Overview of MSFC’s Applied Fluid Dynamics Analysis Group Activities

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Overview

- Introduction
  - Status of programs at MSFC
  - Fluid Mechanics at MSFC

- Relevant Fluid Dynamics Activities at MSFC
  - Combustion devices
  - Turbomachinery
  - Nozzles

- Shuttle Return to Flight
  - SRB Boost Separation Motor
  - External Tank redesign
  - Fuel Feedline Flowliner
  - On-pad debris transport

- Concluding Remarks
Status of programs at MSFC - Prometheus

- Prometheus/JIMO (Jupiter Icy Moon Orbiter)
  - Project lead by JPL.
  - Current in a black-out period due to RFP.
  - Develop nuclear-electronic propulsion systems to provide greater energy for science on-site.
  - JIMO is a nuclear electric pathfinder vehicle.
    - Utilize a nuclear reactor to heat some sort of fluid.
    - Fluid used to generate electricity (Brayton cycle, Stirling cycle, etc.).
    - Electric thrusters provide thrust for delta-V.
    - Excess power is radiated into space.
    - Launch 2011 - 2015, 3-5 year transit to Jupiter.
  - Within Prometheus there are also studies for other, nuclear based propulsion concepts (i.e., nuclear thermal).

Office of Exploration Systems created to implement the President's vision for human space exploration
- "returning to the Moon"
- Code T

- Major Milestones
  - 2008: Initial flight test of CEV
  - 2008: Launch first lunar robotic orbiter
  - 2011 First Unmanned CEV flight
  - 2014: First crewed CEV flight
  - 2015: Jupiter Icy Moon Orbiter (JIMO)/Prometheus
  - 2015-2020: First human mission to the Moon

- HQ centric program, getting engineering support from field centers
- A "mission pull" initiative
  - Technology only if the mission needs it.
Status of programs at MSFC - Code T

- Conducting studies to aid in the establishment of requirements
- Going through the process of reviewing projects that it inherited for relevance to Exploration System needs
  - Relevance review has resulted in cancellation of several former NGLT projects
  - Redirection of others
  - There will be some low level, very focused near term technology activities
- Code will have to live with the same metrics as other programs
  - Support universities, small businesses, etc.
- SBIR program topics being restructured in line with the initiative and consistent with the "mission-pull" concept
- Centennial challenges could be the source of very interesting and spirited competitions
  - Allows NASA to award prize money to individuals/teams that are first in achieving certain technology/capability goals

Status of programs at MSFC - Shuttle RTF

- NASA is being very thorough in its return to flight (RTF) activities
  - It is implementing the CAIB recommendations and beyond
  - Aiming for RTF in March of 05
- You get relatively recent RTF information on the web
- RTF activities are impacting all the code M and code R centers
- Major activities being worked (not all inclusive)
  - Redesigning the ET to eliminate all sources of debris
  - Hardening the shuttle to be more tolerant of debris
  - Improving the orbiter's ability to re-enter safely with minor wing damage
  - TPS on-orbit inspection and repair capability
  - Developing a better RCC properties database
  - Developing a physics based, disciplined debris assessment process
  - Redesign solid rocket booster bolt catcher
  - Improving the film system for improved monitoring of launches (ground and on vehicle)
  - Has established and independent engineering technical authority
  - Reorganized to allow for more effective integration of the shuttle elements
- All activities being performed with extensive testing and analysis support
High-fidelity fluids design & analysis expertise at MSFC focused in the space transportation directorate
- CFD (TD64), induced environments (TD63), cold flow testing (TD62, TD63, TD74), and functional design (TD61)

Fluid dynamics expertise a core competency at MSFC

Support focused in two broad areas
- Space Shuttle propulsion (Shuttle return to flight)
  - SRB office, ET office, and Shuttle Integration Office
- Next Generation Launch Technologies
  - Projects/tasks that survive Office of Exploration Systems (Code T) Relevance Review

Introduction: Role of Fluid Mechanics Expertise

Fluid mechanics applications at MSFC focused on improving the safety, reliability, & cost of space transportation systems

We define geometry, quantify environments, and predict performance
- Incident investigation support (analysis and test)
- Environments and performance definition (analysis and test)
- Develop advanced hardware concepts and designs (analysis and test)

We support the programs in meeting their goals
- Assist the programs in being "smart buyers"
- Provide innovative technical solutions

We work with external partners who possess key capabilities
- Other NASA centers, other government agencies, industry, academia
Introduction: CFD Goals

- Provide personnel with the tools to succeed
  - Maintain and enhance civil service personnel capabilities
  - Provide challenging work, hands-on experience, training
  - Continuously improve analysis techniques, computing resources, and test facilities, reduce cost/analysis

- Acquire/develop capability to perform broad, CFD-based parametric design concept studies
  - Spend more time engineering, less time "CFDing"
  - More efficient use of available computing resources
  - Requires automation in all phases: grid generation, flow solver, post-processing

- Expand range of CFD applicability
  - Improved models, combustion, transient processes, relative motion, cavitation, multi-component, multidisciplinary, ....
  - Greater efficiency and robustness in flow solvers

CFD Software/Hardware in Use at MSFC

- Grid generation
  - Gridgen, Solid Mesh, Corgrid, CFD-Geom, CORGRID

- Post Processing
  - Fieldview, Ensight, Flowshow, Animator, Autoplot

- Flow Solvers
  - FDNS, LOCI-Chem, Corsair, Phantom, Overflow, UNIC

- Computer Hardware
  - Access to NASA-Ames SGI based compute clusters (512p & 1024p)
  - Local PC-based clusters and SGI systems
  - Access to local Army compute clusters

<table>
<thead>
<tr>
<th>Computers</th>
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<th>Processor Speed</th>
<th>RAM</th>
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<td>VMFS</td>
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Combustion Devices

- **Technology need**
  - Contemporary rocket engine combustion devices similar to 1960s-1970s designs
  - Longer life (robust), higher T/W designs required
    - Experimental demonstration of design robustness/life is cost prohibitive
  - Application of CFD in design of combustion devices hampered by real limitations
    - Inadequate accuracy (lack of physical modeling)
    - Inadequate turn-around time
    - Inadequate validation and verification where required physics are included in the CFD tools
  - Current focus at MSFC is in rocket chamber combustion
    - High pressure, all-speed, reacting flows

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Combustion Devices - The Challenge

- We must support programs with the current, limited capability for injector design
- Concurrently, CFD simulation capability improvements must be made in at least 3 areas
  - Fidelity—the ability to model the key details of the physics and geometry
  - Robustness—solution turnaround must be sufficient to cover a large parametric space of independent design variables and operating conditions
  - Accuracy (demonstrated)—we must be able to quantify accuracy; both current and threshold level for design

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At MSFC, we must maintain 2 parallel thrusts

| Program Support |
| Technology Development |
**Key Concept—Simulation Readiness Level**

**Simulation Readiness Level (SRL) = (f, r, a)**

<table>
<thead>
<tr>
<th>Level</th>
<th>Fidelity</th>
<th>Robustness</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Extremely simple physics, boundary conditions and geometry</td>
<td>Have not completed any simulations</td>
<td>Not evaluated other than historical quality of simulation tool</td>
</tr>
<tr>
<td>1</td>
<td>Reasonably precise geometry and boundary conditions, extremely simple physics</td>
<td>Have completed some simulations</td>
<td>Qualitative agreement with existing results of related problems</td>
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<tr>
<td>2</td>
<td>Reasonably precise physics with extremely simple boundary conditions and geometry</td>
<td>Simulations with proven convergence and conservation</td>
<td>Quantitative agreement with existing results of related problems</td>
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<tr>
<td>3</td>
<td>Reasonably precise physics, boundary conditions and geometry ***</td>
<td>Simulations with proven convergence, conservation and grid independence</td>
<td>Qualitative agreement of relevant measures for one representative problem ***</td>
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<tr>
<td>4</td>
<td>Reasonably precise physics, completely precise boundary conditions and as-built geometry</td>
<td>Fire and Forget (95%) simulations with convergence, conservation and grid independence ***</td>
<td>Qualitative agreement of relevant measures over parametric space of actual problems</td>
</tr>
<tr>
<td>5</td>
<td>Completely precise physics, completely precise boundary conditions and as-built geometry</td>
<td>Fire and Forget (95%) simulations with convergence, conservation and grid independence ***</td>
<td>Quantitative agreement of relevant measures over parametric space of actual problem</td>
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Minimum level for significant design impact: 3

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**Combustion Devices**

- **Focus of groups combustion devices activities has been the staged combustion injector technology (SCIT) task**
  - Task objective is to develop, validate, and verify a CFD based injector design process
  - Develop required CFD capabilities for supporting large design parametrics
    - Robustness, physical models, turnaround time
  - Generate validation data sets
    - Gas-gas, liquid-gas, liquid-liquid, H₂-O₂, HC-O₂
    - Verify by testing injector designed using new process

- **Result of relevance review by Code T is to narrow the focus of the task**
  - Program priority will change to advancing design concepts, with CFD capability advancement being secondary
  - Focus on H₂-O₂ injectors, chamber compatibility for expander engines
  - Initial approval for continuation for 3 years
Validation Data Acquisition -- GO2/6H2 at Penn State

- Have tested initial gas-gas elements at PSU (code validation)
- Initial CFD comparisons have been completed
- Additional testing to focus on advance concepts
  - Probably gas-liquid injectors

OBJECTIVE
- To acquire data to validate codes for coaxial GO2/6H2 elements (Model Problem 9.1.1.1)
- To verify validated CFD codes and optimization techniques

CFD used extensively in concert with PSU testing

- Oxidizer tip location study demonstrates importance of pre-test simulations
  - Also shows knowledge of tip location to be critical
- Application of CFD reinforced need for detail data uncertainty analyses

Pre-Test CFD Temperature Fields for 5 Different Tip Locations

Wall Temperature Profiles for 5 Different Tip Locations
Liquid-liquid injector testing at facility TS-115
- 7-element, shear coax, LH2-LOX, preburner conditions
- Testing is underway and data is being reviewed
- Attempts to obtain multi-element CFD simulations have been hampered by several issues, most notably CPU time required to develop solutions

Configuration 1:
Shadowgraph Imaging of Propellant Injection Region & Flame Front

Configuration 2 & 3:
Thermocouple Rakes Provide Measurement of Flow Field Temperatures

Configuration 4: Colorimeter Chamber Measures Wall Heat Rate at 14 Axial Locations

Configuration 5: In-Chamber Raman Measurements Yield Species & Temperature

These layouts assume that the igniter spool can be placed far downstream; this remains to be demonstrated.
• Under SCIT there have been several parallel efforts for code improvement
  - FDNS real fluids development and implementation
  - FDNS robustness and efficiency improvements
  - Chenoweth presentation to discuss in more detail

• Development of LOCI-Chem for reacting flows applications (MSU)
  - Density based, generalized grid capability
  - Developed within multi-disciplinary framework
  - Ed Luke presentation

• Development of LOCI-Stream (UF and Stream Numerics)
  - Pressure based code within LOCI
  - Jeff Wright presentation

• All Three codes undergoing nearly constant validation against suite of test cases

Example: Initial validation of LOCI-Chem unsteady capabilities validated against classic vortex shedding cylinder
  - Validation performed by Bryan Robles (new-hire) as part of familiarization w/Chem
  - Results are pretty good but show dependency with Mach number
Combustion Devices - IPD Support

- **Objective:**
  - Construct a model to evaluate Main Injector and Chamber Wall Environments
  - IPD utilizes (hot) gas-gas H2-O2 main injector

- **Approach is to build on experience with PSU gas-gas injector analyses**
  - Apply Chem’s capabilities to basically a (large) reacting ideal gas problem
  - "Smart" modeling of the multi-element configuration

![Initial IPD multi-element simulation](image1)

![Wall Heat Flux Distribution](image2)

Combustion Devices - RS-84 Support

- **OBJECTIVE**
  - Mitigate design risk by better characterization of thermal environments on baffle elements and on chamber wall

- **APPROACH**
  - Start with Single Element, axisymmetric geometry
  - Finite rate multi-step chemistry, RP-1 modeled as ideal gas
  - Evaluated different GOX injection schemes
  - Evaluated different turbulence models

![Asymmetric simulations of an equivalent baffle (mid-chamber) element and a near wall element were performed](image3)
**Example results:**

Impact of Turbulence Model on RS-84 Heat Flux

- Objective: Construct subscale models to be validated for simulation of large scale combustors
- Approach: Start with Single Element, axisymmetric geometry, RP-1 modeled as ideal gas, Finite rate multi-step chemistry

Impact of GOX swirl RS-84 Heat Flux

- GOX swirl promotes mixing, thus increasing the near-injector wall heat flux.
**Nozzle Activities**

- **Recent/Ongoing Nozzle Technology Activities**
  - Documentation of test and analysis results from recent altitude compensation nozzle activities continues.
  - Nozzle Sideload activity approved for FY04.
    - Delayed one year due to Columbia investigation support.
  - Task includes:
    - Development of CFD based nozzle sideload prediction approach.
    - Development of experimental sideload measurement approach.
    - Testing of different bell nozzle designs in wind.

**Turbomachinery Activities - TPO**

- **Turbopump optimization task**
  - 2 stage supersonic turbine, instrumented rotor.
  - Tool improvements, design process improvements, rig design, manufacture, and testing.
  - First entry testing completed in Feb 2003, preparing for second entry into facility.
  - Test data has been used to make improvements to meanline code.
  - Comparisons of Corsair results are very encouraging.

**Optimized 2 stage supersonic turbine w/ instrumented first stage blades**
Turbomachinery Activities - TPO

Steady state data obtained at all planned set points

Efficiency comparisons

PR_{in} = 8.71

Nozzle pressure distributions comparisons to Corsair results

Blade suction side pressure distributions comparisons to Corsair results

Turbomachinery Activities - TAFT

- TAFT - Turbine AirFlow Tester
- RS-84 turbine airflow test rig
  - Subsonic, high flow turbine, out of U.S. industry
  - Design, analysis, manufacture, testing
  - Instrumented rotor for code validation
  - Testing completed, initial comparisons to data

Test rig installed in facility, initial test run completed

Pretest unsteady CFD analysis of key test points completed

Instrumented blades & nozzles at high freq. p measurements
Perfumed CFD analyses of RS-84 main oxidizer pump feedline
- Concerns with pump inlet velocity profile
- Predicted large distortions with baseline pipe geometry
- Began initial activities towards a redesign when project canceled
- Rothermel presentation
Turbomachinery Activities RS-84 LPOT

- Performed CFD analyses of the RS-84 LPOT
  - 6-stage hydraulic turbine
  - Analyzed with Phantom (unsteady, real LOX properties)
  - Provide steady and unsteady loads, provide insight into unsteady flows
    - Vortex shedding, boundary layer separation, etc.
  - Provide performance predictions

2D results for LPOT, first 3 stages shown

Instantaneous velocity at the trailing edge of vane 2 (ft/sec)

Turbomachinery Activities - Throttling TP Dev.

- Task to develop deep throttling diffuse concepts was not selected for continuation
  - Task included development of advanced pump diffuser concepts
    - Not completed
  - Task also included development of validation database and validation of codes - task was completed
  - Phantom (MSFC), Enigma (Rkdn), and INS3D (Ames) validated against experimental data set

CFD predictions comparison with test data
Impeller exit radial velocity profile

Experimental pump stage geometry and sample, time-averaged result

Diffuser pressure recovery at various Q/N
Shuttle Return to Flight

- As part of the Shuttle return to flight activities all the elements are attempting to address areas of concern
  - Even if not related to the Columbia mishap
- CFD is being utilized at MSFC in several areas in support of returning the shuttle to flight
  - External tank (ET) redesign
  - Solid rocket booster separation motors igniter
  - Orbiter fuel feedline liner cracking (again)
  - Shuttle on-pad debris transport process
- Other shuttle support
  - SSME LPOT potential redesign assessment

Shuttle Return to Flight - ET support

- CFD has been heavily utilized in the redesign of the bipod ramp on the external tank
  - Foam loss from the ET bipod ramp led to Columbia mishap
  - CFD used to assess the various redesign candidates
  - CFD utilized heavily in support of the testing of the redesigns
    - Key to designing the test plan
  - MSFC utilized LOCI-Chem exclusively for this work
  - D’Agostino presentation

Columbia ET bipod ramp configuration
Redesign ET bipod ramp region

Chem comparisons to wind-tunnel data are excellent
- Currently supporting project office assessing redesign of PAL ramps
  - There are two large ramps that shield the cable trays on the exterior of the ET
  - MSFC performing shuttle stack simulations with overflow to generate flight environments
  - CFD predicted flight environment used to design ground tests of potential redesigns
  - CFD also used to understand results from ground tests
  - In this and other Shuttle RTF activities there has been excellent cooperation in the CFD arena between MSFC, JSC, ARC, and LaRC
  - Reed presentation

\[ \text{ET LOX PAL ramp} \]

\[ \text{AEDC ground test configuration} \]

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2D CFD analyses of cable tray and repress line at \( M = 0.70 \)
Flow field unsteady, vortex shedding

Possible solution involves addition of "fence" under the trailing edge of the cable tray to stabilize the flow

\[ \text{PAL ramp approximate height} \]

Complex, 3D local flow (flow in vicinity of the PAL ramps) make simulation in wind tunnel nearly impossible.
Shuttle Return to Flight - SRB support

- Boost separation motors ignition must occur over a very narrow time band in order to separate solid rocket motors from ET safely
  - Erratic behavior in ground test units traced to potential igniter grain cracking during ignition
  - Structural analysis using CFD results pinpointed failure mechanism
    - Lifting of the igniter band line due to excessive flow induced load
- Testing utilized to assess redesign concepts
  - CFD used to provide insight into flow induced loads
  - Several limitations in CFD code prevented delivery of quantitative results
    - CFD results used for relative comparisons

Orbiter fuel feedline liner cracking

- Orbiter fuel feedline liner cracking caused a grounding of the fleet approximately one year prior to Columbia mishap
- A second look after the mishap has led to re-opening of the investigation to assure that the flow liner will survive at least one mission in the event of an engine out abort
- CFD is being performed by MSFC, Rkdn, and Ames in support of the ground-test program
  - Goal of the testing is to provide data needed to reduce generous conservatism in life prediction tools
  - Simulations are being performed to support water flow testing, airflow testing, and LH2 testing
- CFD simulation that include cavitation is most useful
  - Cavitation model being added to Phantom
  - Craft to perform some cavitating simulations
Prior to returning to flight, NASA committed to having in place a discipline process for dealing with debris during a mission:

- All the shuttle elements are generating list of possible debris
- The potential for that debris to cause damage to the shuttle system is evaluated in a two parts process:
  - Debris transport and debris impact
  - Impact testing of key components is being used to determine what is the allowable debris

- CFD is being utilized heavily in the debris transport process
  - Overflow is used to calculate the flow field about the shuttle at specified flight conditions
  - The trajectory that a specific piece of debris will follow is then calculated using a decoupled code
    - As necessary, coupled 6-DOF simulations of debris and shuttle are performed

- JSC has responsibility for the "ascent" debris transport
- MSFC is responsible for the "on-pad" debris transport
- There is a strong incentive for utilizing the same codes at MSFC and at JSC.
There are several risks associated with performing the "on-pad" debris transport calculation:
- Risk that Overflow will not predict the on-pad flow fields
  - Flows dominated by plume induced aspiration
- Risk that the complex geometry of the launch pad/shuttle stack may make the grid generation impractical and/or lead to unacceptable solution run times
- West presentation

Current SSME LPOT has experienced cracking of the 1st stage nozzle:
- Caused by coupling between vortices shedding and structural mode
- After extended test time exposure

The project has requested that potential redesigns that eliminate the potential for nozzle failure be developed.
- MSFC has supported Rocketdyne and Ames with CFD analyses of the baseline design and potential redesigns
- Dorney/Marku presentation
Concluding Remarks

- TD64 focused on supporting the space transportation programs
  - Shuttle return to flight
  - Applying capabilities/technologies to Office of Exploration System needs
- Design and analysis tools being applied and/or under development in the major hardware areas
  - Turbines, pumps, combustion devices, engine systems, propulsion-to-airframe integration, and MDA capabilities continuously being improved
- Increasing the design process efficiency and fidelity is paramount
- Code validation, robustness, reliability key to meeting CFD's promise
- Achieving goals depends on our ability to get maximum return on research investments