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EFFECT OF MOUNTING SYSTEMS ON HEAT TRANSFER FROM INCLINED CYLINDERS IN CROSS-FLOW

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Abstract — Previous studies have shown that heat conduction to mounting systems significantly affects the heat transfer characteristics of cylinders in cross-flow unless the length-to-diameter ratio is large, typically over 1000. For inclined cylinders in cross-flow an additional effect exists due to significant aerodynamic interference of the cylinder supports with the flow. The effective cooling velocity, C, of inclined cylinders such as hot-wire anemometer sensors is frequently described in terms of the velocity with the cylinder normal to the flow, U, and the angle between the cylinder normal and the flow, α, by $C = U(\cos^2\alpha + k^2 \sin^2\alpha)^{0.5}$. Extensive investigations have indicated that k^2 is predominantly a function of the cylinder length-to-diameter ratio. Arguments are presented which show that the k^2 term describes the effective turning of the flow through a small angle. This interpretation shows that for narrow support spacings, flow channelling by the supports, which causes the flow to be more normal to the cylinder, gives the apparent increase in cooling above the 'cosine law' so frequently reported. New measurements with inclined hot-wire anemometers show that when interference with the flow over the cylinder is expected to be a minimum, that is, at large length-to-diameter ratios, typically larger than 1000, k^2 assumes negative values.

NOMENCLATURE

A_1, B_1, C_1,	constants in the cooling function;
C,	cooling velocity;
d,	diameter;
d,	differential;
E,	hot-wire voltage;
k,	cosine law deviation factor defined by equation (1);
K,	hot-wire sensitivity to the stimulus indicated by the subscript;
l,	effective length of hot-wire or cylinder;
U,	free stream velocity.

Greek symbols

α,	angle between flow direction and wire or cylinder normal;
δ,	effective angle turned by flow due to flow interference;
Δ,	finite change.

Subscripts

α,	angle between flow direction and wire or cylinder normal;
C,	cooling velocity;
U,	free stream velocity.

1. INTRODUCTION

CONVECTIVE heat transfer from circular cylinders in cross-flow has been reviewed in considerable detail by Morgan [1]. Subsequent studies by Bremhorst and Gilmore [2], Højstrup *et al.* [3] and others have shown that heat transfer of such cylinders is significantly affected by conduction to the supports unless the cylinder length-to-diameter ratio is large, typically greater than 1000. Such large ratios lead to considerable experimental difficulties. In the first instance, measurements are, therefore, most conveniently attempted with hot-wire anemometers, even though this places a limit on the useful Reynolds number range which can be covered. The present study is restricted in this manner and, furthermore, only the role of the cooling velocity is considered.

Champagne *et al.* [4] suggest that the effective cooling velocity of a hot-wire is related to that with the wire normal to the flow by

$$C = U(\cos^2\alpha + k^2 \sin^2\alpha)^{0.5} \tag{1}$$

where α is the angle between the normal to the wire and the mean flow direction and k is a cosine law cooling deviation factor which depends primarily on the length-to-diameter ratio, l/d, of the wire. Their data yield the correlation

$$k = 0.27 - 0.000408(l/d) \tag{2}$$

which is slightly at variance with the author's conclusion that k is effectively zero at $l/d = 600$ but the difference is minor, particularly as only k^2 matters in all calculations. Only positive values of k were reported. These represent an increase in wire cooling above that given by a cosine law and are attributed to a tangential velocity component along the wire. All wires investigated by Champagne *et al.* [4] had a prong tip spacing which was essentially equal to the wire length so that the designations 'wire length' and 'prong tip spacing' could be used almost interchangeably. Wires tested were attached to prongs of equal length and measurements were made for $\pm\alpha$ about the symmetry position where the wire is normal to the flow [Fig. 1(a)].

Friehe and Schwarz [5] reported results of a more limited experiment. The hot-wire/support arrange-

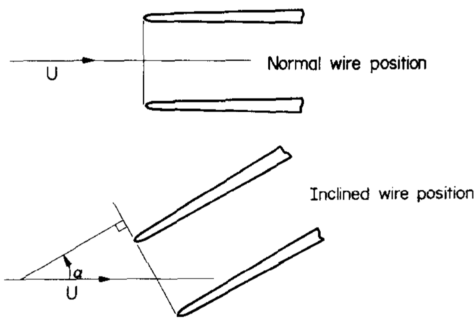

FIG. 1(a). Equal length prong hot-wire probe.

ment was similar to that of Champagne *et al.* [4] but the method of evaluation of the cosine law deviation differed. k^2 was found to be independent of velocity, but contrary to Champagne *et al.* [4], a small dependence on α was observed.

Jørgensen [6], using wires welded on to the prongs as well as wires with a significant length of plated length between the prong tips, confirmed the angular dependence of k^2 but the results also show a most significant difference between the two types of wires which had the same wire diameter and l/d ratio. In the case of the welded-on wire for which the prong spacing equals the wire length, k^2 is much higher than for the wire with end plating, for which the prong spacing was 3 mm whereas the unplated wire length was only 1.25 mm. If this result is correct, the universality of the findings by Champagne *et al.* [4] and Friehe and Schwarz [5] must be questioned as it now appears that k^2 is also strongly dependent on the geometry of the wire supports. A small dependence of k^2 on velocity was also observed. Only probes with equal length prongs were tested.

Most published investigations of heat loss from inclined wires are for wires mounted on equal length prongs. Rotation of the wire is in a symmetrical manner about the $\alpha = 0$ position [Fig. 1(a)]. For this arrangement, prong interference with the flow over the wire at $\alpha \neq 0$ is possible. At $\alpha = 0$, the effective cooling velocity will be a maximum even though it may not exactly equal the free stream velocity as shown by Comte-Bellot *et al.* [7] and Dahm and Rasmussen [8].

Inclined hot-wire measurements, where the present study has an immediate application, are rarely performed with the probe geometry of Fig. 1(a). Generally, the arrangement of Fig. 1(b) is used with or without a plated length. Such a wire is much more difficult to calibrate by the rotational method used by Champagne *et al.* [4] and others. Symmetry no longer exists and it is found that the maximum cooling velocity of the wire occurs not necessarily when the wire is normal to the flow.

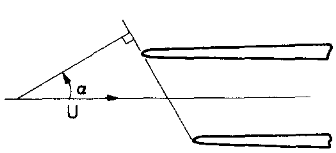

FIG. 1(b). Unequal length prong hot-wire probe.

The present investigation consists of two parts. The first reports measurements of k^2 for wires mounted on prongs of equal length but with different lengths of end plating. In the second part, a perturbation method which does not require measurements at $\alpha = 0$ to obtain k^2, was used for measurements with inclined wires mounted on prongs of unequal lengths.

2. PRELIMINARY CONSIDERATIONS

Flow interference studies by Strohl and Comte-Bellot [9] indicate that as prongs supporting the wire are placed closer to the active portion of the wire, the greater is the flow interference. It is not difficult to verify from potential flow theory that the flow over the wire will have its direction altered due to a channelling effect if the channel were only two-dimensional with infinitely long walls of the channel passing through the prongs normal to the plane of the diagram in Fig. 1(a). Actual prongs are finite in extent in the direction normal to the diagram but because of their comparatively large size, can still be expected to produce some channelling effect as indicated in Fig. 2. This was observed experimentally by placing a second prong next to the downstream prong. The net effect is to make the flow more normal by the angle δ thus giving an increase in cooling above that obtained by the cosine law. This representation of the flow over the wire is in contrast to the commonly used one which, in essence, assumes that in addition to the free stream velocity another component is generated along the wire hence giving an increase in cooling of the wire, Champagne *et al.* [4].

If turning of the flow is indeed the correct interpretation of the physical process, a more meaningful relationship for the effective cooling velocity is given by

$$C = U\cos(\alpha - \delta). \tag{3}$$

For $\delta \ll \alpha$ and $\alpha = 45°$ an expansion of equations (3) and (1) yields that $2\delta = k^2$. A physical explanation of the factor k^2 is, therefore, available in terms of δ and shows that negative values of k^2 simply mean that the

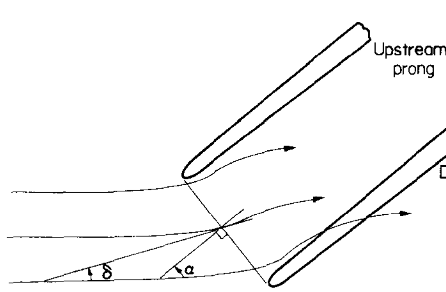

FIG. 2. Flow turning caused by channelling of flow by prongs.

flow becomes less normal to the wire with a consequent reduction in cooling relative to the cosine law.

Generally, only positive values of k^2 are reported — negative values sometimes being attributed, although without proof, to inaccuracies of the experimental data and its interpretation.

3. EXPERIMENTAL APPARATUS AND PROCEDURES

Measurements were performed in a dry air jet of 19 mm dia. just downstream of the exit plane where the turbulence intensity was below 0.5%. Test wires were mounted and rotated in a vertical plane with a mechanism which resulted in rotation of the wire about its mid-point. Pitot tube and hot-wire traverses showed the velocity profile at the jet exit to be flat for most of the exit area. The pitot tube of 1 mm dia. bore and 3 mm dia. body with a shaped tip used for calibration of the wire was placed 9–10 mm to one side of the wire. For any given calibration the air temperature in the plenum chamber upstream of the nozzle was constant to better than 0.5°C. This temperature was used for the evaluation of velocities from pitot tube measurements.

Hot-wires were operated at constant temperature with an overheat ratio of 0.5 for tungsten wires using a DISA 55 MOL system with a 55 M11 CTA bridge. Flow velocities during calibrations were obtained with a Betz micromanometer for velocities above 5 m/s and a Combist micromanometer for lower velocities. Above 91 m/s, pitot head readings were obtained with a mercury in glass U-tube manometer. No static pressure readings were taken and no allowances were made for compressibility effects at the higher velocities.

Hot-wire calibrations were generally performed from 0.7 to 90 m/s although some were taken to higher values. The aim was to perform curve fitting for hot-wire calibrations over approximately the same wire Reynolds number range at all times, thereby avoiding any significant deviations of the results attributable to the nature of the curve fit used.

Bremhorst and Gilmore [10] showed that the three term equation, equation (4), gives the best fit, in the least-squares sense, to hot-wire data over large velocity ranges

$$E^2 = A_1 + B_1\sqrt{U} + C_1 U. \tag{4}$$

The velocity ranges used here exceed those used by these authors but the original proponents of the equation (Siddall and Davies [11]), covered the full range used in the present investigations. To test the sensitivity of the results to the form of the calibration, test data were also fitted to the more commonly used equation

$$E^2 = A_1 + B_1 U^{0.5}. \tag{5}$$

The exponent of 0.5 was also replaced by 0.45, 0.4 and 0.37. It was found that generally the index of 0.4 gave almost as good a fit as equation (4).

Angle measurements during probe rotation were performed with a clinometer attached to the probe stem capable of one minute of arc resolution. Wire mounting angles on the probe were measured with a Hilger Watts projector also with a resolution of one minute of arc. Jet angle measurements were more difficult but hot-wire traverses of the jet as well as hot-wire orientation measurements (varying α at the jet axis about the axis of symmetry of wires mounted on prongs of equal length) indicated that the jet was perpendicular to the machined face of the jet exit.

4. CASE OF EQUAL-LENGTH PRONGS

Figure 3 shows the dimensions and general geometry of the probe tip used for these tests. The wires were of tungsten, 5 μm dia., with copper plated ends and an unplated portion of length l from which heat

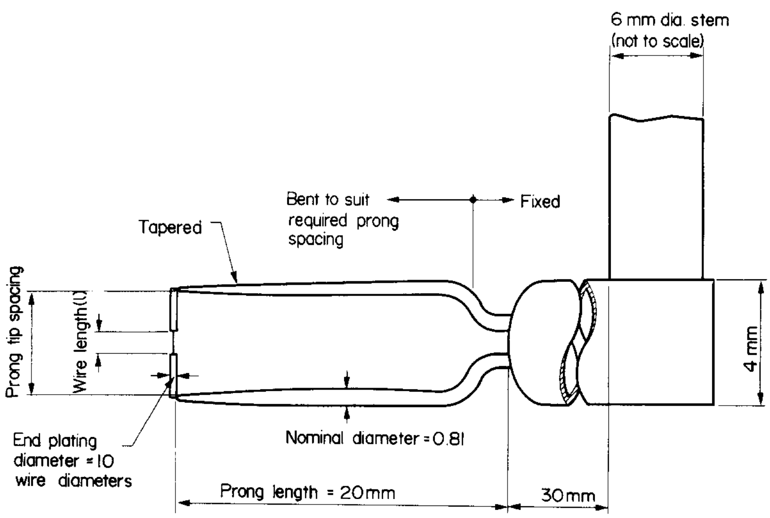

FIG. 3. Dimensions of equal length prong hot-wire probe tested.

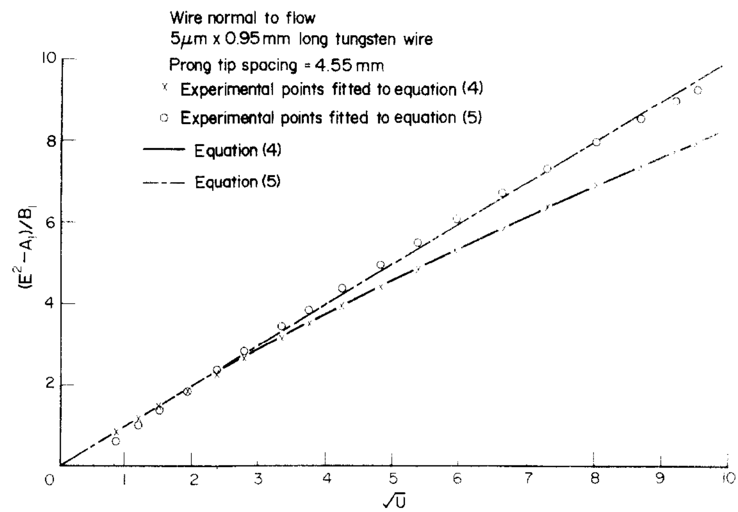

FIG. 4. Cooling function curve-fit.

transfer takes place by convection. The prongs were bent as indicated in Fig. 3 to give the required prong tip spacing.

A hot-wire calibration over the full velocity range was performed with the wire normal to the flow followed by measurements of wire voltage at various α. Figure 4 shows typical least-squares curve fits of the experimental data to equations (4) and (5) from which the superiority of equation (4) can be readily seen. Effective cooling velocities were evaluated from this curve. A plot of cooling velocity against α and the anticipated symmetry about $\alpha = 0$ were used to double check the geometric set-up of the probe. k^2 was then evaluated from the effective cooling velocity and the measured α with equation (1), where U was obtained from the wire voltage at $\alpha = 0$.

Measured values of k^2 for the case of probe tip spacing = wire length are shown in Fig. 5(a) together with the curve fitted through the data of Champagne *et al.* [4] [equation (2)]. The trends of the two results are identical, the difference in level being attributable to differences in detail prong design and prong diameter. Dependence of k^2 on prong tip spacing is shown in Fig. 5(b) where the unplated portion of the wire is essentially constant at 1 mm. The strong influence of the prongs is clearly seen. Champagne's *et al.* [4] results [equation (2)], on the other hand would predict a value of $k^2 = 0.035$ for this l/d. The present results are, however, consistent with those by Jørgensen [6], the difference in level of k^2 being again attributable to differences in prong diameter. From comparison of the results of Figs. 5(a) and (b) it is concluded that the effect on k^2 of prong tip spacing is just as strong as that of wire length.

Negative values of k^2 are noticed for large prong spacings, at least in the present results. From the shape of the plot of equation (2), it cannot be ruled out that Champagne *et al.* [4] would not also have obtained

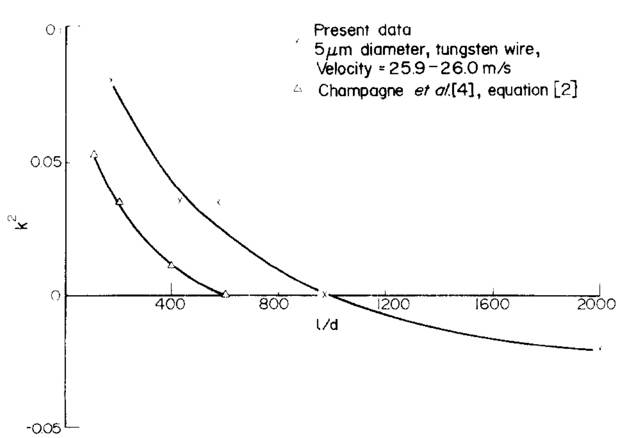

FIG. 5(a). k^2 dependence on l/d for probes with wire length = prong tip spacing, equal length prongs.

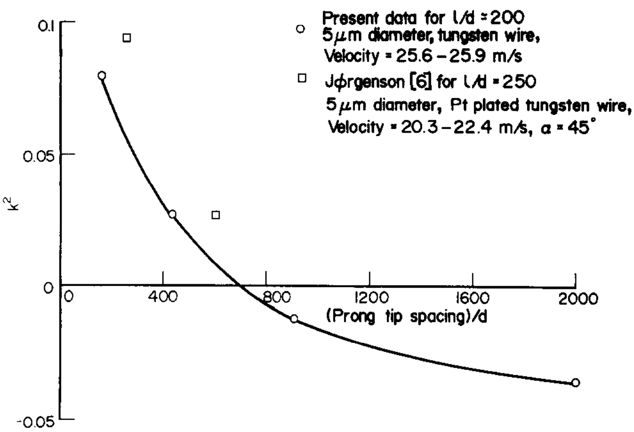

FIG. 5(b). k^2 dependence on prong tip spacing for wires with fixed l/d, equal length prongs.

negative values of k^2 if longer wires had been tested. If k^2 is equivalent to a turning of the flow through an angle δ, it is readily seen that for small prong spacings where a large amount of flow interference and hence flow channelling exists, k^2 takes on large positive values thus indicating that the flow is more normal to the wire than if the prongs had not been there. The negative values of k^2 for large prong spacings indicate that the flow is more along, or tangential to, the wire than indicated by the geometrically measured α. The results further illustrate that very large l/d ratios are required if the wire or cylinder heat transfer is not to be influenced aerodynamically by its supports.

5. CASE OF UNEQUAL-LENGTH PRONGS

For these tests the hot-wire/prong arrangement of Fig. 1(b) was used with the prongs nominally parallel to the stream. The prong tip spacing (distance between attachment points of the wire to the prongs) was kept at 4.5 mm for all tests and the wire length-to-diameter ratio was varied by changing the length of end plating. Other probe details were generally as given in Fig. 3 except that the top prong was shortened to give $\alpha \simeq 45°$. Determination of k^2 for this case was by the more complex method described in Appendix A.

The three curves of Fig. 6, for which only the wire l/d ratio was changed, show that as the wire length decreases relative to the prong tip spacing, k^2 becomes velocity dependent. The wire with the substantially thicker end plating also shows a significant velocity dependence. Furthermore, k^2 for this wire is significantly lower than for that of a similar l/d ratio but with the smaller thickness of end plating. These results are consistent with a turning of the flow to give an effective flow angle different to that measured geometrically. Since in the last case only the end

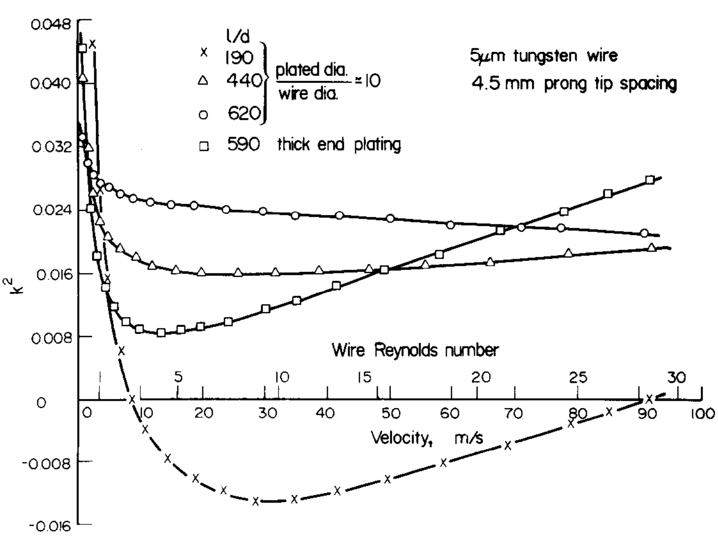

FIG. 6. Dependence of k^2 on wire length-to-diameter ratio and flow velocity, unequal length prongs.

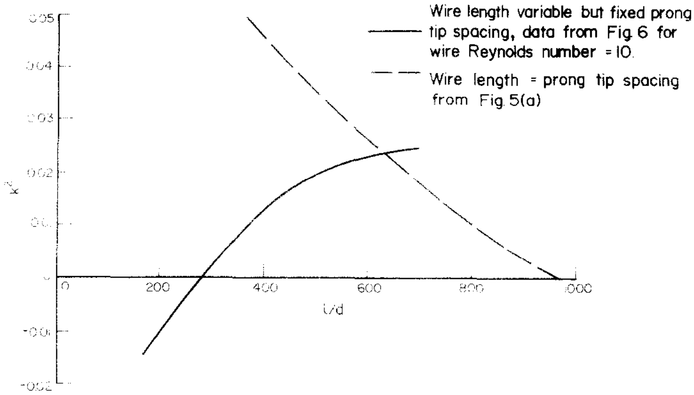

FIG. 7. Comparison of k^2 values for fixed prong tip spacing but varying l/d with those for prong tip spacing equal to wire length.

plating was changed, it must be concluded that this produces an interference effect — most probably in the form of a downwash flow component along the wire. The similarity of trends for the wire with thick end plating and the $l/d = 190$ wire, further reinforces this conclusion as, for the shorter wire, the greater length of end plating allows the downwash flow component to develop more than for wires of larger l/d.

The significant rise of k^2 at wire Reynolds numbers below unity can be attributed to the fact that pure conduction of heat becomes the dominant heat transfer mode thereby reducing the effect of inclination. Similar results were obtained for a 2.5 μm tungsten wire and a 10 μm platinum–iridium wire.

A comparison of k^2 for the three wires of Fig. 6 with the same diameter of end plating and prong tip spacing, with the measurements of Fig. 5(a) are shown in Fig. 7. It is seen that when the prong tip spacing is constant and the wire length is varied by changing the length of end plating, trends for k^2 as a function of l/d directly opposite to those for variable prong tip spacing (but equal to wire length) are obtained.

Instead of using the three term curve-fit, equation (4), to obtain k^2, equation (5) with the exponent 0.5 as well as with 0.45 was tried. The effect was to alter the level of k^2 but the general trends observed in Fig. 7 and the negative values of Figs. 5(a) and (b) were preserved.

The practical question arises in hot-wire anemometry where end plated wires are often used, whether it is better to tolerate the consequent velocity dependence of k^2 or to use the welded-on wires for which prong tip spacing and wire length are equal and for which k^2 is independent of velocity. Since static calibrations of the type used here and by others, imply an infinite scale of turbulence, it follows that in the presence of prong or end plating interference, k^2 will apply only to the large scales of turbulence for which the boundary layer over the prong or end plating can develop fully. The finer scales will not sense the presence of the disturbance until they have passed the wire and will, therefore, yield a different k^2. If this distortion of measurements is to be avoided, the smallest possible diameter of end plating and largest possible prong tip spacing should be used. The latter finding is consistent with the studies of Strohl and Comte-Bellot [9].

6. CONCLUSIONS

Experiments with inclined hot-wires have shown that the factor k^2 in the effective velocity relationship $C = U(\cos^2\alpha + k^2 \sin^2\alpha)^{0.5}$ for inclined wires or cylinders in cross-flow can have a significant dependence on the proximity of supports, the diameter of end plating and the flow velocity. The case of prong tip spacing equal to wire length, shows that k^2 decreases with increasing l/d as is also the case with fixed wire length and increasing prong tip spacings, but for fixed prong tip spacing, k^2 increases with increasing l/d. Cases for which prong and/or end plating interference is expected to be a minimum, k^2 is negative, that is, the cooling of the undisturbed wire is less than that given by the 'cosine law' which is consistent with thickening of the boundary layer when flow is at an angle to the wire or cylinder thus reducing the effective cooling. Positive values of k^2 were observed when significant flow channelling by the prongs can be expected to exist. This is argued to be a consequence of turning of the flow, causing it to be more normal to the wire hence giving the apparent increase in cooling above that expected from the 'cosine law'. At Reynolds numbers below unity, the present measurements indicate that k^2 increases very rapidly due to the increased role of conduction heat transfer. End effects become insignificant only for very large length-to-diameter ratios, typically well over 1000.

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APPENDIX

Perturbation Method for Measurement of k^2

The method of Section 4 cannot be applied readily to probes with unequal prong lengths as the effective wire normal position no longer coincides with the geometrically normal one. Measurements with the present probes have indicated rotations of the flow of up to 7° towards the wire normal thus further emphasizing the flow turning effect of the prongs. In view of this flow disturbance introduced by the prongs, a method of determining k^2 which does not require calibration data for the $\alpha = 0$ position was developed. The method consists of varying the wire angle through small angles about the nominal operating position but still uses the three term curve fit, equation (4), and the cooling velocity function of equation (1).

For calibrations performed in a stream of very low turbulence intensity, the wire voltage, E, for constant resistance operation is a function only of the cooling velocity, C, given by equation (1). If K denotes the wire sensitivity to the stimulus given by its subscript then the following derivations apply:

$$E = E(C) \quad \text{and} \quad C = C(U,\alpha)$$

$$\mathrm{d}E = \frac{\partial E}{\partial C}\frac{\partial C}{\partial U}\mathrm{d}U + \frac{\partial E}{\partial C}\frac{\partial C}{\partial \alpha}\mathrm{d}\alpha$$

$$= K_C K_U \mathrm{d}U + K_C K_\alpha \mathrm{d}\alpha \tag{A1}$$

$$= K_C K_U\left(\mathrm{d}U + \frac{K_\alpha}{K_U}\mathrm{d}\alpha\right).$$

Experimentally, if the $\alpha = 0$ position is not to be used, K_C and K_U cannot be determined separately, but $(K_C K_U)$ is obtainable as a single quantity from a calibration at fixed α by varying U. Application of equation (1) yields

$$\frac{K_\alpha}{UK_U} = \frac{(k^2-1)\sin\alpha\cos\alpha}{\cos^2\alpha + k^2\sin^2\alpha} \tag{A2}$$

from which k^2 can be determined if α is known,

$$k^2 = \frac{1 + \left(\dfrac{K_\alpha}{UK_U}\right)\Big/\tan\alpha}{1 - \left(\dfrac{K_\alpha}{UK_U}\right)\tan\alpha}. \tag{A3}$$

k^2 determined in this manner gives a particularly sensitive result as any error in (K_α/UK_U) is amplified rather than suppressed. As the sensitivities are also α dependent these must be evaluated from the wire voltage change, ΔE, by integration of equation (A1). At constant U, for a change in angle, $\Delta\alpha$.

$$\Delta E = \int_\alpha^{\alpha+\Delta\alpha}(K_C K_U)\left(\frac{K_\alpha}{K_U}\right)\mathrm{d}\alpha. \tag{A4}$$

Assuming that the integrand varies linearly over the range $\Delta\alpha$, and introducing (K_α/K_U) at $\alpha + \Delta\alpha/2$ together with its variations of $\pm\Delta(K_\alpha/K_U)$ about this point allows transformation of equation (A4) to

$$\frac{\Delta E}{\Delta\alpha} = \frac{1}{2}\left[\frac{K_\alpha}{K_U}\right]_{\alpha+\frac{\Delta\alpha}{2}}\left\{(K_C K_U)_{\alpha+\Delta\alpha} + (K_C K_U)_\alpha + [(K_C K_U)_{\alpha+\Delta\alpha} - (K_C K_U)_\alpha]\Delta\left(\frac{K_\alpha}{K_U}\right)\Big/\left[\frac{K_\alpha}{K_U}\right]_{\alpha+\frac{\Delta\alpha}{2}}\right\} \tag{A5}$$

As $K_C K_U$ does not vary significantly with α, the difference term of equation (A5) becomes of second order which may be neglected.

Calibrations were performed by measuring the output voltage at the three angles α, $\alpha + 5°$ and $\alpha - 5°$ with α nominally at 45° at each velocity. The exact value of α was determined prior to the calibration. Mechanical stops were set on the traversing mechanism to ensure repeatability of the $\pm 5°$ positions during calibration. The three term equation, equation (4), was then fitted to the voltage–velocity data at each angle setting. As expected, the coefficients A_1, B_1, C_1 varied with the wire angle. From these curve-fits, $(K_C K_U)$ for the three angles could be evaluated and hence $[K_\alpha/K_U]_{\alpha+\Delta\alpha/2}$ and $[K_\alpha/K_U]_{\alpha-\Delta\alpha/2}$, the arithmetic average of which gave $[K_\alpha/K_U]_\alpha$ for use in equation (A3).

A comparison of this new method with that of Section 4 was attempted for the 5 μm × 0.95 mm long tungsten wire mounted on a probe with prongs of equal length and 4.55 mm apart [one of the points of Fig. 5(b)]. The two methods yielded identical values for k^2. Good agreement is to be expected since any prong interference is included in the calibration in both methods.

EFFET DES SYSTEMES DE MONTAGE SUR LE TRANSFERT THERMIQUE POUR LES CYLINDRES INCLINES EN ATTAQUE TRANSVERSALE

Résumé—Des étubes antérieures ont montré que la conduction dans les systèmes de montage affecte sensiblement les caractéristiques de transfert thermique des cylindres en attaque transversale sauf si le rapport longueur–diamètre est grand, disons supérieur à 1000. Pour les cylindres inclinés il existe un effet supplémentaire du à l'interférence aérodynamique des supports du cylindre avec l'écoulement. La vitesse effective de refroidissement, C, de cylindres inclinés tels que les sondes d'anémomètre à fil chaud, est fréquemment décrite en fonction de la vitesse avec le cylindre normal à l'écoulement U et de l'angle entre le cylindre normal et l'écoulement α, par $C = U(\cos^2\alpha + k^2\sin^2\alpha)^{0.5}$. Des études extensives ont montré que k^2 est principalement une fonction du rapport longueur–diamètre du cylindre. Des arguments sont présentés pour montrer que le terme k^2 décrit la déviation de l'écoulement d'un petit angle. Cette interprétation montre que pour des espacements étroits du support, la canalisation de l'écoulement par les supports, qui rend l'écoulement plus normal au cylindre, donne un accroissement apparent du refroidissement par rapport à la "loi cosinus" si fréquemment citée. De nouvelles mesures avec des anémomètres à fil incliné montrent que lorsque l'interférence avec l'écoulement sur le cylindre est admise être minimale, c'est-à-dire aux grands rapports longueur–diamètre supérieurs à 1000, k^2 prend des valeurs négatives.

EINFLUSS DER HALTERUNGSSYSTEME AUF DEN WÄRMEÜBERGANG AN SCHRÄG ANGESTRÖMTEN ZYLINDERN IM KREUZSTROM

Zusammenfassung — Frühere Untersuchungen haben gezeigt, daß die Wärmeleitung in den Halterungssystemen die Wärmeübertragungscharakteristik von Zylindern im Kreuzstrom bedeutend beeinflußt, es sei denn, das Verhältnis von Länge zu Durchmesser ist groß, z.B. über 1000. Bei schräg angeströmten Zylindern gibt es einen zusätzlichen Effekt durch die bedeutende aerodynamische Beeinflussung der Strömung durch die Zylinderhalterungen. Die effektive Kühlungsgeschwindigkeit C schräg angeströmter Zylinder, wie z.B. der Fühler von Hitzdrahtanemometern, wird oft beschrieben in Abhängigkeit von der Geschwindigkeit in Richtung der Zylindernormalen U und dem Winkel zwischen der Zylindernormalen und der Strömungsrichtung α durch die Beziehung

$$C = U(\cos^2\alpha + k^2\sin^2\alpha)^{0.5}.$$

Umfangreiche Untersuchungen haben darauf hingewiesen, daß k^2 vorwiegend eine Funktion des Längen/-Durchmesser-Verhältnisses des Zylinders ist. Es wird gezeigt, daß der Ausdruck k^2 die effektive Drehung der Strömung um einen kleinen Winkel beschreibt. Dieser Umstand erklärt, daß für kleine Halterungsabstände eine Kanalisierung der Strömung, die die Strömung mehr in die Normalenrichtung des Zylinders lenkt, zu der deutlichen Erhöhung der Wärmeabgabe über das Cosinus-Gesetz hinaus führt, von der so oft berichtet wird. Wenn man minimale Störungen der Strömung am Zylinder erwarten kann, d.h. bei großen Längen/Durchmesser-Verhältnissen von über 1000, zeigen neue Messungen mit schräg angeströmten Hitzdrahtanemometern, daß k^2 negative Werte annimmt.

ВЛИЯНИЕ ДЕРЖАВКИ НА ТЕПЛОПЕРЕНОС ОТ ОБТЕКАЕМОГО ЦИЛИНДРА В СКОШЕННОМ ПОТОКЕ

Аннотация — Проведенные ранее исследования показали, что передача тепла теплопроводностью к державке оказывает существенное влияние на теплообменные характеристики поперечно обтекаемых цилиндров, если отношение длины цилиндра к диаметру не превышает 1000. В случае скошенного потока возникает дополнительный эффект, обязанный значительному аэродинамическому взаимодействию потока с державкой. Эффективная скорость охлаждения C наклонного цилиндра, например нити термоанемометра, обычно выражается через скорость U поперечно обтекаемого цилиндра и величину угла α между нормалью и потоком, т. е.

$$C = U(\cos^2\alpha + k^2\sin^2\alpha)^{0.5}.$$

Во многих работах было показано, что k^2 зависит в основном от величины отношения длины цилиндра к его диаметру. В данной работе высказаны соображения в пользу того, что величина k^2 описывает эффективный поворот потока на небольшой угол. Тогда при небольшом расстоянии между державками скорость охлаждения цилиндра оказывается выше той, которая обычно рассчитывается по «закону косинуса». Новые термоанемометрические измерения с наклонной нитью показали, что при минимальном взаимодействии потока с цилиндром, т. е. при больших значениях отношения длины цилиндра к диаметру, как правило превышающих 1000, величина k^2 принимает отрицательные значения.