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COMBUSTION SYSTEM CFD MODELING AT GE AIRCRAFT ENGINES

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CURRENT COMBUSTION SYSTEM CFD MODELING CAPABILITIES AT GEAE PROVIDED BY THE *CONCERT CODE*

KEY FEATURES INCLUDE;

- FINITE VOLUME, PRESSURE CORRECTION FORMULATION
- SECOND ORDER ACCURATE *QUICK* NUMERICS
- SINGLE STRUCTURED BODYFITTED GRID
- CONVENTIONAL K–E TURBULENCE MODEL WITH LOG WALL FUNCTIONS
- AVAILABLE COMBUSTION MODELS INCLUDE;
    - SINGLE SCALAR PRESUMED SHAPE PDF (FAST CHEMISTRY)
    - TWO SCALAR PRESUMED SHAPE PDF (REACTION PROGRESS VARIABLE)
    - TWO STEP EDDY BREAKUP (ARRHENIUS KINETICS)
- ZELDOVICH THERMAL NOx MECHANISM (FORWARD AND REVERSE REACTIONS)
- BOTH 2D/AXISYMMETRIC AND FULLY 3D VERSIONS AVAILABLE AND IN DAY TO DAY USE
    - CURRENTLY HAVE A USER BASE OF OVER 20 ENGINEERS AT GEAE AND GE–CRD
- TYPICALLY APPLIED TO PREDICT COMBUSTOR PERFORMANCE INCLUDING;
    - EMISSIONS (CO, HC, AND THERMAL NOx), COMBUSTION EFFICIENCY
    - EXIT GAS TEMPERATURE RADIAL PROFILE AND PATTERN
    - GENERAL FLOW FIELD CHARACTERISTICS

CONCERT DEVELOPMENT HISTORY

EFFORT INITIATED IN 1983

INITIAL PRODUCTION VERSION RELEASED TO GEAE USERS IN 1987

FOCUSED TO PROVIDE HIGHLY PRODUCTIVE ENGINEERING ANALYSIS CAPABILITIES

- GRID GENERATION OPTIMIZED FOR THE SPECIFIC GEOMETRY FEATURES OF THE GAS TURBINE COMBUSTOR
  - INCLUDES ROUND DILUTION HOLES, SWIRLER DISCHARGE, AND LINER SLOT FEATURES WITHIN THE GRID
  - EASY INTRODUCTION OF INTERNAL BODIES OF COMPLEX GEOMETRY
- WORKSTATION BASED USER FRIENDLY PRE AND POST PROCESSING FUNCTIONS BUILT AROUND THE SOLVER
- SOLVER HIGHLY OPTIMIZED FOR THE GEAE CRAY C-90 COMPUTER

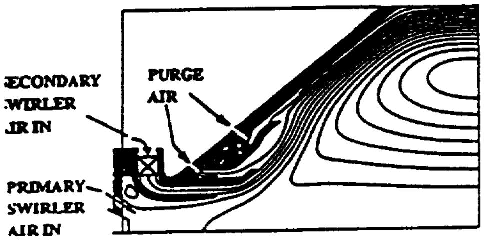
TYPICAL 3D MODEL OF A COMBUSTOR UTILIZING A MESH OF ~100,000 POINTS CAN BE GENERATED, RUN, AND POST PROCESSED WITHIN A SINGLE WORKING DAY!

HAS UNDERGONE CONTINUAL DEVELOPMENT TO IMPROVE AND ENHANCE MODELING CAPABILITIES

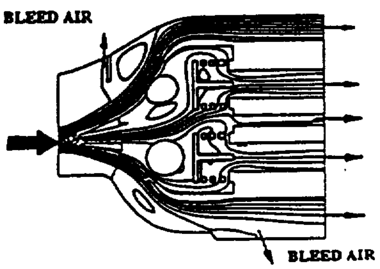
- CURRENTLY ON VERSION 3 RELEASE

CONCERT CFD MODELING PACKAGE PROVIDES DESIGN ENGINEERS WITH A COST AND TIME EFFECTIVE ANALYSIS TOOL THAT REDUCES DEPENDENCE ON COSTLY COMPONENT RIG TESTING.

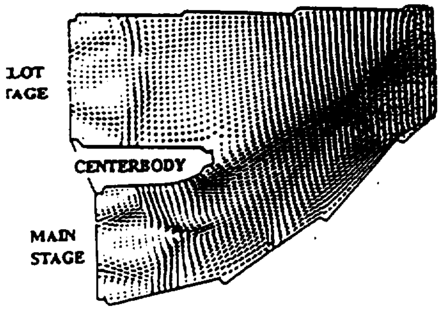
COMBUSTION SYSTEM CFD MODELING IN ACTION AT GEAE



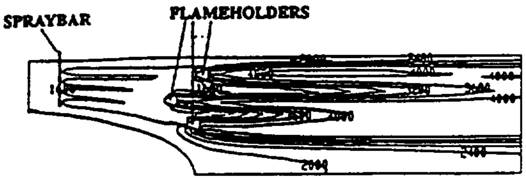
SWIRLCUP/SPRAY MODELING
- RECIRCULATION STRENGTH/SIZE
- FLOW FIELD CHARACTERISTICS
- SPRAY DROPLET TRAJECTORIES
- INPUTS FOR 3D COMBUSTOR MODEL



DIFFUSER FLOW MODELING
- Ps RECOVERIES AND Pt LOSSES
- FLOW FIELD CHARACTERISTICS



MAIN COMBUSTOR MODELING
- FLOW FIELD CHARACTERISTICS/MIXING
- GAS TEMPERATURES AND PATTERNS
- EMISSIONS/EFFICIENCY



AUGMENTOR MODELING
- FLOW FIELD CHARACTERISTICS/MIXING
- GAS TEMPERATURES AND PATTERNS
- EFFICIENCY

MODELING APPLIED FOR DESIGNING ENGINE COMBUSTION SYSTEMS

PRODUCTION ENGINES	DEMONSTRATOR ENGINES	ADVANCED ENGINES
CFM56-5B DUAL ANNULAR	YF120	A/F-X
GE90	F120	NASA/GE HSCT
CF6-80C LOW EMISSIONS	XTE45 IHPTET PHASE I DEMO	NASA ASI PRELIMARY CONCEPTS
LM1600 DLE	XTE46 IHPTET PHASE II DEMO	DOE/GE ATS
LM2500 DLE		
LM6000 DLE		

MODELING APPLIED TO IMPROVE FUNDAMENTAL UNDERSTANDING

CFM56-3 AND CFM56-5B NOx EMISSIONS CHARACTERISTICS DIFFERENCES

CFM56-5A EXIT GAS TEMPERATURE PROFILE SHIFT

F120 PATTERN FACTOR AND RADIAL PROFILE IMPROVEMENT

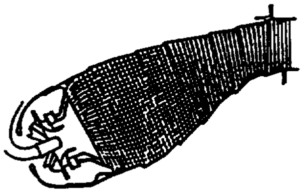
LM2500 CO EMISSIONS REDUCTION EFFORT

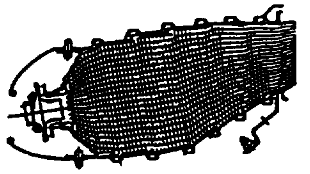
CF34 LINER COOLING MOD IMPACT ON CO EMISSIONS

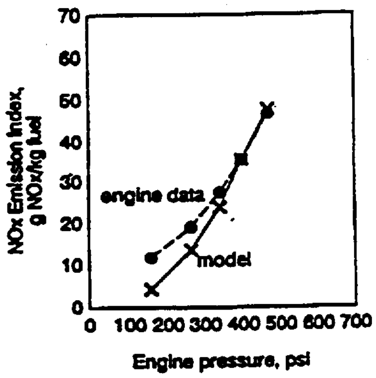
F110X AUGMENTOR MIXER, SPRAYBAR, FLAMEHOLDER INTERACTION OPTIMIZATION

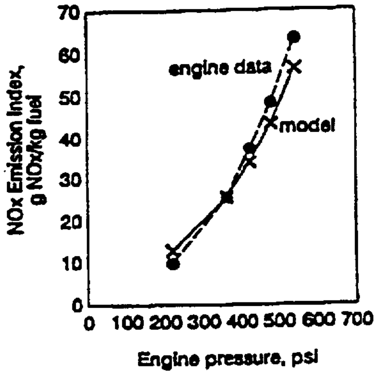
F110-400 AUGMENTOR EXHAUST DUCT LINER FAILURE AND FIX INVESTIGATION

CONCERT3D RESULTS FOR CURRENT PRODUCTION COMBUSTORS

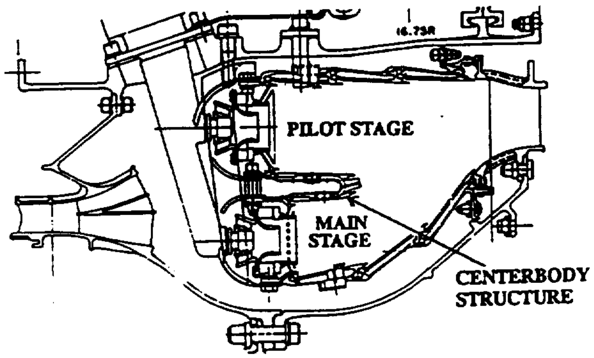


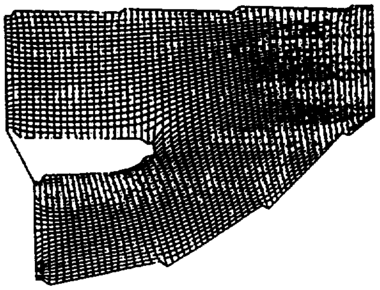






CONCERT3D MODEL OF NASA/GE E3 COMBUSTOR





57X57X25 GRID (81,225 TOTAL MESH POINTS)

VELOCITY VECTORS

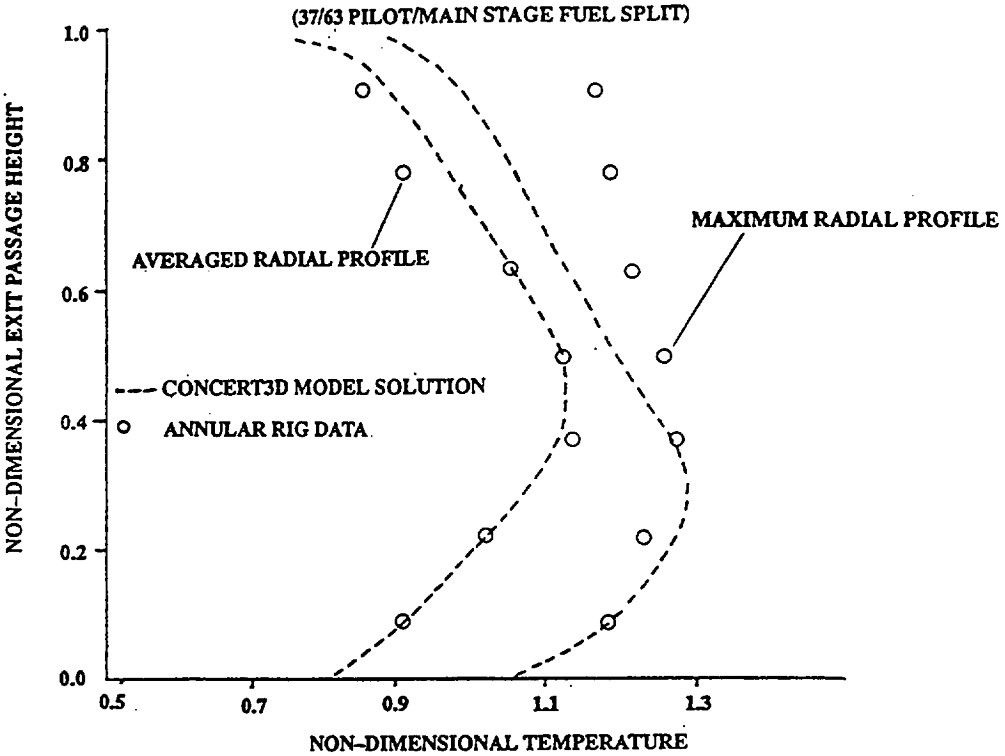
GAS TEMPERATURES (R)

CALCULATED FLOW FIELD IN PLANE IN LINE WITH SWIRLCUPS

CONCERT3D vs. RIG DATA COMPARISON FOR NASA/GE E3 COMBUSTOR

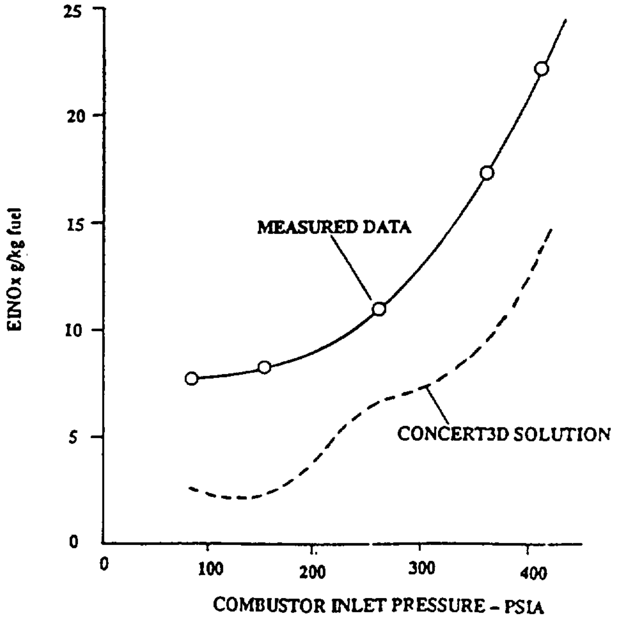
(EXIT GAS TEMPERATURE AVERAGED AND MAXIMUM RADIAL PROFILES)

(37/63 PILOT/MAIN STAGE FUEL SPLIT)



CONCERT3D vs. RIG DATA COMPARISON FOR NASA/GE E3 COMBUSTOR

(NOx EMISSIONS)



GEAE CONCERT EXPERIENCE:

CONCERT3D WITH PRESUMED SHAPE PDF/FAST CHEMISTRY MODEL AND THERMAL NOx MODEL DOES WELL AGAINST REAL ENGINE DATA

CONCERT3D WITH TWO STEP EDDY BREAKUP MODEL DOES NOT CONSISTENTLY DEMONSTRATE ACCEPTABLE AGREEMENT FOR [CO] AND [HC] EMISSIONS

OTHER PERFORMANCE ISSUES NOT AS WELL PREDICTED COMPARED TO PRESUMED SHAPE PDF/FAST CHEMISTRY APPROACH

SHORTCOMINGS:

TWO STEP EDDY BREAKUP MODEL NOT ADEQUATE FOR THE REQUIRED LEVEL OF PREDICTIVE ACCURACY

FAST CHEMISTRY CANNOT PREDICT [CO], [HC], AND IGNITION, BLOWOUT, AND RELIGHT

REQUIRES ACCURATE FINITE RATE CHEMISTRY REPRESENTATION AND MORE ACCURATE TURBULENCE–CHEMISTRY INTERACTION MODELING

GE HAS EMBARKED ON THE DEVELOPMENT OF IMPROVED CONCERT MODELING CAPABILITIES

HYBRID CONCERT CFD / MONTE–CARLO MODELING APPROACH

APPROACH ADOPTED FOR THE NEXT RELEASE OF COMBUSTION CFD MODELING CAPABILITY AT GEAE

RETAINS;

- SINGLE STRUCTURED BODYFITTED GRID
- PRESSURE CORRECTION FINITE VOLUME FORMULATION
- K–E TURBULENCE MODELING WITH LOG WALL FUNCTIONS

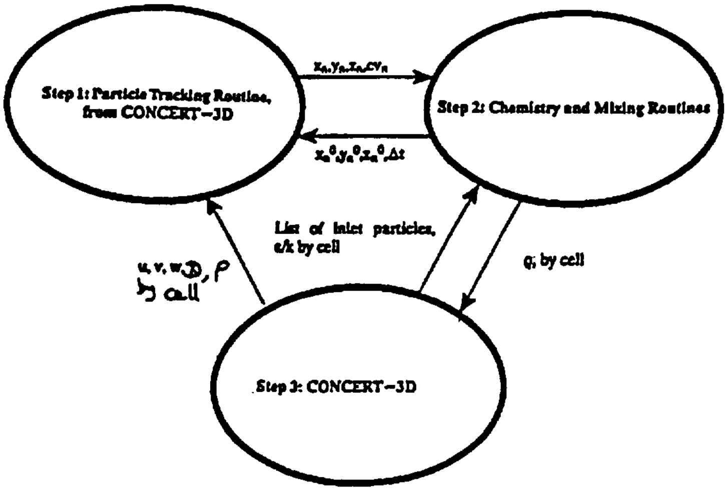
INTRODUCES;

- MONTE–CARLO SCALAR PDF TO ADDRESS TURBULENT COMBUSTION
    - SINGLE ATTRIBUTE (CONSERVED SCALAR) FOR FAST CHEMISTRY
    - MULTIPLE SCALARS FOR FINITE RATE CHEMISTRY OF CH4 AND JETA FUELS BASED ON APPROPIATE REDUCED MECHANISMS

DEVELOPMENT HAS BEEN UNDERWAY SINCE 1992

- 3D CODE DEVELOPMENT INITIATED IN MID YEAR 1993

HYBRID CONCERT CFD / MONTE–CARLO MODELING APPROACH



SCHEMATIC OF COMMUNICATIONS IN THE COMBINED CONCERT / MONTE–CARLO MODELING

HYBRID CONCERT CFD / MONTE–CARLO MODELING APPROACH

BETA TESTING INITIATED BEGINNING OF 1994

FOCUSED ON FAST CHEMISTRY CALCULATIONS AND OPTIMIZING COMPUTATIONAL EFFICIENCY

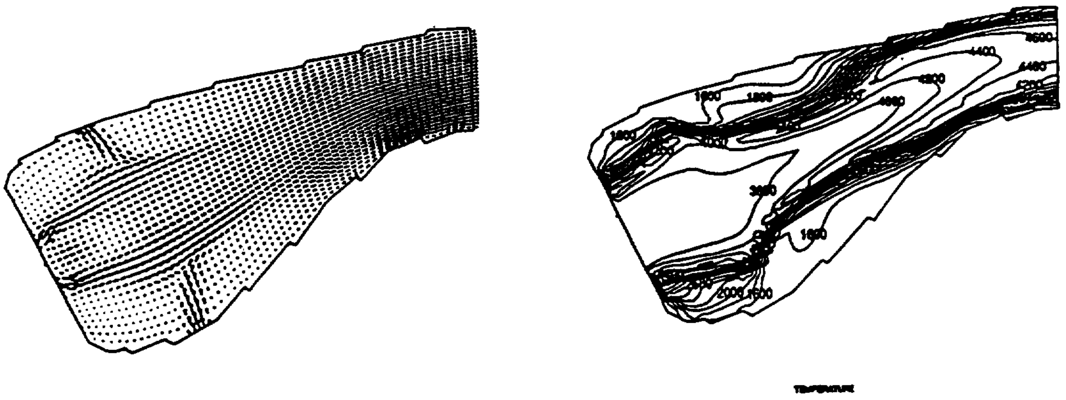
SIGNIFICANT IMPROVEMENT IN COMPUTATIONAL EFFICIENCY ACHIEVED

	TEST CASE 1	TEST CASE 2
NUMBER OF GRID POINTS	9,261	58,621
NUMBER OF M/C PARTICLES	216,000	1,500,000
CPU TIME (CRAY C–90 seconds)		
CONCERT WITHOUT M/C	83	5,400
INITIAL HYBRID CONCERT /MC	39,960	187,560
OPTIMIZED VERSION	1,770	41,400
PERCENT REDUCTION	–95.6%	–77.9%
WALL CLOCK TIMES (seconds) UTILIZING CRAY MULTI-TASKING OPTION	1,500	29,520

RUN TIMES HAVE BEEN REDUCED TO THE POINT WHERE OVERNIGHT TURNAROUND TIMES FOR A TYPICAL 3D COMBUSTOR MODEL ARE POSSIBLE

HYBRID CONCERT CFD / MONTE–CARLO MODELING APPROACH

(INITIAL 3D CALCULATION OF CFM56–3 COMBUSTOR WITH FAST CHEMISTRY)



CALCULATED FLOW FIELD IN PLANE IN LINE WITH INLET SWIRL CUPS

INITIAL CALCULATED RESULTS SHOW A TEMPERATURE FIELD THAT DOES NOT AGREE WELL WITH EXPECTED LEVELS. CALCULATION SHOWS CONSIDERABLY LESS DIFFUSION OF THE SCALAR FIELD (FUEL MIXTURE FRACTION) THAN OBSERVED FROM RIG DATA AND CONCERT CALCULATIONS PERFORMED USING THE PRESUMED SHAPE SCALAR PDF COMBUSTION MODELING APPROACH.

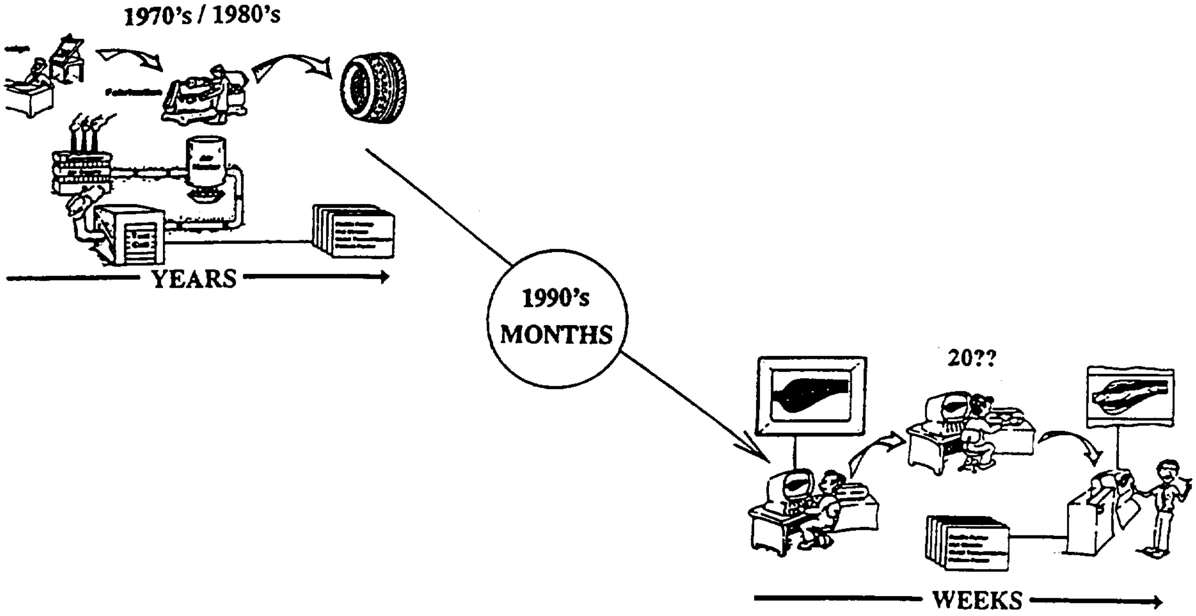
HYBRID CONCERT CFD / MONTE–CARLO MODELING APPROACH

FUTURE WORK PLANNED

- PERFORM CALCULATIONS AGAINST A BENCHMARK REACTING FLOW EXPERIMENT WITH AVAILABLE TEST DATA
  - BLUFF BODY STABILIZED FLAME ; (GULATI AND CORREA)
- SYSTEMATICALLY STUDY THE EFFECTS OF SCHMIDT NUMBER AND OTHER PARTICLE TRACKING PARAMETERS ON THE FAST CHEMISTRY SOLUTION TO IMPROVE AGREEMENT WITH THE DATA
- PERFORM 3D SINGLE AND DUAL ANNULAR COMBUSTOR CALCULATIONS AND COMPARE RESULTS WITH AVAILABLE GEAE DATA BASE
- IMPLEMENT REDUCED CHEMISTRY SCHEMES (MULTIPLE SCALARS) TO PERFORM FINITE RATE CHEMISTRY CALCULATIONS
  - PREDICT [CO], [HC], AND [NOx] EMISSIONS
- RELEASE CODE FOR PRODUCTION USE AT GEAE
  - FAST CHEMISTRY BY END OF FIRST QUARTER OF 1995
  - FINITE RATE CHEMISTRY BY END OF THIRD QUARTER OF 1995

FUTURE MODELING DIRECTIONS

FOCUSED ON IMPROVING THE PREDICTIVE ACCURACY FOR ALL KEY COMBUSTOR PERFORMANCE ISSUES TO LEVELS THAT WOULD ELIMINATE THE NEED FOR COMPONENT RIG DEVELOPMENT TESTING



FUTURE MODELING DIRECTIONS

INDUSTRY WILL LOOK INCREASINGLY TO THE ACADEMIC COMMUNITY (UNIVERSITIES AND NATIONAL LABS) TO DEVELOP THE NEEDED MODELING IMPROVEMENTS

INDUSTRY MUST PROVIDE THE GUIDANCE AS TO WHAT IS NEEDED

FUTURE GENERATION MODELS MUST;

- PROVIDE MORE RIGOROUS REPRESENTATION OF COMPLEX PHYSICAL PROCESSES
- BE COST EFFECTIVE AS A ROUTINE APPLIED DESIGN/ANALYSIS TOOL
- RETAIN USER FRIENDLY CHARACTERISTICS
- PROVIDE THE LEVEL OF ACCURACY AND CAPABILITIES DEMANDED OF IT

COMPUTING PLATFORM CAPABILITIES ARE ADVANCING AT A RAPID PACE

THE PRACTICALITY OF ADVANCED MODELS IN INDUSTRY MAY NOT BE TOO FAR INTO THE FUTURE

TIME TO START NOW ON DEVELOPMENT OF THE ADVANCED MODELS OF THE FUTURE INTO PRACTICAL TOOLS TO HAVE THEM READY FOR USE WHEN THE REQUIRED COMPUTING PLATFORMS BECOME AVAILABLE IN INDUSTRY

Computational Turbulence 1994	1 ---- 6	Calculation of turbulent heat transfer in "cluttered spaces", by BRIAN SPALDING Topic 1: The WDIS & WGAP calculation.

The need:

- Prandtl-mixing-length models require knowledge of distance from nearby walls AND between walls (eg Nikuradze formula)
- Many low-Re models require the distance from nearby walls
- In spaces "cluttered" with solids (eg electronics cooling), calculation of distances and gaps has, in the past, been time-consuming.

The solution:

- This contribution computes WDIS and WGAP (the required quantitities) by solving:

$$\text{div grad } L = -1$$

with L fixed to zero in solids.

Computational Turbulence 1994	2 ---- 6	Outline of the theory

Obviously L values which satisfy this equation will be proportional to the distance from the wall at points which are close to it. The question is: what is the proportionality constant?

The constant depends also on the distance across the inter-solid space, which however is the other unknown which it is desired to determine.

The practice adopted by the author is to deduce both the required quantities, WDIS the distance from the wall, and WGAP the distance between walls (whatever these quantities may mean in "cluttered spaces"), from the an algebraic fucntion of the local values of L and its gradient.

Computational Turbulence 1994	3 ---- 6	The results

The formula employed gives exact results for situations where WDIS and WGAP have unequivocal meanings, namely for the space between two parallel plates or within a long circular-sectioned pipe; and it gives plausible results for more complex cases.

The equation for L, with the appropriate boundary conditions, is of course very easy to solve by numerical means; so WDIS and WGAP can be quickly computed before the flow simulation starts.

The use of the method is illustrated by a PHOENICS calculation for a geometry involving two boxes, a connecting arc, an inlet and an outlet. It was performed by I Poliakov and S Semin, of CHAM, to whom the author's thanks are due.

Computational Turbulence 1994	4 ---- 6	Calculation of turbulent heat transfer in "cluttered spaces", by BRIAN SPALDING Topic 2. The LVEL model.

The need:

- In "cluttered" regions, the between-solid distances are too often too small for fine-grid resolution.

- Reynolds numbers are usually low, at least in some plsces.

- A model is needed which gives plausible results in these circumstances AND fits experimental data for better-studied ones.

The solution:

- The LVEL model of PHOENICS gets local effective viscosities from the analytical nuplus-versus-uplus relation which fits the laminar, transitional & full-turbulent ranges very well Only local velocity and WDIS (wall distance) are needed.

Computational Turbulence 1994	5 ---- 6	Outline of the theory

The u-plus versus y-plus formula of Spalding (1961) is employed namely:

```
       y+ = u+ + (1/E) * [ exp(K*u+) - 1 - K*u+ - (K*u+)**2/2
                            - (K*u+)**3/6 - (K*u+)**4/24 ]
```

which implies the formula for dimensionless effective viscosity:

```
       v+ = 1 + (K/E) * [ exp(K*u+) - 1 - K*u+ - (K*u+)**2/2
                                               - (K*u+)**3/6 ]
```

With the wall-distance and the velocity known at every point, the effective viscosity can also be computed at every point.

The method is valid for the whole range of Reynolds numbers; but it is best supplemented by a low-Re "v+-collapse" formula.

Computational Turbulence 1994	6 ---- 6	The results

The LVEL model gives the well-known experimental results for simple circumstances, such as flow in pipes and between parallel plates; and it gives plausible results for more complex cases.

The use of the method is illustrated by a PHOENICS calculation of the flow and heat transfer in a small part of a large space cluttered with solids which participate in the heat-transfer process.

The method is the only plausible and practicable one known to the author for handling heat transfer in electronics-cooling problems, because of the excessive grid-fineness requirements of low-Reynolds-number k-epsilon extensions.