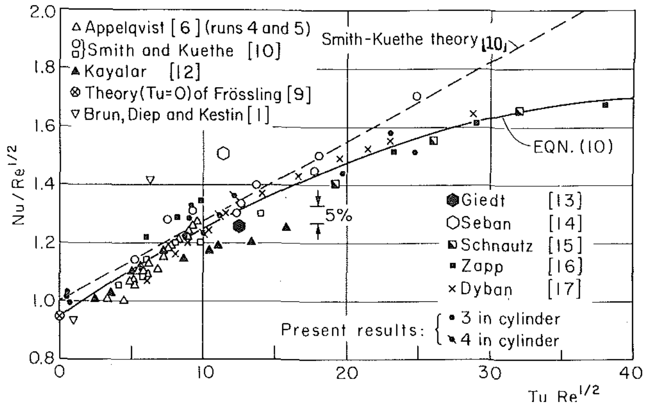

Fig. 8 Measurements for the local rate of heat (mass) transfer at the stagnation line of cylinders in cross flow

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DISCUSSION

A. M. Kuethe[2]

In their discussion of the theory and experiments given by Smith and Kuethe in reference [10], the authors state "...the theory describes the measurements of its authors reasonably well, but . . . it fails to conform to the general trend of the remaining body of data." The theory referred to, as Messrs. Kestin and Wood are aware, is the only one extant; it contains only one empirical constant and it fits satisfactorily *most* of the experimental data of Fig. 8. The theory may require modification for $Tu\ Re^{1/2} > 20$, though the data of Fig. 8 needs checking for high $Tu\ Re^{1/2}$ since the points in this range were taken (see Fig. 1 and Table 1) in the region where the distance from the grid is less than 10 mesh lengths; hence the turbulence would not be homogeneous and its magnitude would vary greatly over the diameter of the cylinder.

Arun S. Mujumdar[3] and W. J. M. Douglas[4]

The purpose of this discussion is to make a few observations based on the data of Kestin and Wood and our own results which are reported elsewhere [18]. Specifically, we observed during our study of the effects of free-stream turbulence on the stagnation point and overall heat transfer from cylinders that the Frössling number could be correlated better in terms of a turbulence Reynolds number, Re_T ($= I$ Re, where I is the fractional intensity of turbulence and Re is the nominal Reynolds number), rather than with the Smith and Kuethe parameter, $I\ Re^{1/2}$, which is based on a phenomenological hypothesis. This observation is, of course, difficult to justify physically.

In view of our favorable experience with the use of the turbulence Reynolds number, we made a comparative analysis of the data under discussion. Specifically, a least-squares analysis of the data of Kestin and Wood for 3-in. cylinders (their Table 3), made without forcing the curve to pass through the Frössling value of $Nu/Re^{1/2} = 0.945$ for $I = 0$, yields the following correlations:

1 With the Smith and Kuethe parameter ($I\ Re^{1/2}$)

$$\frac{Nu}{Re^{1/2}} = 0.9762 + 0.0138\,I(Re \times 10^{-3})^{1/2} - 1.32 \times 10^{-6}(I\sqrt{Re})^2$$

(standard error = 0.0477)

2 With Re_T ($= I$ Re)

$$\frac{Nu}{Re^{1/2}} = 0.981 + 1.017 \times 10^{-4}\,Re_T + 2.74 \times 10^{-9}\,Re_T^2$$

(standard error = 0.0329)

The standard error increases if the curves are forced through $Nu/\sqrt{Re} = 0.945$ for $I = 0$.

It is apparent that, for the case of the Kestin and Wood data, the comparison between the Smith and Kuethe parameter and the turbulence Reynolds number does not indicate a clear choice between the two.

The use of Re_T as a correlation parameter appears to date from its use by Lavender and Pei [19] in the correlation of their data for spheres. However, very recently Gostowski and Costello [20] had only rather limited success when they used Re_T in correlating their data for stagnation-point heat transfer data for spheres. This may be due in part to the extremely high turbulence levels (up to 40 percent) employed to generate data for high values of Re_T. Under these conditions the free stream would be highly anisotropic and would contain discrete frequency fluctuations depending on the grid geometry and the mean flow. Such streams may not be classified as truly turbulent. By contrast, our own heat transfer results showed that Re_T is a good correlation parameter for both the average and the stagnation-point heat transfer. Even including the above comparison based on the data of Kestin and Wood, the case for the use of the turbulence Reynolds number therefore remains unresolved.

Also, we wish to point out that mass-transfer data may be influenced by the rather small span-to-diameter ratio test models

[2] Aerospace Engineering Department, University of Michigan, Ann Arbor, Mich.

[3] Mechanical Engineer, Research Div., Carrier Corp., Syracuse, N. Y.

[4] Professor of Chemical Engineering, McGill University, Montreal, Canada.

used by Kestin and Wood. Morsbach [21] has shown that, in the subcritical region, there is no appreciable influence of the span-to-diameter ratio on the flow at the middle section of the cylinder. However, it has been shown by Achenbach [22] that for small values of span-to-diameter ratio (<3.0) in the critical region, the flow at the middle section is affected by the walls. Referring to Bearman's correlation [23] between the critical Reynolds number for cylinder and turbulence parameters, it would appear that any possible effect of the finite length of the cylinder would be limited to the large-diameter test model (4 in.) and the highest turbulence intensity (7.2 percent). It is impossible to assess the magnitude of this effect quantitatively without experimentation. It may not exceed the level of experimental uncertainty.

Further comments by Professor Kestin or his co-workers on the points raised in this discussion would be appreciated by all investigators of these phenomena, particularly because his group is identified with so much of the present-day knowledge in this field.

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Authors' Closure

We wish to thank our discussers for their comments, and we shall attempt to answer their observations in turn.

First, it was not our intention to disparage the theory of Smith and Kuethe; indeed, as Professor Kuethe notes, this is the only semiempirical theory that fits satisfactorily most of the experimental data. (By comparison, the results of semiempirical theory proposed by Kayalar [12] are inferior.) However, we did see the need to provide an empirical correlation of the data in order to estimate their consistency.

The behavior of our experimental results for $Tu\text{Re}^{1/2} > 20$ has clear support from the other heat- and mass-transfer measurements shown in Fig. 8. Thus, there is little reason to suspect that our grid III placement, which was slightly more than 10 mesh lengths (15 in.) from the stagnation line, biased the spanwise uniformity of our results. Furthermore, the grid in question consisted of horizontal rods whose axes were parallel with the axis of the cylinder, so that the free-stream turbulence was probably homogeneous in the spanwise direction. In this connection, we should remark that almost all grid-generated turbulence is quite anisotropic, being at best homogeneous in planes parallel with the grid before the influence of the model takes hold. Fortunately, the turbulence energy (intensity), and not the scale, is the dominant variable.

Still on the subject of our data, we neglected to mentioned that the 10-in. coated cylinder was fitted with tubular end adapters to form a composite cylinder equal in length to the shorter dimension of our 22-in. × 32-in. test section. Hence, we observed some end effects near the edges of the coating, but they did not appear to influence the center-span mass transfer. One might also question the influence of blockage, except that the maximum blockage ratio was a tolerable 12 percent, and the agreement between the results for the 3-in. and 4-in. cylinders is within our experimental precision.

We must agree with the conclusion of Mujumdar and Douglas that empirically it is not possible to define a clear choice between the Smith–Kuethe parameter and the turbulence Reynolds number. (Apparently the latter was first utilized as a correlating parameter by Van Der Hegge Zijnen [24].) Moreover, an adequate theory to describe the interaction of free-stream turbulence with the three-dimensional flow pattern might not substantiate the choice of either parameter. For example, our stability analysis [2] has revealed that the wavelength of the three-dimensional motion is dependent on the $\frac{1}{3}$-power of the wall shear-stress rate, which, in turn, is influenced by the free-stream turbulence in a currently unknown manner. The amplitude of the motion also depends on the turbulence, and both the amplitude and the wavelength govern the transfer processes nonlinearly.

In view of the unstable nature of two-dimensional stagnation flow, it is doubtful that the theoretical Frössling limit, $\text{Nu}/\text{Re}^{1/2} = 0.945$, can ever be realized in the laboratory. Therefore, following the above work of Mujumdar and Douglas, we would suggest that future empirical correlations allow the data and the fit criterion to determine the zero-turbulence heat-transfer coefficient.

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