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LOCAL HEAT TRANSFER FROM A SINGLE SPHERE TO A TURBULENT AIR STREAM

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Abstract—The local heat transfer between a sphere and a turbulent air stream was studied. The flow conditions covered Reynolds number between 2600 and 6100 and turbulence intensities from 0.45 to 6.0%. The results obtained show that the boundary layer over the leading surface becomes turbulent at the laminar separation point. This turbulent layer becomes reattached to the surface and separates further downstream, resulting in a turbulent wake. These phenomena occur at low Reynolds number through the interaction between the freestream turbulence and the boundary layer.

NOMENCLATURE

$A, B, C, D,$ fitted coefficients;
m, exponent of Reynolds number;
n, exponent of turbulent Reynolds number;
Fs, Frossling number;
N, surface renewal number;
Nu, Nusselt number based on the sphere diameter;
Pr, Prandtl number;
Re, Reynolds number based on the sphere diameter;
Re_T, turbulent Reynolds number;
Sc, Schmidt number;
Sh, Sherwood number based on the sphere diameter;
Tu, turbulence intensity;
η, intensity of heat-transfer fluctuations.

Subscripts
i, local;
w, at the wall;
∞, at freestream conditions.

Superscripts
$\bar{}$, time averaged;
$'$, fluctuating.

INTRODUCTION

THE TRANSPORT phenomena which occur between solid spheres and fluids have been of interest since the beginning of the twentieth century. The simplest correlations of the heat transfer were based on a phenomenological approach, that is, the models describe the gross behaviour of the system without regard to the underlying mechanisms which give rise to the observed behaviour. One of the first widely used correlations of the heat transfer between a sphere and an air stream was produced by Williams [1]. About the same time, Frossling [2] correlated the mass transfer from evaporating water drops. It gave values similar to those calculated from Williams correlation when the Sherwood and Schmidt numbers were replaced by the Nusselt and Prandtl numbers respectively. This analogy between heat and mass transfer has been used with a great deal of success. Recently, this analogy was the subject of an experimental study [3] which confirmed its applicability to convective transport from both spheres and cylinders.

Although these phenomenological correlations yielded useful design information, little of the underlying mechanisms was revealed. An overall review by Rowe *et al.* [4] demonstrated that the "best" exponent of the Reynolds number in correlating the heat transfer data increased with the Reynolds number. This was attributed to an increase in the strength of the wake, however the authors were quick to mention that the variance of the data made any conclusions rather dubious. This showed that the transfer process is more complex than that suggested by these correlations.

A more comprehensive description of the transport phenomena was provided by examination of both the flow behaviour involving flow visualization techniques and the local heat-transfer characteristics around the sphere. Torobin and Gauvin [5] reviewed several studies of the flow behaviour around a sphere. Between Reynolds number of 24 and 500, the wake was suggested to consist of a single vortex ring attached to the sphere. As the Reynolds number was increased, the ring grew in size until, at a value of 130, the downstream point became unstable and began to oscillate. At some value of the Reynolds number between 200 and 1000, vortex shedding was observed, forming a chain like wake structure. At higher Reynolds numbers, these vortices coalesced resulting in the shedding of periodic balls of vorticity, and above 2000, a complex spiral wake structure was observed.

The first measurements of the local heat-transfer coefficients as a function of the position on the surface of a sphere were obtained by Cary [6] and followed by Xenakis *et al.* [7] and Wadsworth [8]. These three investigations covered Reynolds numbers between 2×10^4 and 1.3×10^6. Each of these studies included correlations of the overall Nusselt numbers, calculated by integrating the local values over the surface of the sphere. The data of Xenakis and Wadsworth were in good agreement with that of Williams [1] however the data of Cary were substantially lower.

The general form of the relation between the local Nusselt number and the polar angle, measured from the front stagnation point, decreased from a maximum at the front stagnation point to a minimum at the flow separation point. The values of the local Nusselt number over this region were found to vary approximately with the square root of the Reynolds number as predicted by the laminar boundary-layer solutions. Following the minimum, a sharp peak in the heat transfer was observed, the maximum occurring at an angle of 120°. The height of this peak was strongly dependent on the Reynolds number, increasing from a slight break point at $Re = 2 \times 10^4$ to a dominant feature at $Re = 10^5$. Xenakis [7] did not observe this break point at the lower Reynolds number, but this was probably due to the low sensitivity of the experimental method at low heat-transfer rates. The minimum following the peak occurred at an angle of between 130 and 140°. The curve then increased from this point to a maximum at the rear stagnation point.

Lee and Barrow [9] obtained measurements of local mass-transfer coefficients by examining the change of naphthalene spheres exposed to an air stream. The results were similar to those of the heat-transfer studies. These studies of the local transfer rates provide a good qualitative description of the flow patterns around a single sphere. The distinction between the heat-transfer properties of the wake and the front laminar boundary-layer region was particularly important in resolving the variation of the Reynolds number exponent between the various simple correlations.

Another characteristic of the flow situation, turbulence, was also the subject of several studies. Wadsworth [8], in the study discussed previously, investigated the local transport at two different turbulence levels, however, no substantial difference in the Nusselt number was noted. It would appear that the major source of error was the low temperature difference between the surface and the air stream which may have limited the resolution of the measurements from the local sensor. Galloway and Sage [10] combined much of the data available from the literature and developed a correlation for the local heat transfer including the effects of the freestream turbulence. This correlation, based on a random eddy penetration model, was expressed in terms of a Frossling number as:

$$Fs_i = A\left(\frac{v_\infty}{v_w}\right)^{1/6} + [BTu(Tu+C)+D]Re^{1/2}Pr^{1/6} \quad (1)$$

where A, B, C and D are fitted coefficients. These coefficients were presented graphically as functions of both the Reynolds number and the turbulence intensity as well as the polar angle. It is apparent from this correlation that several types of turbulent transfer processes may take place at different locations on the surface of a sphere. The effects of turbulence were found to be greatest at the front stagnation point, decreasing as the polar angle increased. The freestream turbulence was reported to have little influence on the heat transfer over the wake region.

Boulos and Pei [11] proposed a correlation of the heat transfer in the wake region of a sphere based on a similar surface renewal model. The fluid at the surface was assumed to be renewed by eddies with a fixed contact time, during which heat was transferred by unsteady state conduction. The final correlation was expressed as:

$$Nu_i = 2 + 1.125Re^{1/2}Pr^{1/2}N_i^{1/2} \quad (2)$$

where N, a surface renewal number, is a function of the polar angle. This correlation, if rearranged with a Frossling number on the left hand side, is analogous to equation (1). Surface renewal numbers, calculated from the correlation of Galloway and Sage [10], over the wake region were found to be quite sensitive to the freestream intensity of turbulence, however there was a considerable amount of scatter in the data leading to this conclusion.

An alternate approach was used by Kestin [12], who reviewed the available data for turbulent flow near the leading stagnation point of several flow geometries. Generally the heat transfer increased with the intensity of turbulence, although the curves presented for spheres suggested the presence of a minimum. Two possible interactions between the freestream turbulence and the boundary layer were conjectured. The first assumed the velocity at the outer edge of the boundary layer to fluctuate at the freestream turbulence level. It was shown that for harmonic oscillations, the boundary-layer thickness alternately increased and decreased, but that the time averaged thickness was smaller than that of the laminar layer, resulting in increased heat-transfer rates. This would not necessarily be the case for random fluctuations since the effect depends on the wave form of these fluctuations. An asymmetric wave could conceivably result in an increase in the average boundary-layer thickness and hence in decreased heat-transfer rates. The magnitude of this effect was estimated but found to be much smaller than that determined experimentally. The other interaction involved the stretching of vortices in the turbulent flow impinging on the surface. The divergence of the streamlines near the stagnation point of a three dimensional body causes the turbulence intensity near the surface to increase greatly. The damping due to viscosity would also become more significant, reducing this increased turbulence. A balance between these two effects would lead to a critical wavelength below which the fluctuations would be damped by viscosity and above which, amplified by vortex stretching.

Mujumdar and Douglas [13] obtained autocorrelation functions from velocity measurements in the wake of a sphere. At low freestream turbulence levels, definite periodic components were noted, probably corresponding to vortex shedding. However, the signal was quite random at higher turbulence levels. The fact that the eddies shed from the sphere were not observed at the higher turbulence levels suggests a change in the wake flow regime. This is in agreement with the sensitivity of the heat-transfer coefficients over the rear hemisphere to the freestream turbulence conditions indicated by the surface renewal correlations.

No study of the dynamic aspects of the heat transfer from spheres has yet come to the attention of the authors. However, the results obtained from other flow geometrics may yield some insight into the flow behaviour near the surface of a sphere. A major study of the dynamics of the heat transfer from cylinders was carried out by Boulos and Pei [14]. The intensity of the heat-transfer fluctuations was defined analogously to that of the freestream turbulence by:

$$\eta = [\overline{Nu'^2}]^{1/2}/\overline{Nu}. \quad (3)$$

The intensity of the heat-transfer fluctuations, η, was found to have a peak near the flow separation point. The fluctuations were an order of magnitude higher over the wake than over the front hemisphere. It was also noted to be a function of the freestream intensity of turbulence. The fluctuations at the front stagnation point were found to increase with the freestream turbulence, while the opposite was true at the rear stagnation point. Frequency domain analyses of the heat-transfer signals over the wake region revealed that the periodic component decreased to a minimum at an angle of 120°. This suggested the presence of two flow regimes in the wake. The frequency of this periodic component was equal to that of the vortex shedding.

To summarize, although many correlations of the time averaged convective heat transfer from a sphere have been proposed, no comprehensive description of the flow patterns and the dynamics of heat transfer around a sphere have yet been developed. Therefore, it is the purpose of this experimental study to investigate both the steady and the fluctuating components of the local heat transfer from a single sphere to a turbulent air stream.

EXPERIMENTAL DESCRIPTIONS

The wind tunnel used in this study was a low speed closed loop unit which gives a low level of background turbulence and a flat velocity profile in the test section. The desired turbulence characteristics were generated by placing wire grids across the test section entrance. The velocity profiles and turbulence intensities were measured by traversing a calibrated hot wire velocity probe across the test section, 30 cm downstream from the position of the turbulence generating grids.

The sphere (diameter = 2.67×10^{-3} m) used was a thin walled glass ball with two small platinum film sensors deposited onto the surface. One film served as the local sensors (5.5×10^{-3} m in length and 1×10^{-3} m in width) while the other film surrounding it acted as a guard heater (1.2×10^{-2} m in length and 4.5×10^{-3} m in width). Both were powered by constant temperature anemometer circuits which controlled the temperatures. An output signal based on the voltage across the local sensor was linearized to avoid distortions introduced by the nonlinear relationship between the signal and the power dissipation. The frequency response of the sensor is ± 2 dB up to 10 kHz. This linearized signal was then analyzed to obtain the time averaged local Nusselt number, the intensity of the heat-transfer fluctuations and the frequency spectra of these fluctuations. A complete description of the experimental equipment and a deviation of the necessary relationships are presented elsewhere [17].

ANALYSIS AND DISCUSSION OF RESULTS

The time averaged values of the local Nusselt numbers were averaged over the surface of the sphere to yield corresponding values of the overall Nusselt number. The overall Nusselt numbers are presented as a function of the Reynolds number in Fig. 1. The agreement between the data obtained and the correlation of Williams [1] was good. It must be noted, however, that the turbulence conditions represented by Williams' correlation were not specified.

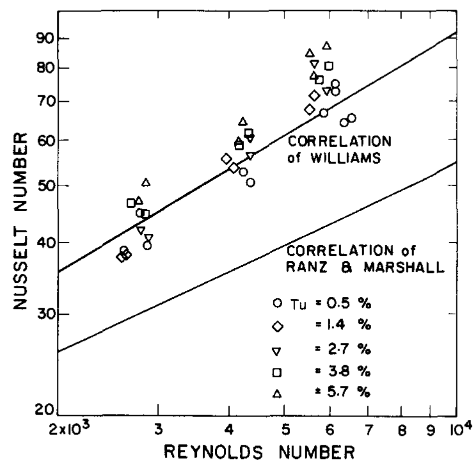

FIG. 1. Overall Nusselt number vs Reynolds number.

Figure 2 shows several typical distributions of the local heat transfer over the sphere surface. The general shape of these distributions was similar to those observed by several other workers [6, 7, 18]. The local Nusselt numbers decreased from a maximum at the front stagnation point to a minimum at an angle of 100°. This behaviour resulted from the development of a boundary layer over the front of the sphere. The minimum heat transfer at 100° corresponded to the flow separation point where the surface velocity approaches zero. After this point, the Nusselt number rose sharply to a maximum between 110 and 120° and decreased to another minimum at 130°. This variation in the heat transfer was attributed by Wadsworth [8], to the formation of a separation bubble followed by the reattachement of a fully turbulent boundary layer. The second Nusselt number minimum would correspond

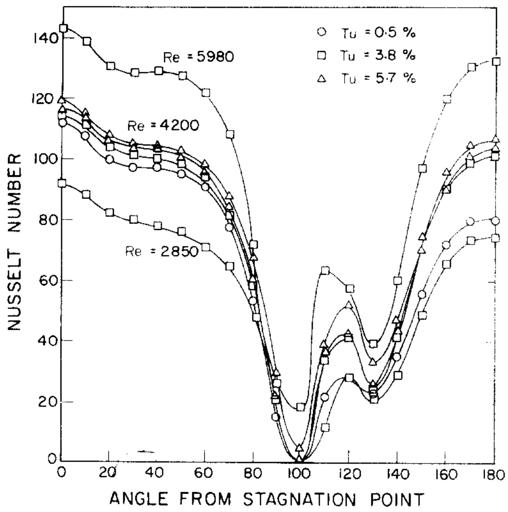

FIG. 2. Local Nusselt number vs angle from front stagnation point.

to the final separation of this layer. The heat transfer then increased smoothly over the wake region to another maximum at the rear stagnation point.

The formation of the separation bubble was not observed by Wadsworth [8] at Reynolds numbers of less than 7.8×10^4, however Lee and Barrow [9] observed a mass-transfer peak after the separation point at Reynolds numbers as low as 3.2×10^3.

An analysis was attempted here to study the dependence of the local Nusselt number on both the Reynolds number and the turbulence intensity. The expression for the correlation was of the form

$$Nu_i = A Re^m Re_T^n \tag{4}$$

where A, m and n are parameters estimated by an iterative nonlinear regression technique. This relationship was chosen as the simplest of many correlations available from the literature. Obviously, this form of correlation is limited to turbulent flow. As the flow becomes laminar, the Nusselt number approaches zero which is not physically valid. It does, however, reveal the sensitivity of the heat transfer to changes in the respective flow conditions.

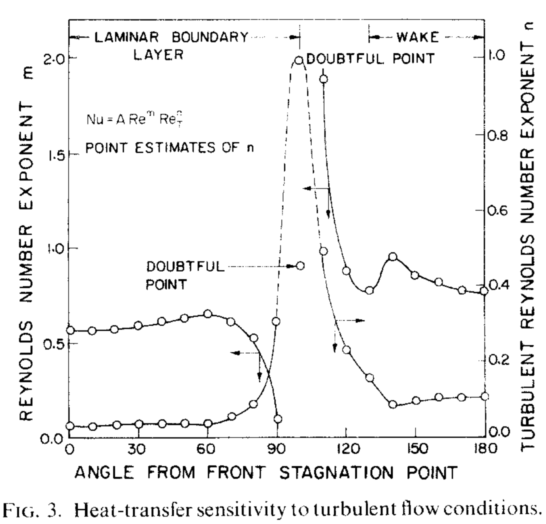

FIG. 3. Heat-transfer sensitivity to turbulent flow conditions.

In Fig. 3, the exponent of the Reynolds number, m, remained essentially constant up to an angle of 70° from the front stagnation point. The value was slightly higher than that of 0.5 predicted for laminar boundaries. This may be attributed to the influence of the freestream turbulence on the boundary layer. The exponent of the turbulent Reynolds number, n, also shown in Fig. 3, remained constant over this region of the sphere. The value, however, was quite small, indicating that the heat transfer from the front of the sphere was not greatly affected by the freestream turbulence.

The sharp drop in m to a minimum at the flow separation point reflects the decrease in both the surface velocity and velocity gradients. Since these quantities approach zero at the separation point, the heat transfer becomes independent of the Reynolds number. The only convective heat transfer at the flow separation point, then, occurs through turbulence, therefore the parameter n was at its maximum at this point.

Beyond the separation point, m increased sharply due to the reattachment of a fully turbulent boundary layer. This also corresponds to the peak observed in the local Nusselt number distributions. The value of n then decreased sharply and with less certainty. A smaller peak in the value of m was observed at an angle of 140° where the final separation of the boundary layer occurred. Over the wake region the value of m was approximately 0.8 which is in good agreement with that of 0.78 reported by Lee and Barrow [9]. On the other hand, the value of n decreased from the maximum at the flow separation point to become constant over the wake region. It is interesting to note that the main effects of turbulence occur in the region of the flow separation point, while the heat transfer over the remainder of the surface was not greatly influenced by the freestream turbulence.

The variations of the parameters m and n as well as the local Nusselt number distributions have outlined three distinct flow regimes on the surface of a single sphere, namely a laminar boundary layer, a turbulent boundary layer and a wake. Each region has unique properties with respect to both the flow and heat-transfer characteristics.

It has been suggested [19] that the influence of the freestream turbulence on the laminar boundary layer is due to the penetration of energy containing eddies into the boundary layer. This transfer of momentum into the layer results in an increase in the fullness of the velocity profile, and therefore an increase in the surface transport gradients. This penetration model would predict that the effects of the turbulence on the heat transfer would be mainly dependent on the turbulence intensity, a measure of the momentum contained in the eddies. The scale of turbulence also exerted a smaller effect on the heat transfer. Figure 4 presents the intensity of the heat-transfer fluctuations observed at the front stagnation point. The linear relationship with the freestream turbulence intensity strongly supports the eddy penetration hypothesis. The intercept obser-

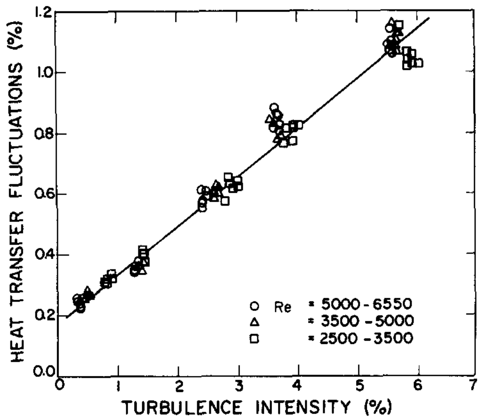

FIG. 4. Heat-transfer fluctuations vs turbulence intensity at front stagnation point.

ved was due mainly to electrical noise generated within the instruments of the signal processing system. Further downstream, the relationship between the heat transfer fluctuations and the freestream turbulence intensity became more complex, and a dependence on the Reynolds number became apparent. This is illustrated in Fig. 5, which presents the fluctuation data taken at an angle of 40°. The effect of the length scale of turbulence on the heat transfer was not measured in this investigation.

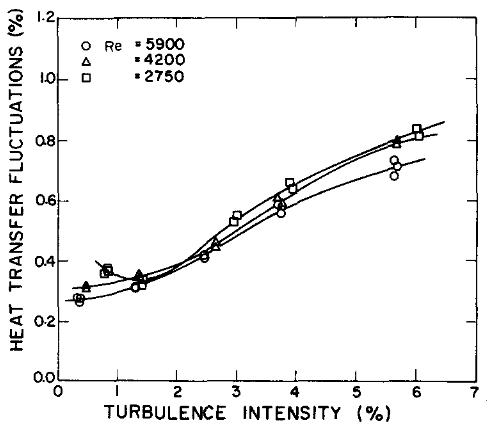

FIG. 5. Heat transfer fluctuations vs turbulence intensity at 40° from front stagnation point.

The intensity of the local heat-transfer fluctuations are shown in Fig. 6. The fate of the eddies entrained by the boundary layer is governed by a rather complex mechanism. After the stagnation point, amplification of the intensity through the stretching of the entrained vortices was observed, especially at high freestream turbulence intensities. Further downstream, the fluctuations decreased as the polar angle increased. This was attributed to a viscous damping process enhanced by the favourable pressure gradient. It has been shown [20] that the stability of a laminar boundary layer is directly related to the surface pressure gradient. A favourable, that is to say, negative gradient leads to stability, while the opposite is true for adverse gradients. The point of minimum pressure on the surface of a sphere occurs in the vicinity of 70° from the

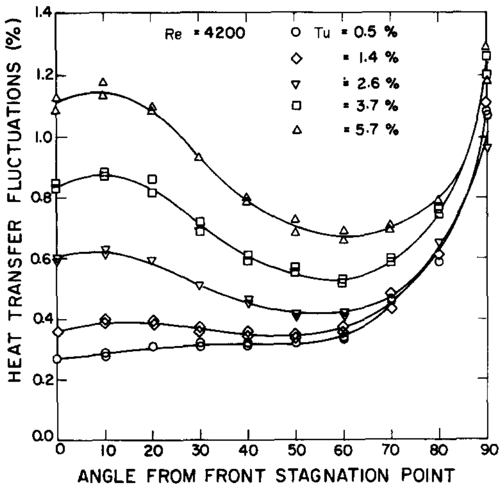

FIG. 6. Intensity of local heat-transfer fluctuations.

stagnation point. A rapid increase in the intensity of the heat-transfer fluctuations due to the transition to an unstable boundary layer was observed, and is shown in Fig. 6.

The formation of a separation bubble as proposed by Wadsworth [8] appears to be consistant with the results of this study. As a result of the increasing boundary-layer instability and the presence of flow disturbances in this layer, the separated shear layer became fully turbulent. The characteristic increase in the thickness caused by this transition enabled the lower edge of the turbulent shear layer to contact the surface of the sphere and become reattached. The size of a small separation bubble has been suggested by Houghton and Boswell [21] to be of the order of 1% of the chord length, which in the case of a sphere, represents an arc of approximately 2°. Since this was smaller than the minimum angular resolution of the sensor, the presence of a separation bubble could not be verified. Nevertheless, the heat-transfer data shown in Fig. 2 support this hypothesis. The rapid increase and subsequent decrease in the local Nusselt number between 100 and 130° are the result of a transition to and growth of a turbulent boundary layer.

The intensity of the heat-transfer fluctuations over this region was much higher than that observed before the separation as shown in Fig. 7. The increase in the intensity over this region was also attributed to the effect of the adverse pressure gradient. The relationship between the fluctuations and the freestream conditions was quite complex as indicated by the data obtained at an angle of 120°, shown in Fig. 8. A general decrease in the fluctuations with increasing freestream turbulence was noted, however the Reynolds number was also a significant factor.

The final separation of the turbulent boundary layer and the resulting formation of the wake occurred at a polar angle of approximately 130°. The heat transfer over the wake region increased smoothly to a maximum at the rear stagnation point as shown in Fig. 6. The intensity of the fluctuations remained essentially constant over this region, however, a peak was noted

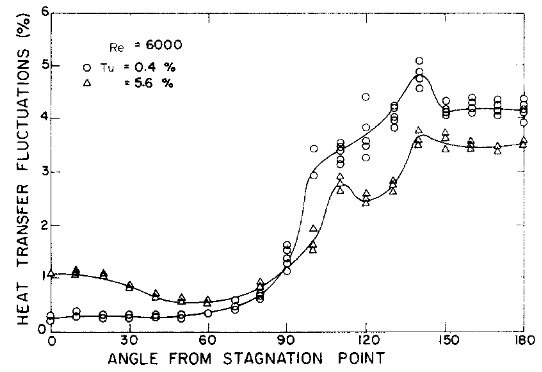

FIG. 7. Intensity of heat-transfer fluctuations vs angle from front stagnation point.

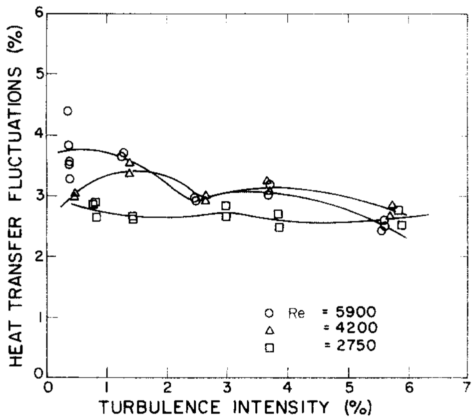

FIG. 8. Heat-transfer fluctuations vs turbulence intensity at 120° from front stagnation point.

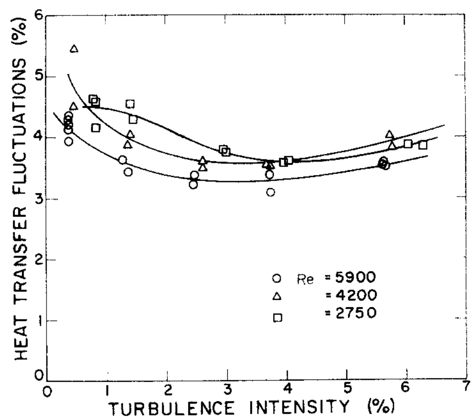

FIG. 9. Heat-transfer fluctuations vs turbulence intensity at back stagnation point.

at an angle of 140°. This was the result of the instability at the final separation point.

The formation of a stable vortex structure in the wake, such as that reported by Foch and Chartier [22] is unlikely where the boundary layer is turbulent before separation. The initial vortex filament which develops at the separation point would immediately break up due to the high shear caused by the turbulence. Figure 9 shows the heat-transfer fluctuation intensity at the rear stagnation point as a function of the freestream turbulence level. The higher values at the low turbulence levels may reflect the formation of a short lived vortex structure, however the subsequent decrease in the fluctuations suggests that any form of wake structure is very sensitive to the freestream turbulence.

The formation of a structured wake resulting from a vortex shedding mechanism would induce a strong periodic component in the heat-transfer fluctuations. An analysis of the frequency spectra of these fluctuations was carried out to examine the shedding behaviour.

The spectra obtained at turbulence intensities above 1.4% showed no periodic behaviour. The decrease in the amplitude with increasing frequency represented the viscous dissipation of randomly distributed eddies. At the lowest turbulence level, some small peaks were discerned, however in view of the freestream turbulence structure, these were not conclusive. These observations of the random nature of the wake in a turbulent freestream are in agreement with the results of Mujumdar and Douglas [13] who observed shedding only at very low freestream turbulence levels.

CONCLUSIONS

This experimental study may be summarized in terms of the following conclusions:

1. Three flow regimes around a sphere in a turbulent air stream have been observed at Reynolds numbers between 2600 and 6100. These consist of a laminar boundary layer over the leading part of the sphere, a turbulent boundary layer and a turbulent wake.
2. The properties of each flow regime are unique, hence correlations of the overall heat-transfer data must consider the contribution of each region separately.
3. The increase in the heat transfer due to the freestream turbulence is likely caused by the penetration of eddies into the boundary layer, most significantly near the flow separation point.
4. The disturbances in the laminar boundary layer are amplified by an adverse pressure gradient. The instability of this layer then results in the transition to a turbulent layer at the laminar separation point.
5. The wake formed after the separation of the turbulent boundary layer is also fully turbulent.

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TRANSFERT THERMIQUE LOCAL ENTRE UNE SPHERE ET UN ECOULEMENT TURBULENT D'AIR

Résumé—On étudie le transfert thermique local entre une sphère et un écoulement turbulent d'air. Les conditions d'écoulement correspondent à un nombre de Reynolds entre 2600 et 6100 et à des intensités de turbulence entre 0,45 et 6%. Les résultats obtenus montrent que la couche limite sur la surface devient turbulente au point de séparation laminaire. Cette couche turbulente se rattache à la surface puis se sépare en aval pour conduire au sillage turbulent. Ce phénomène a lieu à un petit nombre de Reynolds à cause de l'intéraction entre la turbulence de l'écoulement libre et la couche limite.

DER ÖRTLICHE WÄRMEÜBERGANG AN EINER EINZELNEN KUGEL IN EINEM TURBULENTEN LUFTSTROM

Zusammenfassung—Es wurde der örtliche Wärmeübergang an einer Kugel in einem Luftstrom untersucht, wobei die Reynolds-Zahl von 2600 bis 6100 und der Turbulenzgrad von 0,45 bis 6% variiert wurde. Die Ergebnisse zeigen, daß die Grenzschicht über der Anströmseite am laminaren Ablösepunkt turbulent wird. Diese turbulente Schicht legt sich jedoch wieder an und löst sich erst weiter strombwärts ab, woraus dann ein turbulentes Totwassergebiet entsteht. Bedingt durch die gegenseitige Beeinflussung zwischen Friestrahlturbulenz und Grenzschicht treten diese Phänomene bei niedrigen Reynolds-Zahlen auf.

ЛОКАЛЬНЫЙ ПЕРЕНОС ТЕПЛА ОТ ШАРА К ТУРБУЛЕНТНОМУ ПОТОКУ ВОЗДУХА

Аннотация — Исследуется локальный теплообмен между шаром и турбулентным потоком воздуха в диапазонах чисел Рейнольдса от 2600–6100 и интенсивности турбулентности от 0,45–6%. Полученные результаты показывают, что пограничный слой на поверхности становится турбулентным за точкой ламинарного отрыва. Турбулентный слой вновь присоединяется к поверхности, а затем отрывается, образуя турбулентный след. Эти явления имеют место при низких значениях числа Рейнольдса вследствие взаимодействия турбулентности свободного потока с пограничным слоем.