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LARGE EDDY SIMULATION OF NEW SUBGRID SCALE MODEL FOR THREE-DIMENSIONAL BUNDLE FLOWS

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ABSTRACT

Having led to increased inefficiencies and power plant shutdowns fluid flow induced vibrations within heat exchangers are of great concern due to tube fretting-wear or fatigue failures. Historically, scaling law and measurement accuracy problems were encountered for experimental analysis at considerable effort and expense. However, supercomputers and accurate numerical methods have provided reliable results and substantial decrease in cost. In this investigation Large Eddy Simulation has been successfully used to simulate turbulent flow by the numeric solution of the incompressible, isothermal, single phase Navier-Stokes equations. The eddy viscosity model and a new subgrid scale model have been utilized to model the smaller eddies in the flow domain. A triangular array flow field was considered and numerical simulations were performed in two- and three-dimensional fields, and were compared to experimental findings. Results show good agreement of the numerical findings to that of the experimental, and solutions obtained with the new subgrid scale model represent better energy dissipation for the smaller eddies.

INTRODUCTION

A major technological issue in the nuclear power industry is vibration induced fatigue and subsequent failure of steam generator tubes. Turbulent eddies within steam generators produce instabilities, vortices and turbulent momentum transfer to the solid boundaries. Therefore, accurate analyses of this flow field are of great potential benefit. Experimental studies are costly and are subject to the applicability of scaling laws. Numerical studies may complement useful information without the considerable expenses of experimental facilities. The goal of this investigation is to provide practical applications of the Large Eddy Simulation (LES) technique to turbulent flow by implementing a new subgrid scale model developed by Lee ,[1] as well as three-dimensional simulations. The major area of concern for this investigation is the single phase cross flow region in a vertical U-tube steam generator as seen in figure 1.

Although turbulent flow encompases a wide range of length and time scales, LES has been successfully used to simulate turbulent flow by numeric solution of the Navier-Stokes equations.[1-6] LES directly calculates the large eddies that are responsible for the production of energy, and approximates the viscous energy dissipation of the smaller eddies. In LES, the Navier-Stokes equations are averaged over a small spatial region in order to remove small scale fluctuations. The filtering process necessitates closure models that are called subgrid scale (SGS) terms that model smaller eddies in the flow domain. A good SGS model is required for the accuracy of LES. However, very few of the SGS models developed so far have been validated in geometrically complex, turbulent flow fields such as those that occur in nuclear power plant components.

SGS models may be tested by using full direct simulation or by comparison with experimental observations. Full direct turbulence simulations help make detailed comparisons of model predictions and exact values; however, at the present time, these are restricted to low Reynolds numbers and simple flows. Experimental observations have neither of these restrictions but are not sufficiently detailed to permit detailed comparisons with models; indirect approaches must then be employed.

THEORY

In the statistical description of turbulence, there are more unknowns than equations, creating a closure problem that can be closed only with models and estimates based on intuition and experience. SGS models can be categorized into eddy viscosity models, scale similarity models, models involving partial differential equations for subgrid stress transport, Reynolds stress and Algebraic models and Group renormalization methods.

SGS modeling necessitates combining the fluctuating components included in filtered Navier-Stokes equation with mean components. This expression must reflect the accurate effects of SGS motions into the mean equation. Some of the models that have been previously developed are discussed below as well as the development of a new SGS model.

Eddy Viscosity Models

The most widely used and simple SGS model is the eddy viscosity model. This model borrowed the idea of mixing length and the eddy viscosity concept from the conventional time averaging method. The SGS Reynolds stress term (τ_{ij}) is assumed to be proportional to the velocity gradient in eddy viscosity SGS models.

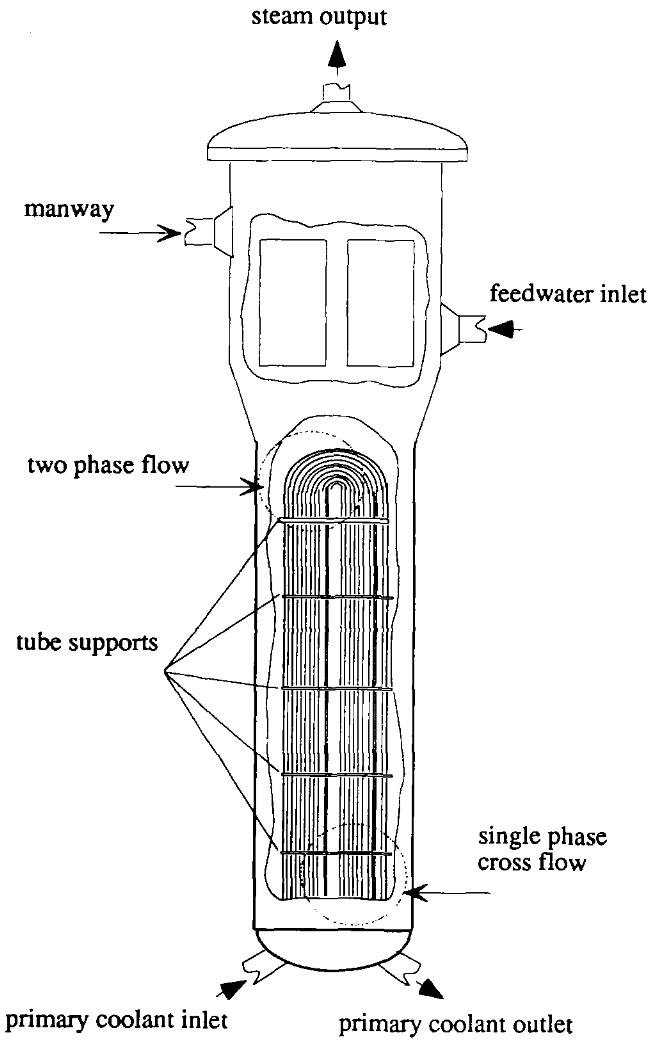

Figure 1: U-tube steam generator

$$\tau_{ij} = \nu_t \left(\frac{\partial \bar{U}_i}{\partial x_j} - \frac{\partial \bar{U}_j}{\partial x_i} \right) \quad (1)$$

Here ν_t is the turbulent or eddy viscosity which depends strongly on the statue of turbulence and is not a constant. There have been many different models to determine ν_t, but one of the most widely used eddy viscosity models is the Smagorinsky's eddy viscosity model.[7] Smagorinsky's sub grid scale eddy viscosity model is expressed as:

$$\nu_t = (C_s \Delta)^2 \left(\frac{\partial \bar{U}_i}{\partial x_j} \left(\frac{\partial \bar{U}_j}{\partial x_i} - \frac{\partial \bar{U}_i}{\partial x_j} \right) \right)^{1/2} \quad (2)$$

where C_s is the Smagorinsky constant and Δ is a filter width and typically two times of mesh spacing.[8] Values of C_s ranging from 0.10 to 0.20 are usually used.

It has been shown that eddy viscosity models are able to maintain the correct mean energy balance of the large scale flow field while giving poor representations of the Reynolds stresses on a local basis by comparing with full direct simulations.[9] There are also some incorrect assumptions in the eddy-viscosity models. One of them is the 'production equals dissipation' assumption. This means the net rate of energy transfer from the large scale field equals the rate of dissipation of SGS energy. Because of the initial kinetic energy in the SGS field the rate of energy transfer is always smaller than the SGS energy dissipation.[10]

Bardina's Model

The basic assumption of Bardina's model is that the net rate of energy transfer from the filtered flow field to the SGS flow field is determined by eddies whose size is the filter width. These eddies are simultaneously the smallest eddies of the filtered flow field and the largest eddies of the SGS flow field. Bardina applied the filtering operation to the filtered field and the SGS field and called it the 'transfer flow field' introducing the scale similarity model.[10]

This model showed good correlation with local Reynolds stresses but did not capture the energy dissipation. For isotropic and homogeneous turbulence the kinetic energy always decreases with time (i.e. can not be statistically stationary). But the scale similarity model is not dissipative which is physically incorrect. So a linear combination of the eddy viscosity model and the scale similarity model has been suggested to satisfy the physical requirement. In this model the Reynolds stress term is expressed as [10]

$$\tau_{ij} = -2\, \nu_t S_{ij} - M_{ij} \quad (3)$$

where

$$M_{ij} = c_r \left(\overline{\bar{U}_i \bar{U}_j} - \bar{\bar{U}}_i \bar{\bar{U}}_j \right) \quad (4)$$

and

$$S_{ij} = \frac{1}{2} \left(\frac{\partial \bar{U}_i}{\partial x_j} - \frac{\partial \bar{U}_j}{\partial x_i} \right) \quad (5)$$

which is the strain rate tensor. The term $-2\, \nu_t S_{ij}$ of equation (3) is from the eddy viscosity model. Smagorinsky's constant $C_s \approx 0.19$ and model constant $c_r = 1.1$ were recommended for second-order central difference numerical scheme. But his model is mathematically incorrect because the eddy viscosity term is already included in the scale similarity model (M_{ij}).[4]

Leonard's Model

Here the filtered equations of motion are written in a somewhat different form. For the 'Leonard term' ($\overline{\bar{U}_i \bar{U}_j}$) Taylor expansion was used. But replacing the advection term made the filtered Navier-Stokes equation a third order differential equation because the advection term appeared inside a derivative in the filtered Navier-Stokes equation. This caused the boundary condition problem for practical calculation. For the lumped cross term and the Reynolds term (τ_{ij}) Leonard used the Smagorinsky model, i.e.,[5]

$$\tau_{ij} = -\overline{u_i' \bar{U}_j} - \overline{\bar{U}_i u_j'} - \overline{u_i' u_j'}.$$
$$= -2\, \nu_t\, S_{ij} \qquad (6)$$

This results in ignoring the cross terms because the $-2\, \nu_t\, S_{ij}$ term can only approximate $\overline{u_i' u_j'}$. The cross terms represent a random forcing produced by the SGS eddies on the grid scale (GS) eddies and therefore their effect on the smallest GS eddies may be quite significant. As compared to the eddy viscosity model, Leonard's model involves more small-scale energy and covariance and less explicit calculation.

New SGS Model

It has been confirmed that inclusion of cross terms is necessary because the cross terms represent the effect of SGS eddies on GS eddies. Modeling of cross terms together with SGS stress terms may not be appropriate since the nature of the cross terms is completely different from that of the SGS stress terms. The former represent the GS-SGS interaction through the random forcing effect while the latter represent the dissipative effect that the SGS have on the GS. From Bardina's model there is very little correlation between τ_{ij} and the exact SGS stresses, except that the τ_{ij}'s produce about the right dissipation. However, The correlation between the exact and parameterized τ_{ij} improves greatly if another term is added to the Smagorinsky formulation, i.e.,[1]

$$\tau_{ij} = \text{Smagorinsky term} + M_{ij}. \qquad (7)$$

Bardina's model simply linearly combined the eddy viscosity model with the scale similarity model to get one of the important features of turbulent flow, dissipation. The Leonard terms were also included that produce (backscatter) energy from the smallest resolved scales to larger scales.

Bardina's transfer field concept and Leonard's Taylor expansion technique were used by Lee in developing the new SGS model.[1] By obtaining

$$C_{ij} = -\frac{\Delta_f^2}{12} \frac{\partial \bar{U}_i}{\partial x_k} \frac{\partial \bar{U}_j}{\partial x_k} \qquad (8)$$

where the governing equation is

$$\frac{\partial \bar{U}_i}{\partial t} + \frac{\partial \bar{U}_i \bar{U}_j}{\partial x_j} = \frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 \bar{U}_i}{\partial x_j \partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \qquad (9)$$

then

$$\tau_{ij} = C_{ij} - 2\nu_t S_{ij} \qquad (10)$$

The above new SGS will have dissipating characteristics due to the modeling of SGS stresses by eddy viscosity model. The Smagorinsky constant for this new model was set at 0.12.[1] Also the new SGS model will reflect the energy back-scattering because Leonard term and cross terms, which represent the GS-SGS interactions, are included.

RESULTS

Velocity time histories and power spectra as well as force power spectra were calculated for fully developed flow deep within a triangular pitch tube bank. The parameters of interest are the cross-flow velocity magnitude, the orientation of the flow direction relative to the tube bundle geometry, and the pitch-to-diameter ratio.

Experimental Data

Experimental data available for triangular arrays by Owen[11] and Weaver and Grover[12] have been considered. Little is known about the actual experimental procedure and data reduction techniques of Owen's experiment. The ordinate "Normalized Spectral Density" was not explicitly defined, and the peak frequency has an estimated wavelength that is alarmingly identical to the overall length of the entire four row tube bank. Thus some caution must be exercised in validating predicted deep bundle spectra against Owen's data.

Weaver and Grover's data appears to be more representative of a deep bundle than Owen's data, but is presented with arbitrary scaling along the ordinate. Also, Weaver and Grover's data is limited to a smaller non-dimensional frequency range than Owen's data.

Gust Calculations

The simulation investigates turbulent flow around a deep bundle region with doubly periodic boundary conditions

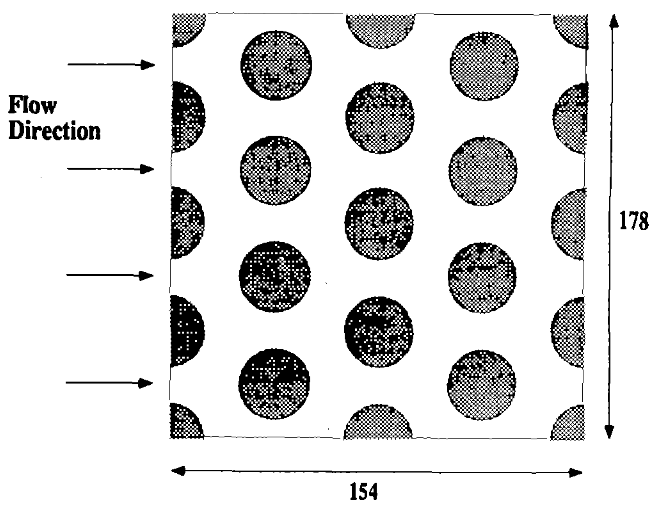

Figure 2: Geometry for triangular pitch deep bundle

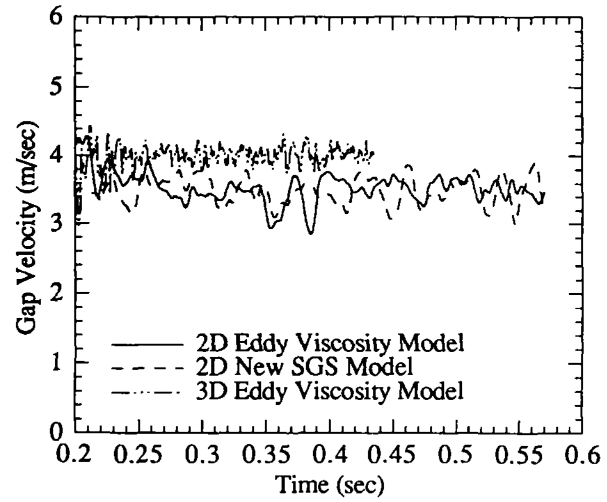

Figure 3: Horizontal gap velocity time history

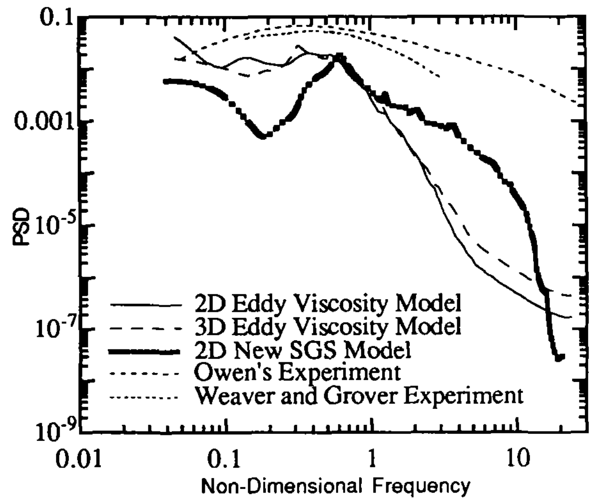

Figure 4: Normalized one-dimensional power spectrum for turbulent triangular bunde flow. Abscissa is given by $[(fd/U_g)(L/d)(T/d)]$

applied to a triangular pitched tube array geometry (L/d = 1.3, T/d = 1.5, d = 0.025m) with a mean pressure gradient of -100 m/sec^2 in the x direction.[6] The investigation was performed using the LES code GUST[13] with the eddy viscosity and the modified subgrid scale models. For the two-dimensional model 154 x 178 nodes with 27,412 cells (figure 2) were used with a time step of 0.3 msec for 1900 cycles of which the last 1024 cycles were used for FFT analysis. For the three-dimensional model a relatively smaller domain was considered comprised of 78 x 90 x17 nodes with 119,340 cells where no slip boundary conditions were applied in the third direction. Here too, a time step of 0.3 msec was considered and the simulation was performed for 1500 cycles.

Figure 3 shows the horizontal gap velocity time history that were averaged at eight locations in each of the cases involved. After reaching steady state the velocities fluctuated between 3.0 and 4.0 m/sec with the three-dimensional simulation having slightly higher velocities at the centerline. It is also clear that the new SGS model reached steady state sooner than the eddy viscosity model for the two-dimensional simulations.

Comparison with experimental data was performed using velocity power spectra from each of the simulations. Figure 4 shows the normalized one-dimensional power spectra as a function of a non-dimensional frequency. The numerical simulations are in good agreement at the low frequency end of the spectrum with that of the experimental data, and the simulation of the new SGS model agrees with the experimental data at higher frequencies as well.

The LES also enabled the force calculation on the tubes within the flow domain. After obtaining the lift and drag forces on the tubes, FFT analysis methods were used to obtain power spectral density (PSD) of the drag coefficient (figure 5). Here, the two- and three-dimensional simulations of the eddy viscosity model, as well as the two-

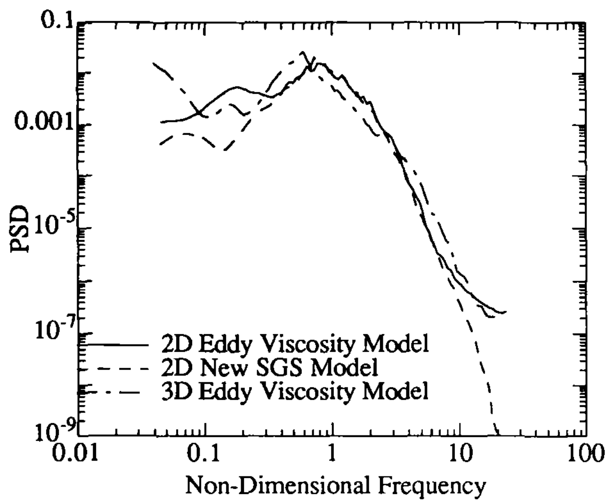

Figure 5: Normalized power spectrum of the drag coefficient for turbulent triangular bundle flow. Abscissa is given by $[(fd/U_g)(L/d)(T/d)]$

dimensional simulation of the new SGS model are in very good agreement. However, at the highest frequencies, the new SGS model clearly predicts accurate energy dissipation of the smaller eddies, while the eddy viscosity simulations do not follow this trend.

The LES simulations were performed on the CRAY-YMP at Texas A&M University, College Station, Texas. For the two-dimensional models about one hour of CPU time was necessary for each 100 cycle of calculations; while the three dimensional simulation required four hours of CPU time for each 100 cycle.

CONCLUSIONS

Progress in turbulence simulation has immediate feedback into a wide range of engineering applications and technological advances affecting many aspects of everyday life. Turbulence simulations in simple geometries are regularly performed, and extensive databases of flow fields have been constructed for the analysis of turbulent flows. On the other hand, turbulence simulations in complex geometries have only emerged recently.

In this study, the Large Eddy Simulation technique was utilized to predict turbulence effects in single phase cross flow deep within tube bundles. The predictions obtained by the GUST code have been compared with available experimental results, and are in general agreement with the experimental findings. The new subgrid scale model predicts accurate energy dissipation and is in better agreement with the velocity power spectra of the experimental findings.

The ultimate goal of subgrid scale modeling is expressing the fluctuating components included in filtered Navier-Stokes equations with mean components. The expression must reflect the accurate effects of subgrid scale motions into the mean equation. Reynolds stress and Algebraic models intended to remove the assumption of proportionality between subgrid Reynolds stress and resolved scale strain cause deficiencies in eddy viscosity models. Algebraic models produce additional equations increasing the cost of calculation. The new subgrid scale model, on the other hand, has mathematically correct form and reflects the subgrid scale effects on the grid scale motion by including the cross terms.

Future efforts should be directed towards further validation of the new subgrid scale model in complex geometries, as well as the possible modification of the code for simulation of two phase cross flow within U-tube steam generators.

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NOMENCLATURE

C_{ij}	=	lumped cross terms, new SGS model
C_s	=	Smagorinsky's constant
L	=	longitudinal pitch
M_{ij}	=	scale similarity model
S_{ij}	=	strain rate tensor
T	=	transverse pitch
U	=	mean velocity (m/s)
c_r	=	Bardina's model correlation coefficient
d	=	tube diameter (m)
f	=	frequency (Hz)
p	=	pressure
t	=	time
u	=	velocity component in specified direction (m/s)
x	=	specified spatial direction
Δ	=	typical mesh spacing (m)
τ_{ij}	=	subgrid scale Reynolds stress term
ν_t	=	turbulent viscosity
ν	=	laminar viscosity

Superscripts

$\bar{}$	=	spatial or temporal average
$'$	=	spatial or temporal fluctuating component

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The Numerical Simulation of Thermohydraulic Processes in Complicated Shape Channels

M.D. Segal (Russian Academy Sci.)
L.P. Siulrnov (Kurchatov Inst.)