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Intermittency measurements in contaminated turbulent flows

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THE MECHANISM of entrainment of ambient fluid and the consequent diffusion of material within an intermittently turbulent field are known to depend upon the nature of the turbulent/non-turbulent interface. We consider here one aspect of the question — the proper identification of the interface and the characteristics of the fields when described in terms of both turbulent velocity and contaminant intensity. We have examined a number of flows, in which temperature has been used as the contaminant, and employed various rational methods for deciding when the motion could be considered turbulent. It is concluded, that superior resolution of the interface can be obtained by means of the instantaneous temperature.

Wiadomo, że mechanizm wsysania otaczającej cieczy i wynikająca stąd dyfuzja materiału wewnątrz krytycznego turbulentnego pola przepływu zależą od charakteru powierzchni oddzielającej obszar turbulentny od nieturbulentnego. Rozważono tu jeden aspekt zagadnienia, mianowicie właściwą identyfikację tej powierzchni i charakterystykę pól opisanych za pomocą turbulentnej prędkości i skażonej intensywności. Przebadano dużą ilość przepływów przyjmując temperaturę jako parametr skażenia i przeprowadzono dokładną dyskusję rozwiązania aby wykazać, kiedy dany ruch można uważać za turbulentny. Pokazano, że powierzchnię podziału można dokładniej wyznaczyć o ile skorzysta się z temperatury natychmiastowej.

Известно, что механизм всасывания окружающей жидкости и вытекающая оттуда диффузия материала внутри критического турбулентного поля течения зависят от характера поверхности разделяющей турбулентную область от нетурбулентной области. Рассмотрен здесь один аспект вопроса, именно правильная идентификация этой поверхности и характеристика полей описанных при помощи турбулентной скорости и возмущенной интенсивности. Исследовано большое количество течений, принимая температуру как параметр возмущения и проведено точное обсуждение решения, чтобы показать, когда данное движение можно считать турбулентным. Показано, что поверхность раздела можно точнее определить если используется мгновенная температура.

1. Introduction

A RATHER important problem associated with the entrainment of free turbulent shear flows is the details by which the nonturbulent fluid acquires vorticity. It is known from the early work of CORRSIN (1943) and subsequent investigations by TOWNSEND (1948), CORRSIN and KISTLER (1955), KOVASZNAY et al. (1970) and HEDLEY and KEFFER (1974), among others, that a rather sharp frontier exists separating the turbulent and the non-turbulent fluid. If we were to place a velocity sensing probe within the flow, the signal would take on an intermittent character showing intense, rapid fluctuations during the passage of a turbulent burst, and milder, low frequency oscillations when exposed to the non-turbulent fluid as indicated in Fig. 1. Any conventional technique of treating such an intermittent signal would mask some very interesting, and perhaps critical, features of the flow. It has thus become necessary to devise techniques for separating the flow regimes to investigate the real nature of the turbulent structure.

This problem is undergoing intensive study at the present time at a number of laboratories. As yet no standard technique has emerged but the end result in each case is the generation of a random square wave which is carried along with the turbulent signal and to which the various statistical operations are keyed. For example, as seen from Fig. 1, the flow variables could be averaged during that portion of time only when the indicator function is unity, to produce turbulent zone statistics, or when zero, to give non-turbulent zone statistics, or it can be keyed to the change in magnitude of the indicator function, i.e., either zero to unity or unity to zero, to give various point statistics.

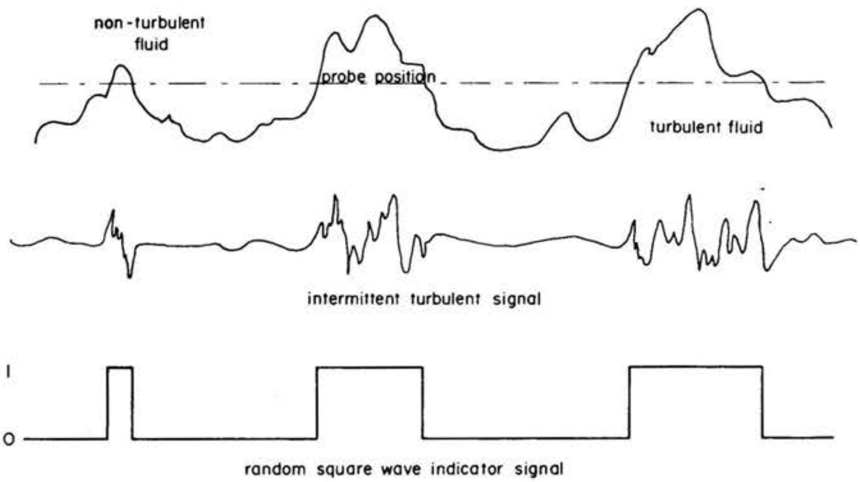


FIG. 1. Conditional averaging.

The means by which the square wave indicator function is produced in an intermittent turbulent flow varies widely. The selection and generation of a suitable detector is complicated since the non-turbulent field itself exhibits random fluctuations in velocity. Invariably, some processing of the intermittent signal is required to give higher order derivatives of the turbulence, i.e., quantities similar in part to the vorticity fluctuations which thus enhance the distinctions between turbulent and non-turbulent fluid. With multiple probes, this goal can be approached more closely, although such a solution introduces experimental complexity.

However, a rather simpler procedure can be effected if the flow is "laced" with some type of passive scalar. Then, on the supposition that the turbulent fluid is everywhere marked by this scalar, one needs only to devise a probe sensitive to the contaminant to record the intermittent passages of the turbulent flow. Such a quantity is temperature. If heat is added to the flow at low enough levels, the marker, i.e., temperature, can be considered a "passive scalar contaminant" and any buoyancy effects can be safely ignored. This procedure can be used solely or in parallel with the velocity-based approach although we shall see that the thermal signal is much sharper and therefore a more precise measure of the edge of the turbulent front is needed.

2. Thermal mixing layer

To pursue the thermal contaminant problem further, we take what at first might appear to be a simple example, the spreading of a pure thermal mixing layer in the absence of any mean shear. The schematic development of this flow is shown in Fig. 2. The background convective motion is a decaying homogeneous turbulent field set up by a grid of parallel cylinders, half of which were heated to produce the initial step change. The evolution of the profile into a self-similar error function is rapid, and most of the measurements were taken at x/M of 41 where M is the spacing between the cylinders. Further details may be found in (KEFFER et al., 1977).

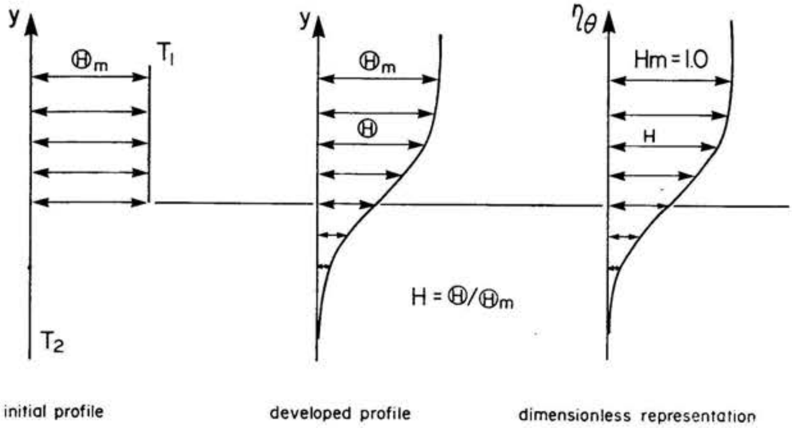


FIG. 2. Definition sketch of thermal mixing layer.

The physical aspects of this flow are quite interesting. The thermal layer expands laterally into the uncontaminated or cold fluid at the lower edge of the flow. But as well there is a concomitant spread of the well-mixed hot and cold fluid with the upper hot region of the flow. These processes may be considered equivalent to the spread of vorticity fluctuations at an interface in a free shear flow. That is, we expect an analogous intermittent thermal structure where "cold" bursts or pulses occur in the upper portion of the mixing layer and "hot" bursts in the lower section. The evaluation of a suitable turbulence indicator function and subsequent processing of the signals would thus enable us to obtain various conditionally averaged data.

We have in fact been able to do this. The detector chosen was $(\partial\theta/\partial t)^2$, where Θ is the instantaneous value of temperature. This was smoothed over the equivalent of a Taylor microscale

$$\tau_\theta = \langle(\bar{\theta}^2)/(\overline{\partial\Theta/\partial t})^2\rangle^{1/2},$$

where θ is the fluctuating component, to eliminate spurious signal drop-out (HEDLEY and KEFFER, 1974). The threshold level for the detector signal, required to eliminate background "noise", was evaluated by rather arbitrary means. Along the centre-line of the flow it was assumed that the intermittency factor γ was unity. This is effectively a definition for the homogeneity of the warm thermal field in the core of the flow. It furthermore implies that the largest turbulent eddies are much smaller than the dimensions of the thermal field, a not unreasonable assumption, since we are dealing with grid flow turbulence. In the completely cold region of the flow, γ was taken as zero. To obtain threshold levels at these points, the probability density functions of $(\partial\Theta/\partial t)^2$ were evaluated and the 99 per cent limits were used for the thresholds. The intersection of the probability density functions was assumed to define the threshold level for $\gamma = 0.5$. With these three points then, the variation of threshold level with lateral position could be obtained. Further details may be found in KEFFER et al. (1977). The technique was used for both the upper and lower regions of the flow and yielded the distribution of the intermittency factor shown in Fig. 3. The anomaly in the upper region was due to the existence of a background thermal fluctuation field generated by the heating grid. There is no quiescent hot flow in the experiment. The problem is equivalent to that of background turbulence in a so-called potential motion at the turbulent/non-turbulent interface.

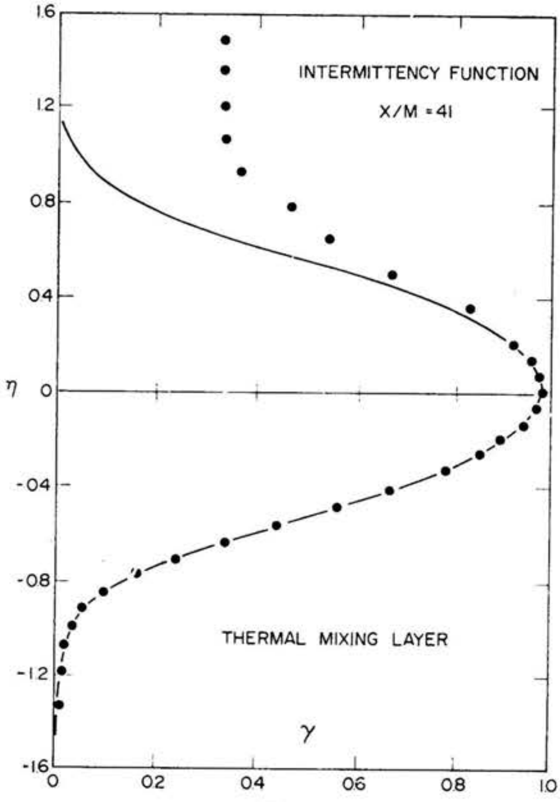
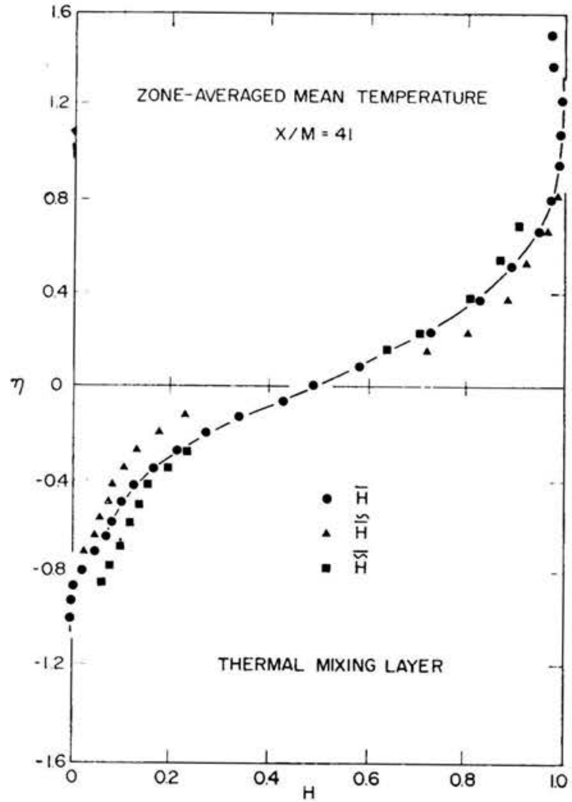


FIG. 3.

With the indicator function thus defined, it becomes possible to process the results and obtain the various interesting conditional statistics. All data were recorded, sampled digitally and processed by computer. The examples for the mean temperature field shown in Fig. 4 and the distribution of $\overline{\theta^2}$-stuff in Fig. 5 are consistent with the hot and cold burst concept, described above.(*)

*) The operations $-$, $\simeq$, $\approx$, refes to conventional, turbulent zone and non-turbulent zone averages, respectively.


ZONE-AVERAGED MEAN TEMPERATURE
X / M = 41
THERMAL MIXING LAYER
η
H
1.6
1.2
0.8
0.4
0
-0.4
-0.8
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0
0.2
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FIG. 4.

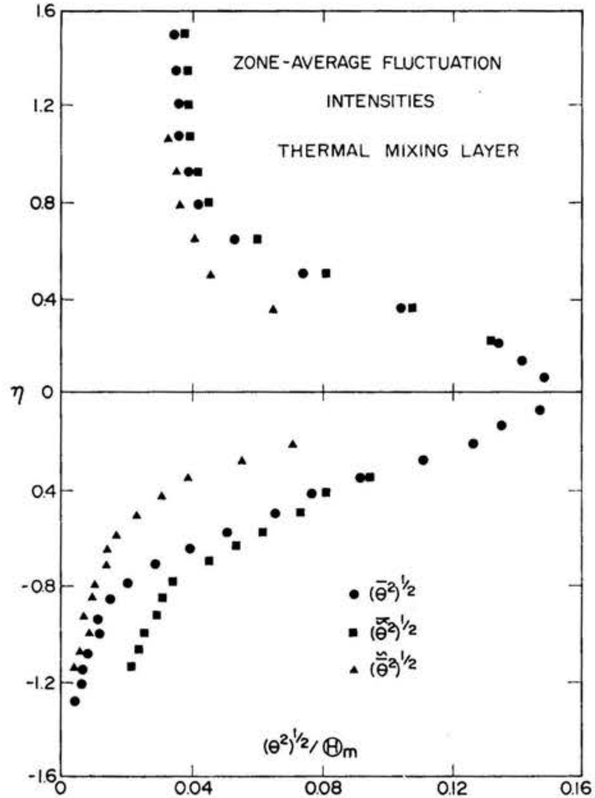
ZONE-AVERAGE FLUCTUATION
INTENSITIES
THERMAL MIXING LAYER
η
$(\theta^2)^{1/2}/\Theta_m$
1.6
1.2
0.8
0.4
0
0.4
-0.8
-1.2
-1.6
0
0.04
0.08
0.12
0.16

FIG. 5.

3. The plane hot jet

A second and intrinsically more complicated situation is the flow of a slightly heated, two-dimensional turbulent jet. The definition sketch, Fig. 6, illustrates this case. Mean velocity shear is present so that the turbulent field will be more complex in structure than the previous flow. For the fully developed motion, we may assume that the heat will have spread throughout the turbulent fluid and that the interface for temperature and that for vorticity will be co-incident.

We examined the structure of the two fields separately (DAVIES et al., 1975), using detector functions for the turbulence and temperature, $(\partial U/\partial t)^2$ and $(\partial \Theta/\partial t)^2$, respectively. These were smoothed using the Taylor micro-scales

$$\tau = \langle(\overline{q^2})/(\overline{\partial Q/\partial t})^2\rangle^{1/2},$$

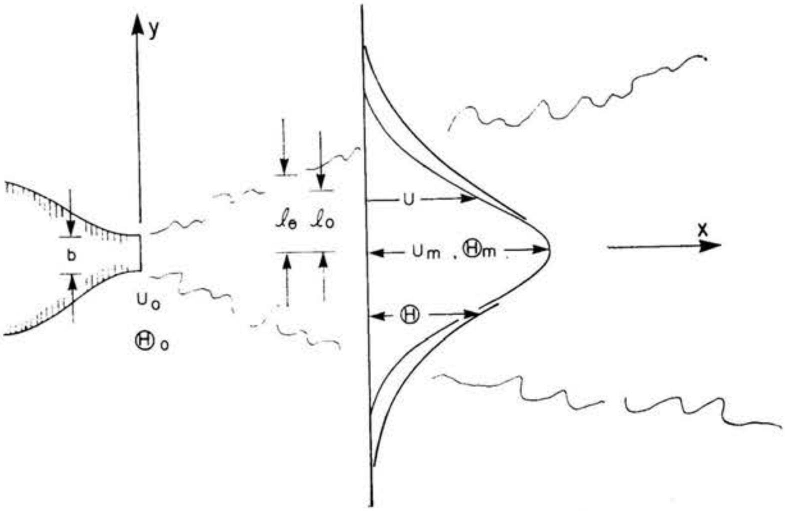

FIG. 6. Definition sketch of 2-dim heated jet.

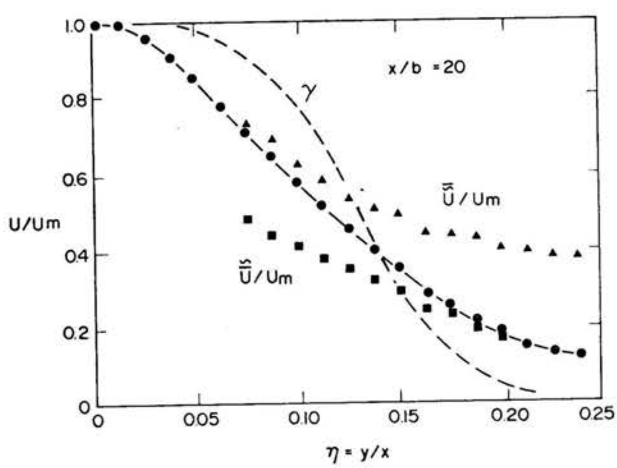

FIG. 7. Zone-averaged mean velocities of heated plane jet.

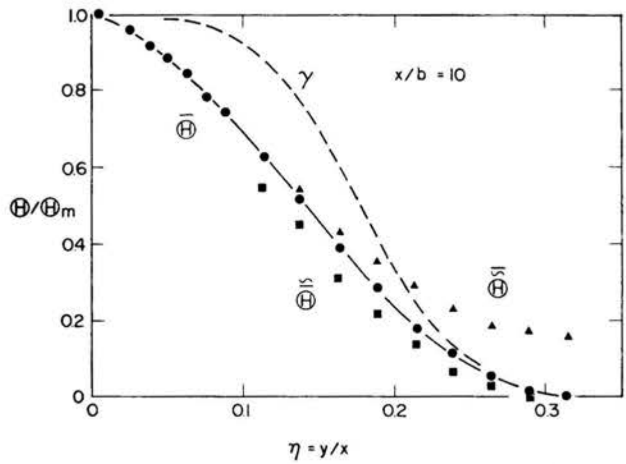

FIG. 8. Zone-averaged mean temperatures of heated plane jet.

where Q and q are the instantaneous and fluctuating components of either velocity U, or temperature θ. A novel technique was employed to evaluate the threshold levels for these functions. Characteristically, it is observed that the intermittency function can be modelled by the Gaussian cumulative distribution function (TOWNSEND, 1956; HEDLEY and KEFFER, 1974b). For this flow we assumed the Gaussian form. By choosing arbitrary initial values of threshold level C for each lateral position and iterating towards the appropriate value of γ for that position, a final value of threshold level was obtained after a fairly rapid convergence. This gave C as a function of the cross-stream coordinate. The indicator functions could thus be generated and carried along with the signals to give the conditional statistics. Typical results are shown in Fig. 7 for the mean velocity and in Fig. 8 for the mean temperature.

4. Heated plane wake

An equivalent problem, in that a co-incident interface occurs for the temperature and vorticity, is the two-dimensional, slightly heated, turbulent wake, shown schematically in Fig. 9. In this example the indicator functions for temperature and turbulence were established directly, using a method similar to that of HEDLEY and KEFFER (1974), rather than assuming *à priori* a Gaussian fit to the intermittency factor. Smoothing time was kept constant to within 6 sampling intervals of the digitization for velocity and 2 for the temperature. Threshold levels used produced indicator functions which were found to be consistent with the observed intermittency of the signal (KAWALL and KEFFER, 1977).

The intermittency factor for turbulent velocity and temperature which resulted is shown in Fig. 10 and both are seen to display the expected Gaussian form. One essential feature of this study was that the processed temperature signal proved superior in defining the characteristics of the interface. Typical results for conditional point statistics across the frontier separating the turbulent and non-turbulent fluid are illustrative. A comparison

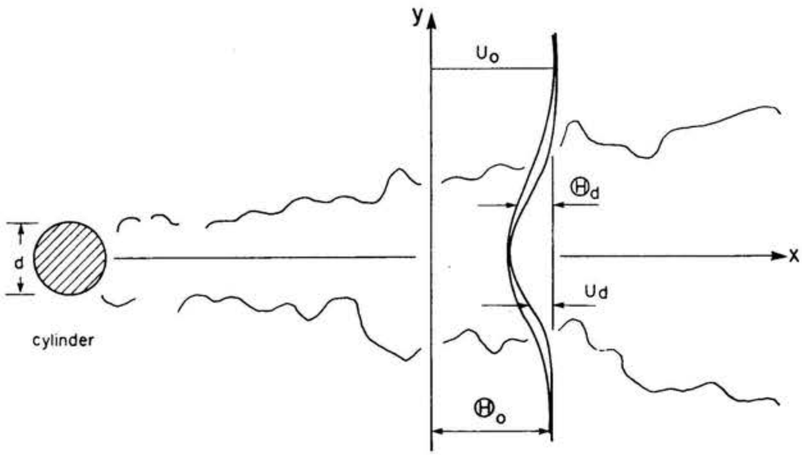

FIG. 9. Definition sketch for heated wake.

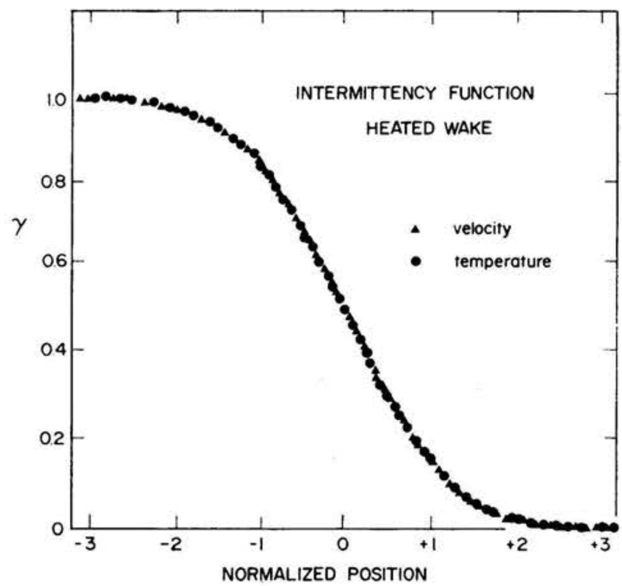

FIG. 10.

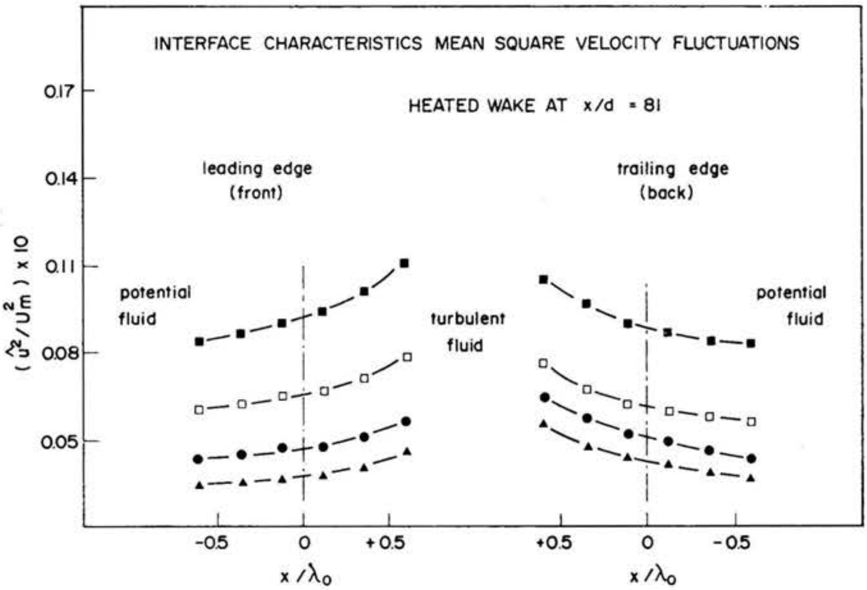

FIG. 11. Interface characteristics mean square velocity fluctuation.

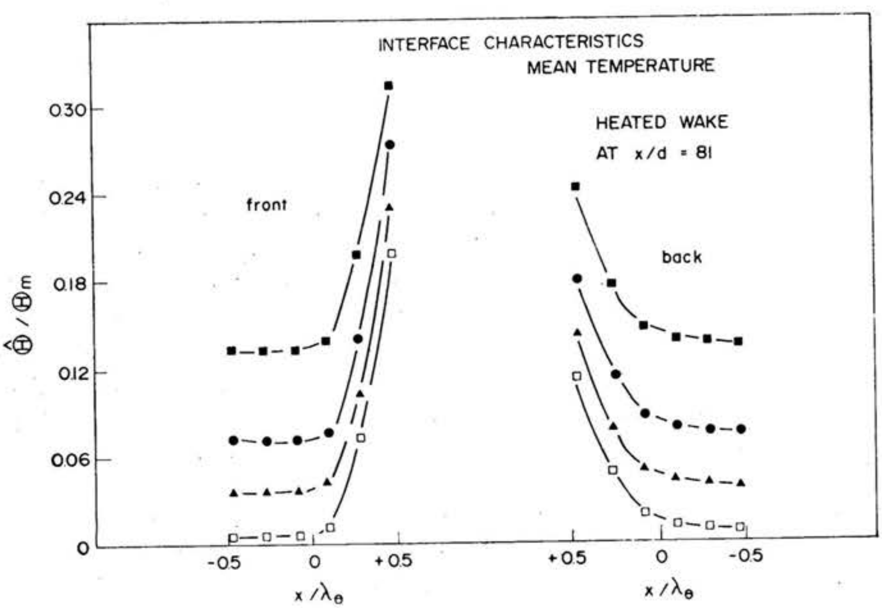

FIG. 12. Interface characteristics mean temperature.

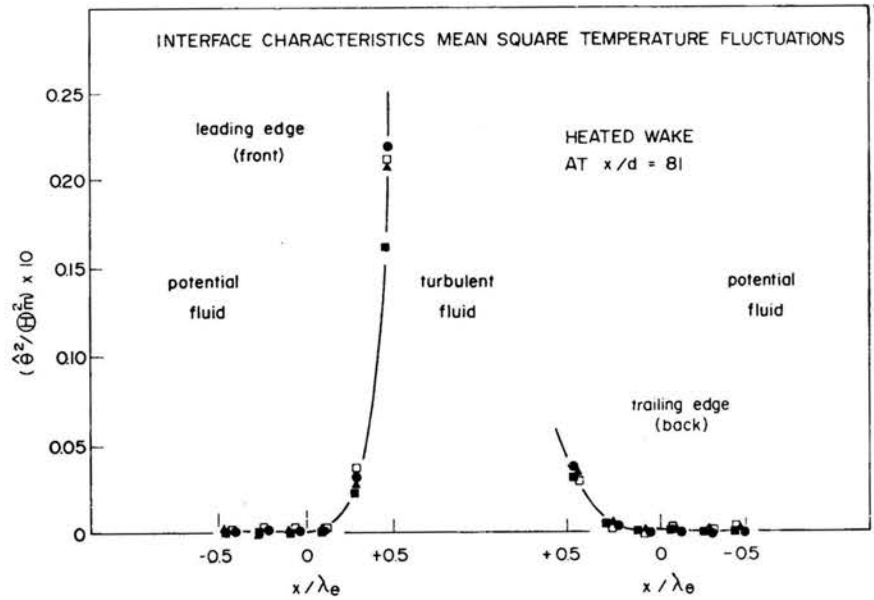

FIG. 13. Interface characteristics mean square temperature fluctuations.

of Figs. 11, 12 and 13 shows that even with mean temperature Θ, improved resolution is obtained and with the fluctuating component θ, an extremely sharp definition results. One reason for this is that we have used only one velocity component in constructing the detector signal, namely U. However, the turbulent field is three-dimensional and better detection would have required that we add at least the lateral component V to the function.

5. Summary

Temperature as a passive scalar contaminant has proved to be a simple and accurate means of specifying the intermittent characteristics of a free shear flow. Nevertheless, some difficulties remain. When the turbulence is expanding into a quiescent medium, as in the case of a jet, the measurement of instantaneous temperature, say, using a resistance thermometer or cold-wire, may be subject to an error due to thermal conduction through supports of the cold-wire. Furthermore, if one is, at the same time, attempting to measure the correlations, $\overline{u\theta}$ or $\overline{v\theta}$ with a multiple wire, hot-wire system, the necessarily close proximity of the wires can cause a contamination of the cold-wire by the hot-wire(s) due to the large convective motions in the intermittent region (BÉGUIER, et al., 1977).

In a wake-type motion, the conduction loss is not a problem, since the external mean velocity is generally high enough to eliminate the effect. Furthermore, the large eddy motion, although still present, is dominated by the streamwise convection velocity and spurious temperature fluctuations are not recorded in the cold-wire signal. The problem at the free edge can in principle be avoided by using a single probe for temperature and a passive device such as a laser-Doppler anemometer for the turbulent velocity field, although the conduction cooling of the supports for the cold wire would still take place. We are presently in the process of realizing this method.

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