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

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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

SECONDARY SWIRLER AIR IN
PRIMARry SWIRLER AIR IN

SWIRL/CUP/Spray MODELING
- RECIRCULATION STRENGTHENING
- FLOW FIELD CHARACTERISTICS
- SPRAY DROPLET TRAJECTORIES
- INPUTS FOR 3D COMBUSTOR MODEL

LOTAGE
CENTERBODY
MAIN STAGE

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

BLEED AIR

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

Sspraybar
Flameholders

AUGMENTOR MODELING
- FLOW FIELD CHARACTERISTICS/MIXING
- GAS TEMPERATURES AND PATTERNS
- EFFICIENCY
MODELING APPLIED FOR DESIGNING ENGINE COMBUSTION SYSTEMS

<table>
<thead>
<tr>
<th>PRODUCTION ENGINES</th>
<th>DEMONSTRATOR ENGINES</th>
<th>ADVANCED ENGINES</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFM56-5B DUAL ANNULAR</td>
<td>YF120</td>
<td>A/F-X</td>
</tr>
<tr>
<td>GE90</td>
<td>F120</td>
<td>NASA/GE HSCT</td>
</tr>
<tr>
<td>CF6-80C LOW EMISSIONS</td>
<td>XTE45 HPTET PHASE I DEMO</td>
<td>NASA ASI PRELIMINARY CONCEPTS</td>
</tr>
<tr>
<td>LM1600 DLE</td>
<td>XTE46 HPTET PHASE II DEMO</td>
<td>DOE/GE ATS</td>
</tr>
<tr>
<td>LM2500 DLE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LM6000 DLE</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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
- F100X 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

VELOCITY VECTORS

GAS TEMPERATURES (K)

CALCULATED FLOW FIELD IN PLANE IN LINE WITH SWIRLCUPS

57X57X25 GRID (81,225 TOTAL MESH POINTS)
CONCERT3D vs. RIG DATA COMPARISON FOR NASA/GE E3 COMBUSTOR
(Exit gas temperature averaged and maximum radial profiles)

(CONCERT3D MODEL SOLUTION)

MAXIMUM RADIAL PROFILE

CONCERT3D vs. RIG DATA COMPARISON FOR NASA/GE E3 COMBUSTOR
(NOx EMISSIONS)

CONCERT3D SOLUTION
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 APPROPRIATE REDUCED MECHANISMS

DEVELOPMENT HAS BEEN UNDERWAY SINCE 1992

- 3D CODE DEVELOPMENT INITIATED IN MID YEAR 1993
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

<table>
<thead>
<tr>
<th></th>
<th>TEST CASE 1</th>
<th>TEST CASE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMBER OF GRID POINTS</td>
<td>9,261</td>
<td>58,621</td>
</tr>
<tr>
<td>NUMBER OF M/C PARTICLES</td>
<td>216,000</td>
<td>1,500,000</td>
</tr>
<tr>
<td>CPU TIME (CRAY C–90 seconds)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CONCERT WITHOUT M/C</td>
<td>83</td>
<td>5,400</td>
</tr>
<tr>
<td>INITIAL HYBRID CONCERT/MC</td>
<td>39,960</td>
<td>187,560</td>
</tr>
<tr>
<td>OPTIMIZED VERSION</td>
<td>1,770</td>
<td>41,400</td>
</tr>
<tr>
<td>PERCENT REDUCTION</td>
<td>−95.6%</td>
<td>−77.9%</td>
</tr>
</tbody>
</table>

WALL CLOCK TIMES (seconds) UTILIZING CRAY MULTI–TASKING OPTION

<table>
<thead>
<tr>
<th></th>
<th>TEST CASE 1</th>
<th>TEST CASE 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALL CLOCK TIMES</td>
<td>1,500</td>
<td>29,520</td>
</tr>
</tbody>
</table>

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

1970's / 1980's

YEARS

1990's MONTHS

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
**Computation of turbulent heat transfer in "cluttered spaces", by BRIAN SPALDING**

**Topic 1: The WDIS & WGAP calculation.**

<table>
<thead>
<tr>
<th>The need:</th>
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<tbody>
<tr>
<td>* Prandtl-mixing-length models require knowledge of distance from nearby walls AND between walls (e.g., Nikuradze formula)</td>
</tr>
<tr>
<td>* Many low-Re models require the distance from nearby walls</td>
</tr>
<tr>
<td>* In spaces &quot;cluttered&quot; with solids (e.g., electronics cooling), calculation of distances and gaps has, in the past, been time-consuming.</td>
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</table>

The solution:

* This contribution computes WDIS and WGAP (the required quantities) by solving: \( \text{div} \ \text{grad} \ L = -1 \)
  
  with \( L \) fixed to zero in solids.

<table>
<thead>
<tr>
<th>Outline of the theory</th>
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<tbody>
<tr>
<td>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?</td>
</tr>
<tr>
<td>The constant depends also on the distance across the inter-solid space, which however is the other unknown which it is desired to determine.</td>
</tr>
<tr>
<td>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 &quot;cluttered spaces&quot;), from the an algebraic function of the local values of ( L ) and its gradient.</td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>The results</th>
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<tbody>
<tr>
<td>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.</td>
</tr>
<tr>
<td>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.</td>
</tr>
<tr>
<td>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.</td>
</tr>
</tbody>
</table>
### 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 places.

* 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.

### Outline of the theory

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

\[
y^+ = u^+ + \frac{1}{\varepsilon} \left[ \exp(Ku^+ - 1 - Ku^+ - (Ku^+)^2/2 - (Ku^+)^3/6 - (Ku^+)^4/24 \right]
\]

This implies the formula for dimensionless effective viscosity:

\[
v^+ = 1 + \frac{1}{\varepsilon} \left[ \exp(Ku^+ - 1 - Ku^+ - (Ku^+)^2/2 - (Ku^+)^3/6 \right]
\]

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.

### 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.