Development of Multiscale Turbulent Flow Analysis Code by Finite Element Method

Background

In design and maintenance of fluid flow devices, vessels and piping, we often need to understand the features of temporal fluctuation and spatial variation of velocity, pressure and temperature in a turbulent flow. Though computer simulation is one of the evaluation tools, geometrical complexity of a practical flow and wide spectrum of the eddy scales are problematic in actual computation. To overcome the difficulty, LES (Large Eddy Simulation) is gaining popularity as the LES allows to solve only large eddies with a turbulent model instead of straightforward resolution of small eddies. To develop a universally applicable and reliable model, the multiscale model is attracting scientists' and engineers' attention recently. However, the method studied so far (the spectrum method) is restricted to rather simple geometry and not fully applicable to a practical flow problem of complicated geometry.

Objectives

To formulate and code the finite element method (FEM) model for multiscale turbulent flow analysis as a computer program to develop a universal and practical turbulent flow analysis method.

Principal Results

1. Formulation multiscale FEM

A multiscale FEM for an LES analysis of a turbulent thermal-hydraulic flow was formulated based on the double-scale (large- and small-scale) finite element interpolations for both velocity, temperature and pressure. Figure 1 shows such interpolations of velocity with an unresolvable component. The multiscale FEM formulation made it possible to naturally filter the unresolvable component in space with the large- and small-scale weighting functions employed in the FEM. Furthermore, a suitable turbulent model could be selectively introduced into each FEM equation of different scale. In this formulation, Smagorinsky-type eddy diffusivity was introduced only into the small-scale momentum equation, while no eddy diffusivity was introduced into the large-scale equation.

2. A new numerical technique

The discretized momentum equation system was temporally integrated with an explicit method, where a compound mass matrix lumping (CMML) technique was originally devised in this study to segregate the large-scale and small-scale accelerations from the coupled system without full matrix inversion.

3. Validation of the code

The multiscale finite element formulation was finally implemented in a computer code, which was validated with a 2-D turbulent thermal cavity flow problem shown in Fig.2. The results shown in Figs. 3 and 4 are in good agreement with those of other researchers [P. Le Quere and M.Behnia, J. Fluid Mech., 359, pp.81-107, 1998].

Future Developments

Fully 3-dimensional problems will be solved with the developed code to see the validity and the practicability.

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Reference

Y. Eguchi, 2003, "Development of Multiscale LES Thermal-Hydraulic Analysis Code MISTRAL", CRIEPI Research Report, U03036 (in Japanese)

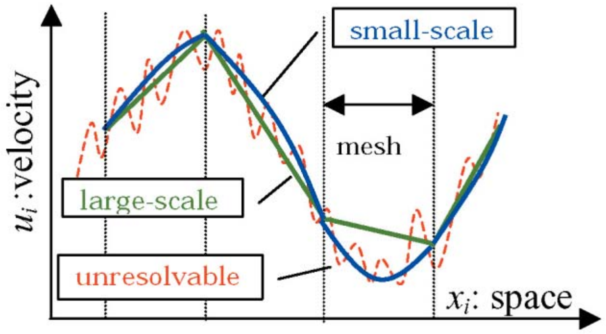

Fig.1 Schematic illustration of multiscale decomposition of one-dimensional velocity

Large-scale velocity is approximated by linearfunction, and the small-scale by quadratic one.

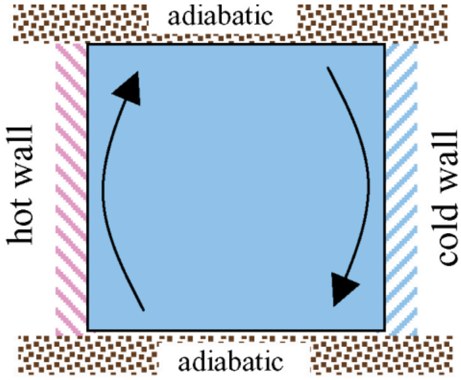

Fig.2 Natural circulation in a square cavity

Heated fluid tends to climb the hot wall due to buoyancy force, while cooled one tends to descend.

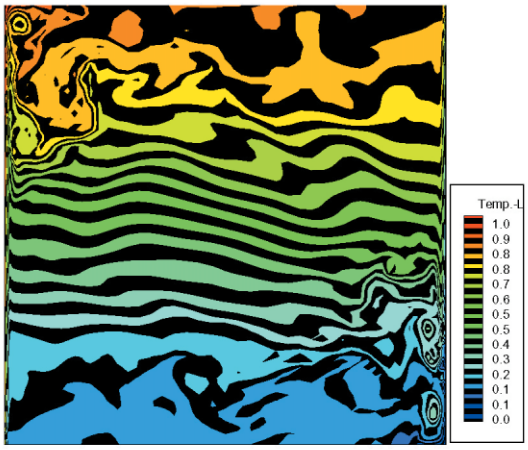

Fig.3(a) Large-scale temperature normalized by wall temperature difference

Eddies of various scales are observed alongthe hot and cold walls.

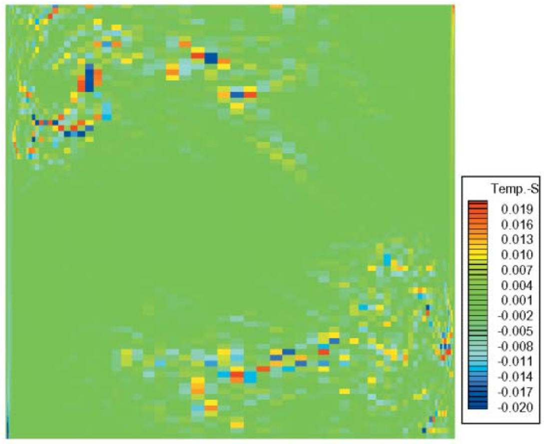

Fig.3(b) Normalized small-scale temperature

Small-scale temperature appears near upperhot wall and lower cold wall, where resolutionis insufficient with large-scale interpolation.

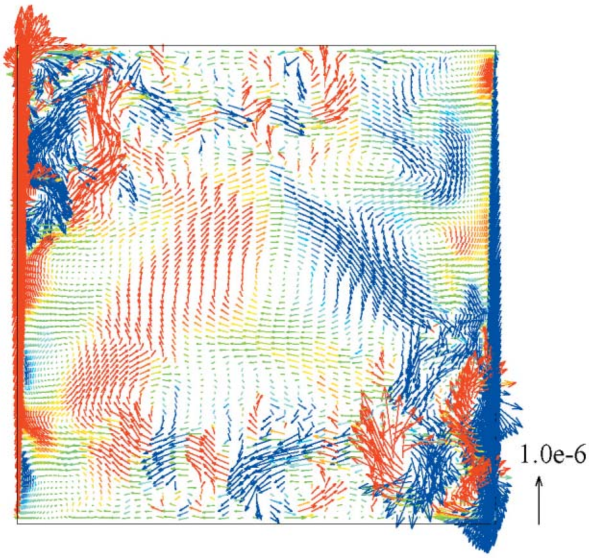

Fig.4(a) large-scale velocity

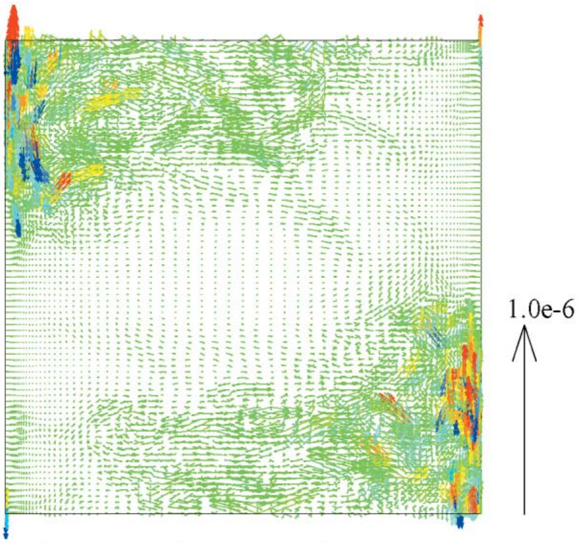

Fig.3(b) Normalized small-scale temperature

Upward velocity vectors are colored red, while downward are blue. Turbulent velocityfield is observed near upper hot wall and lower cold wall, where small-scale velocityis rather significant in magnitude.