Orion CFD Analysis

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Outline

- **CEV (Orion) Aeroscience Project (CAP) Computational overview**
- **Challenges/issues in Orion CFD analysis**
  - Crew Module (CM)
  - Launch Abort Vehicle (LAV)
- **Final thoughts**

CAP Computational Overview

Initial Orion planning was to develop the aero/aerothermal databases using only CFD to reduce costs.

- CAP believes WTT is needed to compliment CFD analysis, and has developed the databases using CFD and testing.
- First cut estimate of planned CFD analysis required ~11 million cpu-hrs
  - Case matrix not intended to cover more than one iteration of the database (frozen design).
  - CAP lacked full understanding of the complexity of the LAV parameter space
  - Estimate was success oriented based on original design similarity to Apollo
- To date, CAP has used ~28 million cpu-hrs – 11 for aerothermal, ~17 aero
  - Orion design has changed/evolved several iterations (not unexpected)
    - Multiple OML changes/re-designs, LAV motor changes, etc.
  - Computational grids required for accurate modeling are larger than original estimates.
  - Several analyses have required case duplication to assess sensitivity to modeling limitations.
  - \+ Current database has large WTT contribution.
    - CFD derived WTT-to-flight corrections for several database segments.

Completed work has focused on Launch Abort Vehicle (LAV) characterization for ascent-abort flight tests.

Current work is focused on analysis supporting EFT-1 – mostly detailed Crew Module (CM) aerodynamics, RCS effects, ...

Orion Aero CFD Challenges/Issues

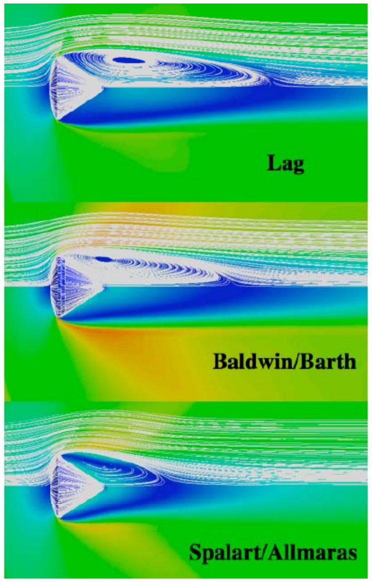
CFD for configurations with separated flows and/or shear layers that drive aerodynamics is not at “database production” maturity level.

- Separation/shear layer flows have been responsible for the vast majority of the issues CAP has encountered.
  - **CM entry** – bluff body separated flow prediction influences subsonic drag and pitching moment.
    - CFD predicted drag at subsonic conditions was lower than WTT – resulting uncertainty drove parachute deploy conditions to be more severe.
  - **CM forward bay cover jettison** – 2 body separation aerodynamics within the CM wake flow.
    - Jettison system performance is insufficient to tolerate current (necessarily) large aero uncertainty in combination with other system dispersions.
    - Defining this highly dynamic aerodynamic environment is challenging.
  - **Jet interactions** (ACM, AM/ACM, AM, CM RCS, LAT jettison)
    - Orion’s LAV configuration and high abort dynamic pressure result in highly non-linear aero with large sensitivity to small plume changes.
    - Plumes are sensitive to the turbulence/shear layer modeling (esp. when inclined to the flow).
    - Shear layer physics differ between cold gas WTT and flight plumes.
    - Turbulence models tuned for shear layers may not perform well for wall bounded flows and vice versa.

CM CFD issues

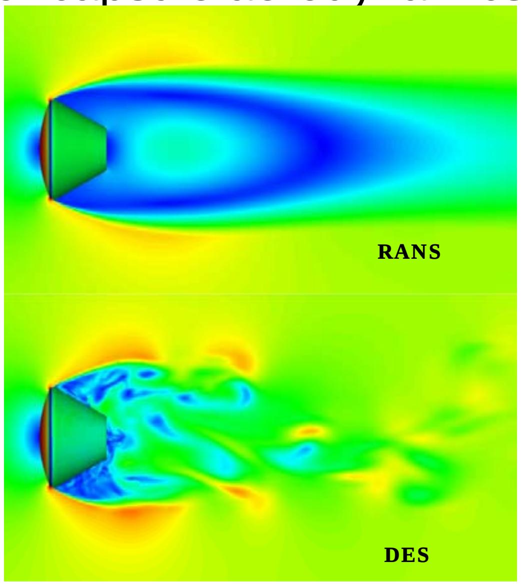
Turbulence modeling for bluff bodies/wake flows

- Available tubulence models are generally tuned for wall-bounded flows.
- CFD analysis of Apollo config during Phase 1 showed large variations of aerodynamics with different turbulence models.
- Apollo WTT data also showed a considerable spread depending on facility/Re#
  - Lead to difficulty in determining the best performing turbulence model(s).
- "Best practices" development effort evaluated turbulence/grid resolution/numerical schemes for capsule aerodynamics.



Img : Neal Chaderjian

- Turbulence models predict widely different wake structures. Lag & Baldwin-Barth predicts long "long/thin" wakes – SA predicts "short/fat" wake and higher drag.
- Performance varied with AOA/Mach
- SST selected as best performer overall.



Img : Scott Murman

- RANS solutions tend to predict large scale coherent steady vortex structure near 180 deg alpha.
- DES has completely different wake structure, but integrated aerodynamic coefficients (time-averaged) tend to be relatively close, while wake environments (FBC or parachutes) are not.

CM CFD recommendations

Grid :

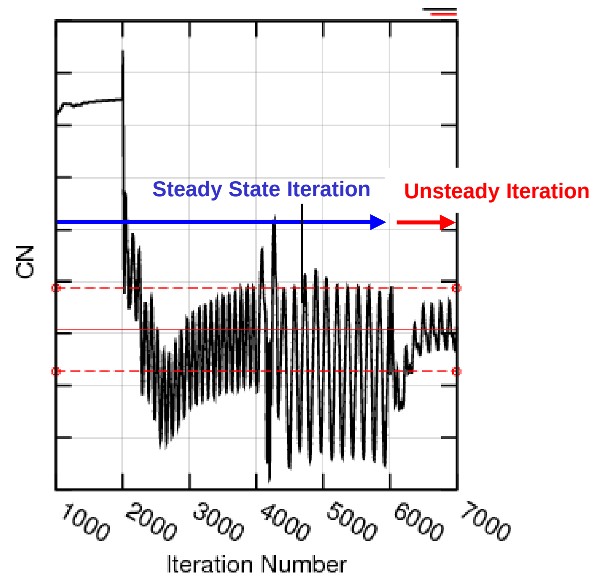
- Ensure grid convergence when performing sensitivity analyses.
  - Models have differing density requirements. To avoid polluting sensitivity analysis results, each model must be grid converged.
- Drive grid refinement to an insignificant component of overall modeling error.
  - Grid refinement error is one that can be readily reduced.
- Ensure refined grid regions needed for flow physics capture fully encompass the feature.
  - For example, wake refinement region must be large enough to prevent prediction of premature wake closure which will affect vehicle drag.

"Respect the physics"

- Avoid attempting to drive unsteady problems to steady-state for example.
- Solvers typically do not converge and aero is inaccurate.

Watch out for (code specific?) numerical issues

- i.e. strain based turbulence production can generate μ_t at shocks and effect boundary layer and shoulder flow/wake behavior.

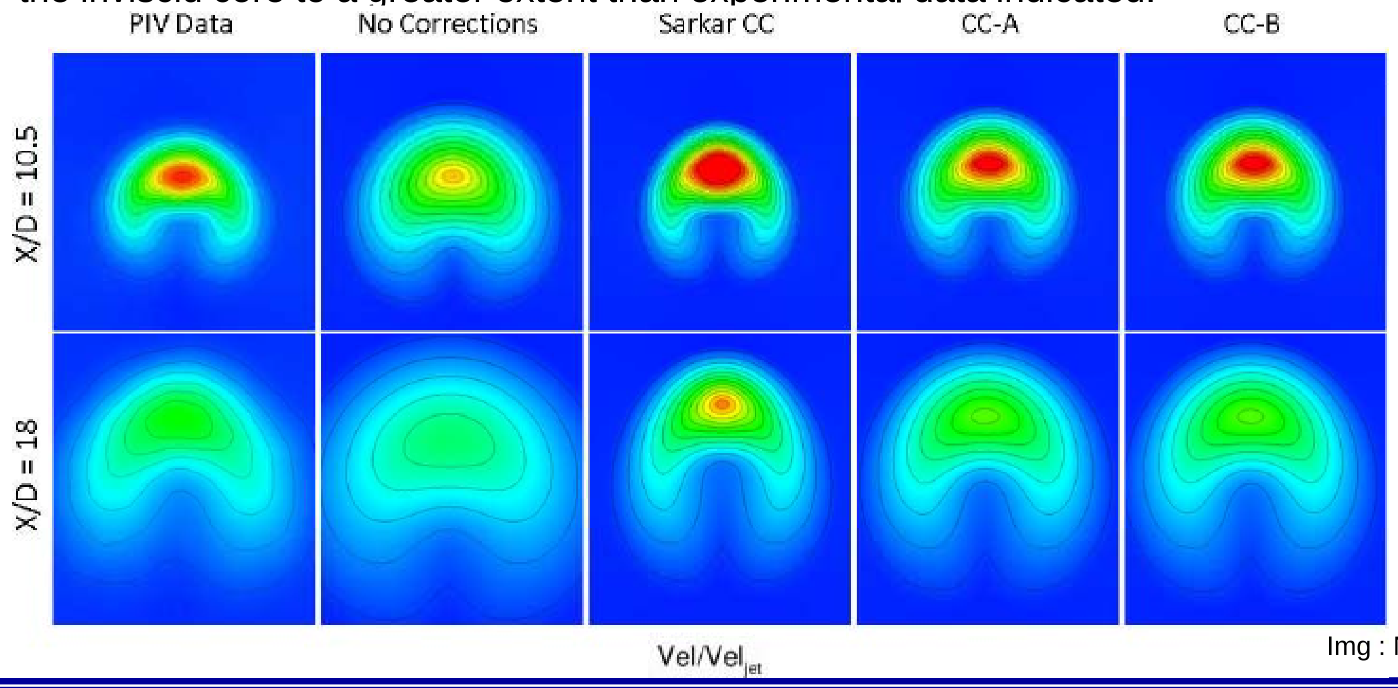


Img : Darby Vicker

LAV/Plume issues

Orion is perhaps uniquely sensitive to plume modeling, but some lessons are general.

- Turbulence modeling has been the largest driver in CFD error for plume simulations.
  - Compressibility correction was widely regarded as necessary for our high exit Mach plumes, yet correlation with WTT data did not improve it's use.
  - Corrections tuned to an axial jets did not perform well for our inclined jet.
    - Performance varied with alpha/Mach, but standard Sarkar corrections tended to preserve the inviscid core to a greater extent than experimental data indicated.



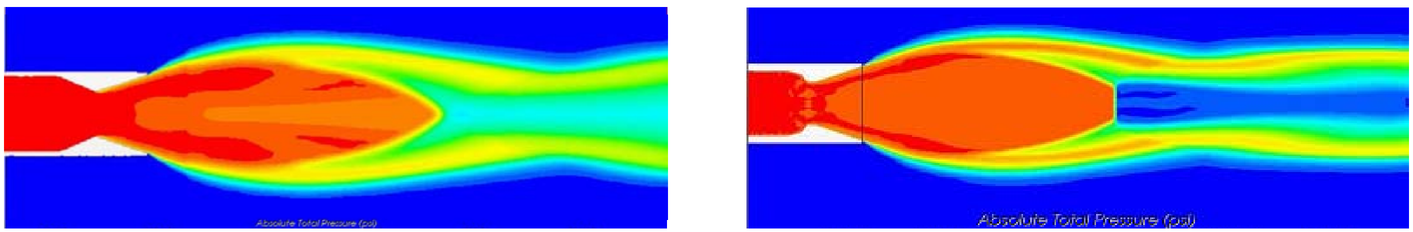
Img : Nico Gross

LAV/Plume issues (cont)

Survey of available turbulence models showed best match to experiment using SST.

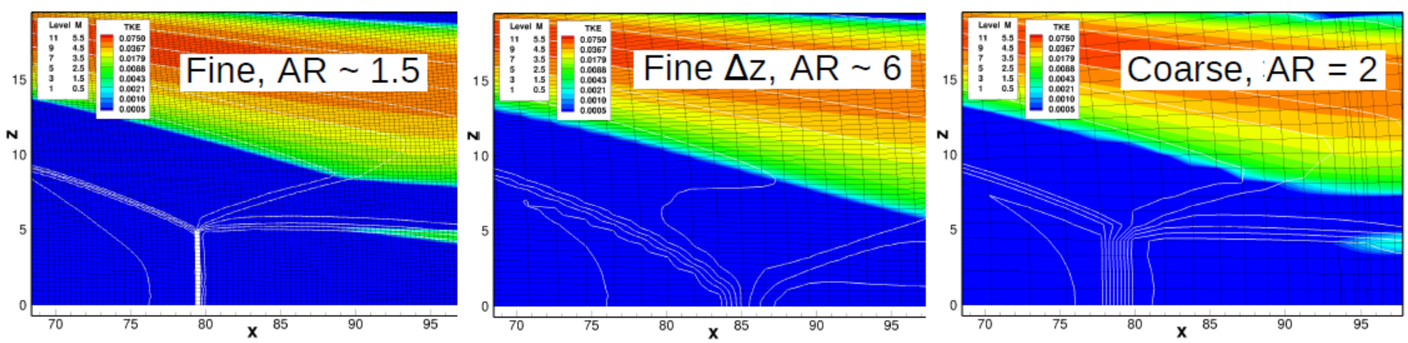
Some conditions match well, others show poor experimental match

- In some of these cases – Schlieren imagery from testing shows a mach disk where the CFD did not which drives plume shape.
  - Small changes in plenum geometry affect Mach disk formation



Img : John Melton/ Robert Childs

  - Mach disk prediction is also influenced by several numerical aspects.
    - Flux scheme, dissipation.
    - Cell aspect ratio

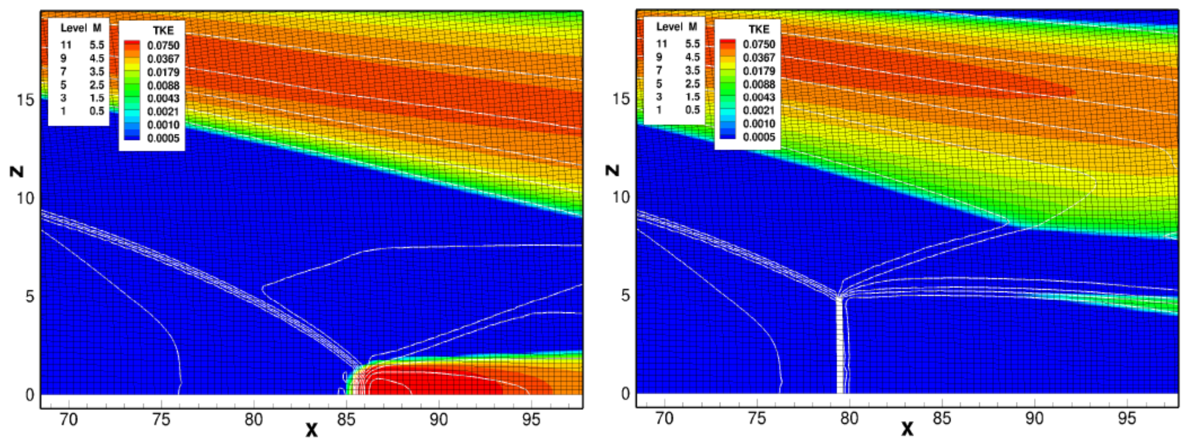


Img : Robert Childs

LAV Plume analysis

- Mach disk (cont)
  - Generally expect this to be an inviscid flow feature, however, sensitivity to turbulence modeling has been seen.
    - SST turbulence kinetic energy production based on strain produced large TKE values through strong shocks.

Standard – production based on strain   Based on diagonal-free strain



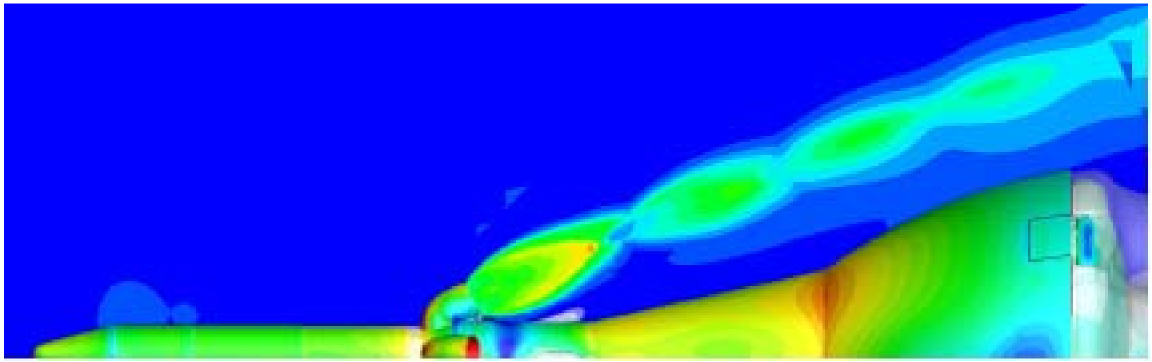
Img : Robert Childs

    - Tends to pull shock disk downstream and/or lead to prediction of no Mach disk.
    - Using high dissipation for solution startup may lock soln into a prediction of no Mach disk

- Plume edge mixing/turbulence seen in full scale tests is not replicated in CFD
  - CFD plume spreading rate is lower in some cases
  - still investigating…

Plume shear layer detail

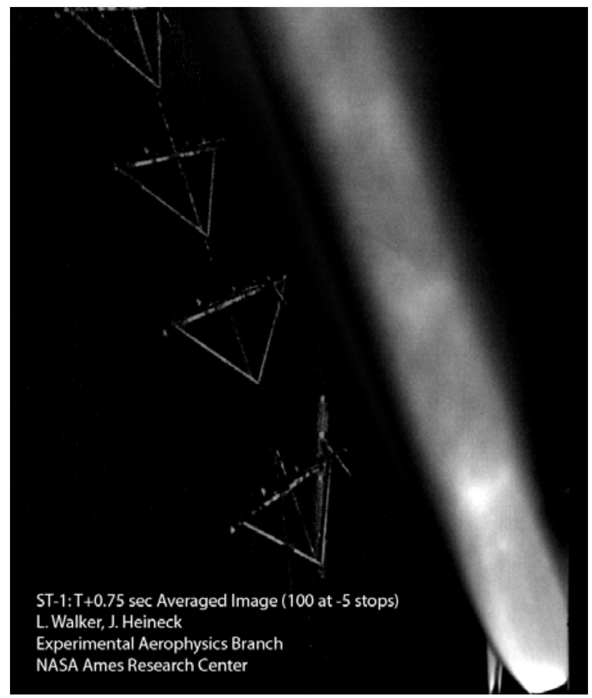
CFD



ST-1 Experiment

50 μs exposure

100 frame average = 5ms exposure



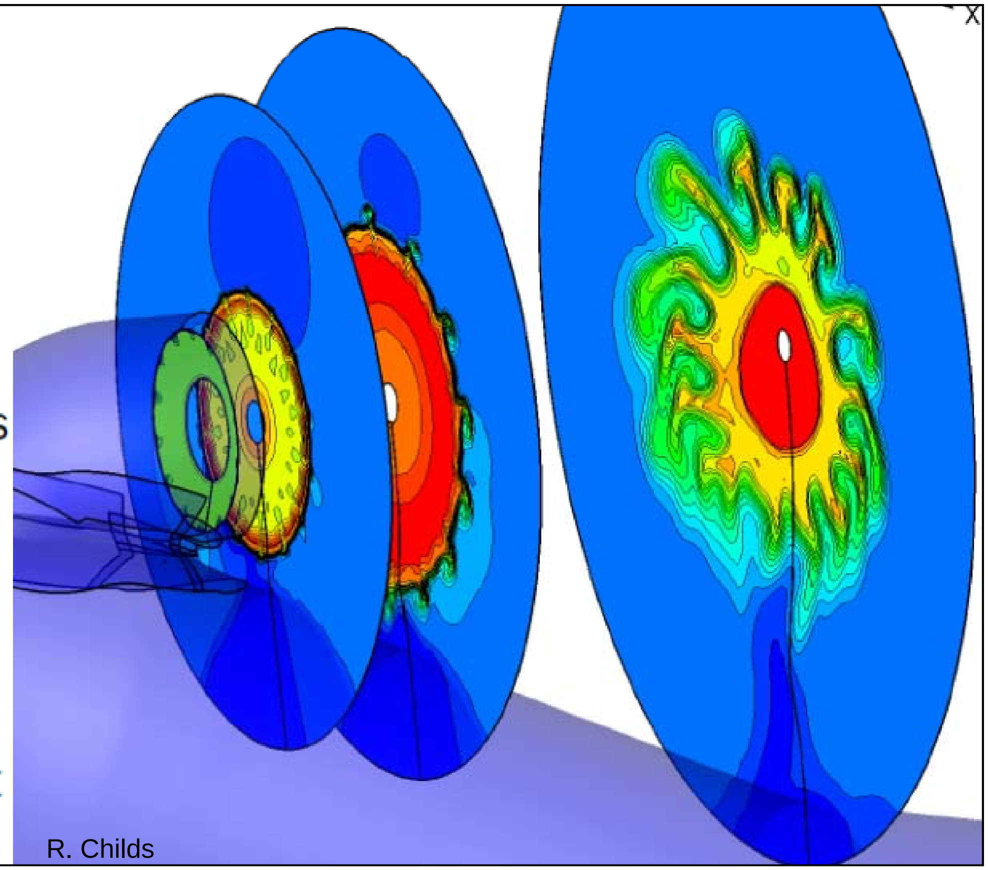
CFD and ST-1 not at same conditions

Shear layer modeling

Orion is sensitive to plume spreading rate and shear layer prediction

- OML/plume configuration places the plume boundary very near to the vehicle at the aft edge, causing large changes as plumes shift with flow conditions, thrust levels, or plume modeling differences.
- Path to fully modeling all aspects of this is not clear – likely expensive regardless…
- Investigated high resolution grid with vorticity seeding

• Streamwise vortices spawn low-speed streaks akin to boundary layer streaks
• Streaks trigger external Görtler vortices
• Physics of turbulence amplification seen, but far downstream



Final Thoughts

From an aerodynamicist's perspective, the issues we have faced and are still facing are interesting problems to work on.

- However, few of us are paid to conduct science experiments/basic physics research.

Our goal is to provide the highest quality environments possible within the available resources.

- Database accuracy needs depend on the system's robustness.

Need for aerodynamics typically leads ability to produce it

- Configuration still in flux, etc.
- Use lower fidelity tools for preliminary data with care/caution
  - Accuracy of tools can be highly configuration dependent and require skill/experience to obtain good results

Good CFD results require a skilled operator

- Fluids/aero experience with knowledge of the numerical models is ideal.

Large compute power does not eliminate the need for quality control of each solution

Use of multiple sources of data to cross-validate is important

- multiple codes, with high quality WTT data preferred
- Need increases for analysis outside of the core experience.

Avoid designs that cannot be analyzed

- Includes designs possible to characterize, but not within budget constraints.

References

[Turbulence Model Assessment for Hot Plumes (Invited)]

Andrea Shestopalov Science and Technology Corporation, Mountain View, CA, UNITED STATES; Robert Childs Science and Technology Corporation, Mountain View, CA, UNITED STATES; John Melton NASA Ames Research Center, Moffett Field, CA, UNITED STATES
AIAA-2011-3340
29th AIAA Applied Aerodynamics Conference, Honolulu, Hawaii, June 27-30, 2011

[Overflow Simulation Guidelines for Orion Launch Abort Vehicle Aerodynamic Analyses (Invited)]

Robert Childs Science and Technology Corporation, Hampton, VA; Joseph Garcia NASA Ames Research Center, Moffett Field, CA; John Melton NASA Ames Research Center, Moffett Field, CA; Stuart Rogers NASA Ames Research Center, Moffett Field, CA; Andrea Shestopolov Science and Technology Corporation, Hampton, VA; Darby Vicker NASA Johnson Space Center, Houston, TX
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