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SHORTER COMMUNICATIONS

HEAT TRANSFER IN THE SEPARATED REGION UPSTREAM OF AN ORIFICE IN A TUBE

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PRIOR experiments on turbulent tube flow have demonstrated [1, 2] that heat-transfer coefficients in the region *downstream* of a flow separation are very much higher than those encountered in conventional tube flows without separation. In the aforementioned investigations, the flow separation was brought about by an orifice situated at the inlet of a heated test section. In the present study, experiments are performed to determine the heat-transfer characteristics in the separated region *upstream* of the obstacle that creates the flow separation.

As is illustrated schematically in Fig. 1, the test apparatus consists, in essence, of an orifice situated in the exit cross-section of a uniformly heated circular tube (ohmic heating within the tube wall). Water is the working fluid. From measurements of the axial temperature distribution along the tube wall, the entering and exit bulk temperatures, and the electric power dissipation, local heat-transfer coefficients can be evaluated. The distribution of the measured heat-transfer coefficients in the region upstream of the orifice provides an indication of the effects of the flow separation.

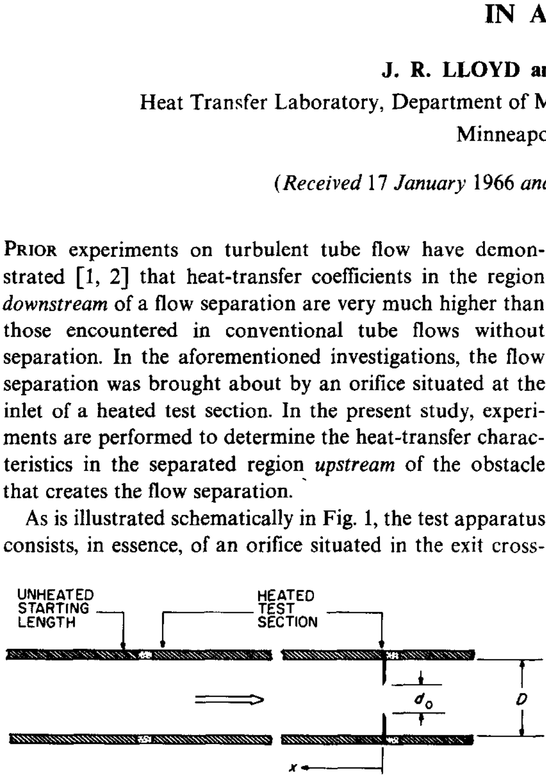

FIG. 1. Schematic diagram of the experimental apparatus.

The heated test section is a stainless steel tube having an internal diameter of 0·752 inches and a length of approximately 30 diameters. It is part of a pressurized closed loop containing a pump, hydrodynamic development section, heat exchanger, flow meter, and control valve. The loop is the same as that previously described [2], and the details will therefore be omitted here. The orifices employed to create separation were fabricated from a free-machining plastic (delrin) in accordance with ASME standards. A plastic was used instead of a metal to minimize heat conduction effects. Two orifices characterized by ratios $d_0/D = \frac{1}{2}$ and $\frac{1}{4}$ were employed (d_0 = orifice bore diameter, D = tube diameter); both orifices were $\frac{3}{32}$ inch thick.

The reduction of the measured data follows lines similar to those described in reference [2]. The local heat-transfer coefficient and Nusselt number were evaluated from their definitions

$$h = q/(T_w - T_b), \qquad Nu = hD/k \tag{1}$$

in which q is the local heat flux, and T_b and T_w are, respectively, the local fluid bulk and local inside wall temperatures. The results are parameterized by the Reynolds number

$$Re = 4w/\pi\mu D \tag{2}$$

where w is the mass rate of flow. The properties appearing in the foregoing were evaluated at the mean bulk temperature. Typically, the difference between the inlet and outlet bulk temperatures was approximately 3·5 degF. To facilitate comparisons with prior work, the tests were performed at a bulk Prandtl number of 3.

RESULTS AND DISCUSSION

Before presenting results for the separated region, brief consideration will be given to the case of flow without separation. It is of particular interest to display the distribution of the heat-transfer coefficient in that portion of the tube which, after installation of the orifice, encompasses the separated region. A representative plot of experimentally determined heat-transfer coefficients for the case of unseparated flow is shown in Fig. 2. The ordinate of the figure is the ratio of the local Nusselt number to a representative fully developed value (subscript fd). The abscissa is the dimensionless axial distance measured upstream from the tube exit (see Fig. 1). Measurements in the neighborhood of the tube inlet are not shown inasmuch as they are not pertinent to the main line of this investigation. An extensive presentation of both entrance region and fully developed heat-transfer coefficients for the Prandtl number range of liquid water is given in reference [3].

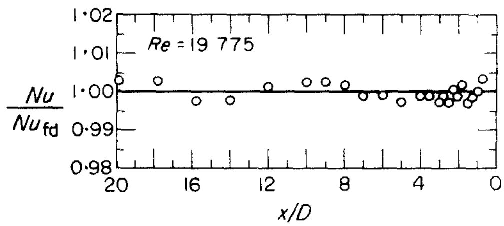

FIG. 2. Nusselt number distribution in a turbulent pipe flow without separation, $Pr = 3$.

Inspection of the figure indicates that thermally developed conditions prevail throughout the entire section of pipe for which results are shown. The plotted points scatter by $\pm 0{\cdot}3$ per cent* about the representative fully developed value. This degree of scatter represents the limit of precision to which data can be collected. The particular relevance of Fig. 2 is that it testifies to the absence of local irregularities in the heating rate and temperatures.

Attention is now turned to the heat-transfer results in the upstream separated region, i.e. upstream of the orifice situated in the exit plane of the test section. This information is shown in Figs. 3 and 4, respectively for ratios of orifice-to-tube diameter $d_0/D = \frac{1}{2}$ and $\frac{1}{4}$. Each figure is subdivided into three graphs which correspond to Reynolds numbers between 10000 and 50000; all results are for $Pr \cong 3$. The ordinate variable is the ratio of the local Nusselt number to the corresponding fully developed value, while the abscissa is the dimensionless axial distance measured in the upstream direction from the upstream face of the orifice.

An overall inspection of the figures reveals certain characteristics that are common to all of the conditions investigated. First of all, it is seen that the upstream flow separation has a remarkably small effect on the local heat-transfer coefficient. Indeed, the maximum increase in the local coefficient relative to the corresponding fully developed value is only 3–4 per cent. This is to be contrasted with increases in the heat-transfer coefficient of 350–900 per cent that are sustained in a downstream separated region, under corresponding operating conditions [2]. The fact that an upstream separation has a lesser effect on heat transfer than a downstream separation is reasonable on physical grounds; however, the quantitative extent of the difference between the results is quite remarkable.

Another characteristic of the present results is that the effect of the flow separation is little influenced by changes

* This corresponds to an uncertainty of approximately $\pm 0{\cdot}05$ degF in the wall-to-bulk temperature difference.

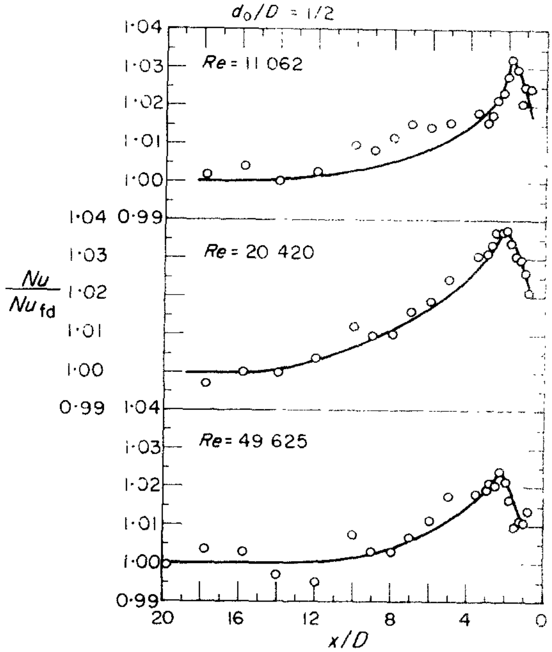

FIG. 3. Nusselt number distribution in the upstream separated region, $d_0/D = \frac{1}{2}$, $Pr = 3$.

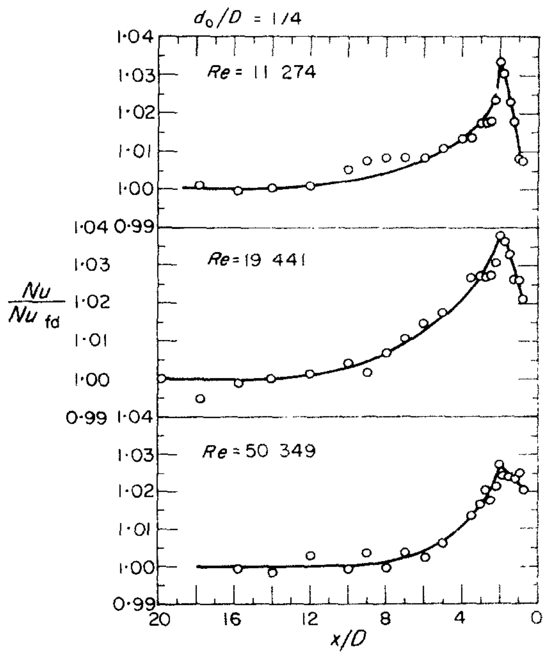

FIG. 4. Nusselt number distribution in the upstream separated region, $d_0/D = \frac{1}{4}$, $Pr = 3$.

in d_0/D and in Reynolds number. This is also in sharp contrast with the heat-transfer results for the downstream separated region. In the latter situation, large increases in Nu/Nu_{fd} were sustained as both d_0/D and Re decreased. For instance, for $Re = 10000$, the peak value of Nu/Nu_{fd} increased from 5 to 9 as d_0/D was varied from $\frac{1}{2}$ to $\frac{1}{4}$. No corresponding variation was found to occur in the upstream separated region.

The peak value of Nu/Nu_{fd} in the upstream separated region typically occurred at about two diameters upstream of the orifice. That a maximum should occur is consistent with physical reasoning, inasmuch as the eddying flow is highly constrained in the region adjacent to the mating of the tube wall and orifice.

In conclusion, the results of this investigation suggest that heat-transfer coefficients in an upstream separated region are little different from those in a thermally developed pipe flow. For practical purposes, it appears reasonable to neglect the effect of the upstream separation in computing heat-transfer results.

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HEAT AND MASS TRANSFER IN MEDIUM WITH VARIABLE POTENTIALS

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1. INTRODUCTION

Real transfer processes usually take place in a medium whose temperature and concentration vary continuously with time. For example when extracting matter out of a porous body by diffusion, it will move continuously to the body surface and then into the surrounding medium. As a result, the extracted mass concentration will continuously increase. A similar phenomenon occurs when drying; the external air humidity is increased and its temperature reduced, while moisture is evaporated and material heated. Analogous problems arise when calculating semi-coking kinetics, diffusion–electrical processes, etc.

The peculiarity of all these problems is caused by the interrelation existing between the internal and external potentials. The mathematical model of heat and mass transfer should consider the variation of the external potentials under adequate boundary conditions. Such a generalization of the boundary conditions makes possible to some extent the application of results obtained when considering transfer phenomena in a stationary or even a moving layer.

Solutions of problems of this type in pure heat or mass transfer are given in references [1–4]. Heat transfer with only the external medium temperature changing considerably with time is discussed in reference [5].

A profound theoretical analysis of transfer processes is given in reference [6]. The present paper is based on that monograph and considers heat and mass transfer in a medium with variable potentials.

2. BASIC EQUATIONS

Internal heat and mass transfer is described by a system of differential equations which, for one-dimensional bodies, can be written in dimensionless form as

$$\frac{\partial T(X, Fo)}{\partial Fo} = \frac{\partial^2 T(X, Fo)}{\partial X^2} + \frac{\Gamma}{X}\frac{\partial T(X, Fo)}{\partial X} - \varepsilon Ko \frac{\partial \theta(X, Fo)}{\partial Fo} \quad (1)$$

$$\frac{\partial \theta(X, Fo)}{\partial Fo} = Lu\left[\frac{\partial^2 \theta(X, Fo)}{\partial X^2} + \frac{\Gamma}{X}\frac{\partial \theta(X, Fo)}{\partial X}\right] - LuPn\left[\frac{\partial^2 T(X, Fo)}{\partial X^2} + \frac{\Gamma}{X}\frac{\partial T(X, Fo)}{\partial X}\right] \quad (2)$$