Technical Progress Report

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

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Prepared for:

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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

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sought and identified. The analytical studies will lead to the determination of the best modeling approaches to be used for heat transfer simulation in 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

During the current reporting period, the EPISO flow simulation code was used to compute motoring flow fields for bowl-in-piston combustion chamber configurations. This work involved code modifications to EPISO and the preprocessor programs which generate grid data for EPISO. A great deal of effort was invested in carefully interpreting the results of the bowl simulations, in order to verify that the solutions were physically meaningful. In addition, progress was made in the simulation of the sudden expansion pipe flow and the investigation of alternative wall layer modeling approaches.

Modification of Grid Generation Procedures

In order to generate accurate results in multi-dimensional calculations, careful attention must be paid to the computational grid used. The node point distribution must vary smoothly across the solution domain and must provide adequate resolution near solid boundaries. This is extremely important for heat transfer calculations. Because of these strict computational mesh requirements for accurate calculations, an in-depth effort was made to provide general capability for automatic generation of near optimum grid distributions.

The governing equations of fluid motion and heat transfer solved by EPISO are written for a curvilinear orthogonal coordinate system, hence, a curvilinear orthogonal set of grid data is required as input to EPISO. In the bowl region, where a cylindrical coordinate system is inadequate for describing the curved surfaces, this grid data is generated by a set

of programs developed by Dr. A. D. Gosman at Imperial College. The coordinates of the grid nodes and the geometrical data describing the computational element faces are calculated by an algorithm that solves the inverse Laplace equations governing the relation between the coordinates in the actual bowl region and coordinates in a rectangular, transformed bowl region. Details of the methodology are described elsewhere¹ and will not be presented here. The grid generation programs were restructured by ITI to make them more flexible and easier to use. The programs were given the capability to smoothly stretch the grid lines towards the boundaries of the bowl in order to provide resolution of near wall boundary layers. Stretching of the grid has also been implemented near the cylinder liner and in the axial direction above the piston. The latter application allows for improved resolution of the near head and near piston crown boundary layers. User specified input to the grid generating procedures has been reduced to specification of the number of grid lines in each direction and the desired near boundary spacings.

An algorithm was developed to reduce the number of axial nodes above the piston as TDC is approached during a simulation. This was found to be necessary after it was discovered that, near TDC, the rapid change in mesh spacing between the severely compressed mesh above the piston and the uncompressed mesh in the bowl (which translates with the piston and does not change during a simulation) resulted in severe errors in the pressure field. Grid lines are deleted in such a way that the transition between the bowl mesh and the mesh above the piston remains smooth. After TDC, the deleted grid lines are added to the mesh as the piston moves towards BDC.

¹Gosman, A. D. and Johns, R. J. R., 'A Simple Method for Generating Curvilinear-Orthogonal Grids for Numerical Fluid Mechanics Calculations,' Imperial College Fluids Section Report FS/79/23.

Modification of EPISO

EPISO was given the capability to accept three separate surface temperatures associated with the head, liner and piston. Previously, only one surface temperature was used to describe the temperatures of all in-cylinder surfaces. In addition, modifications were made to the governing equations in a small region surrounding the grid apex of the curved part of the bowl where the mesh is so severely distorted that orthogonality of the grid lines is not realized. The affected elements in this region are extremely small compared to the bowl dimensions, nevertheless they can distort the solution to a noticeable extent. The modifications that were implemented prevent the generation of spurious velocities and unrealistic temperatures during a simulation.

Motoring Simulation Results

Several motoring simulations were performed of a typical heavy duty truck engine. Relevant data for the engine is presented in Table I and initial conditions are presented in Table II. Simulations were begun at intake valve closing (140° BTDC) and ended at 40° ATDC. Different levels of grid resolution were used in order to determine the grid sensitivity of the results.

Figure 1 presents a mean velocity vector plot for one of the simulations near 20° BTDC. As can be seen from the figure, the strong squish velocities generated by the piston shape are beginning to dominate the flow. Figure 2 presents a comparison of mean heat flux predictions for two different mesh resolutions. The figure shows average heat flux into the piston and demonstrates that the increased resolution gives approximately a 4% difference in peak heat flux for the simulation.

Sudden Expansion Flow

Work continued on the simulation of the sudden expansion pipe flow. Calculations of a 2:1 expansion were performed beginning at a location immediately downstream of the expansion and extending to six pipe

Table I. Engine Data

Bore	0.139 m
Stroke	0.121 m
Connecting Rod Length	0.208 m
Piston-Head Clearance @ TDC	0.004 m
Compression Ratio	14.5:1

Table II. Initial Conditions for Engine Simulations

Engine Speed	2600 RPM
Mean Velocity	Zero everywhere
Pressure	Uniform @ 3.0 bar
Temperature	Uniform @ 413 K
Turbulent Kinetic Energy	Uniform @ $0.75 (\text{mean piston speed})^2$
Turbulent Length Scale	Uniform @ 0.1 bore
Head, Liner and Piston Temperatures	556 K, 489 K, 561 K

VELOCITY VECTOR PLOT

ENG SPEED = 2600.0 RPM
 CA = 341.55 DEG ATDC
 PIST VEL = 6.718 M/S
 CYL PRESS = 6567.50 KPA
 CYL TEMP = 987.53 K
 VEL SCALE : $\rightarrow$ 6.8890 M/S

Figure 1. Mean velocity vectors near 20° BTDC for Cummins V903 motoring simulation at 2600 RPM.

Figure 2. Average heat flux into the piston as a function of crank angle for the Cummins V903 motoring simulation at 2600 RPM. Mesh A corresponds to a resolution of 441 nodes above the piston and 96 nodes in the piston bowl. Mesh B corresponds to a resolution of 2209 nodes above the piston and 370 nodes in the piston bowl.

diameters beyond the expansion. Inlet conditions for the calculation were obtained from data supplied to ITI by the IAHR Working Group on Refined Modeling of flows as mentioned in the previous quarterly report. The standard two layer wall model currently implemented in EPISO was used. Figures 3 and 4 show comparisons of turbulent viscosity and turbulent length scale with the IAHR data set² at various downstream positions. The predicted eddy viscosity and length scale profiles show significant discrepancies with the measured profiles within the recirculating flow region (less than 2.0 diameters downstream of the expansion). Predicted values of both length scale and viscosity are much higher within this region of the flow. The significance of these errors in relation to convective heat transfer predictions in complex turbulent flows is further illustrated in Figure 5 which shows the comparison of predicted and measured turbulent viscosities near the pipe wall. In the recirculating flow region, the turbulent diffusion coefficient is over-predicted by as much as a factor of 2, which will translate directly into substantial errors in heat transfer predictions. Accurate modeling of the turbulent diffusion is critical to the accurate modeling of convective heat transfer processes since, near solid boundaries, the flow is dominated by diffusion.

Future Activities

Future work will involve completion of the bowl-in-piston simulations of the heavy duty truck engine. All problems encountered with the use of EPISO for this application will continue to be carefully studied and documented so that accurate bowl-in-piston simulations can be performed dependably in the future. Work will also continue on the sudden expansion pipe flow study. A calculation beginning upstream of the expansion will be performed and simulations including heat transfer will be conducted. Formulation of alternative turbulent transport models will also begin in the near term. As mentioned above, accurate repre-

²Details of how the viscosities and length scales were deduced from flow measurements were not provided with the data set. A technical memorandum dealing with this subject is being prepared by the IAHR group.

Figure 3. Turbulent viscosity vs radial position for sudden pipe expansion flow. Lines with symbols correspond to calculated results at the axial positions indicated in the legend. Lines without the symbols correspond to the IAHR data at the same axial locations as the calculated profiles.

Figure 4. Turbulent length scale vs radial position for sudden expansion pipe flow. Lines with symbols correspond to calculated results at the axial positions indicated in the legend. Lines without the symbols correspond to the IAHR data at the same axial locations as the calculated profiles.

Figure 5. Turbulent viscosity vs radial position in the near wall region of the sudden expansion pipe flow. Lines with symbols correspond to calculated results at the axial positions indicated. The symbols alone correspond to the IAHR data at the same axial locations as the calculated profiles.

sentation of the transport processes is critical to the calculation of convective heat transfer.

Status of Milestones

Work continues on Milestone a., formulation of approach, Milestone b., identification of experimental data and Milestone c., setup of test codes. Work has started on Milestone d., model testing.

Communications/Visits/Travel

Presentation was given at the 18th DHC Group Meeting held at MIT, April 9 and 10, 1987.

Problems Encountered

None.

Publications

None.

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U.S. DEPARTMENT OF ENERGY
SUMMARY REPORTFORM APPROVED
OMB NO. 1901-1400

1. IDENTIFICATION NUMBER DE-AC04-86AL33183		2. PROGRAM/PROJECT TITLE Multi-Dim. Modeling				3. REPORTING PERIOD May 14, 1986 thru April 30, 1987											
4. PARTICIPANT NAME AND ADDRESS Integral Technologies Inc. 415 East Plaza Drive Westmont, IL 60559						5. START DATE: May 14, 1986											
						6. COMPLETION DATE June 14, 1989											
7. FY86/87		8. MONTHS															
9. COST STATUS																	
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c. Set Up Test Codes																	
d. Test Models																	
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12. SIGNATURE OF PARTICIPANT'S PROJECT MANAGER AND DATE																	
James M. [Signature] 6/23/87																	

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SUMMARY REPORT

1. IDENTIFICATION NUMBER DE-AC04-86AL33183		2. PROGRAM/PROJECT TITLE Multi-Dim. Modeling				3. REPORTING PERIOD May 1, 1987 thru May 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											
7. FY87/88 8. MONTHS		M	J	J	A	S	O	N	D	J	F	M	A				
9. COST STATUS																	
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d. Actual Costs Prior Years 9.4		16															
e. Planned Costs Prior Years 12.5		12															
f. Total Estimated Cost for Contract 40.1		8															
g. Total Contract Value 42.9		4															
h. Estimated Subsequent Reporting Period 15.8		0															
Accrued Costs	g. Planned	1.4	1.4	1.4	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5				
	h. Actual	1.3															
	i. Variance	(.1)															
	j. Cumulative Variance	(.1)															
10. LABOR STATUS																	
a. Labor Expressed in: Exact Hours																	
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LEGEND Planned: ----- Actual: ----- Projected: -----		400															
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Labor	g. Planned	165	165	165	165	165	165	165	165	165	165	165	165				
	h. Actual	170															
	i. Variance	5															
	j. Cumulative Variance	5															
11. MILESTONES		STATUS												COMMENTS			
a. Form of Approach																	
b. I.D. of Exp. Data																	
c. Set up Test Cases																	
d. Test Models																	
e. Alt. to Grad. Diff.																	
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1. TITLE		2. REPORTING PERIOD		3. IDENTIFICATION NUMBER																		
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1.	Form. of Approach																				90	70
2.	I.D. of Exp. Data																				90	60
3.	Set Up of Test Cases																				90	70
4.	Test Models																				70	30
5.	Alt. to Grad. Dif.																				0	10
6.	Wall Func. Form.																				0	0
7.	Combustion Effects																				0	0
8.	Method's of Use																				0	0
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