Int. J. Heat Mass Transfer. Vol. 24, pp. 491–496
Pergamon Press Ltd. 1981. Printed in Great Britain

0017-9310/81/0301-0491 $02.00/0

THE EFFECT OF VERTICAL VIBRATIONS ON NATURAL CONVECTION HEAT TRANSFER FROM A HORIZONTAL CYLINDER

A. S. DAWOOD, B. L. MANOCHA and S. M. J. ALI

Mechanical Engineering Department, College of Engineering,
University of Mosul, Mosul, Iraq

(*Received* 25 *April* 1980)

Abstract — Experiments were carried out to determine the increase in heat transfer rates as a result of mechanical vertical vibrations applied to horizontal cylinders. Two cylinders, one of 0.85 cm and other of 1.27 cm external diameter heated from inside by electrical resistance heaters were vibrated in still air. The ranges of amplitude, a, frequency, f, and the surface–air temperature difference, ΔT, for the first cylinder were 0–1.715 cm, 0–63.7 c/s and 18–150°C respectively. The corresponding values for the second cylinder were 0–1.78 cm, 0–68 c/s and 22–90°C. It was observed that for amplitude to diameter ratios exceeding 0.5, the relative vibrational heat-transfer coefficient increased almost linearly with the former irrespective of the frequency of vibration. Simple correlations based on experimental observations have been given to predict the vibrational heat-transfer coefficient from the known values of ΔT, a and f.

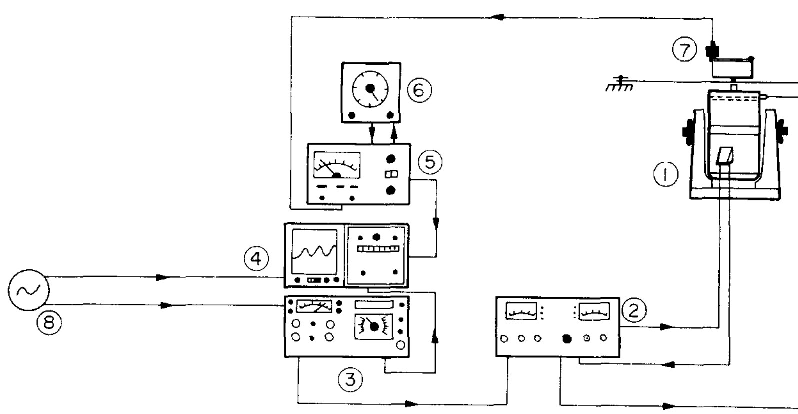
NOMENCLATURE

- a, sinusoidal displacement amplitude of vibration [m];
- f, frequency of vibration [s^{-1}];
- D, outside diameter of cylinder [m];
- h_0, coefficient of heat transfer in the absence of vibration [$W/m^2 K$];
- h_v, coefficient of heat transfer in the presence of vibration [$W/m^2 K$];
- af, intensity of vibration (product of amplitude and frequency of vibration) [m/s].

INTRODUCTION

SEVERAL investigations [1–10] have been undertaken in the past to determine the increase in heat transfer rates resulting from vibrations applied to cylinders. Both mechanical and sound vibrations have been used. The cylinders used in the past investigations have tended to be either very small in diameter [3, 4] or very large [5] in relation to the amplitude of vibrations used, thus giving either very large or very small values of amplitude to diameter ratios. Horizontal and vertical vibration have both been employed on horizontal cylinders. No comprehensive mathematical theory has so far been advanced to explain the observed facts. Experimental observations have been limited, and in some cases, at considerable variance, with one another [3–6].

The present work was undertaken with a view to studying experimentally the effect of such mechanical vertical vibrations on horizontal cylinders as yield



(1) The exciter (2) Power amplifier (3) Sine random generator (4) Oscilloscope
(5) Vibration meter (6) The filter (7) The accelerometer (8) The main supply

FIG. 1. Experimental set-up.

amplitude to cylinder diameter ratios of the order of magnitude of unity. The surrounding medium for these vibrations was air.

EXPERIMENTAL ARRANGEMENT

The test rig for the experimental work is shown in Fig. 1. It was essentially a vibrating strip bolted to a rigid supporting frame and excited by an electrodynamic exciter (B & K). The heated cylinder fixed at both ends was carried on brackets mounted on the vibrating strip and receiving vibrations through it. The strip received vibrations by the impact of a rigid pin welded to a square plate mounted on the exciter head. An accelerometer was used to pick up vibration signal from the cylinder and transmit the same to a vibration meter which could measure amplitude, velocity or acceleration. The frequency of the vibration could be read from a scale on the sine random generator. An oscilloscope suitably connected was used for visual observation of the vibration signals.

The heating of the cylinder was done by a resistance element fixed inside it. The surface of the cylinder was polished to reduce radiation. Six copper–constantan thermocouples were soldered to the cylinder surface for surface temperature measurement. The cylinder was isolated from the surrounding objects by enclosing it in a transparent canopy of plastic sheets vented to the atmosphere. The ends of the cylinder were insulated using cork stoppers which also acted as end supports for the heating element. Any windows near the experimental set-up were closed to avoid draught.

EXPERIMENTAL PROCEDURE

The operating procedure was divided into two parts: (a) natural convection condition without vibration; (b) convection with vibration.

In the first part, a random electrical input was given to the heater inside the cylinder. The cylinder surface was allowed to reach steady state condition. When two consecutive readings of a thermocouple were the same, the output was recorded. The thermocouple outputs were not found to be the same because of their different locations on the cylinder surface. An average value of the thermocouple outputs was assumed to represent the average temperature difference between the cylinder surface and the ambient.

In the second part, the electrical heater was given an arbitrary input. The amplifier was first set to power-on position and about 10 s later to power-load position, thus starting the vibration of the cylinder. The generator frequency was adjusted to the desired level. The output from the accelerometer, which was mounted on the bracket carrying the cylinder, was fed to the vibration meter on which amplitude, velocity or acceleration could be read. After the steady state was reached, the temperature difference, frequency, peak-to-peak values of amplitude, voltage, current electrical power and the ambient temperature were recorded. The experimental ranges are summarized in Table 1.

Probable maximum error in the determination of

Table 1

	Model 1	Model 2
Outside diameter	0.85 cm	1.27 cm
Frequency, f	0–63.7 c/s	0–68 c/s
Amplitude, a	0–1.715 cm	0–1.78 cm
Temp. difference, ΔT	18–150°C	22–90°C

heat-transfer coefficient as a result of errors in the measurement of temperature difference and metered electrical power input was calculated as 4%. The surface emissivity for the cylinders was determined in a separate standard experimental set-up. The average value of surface emissivity was 0.089 which was used to infer the radiation loss. The net power dissipated in an experiment was found by subtracting the estimated conduction and radiation losses from the gross electrical power input. Both these losses depend upon the average cylinder surface temperature which is maximum when it is not subject to vibration. The maximum combined loss is about 10% and decreases rapidly with the decrease in surface temperature caused by vibration.

RESULTS AND DISCUSSION

For the purpose of analysis, the raw data was divided into 3 main categories: data on horizontal, internally heated cylinders without vibration; that with vibration of such cylinders at low intensities ($af \leq 0.15$ m/s) and that with vibration at higher intensities ($af \geq 0.2$ m/s). The heat-transfer coefficient in the first category generally depends on $Gr \times Pr$. However, for the case of air as the surrounding fluid, the value of h_0 is given by McAdam's equation (12):

$$h_0 = 1.32\left(\frac{\Delta T}{D}\right)^{1/4} \qquad (1)$$

where h_0 is in W/m^2 K, ΔT is the average temperature difference between cylinder surface and the surrounding air in Kelvins and D is the cylinder diameter in meters.

Regression analysis on the present data gave the equation

$$h_0 = 0.57\left(\frac{\Delta T}{D}\right)^{0.34} \qquad (2)$$

Calculation of h_0 for a few values of $(\Delta T/D)$ using equations (1) and (2) shows that in the temperature range of the present experiments the two calculations are within 10% of each other. This established that the procedure adopted for the calculation of heat losses was quite satisfactory.

Major variables which influence heat transfer during vibration of the cylinder are the amplitude and frequency of vibration apart from the temperature difference ΔT. It has been pointed out [5] that the product, af, acts as the sole vibrational variable. Also, it has been inferred in the past that the relative increase

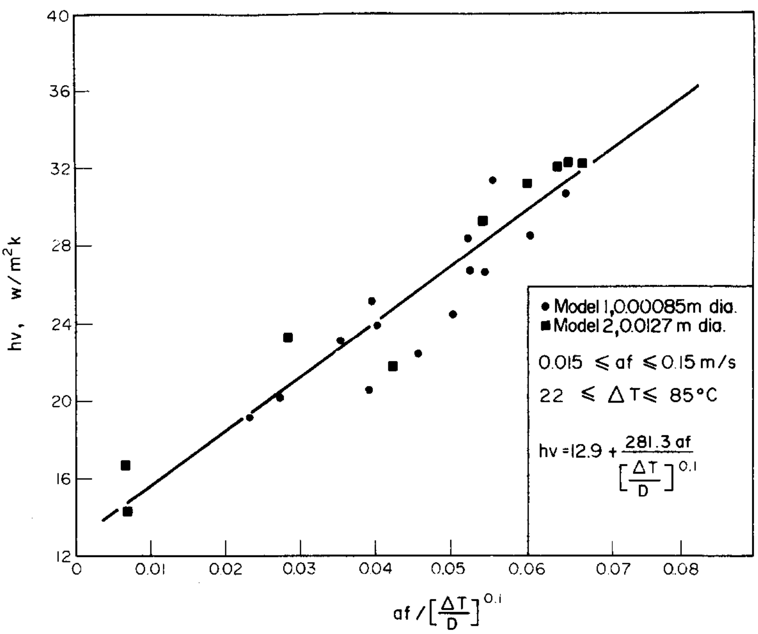


FIG. 2.

of vibrational heat-transfer coefficient over that without vibration i.e. hv/h_0 depends upon the relative values of vibrational Reynolds number and Grashof number [4]. With these ideas as the initial guides, the experimental values of h_v were plotted against the group $af/(\Delta T/D)^{0.1}$ where the best exponent of $(\Delta T/D)$ was established by multilinear regression analysis. This plot is shown in Fig. 2. Further calculations establish the following equation to the best fitting straight line:

$$h_v = 12.9 + \frac{281.3\,af}{(\Delta T/D)^{0.1}}. \tag{3}$$

The range of applicability of this equation is indicated by the following:

$$0.015 \leq af \leq 0.15\,\text{m/s}$$

$$22 \leq \Delta T \leq 85^\circ\text{C}.$$

It may be seen from this figure that the maximum deviation of any experimental point from equation (3)

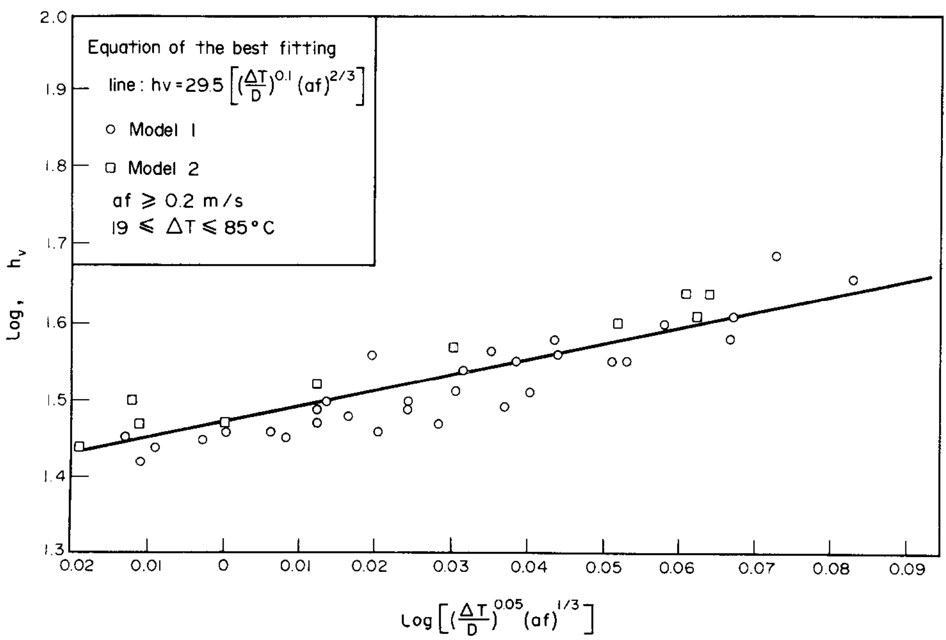


FIG. 3.

Table 2

ΔT (°C)	af (m/s)	0.4	0.5	0.6
60		(38.1) (31.9)	(44.2) (39.9)	(50) (47.8)
70		(38.7) (32.9)	(44.9) (41.1)	(50.8) (49.3)
80		(39.2) (33.8)	(45.5) (42.2)	(51.5) (50.7)

is less than 15%. A few interesting features of this plot are: a rapid increase in heat-transfer coefficient starting with as small a value of af as 0.015 m/s. This observation is at variance with Fand and Kaye's [5] wherein no substantial increase in h_v was observed till vibrational intensity increased to about 0.1 m/s. This observed difference is probably as a result of much higher values of relative amplitude, a/D, in the present data. If the straight line is extended to zero value of the parameter $af/(\Delta T/D)^{0.1}$, it gives a value of heat-transfer coefficient which is equal to that of the non-vibrating horizontal cylinder at $\Delta T = 85$°C (the maximum temperature difference for this set of experiments).

Figure 3 represents the graph between $\log h_v$ and $\log(\Delta T/D)^{0.05}\,(af)^{1/3}$. The exponents were again established using multilinear regression on the data in the range of vibrational intensities, $af \geq 0.2$ m/s. The graph is a straight line with the equation:

$$h_v = 29.5\left(\frac{\Delta T}{D}\right)^{0.1}(af)^{2/3}. \tag{4}$$

The maximum deviation of any single data point from equation (4) was found to be less than 15%.

For the purpose of comparison, Fand and Kaye's [5] equation

$$h_v = 14\left(\frac{\Delta T}{D}\right)^{0.2} af \tag{5}$$

with the restrictions

$$\Delta T \geq 55\,°\text{C}$$

$$af \geq 0.275\ \text{m/s}$$

was taken. Table 2 gives a few representative values obtained from equations (4) and (5) for a horizontal cylinder of 1 cm dia.:

Each first bracketed value in this table represents h_v in W/m^2 K calculated from equation (4) and second value is h_v calculated by the use of equation (5). Thus the difference in the two values becomes less and less as the intensity and/or the temperature difference becomes more. It appears that important vibrational variable is the product of a and f only at higher intensities whereas at lower intensities, amplitude and frequency act independently. The contribution to heat transfer is more significant by amplitude than by frequency in this range.

The present data is insufficient in the range $0.15 < af < 0.2$ m/s. However, a sharp decrease in the h_v values seems to take place in this range of intensities.

Considering that an important parameter in determining the increase in heat-transfer coefficient of a

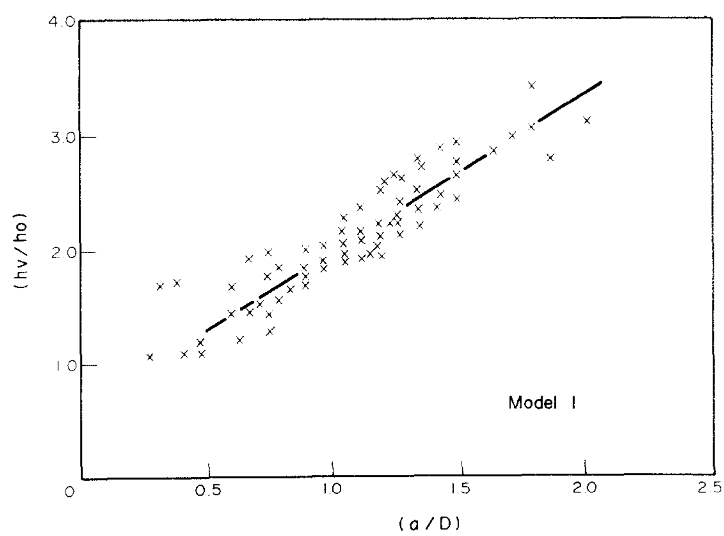


FIG. 4.

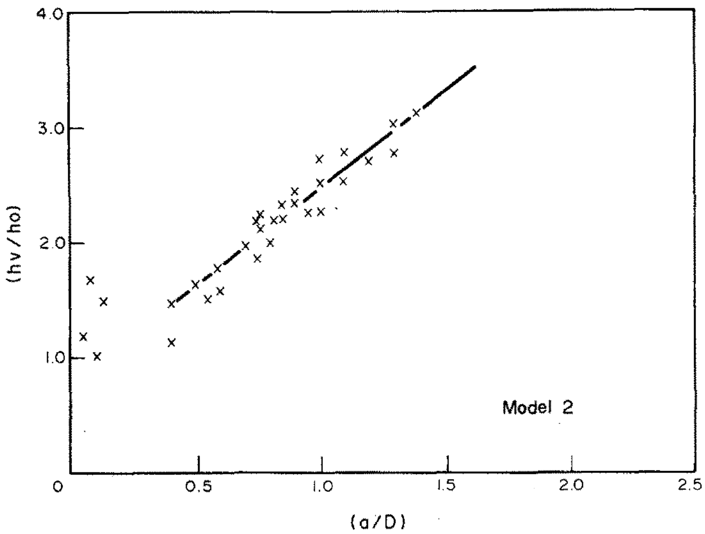


FIG. 5.

vibrating horizontal cylinder over that of a non-vibrating one is the ratio a/D and the order of magnitude of a/D is unity in the present experimental data as distinct from such order of magnitude in Lemlich's work [3], or Lemlich and Anandha Rao's work [4], where $a/D \gg 1$ or Fand and Kaye's work [5] where $a/D \ll 1$, it was considered proper to plot variation of h_v/h_0 against a/D. This variation is shown in Figs. 4 and 5 for models 1 and 2 respectively. It is clear that for $a/D > 0.5$, the experimental points cluster around straight lines. The slopes of the two straight lines representing the best fit, are somewhat different for the two models, being less for model 1 than for model 2. For the range of parameters in the present experiments,

$$\frac{h_v}{h_0} = 1.36\left(\frac{a}{D}\right) + 0.63 \tag{6}$$

$$\frac{a}{D} > 0.5 \qquad \text{Model 1}$$

and

$$\frac{h_v}{h_0} = 1.67\left(\frac{a}{D}\right) + 0.79 \tag{7}$$

$$\frac{a}{D} > 0.5. \qquad \text{Model 2}$$

Equations (6) and (7) give a deviation of 20% or more. However, they do stress the importance of amplitude of vibration in increasing heat-transfer coefficient.

CONCLUSIONS

1. Vertical mechanical vibrations of heated cylinders in air can increase the heat-transfer coefficient to more than 3 times the value of the heat-transfer coefficient from the cylinders without vibration.

2. For values of a/D exceeding 0.5, h_v/h_0 increases almost linearly with a/D irrespective of the frequency, ΔT etc.

3. If a/D values are sufficiently large (> 0.25), the increase in heat-transfer coefficient takes place almost as soon as vibrations start and it is not necessary to increase the vibrational intensity beyond a critical value (5) to realise a significant increase in heat-transfer rates.

4. Correlations represented by equations (3) and (4) can be used to predict heat-transfer coefficient during vibration of cylinders to within 15% of their experimental values if amplitudes of vibration are of the same order of magnitude as the cylinder diameter.

Acknowledgement — The authors are grateful to the authorities of the University of Mosul for providing the necessary facilities for experimental work included herein.

REFERENCES

1. R. C. Martinelli and L. M. K. Boelter, The effect of vibration on heat transfer by free convection from a horizontal cylinder, in *Proceedings of the Fifth Congress of Applied Mechanics*, pp. 578–5784 (1938).
2. F. K. Deaver, W. R. Penny and T. B. Jefferson, Heat transfer from an oscillating horizontal wire to water, *J. Heat Transfer* **84C**, 251–256 (1962).
3. R. Lemlich, Effect of vibration on natural convective heat transfer, *Ind. Engng Chem.* **47**, 1175–1180 (1955).
4. R. Lemlich and M. A. Rao, The effect of transverse vibration on free convection from a horizontal cylinder, *Int. J. Heat Mass Transfer* **8**, 27–33 (1965).
5. R. M. Fand and J. Kaye, The influence of vertical vibrations on heat transfer by free convection from a horizontal cylinder, *Int. Dev. Heat Transfer*, pp. 490–498. A.S.M.E., New York (1961).
6. W. W. Carr and W. Z. Black, Interferometric measurement of instantaneous local heat transfer from a horizontally vibrating isothermal cylinder, *Int. J. Heat Mass Transfer* **17**, 633–642 (1974).
7. B. F. Armaly and D. H. Madsen, Heat transfer from an oscillating horizontal wire, *J. Heat Transfer* **93C**, 239–240 (1971).

8. R. M. Fand, Mechanism of interaction between vibrations and heat transfer, *J. Acoust. Soc.* **A34**(12), (1962).
9. R. S. Dougall, T. Chiang and R. M. Fand, A study of the differential equation of coupled vibrations and free convection from a heated horizontal cylinder, Aeronautical Research Laboratory Office of Aerospace Research, U.S.A.F., Part I, p. 31.
10. P. D. Richardson, Effects of sound and vibration on heat transfer, *Appl. Mech. Rev.* **20**(3), 201–217 (1967).
11. A. M. Dawood, The effect of vertical vibrations on natural convection heat transfer from a horizontal cylinder, A Thesis submitted to the University of Mosul for M.Sc. Mech. Engng (1979).
12. J. R. Welty, *Engineering Heat Transfer*. John Wiley, New York (1978).

EFFET DES VIBRATIONS VERTICALES SUR LA CONVECTION THERMIQUE NATURELLE AUTOUR D'UN CYLINDRE HORIZONTAL

Résumé — On détermine expérimentalement l'accroissement de transfert thermique par vibration verticale d'un cylindre horizontal. Deux cylindres, l'un de 0,85 cm de diamètre extérieur et l'autre de 1,25 cm, chauffés électriquement par résistance interne, sont mis en vibration dans l'air calme. Les domaines d'amplitude a, de fréquence f et de différence de température surface — air ΔT, sont pour le premier cylindre respectivement 0–1,715 cm, 0–63,7 cm et 18–150°C. Les valeurs correspondantes pour le second cylindre sont 0–1,78 cm et 22–90°C. On observe que pour un rapport amplitude/diamètre supérieur à 0,05, le coefficient relatif de transfert thermique croît presque linéairement avec lui indépendamment de la fréquence de vibration.

Des formules simples basées sur l'expérience sont données pour prévoir le coefficient de transfert à partir des valeurs de ΔT, a et f.

DER EINFLUSS VERTIKALER SCHWINGUNGEN AUF DEN WÄRMEÜBERGANG BEI FREIER KONVEKTION AN EINEM WAAGERECHTEN ZYLINDER

Zusammenfassung—Es wurden Untersuchungen durchgeführt, um die Zunahme des Wärmeübergangs infolge mechanischer senkrechter Schwingungen zu bestimmen, zu denen ein horizontaler Zylinder angeregt wurde. Zwei Zylinder, einer mit 0,85 cm, der andere mit 1,27 cm Außendurchmesser, die im Innern mit einer elektrischen Widerstandsheizung beheizt sind, wurden in ruhender Luft in Schwingung versetzt. Die Bereiche der Amplitude a, der Frequenz f und der Oberflächentemperaturdifferenz ΔT betrugen beim ersten Zylinder 0 ÷ 1,715 cm, 0 ÷ 63,7 Hz und 18 ÷ 150°C, beim zweiten Zylinder 0 ÷ 1,78 cm, 0 ÷ 68 Hz und 22 ÷ 90°C. Es wurde beobachtet, daß bei Verhältnissen von Amplitude zu Durchmesser von über 0,5 der relative schwingungsbedingte Wärmeübergangskoeffizient unabhängig von der Frequenz praktisch linear mit diesem Verhältnis zunahm. Einfache Beziehungen, die auf experimentellen Beobachtungen beruhen, werden für die Bestimmung des Wärmeübergangskoeffizienten bei Vibration aus bekannten Werten von ΔT, a und f angegeben.

ВЛИЯНИЕ ВЕРТИКАЛЬНЫХ ВИБРАЦИЙ НА ТЕПЛОПЕРЕНОС ПРИ СВОБОДНОЙ КОНВЕКЦИИ ОТ ГОРИЗОНТАЛЬНОГО ЦИЛИНДРА

Аннотация — Проведено экспериментальное исследование интенсификации теплообмена за счет механических вертикальных вибраций горизонтальных цилиндров. Два цилиндра с наружными диаметрами 0,85 и 1,27 см, нагреваемые изнутри электрическим током, подвергались вибрации в спокойной среде воздуха. Амплитуда a и частота колебаний f первого цилиндра, а также разность между температурами поверхности цилиндра и воздуха ΔT изменялись в следующих диапазонах: 0–1,715 см, 0–63,7 Гц и 18–150°C, соответственно. Для второго цилиндра указанные величины изменялись в диапазонах 0–1,78 см, 0–68 Гц и 22–90°C. Показано, что при отношениях амплитуды к диаметру, превышающих 0,5, соответствующий коэффициент вибрационного теплопереноса возрастал почти линейно независимо от частоты колебаний. На основании экспериментальных наблюдений получены простые соотношения для расчета коэффициента вибрационного теплопереноса по известным значениям ΔT, a и f.