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Technical Progress Report

DOE/AL/33183--T17

MULTIDIMENSIONAL MODELING OF CONVECTIVE
HEAT TRANSFER WITH APPLICATION TO I.C. ENGINES

DE91 006927

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Objectives/Scope

The objective of this project is to develop a more comprehensive understanding of the convective heat transfer process in complex, unsteady turbulent reacting flows, typical of those which occur in internal combustion engines. The specific area of research will be the representation of heat transfer in detailed multi-dimensional Navier-Stokes models, and modeling of turbulent transport mechanisms. The detailed tasks will include a review of relevant prior work. Based on this review, and original work done under this contract, several modeling approaches will be formulated and further studied and tested. The tests will be carried out on flow cases which have relevance to engine flows, and for which reliable experimental data exist. Such data will be sought and identified. The analytical studies will lead to the determination of the best modeling approaches to be used for heat transfer simulation in

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internal combustion engines. Following that, a detailed study will be carried out of spatial and temporal heat flux distribution in a representative engine. This will be complemented by a parametric study of engine heat transfer dependence on intake flow details, combustion chamber geometry, engine speed and engine load.

Technical Highlights

Formulation of alternative turbulence modeling approaches for improved heat transfer predictions has been started. The work focused on the modeling of turbulent diffusion and explored alternatives to gradient diffusion approximations. Specifically, the turbulent transport of a passive scalar was considered as a starting point for the research efforts. The statistical embodiment of this transport is given by the velocity scalar correlation appearing in the mean transport equation for a scalar. The treatment of this term has important implications regarding heat transfer calculations since such a term appears in the transport equation for the mean fluid internal energy. Much of the modeling work was carried out at the 1987 Summer research program hosted by the Stanford University Center for Turbulence Research and NASA-Ames. Participation in the program allowed for interaction with the leading researchers in the field of turbulence and turbulence modeling.

In addition to the scalar transport modeling, simulations of the one-dimensional compression of homogeneous turbulence were conducted to look at the accuracy of $k-\epsilon$ turbulence model predictions in engine flows.

Turbulent Transport Modeling

The accurate representation of turbulent transport is one of the fundamental issues of turbulence modeling. In the averaged equations governing the fluid motions, the transport appears as terms involving correlations between fluctuating quantities. At any level of turbulence closure there are a number of correlation terms to be modeled since they contain information that is available only at the next higher level of

closure. Currently, the modeling of these transport terms is almost exclusively done using a gradient diffusion approach, the assumption being that the turbulent flow is comprised of a large number of eddies which transport quantities in an analogous fashion as the interaction of molecules in laminar diffusion. The flaw in such an assumption is that the turbulent motions can be large in scale relative to the characteristic dimensions of the flow. As a result, in complex flows, transport can take place over larger distances than the scale represented by the local gradients. The work performed at the Stanford CTR concentrated on the investigation of an alternative representation of turbulent transport that would take into account the interaction of fluid regions over large distances and the preferred directions over which the interaction would take place.

The concept investigated at CTR was to represent transport as net convection by fluctuating turbulent motions, which exchange small volumes of fluid between neighboring points. In this approach, it is assumed that only points that are close enough to be able to influence each other directly need be considered. This is based on the premise that the spatial extent of turbulent transport is controlled by the extent over which the motions are coherent. That implies that the turbulent transport of any quantity is directly linked to the coherence and dynamics of the fluid motions. A further assumption made in this preliminary modeling effort is that the influence of mean shear on the turbulent transport of a quantity is accounted for indirectly through the action of mean shear on the velocity fluctuation field, resulting in its distortion, anisotropy and preferred lines of communications. The turbulent transport of a mean quantity can then be deduced from the interaction of the distorted turbulent velocity field with the spatial distribution (gradients) of the quantity itself. The modeling of the turbulent flux of a scalar quantity, ϕ , was considered in order to develop the above ideas. This flux is represented by the correlation $u_i\phi$ which appears in the transport equation for the mean ϕ .

An appropriate formulation of the transport term, which would properly represent the physical picture presented, was constructed by considering two small volumes, one centered on a given point P and the other on some arbitrary point in the neighborhood of P. These two volumes interact and exchange fluid carrying with them the scalar quantity ϕ . The particular form used to describe this process is an integral over the entire domain giving the transport of ϕ in the i-direction, $\overline{u_i \phi}$, at point P. This integral involves the difference between the ϕ at point P and the points in the surrounding field, a dimensionless correlating function which characterizes the fluctuating velocity field, a characteristic time scale of the turbulent motions and a direction cosine which forces the transport between any two points to be directed along the radial vector connecting the two points. The general nature of this form is such that the transport calculated can produce counter-gradient flux in certain types of non-homogeneous flows. Furthermore, the modeled $\overline{u_i \phi}$ term is in general non-isotropic, depending on the correlating function, making it more general than commonly used scalar diffusivity models.

A key element in the model is the selection of the correlating function. Building on the premises of this approach, it seemed worthwhile to investigate the usefulness of basing this function on the two-point velocity correlations. This is because these correlations contain the information about the extent over which the turbulent motions are coherent and also about the directions in which they communicate.

One possible choice, based on the assumption above about the direction of the average flux between two points being directed along the radial vector connecting them, is a special type of two-point velocity correlation which correlates the velocity component along the radial vector. Such a correlation is a contracted form of the standard two-point velocity correlation tensor. The contraction is obtained through successive multiplications of the direction cosines of the radial vector connecting two points. The contracted correlation is a scalar function of the spatial position. In an isotropic flow this function has spherical contours centered on the correlating point and its value decays along any

ray extending from the origin according to the well established correlating function $f(r)$. In a shear flow this function is much more complex.

To test the ideas proposed above during the stay at CTR, advantage was taken of the available data produced through direct numerical simulations of turbulent flows at Stanford University and at NASA Ames. One such flow was a homogeneous shear flow, with a passive scalar field, calculated by Rogers et al (1986) at a fairly low turbulent Reynolds number. The two-point $\overline{u_1 u_1}$, $\overline{u_2 u_2}$, $\overline{u_1 \phi}$ and $\overline{u_2 \phi}$ correlations are shown in Figures 1a-d for the x-y plane through the correlating point, respectively. Inspection of the contours shows a distinct similarity between the two types of correlations. The $\overline{u_1 \phi}$ correlation appears to be strongly influenced by the $\overline{u_1 u_1}$ correlation. The $\overline{u_2 \phi}$ contours are somewhat similar to the $\overline{u_2 u_2}$ contours, although there also appears to be some influence from the $\overline{u_1 u_2}$ correlation, which is not shown here. This tends to support the view that two-point velocity correlations are relevant to scalar transport.

The contracted correlation described above is a linear combination of the individual velocity correlations. Its contours are shown in Figure 2 for the three planes x-y, y-z and x-z. It may be seen that this correlation is very different from the individual components. Its values are mostly positive with only very weak negative lobes. In the x-y plane (Figure 2a) this correlation has a very distinctive shape. This is partly caused by the fact that it has a singular behavior at the origin, where its value depends on the direction from which this point is being approached. The butterfly-like shape seen in this plane is mainly produced by the contributions from the $\overline{u_1 u_2}$ and $\overline{u_2 u_1}$ correlations, and it is absent in the other two planes. In the spirit of the discussion above, this shape of the correlation volume may be interpreted as an indication of the preferred lines of communication set up in a strained turbulent field. It is seen that the preferred communication is along a direction close to the mean flow direction, while a very poor communication is set up along a direction inclined about 70 degrees from the x-direction. This anisotropy

may be expected to have a major effect on turbulent transport and perhaps on other processes as well.

To complement the data presented above, a brief study was made of two-point correlations in the channel flow simulation data generated by Kim, Moin and Moser (1986). The Reynolds number based on wall friction velocity u_τ and channel halfwidth H was 180. Figures 3 and 4 show the contours of the $\overline{u_1 u_1}$, $\overline{u_2 u_2}$, $\overline{u_3 u_3}$ and $\overline{u_1 u_2}$ two-point correlations at distances of one quarter and one half H from the wall, respectively. At the one-quarter H location (Figure 3), $\overline{u_1 u_1}$ and $\overline{u_3 u_3}$ contours are stretched and inclined towards the channel wall. The $\overline{u_2 u_2}$ contours are again much less inclined. Most of the contours are seen to be affected by the presence of the wall, especially those at lower correlation levels which are farther away from the origin. This general behavior is also seen at the half H point, except that the wall effects are diminished and some similarities with the homogeneous shear flow begin to emerge.

Model calculations were performed for the homogeneous shear flow case described above. For this flow case, the integral form of the turbulent flux term $\overline{u_i \phi}$ can be expanded in a Taylor series which reduces to a tensor diffusivity times the gradient of the mean ϕ . The homogeneous shear data was used to compute the components of the tensor diffusivity and comparisons were made to the tensor diffusivity model developed by Rogers et al (1987). The Rogers model represents an algebraic transport model derived from the transport equation for $\overline{u_i \phi}$. It was tuned to reproduce the homogeneous turbulent shear flow results of the direct numerical simulations. The calculated diffusivity components exhibited the correct trends in relative magnitudes given by the Rogers model. The magnitudes of the components were not predicted well, however. Another failing of the current modeling approach is that the tensor diffusivity is symmetric in homogeneous flows. The Rogers et al (1986) analysis of the homogeneous shear flow indicates that this is not the case.

In summary, an alternative type of modeling has been proposed for the turbulent transport terms in Reynolds-averaged equations. During the CTR

Summer Program, one particular implementation of the model has been considered, based on the two-point velocity correlations. The model was found to reproduce the trends but not the magnitude of the non-isotropic behavior of the turbulent transport. Some interesting insights were developed regarding the relation of the two point velocity correlations to turbulent transport which will guide future modeling efforts.

Homogeneous Turbulence Simulations

Calculations were made of the one-dimensional compression of homogeneous turbulence in order to determine the accuracy of the normal Reynolds stress components predicted by the $k-\epsilon$ turbulence model. These calculations were performed as an extension of the work presented in the February, 1987 quarterly report which focused on the simulated flow field in a motoring, pancake geometry engine. The results of the simulations revealed the presence of two recirculating flow regions near the head-cylinder and piston-cylinder intersections. The flow field was found to be driven by normal Reynolds stresses predicted by the $k-\epsilon$ model in the corner regions of the cylinder. The question arose as to the accuracy of the calculated nonisotropy of the turbulence since the form of the $k-\epsilon$ Reynolds stress tensor was a consequence of the eddy viscosity hypothesis. The homogeneous flow calculations to be discussed shed light on the accuracy of the Reynolds stress predictions in regions of the flow that are far removed from the effects of the solid boundaries. They do not provide information regarding the development of the flow field along the head, piston and liner. However, the results are still useful in the sense that they demonstrate the accuracy of the turbulence model in the simpler regions of the flow.

The governing equations for the mean field and turbulence field are greatly simplified when homogeneous flow is assumed. The partial differential equations are reduced to ordinary differential equations and the mean field equations become decoupled from the turbulence equations because the convective terms are all zero. As a result, the simulation of

homogeneous turbulence subjected to various strains provides a simple set of test cases for the evaluation of turbulence models.

In order to assess the accuracy of the $k-\epsilon$ predictions, comparisons were made to calculations using a Reynolds stress model developed by Wu et al (1985) specifically for the simulation of turbulence subjected to isotropic compression and axisymmetric strain. The model was constructed using the results of direct numerical simulations of homogeneous turbulence and it gives excellent agreement with the numerical data for one-dimensional compression of homogeneous turbulence for strain rates similar to those occurring in engines. Because of this, results generated with this model can be regarded as an accurate representation of the development of turbulence subjected to compression.

Figure 5 shows the development of the axial Reynolds stress and the nonisotropy of the radial and axial Reynolds stresses for a simulation in which the imposed compressive strain duplicates that occurring in an engine operating at 1500 RPM. The figure indicates that the $k-\epsilon$ model predictions are satisfactory for the first 120° of the compression stroke. In Figure 5a, the axial Reynolds stress predicted by the Reynolds stress model is amplified much more than that predicted by the $k-\epsilon$ model near TDC. This is reflected in the ratio of the radial to axial components of the Reynolds stress tensor shown in Figure 5b. For the $k-\epsilon$ model, the nonisotropy of these stresses goes to zero at TDC because of the form of the $k-\epsilon$ Reynolds stress tensor. As the Reynolds stress model results show, the radial and axial stresses are far from being equal at TDC.

These calculations demonstrate that the $k-\epsilon$ predictions are sufficiently accurate during the first portion of the compression stroke, but are in serious error near TDC. These results do not indicate the level of accuracy of the $k-\epsilon$ predictions in the nonhomogeneous regions of the flow. Careful experimental measurements of the response of isotropic turbulence to compression in a pancake geometry engine would be needed to provide a definite answer regarding the accuracy of the $k-\epsilon$ results.

Future Activities

Future activities will concentrate on the further development of alternative turbulent transport modeling approaches. This will include possible reformulation of the approach taken at CTR to overcome some of the shortcomings noted above. Also, review of previous work done on algebraic transport models and Reynolds stress models will be done in order to develop other useful modeling approaches and ideas.

REFERENCES

Kim, J., Moin, P. and Moser, R. D. (1986), "Turbulence Statistics in Fully Developed Channel Flow at Low Reynolds Number," Submitted to JFM.

Rogers, M. M., Mansour, N.N. and Reynolds, W. C. (1987), "An Algebraic Model for the Turbulent Flux of a Passive Scalar," To BE Published.

Rogers, M. M., Moin, P. and Reynolds, W. C. (1986), "The Structure and Modeling of the Hydrodynamic and Passive Scalar Fields in Homogeneous Turbulent Shear Flow," Stanford University Department of Mechanical Engineering, Report No. TF-25.

Wu, C-T., Ferziger, J. H. and Chapman, D. R. (1985), "Simulation and Modeling of Homogeneous, Compressed Turbulence", Stanford University Department of Mechanical Engineering, Report No. TF-21.

STATUS OF MILESTONES

Work progressed on Milestone a., formulation of approach, Milestone c., setup of test codes, and Milestone d., model testing.

COMMUNICATIONS/VISITS/TRAVEL

Thomas Morel and Mark Jennings worked on the formulation of modeling approaches at the 1987 Stanford Center for Turbulence Research Summer Program held at Stanford University from July 13, 1987 to August 9, 1987.

PROBLEMS ENCOUNTERED

None.

PUBLICATIONS

M. J. Jennings and T. Morel, "Modeling of Turbulent Heat Transfer with Application to I.C. Engines," submitted for 1987 SAE Fuels and Lubricants Meeting.

M. J. Jennings and T. Morel, "Observations on the Application of the k- ϵ Model to Internal Combustion Engine Flows," submitted for publication in Combustion Science and Technology.

DISCLAIMER

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Figure 1. Two point velocity-velocity and velocity-scalar correlations for the homogeneous shear flow simulation of Rogers et al. (1986); (a) $\overline{u_1 u_1}$ correlation (b) $\overline{u_2 u_2}$ correlation (c) $\overline{u_1 u_2}$ correlation (d) $\overline{u_2 u_1}$ correlation.

Figure 2. Contracted two-point velocity-velocity correlation contours for the homogeneous shear flow of Rogers et al. (1986); (a) x-y plane (b) x-z plane (c) y-z plane.

Figure 4. Two point velocity-velocity correlation contours for the channel flow simulation of Kim et al (1986) at $h/2$; (a) $u_1 u_1$ correlation (b) $u_2 u_2$ correlation (c) $u_1 u_2$ correlation (d) $u_2 u_3$ correlation.

Figure 5. Results of one-dimensional compression of homogeneous turbulence as calculated by the k- ϵ turbulence model and the Reynolds stress model of Wu et al. (1985); (a) Axial Reynolds stress component nondimensionalized by the square of the mean piston speed. (b) Ratio of the radial to axial Reynolds stress components.

U.S. DEPARTMENT OF ENERGY
SUMMARY REPORT

FORM APPROVED
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1. IDENTIFICATION NUMBER DE-AC04-86AL33183		2. PROGRAM/PROJECT TITLE Multi-Dim. Modeling		3. REPORTING PERIOD May 1, 1987 thru Aug. 31, 1987	
4. PARTICIPANT NAME AND ADDRESS Integral Technologies Inc. 645 Blackhawk Drive Westmont, IL 60559		5. START DATE: May 14, 1986			
		6. COMPLETION DATE June 14, 1989			

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