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13. ABSTRACT (Maximum 200 words)

Using results from direct numerical simulations of a planar turbulent jet, the small-scale dynamics and subgrid-scale interactions in turbulent shear flows has been investigated. Subgrid-scale energy transfer is found to arise from two distinct effects: one involving 'local' energy exchanges between coherent vortical structures of size comparable to that of the cutoff wavenumber, the other involving 'nonlocal' transfers of energy from the resolved to disparate subgrid scales of motion. In the physical space, the former gives rise to intense regions of forward transfer as well as backscatter of energy, while the latter results in a low intensity, background forward transfer of energy. A dynamic two-component subgrid-scale model (DTM), incorporating the dual character of subgrid-scale energy transfer observed in these studies, has been developed. The model predicts a spatial distribution of subgrid-scale dissipation in good agreement with results from filtered DNS in *a priori* tests, and when applied to large-eddy simulations of transitional and turbulent flows it predicts statistics, spectra and structures in better agreement with data from direct numerical simulations than existing dynamic eddy viscosity models. The proposed model should enhance the utility of LES in the computations of complex engineering flows.

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Objectives

The objective of this study is to provide a better understanding of the dynamics of the small scales in turbulent shear flows and to incorporate this understanding into improved subgrid-scale models for large-eddy simulation of turbulent flows in practical engineering applications. Specific objectives are to; (i) characterize the universal features of the intermittent fine-scale structure of vorticity, passive scalar and dissipation fields in turbulent shear flows using results from DNS, (ii) provide a better understanding of the nature of subgrid-scale energy transfer and the role of organized vortical structures in interscale energy transfers, and (iii) incorporate this understanding into improved subgrid-scale models for LES of turbulence. The ultimate goal of this study is to enhance the utility of LES as an engineering tool for the prediction of complex turbulent flows of practical interest.

Summary of Results

To study the structure and dynamics of the small scale in turbulent shear flows, a direct numerical simulation was performed of a temporally growing planar turbulent jet. The final fully-developed jet had a Reynolds number of 6800 based on jet width and centerline velocity, corresponding to a Taylor microscale Reynolds number of $Re_\lambda \approx 110$. The computations were carried out with a resolution of $128 \times 128 \times 256$ in the streamwise (x), spanwise (y), and normal (z) directions using standard Fourier/mapped Chebyshev pseudospectral methods implemented in parallel on the 64-node iPSC/860 Intel hypercube at San Diego Supercomputer Center. The resulting grid spacing was on the order of 4 Kolmogorov scales in the streamwise and spanwise directions, and 2 Kolmogorov scales in the normal direction. A passive scalar with a Schmidt number of 0.6 was also included in the simulations to allow direct comparisons with recent experimental measurements of passive scalar fields in turbulent jets.

The fully-developed turbulent jet had one- and two-point statistics in good agreement with available experimental data. The kinetic energy and scalar variance spectra in the jet each displayed a well-defined inertial range, with a Kolmogorov constant of $C_K = 1.4$ and an Obukhov-Corrsin constant of $C_\theta = 0.85$, respectively. All small scale quantities showed strong intermittency, manifested by their non-Gaussian statistics and scale dependent PDFs. Visualization of the flow confirms that these intermittency effects are associated with high intensity vortical structures in the form of elongated vortex tubes with diameter on the order of 10 Kolmogorov scales and length on the order of an integral scale, which are superimposed on the background of lower intensity random vorticity. The vortex tubes are preferentially aligned along the direction of the principal axis of the mean flow strain field and give rise to rod-like and sheet-like regions, respectively, of high intensity kinetic energy- and scalar-dissipation at their periphery. The thickness of these dissipative structures coincides with the scale at which the corresponding dissipation spectra reach their peaks. Nearly one third of overall kinetic energy and scalar dissipation occurs in these intermittent regions which occupy less than 10% of the jet volume.

To evaluate the role of these organized structures in subgrid-scale energy transfer and in the overall dynamics of the energy cascade, the detailed physical-space and spectral-space energy transfers across selected cutoff wavenumbers in the inertial range were studied in the above database. The results show that subgrid-scale energy transfer arises from two distinct effects: one involving 'local' (in wavenumber space) energy exchanges between the resolved and the subgrid scales of comparable magnitude, the other involving 'nonlocal' (in wavenumber space) transfers of energy from the resolved to distant subgrid scales of motion. The 'local' interactions can be attributed to mutual straining of resolved and subgrid coherent vortical structures of size comparable to the scale of the cutoff wavenumber. These interactions give rise to strong and coherent regions of forward as well as reverse transfer of energy across the cutoff wavenumber. The 'nonlocal' interactions represent the straining of the small scales by the larger scales and result in only a forward transfer of energy from the large to the small scales of motion. In the development of subgrid-scale models for LES of turbulence, these two effects need to be modeled separately.

A dynamic two-component subgrid-scale model (DTM), incorporating the dual character of subgrid-scale energy transfer observed in these studies has been developed. Two separate terms are included in this model; one representing the low-intensity background forward transfer of energy due to 'nonlocal' (in wavenumber space) energy exchanges, and the other representing the intense forward and reverse transfers of energy due to 'local' energy exchanges between resolved and subgrid scales near the LES cutoff. The former is modeled using a Smagorinsky-type eddy viscosity model. The latter is modeled using the resolved velocity field near the cutoff wavenumber. A dynamic procedure is used to compute the model coefficient without the need for external input. The only input parameter to the model is the ratio of test filter to LES filter, α and the model has been shown to be insensitive to the exact choice of α. Furthermore, it is shown that the model has the correct asymptotic behavior in laminar and transitional flows and near solid boundaries.

The model has been applied to LES of transitional and turbulent jet and channel flows. The results indicate that DTM can predict statistics comparable to or in better agreement with DNS than existing dynamic eddy viscosity models and, in addition, is more successful in capturing the accurate large-scale vortical structure and the energy spectrum of the flow.

These results indicate that DTM should greatly enhance the utility of LES in computations of complex turbulent flows of practical interest.

Personnel

1. Amid Ansari- doctoral student.
2. Norberto Mangiavacchi- doctoral student.
3. Wen-Je Jung- doctoral student.

Publications

W.J. Jung, N. Mangiavacchi and R. Akhavan, "Suppression of turbulence in wall-bounded flows by high-frequency spanwise oscillations," *Phys. Fluids A*, 4(8):1605-1607, 1992.

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Wen-Je Jung- Thesis Title: "Response of Wall Turbulence to High Frequency Streamwise and Spanwise Oscillations", The University of Michigan, February 1993.

Norberto Mangiavacchi- Thesis Title: "Dynamics of a Turbulent Jet Interacting with a Free Surface", The University of Michigan, September 1994.

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Patents

R. Akhavan, "Method for control of turbulence in wall flows", filed June 30, 1993, US serial # 08/085747.

Knowledge Transitioned to Application

We are currently collaborating with Amid Ansari at WPAFB to incorporate the DTM model into the COBALT code used at Wright Patterson Air Force Laboratory for external flow computations.