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SHORTER COMMUNICATIONS

HEAT TRANSFER BY NATURAL CONVECTION FROM CORRUGATED PLATES TO AIR

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NOMENCLATURE

- A, base area of corrugation, see equation (1) [mm^2];
- c_p, specific heat at constant pressure [J/kg K];
- g, acceleration of gravity [m/s^2];
- h, heat-transfer coefficient by natural convection based on base area [W/m^2 K];
- k, thermal conductivity of plate [W/m K];
- L, corrugation side-length [mm];
- m, constant;
- p, pitch [mm];
- q, heat flux density based on base area [W/m^2];
- t_a, air temperature [°C];
- t_f, film temperature, $= (t_w + t_a)/2$ [°C];
- t_w, air-side plate temperature [°C];
- w, plate length [mm];
- ψ, corrugation angle [degree];
- μ, dynamic viscosity [$N s/m^2$];
- ρ, density [kg/m^3];
- β, volumetric coefficient of expansion [1/K];
- Nu_L, Nusselt number, $= hL/k$;
- Gr_L, Grashof number, $= g\beta(t_w - t_a)p^2L^3/\mu^2$;
- Pr, Prandtl number, $= c_p\mu/K$.

INTRODUCTION

THE TRANSFER of heat by natural convection from a hot surface to the surrounding air is used in many practical applications. In many cases the resistance to heat flow on the air side of the surface is high compared to the resistance on the other side. In such cases the use of extended surfaces becomes a necessity, especially where space is limited. The corrugated plate provides an attractive solution in this condition. The heat-transfer surface is more than that of a flat plate occupying the same space. Furthermore corrugated plates can easily be made from flat plates by merely pressing or bending. This method of manufacture is much easier than that required for the finned plates commonly used as extended surfaces.

The only data available on corrugated plates, as far as the authors know, are those of Chinnappa [1]. He carried out experiments to study natural convection heat transfer from a hot triangularly corrugated 60° horizontal plate facing upwards to a colder plate above it through an air gap, a case found in solar water-heaters.

Applications in which the corrugated plate can be used with advantage include wall and floor type room heaters, roof type fluid coolers, central heating systems radiators and cases of electric devices with internal heat generation (such as transformers).

The possible shapes of corrugations are numerous. These include the triangular, the trapezoidal and the sinusoidal corrugations. The plates can be vertical or horizontal. This research work was carried out to study natural convection heat transfer from triangularly corrugated horizontal hot surfaces facing upwards to the surrounding air. As can be seen from Fig. 1, corrugations of this type can be defined by the "corrugation angle ψ" and the "corrugation-side length L".

APPARATUS

The apparatus used is shown diagrammatically in Fig. 1. It consists of the test plate 1 which is placed horizontally with the upper surface facing upwards. The lower surface of the plate is heated by condensing steam at atmospheric pressure in the inner jacket 3. The outer jacket 4 thermally insulates the inner jacket.

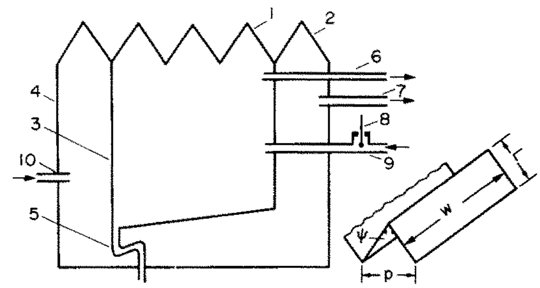

FIG. 1. Diagrammatic sketch of apparatus. (1) Test plate. (2) Guard corrugation. (3) Inner jacket. (4) Outer jacket. (5) Condensate outlet tube. (6) Inside jacket steam vent. (7) Outside jacket steam vent. (8) Thermometer. (9) Inner jacket inlet steam tube. (10) Outer jacket inlet steam tube.

A polished tin-plated iron sheet (0.3-mm thick) was used to make the test plates. Forty plates with different corrugation angles (from 30 to 160°) and different corrugation-side lengths (from 10 to 150 mm) were tested.

As the resistance to heat flow on the steam-side of the plate is very low compared to that on the air-side, the temperature of the steam-side surface of the plate can be considered equal to the steam saturation temperature and the temperature of the air-side surface can be determined by calculating the drop in temperature through the plate metal.

To obtain heat-transfer values corresponding to a corrugated plate with an infinite number of corrugations (infinite width) and of infinite plate length, end effects had to be eliminated. This was achieved by two guard corrugations lengthwise and by limiting the inner jacket length so that 100 mm was left between the inner and outer jackets. Previous work on heat transfer by natural convection from flat plates facing upwards and heated in the same way as the present plates [2] showed that edge-effects disappear after some 75 mm from the plate edges.

Separate experiments were carried out on each plate to determine the radiation shape factor required for the calculation of radiation losses.

RESULTS AND DISCUSSION

As the purpose of the present work was to investigate the possibility of using the corrugated surface as extended surface the heat-transfer coefficient was based on the "base area of the corrugation A" as given by equation (1) (see Fig. 1)

$$A = p \times w. \qquad (1)$$

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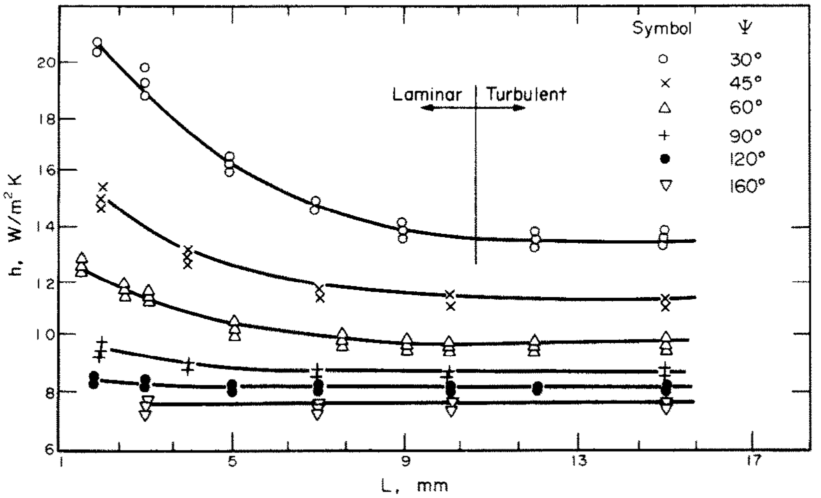

FIG. 2. Variation of heat-transfer coefficient h with corrugation length L.

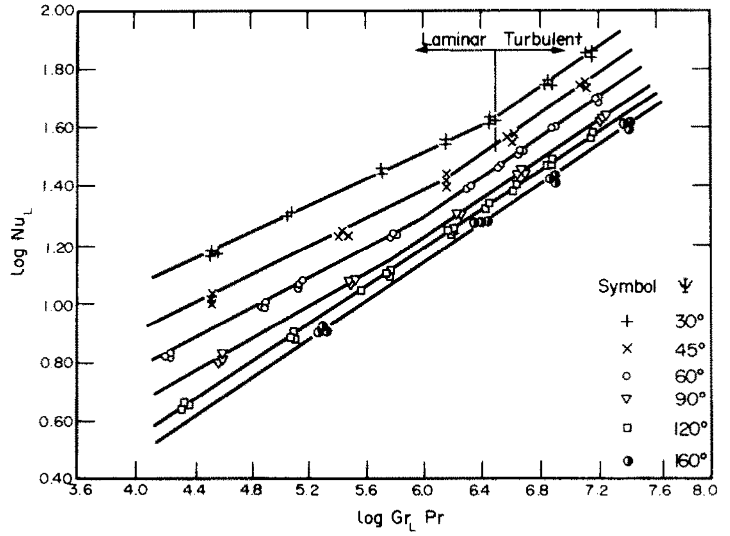

FIG. 3. Variation of $\log Nu_L$ with $\log (GrPr_L)$.

Two factors affect the heat-transfer coefficient thus calculated, the corrugation-side length L and the corrugation angle ψ. Figure 2 shows the effect of these factors. It can be seen that the heat-transfer coefficient decreases with the increase of both L and ψ.

Figure 3 shows a plot between $\log Nu_L$ and $\log Gr_L Pr$ calculated with the corrugation-side length as the characteristic linear dimension taking the air physical properties at the film temperature t_f. The values corresponding to the same corrugation angle, as can be seen, lie on two different straight lines, the first one with a slope which increases with the corrugation angle and the second one with a slope equal to 1/3. These lines represent the laminar and the turbulent regions. The two regions can also be seen in Fig. 2. The value of $(Gr_L Pr)_{cr}$, the critical value at which turbulence begins, decreases with the corrugation angle. At an angle of 160° the plates become almost flat plates and are wholly in the turbulent region.

The heat transfer in the two regions mentioned can be represented by the equations:

for the laminar region,

$2.5 \times 10^4 < Gr_L Pr < (Gr_L Pr)_{cr}$

$$Nu_L = C_1 (Gr_L Pr)^m \tag{2}$$

and for the turbulent region,

$(Gr_L Pr)_{cr} < Gr_L Pr < 2 \times 10^7$

$$Nu_L = C_2 (Gr_L Pr)^{1/3} \tag{3}$$

m, $(Gr_L Pr)_{cr}$, C_1 and C_2 depend on the corrugation angle of the plate. They can be represented by the following equations:

$$m = 0.148 \sin\frac{\psi}{2} + 0.187 \tag{4}$$

$$(Gr_L Pr)_{cr} = 15.8 \times 10^5 - 14 \times 10^5 \sin\frac{\psi}{2} \tag{5}$$

$$C_1 = \frac{0.46}{\sin\frac{\psi}{2}} - 0.32 \tag{6}$$

$$C_2 = 0.090 + \frac{0.054}{\sin\frac{\psi}{2}}. \tag{7}$$

The lines representing equations (2) and (3) are drawn together with the experimental points in Figs. 4 and 5 respectively. As can be seen the experimental points are represented by the equations within $\pm 8.5\%$.

It is of interest to find from the previous equations the value of Nu_L for an angle $\psi = 180°$, in which condition the test plate becomes a flat plate. As the apparatus was designed to give the heat transfer from plates of infinite length and width, and as in this condition the whole plate surface would be in the turbulent region, both equations (2) and (3) give, as they should, the same value of Nu_L as in equation (8):

$$Nu = 0.144 (Gr_L Pr)^{1/3}. \tag{8}$$

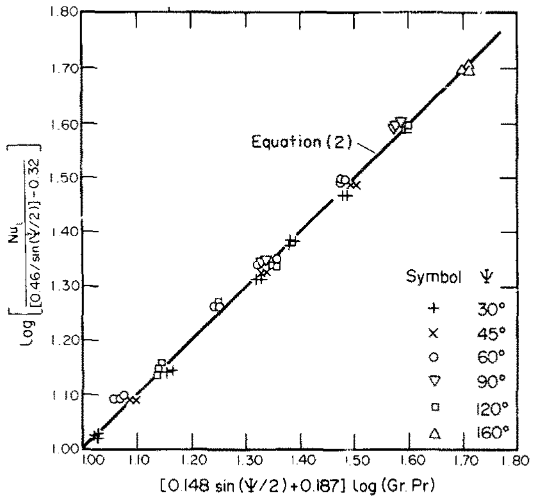

FIG. 4. Correlation of heat-transfer data according to equation (2).

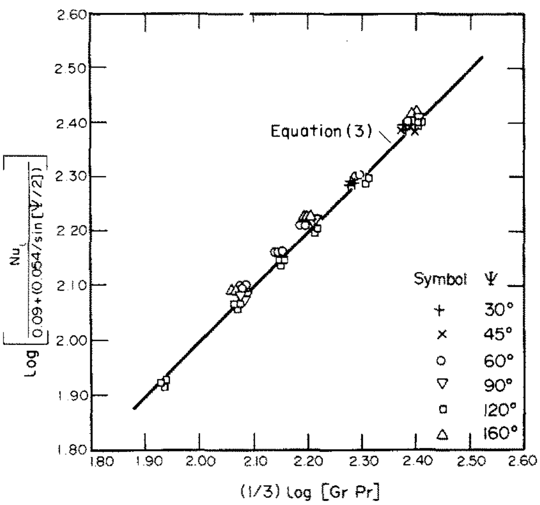

FIG. 5. Correlation of heat-transfer data according to equation (3).

Fishenden and Saunders [3] give for this condition a similar equation with a constant; = 0.14. This agreement confirms equations (2) and (3).

Comparison with finned plates

Some experiments were carried out to compare the heat transfer from the corrugated plate with that from the "corresponding finned plate". The latter was taken as a finned plate with a fin pitch equal to the corrugation pitch and with fins of the same thickness as the plates and a fin height chosen so that the weight of the two plates will be the same. The two plates will then occupy the same space and consume the same amount of metal (Fig. 6).

The range of corrugation angles which can be useful in practice, as can be seen from Fig. 2, lies between the angles 30 and 60°. The experiments were, therefore, carried out on the 30° and the 60° corrugated plates only. The results obtained are shown in Fig. 7 as heat flux density q (based on the base area $p \times w$) against pitch p. It will be seen that the 30°

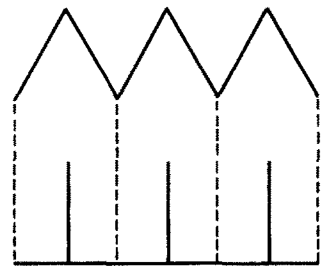

FIG. 6. Comparison between corrugated plate and corresponding finned one.

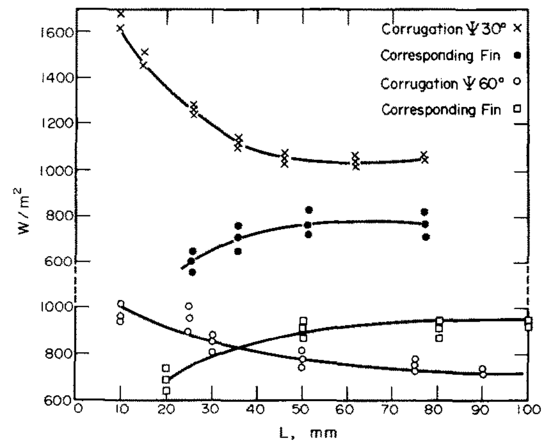

FIG. 7. Comparison between corrugated plates and corresponding finned ones.

corrugated plate gives heat-transfer values higher than those given by the finned plate in the whole range of pitch used. Increasing the corrugation angle to 60°, however, reduces the range in which the corrugated plate gives higher heat transfer to pitches smaller than 30 mm. As this is the range used normally in practice the use of the corrugated plate as extended surface is no doubt worth considering.

CONCLUSION

1. The corrugated plate provides an extended heat transfer surface worth considering.
2. Experiments on isothermal triangularly corrugated plates facing upwards showed that the heat transfer to the surrounding air, based on the corrugation base area, decreases with the increase of both corrugation length and corrugation angle.
3. Dimensionless relations have been derived from which the heat transfer from the plates can be calculated for any corrugation length and any corrugation angle.

REFERENCES

1. J. C. V. Chinnapa, Free convection in air between a 60° Vee-corrugated plate and a flat plate, *Int. J. Heat Mass Transfer* **13**, 117–123 (1970).
2. M. Al-Arabi and M. K. El-Reidy, Natural convection heat transfer from isothermal horizontal plates of different shapes, *Int. J. Heat Mass Transfer* **19**, 1399–1404 (1976).
3. M. Fishenden and O. A. Saunders, *An Introduction to Heat Transfer*. Oxford University Press, London (1950).