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DISCUSSION

J. Kestin[2]

Since the publication of our earlier paper (authors' reference [3]) we have performed a number of measurements and theoretical studies on the effect of free-stream turbulence on heat-transfer rates which have been recently summarized in a review article.[3] In general, there is agreement with the authors' measurements for similar configurations.

It is possible to summarize our results by the following statements:

1 Generally speaking, a change in the intensity of turbulence in the free stream exerts a larger effect on heat-transfer rates than on skin-friction coefficients.

2 A change in the intensity of turbulence in the free stream has no effect on the heat-transfer rate from a flat plate at zero incidence beyond that produced by an advancement and possible spreading of the region of transition.

3 A change in the intensity of turbulence has no effect on the heat-transfer rate across a turbulent boundary layer.

4 A change in the intensity of turbulence has only a small effect (of the order of 10 percent) on the transfer of heat across a laminar boundary layer developed under the influence of a favorable pressure gradient.

5 A change in the intensity of turbulence has a very large effect (of the order of 70–80 percent for an intensity of turbulence of 2.5–3.0 percent) across a laminar boundary layer formed around the stagnation line of a cylinder and presumably also across one formed around the stagnation point of a sphere or similar blunt body.

It should be noted that the large increase in the heat-transfer rate across a laminar boundary layer on a flat plate with a favorable pressure gradient reported by Kestin, Maeder, and Wang (authors' reference [3]) has not been confirmed, as reported later.[4]

It is sometimes said that a boundary layer does not remain truly laminar in the presence of a turbulent free stream. It is, however, necessary to realize that all laminar boundary layers encountered in practice carry stochastic oscillations whose

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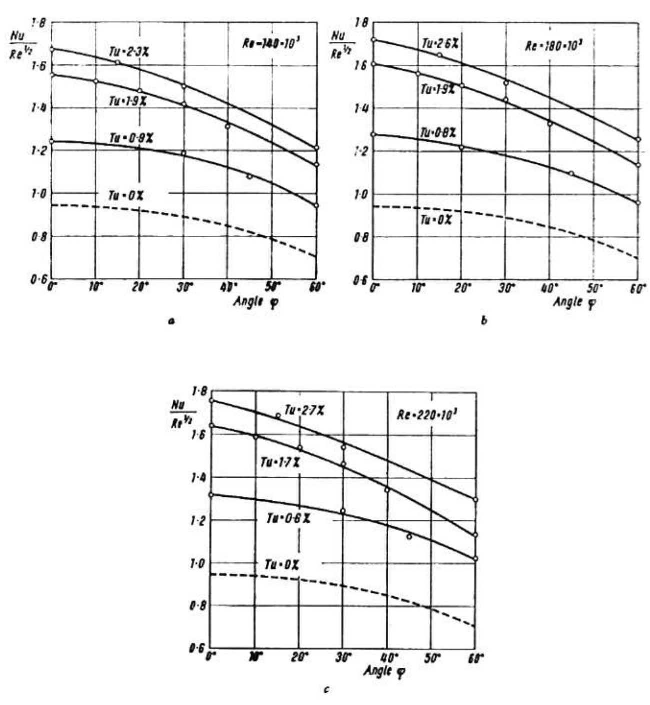

Fig. 12 Variation of local Froessling number $Fr = Nu/Re^{1/2}$ on a circular cylinder with turbulence intensity, angular coordinate, and Reynolds number. Theory (broken line) after Foessling. Measurements (full line) by Kestin, Maeder, and Sogin.

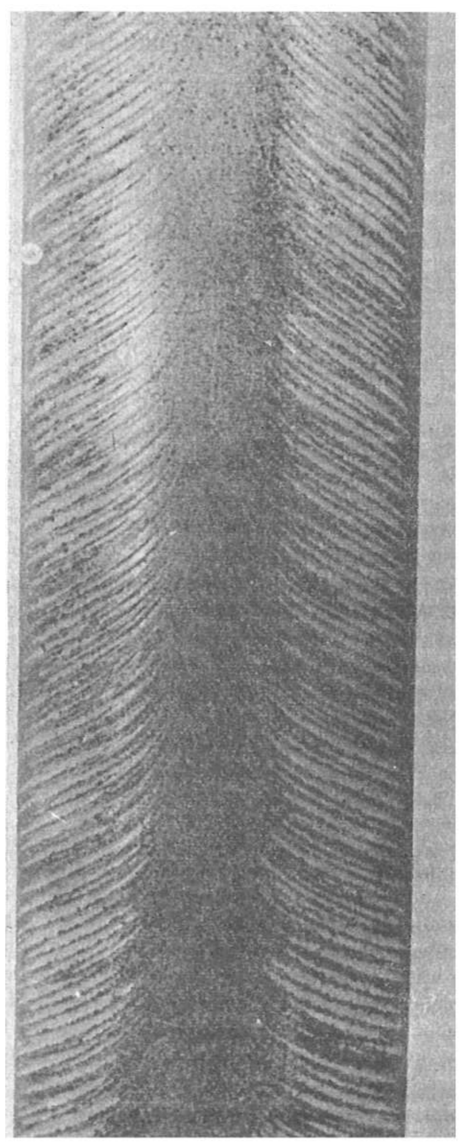

Fig. 13 Appearance of yawed cylinder after 1 hr at Re = 93,000 (D = 6 cm; U_∞ = 24 m/sec) and Tu = 0.3 percent. Angle of yaw Λ = 36 deg with respect to normal to free stream.

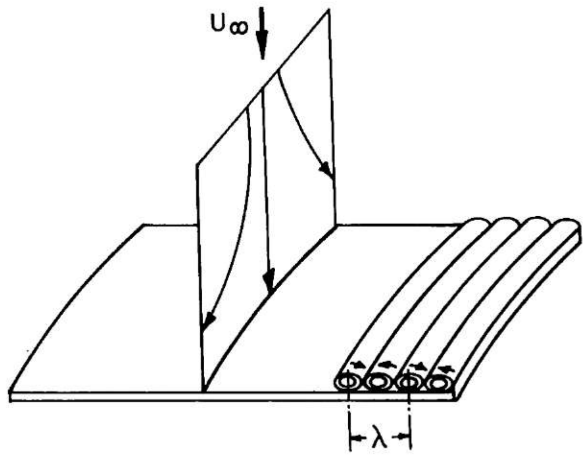

Fig. 14 Appearance of a regular system of vortices at the stagnation line on a cylinder

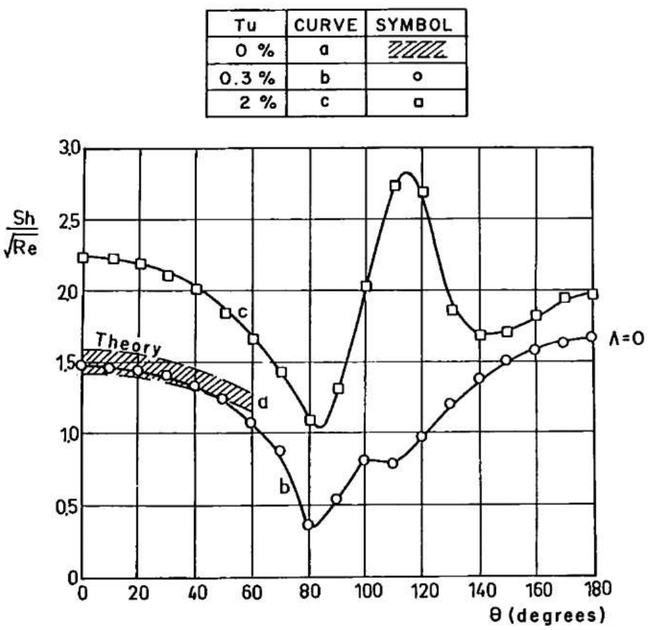

Fig. 15 The rate of mass transfer around a circular cylinder in crossflow at Re = 93,000 and at two levels of turbulence. (D = 6 cm; U_∞ = 24 m/sec; Tu = 0.3 and 2.0 percent.)

amplitude and frequency spectrum is related to the turbulence intensity in the free stream. This is recognized in the Tollmien-Schlichting theory of stability which regards the boundary layer as laminar if these disturbances do not amplify.

Conclusion (5) constitutes probably the most unexpected outcome of our work, and for this reason the results due to Kestin, Maeder, and Sogin[4,5] are shown reproduced in Fig. 12. In order to understand this as well as the preceding results, a tentative hypothesis has been adopted in the past according to which the effect was supposed to be produced by the oscillations induced by turbulence present in the boundary layer in the free stream. It was thought that these in turn generate secondary flows in the boundary layer in analogy with a sound field. The speaker is of the opinion that this hypothesis is untenable and cannot be brought into accord with experimentally established facts.

An explanation must be sought in an alternative idea contained in a paper by Sutera, Maeder, and Kestin[6] according to which the diverging streamlines in stagnation flow effect a stretching of the vortex filaments which exist in the free stream when the latter is turbulent. Owing to the simultaneous action of viscosity, only vorticity of a wavelength exceeding a certain critical value is amplified and imposes itself on the boundary layer. This produces an essentially three-dimensional flow pattern which can be shown to increase the averaged heat-transfer rate much more than the corresponding averaged skin-friction coefficient.

In an investigation by Brun, Diep, and Kestin[7] a successful attempt was made to render these amplified vortices visible. The experiments were performed with sublimating cylinders made of para-dichlorobenzene. The photograph in Fig. 13 shows the appearance of the forward portion of a yawed cylinder on whose surface there appear grooves eroded by a three-dimensional system of vortices whose axes align themselves in the flow direction. Although this photograph shows a yawed cylinder, the same distribution of grooves was observed at $\Lambda = 0°$ (cylinder in crossflow). The sketch in Fig. 14 shows the arrangement of vortices on a cylinder in cross flow.

From these experiments we conclude that: The free stream outside a stagnation line does not stay two-dimensional but develops a three-dimensional, regular pattern of vortices. In air, the spacing of these vortices depends on three parameters: (*a*) the Reynolds number; (*b*) the intensity of turbulence; (*c*) the angle of yaw. Table 1 gives preliminary results of spacing of vortices on yawed cylinders at Re = 93,000. The tentative results summarized in Table 1 suggest that the diverging pattern of streamlines selectively amplifies vorticity of a particular wavelength, depending on turbulence intensity, but the detailed mechanism which effects such a filtering is not understood at the present time.

Table 1 Spacing of vortices on yawed cylinders at Re = 93,000 (preliminary results)

Λ	Tu = 0.3% λ cm	Tu = 2.0% λ cm
0°	0.08	0.10
9°	0.10	0.14
18°	0.14	0.16
36°	0.27	0.30

The diagram in Fig. 15 shows that the mass-transfer rate also increases considerably, even when the increase in the intensity of turbulence is not very large.

For reasons explained in the speaker's summary article, it is not possible to obtain a correlation of diverse experimental results in terms of free-stream turbulence.

Authors' Closure

The authors wish to thank Professor Kestin for this review of his recent data and conclusions. We agree in general with his comments and believe that the discussion represents a valuable contribution to the literature.

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