Int. J. Heat Mass Transfer. Vol. 13, pp. 117–123. Pergamon Press 1970. Printed in Great Britain

FREE CONVECTION IN AIR BETWEEN A 60° VEE-CORRUGATED PLATE AND A FLAT PLATE

J. C. V. CHINNAPPA
Faculty of Engineering, University of Ceylon, Peradeniya, Ceylon

(*Received* 27 *May* 1969)

Abstract—The heat transfer by free convection from a heated 60° vee-corrugated plate to a cooled flat plate placed above it has been studied, with the cold flat plate and the vees horizontal. Correlations of Nusselt and Grashof numbers have been obtained, and discussed in relation to the correlations obtained by other workers for free convection in air layers bounded by parallel flat surfaces.

NOMENCLATURE

- A, area of plate;
- g, gravitational acceleration;
- H, height of vertical plane fluid layer;
- h, convection heat transfer coefficient;
- k, thermal conductivity;
- L, distance between midpoint of side of vee and cold plate;
- L', distance between tip of vee and cold plate;
- Q, convection heat transfer;
- t, temperature;
- W, width of vertical plane fluid layer;
- x, distance;
- α, thermal diffusivity;
- β, thermal expansion coefficient;
- ν, kinetic viscosity.

Suffixes
- c, cold upper plate;
- g, guard heater;
- h, heated centre vee-plate;
- h_0, heated outer vee-plate;
- l, local.

Dimensionless parameters
- Gr, Grashof number, $\beta g(t_h - t_c)L^3/\nu$;
- Nu, Nusselt number, hl/k;
- Pr Prandtl number, ν/α;
- Ra, Rayleigh number $(Gr)(Pr)$.

INTRODUCTION

SPECTRALLY selective surfaces are presently employed in solar water heaters. Tabor [1] and Hollands [2] have shown that when a spectrally selective surface consists of vee-grooves and reflects specularly then an overall improvement in the solar energy collection characteristic of the plate can be expected. The design of a solar collector using a vee-grooved plate would require a knowledge of the coefficient of free convection heat transfer upwards from the plate through an air gap to the glass cover. Tabor [1] suggests that where the vee length is 1 cm or less then the free convection coefficient is substantially the same as that of a flat plate with the same projected area. With regard to larger vees there is no information available.

In view of this uncertainty an attempt has been made in this study to assess the free convection loss upward from a vee-corrugated plate to a flat plate above it. The angle of the vee was 60°.

Considerable experimental work has been done on free convection transfer across fluid layers bounded by parallel surfaces [3–9]. The results obtained in this investigation are discussed below in relation to this published work.

APPARATUS

The details of this apparatus are shown in Fig. 1.

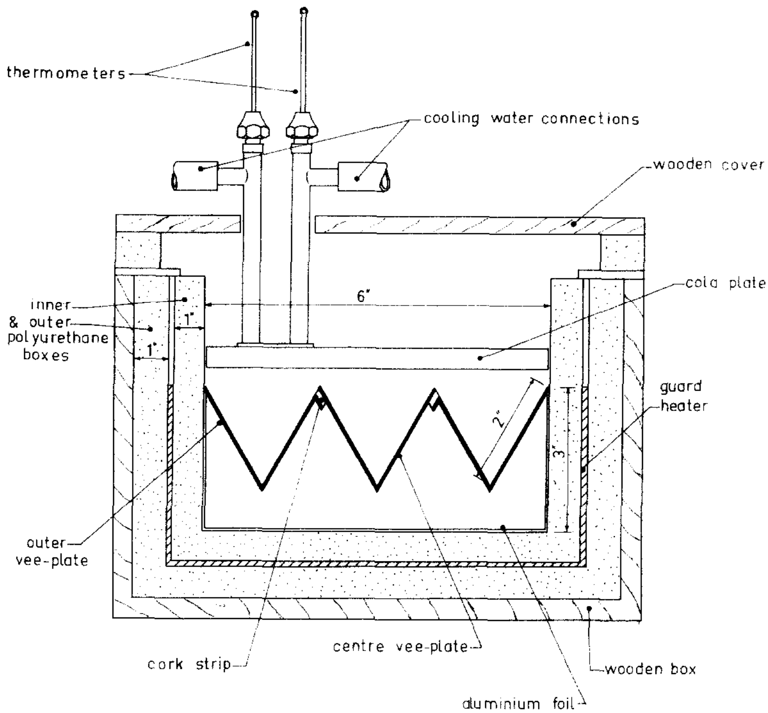

FIG. 1. Diagrammatic section of apparatus.

The heated vee plate was made up in two sections (Fig. 1). The centre plate was surrounded by the outer plate and insulated from it by a cork strip 0·125 in. thick, 0·25 in. wide. The cork strip was attached with adhesive to both the centre and the outer plates. The arrangement ensured that the edge loss by conduction from the centre to the outer plate for a temperature difference of approximately 1·5°F was less than 1 per cent of the measured free convection transfer upwards from the centre plate during a test run, and was therefore negligible.

The vee plates were of copper to which Nichrome ribbon was attached on the underside with adhesive. The top surfaces of the plates were nickel-plated and polished.

The cold plate consisted of a brass plate in which passages for cooling water were machined. The underside of the brass plate was nickel-plated and polished. The cold plate was separated from the vee plate by wooden distance pieces of specified thickness at each end of the outer vee-plate.

More than a hundred copper–constantan thermocouples were installed, including 6 on the cold plate, 21 on the centre plate, 52 on the outer plate, and the others on the inside and outside surfaces of the sides and ends of the inner polyurethane box. All the thermocouple leads (except the cold plate thermocouple leads) together with the heating circuit leads were coiled twice and placed just below and in contact with the copper guard heater before being led to terminals outside the box. Measurements were made on a Leeds and Northrup multichannel recording potentiometer and a Cambridge potentiometer.

The copper guard heater was constructed by soldering Pyrotenax heating wire to the copper plate.

The temperature of the water to the cold plate was thermostatically controlled at 70°F and the flow rate was maintained constant by a constant head device. Power for the heating circuits was supplied through a voltage stabiliser and variacs. The resistances of the heating circuits was measured separately and this enabled the power supplied to be calculated when the current was known.

The whole apparatus was placed in a constant temperature room where the ambient temperature was maintained at 70°F.

EXPERIMENTAL PROCEDURE

The thermal circuit for the box containing the vee plate and the cold plate is given to Fig. 2. The three circuits separately supplying heat to the centre vee-plate, the outer vee-plate and the guard heater respectively were regulated so that $t_h = t_{ho} = t_g$.

This ensured that heat losses from the centre vee plate in all directions other than upwards to the cold plate were negligible.

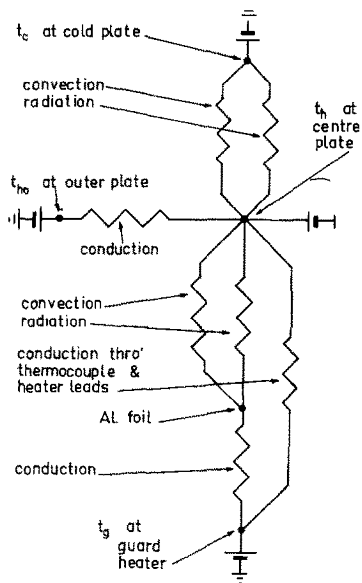

FIG. 2. Thermal circuit for apparatus.

The steady state was judged to have been reached when temperatures at various points in the box were constant for at least an hour. When this state was attained the power supplied to the centre vee-plate gave the total heat transfer by free convection and radiation from that plate to the cold plate above it.

Five series of tests were performed. The details for the first three of these series ie. series A, B and C, were as follows:

Side of vee	2 in.
Outer vee-plate length	16 in.
Outer vee-plate width	6 in.
Centre vee-plate length	8 in.
Centre vee-plate width	2 in.

The details for the remaining series, i.e. series F and H were:

Side of vee	0·75 in.
Outer vee-plate length	16 in.
Outer vee-plate width	3 in.
Centre vee-plate length	8 in.
Centre vee-plate width	1·5 in.

For all the tests the vee-corrugations and the cold (upper) plate were horizontal.

The temperature difference between the hot and cold plates varied from 20 to 110°F in each series of tests.

The other particulars regarding these tests are given in Table 1.

Table 1. Distance between heated vee-corrugated plate and cooled flat plate

Test series	Distance of mid-point of side of vee from cold plate (in.)	Distance of crest of vee from cold plate (in.)	L'/L
A	1·12	0·25	0·22
B	1·62	0·75	0·46
C	2·12	1·25	0·59
F	0·62	0·30	0·47
H	0·76	0·44	0·58

The radiation transfer between the centre vee-plate and the cold plate was calculated using the values of emissivity obtained by Hollands [2] using a method of Eckert and Sparrow. The total heat transfer from the centre vee-plate upwards less the radiation transfer gave the free convection component Q.

Hence the convection coefficient $h = Q/A_h(t_h - t_c)$ where A_h = surface area of the centre vee-plate, $(t_h - t_c)$ = temperature difference between hot and cold plates.

So $Nu = hL/k$
and $Gr = g\beta(t_h - t_c)L^3/\nu$
where L = distance of the cold plate from midpoint of the side of the vee.

The values of conductivity, etc. were taken at the mean of t_h and t_c.

The plot of log Nu vs. log Gr obtained for the series, A, B, C, F and H is shown in Figs. 3 and 4.

DISCUSSION

Descriptions of the manner in which heat transfer takes place across a fluid enclosed between plane surfaces, in which the lower surface is heated, are to be found in the literature [3–5]. While in the main three regimes (conduction when the gap is small, laminar flow free convection and later turbulent flow free convection as the gap increases) can be discerned for these layers whether horizontal, vertical or inclined, differences in flow patterns have been observed. These differences are reflected in the empirical relationships which have been proposed for plane layers at different inclinations.

In general, for free convection heat transfer across these layers dimensional analysis indicates that the Nusselt number is a function of the Rayleigh number together with terms including the height (or length), width and angle of inclination.

It has been customary for workers to obtain separate correlations for different angles of inclination in which case this term does not occur in the correlation.

Where edge effects are significant, as in vertical layers which are not large, the correlation has usually taken the form [5, 9]

$$Nu = C(Ra)^m (H/L)^n$$

where H = height
and L = thickness of the layer.

For large horizontal layers, where edge effects are not significant, the correlation becomes [3, 4, 6, 8]

$$Nu = C(Ra)^m.$$

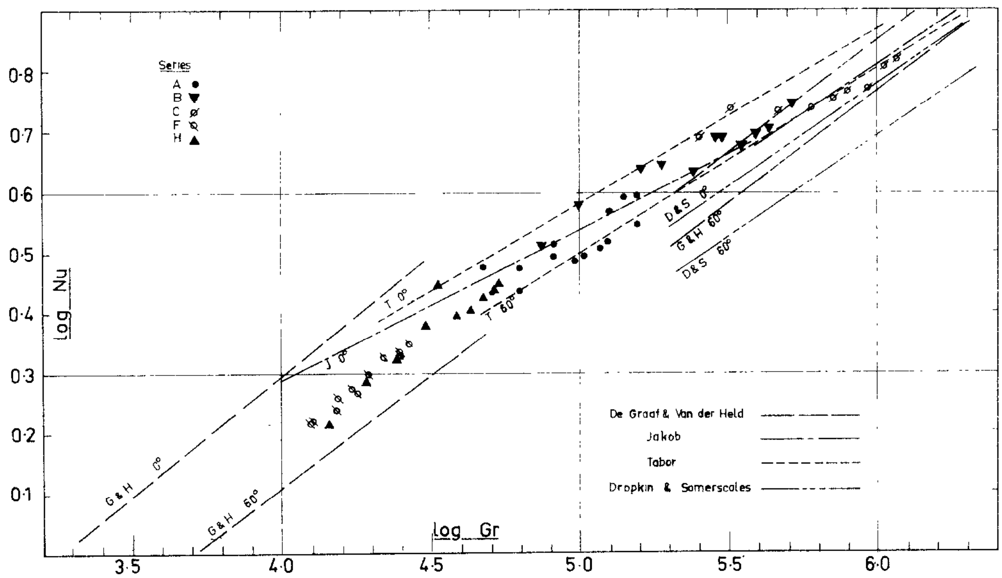

FIG. 3. Plot of results with correlations of other workers.

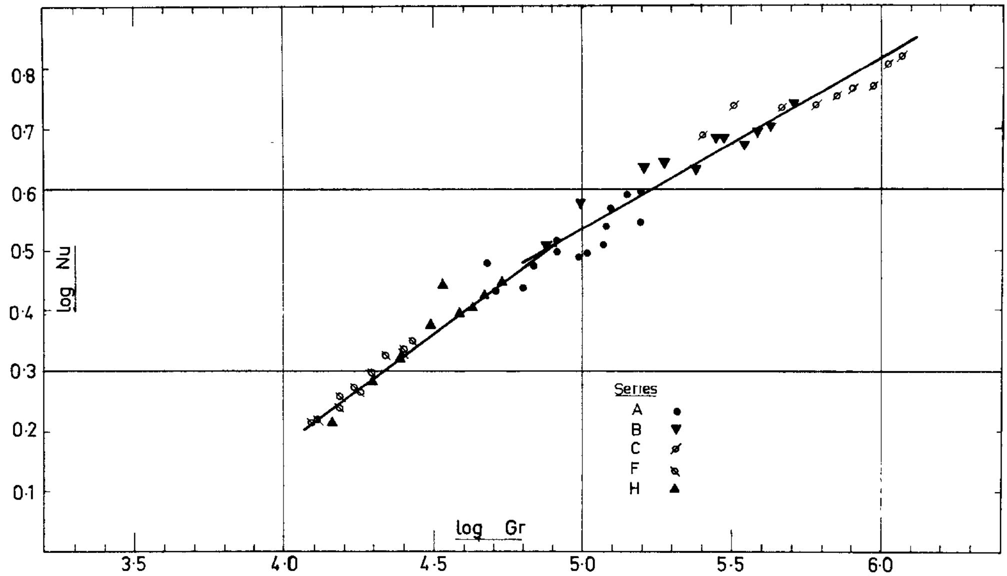

FIG. 4. Plot of results with proposed correlations—equations (1) and (2).

The same form of correlation is employed in the case of inclined layers. Several workers [3, 4, 6–8] have listed correlations for specific inclinations. These correlations for inclinations of 0° and 60° are given in Table 2. Changes both in the constant and the exponent can be noticed as the inclination changes.

The present experiments were devised so that the layer tested (ie. between the centre vee-plate and the cold plate) was in effect, part of a layer very extensive both in length and width. The correlation sought therefore was for heat transfer across an air layer bounded below by a heated extensive 60-vee-corrugated surface and above by a flat surface. Edge effects do not arise but it is possible that a term may be necessary in the correlation to take into account the depth of the vees. Thus for any particular angle of inclina-

Table 2. Correlations for free convection across plane enclosed air layers at 0° and 60° inclination to the horizontal (heat flow upward)

Investigators	Angle of tilt (horizontal = 0°)	Grashof number limits	Correlation
Jakob [3]	0°	$10^4 < Gr < 3{\cdot}7 \times 10^5$	$Nu = 0{\cdot}195\ (Gr)^{1/4}$
		$3{\cdot}7 \times 10^5 < Gr < 10^7$	$Nu = 0{\cdot}068\ (Gr)^{1/3}$
De Graaf and Van der Held [4]	0°	$2 \times 10^3 < Gr < 5 \times 10^4$	$Nu = 0{\cdot}507\ (Gr)^{0.40}$
		$5 \times 10^4 < Gr < 2 \times 10^5$	$Nu = 0{\cdot}38$
		$Gr > 2 \times 10^5$	$Nu = 0{\cdot}0426\ (Gr)^{0.37}$
	60°	$5 \times 10^3 < Gr < 5 \times 10^4$	$Nu = 0{\cdot}0431\ (Gr)^{0.37}$
		$Gr > 2 \times 10^5$	$Nu = 0{\cdot}0354\ (Gr)^{0.37}$
Robinson and Powlitch [7]	0°	$10^4 < Gr < 10^7$	$Nu = 0{\cdot}152\ (Gr)^{0.281}$
(presented by Tabor [6])	60°	$10^4 < Gr < 10^7$	$Nu = 0{\cdot}089\ (Gr)^{0.31}$
Dropkin and Somerscales [8]	0°	$2{\cdot}11 \times 10^5 < Gr < 10{\cdot}55 \times 10^8$	$Nu = 0{\cdot}60\ (Gr)^{1/3}$
	60°	$2{\cdot}11 \times 10^5 < Gr < 3{\cdot}52 \times 10^8$ (assuming = 0·71 for air)	$Nu = 0{\cdot}0495\ (Gr)^{1/3}$

tion to the horizontal the correlation may be stated as

$$Nu = C\,(Gr)^m\,(L'/L)^p$$

Where $(L'/L) = 1$ the lower surface is flat. The values of (L'/L) tested may be observed in Table 1.

Examination of the results plotted on log Nu and log Gr coordinates in Figs. 3 and 4 shows that the data can be represented better by a single correlation than by a family of curves. The effect of (L'/L) is therefore not significant for the range of values of (L'/L) tested in this configuration.

Clearly this result is due to the flow patterns prevailing but further explanation must await visual studies of these flow regimes.

On the basis of the data collected two more conclusions may be drawn. Firstly there is evidence of a change in the flow pattern at values of log Gr of about 4·8. This is in agreement with the results of other workers both for horizontal layers and layers inclined at 60°, and indicates the Grashof number at which laminar flow changes to turbulent flow.

Secondly the points as plotted in Fig. 3 lie between the correlations obtained by de Graaf and Van der Held for the horizontal case and the 60° inclination case for log $Gr < 4{\cdot}8$; and between Tabor's correlations for the horizontal layer and the 60° inclined layer for $Gr > 4{\cdot}8$. Tabor's proposals are based on a comprehensive survey of the work of Jakob, de Graaf and Van der Held, and Robinson and Powlitch. This suggests that in the present configuration the total heat transfer effect is the sum of the effects at the two heat transfer surfaces, one horizontal and the other (the vee-surface) inclined at 60°.

The proposed correlations for the present case are as follows:

$$10^4 < Gr < 8 \times 10^4, \qquad Nu = 0{\cdot}054\,(Gr)^{0{\cdot}36} \tag{1}$$

$$8 \times 10^4 < Gr < 10^6, \qquad Nu = 0{\cdot}139\,(Gr)^{0{\cdot}278}. \tag{2}$$

In view of the greater scatter of the points in the turbulent region equation (2) was obtained by a least-squares method [10] and represents the best fit. The equation itself compares reasonably well with the equations proposed by other workers for plane layers with 0° and 60° tilt.

ACKNOWLEDGEMENTS

This investigation was conducted by the author while on leave from his present post and working at the Commonwealth Scientific Industrial and Research Organisation Mechanical Engineering Division, Highett, Victoria, Australia.

The author is grateful to R. H. Morse, Chief of Division for the facilities provided, and to his co-workers in the Division for advice and assistance particularly R. V. Dunkle (who initiated the project) and K. G. T. Hollands.

A special word of thanks is due to Stanley O. Jones whose contribution to the work far exceeded the skilful construction of the apparatus, and to E. A. Christie for assisting with readings.

REFERENCES

1. H. Tabor, Selective surfaces for solar collectors, in *Low Temperature Engineering Applications of Solar Energy*, Chapter IV. A.S.H.R.A.E., New York (1967).
2. K. G. T. Hollands, Directional selectivity, emittance and absorptance properties of vee corrugated specular surfaces, *Solar Energy* **7**, 108–116 (1963).
3. M. Jakob, Free convection through enclosed plane gas layers, *Trans. Am. Soc. Mech. Engrs* **68**, 189 (1946).
4. J. G. A. de Graaf and E. F. M. Van der Held, The relation between the heat transfer and the convection phenomena in enclosed plane air layers, *Appl. Sci. Res.* **A3**, 393 (1953).
5. E. R. G. Eckert and W. O. Carlson, Natural convection in an air layer enclosed between two vertical plates with different temperatures, *Int. J. Heat Mass Transfer* **2**, 106–120 (1961).
6. H. Tabor, Radiation, convection and conduction coefficients in solar collectors, *Bull. Res. Coun. Israel* **6C** (3), 155–176 (1958).
7. H. E. Robinson and F. J. Powlitch, The thermal insulating value of airspaces, Housing Research Paper No: 32, Housing and Home Finance Agency, Washington, D.C. (1954).
8. D. Dropkin and E. Somerscales, Heat transfer by natural convection in liquids confined by two parallel plates which are inclined at various angles with respect to the horizontal, *J. Heat Transfer* **87C**, 77–82 (1965).
9. A. Emery and N. C. Chu, Heat transfer across vertical layers, *J. Heat Transfer* **87C**, 110–116 (1965).
10. A. G. Worthing and J. Geffner, *Treatment of Experimental Data*, pp. 239–242. John Wiley, New York (1946).

CONVECTION NATURELLE DANS L'AIR ENTRE UNE PLAQUE AVEC DES RIGOLES EN V DE 60° ET UNE PLAQUE PLANE

Résumé—Le transport de chaleur par convection naturelle à partir d'une plaque rugueuse avec des rigoles en *V* à 60° vers une plaque plane refroidie placée au-dessus d'elle a été étudié avec la plaque plane froide et les *V* horizontaux. On a obtenu des corrélations entre les nombres de Nusselt et de Grashof, et on les a discuté en relation avec les corrélations obtenues par d'autres chercheurs pour la convection naturelle dans des couches d'air limitées par des surfaces planes parallèles.

FREIE KONVEKTION IN LUFT ZWISCHEN EINER 60° V-GEWELLTEN PLATTE UND EINER EBENEN PLATTE

Zusammenfassung—Der Wärmeübergang durch freie Konvektion von einer auf 60° beheizten gewellten Platte auf eine gekühlte ebene Platte darüber, wurde bei waagerechter Anordnung der beiden Platten untersucht. Nusselt- und Grashof-Zahlen wurden korreliert und hinsichtlich der von anderen Autoren erhaltenen Korrelationen für eben begrenzte Luftschichten diskutiert.

СВОБОДНАЯ КОНВЕКЦИЯ В ВОЗДУХЕ МЕЖДУ У-ОБРАЗНО ИЗОГНУТОЙ ПОД УГЛОМ 60° И ПЛОСКОЙ ПЛАСТИНАМИ

Аннотация—Изучался перенос тепла свободной конвекцией от нагретой ло 60° пластины с *V*-образными гофрами к находящейся горизонтально над ней охлажденной плоской пластине.

Получены выражения для критериев Нуссельта и Грасгофа и проведено их сопоставление с соответствующими выражениями, полученными другими исследователями для свободной конвекции в слоях воздуха, ограниченных параллельными плоскими поверхностями.