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THE HEAT TRANSFER FROM BARE STRANDED CONDUCTORS BY NATURAL AND FORCED CONVECTION IN AIR

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Abstract—Experimental results are given for the convective heat transfer to air from bare stranded electrical conductors in the ranges $140 \leqslant (Re)_{D,f} \leqslant 47000$ and $4500 \leqslant (Gr\,.\,Pr)_{D,f} \leqslant 149000$. With natural convection the roughness of the surface, in the range $0{\cdot}042 \leqslant H_r/D \leqslant 0{\cdot}366$, had negligible effect on the heat transfer, but inclination of the conductor to the horizontal decreased the heat transfer. With forced convection, roughening of the surface had no effect below the critical Reynolds number, equal to $130/(H_r/D)$, but above this value, the heat transfer increased at a greater rate than with a smooth cylinder. Yaw of the conductor decreased the heat transfer. A conductor placed 10–15 diameters downstream from a similar parallel conductor had its heat transfer increased by 11–12 per cent.

NOMENCLATURE

- B, a constant;
- c, specific heat capacity at constant pressure [$Jkg^{-1}\,K^{-1}$];
- d, diameter of wires in outer layer [m];
- D, diameter of circumscribing circle [m];
- g, acceleration due to gravity [ms^{-2}];
- (Gr), Grashof number $= D^3\theta\beta g\gamma^2\mu^{-2}$;
- h, heat transfer coefficient [$Wm^{-2}\,K^{-1}$];
- H, height [m];
- H_r/D, roughness ratio $= d/2(D-d)$ for a stranded conductor;
- l, length [m];
- m, n, constants;
- (Nu), Nusselt number $= hD\lambda^{-1}$;
- (Pr), Prandtl number $= c\mu\lambda^{-1}$;
- (Ra), Rayleigh number $= D^3g\theta\beta c\gamma^2\mu^{-1}\lambda^{-1}$;
- (Re), Reynolds number $= UD\gamma\mu^{-1}$;
- S, surface area [m^2];
- T, thermodynamic temperature [K];
- U, flow velocity [ms^{-1}].

Greek symbols

- α, angle of inclination relative to horizontal [deg.];
- β, temperature coefficient of volumetric expansion [K^{-1}];
- γ, density [$kg\,m^{-3}$];
- ε, emissivity;
- θ, temperature rise [K];
- λ, thermal conductivity [$Wm^{-1}\,K^{-1}$];
- μ, viscosity [Nsm^{-2}];
- σ, Stefan–Boltzmann constant $= 5{\cdot}6697 \times 10^{-8}$ [$Wm^{-2}K^{-4}$];
- ψ, angle of attack [deg.].

Subscripts

- a, ambient;
- crit, critical;
- D, diameter;
- f, film temperature;
- r, roughness;
- s, surface temperature.

INTRODUCTION

THE EFFECT that protrusions from the surface of a circular cylinder have on the convective heat transfer depends on their height and the nature of the flow. The roughness of the surface may be of the uniform, or sand type; or it may take the form of two-dimensional elements such as longitudinal wires or slots; or three-dimensional elements such as threads, corrugations, notches, pins, fins or transverse slots or wires.

There is little published data on the heat transfer from roughened cylinders with natural convection. Tsubouchi and Masuda [1] found that the heat transfer from a 2·15 cm dia cylinder with longitudinal or circumferential slots was similar to that for a smooth cylinder having the same circumscribing diameter, D. Prasalov [2] reported that, for $10^5 \leqslant (Gr.Pr)_{D,f} \geqslant 3 \times 10^6$ roughness had no effect on the heat transfer, but for $3 \times 10^5 \leqslant (Gr.Pr)_{D,f} \leqslant 10^6$, the heat transfer was increased by 50–90 per cent.

With forced flow, the roughness has little effect if the protrusions from the surface do not project through the laminar sub-layer of the boundary layer [3, 4]. However, if they project beyond the sub-layer into the buffer layer, they will trigger turbulence which will enhance the heat transfer locally downstream [5, 6]. This occurs when the height of the roughness element exceeds 0·3 times the displacement thickness of the boundary layer [4].

Brun *et al.* [7] have studied the effect of sand-type roughness on cylinders over the ranges $0{\cdot}02 \leqslant H_r/D \leqslant 0{\cdot}12$ and $6000 \leqslant (Re)_{D,f} \leqslant 15000$, where H_r is the height of the roughness elements and D is the diameter of the cylinder. They obtain the relationship

$$(Nu)_{D,f} = 0{\cdot}425\,(H_r/D)^{0{\cdot}27}(Re)_{D,f}^{0{\cdot}9}. \qquad (1)$$

Reiher [8] measured the convective heat transfer from smooth cylinders and those roughened with longitudinal slots in the range $3700 \leqslant (Re)_{D,f} \leqslant 6200$. He found that the surface roughness increased the heat transfer by about 11 per cent at the lower end of the range and about 29 per cent at the upper end.

Gomelauri [9] studied the effect of turbulent axial flow of air on the heat transfer from cylinders roughened with circumferential rings having circular and square sections and pitch s. He correlated his own results with those found by others for roughened tubes in the form

$$(Nu)_{D,f} = 0{\cdot}0218(Re)_{D,f}^{0{\cdot}8}\,(Pr)_f^{0{\cdot}47}\left\{\frac{(Pr)_f}{(Pr)_s}\right\}^{0{\cdot}25} \exp\left\{\phi\left(\frac{s}{H_r}\right)\right\} \qquad (2)$$

in the ranges $6 \times 10^3 \leqslant (Re)_{D,f} \leqslant 9 \times 10^4$, and $1 \leqslant (Pr)_f \leqslant 80$. For $s/H_r \leqslant 13$, $\phi(s/H_r) = 0{\cdot}065\, s/H_r$; and for $s/H_r > 13$, $\phi(s/H_r) = 11\, H_r/s$.

This paper describes measurements of the heat transfer by natural and forced convection from roughened cylinders in the form of bare stranded electrical conductors used for overhead electric power transmission. The conductors consist of a number of wires stranded helically in one or more layers, adjacent layers being applied with opposite directions of lay. Although the temperature rise of such conductors carrying electrical currents has been measured previously [10–18], only Hutchings and Parr [16] have published data for the heat transfer by convection.

EXPERIMENTAL WORK

Relevant details for the electrical conductors studied by the author are given in Table 1. All the conductors were new, except the 54/7 strand a.c.s.r. (aluminium conductor, steel reinforced) which had been exposed in a rural atmosphere for one year, but was still fairly bright. Some of the measurements were made with the conductor as received; for others, the conductors were painted with matt-black paint. The total emissivity of the bright conductors, measured by a comparative thermopile method against copper black (total emissivity = 0·98), varied from 0·18 to 0·43. The total emissivity of the blackened conductors was 0·95.

Still-air tests

A 10 m length of each conductor was tensioned horizontally at normal operating tension ($\sim 10^4$ N) in a draught-free laboratory 16 m long, 10 m wide and 5 m high. Stabilized alternating current at 50 Hz was passed through the conductor by means of compression anchor clamps at each end. Glass-insulated 36 s.w.g. (0·193 mm) iron–constantan thermocouples peened or soldered to the surface were used to measure the surface temperature. The current was allowed to flow until thermal equilibrium was reached. This was taken to be the case when the output voltages from the thermocouples did not vary by more than 5 μV over a period of 10 min.

When the measurements on each bright conductor were completed, it was painted matt-black and the measurements were repeated. Typical temperature rise/current characteristics are shown in Fig. 1. The natural-convection heat transfer coefficients were calculated after the computed radiation loss $\pi D l \sigma \varepsilon (T_s^4 - T_a^4)$ had been subtracted from the total heat loss. The Nusselt numbers, based on the circumscribing diameter D, are plotted against the product $(Gr \cdot Pr)_{D,f}$ in Fig. 2. The results of other workers are shown for comparison. One series of measurements was made with the conductor inclined at various angles to the horizontal, and the results are given in Fig. 3.

Wind-tunnel tests

Due to problems of availability, four different wind tunnels were used at various times for these tests. The smallest effective diameter was

Table 1. Details of conductors

Symbol	Material	Total wires		Wires in outer layer		Circumscribing dia D (mm)	Surface roughness ratio $d/2(D-d)$	Surface area factor $S/\pi D$
		Number	Dia (mm)	Number n	Dia d (mm)			
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
▽	Copper	3	3·64	3	3·64	5·69	0·366	1·160
⧩	Copper	3	3·64	3	3·64	8·05	0·366	1·160
⧨	Copper	7	3·46	6	3·46	10·38	0·250	1·333
▼	Copper	7	4·90	6	4·90	14·7	0·250	1·333
+	Copper	90†	1·95	36	1·95	25·2	0·042	1·462
△	Aluminium	7	3·10	6	3·10	9·30	0·250	1·333
◮	Aluminium	7	4·39	6	4·39	13·2	0·250	1·333
◭	Aluminium	19	3·24	12	3·24	16·25	0·125	1·400
◨	Alum. alloy	7	2·34	6	2·34	7·01	0·250	1·333
	Alum. alloy	7	4·67	6	4·67	13·95	0·250	1·333
■	Alum. alloy	19	3·76	12	3·76	18·8	0·125	1·400
○	Aluminium	6	4·72	6	4·72	14·17	0·250	1·333
	Steel	7	1·57					
◑	Aluminium	30	2·80	18	2·80	19·6	0·083	1·428
	Steel	7	2·80					
◐	Aluminium	12	*	12	*	18·6	Nil	1·000
	Aluminium	6	*					
	Steel	7	2·28					
●	Aluminium	54	3·18	24	3·18	28·6	0·063	1·444
	Steel	7	3·18					

* Compacted.

† Hollow-core. $S = n\pi d l \left(\frac{1}{2} + \frac{1}{n}\right)$.

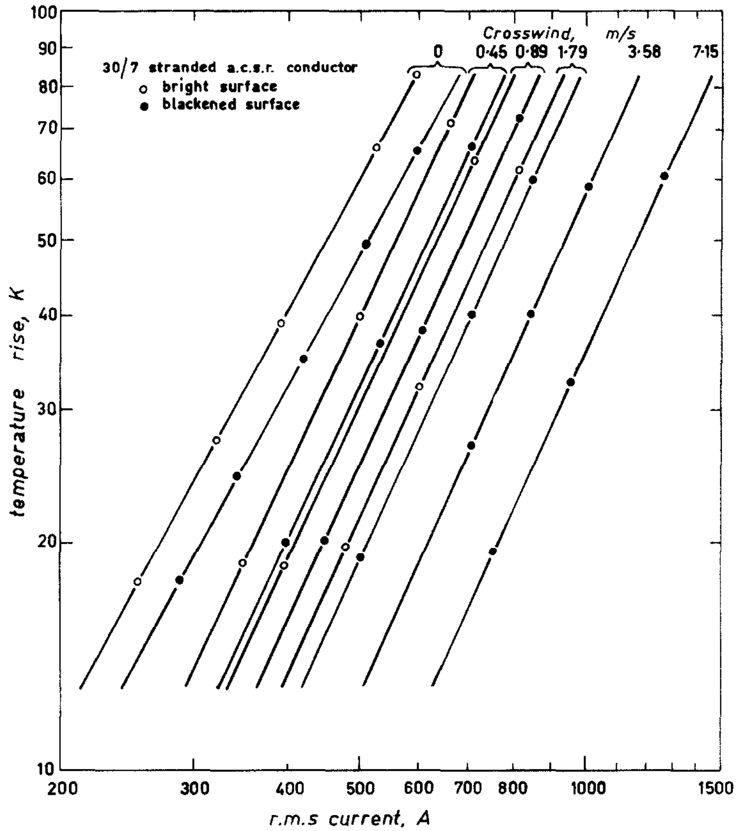

FIG. 1. Typical heating characteristics for conductors carrying current.

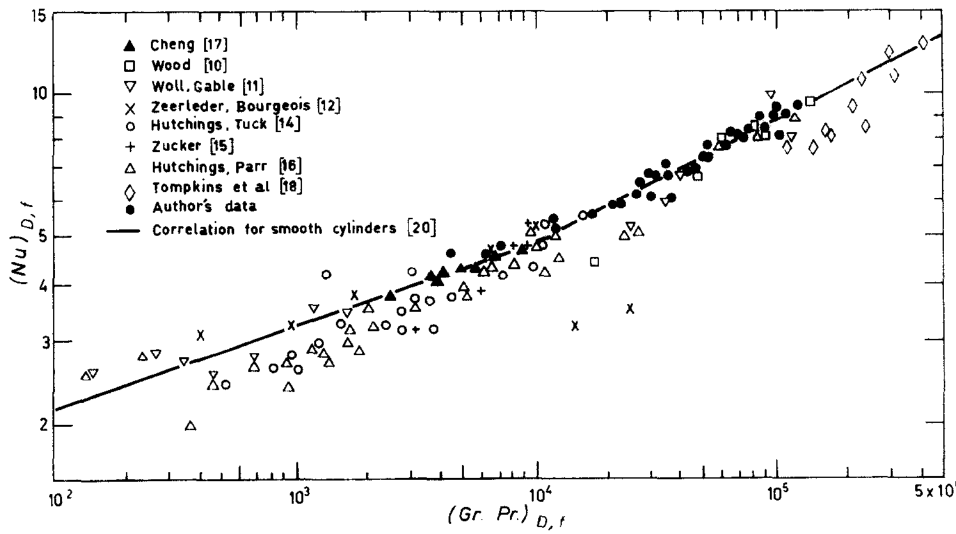

FIG. 2. Relation between Nusselt and Rayleigh numbers for natural convection from stranded conductors.

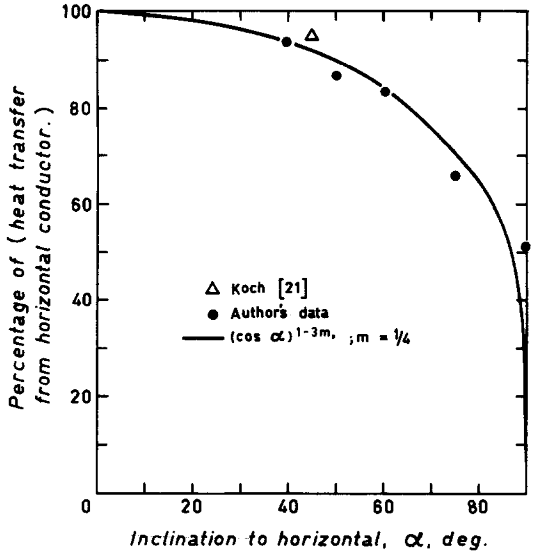

FIG. 3. Effect of inclination to horizontal on natural convective heat transfer.

2·14 m; the intensity of turbulence in the direction of flow did not exceed 0·1 per cent; and the flow velocity was uniform over most of the working section. The consistency of the results from the various tunnels points to the tunnels being similar aerodynamically.

The conductor was tensioned horizontally across the tunnel, and it was heated by passing power-frequency current through it. Glass-insulated 36 s.w.g. (0·193 mm) iron–constantan thermocouples were used to measure the temperatures of the air, the tunnel wall and the conductor surface. It is clear from Fig. 4 that taking the thermocouple wires away from the conductor externally did not alter the value of the heat transfer from that measured with thermocouple wires brought out internally through the hollow core of the conductor. Since temperature measurements were taken at the centre of the length, and the aspect ratio,

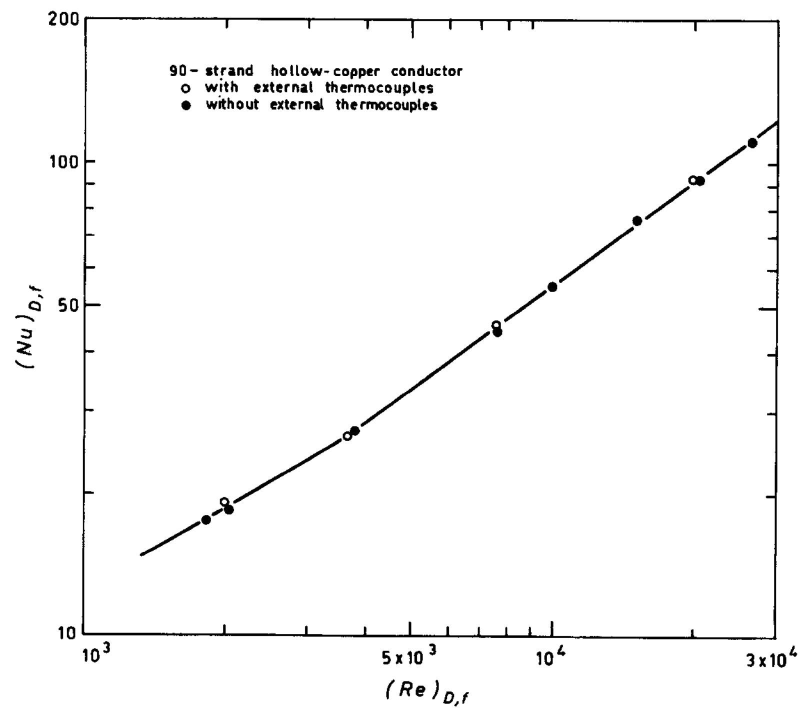

FIG. 4. Effect of externally mounted thermocouples on heat transfer with crossflowing air.

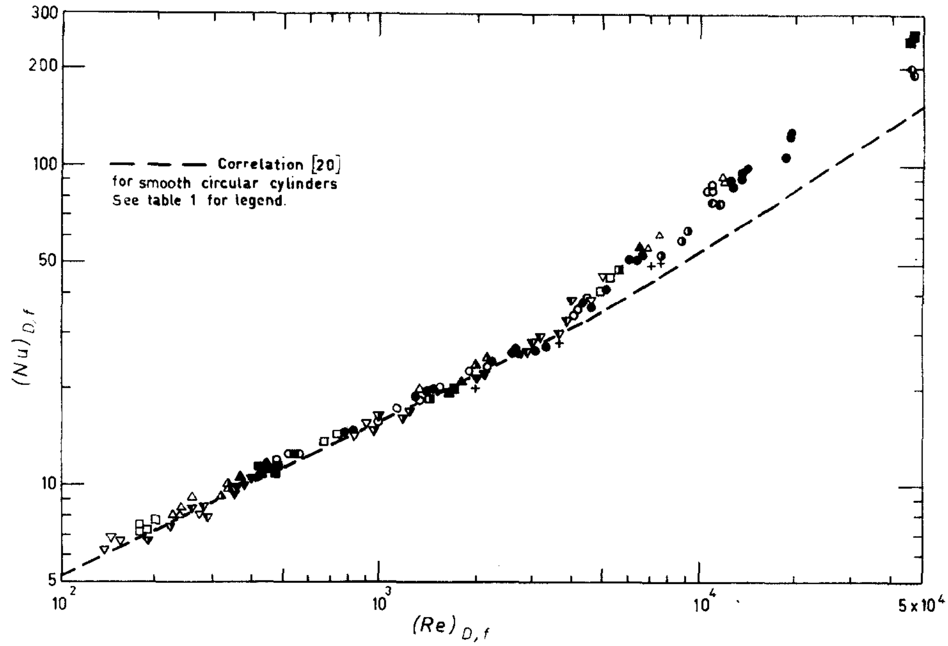

FIG. 5. Relation between Nusselt and Reynolds numbers for stranded conductors with crossflowing air.

l/D, varied from 100 to 480, the conduction error was negligible [29].

Typical temperature rise/current curves are given in Fig. 1. The difference in temperature rise between the bright and the blackened conductors for equal current is due to their differing emissivities; this difference decreases as the wind velocity increases, since the radiation loss is then much less than the convection loss. When corrected for radiation loss, the Nusselt numbers for the bright and blackened conductors were equal for the same Reynolds number. The results of all the crossflow tests are shown in Fig. 5 and the effect of yawing the wind on the overall and local heat transfers is given in Figs. 6 and 7 respectively. The results of the measurements on twin and quadruple conductors are shown in Fig. 8. Complete tabulated results for all these tests are given elsewhere [19]. The correlations given in Figs. 2 and 5 are those of the author

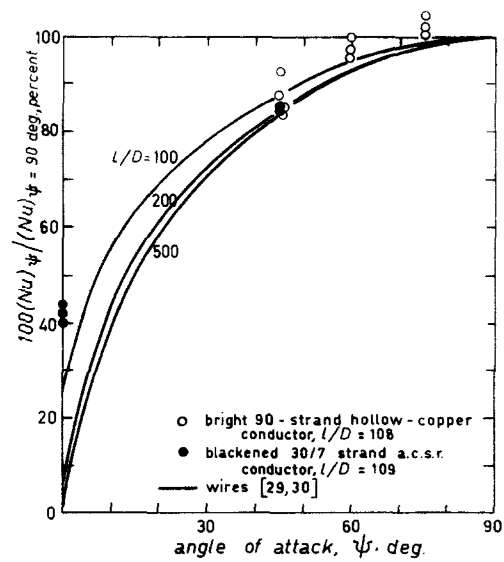

FIG. 6. Effect of yaw on the overall convective heat transfer for forced flow of air.

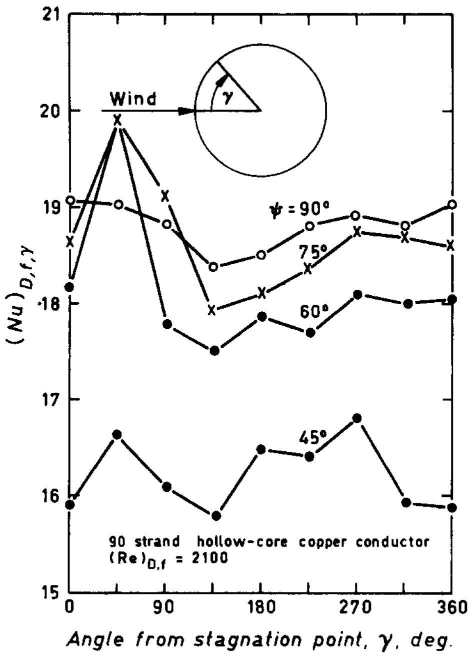

FIG. 7. Effect of yaw on the local forced convective heat transfer from a stranded conductor in air.

[20]. The correlations used for natural convection are:

for $10^2 < (Gr \,.\, Pr)_{D,f} \leqslant 10^4$,

$$(Nu)_{D,f} = 0{\cdot}85\,(Gr \,.\, Pr)_{D,f}^{0{\cdot}19};$$

and for $10^4 < (Gr \,.\, Pr)_{D,f} < 10^7$,

$$(Nu)_{D,f} = 0{\cdot}48\,(Gr \,.\, Pr)_{D,f}^{0{\cdot}25}.$$

The correlations used for crossflow convection in air are:

for $35 < (Re)_{D,f} \leqslant 5 \times 10^3$,

$$(Nu)_{D,f} = 0{\cdot}58\,(Re)_{D,f}^{0{\cdot}47};$$

and for $5 \times 10^3 < (Re)_{D,f} \leqslant 5 \times 10^4$,

$$(Nu)_{D,f} = 0{\cdot}15\,(Re)_{D,f}^{0{\cdot}63}.$$

DISCUSSION

Natural convection

It may be seen from Fig. 2 that roughening of the surface by stranding does not vary the Nusselt number based on overall diameter from that for a smooth cylinder in the range $10^2 \leqslant$

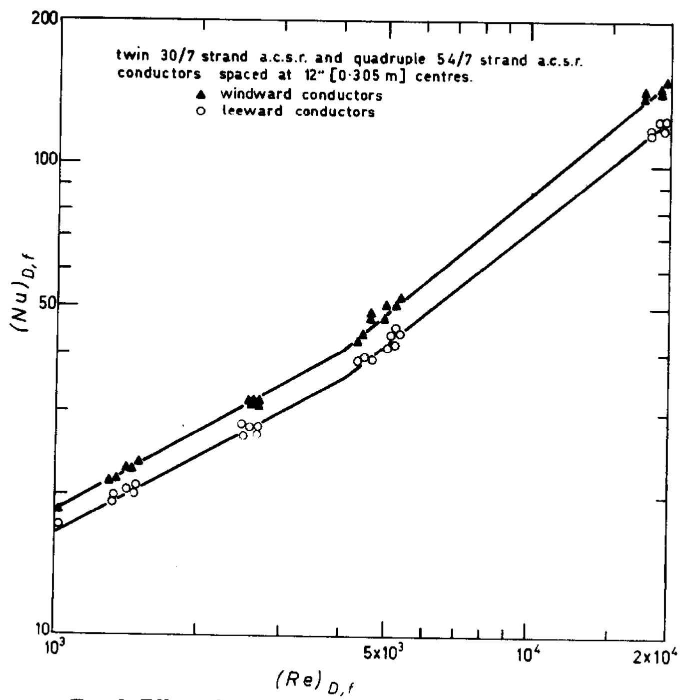

FIG. 8. Effect of an upstream conductor on the convective heat transfer in crossflowing air.

$(Gr\,.\,Pr)_{D,f} \leqslant 4 \times 10^5$. This is remarkable, because the surface area of a stranded conductor is up to 44 per cent greater than that of the smooth cylinder having the same overall diameter. This agrees with the results of Tsubouchi and Masuda [1] for cylinders having longitudinal or circumferential grooves in the range $1{\cdot}5 \times 10^4 \leqslant (Gr\,.\,Pr)_{D,f} \leqslant 4{\cdot}7 \times 10^4$ and those of Prasalov [2] for cylinders with overall roughness in the range $10^5 \leqslant (Gr\,.\,Pr)_{D,f} \geqslant 3 \times 10^6$. The reason for this is that the fluid rising past the cylinder flows from the crest of one roughness element to that of the next without following the interstitial surface. This effect is most pronounced with cylinders having a low roughness ratio, H_r/D or $d/2(D - d)$, and is less pronounced with those having high roughness ratios, e.g. 3-strand conductors.

The present results for horizontal stranded conductors are seen to be in good agreement with those of other workers, except those of Zeerleder and Bourgeois [12] who covered their thermocouple junctions with thick asbestos. However, the results do not extend into the region of turbulent flow, i.e. $(Gr\,.\,Pr)_{D,f} > 10^7$, and it is possible that the increased surface area of the stranded conductors would then cause an increase in the Nusselt number. The greater scatter of results with $(Gr\,.\,Pr)_{D,f} < 10^4$ is due to the difficulty of measuring the surface temperature of small conductors and the increased error in measuring small temperature rises with the larger conductors. The effect on the heat transfer caused by slight draughts also becomes appreciable with low values of $(Gr\,.\,Pr)_{D,f}$.

When the conductor is inclined at an angle α to the horizontal, there is an axial component of flow and a thickening of the boundary layer, causing a decrease in the convective heat transfer, as seen in Fig. 3. This effect is small for small inclinations, $(Nu)_{D,f}$ decreasing by only 8 per cent as α increases from zero to 45 degrees, but as the axis of the conductor approaches the vertical, the heat transfer falls rapidly. If the Nusselt and Grashof numbers are based on the vertical dimension, i.e. diameter D for a horizontal cylinder, $D/\cos\alpha$ for an inclined conductor and height H for a vertical conductor, then the Nusselt number can be successfully correlated with the Grashof number. It can be shown that, except as $\alpha \to 90$ deg, the ratio of $(Nu)_{D,f}$ with inclination α to that with $\alpha = 0$ deg. is equal to $(\cos\alpha)^{1-3m}$ where m is the exponent in the equation $(Nu)_{D,f} = B(Gr\,.\,Pr)^m_{D,f}$ and B is a constant. It is seen from Fig. 3 that this agrees quite well with the present results and those of Koch [21] for smooth cylinders.

Forced convection

It can be seen from Fig. 5 that, in the range $140 \leqslant (Re)_{D,f} \lesssim 2000$, stranding has very little, if any, effect on the overall heat transfer. At most, $(Nu)_{D,f}$ is increased by 3 per cent, although this is the estimated uncertainty of the present results. Since $(Nu)_{D,f}$ is based on the circumscribing diameter, the increased surface area due to the stranding does not contribute to the heat transfer. This implies that laminar separation of the boundary layer occurs at the crest of each strand, and laminar re-attachment occurs at the crest of the next strand. There will be regions of stagnation in the interstices, with thickening of the boundary layer there.

Above $(Re)_{D,f} \simeq 2000$, the picture changes. The vortex sheet in the rear of the cylinder gives way to a turbulent wake and the rate of heat transfer increases. However, this increase is greater than that which occurs with a smooth cylinder at $(Re)_{D,f} \simeq 5000$. This is because, although the flow separation at the strands near the front of the cylinder may still be laminar, re-attachment is turbulent, thus producing a scouring effect in the interstices, with a consequent reduction in the thickness of the boundary layer and, hence, an increase in the overall heat transfer. Confirmation of this process was given by Richards [22], who found, using a flow visualization technique, that at $(Re)_{D,f} \simeq 30000$, discrete secondary vortices were being formed by the detached fluid in the region between the strands. These secondary vortices were found to

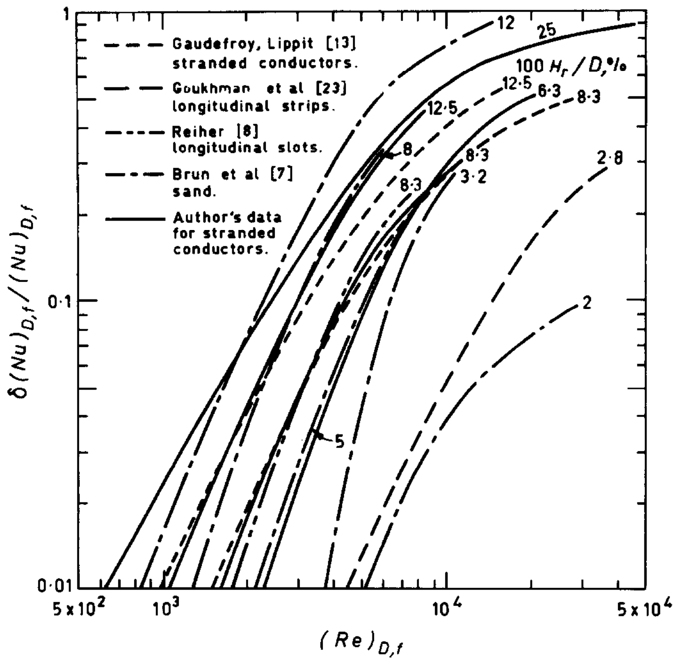

FIG. 9. Effect of the roughness ratio of the surface on the convective heat transfer from cylinders in crossflowing air.

originate at the stagnation point and to increase in strength as they followed the strands of the conductor.

It may be seen from Fig. 9 that, for constant Reynolds number, the Nusselt number increases with the roughness of the surface. It is also clear that the critical Reynolds number, i.e. the value of $(Re)_{D,f}$ at which the increase in heat transfer above that for a smooth cylinder of the same diameter becomes significant, decreases as the roughness increases. It is found that, for an increase in heat transfer of 1 per cent,

$$\frac{H_r}{D} = \frac{130}{(Re)_{D,f,\mathrm{crit}}} \tag{3a}$$

$$\text{i.e. } (Re)_{D,f,\mathrm{crit}} = 130/(H_r/D). \tag{3b}$$

Kraemer [6] found that, for large wires on a flat plate, the critical Reynolds number was given by approximately 100/(roughness ratio), while for small wires it was approximately 900/(roughness ratio). It is interesting to compare the effect on

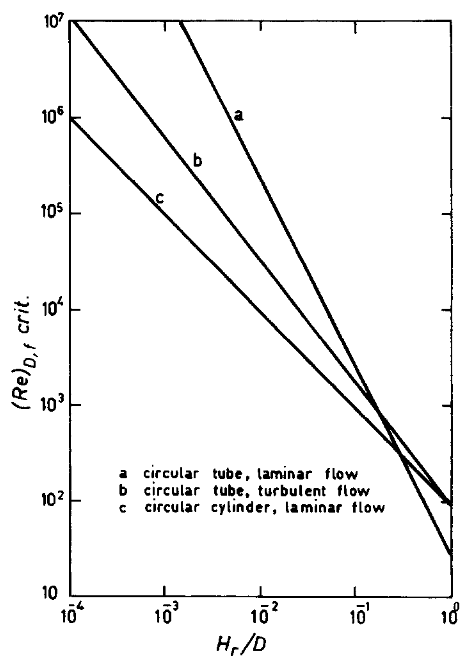

FIG. 10. Relation between the critical Reynolds number and the roughness ratio of the surface.

the heat transfer of stranding with that of other types of roughness. The results of Brun *et al.* [7] for sand-type roughness, Reiher [8] for longitudinal slots, and Goukhman *et al.* [23] for longitudinal wires agree very well with the present data and those of Gaudefroy and Lippitt [13] for stranded conductors. The increase in the convective heat transfer from a roughened circular cylinder can be expressed in the form

$$\frac{\delta(Nu)_{D,f}}{(Nu)_{D,f}} = 0{\cdot}01 + 0{\cdot}0335\left\{\frac{(Re)_{D,f} - (Re)_{D,f,\mathrm{crit}}}{(Re)_{D,f,\mathrm{crit}}}\right\}^{1{\cdot}072}. \quad (4)$$

In the case of flow inside tubes, the critical Reynolds number with laminar flow is given by [3]

$$(Re)_{D,f,\mathrm{crit}} = 26{\cdot}6/(H_r/D) \quad (5)$$

and with turbulent flow it is found from [24].

$$(Re)_{D,f,\mathrm{crit}} = 73{\cdot}9/(H_r/D)^{\frac{4}{5}}. \quad (6)$$

The relationships in equations (3), (5) and (6) are plotted in Fig. 10. It is seen that roughness on the surface of a cylinder results in a lower critical Reynolds number than roughness inside a tube; this is probably due to the differing curvatures of the surfaces.

The effect of the proximity of other conductors can be seen from Fig. 8; in the range $10^3 \leqslant (Re)_{D,f} \leqslant 2 \times 10^4$, the heat transfer from the leeward twin and quadruple conductors was 11–12 per cent higher than that from the windward conductors, due to the vortex sheet or, at $(Re)_{D,f} > 4000$, the turbulent wake generated by the windward conductor. This agrees reasonably well with the results of Kostić and Oka [25], who measured 17 per cent increase in the heat transfer from a 10 cm dia cylinder placed up to 9 diameters downstream from a similar cylinder in the range $1{\cdot}2 \times 10^4 \leqslant (Re)_{D,f} \leqslant 4 \times 10^4$. The results are also compatible with published data for in-line tubes, for which increments of 10–30 per cent have been reported [26–28]. When the conductors were not in line with the flow, the incremental heat transfer depended on how much of the wake from the windward conductor washed the leeward conductor. This also agrees with published data for staggered rows of tubes [26–28], for which increments of 10–30 per cent were found.

It is seen from Fig. 6 that the present results with yawed stranded conductors agree reasonably well with those for previous work with smooth cylinders, except that there was a maximum in the heat transfer when the angle of attack was approximately 75 deg. This is because the maximum heat transfer occurs when the individual wires of the outer layer of the conductor are normal to the direction of flow. This occurs for either the top or bottom wires when $\psi = 90\,\mathrm{deg} \pm \zeta$, where ζ is the angle of lay of the wires. This effect can be clearly seen in Fig. 7, which shows the variation of the local heat transfer around a stranded conductor with various angles of attack. It will again be noted that the maximum overall heat transfer occurred when $\psi \simeq 75$ deg. Since the lay angle for this conductor was 12 deg, one would expect maximum heat transfer when $\psi = 78$ deg, which agrees closely with the experimental value. It is interesting to note that the maximum local heat transfer occurs at an angle γ of 45 deg from the stagnation point in the plane normal to the axis of the conductor. This is due to secondary vortices originating at the stagnation point increasing in strength as they follow the strands of the conductor, until they eventually detach from the surface at approximately 45 deg from the stagnation point.

CONCLUSIONS

With natural convection, roughening the surface of a circular cylinder by means of helically wound wires does not significantly affect the Nusselt number based on circumscribing diameter compared with that for a smooth cylinder in the ranges $0{\cdot}042 \leqslant H_r/D \leqslant 0{\cdot}366$ and $100 \leqslant (Gr\,.\,Pr)_{D,f} \leqslant 4 \times 10^5$. Inclination of the axis to the horizontal reduces the convective heat transfer from the cylinder; the

Nusselt number can be successfully correlated with the Grashof number when the latter is based on the height of the vertical cross-section through the cylinder.

With crossflow forced convection in air, the convective heat transfer is not significantly changed by roughening of the surface in the range $0{\cdot}042 \leqslant H_r/D \leqslant 0{\cdot}366$, provided the Reynolds number is below the critical value, given by $130/(H_r/D)$ for 1 per cent increase in heat transfer. Above this critical value, the heat transfer increases at a greater rate than with a smooth cylinder. The maximum heat transfer from a stranded conductor occurs when the top or bottom strands are normal to the flow, not when the axis is normal to the flow. Yawing the conductor in the wind stream decreases the convective heat transfer. A stranded conductor placed 10–15 diameters upstream from a similar conductor increases the heat transfer from the latter by 11–12 per cent for $1000 < (Re)_{D,f} < 2 \times 10^4$.

ACKNOWLEDGEMENTS

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TRANSFERT THERMIQUE PAR CONVECTION LIBRE ET FORCEE DANS L'AIR DEPUIS DES CONDUCTEURS NUS ET TORONNES

Résumé—On présente des résultats sur le transfert thermique par convection dans l'air depuis des conducteurs électriques nus et toronnés pour des domaines expérimentaux correspondants à $140 \leqslant (Re)_{D,f} \leqslant 47\,000$ et $4500 \leqslant (Gr.Pr)_{D,f} \leqslant 149\,000$. En convection libre dans le domaine $0{,}042 \leqslant H_r/D \leqslant 0{,}366$ la rugosité de la surface a un effet négligeable sur le transfert thermique, mais l'inclinaison du conducteur par rapport à l'horizontale diminue le transfert thermique. Pour la convection forcée, la rugosité de la surface n'a pas d'effet en-dessous du nombre critique de Reynolds, égal à $130/(H_r/D)$ mais au-dessus de cette valeur, le transfert thermique augmente plus vite qu'avec un cylindre lisse. L'obliquité du conducteur diminue le transfert thermique. Un conducteur placé à une distance égale à 10 ou 15 diamètres en aval d'un conducteur parallèle identique voit son transfert thermique accru de 11 à 12 pour cent.

WÄRMEÜBERTRAGUNG VON FREILIEGENDEN LITZENKABELN BEI NATÜRLICHER UND ERZWUNGENER KONVEKTION IN LUFT

Zusammenfassung—Es sind experimentelle Lösungen für die konvektive Wärmeübertragung an Luft von freiliegenden elektrischen Litzenkabeln in den Größen $140 \leqslant (Re)_{D,f} \leqslant 47000$ und $4500 \leqslant (Gr \cdot Pr)_{D,f} \leqslant 149\,000$ gegeben. Bei natürlicher Konvektion konnte die Oberflächenrauhigkeit zwischen $0{,}042 \leqslant H_r/D \leqslant 0{,}366$ für die Wärmeübertragung vernachlässigt werden, jedoch verminderte die Neigung des Kabels zur Horizontalen die Wärmeübertragung. Bei erzwungener Konvektion hatte die Oberflächenrauhigkeit keinen Einfluß unterhalb der kritischen Reynolds-Zahl $130/(H_r/D)$. Oberhalb dieses Wertes wurde die Wärmeübertragung jedoch größer als bei einem glatten Zylinder. Durchmesserschwankungen des Kabels verminderten die Wärmeübertragung. Ein Kabel, das 10 bis 15 Durchmesser in Strömungsrichtung von einem gleichen parallelen Kabel angeordnet war, wies eine um 11 bis 12% vergrößerte Wärmeabgabe auf.

ПЕРЕНОС ТЕПЛА ЕСТЕСТВЕННОЙ И ВЫНУЖДЕННОЙ КОНВЕКЦИЕЙ ОТ НЕИЗОЛИРОВАННЫХ ПРОВОДНИКОВ К ВОЗДУХУ

Аннотация—Представлены экспериментальные результаты по конвективному переносу тепла к воздуху от неизолированных многожильных электрических проводников в диапазонах $140 \leqslant (Re)_{Df} \leqslant 47\,000$ и $4500 \leqslant (Gr\,.\,Pr)_{Df} \leqslant 149\,000$. При естественной конвекции шероховатость поверхности оказывала пренебрежимо малое влияние на перенос тепла в диапазоне $0{,}042 \leqslant H_r/D \leqslant 0{,}366$, в то время как наклон проводника к горизонтали уменьшал перенос тепла. В случае вынужденной конвекции шероховатость поверхности не играла роли при значениях числа Рейнольдса ниже критического, равного $130/(H_r/D)$, однако выще этого значения перенос тепла увеличивался интенсивнее по сравнению с гладким цилиндром. Угловое перемещение проводника снижало перенос тепла. Если проводник помещался на расстоянии 10–15 диаметров вниз по потоку от аналогичного параллельного проводника, перенос тепла увеличивался на 11–12%.