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THE EFFECT OF TURBULENCE ON HEAT TRANSFER AT A STAGNATION POINT

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Abstract—An experimental study on heat transfer of impinging circular jets shows the effect of turbulence for the stagnation zone. The work relates to cases of small nozzle-to-plate distances. A new measuring technique using liquid crystals has been employed. The effect of jet turbulence is described by the same type of relationship as given in the literature for stagnation point heat transfer for cylinders. It is shown that the relative increase at the stagnation point for impinging jets is the same as for cylinders in a free stream. For small z/D values Nu at the stagnation point is smaller than for points in the region directly around it, but only in those cases where the turbulence level in the issuing jet is low ($< 1\%$). This relative minimum disappears for $z/D > 5$ and for a turbulent primary jet stream.

NOMENCLATURE

D,	nozzle diameter;
r,	radial distance from stagnation point;
v,	axial velocity;
v_0,	jet velocity at exit;
w,	radial velocity;
z,	axial distance from nozzle exit;
Nu,	Nusselt number based on nozzle diameter;
Nu_0,	Nusselt number at stagnation point for zero turbulence;
Tu,	turbulent intensity (%), based on main velocity component;
Re,	Reynolds number based on nozzle diameter and "local" velocity of jet;
ν,	kinematic viscosity.

INTRODUCTION

Recently the effect of turbulence on forced convective heat transfer from cylinders has been widely investigated. The main effects were found at the stagnation point. Several relations to predict the increase in heat transfer due to the turbulence intensity have been presented. Also, a number of studies have been reported on the heat transfer in the stagnation zone of a free jet impinging on a surface. Gardon *et al.* [1] reported that for this case also turbulence can be of great importance. The heat transfer of impinging jets is important for a number of applications in the glass, paper and metallurgical industries. In the last case impinging jet flames are often used. The heat flux in the stagnation zone of such a hot jet might be critical in limiting the heating-up of a material. As part of a study on impinging flames we studied the effect of turbulence at the stagnation point of jets.

In our study we tried to relate the results found with cylinders to experiments we did with impinging air jets, taking into account the turbulence intensity of the free jet. Tests were done on the heat transfer from a slightly heated plate to air in the stagnation zone for different, but small plate-to-nozzle distances.

FLOW CONSIDERATIONS

(a) *Heat transfer at the stagnation point of cylinders*

In a recent paper Lowery and Vachon [2] gave a good review of the heat transfer at the forward stagnation point of a cylinder placed in a uniform flow. Smith and Kuethe [3] were the first to suggest a relation between $(Nu/Re^{1/2})$ and the product of $TuRe^{1/2}$; Kestin and Wood [4] gave this relation as:

$$\frac{Nu}{Re^{1/2}} = 0.945 + a\left(\frac{TuRe^{1/2}}{100}\right) - b\left(\frac{TuRe^{1/2}}{100}\right)^2 \quad (1)$$

with $a = 3.48$ and $b = 3.99$ for a Re-number range from $7.5 \cdot 10^4$ to $12.5 \cdot 10^4$. For lower Reynolds number ($\simeq 2 \cdot 10^4$) Sikmanovic [5] derived values of $a = 1.94$ and $b = 2.41$. Lowery and Vachon [2] extended the measurement to high values of Re ($3 \cdot 10^5$) reaching values for $TuRe^{1/2}/100$ of 0.65. They gave $a = 2.62$ and $b = 3.07$; however, instead of the constant 0.945 for the case of zero turbulence they used a value of 1.01.

(b) *Heat transfer for impinging circular jets*

The flow in a free jet for small distances z from the nozzle exit exhibits an undisturbed potential core up to $z/D \simeq 5$; outside this jet turbulence develops. In our case interest was mainly in the heat-transfer data for small z/D values, from 2 to 8. This means that we will have effects both from the potential core flow and from jet turbulence. Schlünder [6], Scheuter and Dosdogru [7] and Gardon [1] have shown that for $z/D > 5$ the stagnation point heat-transfer coefficient increases strongly. For these cases Nu values are found that are much higher than predicted for the heat transfer in a rotational symmetrical laminar flow. Kezios [8], using a relation from Sibulkin [9], derived for the Nu-value for the case of a laminar circular jet at the stagnation point:

$$Nu_0 = 0.67D\left(\frac{C}{\nu}\right)^{1/2}, \quad (2)$$

with C derived from an empirical relation from Schrader [10]

$$C = \left(1.04 - 0.034\frac{z}{D}\right)\frac{v_0}{D}. \quad (3)$$

For $z/D \simeq 3$ this results for air ($Pr = 0.71$) in:

$$Nu_0 = 0.65Re^{1/2}; \quad (4)$$

Gardon and Akfirat [1] studied the effect of turbulence on heat transfer from impinging two-dimensional and circular jets in the zone around the stagnation point. They showed for circular jets that for small ($z/D < 4$) nozzle-to-plate distances the Nu number may show a relative minimum for the stagnation point in a plot showing the lateral variation of Nu. They attribute this to Kezios' [8] finding that the laminar boundary layer along the plate decreases in thickness for increasing values of r/D up to 0.5. Recently Baines and Keffer [11] reported on a study they made on shear stress in the stagnation point of two-dimensional jets. From this they predicted the heat transfer at the stagnation point, they found a relative minimum value for z/D values up to 48, whereas Gardon [1] found this behaviour only for circular jets $z/D < 4$. A second relative minimum is found for $r/D \simeq 1.2$; at this point we get the transition from the laminar to the turbulent boundary layer, for low Re numbers this minimum will disappear. An important question for small nozzle-to-plate distances is how the turbulence level in the jet as it leaves the nozzle affects the stagnation point behaviour.

Also Dup. Donaldson, Snedeker and Margolis [12] made an extensive study on the heat transfer for impinging jets; for the case of a constant heat flux boundary condition they studied the effect of turbulent structure of circular jets for both the stagnation heat transfer and the heat transfer in the wall jet region. They indicated that turbulent intensity, has an effect on the laminar heat-transfer rate in the stagnation point. They compared their results for the stagnation point with the predictions of Smith and Kuethe for cylinders, however their data were not in detail in agreement with that prediction.

The Smith and Kuethe relationship between Nu and Re is essentially a linear one. In view of the more recent results found by Lowery and Vachon for the heat transfer in the stagnation point of cylinders it seems plausible to expect for the use of impinging jets also a non-linear relation between ($Nu/Re^{1/2}$) and ($TuRe^{1/2}$):

$$\frac{Nu}{Re^{1/2}} = p + q\left(\frac{TuRe^{1/2}}{100}\right) - r\left(\frac{TuRe^{1/2}}{100}\right)^2. \quad (5)$$

For small z/D values (~ 3) one would expect p to be equal to 0.65, as found semi-theoretically for the laminar case. If the relative effects of ($TuRe^{1/2}$) on the increase of Nu from the laminar value to the actual value is the same as given for the cylinder by Kestin and Wood one would predict $q = 2.4$ and $r = 2.7$ and from the Sikmanovic data $q = 1.3$ and $r = 1.6$.

EXPERIMENTAL

Tests were done with air jets at ambient temperatures cooling a slightly heated-plate.

Two different nozzles were used to obtain the jets. One nozzle (a) being similar to the exit of a long straight pipe and the other (b) having a smooth flow contraction at the exit of a wider pipe. In both cases the nozzle diameter was 57 mm. The air jet issuing directly from the pipe had an initial velocity profile typical for pipe flow; the smooth flow contraction nozzle gave a much more uniform velocity distribution in the nozzle exit at a low turbulence level. To increase the primary turbulence level of the jet wire grids were used with nozzle a. Wire sizes of 0.5 and 2 mm with mesh-width of 2, 5 and 10 mm were used. This increased the turbulence level to about 5%.

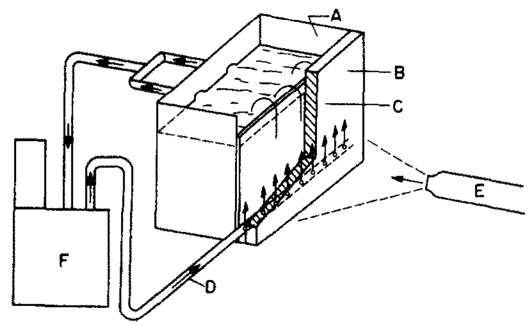

FIG. 1. Experimental set-up: (A) Hot water reservoir; (B) Layer of liquid crystals; (C) Glass plate; (D) Water recirculation; (E) Air nozzle; (F) Thermostat.

In the experimental set-up (Fig. 1) a glass plate was used heated at the back by an intensive flow of hot water. At the front of the plate liquid crystals embedded in a thin 30 μm resin layer were applied. In this way local surface temperatures could be measured without any obstructions for the air flow. As the thermal conductivity of the glass plate had been measured, the local heat-transfer rate could be obtained from the surface and water temperatures. In this method the thermal boundary condition comes close to that of constant wall temperature. Details of this method are given by Hoogendoorn and Den Ouden [13]. Velocities and turbulence were measured with a calibrated hot wire (10.5 μm) using DISA equipment. As turbulence levels where in general below 20%, a simple RMS meter could be used to determine the Tu-values. Static pressures along the plate were measured by small pressure taps in a special (non-heated) plate.

DISCUSSION OF RESULTS

(a) *Stagnation point*

Figure 2 shows the velocity distributions at the two nozzle exits.

Nozzle b shows a uniform velocity profile, with a low initial turbulence. This can be seen from Fig. 3, where for the free jet the turbulence and velocity are given along the jet axis. Nozzle b shows a turbulence level of only 0.5% in the exit, against about 3.2% for nozzle a. The radial distributions of axial velocity and turbulence for nozzle b at two axial distances are shown in Fig. 4. For $z/D = 2$ the potential core is clearly visible; for $z/D = 10$ the jet has spread and the axial velocity

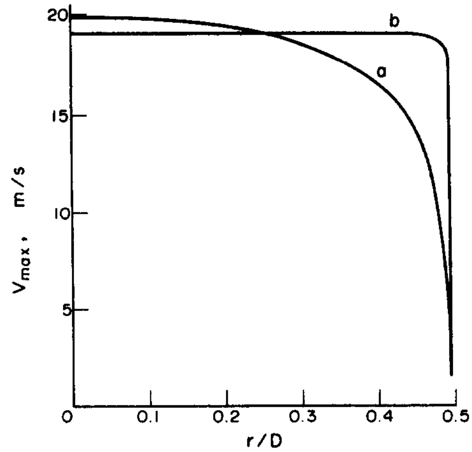

FIG. 2. Velocity distributions at nozzle exit. For nozzles *a* and *b*.

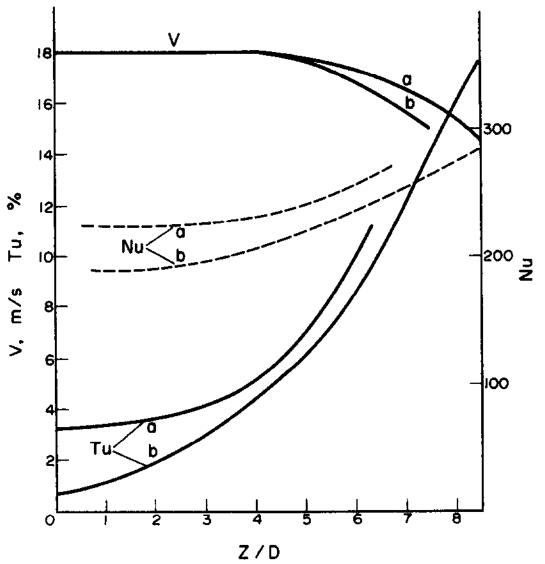

FIG. 3. Axial distribution of v and Tu in free jet and Nu for impinging jet for nozzles *a* and *b*, $Re = 66 \cdot 10^3$.

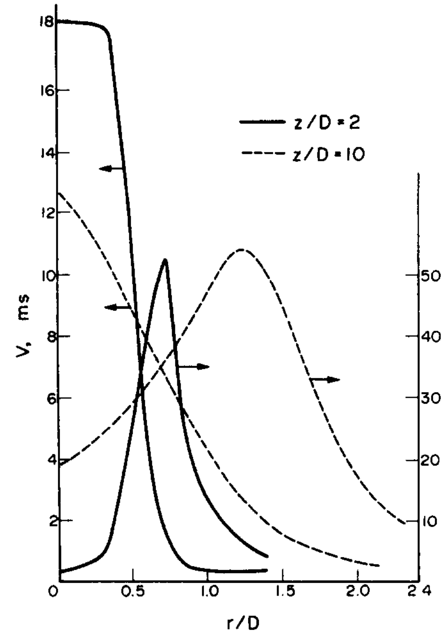

FIG. 4. Radial distribution of v and Tu for free jet, $Re = 66 \cdot 10^3$.

has been reduced, the maximum jet turbulence being at $r/D \simeq 1.3$. Figure 3 also shows the stagnation point Nu values as measured. There is clearly a difference between nozzles *a* and *b*, which can be ascribed to the difference in turbulence level. For the potential core $z/D < 4$ the Nusselt number is nearly constant; for $(z/D > 4)$ Nu increases up to the maximum distance $(z/D = 10)$ used in the tests. This increase for $z/D > 4$ is directly related to the strong increase in turbulence level on the jet axis, which completely counteracts the decrease in velocity.

To describe the simultaneous effect of turbulence and velocity on the heat transfer in the stagnation point our results for air ($Pr = 0.71$) in the Reynolds number range from $2 \cdot 10^4$ to $9 \cdot 10^4$ and $9\% < Tu < 20\%$ for z/D values between 1 and 10 for both nozzles were correlated with $TuRe^{1/2}$; see Fig. 5.

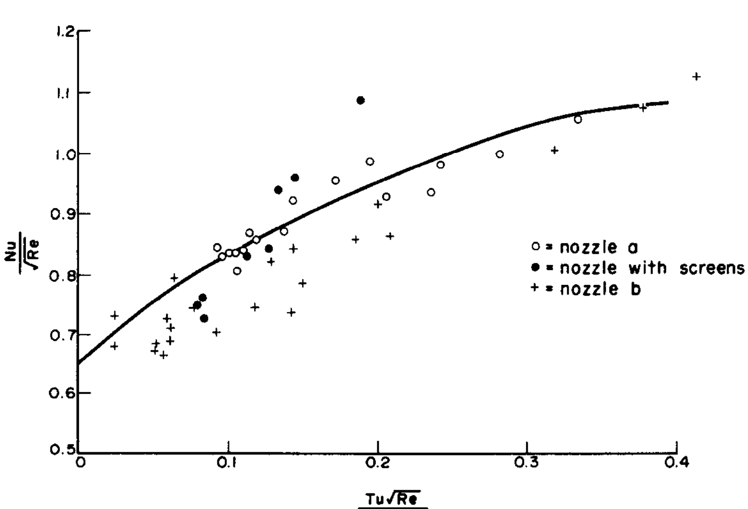

FIG. 5. Correlation for stagnation point heat-transfer data.

Within an accuracy of 8% the data could be correlated by a relation like the one found for the cylinders [equation (1)]; we found:

$$Nu/Re^{1/2} = 0.65+2.03\left(\frac{TuRe^{1/2}}{100}\right)-2.46\left(\frac{TuRe^{1/2}}{100}\right)^2; \quad (Pr = 0.71) \quad (6)$$

for Re and Tu, the "local" values on the free jet axis (without the plate) in the plane of impingement were taken at z/D equal to that for the plate during the heat-transfer tests. This choice of Re and Tu was made as it was the most relevant one for the central stagnation point, when comparing with the literature data on cylinders. Figure 5 includes some tests where the jet turbulence has been increased by using different grids in the exit of nozzle *a*. Within the accuracy of the measurement these data also fit the given correlation.

In general, the data for nozzle *a* are slightly higher than for nozzle *b*, which might be due to a difference between the structure (scale) of turbulence. Still, if there is any such effect, it is small compared to the effect of the turbulence level itself.

A significant effect of Reynolds number on the stagnation point heat-transfer relation [equation (6)] could not be detected either, in the range of Reynolds numbers of our tests ($2 \cdot 10^4$–$9 \cdot 10^4$). This has also been found by Lowery [2] for cylinders. To compare the results with those found for cylinders the relative effect of $TuRe^{1/2}$ has been considered by calculating the value of stagnation point Nu relative to the laminar value Nu_0 for $Tu = 0$.

For the plate we took $Nu_0 = 0.65$ and for the cylinder $Nu_0 = 0.945$.

Figure 6 gives the comparison. As can be seen, our correlation for the plate fits within the correlations for cylinders as reported in the literature. In general they agree with those of Lowery and Kestin and Wood, except that the first used for the extrapolated Nu at $Tu = 0$ a value which is about 12% above Nu_0 for cylinders.

Such a difference for the extrapolated $Nu(Tu = 0)$ value from Nu_0 does not occur in our tests (see Fig. 6).

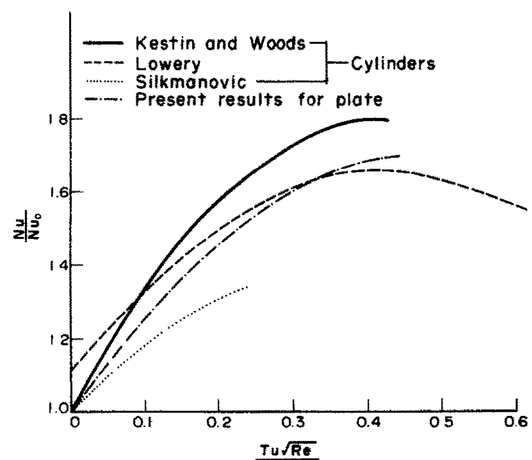

FIG. 6. Comparison of stagnation point Nu correlations.

The Sikmanovic data values are somewhat lower than the other data however they do not extend to high $TuRe^{1/2}$. In view of the accuracy of this kind of measurements one can conclude that all data on the relative effect of turbulence level fit one general correlation.

Comparison with the study of Donaldson *et al.* is more difficult as their work relates to $7 < z/D < 30$ and they base their Nu and Re numbers to the local value of the half-radius of the free jet.

This was not measured in this study, however for $z/D < 6$ the difference between nozzle radius and jet half-radius is small. Their results were for higher ($TuRe^{1/2}$) values below the linear relationship of Smith and Keuthe [3] and they showed little effect of Reynolds number in their range of $5 \cdot 10^4$–$20 \cdot 10^4$ and z/D from 10 to 30. In general however their results are in accordance with those found here.

(b) *Region around stagnation point*

The flow and heat-transfer results for the region around the stagnation point (up to r/D values of 3.0) for z/D between 2 and 6 are given in Figs. 7–9.

The velocity and turbulence profiles in the boundary layer for $z/D = 2$ as measured with the hot-wire anemometer are shown in Fig. 7. Typical for the Re-range of this investigation they show a low Tu level for $r/D < 1$ and increasing Tu for $r/D > 1$. The boundary-layer thickness increases to about 0.7 mm for $r/D = 2.8$. Figures 8(a) and 8(b) show the radial distribution of the maximum value of velocity w_{max} and the turbulence level at the point where w_{max} has been found in the boundary layer for two z/D values. The transition from the laminar to the turbulent boundary layer is for $r/D \simeq 1$ for the case where $z/D = 2$. For $z/D = 6$ both

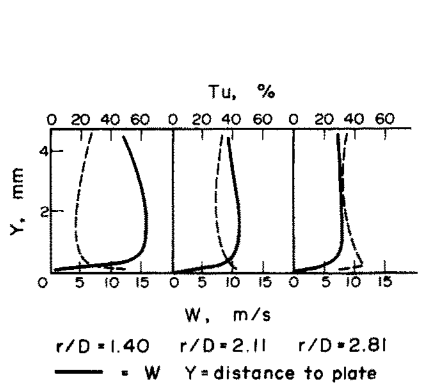

FIG. 7. Boundary layer v and Tu. Distributions at $Re = 66 \cdot 10^3$ for $z/D = 2$.

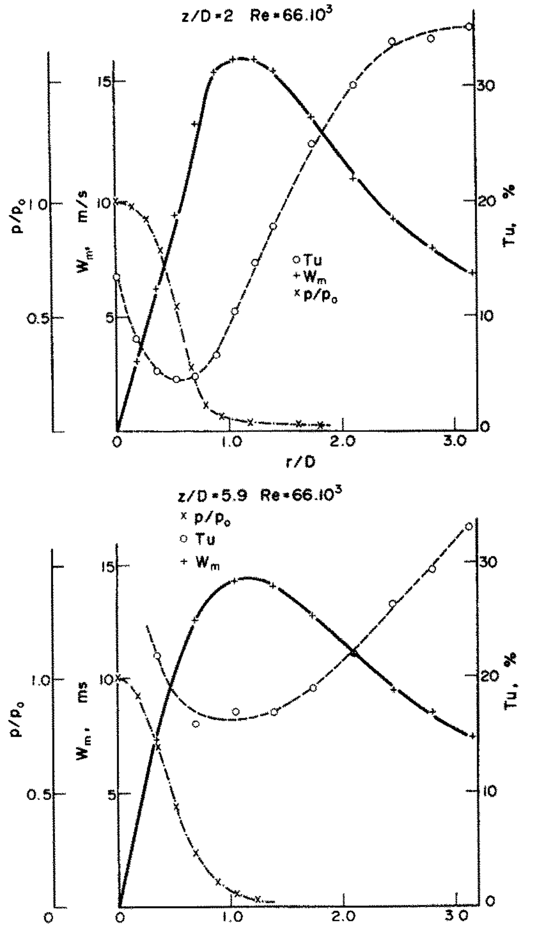

FIG. 8(a, b). Radial distributions of v_{max}, Tu and P/P_0 in boundary layer.

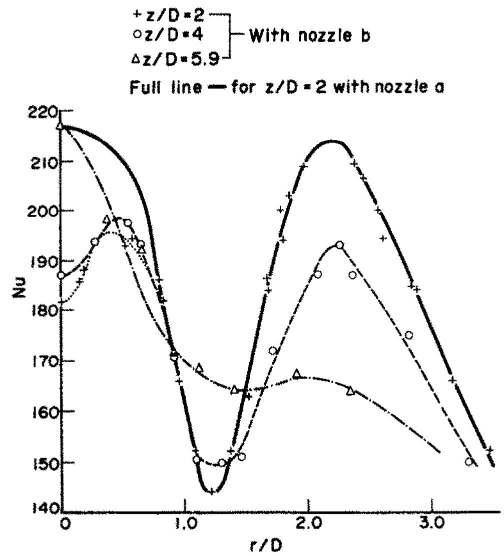

FIG. 9. Radial distributions of Nu for impinging jet, $Re = 66 \cdot 10^3$.

velocity and Tu-level show a transition effect at $r/D = 1.2$; however, the boundary layer is already turbulent at small r/D values due to the high jet turbulence. Figure 8 also gives the static pressure distribution along the plate. The heat-transfer results typical for the Re-number range of our tests are given in Fig. 9. For the small z/D values $= 2$ and 4 they show a relative minimum in Nu for the stagnation point, with a relative maximum for $r/D \simeq 0.45$. This is in agreement with Gardon's results and Kezios' prediction of a decreasing boundary-layer thickness in the zone $0 < r/D < 0.5$. For r/D values above 0.5 the laminar boundary-layer thickness increases until the transition point at $r/D \simeq 1.2$ has been reached. For $z/D > 6$ the relative minimum for Nu_0 disappears. In that case a maximum Nu is found in the stagnation point, due to the effect of the large Tu value of the free jet at that point. This also occurs at small z/D values for the nozzle a which has already a higher primary turbulence level in its exit. These results differ from those reported by Baines and Keffer for a two-dimensional jet. However, they used a hot-wire probe to derive the wall shear stress. From this they predicted the heat-transfer coefficients, which however gave an unrealistic picture of the heat transfer.

Another difference with the results of Baines and Keffer is that the effect of z/D on the stagnation point Nu_0 shows a continuously decreasing Nu_0 from $z/D = 2$, whereas our results and those of Gardon and others show an increase in Nu up to $z/D = 10$ (Fig. 3).

The $Tu-r/D$ plots [Figs. 8(a) and (b)] show the transition to the fully turbulent boundary layer at $r/D \simeq 1$ for $z/D = 2$, whereas for $z/D = 6$ a smaller effect can be observed. The second maximum in Nu for $r/D \simeq 2.3$ disappears at the higher z/D values.

This is clearly related to the fact that in the latter case the turbulence level near the plate is already important at small r/D values (Fig. 8).

CONCLUDING REMARKS

Using a liquid crystal measuring technique it was possible to measure accurately local values for the heat-transfer coefficients for impinging jets. It was possible to do this without any obstructions at the surface and the technique made it possible to observe clearly the occurrence of heat-transfer coefficient maxima and minima. The stagnation point heat-transfer data for air ($Pr = 071$) at a Reynolds number range of 2.10^4–$9 \cdot 10^4$ and z/D between 1 and 10 were correlated within 8% by equation (6) showing the effect of $(TuRe^{1/2})$ in a similar way as found for cylinders in a turbulent flow. The relative effect of turbulence for this study was equal to that found for cylinders. Effects of scale of turbulence were not studied, however they seem to be within the range of the experimental accuracy ($\pm 8\%$).

In the region directly around the stagnation point a Nu value slightly higher than the stagnation point value has been measured for $z/D < 5$ in the Reynolds number range of this investigation, when using a low turbulence jet from a nozzle with a smooth construction.

The radial distribution of the Nu-numbers showed at $z/D < 8$ a (second) maximum for the Re-range of our tests at $z/D \simeq 2.3$ where the turbulence level in the boundary layer is very high.

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EFFET DE LA TURBULENCE SUR LE TRANSFERT THERMIQUE AU POINT D'ARRET

Résumé—Une étude expérimentale sur des jets circulaires incidents montre l'effet de la turbulence dans la zone d'arrêt. Le travail concerne le cas des courtes distances entre tuyère et plaque. On utilise une nouvelle technique de mesure par cristal liquide. L'effet de la turbulence du jet est décrit par une relation du même type que celle donnée dans la littérature pour le point d'arrêt sur le cylindre. On montre que l'accroissement relatif au point d'arrêt pour les jets incidents est le même que pour les cylindres dans un écoulement libre. Pour les petites valeurs de z/D, Nu au point d'arrêt est plus petit que pour les points dans la région qui entoure immédiatement, mais seulement dans le cas où le niveau de turbulence dans le jet est faible ($< 1\%$). Ce minimum relatif disparait pour $z/D > 5$ et pour un écoulement de jet turbulent.

DER EINFLUSS DER TURBULENZ AUF DEN WÄRMEÜBERGANG AM STAUPUNKT

Zusammenfassung—Der Einfluß der Turbulenz auf Wärmeübergang im Bereich des Staupunkts wird mit auftreffenden, runden Strahlen experimentell untersucht. Es werden nur kleine Düsen-Platten-Abstände in Betracht gezogen. Eine neue Meßmethode mit Flüssigkristallen wurde verwendet. Der Einfluß der Strahlturbulenz wird in derselben Art beschrieben, wie er beim Wärmeübergang am Staupunkt von Zylindern in der Literatur angegeben ist. Es wird gezeigt, daß die relative Zunahme des Wärmeübergangs am Staupunkt auftreffender Strahlen gleich derjenigen bei Zylindern in freier Strömung ist. Solange der Turbulenzgrad im austretenden Strahl gering ist ($< 1\%$), sind bei kleinen Werten Z/D die Nusselt-Zahlen am Staupunkt selbst geringer als in der unmittelbaren Umgebung. Dieses Minimum verschwindet bei $Z/D > 5$ und bei Strahlen mit stärkerer Turbulenz.

ВЛИЯНИЕ ТУРБУЛЕНТНОСТИ НА ПЕРЕНОС ТЕПЛА В КРИТИЧЕСКОЙ ТОЧКЕ

Аннотация — С помощью экспериментального исследования процесса теплообмена падающих круглых струй показано влияние турбулентности в критической точке. Эксперименты проводились при небольших зазорах между соплом и пластиной. Для измерений использовалась новая техника на жидких кристаллах. Влияние турбулентности струи описывается соотношением такого же типа, что и теплообмен цилиндров в критической точке. Показано, что в случае падающих струй наблюдается такое же относительное увеличение турбулентности в критической точке, что и при свободном обтекании цилиндров. При небольших отношениях z/D значение числа Nu в критической точке ниже значений в точках, расположенных в непосредственной близости к критической, но только в случае низкого уровня турбулентности истекающей струи ($<1\%$). При $z/D>5$ и турбулентности основного первичного потока этот относительный минимум исчезает.