journal of
heat
transfer

discussion

Heat Transfer From Spheres in Naturally Turbulent, Outdoor Environment[1]

A. S. Mujumdar.[2] The authors should be complimented for an interesting experimental investigation that clearly demonstrates that near the ground the heat transfer from spherical bodies is higher than what would be estimated from wind tunnel tests using artificially induced turbulence. However, they do not offer any physical explanation for this phenomenon. The objective of this discussion is to present a possible explanation that would have to be tested by direct experimentation.

The main difference between the wind tunnel studies the authors refer to and the naturally turbulent flow is of course the presence of shear and turbulence intensity gradients and the scale (temporal and spatial). Effects of shear and turbulence intensity gradients may be ignored since the test spheres were only 7.62 cm dia. However the temporal and spatial scales are one or several orders-of-magnitude different. The scale of turbulence referred to in references [7–9] is different from the mixing length concept used by the authors. In my opinion the main difficulty in studying small objects in atmospheric turbulence resides in the definition of the appropriate scale of turbulence.

Since natural turbulence contains very small frequency fluctuations (i.e., very large wavelength disturbances which contribute significantly to the extremely large spatial scales calculated), when studying small objects one must decide what the lowest frequency is of a truly turbulent fluctuation. In other words, depending upon the low frequency "cut-off" so chosen, a corrected turbulence intensity can be computed. Thus, one must (unfortunately, empirically) define the low frequency (or low wavenumber) cut-off of the turbulence energy spectrum and then proceed to compute the turbulence scale and intensity either digitally or using analog circuitry. Both the scale and intensity thus obtained will be lower than the ones obtained by the authors which will in turn bring their results closer to the wind tunnel measurements.

In the opinion of the discusser the very low frequency fluctuations contained in natural turbulence would be seen by the small spheres as fluctuations in the magnitude and direction of the mean incident velocity (i.e., mean Reynolds number). Thus there would be some augmentation in the local and mean heat transfer rates because the body is effectively exposed to an oscillatory external flow.

Another plausible physical explanation for the phenomenon observed by the authors is that low frequency fluctuations of turbulence generally are more "energetic" and hence are better able to penetrate into the wall region and enhance the heat transfer rate. Natural turbulence has more energy contained in the low frequency region than does wind tunnel turbulence. Thus the authors' results are hardly unexpected. Some recent studies on turbulent heat transfer in pipe flow lend support to this hypothesis. It has been observed, for example, that there is a better correlation between velocity and temperature fluctuations (in the wall region) at the low frequency end of the spectrum than at the high frequency end. Indeed, at very high frequencies the two are statistically independent.

Unfortunately little work appears to have been done on assessing the influence of the turbulence spectrum on heat transfer from bluff bodies. Mujumdar and Douglas[4] made perhaps the first and only preliminary study of the effect of the free-stream turbulence spectrum on heat transfer from cylinders in cross-flow. Although these results were not sufficiently extensive they indicated that the low frequency of the spectrum is more important than the low energy, high frequency region of external turbulence in enhancing blunt body heat transfer.

Finally, if the authors have made spectral measurements of turbulence under conditions encountered in the heat transfer study, I would appreciate their comments on the hypotheses proposed here. Ideally, a more conclusive proof will require measurement of the cross-correlation between the external turbulence fluctuations and wall heat transfer fluctuation.

Authors' Closure

The authors appreciate the comments of Professor Mujumdar, and agree that the physical reasons for the large enhancement in heat transfer for spheres near the ground are not well understood. We feel that the agreement between much of the present data and the wind tunnel tests, as represented in Fig. 6 of the paper, implies that the same mechanisms are present here as in wind tunnels.

The suggestion that low frequency (large scale) fluctuations act to expose the spheres to an oscillatory flow is plausible although it should be realized that oscillations occur in flow direction as well as magnitude. However, the greatest discrepancy represented in Fig. 6 is not for the lowest oscillations which occur at the greatest height. Also, it does not seem that lowered computed values of scale and intensity will bring our results more in line with wind tunnel measurements. Rather, our results are compatible with the higher values (Fig. 6). We were mainly interested in determining heat transfer coefficients, and did not make any turbulence measurements to support these suggestions.

As discussed in the paper, turbulence scale has been found to have a negligible effect in wind tunnel studies. Our results, in the main, agree with this conclusion, even though, as the discussor points out, the conventional definition of scale differs from that used in the paper (i.e., mixing length). It is only for the largest sphere closest to the

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[2] by G. J. Kowalski and J. W. Mitchell, published in the Nov. 1976 issue of the JOURNAL OF HEAT TRANSFER, TRANS. ASME, Series C, Vol. 98, No. 4, pp. 649–653.

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[4] Mujumdar, A. S., and Douglas, W. J. M., "Some Effects of Turbulence and Wake-Induced Periodicity on Local Heat Transfer From Cylinders in Cross-Flow," 20th Canadian Society Chemical Engineering Conference, Sarnia, Ontario, Canada, Oct. 1970.

ground that a significant difference between outdoor and wind tunnel tests occurs. Here, the ratio of mixing length to sphere diameter is about 0.5, and it may be that there is some effect in this range. We agree that further experiments are needed to resolve the apparent discrepancies, and to better understand the reasons for enhanced heat transfer outdoors.

A Mathematical Model for Transient Subchannel Analysis of Rod-Bundle in Nuclear Fuel Elements[1]

S. Gołos.[2] Dr. Rowe in his paper describing the COBRA-III program assumes that "one-dimensional two-phase *slip flow* exists in each selected flow subchannel during boiling." Such assumption means that the slip ratio, following the definition of Dr. Tong[3] is as follows:

$$S = \frac{V_v}{V_\ell} = \frac{X}{1 - X} \cdot \frac{1 - \alpha}{\alpha} \cdot \frac{\rho_\ell}{\rho_v}, \tag{1}$$

where:

V_v = axial velocity of saturated vapor,

V_ℓ = axial velocity of saturated liquid,

X = quality,

α = void fraction,

ρ_ℓ= density of saturated liquid,

ρ_v = density of saturated vapor,

does not equal one.

Dr. Rowe has obtained his equation (3) using the relation:

$$m = \rho \cdot A \cdot u \tag{2}$$

from which he obtains his effective momentum velocity

$$u = \frac{m \cdot v'}{A} \tag{3}$$

From the foregoing relations it follows immediately that Dr. Rowe uses the identity

$$v' = \frac{1}{\rho} \tag{4}$$

The density of two-phase medium is described, using the definitions of Dr. Tong and Dr. Rowe, as well by the relation:

$$\rho = \alpha \cdot \rho_v + (1 - \alpha) \cdot \rho_\ell \tag{5}$$

However the effective specific volume for momentum is defined as:

$$v' = \frac{X^2}{\alpha \cdot \rho_v} + \frac{(1 - X)^2}{(1 - \alpha) \cdot \rho_\ell} \tag{6}$$

Inserting relation (1) into equation (6) one obtains for v^1 the following form of (6):

$$v' = \frac{1}{\alpha \cdot \rho_v + (1 - \alpha) \cdot \rho_\ell} \cdot \left[1 + X \cdot (1 - X) \cdot \left(S + \frac{1}{S} - 2\right)\right] \tag{7}$$

or

$$v' = \frac{1}{\rho} \cdot [1 + X \cdot (1 - X) \cdot (S - 1)^2/S] \tag{8}$$

It is obvious that identity (4) will only be true in the case when the slip ratio $S = 1$ for $0 < X < 1$. But this fact means that the *nonslip flow* model is taken into consideration, that which contradicts Dr. Rowe's assumption. It seems that Dr. Rowe should not refer to the slip flow model in his paper if just the nonslip flow model is considered.

Author's Closure

A slip flow model is included in the development of the mixture momentum equation of the referenced paper. The claimed contradiction occurs because of the definitions assumed in equations (2) and (4). The entire development of the mixture equations is done by retaining mixture mass flow rate as a total quantity. A definition for velocity as assumed by equation (2) is not used. Since the group mv'/A appears when differentiating the momentum flux terms, this group is defined as the effective momentum velocity and is denoted by u in the referenced paper and by equation (3). Therefore, equation (4) does not follow and the inconsistency does not exist.

Although not stated, the derivation implicitly assumes equal slip ratio for the axial and lateral velocities. While this is satisfactory for many applications, there are some where this could be overly restrictive. For instance, experimental data suggest that the liquid and vapor lateral velocities between subchannels are in counter flow for some situations. Since the slip ratio is not well defined through a flow reversal, an alternate formulation using a drift flux model would be preferred. This model has the added advantage of using a less confusing set of definitions which do not call for "effective" densities or velocities. The physical processes of the flow field are also more clearly displayed in the equations and the model would have wider applications. Modification to include drift flux concepts into the development of the COBRA code are currently being pursued for use in nuclear reactor safety application.

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[1] By D. S. Rowe, published in the May 1973 issue of the JOURNAL OF HEAT TRANSFER, TRANS. ASME, Series C, Vol. 95, pp. 211-217.

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[3] Tong, L. S., *Boiling Heat Transfer and Two-Phase Flow*, Wiley, New York, 1965, pp. 59, 208.

The Numerical Prediction of the Turbulent Flow and Heat Transfer in the Entrance Region of a Parallel Plate Duct[1]

A. S. Mujumdar[2] and **Y-K. Li.**[3] The objective of this communication is to present some new computational results we have obtained using the now well-known TEACH-T computer code[4] developed at Imperial College, London, England, and to compare them with the

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[1] By A. F. Emery and F. B. Gessner, published in the Nov. 1976 issue of the JOURNAL OF HEAT TRANSFER, TRANS. ASME, Series C, Vol. 98, pp. 594-600.

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[4] Gosman, A. D., Launder, B. E., and Whitelaw, J. H., "Flow, Heat and Mass Transfer in Turbulent Recirculating Flows-Prediction and Measurements," Course Notes, Chemical Engineering Department, McGill University, Montreal, Canada, Aug. 6-8, 1976.