Skewness of the temperature derivative in an asymmetrically heated wake

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Measurements in an asymmetrically heated two-dimensional wake show that the temperature (temporal) derivative skewness becomes slightly positive in the region between the mean velocity minimum and the mean temperature maximum, while remaining appreciably negative elsewhere.

Measurements in a variety of heated turbulent shear flows (for a summary, see, for instance, Sreenivasan and Antonia[1]) have shown that the skewness S of the temporal temperature derivative $\partial\theta/\partial t$ has a magnitude of order unity (in flows where Taylor's approximation is valid, S is equal in magnitude and opposite in sign to the skewness of the streamwise temperature derivative $\partial\theta/\partial x$). In most experimental setups, the dominant mean velocity and mean temperature gradients have been nearly perpendicular to the mean flow U, and the sign of S could be determined from the relative orientations of these two mean gradients as[2]

$$\operatorname{sgn} S = \operatorname{sgn}\left(\frac{\partial U}{\partial y}\right) \operatorname{sgn}\left(\frac{\partial T}{\partial y}\right). \tag{1}$$

Sreenivasan and Tavoularis[3] have recently verified (1) in homogeneous sheared turbulence and have further shown that, in that flow, S is nonzero if, and only if, both mean gradients are nonzero. A brief survey of the literature has not revealed any strong test of (1) in nonhomogeneous turbulence. In most such cases with measurements of S, the mean velocity and mean temperature profiles are either monotonic or reach their stationary points simultaneously, so that the right-hand side of (1) is constant throughout the flow, except possibly in a region of negligible width where both mean gradients might vanish together. For example, S was found to be essentially a negative constant in the central core of the wake of a heated cylinder[4] even on the axis of symmetry, where both mean gradients are zero. Similarly, S was positive on the axis of a heated jet.[1] These results are not necessarily incompatible with (1) (as the formal requirement that $\operatorname{sgn} 0 = 0$ would imply), if the singular value of the right-hand side of (1) on the axis is replaced by its continuous limit obtained through a Taylor's expansion of the two mean gradients. Since the derivatives of both mean gradients preserve their signs across the axis, the continuous extension of the right-hand side of (1) is a constant throughout the flow (negative for the heated wake, positive for the heated jet). A related physical explanation, consistent with the model to be presented later in this note, is that any tendency for S to vanish on the axis is overwhelmed by transport from neighboring regions where S has a sign determined by (1).

On the other hand, the situation is more complex in shear flows with asymmetries. For instance, S was found to vary considerably across the complex wake of two equal, parallel cylinders only one of which was heated.[5] Indeed, in regions where both the mean velocity and the mean temperature were monotonic, S was about -1 [with the sign dictated by (1)], but it was near zero (even slightly positive) over an extensive intermediate range. Again, that near-zero value of S is not inconsistent with (1) [note that (1) does not imply anything about the magnitude of S] and can possibly be attributed to the absence of mean shear,[3] because in the latter range, the mean velocity profile was essentially flat without a well-defined minimum. Some recent experiments in the wake of an asymmetrically heated flat plate[6] appear to represent a better configuration for providing a more stringent test of (1), but unfortunately they contain no measurements of S.

The following experiment was designed especially to provide such a test of (1) in nonhomogeneous turbulence. The flow consisted of the wake of a smooth, cylindrical, brass rod of diameter $d = 11$ mm, in a uniform stream with velocity $U_\infty = 6.6$ m/sec. The Reynolds number $R_d \equiv U_\infty d/\nu$ was about 5000, sufficiently high for the wake to be fully turbulent. Three pairs of Nichrome wires of 0.13 mm diam were stretched parallel to the rod at the downstream station $x/d \approx 5$ and at transverse distances $y/d = 1.2$, 2.0, and 2.8 from the symmetry plane of the wake. Velocity was measured with a standard DISA 55P11 hot-wire of 5 μm diam and 1.2 mm length operated by a DISA 55D01 constant temperature anemometer. Temperature was measured with a DISA 55P31 "cold" wire of 1 μm diam and 0.4 mm length operating at a constant current of about 0.3 mA with the use of a homemade circuit.[7] The temperature signal was amplified, low-pass filtered at 1.1 kHz, and digitized at a rate of 2000 samples per second. The temperature derivative was estimated from the differences of consecutive samples. Corrections for electronic noise and velocity sensitivity of the cold wire were applied to the results but were less than 10%

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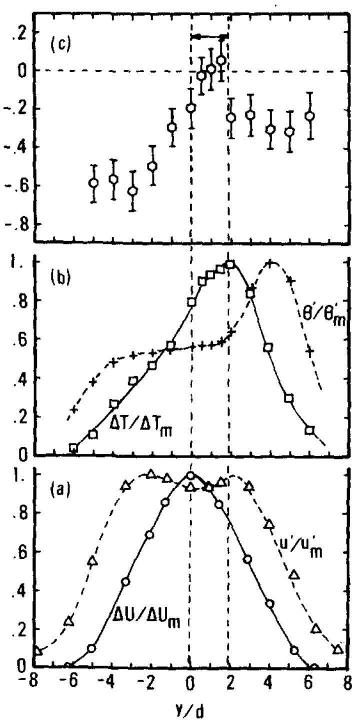

FIG. 1. Transverse profiles of (a) the mean velocity deficit and the streamwise rms turbulent velocity, (b) the mean temperature rise and the rms temperature fluctuations and (c) the temperature derivative skewness. Quantities are normalized with their corresponding maximum values; vertical bars denote estimated error bounds; arrows enclose area where the right-hand side of (1) is positive.

on all skewness values reported here. All reported measurements were performed at $x/d = 100$ where a reasonable degree of self-similarity of the mean velocity profile and of the width of the wake should be expected.[8]

Transverse profiles of the mean velocity deficit $\Delta U \equiv U_\infty - U$ and of the streamwise rms velocity fluctuations u', shown in Fig. 1(a), are practically symmetric, demonstrating that the effects of buoyancy and of the wire wakes were insignificant at this measuring station. In contrast, profiles of the mean temperature rise $\Delta T \equiv T - T_\infty$ and of the rms temperature fluctuations θ' [Fig. 1(b)] are strongly asymmetric, reflecting the asymmetry in the introduction of heat. The mean temperature profile reaches its maximum at about $y/d \approx 2$, away from the axis ($y/d = 0$) where the mean velocity is minimum. If (1) is valid, a change in the sign of S should be anticipated in the range $0 \lesssim y/d \lesssim 2$.

Figure 1(c) shows that, within the experimental uncertainty, S is clearly negative at $y/d < 0$ and $y/d > 2$, as required by (1); its magnitude is (incidentally) fairly constant away from the region $0 < y/d < 2$. In the latter region, S gradually decreases in magnitude and it becomes slightly positive for $0.5 \lesssim y/d \lesssim 1.5$. Considering the appreciable measuring scatter and other possible inaccuracies, it is evident that expression (1) is rather well satisfied.

At this point, we may conclude that expression (1) adequately describes the sign of S in a variety of circumstances. However, the detailed behavior of S across the wake is quite complicated and deserves further investigation. A qualitative explanation of the observed variation of S is possible by extending a phenomenological model devised recently by Tavoularis and Corrsin[9] for homogeneous shear flow. According to this model, migrating "lumps" of fluid develop local stagnation regions along sharp "interfaces" which are then tilted by the shear. The skewness S is considered to be a result of sharp drop-offs (or sharp rises) of the temperature across these interfaces, with the sign of S determined by (1). In homogeneous shear flow these ("internal") interfaces have a statistically preferred orientation so that the sign and magnitude of S are unambiguously defined, provided that the total strain and the mean temperature gradient are sufficiently large (see also the discussion in Ref. 3). In the asymmetrically heated wake, it seems that two opposing mechanisms control S, especially in the range $0 < y/d < 2$. Lumps of fluid originating in this region produce positive S, consistent with the local directions of the two mean gradients. However, lumps originating elsewhere in the flow and transported into this region by random motion (traveling transverse distances typically of order d or larger) produce negative S, again consistent with the relative directions of the mean gradients at an earlier stage of the life-time of these lumps. The sign and exact magnitude of S at each location depend on the relative balance of the effects of these two general types of lumps. The description of this phenomenon is further complicated by the possible large variability of the size and "strength" of such lumps, as implied by the inhomogeneity of the wake turbulence. In any case, a quantitative description of S clearly exceeds the scope of the present model.

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