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HEAT TRANSFER BY FREE CONVECTION FROM A LONGITUDINALLY VIBRATING VERTICAL PLATE

K. KRISHNA PRASAD and V. RAMANATHAN*

Department of Mechanical Engineering, Indian Institute of Science, Bangalore-12, India

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Abstract—The effect of longitudinal harmonic oscillations on free convective heat transfer from an electrically heated vertical plate is considered. Experiments have been performed for frequencies ranging from 10 to 20 cps at an amplitude of 0·25 in. at plate temperatures varying from 100 to 200°F. The temperature profiles in the boundary layer have been measured by a Mach–Zehnder interferometer. The results have been presented in terms of the local values of Nusselt number, Nu_x, Grashof number, Gr_x and vibrational Reynolds number, $V_{Re,x}$. Vibrations in the range of variables considered here increase steady heat transfer rates. The extent of this increase is determined by the relative strength of the oscillation parameter $V_{Re,x}$ compared to that of Gr_x. A maximum increase in heat-transfer rate of 33 per cent has been recorded. A plot of $4Nu_x/V_{Re,x}^{\frac{1}{2}}$ against $Gr_x^{\frac{1}{2}}/V_{Re,x}$ reveals that the results of the present investigation lie in the steady combined forced and free convection regime and are in adequate agreement with the approximate analysis due to Acrivos.

NOMENCLATURE

T, absolute temperature [°R];
x, distance along the plate measured from the leading edge;
y, distance normal to the plate measured from the plate;
Gr_x, local Grashof number $= g\beta(\Delta T)_w x^3/\nu^2$;
g, acceleration due to gravity;
β, coefficient of volumetric expansion at constant pressure;
$(\Delta T)_w$, temperature difference between the wall and the ambient;
ν, kinematic viscosity;
Nu_x, local Nusselt number $= hx/k$;
h, local heat-transfer coefficient;
k, thermal conductivity of air;
$V_{Re,x}$, vibrational Reynolds number $= a\omega x/\nu$;
a, amplitude of the vibration;
ω, angular frequency of vibration;
Pr, Prandtl number $= \mu c_p/k$;
μ, dynamic viscosity;
c_p, specific heat at constant pressure.

1. INTRODUCTION

IN RECENT years the possibilities of using oscillations to increase convective heat transfer have received much attention. Oscillations can be produced either by the motion of the heated surface or by the injection of acoustic vibrations into the fluid by some external agency. Both these methods have the same objective of

* Present Address: Graduate Student, Dept. of Mechanics, New York State University at Stony Brook, New York.

creating an oscillating relative velocity vector between a heated surface and a fluid medium.

The effect of oscillations upon convective heat transfer has been investigated for flat plates, cylinders and wires; for varied orientation of the vibration vector relative to these surfaces; for different ranges of vibration parameters—the amplitude and frequency; and for different surface heating conditions. The results of these investigations vary from large increases to none or even decreases in heat-transfer rate. Further, no analytical results are yet available for predicting all the experimentally observed effects.

A considerable body of literature has grown up relating to the general problem of the interaction between vibrations and convective heat transfer. A comprehensive outline of the literature available on this subject is given by Richardson [1]. This survey points out that only very few results have been reported on free convection from vertical surfaces subjected to either transverse or longitudinal vibrations.

The only work reported for the case of heat transfer by free convection from a vertical plate oscillating in its own plane is that of Eshgy *et al.* [2]. Their analysis by a perturbation method—limited to small oscillations—showed a decrease in laminar heat-transfer rate as a result of vibrations. This prediction is in agreement with the experimental results at small amplitudes of vibrations. Further it has been suggested that the increased heat transfer observed at higher amplitudes is due to a possible change in the flow pattern. An approximate analysis of the experimental results in [2] shows that $V_{Re,x}$, the local vibrational Reynolds number, must be greater than $\frac{1}{4}Gr_x^{\frac{1}{4}}$, the local Grashof number, for the plate oscillations to increase the heat transfer.

The brief discussion presented above reveals the lack of a generalized treatment of the problem of free convective heat transfer coupled with longitudinal oscillations. In order to explain the discrepancy between theory and experiment, an investigation was undertaken to obtain information concerning the physical mechanisms involved in coupled longitudinal oscillations and heat-transfer phenomena. This paper presents some results obtained by an interferometric study of heat transfer by free convection from a heated vertical plate executing harmonic oscillations in its own plane.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The experiment is designed to produce a two-dimensional boundary layer on a vertical, finite, flat plate executing longitudinal harmonic oscillations in its own plane and in a direction parallel to the external force field.

The test plate in all its basic features is similar to the one employed in [3]. The construction of the plate is shown in Fig. 1. It is a 6 in. square plate 0·375 in. thick with a 5 in. square heated area. The test section is of a sandwich type construction providing one undisturbed surface for heat-transfer study. Thermocouples at various points behind the test surface and close to it as well as on its edges have been provided to check the isothermality of the surface. The test section is mounted in a cage which is bolted to a 12 in. dia. mild steel disc. A variac to adjust the power input to the heater, a voltage stabilizer to assure constant supply voltage and a watt-meter for monitoring the power input are included in the circuit.

A reaction type vibration machine is used to vibrate the test section. This system essentially consists of two rotating shafts each carrying an equal unbalanced mass. The reaction of the force, generated by the rotation of the unbalanced masses on the table causes the table to vibrate. As the equal unbalanced masses are rotating in opposite directions, the generated body force from each may be made to cancel in one direction and add in the direction normal to the table, generating a rectilinear sinusoidal force in the preferred direction. The details of design, construction and characteristics of operation of the machine are available elsewhere [4]. It is sufficient to state here that the machine operates satisfactorily in the range of 10–20 cps

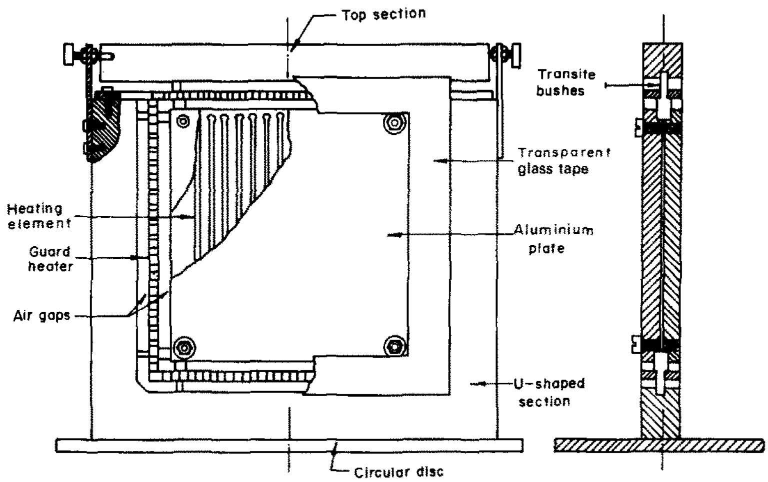

FIG. 1. Construction of test plate.

and a peak-to-peak amplitude of 0·25 in. The machine carries a 10 in. long screwrod on top of which is located the test section, thus facilitating the adjustment of the height of the test section. Figure 2 shows details of test section and the vibration machine assembly.

Frequency is measured by a tachometer recording the speed of the motor driving the machine. The vibration amplitude and average velocity are measured by a pick-up type 4-103 and a vibration meter type 1-110 B of Consolidated Engineering Corporation, Los Angeles, USA. The displacement wave form is recorded on a Brush pen type recorder, type B1-202. The pick-up and the meter are calibrated by sighting a stroboscope illuminated sharp edge mounted on the test plate through a travelling microscope.

A Mach–Zehnder interferometer is employed for measuring the temperature profile in the boundary layer. The interferometer was fabricated in the laboratory for the present investigation [5]. The field of view available for study is approximately an ellipse of 2·75 in. major axis and 1·6 in. minor axis. Since the test section height is adjustable any portion of the test section can be investigated. A 35 mm Exakta camera with Kodak 250 ASA film was used for recording the interferograms.

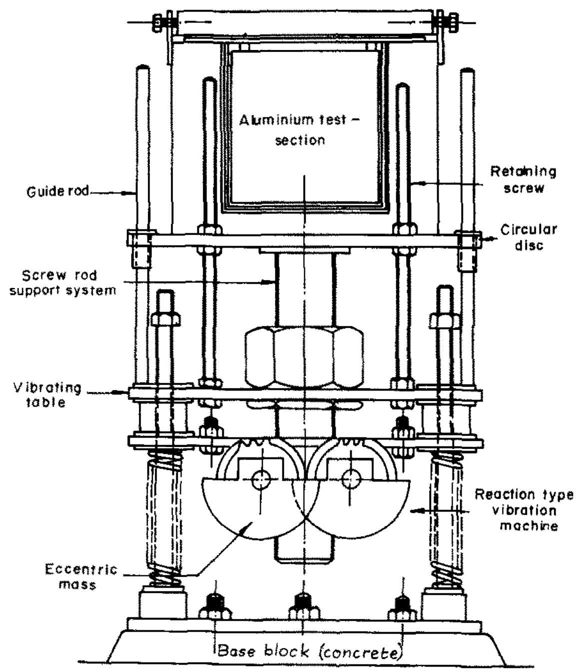

FIG. 2. Details of test section and vibration machine assembly.

The interferometer is adjusted to produce horizontal fringes. The following procedure is followed during the course of investigation. A specified voltage and current are supplied to the test section by adjusting the variacs. A period of usually four hours is required to establish steady state under non-oscillating conditions. The uniformity of surface temperature is determined by recording the thermocouple outputs. The variation among them for all the heat loads considered in the present investigation is less than 0·5 per cent. It may be pointed out here, that these results were obtained without the use of the guard heater. A photograph is taken of the steady state fringe pattern. In addition the ambient temperature and the wattmeter reading are also recorded.

Next the test section is vibrated at the desired frequency and amplitude by adjusting the frequency of the vibration machine. Steady state under oscillating conditions is obtained in a period of about $1\frac{1}{2}$ h. The uniformity of vibration of the test plate is checked periodically by noting the speed of the motor and the vibration meter reading for amplitude. For all the frequencies considered in this investigation, the waveforms were found to be sinusoidal. Again the interferogram, the room temperature and the wattmeter reading are obtained.

The above experiment is performed for six different frequencies ranging from 10 cps to 20 cps for each heat input. The set of experiments is repeated for six different heat inputs corresponding to six plate temperatures.

For qualitative studies the interferometer is adjusted for zero fringe field. The fringes thus obtained represent isotherms and hence can be employed for observing qualitatively any changes in flow pattern that may occur with oscillations. The procedure for this purpose consisted in oscillating the plate at different frequencies for all the heat loads considered. Photographs of the fringe pattern are taken for each case.

The usual precautions necessary for obtaining consistent results in free convection studies are taken.

3. RESULTS AND DISCUSSION

The interferograms are evaluated for temperature distribution in the boundary layer. The fringe shift is directly measured from the 35 mm negative with the aid of a profile projector. The wall heat flux is estimated by calculating the temperature gradient at the wall from the measured temperature distribution with a fifth order numerical differentiation formula. An interval of 0·004 in. proved to be satisfactory for use in the differentiation formula.

Since the interferometer was being used for the first time after construction, a few preliminary tests on natural convection from the plate described earlier were carried out for temperatures varying from 110°F to 275°F. The temperature profiles as obtained from the present work are compared with the analytical results of Ostrach [6] and experimental results of Schmidt and Beckmann [7]. These are shown plotted in Fig. 3 in terms of Ostrach's variables, namely,

$$\theta = \left(\frac{T - T_\infty}{T_w - T_\infty}\right) \text{ and } \quad \eta = \left(\frac{Gr_x}{4}\right)^{\frac{1}{4}} \frac{y}{x}$$

for two different values of x and several plate temperatures. Barring the values at large values of η, the present results are in excellent agreement with those of Ostrach and those of Schmidt and Beckmann. The somewhat large deviation of the results at high values of η (incidentally, these are also present in the results of Schmidt and Beckmann) is probably due to convection currents in the room which are difficult to avoid. For heat-transfer results, the region of interest is close to the wall and the deviation of the present results in this region from Ostrach's prediction is less than 4 per cent. It is expected that the results under oscillatory conditions are of the same order of accuracy.

All the heat-transfer results of the present investigation have been presented in terms of the non-dimensional parameters Nusselt, Grashof and the vibrational Reynolds numbers. All the values are local values evaluated at a dis-

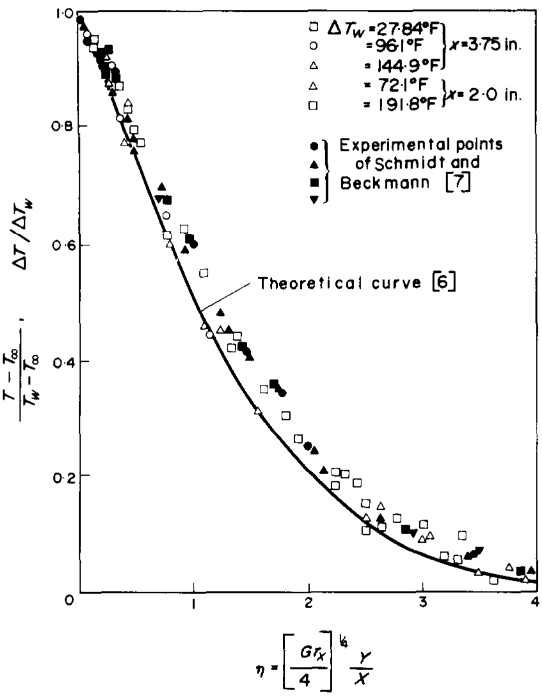

FIG. 3. The free convection temperature profile.

tance of 3·5 in. from the leading edge. All fluid properties have been evaluated at the undisturbed condition, that is the room temperature. The Reynolds numbers, obtained in the investigation, ranged from 1000 to 2000 and Grashof numbers varied from 6×10^5 to 5×10^6. Results of a total of 36 runs (for a combination of six plate temperatures and six frequencies) with a set of six runs without oscillation for purposes of comparison are presented. The results pertain only to steady effects produced on free convection by purely periodic disturbances. No efforts were made to obtain the transient effects or steady periodic variation of heat transfer.

Temperature profiles

Dimensionless temperature profiles are plotted in Fig. 4 in terms of Ostrach variables for two extreme Grashof numbers and several vibrational Reynolds numbers. Unless otherwise stated the Grashof numbers have been calculated on the basis of plate temperature under stationary conditions, but with the same heat load. In both cases temperature profiles for the stationary plate are drawn to observe the changes caused by oscillations in the temperature field.

In these figures temperature profiles under oscillating conditions shift downwards from

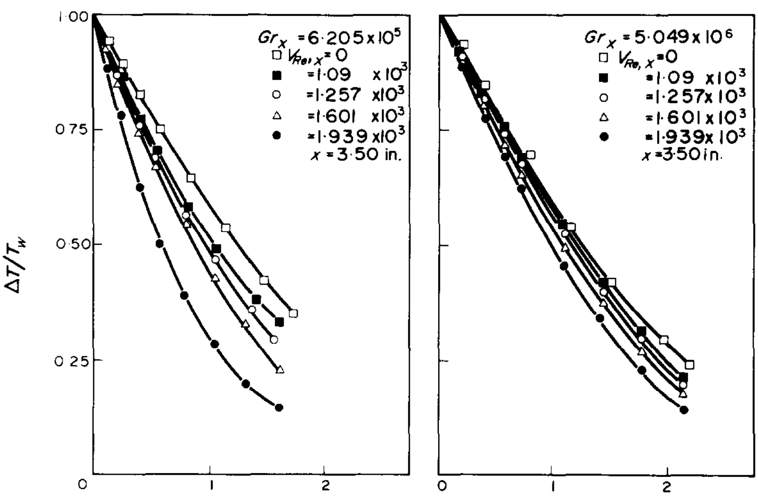

FIG. 4. Effect of $V_{Re,x}$ on temperature profiles at $Gr_x = 6{\cdot}205 \times 10^5$ and $Gr_x = 5{\cdot}049 \times 10^6$.

those of the stationary case with a consequent increase in the wall temperature gradients. The shift increases as the vibrational Reynolds number increases. A comparison of the two figures shows that the effect of oscillations is more pronounced in the case of a lower Grashof number. In other words, the profiles imply that the influence of oscillations on the temperature field is determined by the relative strength of inertia forces and buoyancy forces with respect to viscous forces.

It may also be pointed out that temperature profiles plotted at various heights of the plate in terms of the Ostrach variables showed that these are not the relevant similarity variables for the problem under consideration.

Heat-transfer results

We next turn to the heat-transfer results. The results are presented in terms of local Nusselt numbers. Following the method of Eshgy *et al.*, the percentage change in Nu_x with vibration, given by

$$\frac{(Nu_x)_v - Nu_x)_0}{(Nu_x)_0} . 100$$

are plotted against af in Fig. 5 for all the six values of Gr_x investigated. $(Nu_x)_v$ represents the local Nusselt number of the oscillating plate while $(Nu_x)_0$ that of the stationary plate. This curve and the succeeding straight line curves are fitted by the method of least squares. An inspection of Fig. 5 shows that vibration causes a significant increase in Nu_x and hence steady rate of heat transfer. The maximum percentage increase varies from 9 per cent for Gr_x of $5{\cdot}049 \times 10^6$ to 33 per cent for Gr_x of $6{\cdot}025 \times 10^5$. Thus the influence of oscillations diminishes as Gr_x increases. At higher values of Gr_x free convection effects dominate over the oscillation effects. The opposite situation prevails at low values of Gr_x.

This argument is further substantiated by referring to Fig. 6, which is a free convection correlation of the results with $V_{Re,x}$ as a parameter. The plot shows that as Gr_x increases the effects of oscillation are considerably reduced and all the curves tend to merge with the pure free convection curve. Incidentally, this figure also provides a comparison of the present free convection results with the theoretical result [8].

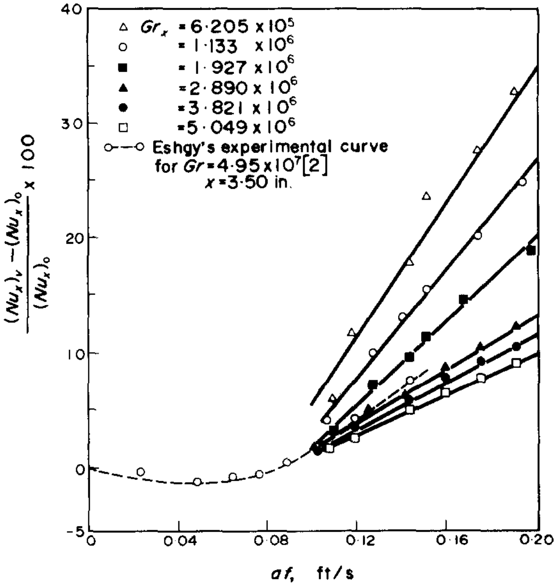

FIG. 5. Present results compared with those of [2].

It is appropriate here to compare the present results with the work of Eshgy *et al.* [2]. The small oscillation theory of [2] is not applicable since for the amplitude and frequencies considered in the present investigation, the perturbation parameter takes on values greater than unity. However, the few experimental results reported there have been replotted in Fig. 5 in terms of the variables adopted in the present investigation. It is seen from the figure that the present work lies in the range where the earlier work showed increased heat-transfer rates. There is an apparent discrepancy among these results. For the value of $GrPr$ of $3{\cdot}56 \times 10^7$ (the one investigated in [2]) the curve should have been lower than those of present set. But instead it lies somewhere in between. This

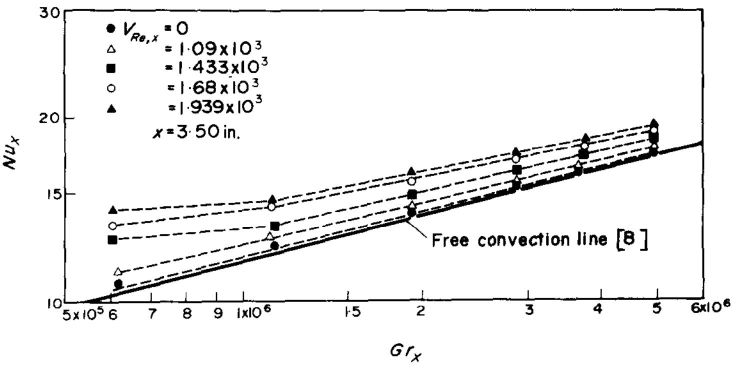

FIG. 6. Free convection correlations.

discrepancy may be partially explained by the fact that the present work reports local heat-transfer coefficients while Eshgy *et al.* reported average heat-transfer coefficients. Further study is necessary to explain this behaviour satisfactorily.

From the foregoing it is evident that the oscillations introduce a new flow pattern. The nature of these changes are demonstrated by a typical set of zero-fringe interferograms illustrated in Fig. 7. These interferograms are taken for all $V_{Re,x}$ investigated at the lowest Grashof number considered in the present work. In other words they represent the situation where the oscillations have the most pronounced influence on heat transfer. A comparison of these interferograms with that reproduced from Eckert and Drake [9] indicates that the oscillations do not cause transition from laminar to turbulent flow in the boundary layer. Thus the increased heat transfer cannot be attributed to this reason as has been suggested by Blankenship and Clark [3] for the case of transverse vibrations. It may be pertinent here to point out other facts that tend to support the above conclusion. In the data presented in Figs. 5 and 6, there are no systematic departures from a definite trend to indicate transition. From the point of view of free convective conditions alone, the Grashof number range is well below the transition Grashof numbers from 10^8 to 10^{10} as reported by Eckert and Jackson [8]. Blankenship and Clark [3] present a chart—obtained by smoke studies on a vertical plate executing transverse vibrations—indicating a relationship between $GrPr$ and $V_{Re}^2/(Gr_L^a)$ for transition from laminar region to turbulent region. For the present Grashof number range, turbulent region exists for values of $V_{Re}^2/(Gr_L^a)$ greater than 70. The values of $V_{Re}^2/(Gr_L^a)$ in the present investigation are less than 17 and as such well below the above number. Though the result of Blankenship and Clark is not strictly applicable for the present investigation, it is believed that the result gives a qualitative confirmation of the fact that the present investigation is in the laminar regime. Lastly, one of the interferograms in Fig. 7 shows a situation in which the plate was vibrating nonuniformly with a component in the transverse direction. The interferogram shows a wavy motion at the edge of the boundary layer. In the interference patterns observed on the screen of the interferometer under these conditions, it was noticed that these waves propagated along the height of the plate without amplification, thus indicating that the boundary layer was essentially stable in this investigation.

Thus it seems probable that the oscillations introduce a pure forced convection effect on the heat-transfer process. With this in view a forced convection correlation is attempted to predict the phenomenon. The pure forced convection result is [8]

$$Nu_x = 0{\cdot}332\, Re_x^{\frac{1}{2}}\, Pr^{\frac{1}{3}}. \tag{1}$$

In the present case Re_x is replaced by $V_{Re,x}$ and a plot along these lines with Gr_x as a parameter is shown in Fig. 8. This plot shows that for higher Gr_x values, Nu_x is virtually independent of $V_{Re,x}$. However for low Gr_x values, the curves tend to merge with the curve representing equation (1). It has already been pointed out that in this region free convection effects are not completely masked by the oscillations. From the above discussion, it follows that both free and forced convection effects influence the steady heat transfer rate.

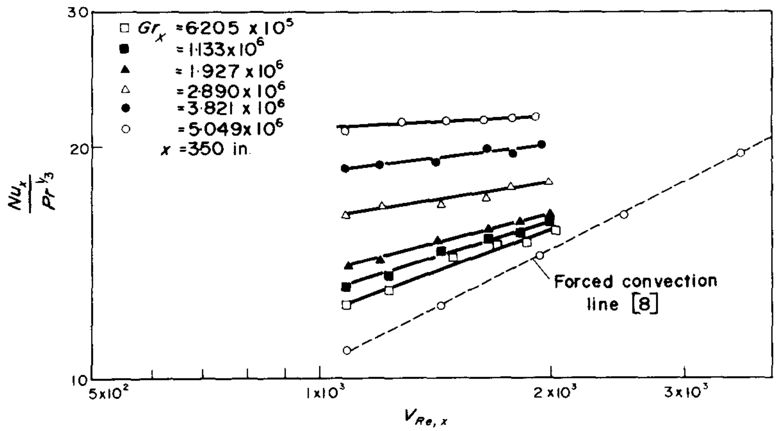

FIG. 8. Forced convection correlations.

The above observations suggest that a mixed free and forced convection might be more successful in describing the present experimental results. Dimensional analysis of the governing equations shows that such data can be presented as

$$Nu_x = Nu_x\left(\frac{Gr_x}{Re_x^2}\right)$$

for a given Prandtl number. The exact functional relationship is not known as the problem of mixed forced and free convection has not been solved for the geometry of a vertical flat plate. However, two approximate solutions by Sparrow and Gregg [10] and Acrivos [11] are available. The solution of Sparrow and Gregg constructed by a perturbation method is valid for values of $Gr_x^{\frac{1}{2}}/Re_x$ less than 0·27. This theory is not applicable for the present results as all of them lie in the region $Gr_x^{\frac{1}{2}}/Re_x$ greater than 0·35. However, the solution of Acrivos obtained by the integral method is valid for the entire range of $Gr_x^{\frac{1}{2}}/Re_x$. The results obtained by numerical integration of two non-linear ordinary differential equations have been presented graphically as

$$\frac{Nu_x}{Re_x^{\frac{1}{2}}}\left(\frac{Re_x^2}{Gr_x}\right)^{\frac{1}{4}} \text{ vs. } \frac{Gr_x}{Re_x^2}.$$

This has been shown plotted in Fig. 9 in terms of Sparrow's variables for a Prandtl number of 0·73 [10]. Acrivos examined the accuracy of the integral method by comparing the asymptotic values of his solution in the forced and free convection limits with the exact solutions for these limits. These have also been plotted in the figure and it is seen that the Acrivos asymptotic values are about 4 per cent lower than the

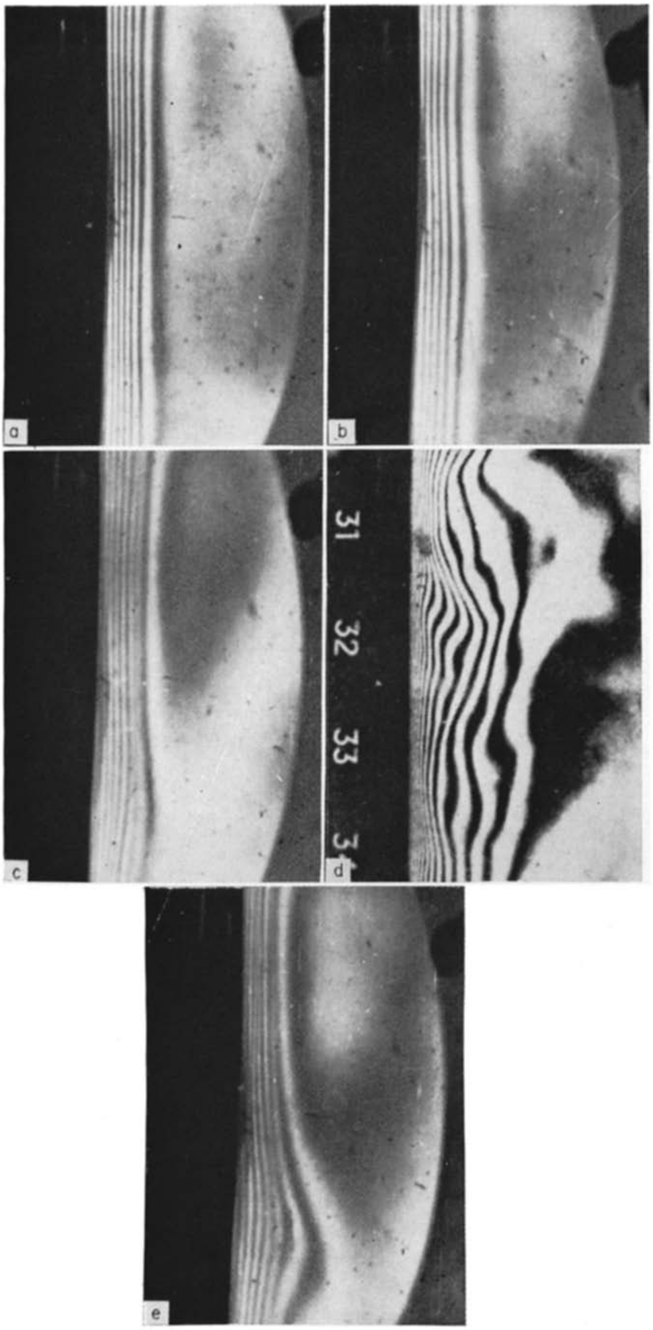

FIG. 7. Zero-fringe interferograms of the boundary layer under oscillating plate conditions

(a) Stationary plate
(b) $f = 10$
(c) $f = 20$
(d) Turbulent free convection [9]
(e) With transverse vibrations.

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exact ones. The experimental results obtained in the present investigation with Re_x replaced by $V_{Re,x}$ have been plotted in this figure. In contrast with the earlier figures, the Grashof numbers used in this plot correspond to the measured plate temperatures under oscillating conditions. For convenience of reference, the stationary plate Grashof numbers have also been listed in the figure. It is seen that the experimental results are higher than the Acrivos result, the differences being largest (up to 16 per cent) for

$$\frac{Gr_x^{\frac{1}{2}}}{Re_x} > 1{\cdot}2 \text{ and minimum for } \frac{Gr_x^{\frac{1}{2}}}{Re_x} < 0{\cdot}45$$

(as low as 1·5 per cent).

A proper interpretation of the foregoing plot is possible if we consider some of the features of analysis and experiment. It is first to be noted that the results of a combined forced and free convection analysis asymptotically tend to pure forced convection result as $Gr_x \to 0$ and a pure free convection result as $Gr_x \to \infty$. For quantitative identification of these limits in a practical situation, a suitable criterion can be adopted to distinguish three regions in a convection study. As suggested by Sparrow [12], whenever the combined convection analysis result is within 5 per cent of the asymptotic solution, the latter can be used with adequate accuracy. According to this the Acrivos result has been divided into a forced convection region, a combined convection region $(0{\cdot}3 < (Gr_x^{\frac{1}{2}}/Re_x) < 1{\cdot}35)$ and a free convection region, as shown in Fig. 9. It is noticed that most of the present experimental data lie in the combined convection region. However, the Acrivos result can be expected to be lower than an exact solution by about 4 per cent (as can be gathered by this asymptotic form) and the present experimental results are likely to be higher by about 5 per cent than the exact result (as can be seen by the free convection result on a stationary plate shown in Fig. 6). On the basis of these, it can be stated that the steady heat-transfer rate, by free convection from a vertical oscillating plate may be predicted adequately by the solution of the combined convection problem provided $Gr_x^{\frac{1}{2}}/V_{Re,x}$ is in the range indicated in the figure. Further, the

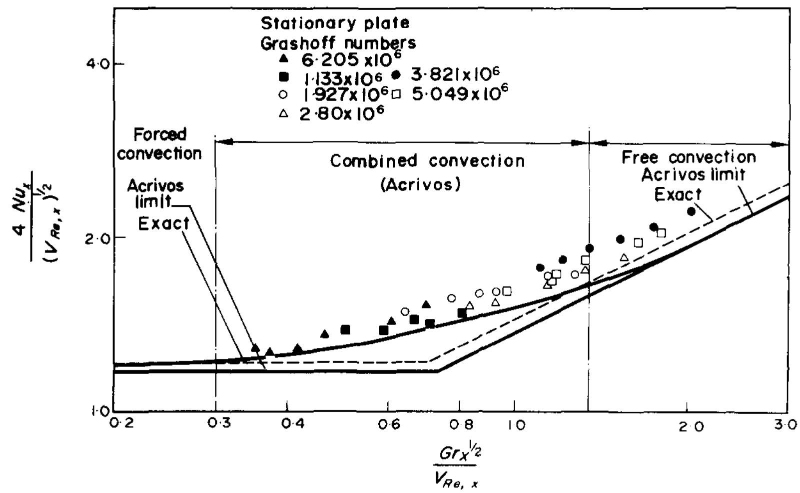

FIG. 9. Combined convection correlations.

Acrivos solution is a good approximation to the problem.

It is interesting to note that the range for combined convection for a wedge [12] shifts to the right of that shown in Fig. 9 ($0.57 < (Gr_x^{\frac{1}{2}}/Re_x) < 4$). This is partly due to the fact that the forced convection solution for a wedge is about 25 per cent higher than the flat plate solution. This suggests that the range of an exact solution for the vertical flat plate might be somewhat to the right of that indicated earlier. This implies that the points just outside the right line in Fig. 9 will also lie in the combined convection region. However the present experiments show enough evidence to state that as one moves closer to the free convection limit, the combined convection correlation becomes poorer. It can be expected that for $(Gr_x^{\frac{1}{2}}/V_{Re,x}) > 4$ or so, the oscillations will continue to increase steady heat transfer rates subject to the proviso that vibrational Reynolds number is sufficiently high.

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TRANSFERT THERMIQUE PAR CONVECTION NATURELLE À PARTIR D'UNE PLAQUE VERTICALE VIBRANT LONGITUDINALEMENT

Résumé—On considère l'effet d'oscillations harmoniques longitudinales sur le transfert thermique à convection naturelle à partir d'une plaque verticale chauffée électriquement. On a conduit des expériences pour des fréquences variant de 10 à 20 Hertz, à une amplitude de 6,35 mm et à des températures de paroi variant de 37,3 à 93,5°C. Les profils de température dans la couche limite ont été mesurés par un interféromètre de Mach–Zehnder. Les résultats ont été représentés à l'aide des valeurs locales du nombre de Nusselt, Nu_x, du nombre de Grashof, Gr_x, et du nombre de vibration de Reynolds, $V_{Re,x}$. Dans le domaine des variables considérées ici, les vibrations accroissent les flux thermiques permanents. On détermine l'importance de cet accroissement à partir de l'influence relative du paramètre d'oscillation $V_{Re,x}$, comparée à celle de Gr_x. On a enregistré un accroissement maximum de 33 pour cent dans le flux thermique. Une courbe représentant $4Nu_x/V_{Re,x}^{\frac{1}{2}}$ en fonction de $Gr_x^{\frac{1}{2}}/V_{Re,x}$ révèle que les résultats de cette étude concernent le régime de convection mixte permanent et qu'ils sont en bon accord avec l'analyse approchée d'Acrivos.

WÄRMEÜBERTRAGUNG DURCH FREIE KONVEKTION AN EINER LÄNGS SCHWINGENDEN SENKRECHTEN PLATTE

Zusammenfassung—Es wird die Wirkung von harmonischen Längsschwingungen auf den Wärmeübergang durch freie Konvektion von einer elektrisch beheizten senkrechten Platte untersucht. Die Experimente wurden bei Frequenzen von 10 bis 20 Schwingungen pro Sekunde, einer Amplitude von 6,3 mm und Plattentemperaturen zwischen 38 und 93°C durchgeführt. Die Messung der Temperaturprofile erfolgte mit einem Mach-Zehnder-Interferometer. Die Ergebnisse werden als Funktion der lokalen Werte der Nusselt-Zahl Nu_x, der Grashof-Zahl Gr_x und der Reynolds-Zahl für Schwingungen $V_{Re,x}$ dargestellt. Schwingungen im betrachteten, variablen Bereich bewirken hier ein stetiges Anwachsen der übertragenen Wärmemenge. Der Bereich dieses Anstiegs wird bestimmt durch die relative Grösse der Grashof-Zahl Gr_x. Ein maximaler Anstieg von 33% wurde beobachtet. Trägt man $4\,Nu_x/V_{Re,x}^{\frac{1}{2}}$ gegen $Gr_x^{\frac{1}{2}}/V_{Re,x}$ in ein Diagramm ein, zeigt sich, dass die Ergebnisse dieser Untersuchung im Bereich kombinierter, erzwungener und freier Konvektion liegen und dass sie mit der Näherungslösung von Acrivos übereinstimmen.

ТЕПЛООБМЕН ПРИ СВОБОДНОЙ КОНВЕКЦИИ НА ВЕРТИКАЛЬНОЙ ПЛАСТИНЕ ПРИ ПРОДОЛЬНОЙ ВИБРАЦИИ

Аннотация—Рассматривается влияние продольных гармонических колебаний на теплообмен при свободной конвекции на вертикальной пластине, нагреваемой электричеством. Проведены эксперименты для частот от 10 до 20 герц при амплитудах 0,25 дюймов и температурах пластины от 100 до 200°F. Распределения температуры в пограничном слое измерялись с помощью интерферометра Цендара-Ма-ха. Результаты представлены в виде локального числа Нуссельта Nu_x, числа Грасгофа Gr_x и вибрационного числа Рейнольдса $V_{Re,x}$. Вибрации в рассматриваемом диапазоне переменных увеличивают скорость стационарного теплообмена. Степень этого увеличения определяется относительной величиной параметра колебаний $V_{Re,x}$ по сравнению с величиной Gr_x. Максимальное увеличение скорости теплообмена равно 33%. График зависимости $\frac{4Nu_x}{V_{Re,x}^{1/2}}$ от $\frac{Gr_x^{1/2}}{V_{Re,x}}$ показывает, что результаты данного исследования относятся к стационарному режиму смешанной вынужденной и свободной конвекции и находятся в хорошем соответствии с приближенным анализом Акривоса.