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Direct numerical simulation of buoyantly driven turbulence

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Abstract

Numerical simulations of homogeneous turbulence subject to buoyant forcing were performed. The presence of a mean temperature gradient combined with a gravitational field results in a forcing term in the momentum equation. The development of the turbulence was studied and compared to the decay of similar fields in the absence of gravity. In the buoyantly driven fields, the vorticity is preferentially aligned with the intermediate eigenvector of the strain-rate tensor and the local temperature gradient is more likely to be aligned with the most compressive eigenvector. These relationships are qualitatively similar to those observed in previous shear flow results studied by Ashurst *et al.* (1987). A tensor diffusivity model for passive scalar transport developed from shear flow results in Rogers, Moin & Reynolds (1986) also predicts this buoyant scalar transport, indicating that the relationship between the scalar flux and the Reynolds stress is similar in both flows.

Discussion

During the workshop period, calculations were made with 64 by 32^2 grids in order to examine the effect of forcing the velocity field with scalar fluctuations. With the Boussinesq assumption of a zero divergent velocity field, the modifications to the Rogallo (1981) code were simple. The buoyant forcing develops flow patterns at large length scales in the gravity direction. Because of this, a grid which is longer in the gravitational direction is used. The flow is analyzed at a time before the large scales feel the effect of the periodic boundary conditions. Calculations were made with and without gravity, that is forcing and no forcing.

The Rayleigh number based on the Taylor microscale of the velocity field, λ, is defined as $Ra_\lambda = (g/T_0)|\frac{\partial T}{\partial z}|\lambda^4 Pr/\nu^2$, where z is the gravitational direction and g is the gravitational acceleration. The Prandtl number, Pr, was taken to be 0.7 and the Taylor-microscale Reynolds number was 7.4. In the field analyzed here $Ra_\lambda = 93$ and the ratio $Ra_\lambda/(Re^2 Pr)$ is 2.4.

Previous work by Ashurst *et al.* (1987) indicated a coupling between the vorticity field and the eigenvectors of the strain-rate tensor (ordered so that $\alpha \geq \beta \geq \gamma$) as determined from single point analysis of the alignment between the vorticity vector and the strain-rate directions. This analysis was repeated for the buoyantly driven fields and similar results were found in that vorticity has a large probability to

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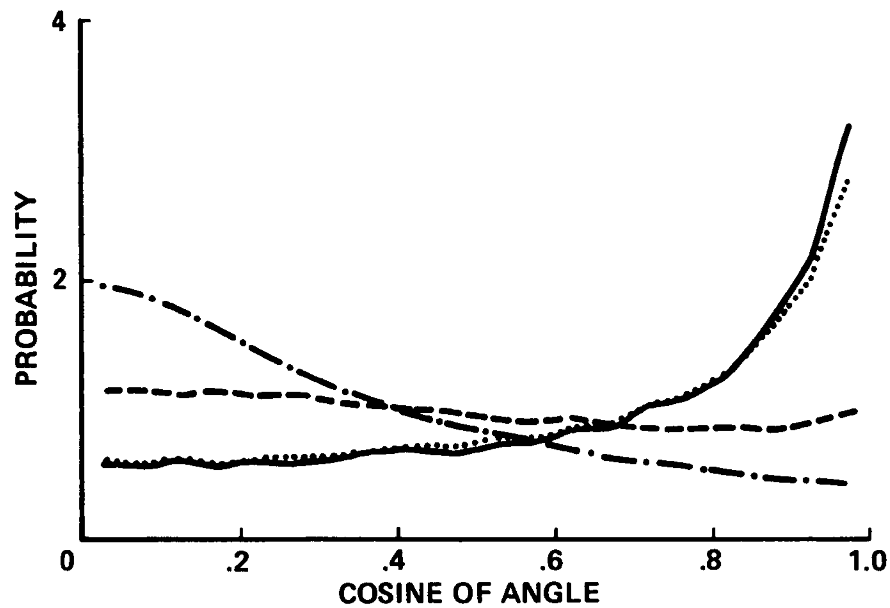

FIGURE 1. Pdf of the cosine of the angle between the vorticity and the principal strain-rate directions. ---- $\omega \cdot \alpha$, ······· $\omega \cdot \beta$, —·— $\omega \cdot \gamma$, —— $\omega \cdot \beta$ for $\beta > 0$. Note the increased probability for alignment with the intermediate strain-rate, β.

align with the intermediate strain-rate direction (Figure 1) and at large strains this intermediate strain-rate is extensional. In this buoyant flow we find that both the vorticity and the intermediate strain-rate are more likely not to point in the gravitational direction which is consistent with the fact that the plumes present in this flow tend to produce vorticity normal to the gravitational direction.

The behavior of the temperature gradient is also similar to that observed in homogeneous turbulent shear flow. Figure 2 presents the alignment of the temperature gradient with the three strain-rate eigenvectors. The most probable direction is the most compressive strain-rate direction with a peak value that is twice that found in previous passive scalar simulations.

Figure 3 presents scalar dissipation values conditioned on the energy dissipation value. As in the passive scalar shear flow results there is an increasing power-law dependence with increasing strain-rate.

A comparison between the heat flux observed in the simulations studied here with flux predictions from the model developed in Rogers, Moin & Reynolds (1986) is shown in Figure 4. The qualitative agreement is good and slight adjustments to the fitting function used for the single model constant could improve the results further. It is not surprising that the fitting function may require modification because it was developed from homogeneous shear flow results at $Re_\lambda \approx 100$ and therefore a significant extrapolation is required to the field examined here with $Re_\lambda = 7.4$.

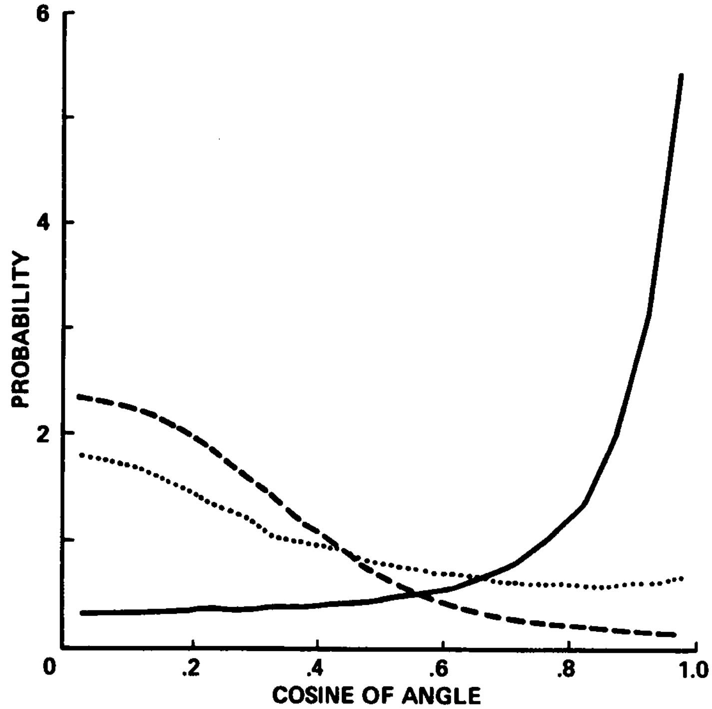

FIGURE 2. Pdf of the cosine of the angle between the temperature-gradient vector and the principal strain-rate directions. ---- $\nabla T \cdot \alpha$, ······· $\nabla T \cdot \beta$, —— $\nabla T \cdot \gamma$. Note the increased probability for alignment with the most compressive strain-rate, γ.

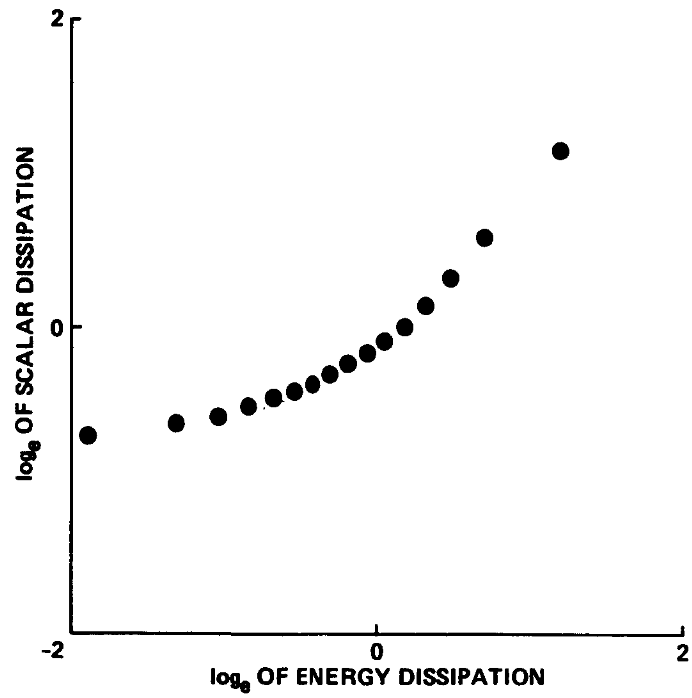

FIGURE 3. Mean scalar dissipation ($D\nabla T \cdot \nabla T$) conditioned on energy dissipation reveals a changing power-law dependence.

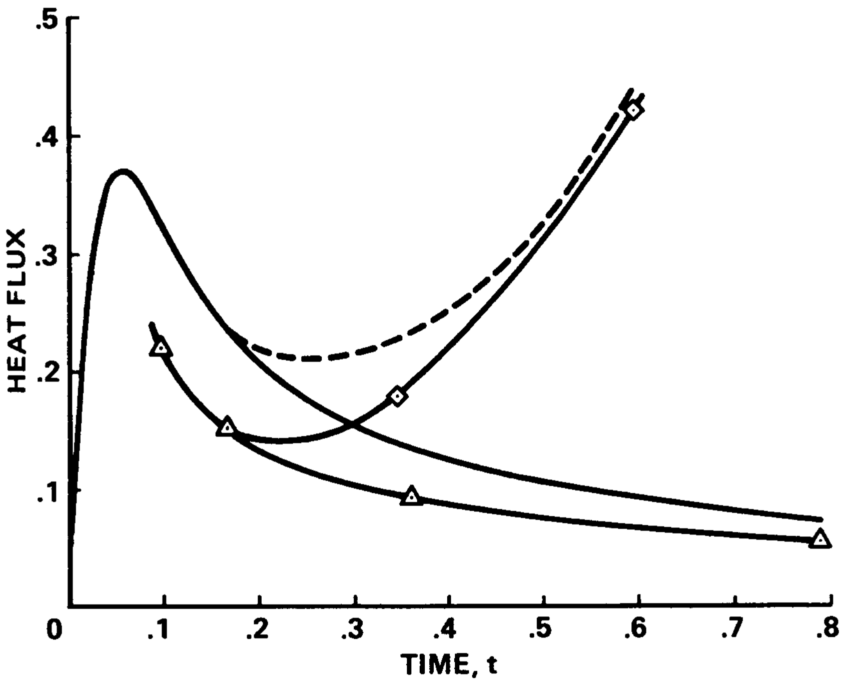

FIGURE 4. Comparison between the heat flux from the numerical simulations and that predicted by the model developed in Rogers, Moin & Reynolds (1986). —— simulation g=0, ---- simulation g=30, △ model g=0, ◇ model g=30.

In conclusion, much of the behavior of this buoyantly driven homogeneous turbulence resembles the behavior of homogeneous turbulent shear flow, despite the different production mechanisms of these two flows.

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