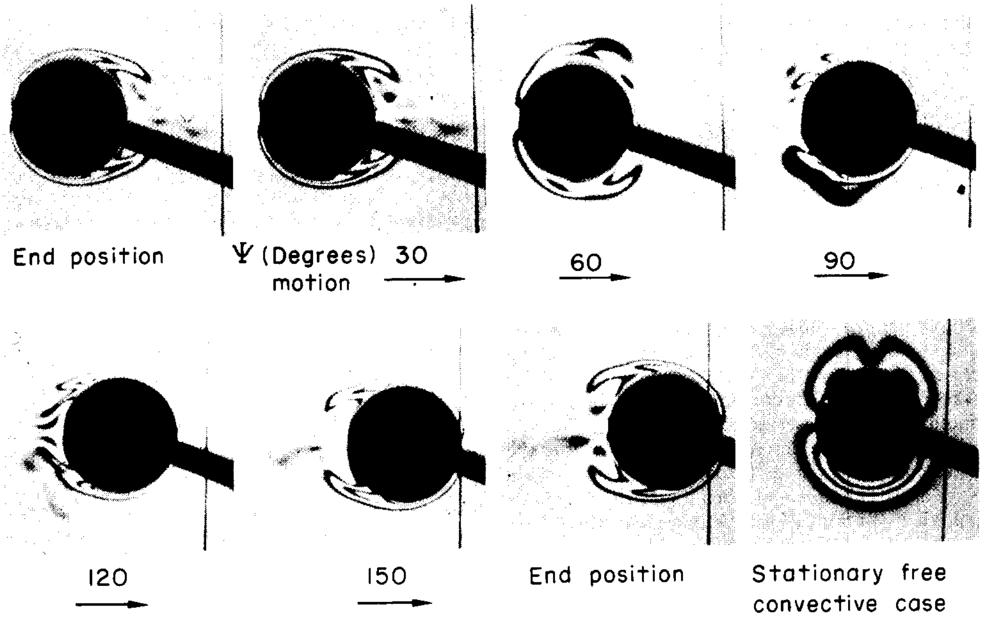

FIG. 2. Vertical fringe interferograms for $A/D = \frac{1}{2}$, $Re_A \cong 600$ and $Gr \cong 4{\cdot}5 \times 10^4$.

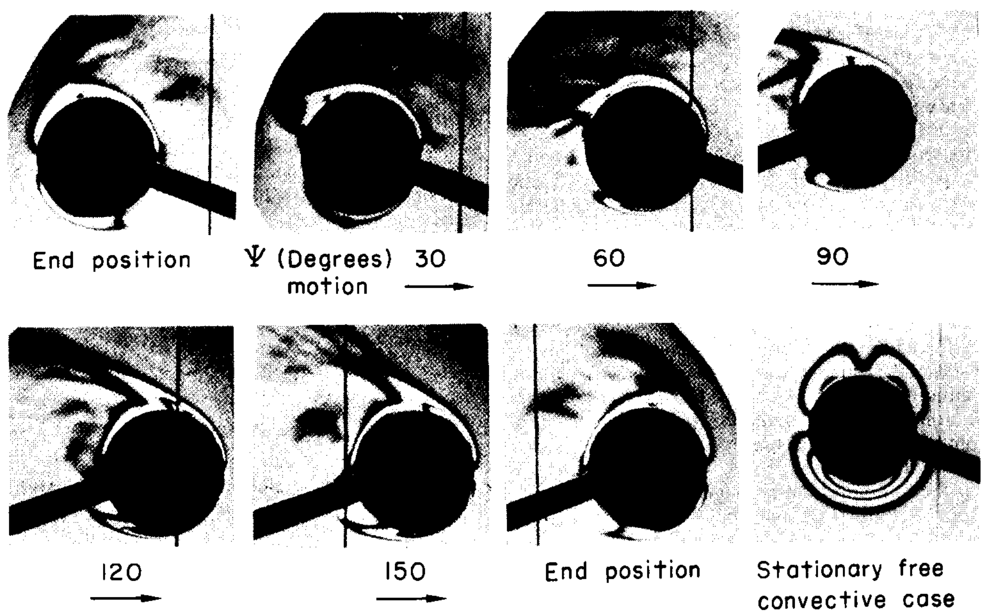

FIG. 3. Vertical infinite fringe interferograms for $A/D = \frac{7}{4}$, $Re_A \cong 600$ and $Gr \cong 4{\cdot}5 \times 10^4$.

that of free convection. Vertical flow resembling a free convective plume was present but swayed as the cylinder oscillated. A vortex appeared to be shed from the upper quadrant of the cylinder on the trailing side, and the side on which the shedding occurred alternated with the direction of motion of the cylinder. The boundary layer on the bottom half of the cylinder thinned locally near the leading side and thickened on the trailing side, but the flow was not drastically altered from that for free convection. Although the heat transfer on the leading edge increased, the heat transfer on the trailing edge decreased which results in only minor increases in the average heat-transfer rate above the free convective values. Richardson [2] concluded that the changes in the flow pattern from free convection are progressive and that the critical vibration intensity necessary to produce significant increases in the heat-transfer rate is not a sudden phenomenon, and therefore, has no intrinsic fluid-mechanical significance. Others [1, 9, 10] have claimed that the vortex flow begins to form only when the vibrational intensity has reached a critical value. The flow visualization study appears to substantiate Richardson's conclusion.

Intermediate values of A/D ($\frac{3}{8}$ *and* $\frac{1}{2}$)

For intermediate values of A/D ($\frac{3}{8}$ and $\frac{1}{2}$) and for $Re_A = 150$, the flow patterns that were observed can be described with the aid of Fig. 1 which contains interferograms for the case where $A/D = \frac{1}{2}$ and $Re_A = 150$. The frequency of oscillation is two hertz. When the cylinder is positioned at the extreme left, the flow on the left side of the cylinder has forced flow characteristics. However, the right side and top of the cylinder show the influence of combined free and forced flow. Vortex motion can be observed in the flow field on the upper right side of the cylinder. As the cylinder moves to the right, the heated air resembling a free convective plume sways over the top of the cylinder, and when it reaches the middle of the upper left quadrant of the cylinder, it is sheared off and left behind the cylinder. The flow field separates near the middle of the upper quadrant of the left side of the cylinder and begins to trail the cylinder, and vortex-type flow is present in the outermost regions of the flow field. As the cylinder decelerates, the circulation on the trailing side becomes less evident. These changes in the flow pattern from the free convective flow pattern are reflected in Table 1 which shows that the heat-transfer rate increased by as much as 33 per cent for $A/D = \frac{1}{2}$ and $Re_A = 150$.

When Re_A is increased to 300, the flow pattern has characteristics resembling those at $Re_A = 150$, but the forced convective and oscillatory characteristics are more dominant, and the free convective characteristics are less pronounced. When Re_A is increased to about 600, the free convective characteristics disappear. This can be seen in Fig. 2 which contains interferograms for the case where $A/D = \frac{1}{2}$ and $Re_A = 600$, which corresponds to a frequency of oscillation of eight hertz. The flow appears to be completely dominated by oscillatory forces, and free convective effects are small since the flow patterns for the upper and lower halves of the cylinder are nearly symmetrical.

When the cylinder is in the extreme left position, the flow resembles forced flow with boundary-layer separations on the right side of the cylinder near the center of the upper and lower quadrants. However, due to the high deceleration that occurs near the end point of oscillation, the separated regions have begun to overtake the cylinder. As the cylinder accelerates to the right, the separated flow is forced over the top and under the bottom of the cylinder, and vortices appear to roll over the top and bottom of the cylinder. The boundary layer on the right side resembles a forced convective boundary layer. The complete change in types of flow patterns from a free convective flow pattern to a forced flow pattern combined with the oscillatory phenomenon of boundary layer shedding resulted in an increase in the heat-transfer rate by as much as 170 per cent at $A/D = \frac{1}{2}$ and $Re_A = 600$.

Large values of A/D (1 *and* $\frac{7}{4}$)

For larger values of A/D (1 and $\frac{7}{4}$) and $Re_A = 150$, the flow patterns were similar to those for intermediate values of A/D, but the free convective effects were more dominant and the effect of previous oscillations was much smaller due to lower frequency of oscillation at the higher A/D. The resulting increase in the heat-transfer rate due to vibration was as much as 38 per cent for $A/D = \frac{7}{4}$ and $Re_A = 150$.

When Re_A was increased for larger A/D, the force convective characteristics were more dominant, but the free convective characteristics were still present even at $Re_A = 600$. For example, at $A/D = \frac{7}{4}$ and $Re_A = 600$, which correspond to a frequency of oscillation of 2·3 Hz, free convective characteristics can be seen (see Fig. 3). For $90° < \psi < 180°$, regions of separated flow trail the cylinder slanted upward revealing the free convective influences on the flow, and the flow above the cylinder appeared to be turbulent. The large effect of the forced-type flow on the free convective flow pattern resulted in a very large increases in the heat-transfer rate. Increases up to 200 per cent for $A/D = \frac{7}{4}$ and $Re_A = 600$ were measured.

CONCLUSIONS

Several basic conclusions were drawn from the flow visualization study. The heat-transfer mechanism at low A/D ($\frac{1}{8}$ and $\frac{1}{4}$) was primarily free convection with vortex motion in the upper quadrant superimposed on the free convection. Although the critical vibrational intensity was unattainable at low values of A/D and the increases in heat transfer above the free convective values were small, the flow visualization indicated that changes in the flow pattern from free convection are progressive, and the critical vibrational intensity does not have any intrinsic fluid-mechanical significance.

For intermediate values of A/D ($\frac{3}{8}$ and $\frac{1}{2}$), the heat-transfer mechanism at low Re_A appeared to be a combination of free convection, forced convection, and the oscillatory phenomenon of boundary-layer shedding both at the bottom and top of the cylinder each time the cylinder changes direction. For the same values of A/D but at higher values of Re_A (600) and corresponding higher frequencies of oscillation, the heat-transfer mechanism is dominated by the oscillatory phenomenon, and the free convective characteristics have disappeared.

For larger values of A/D (1·0 and $\frac{7}{4}$), the heat-transfer mechanism is a combination of free convection, forced convection, and the oscillatory phenomenon of boundary-layer shedding. For large values of Re_A (600), free convective characteristics were less pronounced but were still present.

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Int. J. Heat Mass Transfer. Vol. 18, p. 587. Pergamon Press 1975. Printed in Great Britain

BOOK REVIEW

W. A. Gray and R. Müller, **Engineering Calculations on Radiative Heat Transfer**, 161 pp. Pergamon Press, Oxford. Hard cover $15.50, Flexicover $7.50.

The book deals with radiative heat transfer, beginning with the basic theory and then extending to its prediction and measurement.

The text is written in a clear and concise style. It has many illustrative examples which makes it easy to digest and therefore is an excellent, yet inexpensive introduction for degree students. However, the engineer will find the text inadequate assistance for most industrial problems.

The reader is first taken through the basic principles of emissivity, absorptivity and black body radiation. Worked examples enable a feeling for these properties to be obtained. Following this introductory section the problems of direct exchange, total exchange and exchange with an emitting and/or absorbing media is dealt with in an orderly way. Many texts have dealt with this subject in a confusing manner. The authors' use of many simple examples enables the struggling swimmer the necessary life rafts. However, in these chapters the authors have perhaps allowed their preference for radiosity and mean beam lengths to become too prevalent at the expense of exchange areas.

In dealing with radiation from particles attempts are made to give simple methods of handling this complex problem. While the line of approach is good for engineering purposes the authors are a little inconsistent in their treatment and do not use illustrative examples to such a good effect as in the previous sections.

After the basic theory of radiation exchange has been explained, the authors introduce the reader to how their newly gained knowledge could be applied to a range of general furnace situations, their treatments of heating time and temperature distribution being particularly neat. However, a general treatment similar to Hottel's well stirred furnace model, plus its use to assess the effect of process variables would have been a useful addition to this chapter.

The book ends by including a useful chapter on the measurement of radiation and temperature. The reader is introduced to a range of available techniques; however, he is left slightly at a loss as to when and why to use a particular instrument. Additionally, measuring techniques such as the enthalpy probes, suction radiometer and the venturi pneumatic pyrometer could have been usefully described in this section.

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