CAST: CERN Axion Solar Telescope

$^3$He Gas System CFD simulations

2. Problem Description.
3. Results.
4. Model Revision.
   - Validation
5. Summary.

CFD team supports CERN development
19 May 2011
Technical specifications: Gas System

CAST: detects solar axions → LHC Magnet Magnetic field: Conversion from axions into X-Rays occurs in closed volume filled with $^3$He gas at low T (~1.8K) and low P (~10-100 mbar)

• Parts outside cryostat receive heat from environment → $^3$He gas heats up: convective flow.

REQUIREMENTS: uniform density field along CB’s (Effective measure length)

TARGETS:

- Provide $^3$He density plots in CB’s.
- Verify validity of existing CFD studies.
- Study model’s movement: tilting and rotation.
Problem description: characteristics

- **Boundary conditions (BC’s) not known everywhere in the volume.**
- **Uncertainty** of sensors

- Gas density **NOT ACTUALLY MEASURABLE**
- Lack of experimental data

**Assumptions**

- Choice of BC’s determine the accuracy of the computed solution compared to the real situation

**Expected phenomena:**

- Strong **buoyancy-driven flow** in CB ends: $T_{\text{windows}}$, $T_{\text{Metal}} > T^{3}\text{He}$.
- **Transitional regime.**

*Recirculation* ⬅️ **Gas is still Uniform density expected**
Problem description: gas physics

Reference \(^3\)He conditions:
- \(P_{\text{Ref}} < 140\) mbar
- Static \(T_{\text{\(^3\)He}} \sim 1.8\) K

\(P, T\) far from Ideal Gas range of applicability.

Real Gas vs. Ideal Gas: eq. of state
- Virial Equation (physical description)
- Peng-Robinson.
- Van der Waals Model.

Comparing the four gas models.

Drift between Van der Waals model (red) and experimental data (blue)
Problem description: gas physics

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Real Gas vs. Ideal Gas: eq. of state

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<1% drift between them.

Included in Star CCM+

Comparing the four gas models.

Drift between Van der Waals model (red) and experimental data (blue)
**Problem description: pre-processing**

**Geometry:**
- **CB’s (Pipes)**
- **MRB Side:**
- **MFB Side:**
- **Total length:** 10554 mm
- **Ø 43 mm**
- **CB’s + Sleeves:** 10252 mm

**Boundary Conditions:**
- **Windows:** MRB = 11.16 K; MFB = 17.77 K
- **CB’s (pipes):** T = 1.74 K

- **Metal thicknesses:** MRB: 4.00 K; MFB: 6.00 K

➤ **As a first approach** to the problem
➤ **Check validity of previous CFD studies**
➤ **Achieve a solution** for further simulations.

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Problem description: pre-processing

**Physics:**
- Material properties = \( f(T) \)
- **Steady-state.**
- SST – K-omega turbulence model.
  - Low-Re approach
- Gravity (Natural Convection).
- **Coupled Solver.**
- Boundary layer solved (no wall functions applied).

**Mesh:**
- Polyhedral mesh in both ends.
- CB’s: cylindrical extrusion.
- Windows and metal thicknesses: extrusion
- Prism layer mesh near walls in fluid domain:
  - 16-20 layers, 1,2 stretching factor.

➤ **Number of cells: 6.6M**
**Results: density field**

**67 mbar 0 deg (Horizontal)**

<table>
<thead>
<tr>
<th>X (m)</th>
<th>Place</th>
<th>CB section ρ</th>
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<tbody>
<tr>
<td>10.362</td>
<td>CB end MFB</td>
<td>1</td>
</tr>
<tr>
<td>8.362</td>
<td>CB @2m from MFB</td>
<td>2</td>
</tr>
<tr>
<td>5.262</td>
<td>CB Center</td>
<td>3</td>
</tr>
<tr>
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</tr>
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**Density in the centre of CB’s:** 1.55 kg/m$^3$

➤ *(P$_{ref}$ = 83 mbar): 1.94 kg/m$^3$*
Results: validation

**AXIAL DENSITY distribution**

Desired \( \rho \) homogeneity: \( \Delta \rho = 10^{-3} \text{ kg/m}^3 \)

![Graph showing density distribution along the CB axis](image)

**MASS VALIDATION**

| Ref P  | L where < \( \Delta \rho \) (m) | L(eff) (m) | |L| (m) |
|--------|---------------------------------|------------|----------|
| 67 mbar| 5.23                            | 6.87       | 1.64     |
| 83 mbar| 4.81                            | 6.67       | 1.86     |

\( L_{\text{eff}}(\text{cm}) = 778.6 - 1.33 \times P_{\text{dV}}@18K \)

Length where \( \Delta \rho = 10^{-3} \text{ kg/m}^3 \) SHORTER than expected using CAST’s \( L_{\text{eff}} \) formula.

**SOLUTION VALIDITY:**

- \( N \) (mols) experimentally measured vs. CFD value.
- Error < 3% for both reference Pressures
  - ACCURATE SOLUTION
Model Revision

• WHY?
  ➢ Converged solution ≠ Accurate solution (depends on how the problem is defined)

• CONSIDERED MODEL REVISIONS:
  1. Check **Geometry & Boundary conditions**
     ❖ Phenomena in real experiment:
     - Conduction along the pipe
     - Conduction from magnets supports
     - Window
     - **$^3$He fluid**
     - Radiation from vacuum chamber walls @293K (Negligible)
     - Strongback Net

  2. Apply **SYMMETRY?**
     ❖ Symmetric BC’s & symmetry observed in previous simulations
     ❖ Slow rotation (0.3 deg/min) → Does not affect the gas (CHECKED)

Applied BC’s:
- **T inlet**
- **T CB**
- **T Window**
- **Cryo @1.8 K**
- **Save computation time**
Model revision: boundary conditions

- Computed solution = f(BC’s): values and locations.
  - Same numbers, different assumptions → DIFFERENT SOLUTION

- MESH:
  - Added metal Nets + coupling with Window foils
  - Improved where needed
  - Number of cells: 6.85 M (~ N_{cells} 1^{st} approach)

- Av. Running speed: 30s/it. @Cluster, NP: 32 for ~8300 its.
Results: density field

83 mbar  
0 deg  
(Horizontal)

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Section along right CB (scaled in axial direction 1:30)

Density in the centre of CB’s: 1.86 kg/m³

Transversal Section in MRB volume.

DIFFERENT!

Previous model @83 mbar: 1.94 kg/m³
Results: validation

- **DENSITY FIELD: SAME TREND**
  - $\rho_{\text{CB centre}}$ is different from first model!

- **SOLUTION VALIDITY: OK!**
  - $N$ (mols) experimental vs. CFD
  - Error < 0.7% (FIRST MODEL < 3%) → Closer to real situation

**SUMMARY**

- Better comprehension on the problem → Realistic approach to real system.
- **NEXT** → Perform requested steady simulations for tilted positions of the system (-6 to +6 deg).
- Continuous improvement and revision on the model.
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THANK YOU FOR YOUR ATTENTION!