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THE ROLE OF TURBULENCE IN DETERMINING THE HEAT-TRANSFER CHARACTERISTICS OF IMPINGING JETS

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Abstract—Data on the variation of local heat-transfer coefficients produced by impinging jets have been re-examined in the light of measurements of the velocity and turbulence distributions in submerged jets and in the context of other work on the influence of turbulence on heat transfer. It is shown that some seemingly anomalous heat-transfer phenomena can be explained as effects of the intense and spatially varying turbulence inherent in jets.

NOMENCLATURE

B, width of slot nozzle;
D, diameter of round nozzle;
h, local heat-transfer coefficient;
h_o, heat-transfer coefficient at the stagnation point;
k, thermal conductivity of air;
Nu, local Nusselt number, hB/k;
Nu_o, Nusselt number at stagnation point, h_oB/k;
Re_e, Reynolds number of jet at exit, $u_eB\rho/\mu$;
u, jet velocity;
u_e, jet velocity at nozzle exit;
u_m, center-line velocity of jet;
u', R.M.S. value of fluctuating component of velocity;
x, lateral distance from stagnation point or from center line of jet;
z, distance along jet axis;
z_n, nozzle-to-plate spacing;
Δp, static pressure on plate;
Δp_o, static pressure at the stagnation point;
μ, viscosity of air;
ρ, density of air.

INTRODUCTION

THE RESULTS of measurements of local heat-transfer coefficients between flat surfaces and impinging air jets were reported in two earlier communications [1, 2], which dealt with both axi-symmetric and two-dimensional jets. The fine spatial resolution of local heat-transfer rates, made possible by a very small heat-flow transducer developed for this purpose [3], revealed a number of interesting and previously unexpected phenomena; notably the existence of a maximum in the variation of stagnation point heat-transfer coefficients with nozzle-to-plate spacing, and several secondary peaks in the radial (or lateral) distribution of local heat-transfer coefficients. These phenomena are illustrated in Figs. 1 and 2, taken from reference 2 and pertaining specifically to slot jets. Similar results have been obtained with circular jets also.

This paper represents an attempt to account for these rather complex patterns in the variation of local heat-transfer coefficients in terms of the flow conditions with which they are associated. To anticipate some results briefly, the heat-transfer characteristics of impinging jets can be explained in terms of velocities alone only at very low Reynolds numbers and under otherwise restricted conditions. At higher Reynolds numbers—and even for initially laminar jets—the turbulence generated by the jet itself plays an important role in determining the heat-transfer characteristics of impinging jets. This role is most marked in regions where the mixing-induced turbulence is not yet fully developed and where the sometimes opposed effects of changes in velocity and turbulence account for the non-monotonic variation of heat-transfer coefficients.

We begin this discussion with a brief review of flow in submerged jets and of currently held

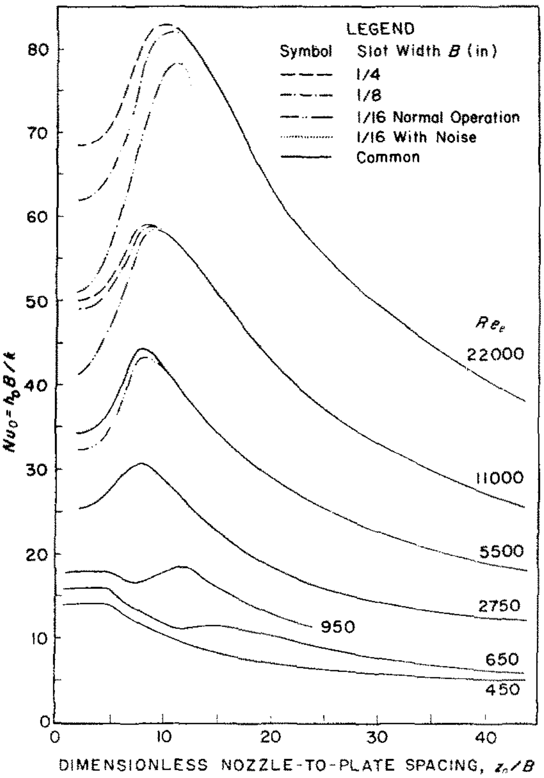

FIG. 1. Correlation of heat-transfer coefficients at the stagnation point of a two-dimensional air jet.

views of the effects of turbulence on heat transfer.

FLOW CONSIDERATIONS

Velocity and turbulence distributions in free jets are schematically indicated in Fig. 3, drawn on the basis of Corrsin's measurements on axisymmetric air jets [4].

Immediately on leaving the nozzle, the air in the jet begins to entrain the surrounding still air. The width of the *mixing region* increases continuously, and at some distance from the nozzle it is wide enough to have penetrated to the center line of the jet. Up to this point the center-line velocity is practically unaffected by mixing and substantially equal to the nozzle exit velocity [cf. Fig. 3(a)]. Beyond the end of the so-called *potential core* the center-line velocity also diminishes as the jet shares its momentum with more and more entrained fluid.

Our measurements of velocities in turbulent slot jets have confirmed those of Albertson *et al.* [5], which showed their potential cores to extend for approximately five slot widths, beyond which their center-line velocity decreases with $\sqrt{(1/z)}$, i.e. less rapidly than for circular jets, for which u_m is proportional to $1/z$.*

As to turbulence, Corrsin's data show that the turbulence generated by mixing is much more intense than that usually encountered in pipe flow, reaching levels of the order of thirty per cent. As we may note from Fig. 3(a), the intensity of turbulence u'/u_m—i.e. the relative magnitude of the R.M.S. fluctuations of the axial velocity (u'), referred to the local values of the time-average axial velocity (u_m)—increases continuously with jet length. The absolute magnitude of the velocity fluctuations reaches a maximum in the neighborhood of $z/D = 8$, as shown by the curve of u'/u_e, in which the R.M.S. fluctuations are related to the (constant) nozzle exit velocity u_e.

It should be noted as a matter of particular importance to the present considerations that the turbulence along the center line of the jet rises appreciably even before the axial velocity has begun to decline significantly.

The radial distributions of turbulence at various positions along the jet are shown in Fig. 3(b). One may note that initially the turbulence is greatest in the center of the mixing region, i.e. at $x = \pm \frac{1}{2}D$. While turbulence starts early to penetrate into the so-called potential core, the peak in the radial distribution of turbulence does not reach the center line of the jet until some distance downstream.

The results of a few exploratory measurements of the turbulence along the center line of slot jets are illustrated in Fig. 4. They confirm that the distribution of turbulence in two-dimensional jets is similar to that found by Corrsin in

* These measurements with a hot wire anemometer in free jets may be contrasted with measurements of the arrival velocities of impinging jets by means of pressure taps at the stagnation point [2]. The latter also show the proportionality to $\sqrt{(1/z_n)}$ but are generally higher, being equal to the velocities in free jets a small distance upstream of the plate. This results from the reduced rate of mixing along the jet axis during deceleration on account of the lateral spread of the impinging jet [7].

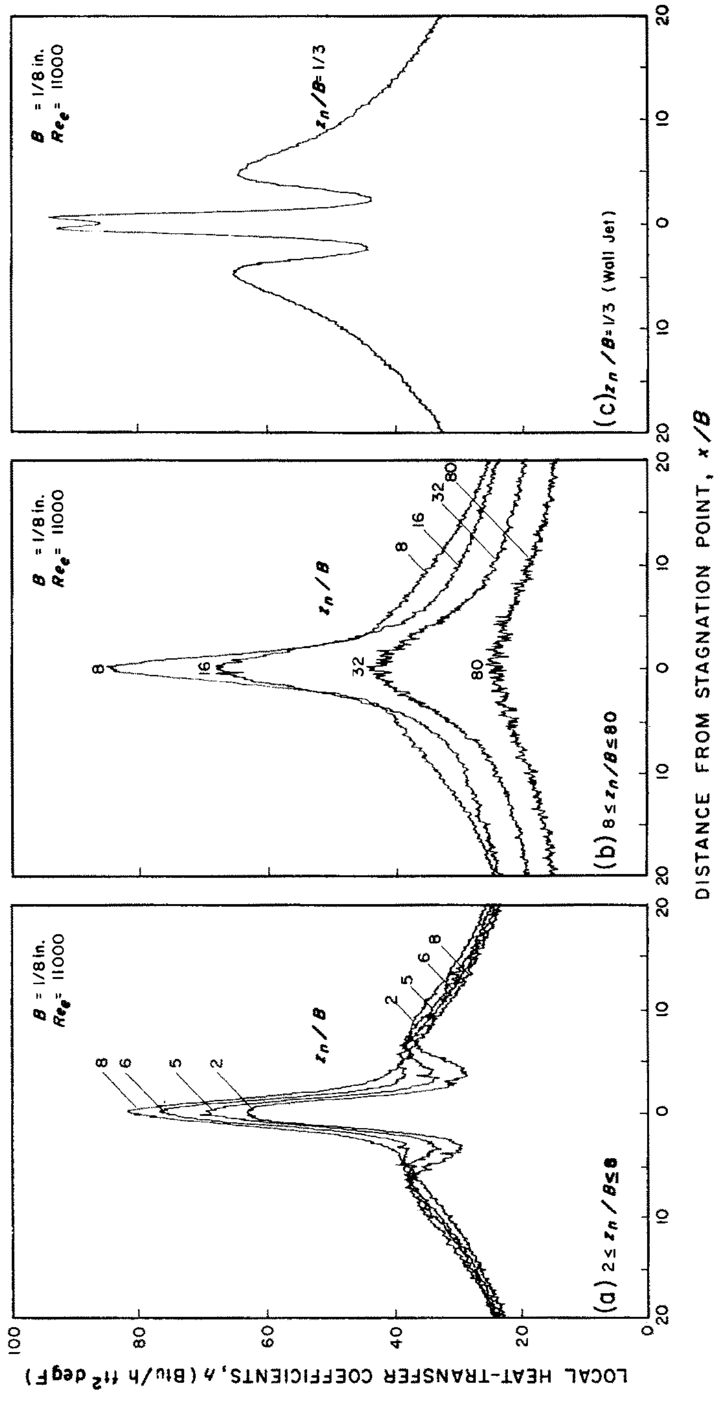

FIG. 2. Lateral variation of local heat-transfer coefficients between a plate and an impinging two-dimensional air jet.

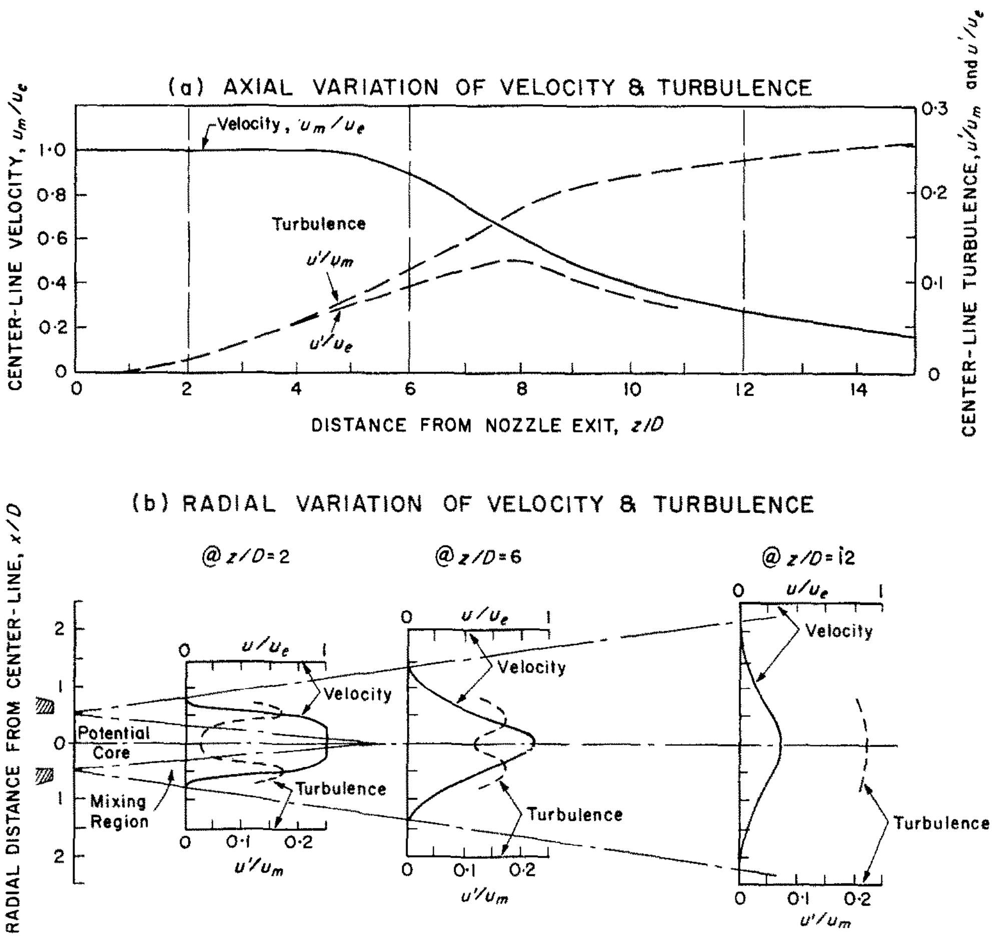

FIG. 3. Schematic distribution of velocity and turbulence in an axi-symmetric jet (after Corrsin).

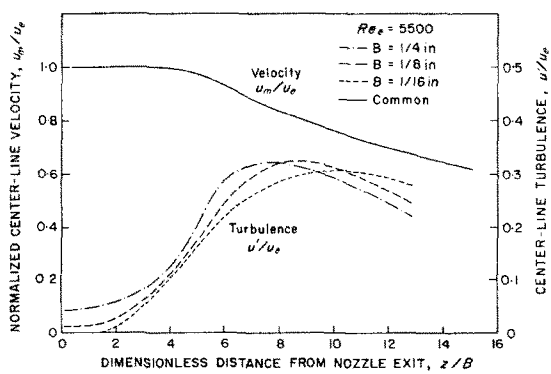

FIG. 4. Variation of velocity and turbulence along the center line of two-dimensional air jets.

axi-symmetric jets. They also show that the turbulence intensities at the exits from our three nozzles differ. This has been attributed to incomplete geometrical similarity, in that the contraction ratios between the nozzle throats and their approach channels differ for nozzles of different size.

To turn from free jets to impinging jets, velocity distributions in these have been studied by Leclerc [6] and Schrader [7], both of whom dealt with circular jets. The former determined the stream lines in an impinging potential flow, using an electric analog, and the latter measured actual velocity distributions in air jets. Their results agree in showing that a submerged circular jet propagates as a free jet to within a distance of roughly 1·2 nozzle diameters from the impacted surface, where its deceleration begins. An exact solution for the boundary-layer thickness in the stagnation region of a laminar flow against an infinite plate has been given by Schlichting [8]. By adapting this treatment to jets of finite size, Schrader has shown that a boundary layer of constant thickness covers a *stagnation region* having a radius of approximately 1·1 nozzle diameters. Beyond this, the boundary layer thickens.* Deflection of an impinged jet takes place in a region including and extending beyond the region of constant boundary-layer thickness. Surrounding this *jet deflection region* is one in which a radial "wall jet" spreads over the surface, substantially parallel to it. This flow is retarded by wall friction on one side and jet mixing on the other.

There is little direct information on the turbulence generated in a stagnation flow [9]. Our own explorations of the stagnation region with a hot wire, though not conclusive, support the view that the velocity fluctuations in various parts of the free jet are carried along in the deflected stream and that mixing-induced turbulence continues to be generated in the wall jet. The continued increase of the turbulence level in the wall-jet region presumably depends on whether turbulence in the jet was fully developed prior to impingement.

The effects of turbulence on heat transfer have been investigated by several workers, certain results obtained on cylinders in cross-flow [10–12] and on flat plates in parallel flow [13, 14] being most relevant to the present considerations. This work is well reviewed in the publications of Kestin *et al.* [12, 13], who have shown that free stream turbulence can affect heat transfer in two ways:

(1) In the absence of pressure gradients—as, for example, over a flat plate parallel to the flow—increased turbulence in the free stream tends to promote the transition from a laminar to a turbulent boundary layer. The distribution of local heat-transfer coefficients is affected only to the extent of the forward shift of the point of transition.

(2) In the presence of pressure gradients—such as may be found on the forward part of a cylinder in cross-flow or on a flat plate in an accelerating stream—increasing free stream turbulence also has a direct effect on local heat-transfer coefficients, increasing them without causing an irreversible change in the character of the boundary layer.

Depending on their sign, pressure gradients also influence the stability of the boundary-layer flow. Negative pressure gradients tend to stabilize it and thus to delay the transition to turbulence.

Since—as shown in Fig. 5—the region of impingement and jet deflection is the seat of marked negative pressure gradients, variations in the turbulence level of the jet could well be expected to affect local heat-transfer coefficients in this region. Beyond this, in the region of flow parallel to the plate, the pressure is already atmospheric. In the absence of pressure gradients further changes in the turbulence level of the "free stream"—in this case the wall jet just outside the boundary layer—would not be expected to affect local heat-transfer coefficients, unless they were to influence the transition (if any) from laminar to turbulent flow in the boundary layer.

* This result is slightly at variance with the theoretical conclusion of Kezios [15] who, on the basis of the radial velocity distribution in an impinging axi-symmetric jet, predicted a slight thinning of the boundary layer in the vicinity of $x/D = 1$. This thinning effect would not be expected to be present in the case of two-dimensional stagnation flows.

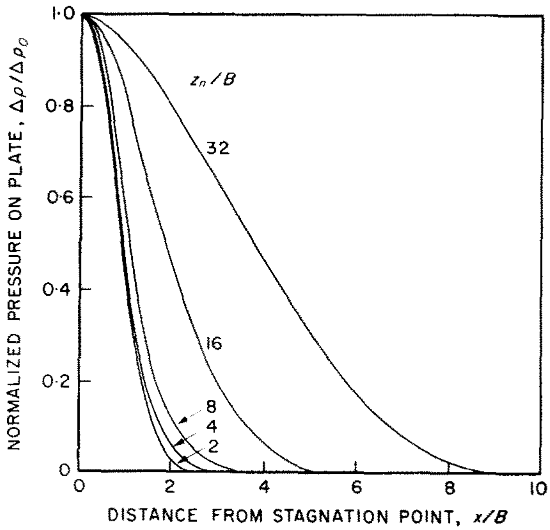

FIG. 5. Distribution of static pressure over the impacted plate.

We turn next to an elucidation of the heat-transfer phenomena observed with impinging jets.

HEAT TRANSFER AT THE STAGNATION POINT

Guided by Schrader's treatment of boundary-layer thickness at the stagnation point, one would expect the stagnation point heat-transfer coefficient produced by a slot jet to be inversely proportional to its width at impact and directly proportional to its velocity at impact. Considering the variation of this velocity with nozzle-to-plate spacing, one would further expect stagnation point Nusselt numbers to be constant for nozzle-to-plate spacings shorter than the potential core, i.e. for $z_n/B < 5$, and to diminish in proportion to $(z_n/B)^{-\frac{1}{2}}$ beyond that. In fact, this is the case only for the lowest Reynolds number studied, as shown in Fig. 1 by the curve for $Re_e = 450$. This clearly refers to a jet laminar throughout its length. The deviation of the behavior of all other jets from this expected pattern is ascribed to the high levels of turbulence inherent in the spreading of submerged jets.

At the other extreme from the $Re_e = 450$ jet are the four jets for which $Re_e > 2750$. While these are turbulent already on emerging from the nozzles, their turbulence is increased by orders of magnitude as a result of mixing. As shown by Figs. 3(a) and 4, the increase in axial turbulence begins already at $z/B = 1$, i.e. well within the potential core. It is this increasing turbulence in a part of the jet in which velocities are still substantially constant that is held responsible for the marked increase of stagnation point heat-transfer coefficients with increasing nozzle-to-plate spacing. Their increase continues even beyond the point at which the arrival velocity begins to diminish at about $z_n/B = 5$. Only at $z_n/B > 8$–10 does the effect of diminishing arrival velocity and increasing jet width begin to dominate over that of a by now almost constant turbulence level, resulting in progressively decreasing stagnation point heat-transfer coefficients.*

To test this hypothesis a turbulence promoter in the form of an 18 mesh screen was installed in the nozzle, $\frac{3}{16}$ inch upstream from its exit. For a $\frac{1}{8}$ in nozzle at $Re_e = 11\,000$ this increased the turbulence at the nozzle exit from 2·5 to 18 per cent. Figure 6 is a reproduction of the recordings of heat-transfer rate as a function of nozzle-to-plate spacing, obtained with and

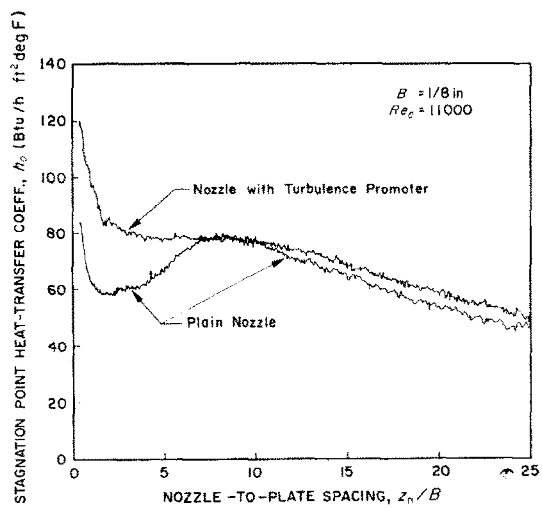

FIG. 6. Effect of artificially induced turbulence on stagnation point heat-transfer coefficients.

* We may note that the peak stagnation point heat-transfer rates coincide, approximately, with the peaks in the absolute magnitude of axial velocity fluctuations, as shown by the plots of u'/u_e in Figs. 3(a) and 4.

without the turbulence promoter. It clearly shows that the non-monotonic variation of h_o with z_n/B can be suppressed by modifying the distribution of turbulence in the impinging jet. It also shows that stagnation point heat-transfer coefficients can be increased by artificially increasing the initial turbulence of the jet. This is most effective at relatively small nozzle-to-plate spacings at which the turbulence induced by mixing, which is increasing with increasing jet length, has not yet masked that due to the turbulence promoter, which is, of course, decaying with increasing distance from the screen [16].

Returning to Fig. 1 and the data obtained at intermediate Reynolds numbers, the flow in the nozzles at $Re_e < 2000$ is laminar. Mixing is correspondingly slower than in initially turbulent jets, and the jets for which $Re_e = 650$ and 950 evidently retain their laminar character for some distance after emerging from the nozzles. The variation of stagnation point heat-transfer coefficients with nozzle-to-plate spacing starts out as for the slowest jet, for which $Re_e = 450$—the Nusselt number being constant for z_n/B up to about 5·5, and then declining proportionately to $(z_n/B)^{-\frac{1}{2}}$. However, the turbulence induced by mixing does before long reach the mid-plane of these somewhat faster jets, causing stagnation point heat-transfer coefficients to rise slightly—at about $z_n/B = 11$ for $Re_e = 650$ and already at $z_n/B = 8$ for $Re_e = 950$.

In summary, the presence of pressure gradients in the stagnation region appears to make this a favorable setting for turbulence in the "free stream" to enhance local heat-transfer coefficients. The non-monotonic variation of stagnation point heat-transfer rates with nozzle-to-plate spacing thus results from the interaction of two opposite effects: that of the center-line turbulence, which increases with jet length, and that of the ratio of arrival velocity to jet width at impingement, which governs the boundary-layer thickness at the stagnation point and decreases with increasing jet length.

In spite of this marked effect of turbulence on heat transfer, the data obtained with fully developed turbulent jets and also with jets that are becoming turbulent as a result of jet mixing are very effectively correlated by Fig. 1 without any separate parameter to characterize turbulence. This suggests that the intensity of turbulence in these jets is uniquely determined by the jet Reynolds number and the dimensionless jet length. Where, as in initially turbulent but not fully developed jets, velocity and turbulence are not yet uniquely related, the simple correlation of Fig. 1 ceases to be adequate. This is shown by the apparent size-dependence of stagnation point Nusselt numbers in the range of $Re_e > 5000$ and $z_n/B < 8$, which is really only a reflection of the different initial turbulence levels in our jets. It is shown even more dramatically in Fig. 6 by the marked susceptibility of h_o to artificially induced turbulence in the jet.

LATERAL VARIATION OF HEAT-TRANSFER COEFFICIENTS

We turn next to the more complex phenomena involved in the lateral variation of local heat-transfer coefficients. These are illustrated in Fig. 2, and our explanation of them is necessarily somewhat speculative.

Again following Schrader's work, a consideration of boundary-layer thicknesses would lead one to expect heat-transfer coefficients to be uniform in the immediate vicinity of the stagnation point ($-1 < x/B < 1$) and to decline towards either side. This is indeed the case for all the curves in Figs. 2(a) and (b), but only in the case of jets impinging at nozzle-to-plate spacings greater than 8 slot-widths does this lateral decrease continue indefinitely. In all other cases the variation of h with x/B is non-monotonic.*

We associate the secondary peaks in heat-transfer rate in the vicinity of $x/B = \pm 7$ with transitions from laminar to turbulent boundary layers. This transition may be aided by the increasing turbulence level in the main stream due to the continued entrainment of ambient air, as a not yet fully developed turbulent jet spreads laterally over the impacted plate. More probably, however—and in line with the theory

* For "wall jets", illustrated in Fig. 3(c) by the curve for which $z_n/B = \frac{1}{2}$, h has a minimum at the stagnation point. This will be considered separately later.

proposed by Kestin *et al.* [13]—the transition is triggered by the disappearance of the pressure gradients which exist in the vicinity of the stagnation point and serve to stabilize the laminar boundary layer, in spite of locally already high turbulence levels in the free stream. Thus, it is only at the outer edge of the jet deflection region that conditions are conducive for a transition from a laminar to a turbulent boundary layer to take place. For jets impinging at relatively small nozzle-to-plate spacings this transition manifests itself by a steep rise in local heat-transfer coefficients at about $x/B = 4$ [cf. recordings for $z_n/B = 2$ and 5 of Fig. 2(a)]. Meanwhile, the tendency of the boundary layer to thicken continues as the deflected jet spreads laterally over the impacted surface. The interaction of these two opposite effects gives rise to the peaks in the h vs. x/B curves at about $x/B = \pm 7$, beyond which heat-transfer coefficients decrease monotonically.

The diminution of the secondary peaks with increasing z_n/B and their disappearance at $z_n/B = 8$ may be explained by the increasing turbulence level on the jet axis as z_n/B is increased from 2 to 8 (cf. Figs. 3 and 4). This leads to progressively higher heat-transfer coefficients in the stagnation region [cf. Fig. 2(a)], so that the scope for their further rise in consequence of the transition from laminar to turbulent boundary-layer flow is correspondingly diminished.

At $z_n/B = 8$ the only remaining indication of some change in the character of the flow is an abrupt change in the slope of the h vs. x/B curve at $x/B = 3{\cdot}5$, still coinciding exactly with the end of the region of measured pressure gradients. This change in slope serves to align the further course of the curve for $z_n/B = 8$ with that of the other curves downstream of the secondary peaks [cf. Fig. 2(b)]. As z_n/B is further increased this change in slope also becomes less and less marked, and, as Fig. 2(b) shows, the lateral distribution of local heat-transfer coefficients has a perfectly smooth bell shape for $z_n/B > 14$. From what we have already seen, this shape can be accounted for by the lateral variation of the thickness of a boundary layer free of transitions. This thickness is determined primarily by velocities, though, in the presence of pressure gradients, heat-transfer coefficients are likely also to be influenced by turbulence in the "free stream".

If indeed a mere change in the slope of the h vs. x/B curves is the last manifestation of a transition in the character of the boundary-layer flow, which at lower values of z_n/B produced the much more marked secondary peaks in local heat-transfer rate, then it would appear that the heat-transfer rate across a laminar boundary layer in the presence of a favorable pressure gradient can be as high as that across a turbulent boundary layer in the absence of the pressure gradient. The distinction between the two cases would seem to have become rather fine. Where, at $z_n/B > 14$, even the abrupt change in the slope of the h vs. x/B curves disappears, there is no further evidence from heat-transfer measurements of any flow transition. Conceivably the boundary layer may have become turbulent from the outset, or the transition may have become gradual with a more gradual diminution of pressure gradients.

In the above we have developed a hypothesis that ties the existence of secondary peaks in the lateral variation of heat-transfer coefficients to the changing turbulence levels in the jet as the nozzle-to-plate distance is varied. As a check on this, we once again inserted a turbulence generating screen in the nozzle. Varying its distance from the nozzle exit enabled us to vary turbulence levels at a constant nozzle-to-plate spacing. Figure 7 compares the lateral variation of heat-transfer rates obtained with various initial turbulence intensities. It also indicates the pressure distribution over the impacted plate, which was but slightly affected. All curves were recorded at $Re_e = 11\,000$ and at the same nozzle-to-plate spacing of $z_n/B = 2$. Curve (a), obtained without a screen, clearly shows the expected secondary peak and is identical with that shown in Fig. 2(a), corresponding to an initial turbulence intensity of the jet of 2·5 per cent. Curves (b) and (c) were obtained under otherwise identical conditions, but with an 18 mesh screen placed in the nozzle at distances of $\frac{1}{2}$ in and $\frac{3}{16}$ in from its exit, thus producing two different levels of artificially induced turbulence

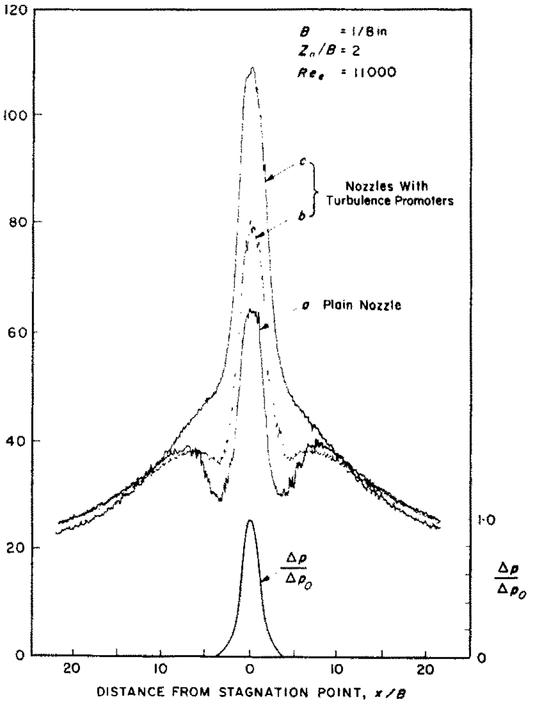

FIG. 7. Effect of artificially induced turbulence on the lateral variation of heat-transfer coefficients.

of 6 per cent and 18 per cent, respectively. Both caused an increase in stagnation point heat transfer and both also affected the lateral variation of heat-transfer rates: in one case only a vestigial "hump" remained of the secondary peak previously observed, in the other case the peak disappeared completely. These three curves, obtained at a constant nozzle-to-plate spacing with artificially varied turbulence, closely resemble the curves for $z_n/B = 2$, 6 and 8 of Fig. 2(a), confirming that the important parameter in bringing about the characteristic lateral variation of local heat-transfer coefficients is the intensity of turbulence in the impinging jet.

Repetition of this experiment with artificial turbulence promoters at a nozzle-to-plate spacing of $z_n/B = 8$, i.e. with an almost fully developed jet, resulted in identical recordings being obtained with and without the screens. This again directs attention to the importance that seems to attach to the attainment of maximum turbulence on the axis of the jet. Thus $z_n/B = 8$ represents, all at once, the upper limit to the range of nozzle-to-plate spacings in which heat transfer is susceptible to artificially induced turbulence in the nozzles, the upper limit for the manifestation of secondary peaks in the lateral variation of local heat-transfer coefficients [cf. Fig. 2(a)], and the locus of the maxima in stagnation point heat-transfer coefficients produced by impinging turbulent jets (cf. Fig. 1). It is noteworthy that for initially laminar jets, in which the diffusion of mixing-induced turbulence is slower than in jets turbulent already at the exit from the nozzles, the occurrence of the maximum stagnation point heat-transfer coefficient may be displaced to higher values of z_n/B (cf. Fig. 1). Correspondingly, secondary peaks in heat-transfer rate have been observed at nozzle-to-plate spacings greater than $z_n/B = 10$ and also at lateral positions beyond $x/B = 7$.

Another aspect of the changing character of the lateral distribution of heat-transfer rates with jet Reynolds number is illustrated in Fig. 8,

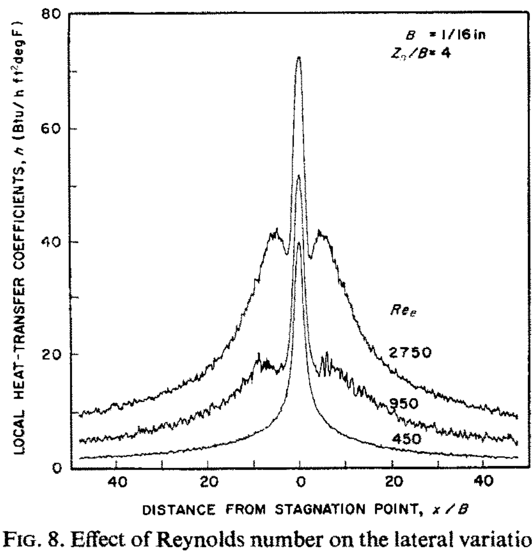

FIG. 8. Effect of Reynolds number on the lateral variation of local heat-transfer coefficients produced by a two-dimensional air jet.

obtained at the relatively short nozzle-to-plate spacing of $z_n/B = 4$. The two upper curves show the by now familiar non-monotonic decrease of h with increasing x/B. This is equally true for the initially turbulent jet ($Re_e = 2750$) and for the initially laminar jet for which

$Re_e = 950$. The only difference between the two is that the secondary peak observed with the latter occurs at a slightly higher value of x/B, reflecting the effect of a lower rate of mixing—and hence slower increase of the intensity of mixing-induced turbulence—on the point of transition to a turbulent boundary layer. As Re_e is further decreased and jet mixing is further slowed, the disturbance of the boundary layer is also delayed further. Thus, local heat-transfer coefficients produced by the $Re_e = 450$ jet decrease monotonically from the stagnation point to $x/B = 48$. This jet is clearly laminar throughout the range of the recording, including its impingement and its lateral spread as a wall jet at least as far as 48 slot-widths. Incidentally, its laminar character is also illustrated by contrasting the smooth h vs. x curve recorded for it with the more "noisy" records produced by the other two jets. In the latter the beginning of turbulence can clearly be traced to the point at which heat-transfer rates begin to increase with increasing distance from the stagnation point. (That the recording at $Re_e = 950$ appears to show more turbulence than that obtained at $Re_e = 2750$ is probably due to the higher sensitivity of the heat-flow meter to turbulence having a larger scale and lower frequency.)

We turn next to the "inner" secondary peaks at $x/B = \pm \frac{1}{2}$, shown in Fig. 2(c). With two-dimensional jets these inner peaks exist only when $z_n/B < \frac{1}{2}$. One is then dealing not with an impinging jet but with a "wall jet" issuing from a gap between the nozzle and the plate that is narrower than the slot opening itself. Under the circumstances, the inner peaks in heat-transfer rate at $x/B = \pm \frac{1}{2}$ are ascribed to the high velocity of the air through this narrowest opening.

With circular jets the inner peaks at $x/D = \pm \frac{1}{2}$ exist over a wider range of nozzle-to-plate spacings, up to about $z_n/D = 3$, as shown in Fig. 9. This figure also shows that—like the outer peaks produced by slot jets (cf. Fig. 8)—*outer peaks* produced by circular jets, which occur at $x/D = 1{\cdot}9$, also disappear below some critical Reynolds number (cf. plot for $R_e = 2500$). The fact that the *inner peaks* do not disappear suggests that they are not caused by turbulence

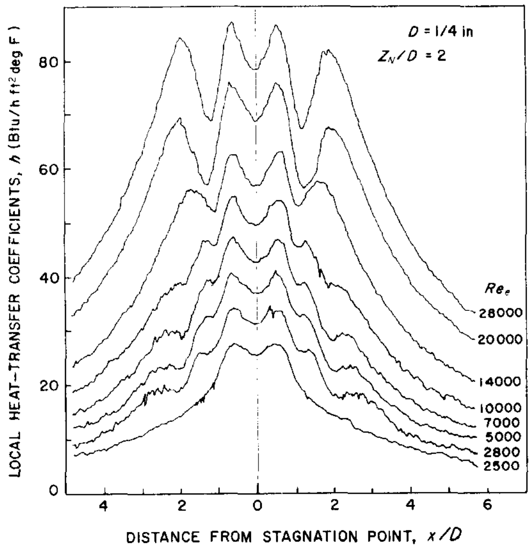

FIG. 9. Effect of Reynolds number on the laterial variation of local heat-transfer coefficients produced by an axi-symmetric air jet.

but by some mechanism inherent in the flow of impinging axi-symmetric jets, regardless of whether they are laminar or turbulent. This lends experimental support to Kezios' theoretical finding that the boundary layer formed in the radial flow of an impinged axi-symmetric jet has a minimum thickness in an annular region centered near $x/D = \frac{1}{2}$ [15].

Finally, we note that the disappearance of the outer peaks at $x/D = \pm 1{\cdot}9$ with diminishing Reynolds number is preceded by their resolution into two distinct peaks, such as those shown by the recording for $Re_e = 2800$ at $x/D = \pm 1{\cdot}4$ and $\pm 2{\cdot}5$. This phenomenon is observed only when working with circular jets that issue from short nozzles having well rounded inlets. It has been noted before [1], and the preceding discussion may also cast some light on its cause. Thus we believe that for circular jets it is the peak at $x/D = \pm 1{\cdot}9$ that corresponds to the secondary peaks observed with slot jets at $x/B = \pm 7$. We have shown the latter to be caused by turbulence, specifically by a transition from laminar to turbulent boundary-layer flow, noting two possible causes for the transition itself. Conceivably the resolution of the outer peak produced by circular jets into two separate peaks as the initial turbulence level is lowered may reflect the separate effects (1) of the diffusion of mixing-induced turbulence to the boundary layer and (2) of transition to a turbulent boundary layer.

SUMMARY AND CONCLUSIONS

Data on the variation of local heat-transfer coefficients produced by impinging jets have been re-examined in the light of measurements of the velocity and turbulence distributions in submerged jets and in the context of other work on the influence of turbulence on heat transfer. It has been shown that the heat-transfer characteristics of impinging jets cannot be explained in terms of velocity- and position-dependent boundary-layer thicknesses alone. They can be explained when one also takes into account the influence of turbulence, which may manifest itself by a transition from laminar to turbulent boundary-layer flow or by a purely local enhancement of the rate of heat transfer across the boundary layer.

The present considerations differ from other studies of the effects of turbulence on heat transfer in that the latter are usually carried out in wind tunnels, in which the turbulence is constant over the test section. In contrast, turbulence in jets is generated by the jets themselves and varies significantly with position in the jet. For both fully developed turbulent jets and for initially laminar jets that are becoming turbulent as a result of jet mixing, the intensity of turbulence appears to be uniquely determined by the jet Reynolds number and the dimensionless jet length. This explains why such a large part of the data on heat-transfer rates can be correlated very effectively without any separate parameter to characterize turbulence, as shown by the present Fig. 1 and Fig. 4 of reference 2. Only where, as in initially turbulent but not fully developed jets, velocity and turbulence are not yet uniquely related does this simple correlation cease to be adequate, as illustrated by Figs. 6 and 7, and by the apparent size dependence—but really turbulence dependence—of some of the data in Fig. 1. This suggests that details of the nozzles, and, indeed, of the flow system upstream, may be important in the design of heat-transfer equipment in which turbulent jets impinge at relatively short nozzle-to-plate spacings; but are secondary if impingement occurs only beyond $z_n/D = 8$.

It is also only in the region of the jet—or wall jet—in which the turbulence of the jet is still developing that the sometimes opposed effects of rising turbulence and falling velocity give rise to seemingly anomalous effects, such as the maxima in the variation of stagnation point heat-transfer coefficients with nozzle-to-plate spacing and the secondary peaks in the lateral distribution of local heat-transfer coefficients.

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Résumé—Les données expérimentales sur la variation des coefficients locaux de transport de chaleur produits par des jets frappant une surface ont été réexaminées à la lumière des mesures des distributions de vitesse et de turbulence dans des jets submergés et en les comparant à d'autres travaux portant sur l'influence de la turbulence sur le transport de chaleur. On montre que quelques phénomènes de transport de chaleur apparemment anormaux peuvent être expliqués comme les effets de la turbulence élevée et non uniforme propre aux jets.

Zusammenfassung—Im Hinblick auf Messungen der Geschwindigkeits- und Turbulenzverteilung in einem Unterwasserstrahl und im Zusammenhang mit anderen Arbeiten über den Einfluss der Turbulenz auf den Waermeübergang wurden Werte über die Änderung der lokalen Wärmeübergangszahl, verurschat von einer aufprallenden Strahlströmung, nachgeprüft. Es wird gezeigt, dass einige vermeintliche anomale Wärmeübergangsphänomene als Auswirkungen der starken und räumlich wechselnden Turbulenz innerhalb von Strahlströmungen erklärt werden können.

Аннотация—Данные по изменению локальных коэффициентов теплообмена при смешении струй были пересмотрены в свете проведенных измерений профилей скорости и турбулентности в затопленных струях и в развитие другой работы по влиянию турбулентности на теплообмен. Показано, что некоторые кажущиеся аномальными тепловые эффекты можно истолковать как результат воздействия интенсивной и пространственно изменяемой турбулентности, присущей струям.