Thermal Stratification Modeling Improvements for Isogrid-Lined Tanks

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Payloads requiring insertion into high altitude orbits are delivered using the upper stages of chemical rockets (ex., Delta and Atlas classes) normally employing cryogenic propellants. During the transfer period between orbits, the upper stage may coast for several hours during which time the thermodynamic state of the propellants may vary due to solar heating. At the conclusion of the coast phase, and in preparation for orbital insertion of the payload, the propellants must be within a narrowly defined range of temperature and pressure for the engine to resume operation. Buoyancy-driven thermal stratification of the propellant is one of the critical mechanisms taking place during this coast phase. Traditional stratification models are based on velocity and temperature correlations developed for flow along smooth vertical walls. In contrast, actual propellant tanks may have a mass-reducing Isogrid internal surface over which the velocity and temperature profiles differ significantly from smooth-wall correlations.

A preliminary study to investigate the impact of Isogrid on the boundary layer has shown that the thickness of the layer adjacent to the wall in a forced freestream flow is substantially thicker (150-700%) than the equivalent flat plate boundary layer thickness. Furthermore, the flow is highly turbulent with many recirculation zones suggesting that the classical idea of a boundary layer may not exist over such geometries.

I. Introduction

PREDICTION of the thermodynamic state of the cryogenic propellants in the upper stage of a launch vehicle is necessary for mission planning and successful execution. Solar heating during orbital transfers may thermally stratify the propellants prior to re-start of the engine. The thermodynamic state of the propellant may vary within the tank, and if the propellant drawn into the turbomachinery is outside a specified temperature and pressure bound the engine may not function. Therefore, it is critical to predict the propellant state at the conclusion of the coast period and a sufficiently detailed model of thermal stratification is essential1, 13, 19.

The Mission Analysis Branch of the Launch Services Program (LSP) at NASA Kennedy Space Center has the responsibility to ensure that the thermodynamic state of cryogenic propellants remain within a specified temperature and pressure boundary prior to engine re-start at the conclusion of orbital coast phases. Many cryogenic propellant tanks utilize an Isogrid inner tank wall for mass reduction and structural support, however, the effects of the Isogrid on the propellant thermodynamics are not known. Items such as propellant stratification and time required to achieve solid body rotation during thermal conditioning roll can be directly influenced by surface conditions. Whereas the flow behavior over various types of geometric and random roughness patterns have been thoroughly examined, no information exists in the open literature on velocity and temperature profiles over an Isogrid surface. An example of an Isogrid surface for the inner wall of a propellant tank is shown in Figure 1 and Figure 2.

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Some of the phenomena taking place inside the cryogenic propellant tanks during the coast period include a microgravity environment, incident solar heating, thermal conditioning (usually accomplished by spinning the spacecraft about its longitudinal axis), buoyancy induced recirculation, molecular diffusion between propellants and corresponding pressurants, boiling heat transfer, ullage gas venting, surface tension effects, and thermal conduction within the propellant and tank walls. Based on a review of current launch vehicles, a range of parameters was identified for this study, which are summarized in Table 1.

### Table 1: Summary of Parameter Ranges for Thermal Stratification Study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Range of Parametric Investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenic Propellants</td>
<td>LH₂, LOX</td>
</tr>
<tr>
<td>Ullage Pressure</td>
<td>140 &lt; P_u &lt; 280 kPa</td>
</tr>
<tr>
<td>Ullage Pressurants</td>
<td>Hydrogen Tank: GH₂</td>
</tr>
<tr>
<td></td>
<td>Oxygen Tank: GOX and He</td>
</tr>
<tr>
<td>Bulk Propellant Temperature, T_b</td>
<td>15 K ≤ T_b,LH₂ ≤ 20 K</td>
</tr>
<tr>
<td></td>
<td>90 K ≤ T_b,LOX ≤ 110 K</td>
</tr>
<tr>
<td>Driving Temperature Difference, θ_w</td>
<td>0.1 K ≤ θ_w ≤ 4 K</td>
</tr>
<tr>
<td>Driving Wall Heat Fluxes, q_w</td>
<td>5 ≤ q_w ≤ 100 W/m²</td>
</tr>
<tr>
<td>Reduced Gravity Ratio, η=g/g₀</td>
<td>10⁻² ≤ η ≤ 1</td>
</tr>
<tr>
<td>Spin Rate, ω</td>
<td>0.1%/s ≤ ω ≤ 10%/s</td>
</tr>
<tr>
<td>Tank Geometry</td>
<td>Square cylinder, L=2R</td>
</tr>
<tr>
<td></td>
<td>Cylindrical tank with flat or domed end-caps</td>
</tr>
<tr>
<td>Initial Tank Fill Height, H</td>
<td>10 % ≤ H ≤ 50 % of L</td>
</tr>
<tr>
<td>Coast Duration</td>
<td>1 – 4 Hours</td>
</tr>
</tbody>
</table>

A schematic representation of a typical Delta IV upper stage is shown in Figure 3. The upper 5 meter diameter tank contains liquid hydrogen and the lower 4 meter diameter tank contains liquid oxygen. Most relevant will be to predict the growth of the thermally stratified layer, Δt(1), and the temperature of this stratum layer, T_s, and the resulting impact on tank propellant temperature and pressure.
Boundary layer transition is marked by streamwise waves called Tollmien-Schlichting (T-S) waves and depends on the Reynolds number. Roughness effectively increases the Reynolds number which causes the waves to become unstable and thus cause vortices; the vortices burst and eject velocity which results in a turbulent boundary layer. Boundary layer comparisons between the top of the rib of the isogrid and the edge of the boundary layer ($u=0.99U_\infty$), as shown schematically in Figure 4 and Figure 5, were completed in a preliminary study. Examples of the types of flow phenomena that occur over sections of the isogrid surface are shown in Figure 5.

![Figure 4: Example of class boundary layer development over a smooth flat plate.](image1)

![Figure 5: Example of flow structures possible over isogrid surface and notation indicating top of rib as isogrid boundary layer reference datum.](image2)

It is unknown how the Isogrid surface will impact thermal stratification of the propellants. Because of the rough surface the boundary layer will be very thick and turbulent (increasing the mixing) thus entraining more fluid. Because of the presence of the Isogrid there will be more heated area which will cause increased heating. Its known for free convective flows on flat plates that at the same conditions, a laminar flow will have a larger max velocity but smaller boundary layer thicknesses; while turbulent flow will have a thicker boundary layer but a smaller max velocity. Its unclear if this is the case with the Isogrid, that is wither or not the Isogrid induces larger boundary layers which are slow moving with a larger heated area (as compared to the flat wall). If so the Isogrid would cause slower stratification but at warmer temperatures as compared to the flat wall.
II. Literature Review and Analytical Modeling

Accurate modeling of propellant thermal stratification requires an understanding of the mechanisms by which mass and energy are transported within the tank. The principal mechanism is buoyancy-induced natural convection which is initiated by solar heating of the tank walls. A boundary layer forms due to the lower density of the warm fluid along the inner walls of the tank. Mass is entrained into the boundary layer, heated, and transported to the upper region of the cold bulk fluid forming a thermally stratified layer. If this layer of fluid propagates to the entrance of the turbomachinery and is warmer that a specified value, the turbopump may not function and thus the engine may not restart. Additionally, the ullage pressure rise associated with a thermally stratified tank is greater than the pressure rise associated with the cryogenic fluid mixed at uniform temperature, leading to loss of propellant through venting, which is especially relevant for the self-pressurizing LH2.

A. Governing Non-Dimensional Numbers

The primary parameter used to classify flows of this type is the non-dimensional Rayleigh number, Ra, which is a product of the Grashof number, Gr (ratio of buoyancy to viscous forces), and Prandtl number, Pr (ratio of viscous to thermal diffusivity). Equation 1 gives the Rayleigh number for buoyancy driven flows with constant wall temperature, $T_w$.

\[ Ra = Gr \Pr = \frac{g \beta \theta_w x^3}{\nu^2} \frac{\kappa \mu c_p}{\nu} \]  

(1)

In this expression $\mu$ is the dynamic viscosity, $\nu$ is the kinematic viscosity, $c_p$ is the specific heat, $k$ is the thermal conductivity, $\beta$ is the liquid expansion coefficient, $g$ is the local acceleration, and $x$ is a vertical coordinate measured from the origin of the boundary layer. The temperature difference, $\theta_w$, is defined as the difference between the wall temperature, $T_w$, and the cold fluid bulk temperature, $T_b$. Typically the boundary layer will transition from laminar to turbulent around $Ra \approx 10^9$ and Eq. (1) may be used to solve for the transition distance, $x_{trans}$. Equation (2) gives a modified Rayleigh number, $Ra^*$, for buoyant flows driven by uniform heat flux.

\[ Ra^* = Gr^* \Pr = \frac{g \beta q^* x^4}{k \nu^2} \frac{\mu c_p}{\nu} \]  

(2)

The transition Rayleigh number for flows with uniform heat flux is around $Ra^* \approx 10^{11}$.

Figure 6 shows non-dimensional maps of $Ra$ and $Ra^*$ vs. reduced gravity ratio, $g/g_0$, for liquid hydrogen and liquid oxygen. The $Ra$ maps are shown for $\theta_w$ values of 0.1, 0.5 and 1 K, and the $Ra^*$ maps are shown for heat fluxes of 5 to 100 W/m². Each map shows $Ra$ and $Ra^*$ transition from laminar to turbulent at values of $10^9$ and $10^{11}$, respectively. The tank geometry utilized to generate the maps is a square cylinder with 3 m diameter, and a liquid fill level, H, of 20% of the tank height, or $H=60$ cm.
Figure 6 demonstrates that for typical values of heat flux experienced during orbital transfers and for the low gravity levels associated with the coast (< $10^{-4} \, g/g_0$) the tank boundary layers may be laminar. This is in contrast to propellant stratification situations that arise when the vehicle is on the launch pad where both Ra and Ra* are orders of magnitude above transition and the boundary layers are turbulent\textsuperscript{1}. The nature of the boundary layer is important in determining how quickly the fluid stratifies and what temperatures within the stratum are achieved.

The thermal stratification problem within a cryogenic propellant tank has been analyzed in numerous references\textsuperscript{1, 13, 14, 19}. The growth of the stratified layer is governed by the rate at which boundary layer mass flow crosses the datum between the stratum and the cold bulk fluid, which is shown in Error! Reference source not found., and is located at $H-\Delta(t)$ as measured from the bottom of the tank. The boundary layer mass flow is given by Eq. (3), where $\rho$ is the liquid density, $u(y)$ is the local vertical velocity profile in the boundary layer, and $\delta$ is the boundary layer thickness.

\[
\dot{m}_{bl} = 2\pi\rho \int_0^\delta u(y) dy \tag{3}
\]

The velocity and temperature profiles within a laminar and turbulent boundary layer can be found in ref. [7].

Since many propellant tanks are dominated by turbulent boundary layers, especially during take-off conditions, many models rely on the results of the turbulent free convection boundary layer at constant wall temperature as analyzed by Eckert\textsuperscript{5}. Assuming constant properties, Bailey\textsuperscript{2} applies an energy balance between the heat entering the tank below the stratum, $H-\Delta(t)$, to the heat exiting the top of the boundary layer at the stratum interface, which can be expressed as:

\[
q^*(H-\Delta) = h\theta_w (H-\Delta) = c_p \rho \int_0^\delta \theta(y) u(y) dy \tag{4}
\]
Combining Eq. (4) and Eq. (3) with the appropriate expressions for the boundary layer and recognizing that the heat transfer coefficient, \( h \), must be evaluated at the vertical location corresponding to the bottom of the stratum (\( H - \Delta(t) \)), which varies with time, yields an expression for the growth of the stratum layer, \( \Delta(t) \). The resulting equations assume that as soon as the mass flow exits the boundary layer it forms a uniform thickness disk of stratified fluid above the bulk. However, at low gravity levels this disk does not form quickly (may take hours), and the radial flow of warm fluid upon exiting the boundary layer into the stratum is not considered here.

To find the stratum temperature a second energy balance is applied in which the heat entering the fluid through the tank vertical walls, \( 2\pi RH \), goes into heating the stratum volume, \( \pi R^2 \Delta \). The energy balance can be written as in Eq. (5).

\[
q'' 2\pi RH = h\theta_w 2\pi RH = \rho \pi R^2 \Delta c_p \frac{d\theta_s}{dt}
\]

Also, in Eq. (5) the heat flux is rewritten in terms of a product of heat transfer coefficient and temperature difference, and it is assumed that this product is the same adjacent to both the bulk fluid and the stratum layer. Furthermore, Eq. (5) neglects any energy interaction with the ullage gas. Eq. (5) can be integrated to find the stratum temperature,

\[
T_s = (\theta_w + T_b) - \theta_w e^\left(-\frac{2Hht}{R\Delta c_p}\right)
\]

At this point, the framework for an analytical model has been developed. However experimental and computational efforts are needed to determine the boundary layer thicknesses and profiles associated with the Isogrid plate.

### III. Experimental and Computational Setup

Experiments were designed such to provide means of comparison to the CFD data. This included determining the mean velocity structure of the boundary layer using a pitot-static tube and a hotwire anemometer. The Florida Tech windtunnel was used to conduct these experiments. The experimental test section is 1.7 m in length, 0.54 m in width, and 0.54 m in height and capable of speeds up to 15 m/s.

The Isogrid geometry for the experiment had to be scaled in order to avoid wall effects from the test section. Furthermore, we wanted to have the ability to compare the data taken from the rough plate to that of a smooth plate. Therefore, we split the plate into two halves longitudinally; one half with a smooth surface and the other with the scaled Isogrid roughness (see Figure 7).
Since we will be using a pitot tube to survey the boundary layer, we need static pressure references at various locations on the plate. Static pressure ports were placed within every roughness element and at one lateral location on the smooth portion of the plate (see Figure 8).

Plate angles (both pitch and roll wise) can be controlled with the adjustable legs shown in figure 3. The plate assembly was designed slightly smaller than the test section width such that yaw orientation could be adjusted. All parts were machined from Al 6061-T6 plate and rod stock. The static pressure ports were made from stainless steel tubing and Tygon tubing.

Boundary layer profiles were taken using mostly a pitot-static tube setup (see Figure 9); some measurements were made using a single component hotwire anemometer. Traverse control and data collection is done using LabView; data reduction and processing is done in Matlab.

CFD studies were done using the commercial code Fluent. 3D geometries were constructed in PRO-E and imported into Gambit for meshing. Figure 10 is an overview of the boundary conditions used. The plate surface is modeled as wall (no slip) and the upper face is far enough away such to use a symmetry conditions (this was validated). The inflow face is set as a velocity inlet such that the freestream velocity and turbulence intensity can be set. Similarly, the outflow face is set as a pressure outlet. All domains have the plate stagnation point inside the
domain. Initial studies showed issues with the boundary layer growth having the corner of the domain as the stagnation point. Placing the stagnation point inside the domain removed this issue.

![Figure 10: Domain Boundary Conditions](image)

Initially 2D studies were performed by varying the roughness width and spacing such to model different planes along the length of the plate (See Figure 11:).

![Figure 11: Various 2D Isogrid-like cross sections](image)

This starting point helped determine the mesh sensitivity while minimizing computational resources. All 2D geometry used structured rectangular mesh (See Figure 12); mesh density was larger in the vicinity of the wall as typically done.
Later the 3D geometry was imported and meshed using Gambit.

The 3D geometry used unstructured tetrahedral mesh; again mesh density was large in the vicinity of the walls. 2D cases were done using the $\kappa$-$\omega$ and RSM (Reynolds Stress Model) viscous models. Mesh sensitivity for 2D cases was checked using backward facing step geometries. A cell spacing of 0.002 m was found to be suitable for prediction of streamline paths and touch down distances (see Figure 14).

3D cases were built up using Spalart-Allmaras and $\kappa$-$\omega$ such to perform mesh refinement. Once the mesh was refined, the RSM and LES (Large Eddy Simulation) models were used (with ~1.5 million cells).

### IV. Results

Comparison of experimental data taken on the flat plate with theory showed good agreement. Since the plate has a trip strip, the flow is for all practical purposes turbulent over the entire plate. The experimental data agrees well with the turbulent 1/$\gamma$th power curve (See Figure 15).
Though boundary layer profiles agreed well with theory, the values for boundary layer thickness were quite far off (See Figure 16). The slopes showed good agreement however which suggests that the conditioning at the front of the plate was poor.

A series of fluids and speeds were used to validate the CFD with theory. As expected, agreement between CFD and theory was quite well (See Figure 17)
Figure 17: Sample comparison of CFD with theory for flat plate at 1 m/s

It was expected in the 2D cases that as the spacing between the roughness elements was reduced, the profiles and thicknesses would further resemble those for a flat surface; this was validated (see Figure 18 and Figure 19).

Figure 18: Sample 2D CFD velocity profiles over various roughness sizes at 1.7 m/s in LH2
Figure 19: Sample 2D CFD boundary layer thicknesses over various roughness sizes at 1.7 m/s in LH2
Speed sensitivity has performed to see how it effected the boundary thicknesses. The induced velocities due to free convection for a smooth wall during a typical mission are known empirically. Utilizing this it can be shown that tank velocities can range between 1 mm/s to upwards of 2 m/s in a tank. Prior to ~1 m/s, boundary layer thicknesses vary little with speed; after which boundary layer thickness varies a significant amount (see Figure 20).
Note that the large ‘spike’ in the boundary layer thickness plots is a result of the disturbed upstream flow pattern and the way that the boundary layer thickness is measured. This ‘spike’ occurrence was also observed in 3D cases as well. The flow (streamlines) is not following this pattern (see Figure 21 and Figure 22).

Figure 21: Sample CFD streamline pattern over Isogrid surface at 1.7 m/s

Figure 22: Sample CFD velocity vector profiles over Isogrid surface at 1.7 m/s
3D Isogrid profiles were taken at 3 different planes along the length of the Isogrid surface (see Figure 23).

Isogrid boundary layer thickness at 1 mm/s was found to be at upwards of 250% larger than flat plate boundary layer thickness (see Figure 24). Profiles taken at location 1 and 2 should show good agreement with the trends observed in the 2D cases (reduction of roughness spacing thinned boundary layer). As velocity is increased, Isogrid boundary layer thickness is ~700% larger than flat surface boundary layer (See Figure 25 and Figure 26).
Figure 25: Sample CFD boundary layer thickness for Isogrid and Flat surface compared to theory in LH2 at 1 cm/s

Figure 26: Sample CFD boundary layer thickness for Isogrid and Flat surface compared to theory in LH2 at 1 m/s

Boundary layer profiles over the Isogrid surface lied in between the classical Blasius and $1/7$th power profiles (see Figure 27); $1/4$th power profile has been shown to be an excellent fit. This has been seen in other roughness experiments (see reference 26).
Boundary layer thickness as expected were larger than flat plate theory. From Figure 28 it was shown that the measurement repeatability was good.
Comparison of the flat plate and Isogrid boundary layers shows that boundary layer thickness was ~170% larger for the Isogrid case (see Figure 29).

![Figure 29: Sample experimental comparison of Isogrid and flat surface boundary layer thickness at 5 m/s](image)

V. Summary and Conclusions

To ensure proper operation of upper stage engine turbomachinery after an orbital transfer coast, accurate modeling of the thermodynamic state of the propellants is needed. The focus of this work was to understand the effect of an isogrid surface on the growing free convection boundary layer located inside of cryogenic propellant tanks. This work has indicated that the thickness of the layer adjacent to the wall in a forced freestream flow is substantially thicker (minimally 150% to upwards of 700%) than the equivalent flat plate boundary layer thickness. Furthermore, the flow is highly turbulent with many recirculation zones suggesting that the classical idea of a boundary layer may not exist over such geometries. These results will be incorporated into an improved thermal stratification model in order to predict the behavior of the cryogenic propellant during long coast phases of upper-stage chemical rockets.

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References