One Dimensional Analysis Model of a Condensing Spray Chamber Including Rocket Exhaust Using SINDA/FLUINT and CEA

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Facility and Exhaust System Description

- Constructed in the 1960s, primarily to support the Centaur upper stage development
- Provides the facilities to simulate a space thermal soak and subsequent altitude firing of an engine propulsion system

Figure 1: Aerial View of Spacecraft Propulsion Research Facility (B-2)
• The facility is sized for hydrogen-oxygen engines up to 445 kN (100,000 lbf) thrust

• Thermal simulation is provided on the cold end by a liquid nitrogen cold wall.

• Engine exhaust products enter a spray chamber which cools and condenses the exhaust through 224,000 gpm of spray water.

• To maintain vacuum conditions during engine firing, there is a steam ejector system to transport the remaining exhaust products (hydrogen) to the atmosphere.

• Spray chamber should not exceed about 1.1 psi.
Executive Summary

• CFD codes:
  – Time consuming (particle tracking)
  – Inaccurate (can’t do condensation very well with noncondensibles)
  – Too cumbersome to model integrated system (wall heat transfer, ejecter pumping system)
  – Don’t take into account droplet conduction – WHY!

• It is hypothesized that given the droplet sizes (on the order of 1500 microns and greater), droplet velocities (on the order of 37 m/s), and size of the spray chamber, that the water droplets may not be fully utilized.
Executive Summary

- The goals of the analysis tool:
  - Transient one dimensional flow and heat transfer
  - **ALL INCLUSIVE**
    - Rocket combustion
    - Rocket duct flow with wall heat transfer
    - Rocket shock and quench,
    - Condensing spray chamber
    - Ejector pumping system
  - Include droplet conduction
  - Include degrading effects of mass and heat transfer due to the presence of noncondensibles
  - Make no presupposition on the condensation efficiency of the spray chamber
  - Compare results to the RL-10 engine pressure test data.
Facility and Exhaust System Description

Figure 2: B2 Facility

- Vacuum Chamber
- Rocket
- Spray Chamber Exhaust to Ejectors
- Spray Bars
- Exhaust Duct
- Water Line
- Rocket Exhaust
- Water Pool

Water Level: 67-74 ft
Ullage Length: 45.6 ft
Figure 3: Condensing Spray System
Facility and Exhaust System Description

Figure 4: Condensing Spray System with Ejectors
Facility and Exhaust System Description

- **CEA (SINDA/FLUINT Subroutine)**
  - Rocket Combustion
  - Rocket Exhaust: Shock & Quench

- **SINDA/FLUINT**
  - Duct Flow (Supersonic!!!!)
  - Duct Wall Heat Transfer
  - Spray Chamber
  - Ejector Pump System
  - Fortran Coding of Droplet Tracking
  - Droplet Conduction

S/F: SINDA/FLUINT
CEA: Chemical Equilibrium with Applications
CEA, Chemical Equilibrium with Applications, is a NASA developed code that calculates mixture chemical equilibrium compositions and properties. The source code is written in ANSI standard FORTRAN, and is appended as a subroutine to the SINDA/FLUINT model of the B2 facility.

- CEA is run as an enthalpy/pressure case (input O/F, area ratios)
- CEA calculates mass flow rate, temperature and pressure (input to S/F)
- CEA is also used to determine duct flow stagnation properties

CEA determines post shock conditions
CEA determines quenched conditions exhaust after shock

Warning: enthalpy and entropy reference states differ between CEA and S/F!!!
Figure 5: SINDA/FLUINT Submodel “A” of Rocket Exhaust Duct
**SINDA/FLUINT Model Setup**

**Figure 6:** SINDA/FLUINT Submodel “B” of Spray Chamber

**Figure 7:** SINDA/FLUINT Submodel “C” of Thermal Conduction in Droplet

**Eq. 1**

\[ G_n = 4\pi k_d \frac{r_n r_{n-1}}{r_{n-1} - r_{n-1}} \]  

Droplet Conductor

Rocket Flow after Shock and Quench

Eq. 1

Condensing Spray Flow Inlet
(User FORTRAN for Particle Dynamics)

Spray Chamber Exhaust (Ejector Pump Curve)

"pancakes"

Water Line
• The rocket exhaust duct flow or duct entrance flow is supersonic (Mach = 6 to 7)

• **Five** significant issues need to be addressed:
  – **First**, a FLUINT set mass flow rate connector (MFRSET), is placed at the duct exit.
  – **Second**, all choking calculations must be turned off in FLUINT.
  – **Third**, set IPDC=0 for the FLUINT connectors, i.e., duct friction calculations are supplied by the user.

• FLUINT does not evaluate fluid properties at a reference temperature in calculating friction factors:

\[
\text{Eq. 2} \hspace{1cm} T_{\text{ref}} = 0.5(T_{\text{wall}} + T_{\text{fluid}}) + 0.22(T_{\text{rec}} - T_{\text{stat}})
\]

\[
\text{Eq. 3} \hspace{1cm} T_{\text{rec}} = Pr^{\frac{1}{3}} (T_{\text{stag}} - T_{\text{stat}}) + T_{\text{stat}}
\]
SINDA/FLUINT Supersonic Flow Modelling

• Set $FC$ as positive (usually negative), $FPOW = 1$:

SINDA/FLUINT Momentum Equation

\[
\frac{dFR_k}{dt} = \frac{AF_k}{TLEN_k} \left( PL_{up} - PL_{down} + HC_k + FC_k \cdot FR_k \cdot |FR|_k^{FPOW_k} + AC_k \cdot FR_k^2 - \frac{FK_k \cdot FR_k \cdot |FR|_k}{2 \cdot \rho_{up} \cdot AF_k^2} \right)
\]

Eq. 5

\[ FC = \frac{F}{2Ac_D^2 \rho} \]

Eq. 6

\[ F = 0.184 \cdot Re^{-0.2} \cdot \frac{L_D}{D_D} \]
– **Fourth**, supply a turbulent heat transfer coefficient is calculated with fluid properties evaluated at $T_{\text{ref}}$ using the Colburn Analogy:

$$h_D = 0.23 \Re^{0.8} \Pr^{1/3} \frac{k}{D_D}$$
– **Fifth**, check velocity limit on the kinetic energy term in the total enthalpy energy equation

• The FLUINT maximum velocity constraint in this analysis was 3000 m/s (SINDA/FLUINT version 5.3). **This constraint did not allow for the conservation of total enthalpy for adiabatic flow.**

• **Cannot necessary change to as high as you want!!!** (3700 m/s max)

• To “conserve” total enthalpy impose heat rates on fluid lumps representing the duct flow:
  – the “pseudo” kinetic energy term that’s missing because of the velocity limit.
Fig 10: SINDA/FLUINT Submodel “B” of Spray Chamber

- Massless
- Uses pump map
- Uses species specific suction

- Ejectors
  - Massless
  - Maintain constant pressure

Tanks 2001 through 2005 represent the stratified B2 spray chamber ullage.
**SINDA/FLUINT Model Details of Spray Chamber**

**Figure 11: SINDA/FLUINT Lump Detail**

- **MFRSET**
  - Tank 2001
  - May contain additional vapor formed from the quench cooling water on the duct

- **Droplet Saturated Liquid**
  - for bookkeeping purposes

- **MFRSET**
  - (for bookkeeping purposes only)

- **MFRSET**

- **Plenum 11001**
  - Condensation

- **Plenum 12001**
  - Evaporation

- **Plenum 1001**
  - Condensation
  - Evaporation
SINDA/FLUINT Model Details of Spray Chamber

Droplets

Droplet Movement:
- FORTRAN coded droplet tracking
- Individual droplets are not tracked
- Characteristic droplet per “pancake”
- Time averaged value of velocity and temperature distribution must be determined for each “pancake”
- Droplets only move downwards

\[ V_{rel} = V_d + V_\infty \]
\[ V_d = \text{Droplet Velocity} \]
\[ V_\infty = \text{Flow Upward} \]

Figure 12: Characteristic Droplet in SINDA/FLUINT Stratified Lump or “Pancake”
• Flooding or Floating!
  – If there is a net upward force – droplets go into a “holding” pattern in their “pancake”
  – Droplets do not experience flow reversal – too complex
  – Droplets from a “pancake” above with a net downward force can still enter
  – If the net force becomes downward again – all droplets travel enmasse to the “pancake” below
Droplet Heat Transfer with Noncondensables:

- During condensation, the noncondensable accumulates at the surface (its partial pressure increases).
- This diffusion barrier:
  - decreases mass transfer of water vapor
  - reduces the saturation temperature at which condensation occurs

\[
\text{Nu} = 2.0 + 0.6 \text{Re}^{0.5} \text{Pr}^{0.33}
\]
• **SINDA/FLUINT SUBROUTINE HTUDIF:**
  
  – returns, $h_{\text{eff}}$, the effective condensation heat transfer coefficient, including the effect of the noncondensible
  
  – Requires the uncorrected film condensation heat transfer coefficient AND the convection heat transfer coefficient
  
  – Can calculate the interface temperature (corrected saturation temperature of droplet)
  
  – uses the Chilton-Coulburn analogy:

  $\frac{h_{\text{conv}}}{m_w} \left( \frac{\rho_{w\infty} - \rho_{wi}}{\rho_{w\infty}} \right) = \frac{p_{\text{tot}}}{p_{\infty}} \rho_{\infty} \left( \frac{\rho_{hi}}{\rho_{h\infty}} \right) \left[ \ln \left( \frac{\rho_{hi}}{\rho_{h\infty}} \right) \right]^{-1} \left[ \rho_{\infty} C_{p\infty} \left( \frac{k_{\infty}}{D_{wh}} \right)^2 \right]^{1/3}$

  Eq. 8
Validation Cases

- Model results were compared to Delta III upper stage hot fire tests that were run in the B2 facility.
- In all the cases presented below the droplets leaving the spray bar were 1500 microns in size and had an initial velocity 37 ft/sec.
Validation Cases

### Figure 14: Summary Table of Delta III Upper Stage Hot Fire Tests

<table>
<thead>
<tr>
<th>Condition</th>
<th>HOT FIRE 3</th>
<th>HOT FIRE 6</th>
<th>HOT FIRE 8</th>
<th>HOT FIRE 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condensing Spray Conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inlet Condensing Spray Temperature (deg F)*</td>
<td>50.6</td>
<td>51.5</td>
<td>55.99</td>
<td>64.2</td>
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<tr>
<td></td>
<td>13878</td>
<td>13878</td>
<td>13878</td>
<td>13878</td>
</tr>
<tr>
<td>Inlet Condensing Spray Flow Rate (kg/sec)</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Level (ft)</td>
<td>67.8</td>
<td>73.8</td>
<td>73.6</td>
<td>64.5</td>
</tr>
<tr>
<td>Ullage Length (ft)</td>
<td>45.65</td>
<td>45.65</td>
<td>45.65</td>
<td>45.65</td>
</tr>
<tr>
<td>Rocket Conditions</td>
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<tr>
<td>Rocket Exit Area (in²)</td>
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<td>1500</td>
<td>1500</td>
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</tr>
<tr>
<td>Rocket Area Ratio</td>
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<td>77</td>
<td>77</td>
<td>77</td>
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<tr>
<td>Rocket O/F Ratio</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Rocket Combustion Pressure (psi)</td>
<td>640</td>
<td>640</td>
<td>640</td>
<td>640</td>
</tr>
</tbody>
</table>

*For spray bar temperature rise due to engine heat exhaust or ejector heat output this was only an initial condition.
Figure 15: Spray Chamber Pressure: Hotfire Test 3 and SINDA/FLUINT Model Results

Spray bar temperature rise from the heat of the engine exhaust
Figure 16: Spray Chamber Pressure: Hotfire Test 6 and SINDA/FLUINT Model Results

Spray bar temperature rise from the heat of the engine exhaust
Figure 17: Spray Chamber Pressure: Hotfire Test 8 and SINDA/FLUINT Model Results

Spray bar temperature rise from the heat of the engine exhaust
Figure 18: Spray Chamber Pressure: Hotfire Test 10 and SINDA/FLUINT Model Results

Spray bar temperature rise from the heat of the engine exhaust
Candidate test article larger than the previously conducted engine tests.
Two point engine test sequence lasting for 700 seconds.
Droplets 1500 microns with an initial velocity 37 ft/sec
Assumed spray bar water temperature rose due to the effect of engine exhaust heat.

![Figure 19: Summary Table of Candidate Test Article](image)

*For spray bar temperature rise due to engine heat exhaust or ejector heat output this was only an initial condition.*
The exhaust system can support a 700 second duration engine firing.

Figure 20: Spray Chamber Pressure: Candidate Test Article and SINDA/FLUINT Model Results
Figure 22: Chamber Spray Temperature Rise: Candidate Test Article SINDA/FLUINT Model Results
Conclusions

- A “solid conduction” model of droplets that correspond to each of the time averaged characteristic droplets is important to capture the physics of a condensing spray chamber.
- The model can be useful in predicting exhaust system performance for various hydrogen-oxygen engine combinations and testing durations.
- Future engine testing at B-2 will provide opportunities to evaluate and refine the model.