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THERMAL STRATIFICATION

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Abstract

In 1997, NASA initiated a study of a liquid oxygen and ethanol orbital maneuvering and reaction control system for space shuttle upgrades as well as other reusable launch vehicle applications. The pressure-fed system uses sub-cooled liquid oxygen at 2413.2 KPa (350 psia) stored passively using insulation. Thermal stratification builds up while the space shuttle is docked at the international space station. The venting from the space shuttle's liquid oxygen tank is not desired during this 96-hr time period. Once the shuttle undocks from the space station there could be a pressure collapse in the liquid oxygen tank caused by fluid mixing due to the thruster firings. The thermal stratification and resulting pressure rise in the tank were examined by a computational fluid dynamic model. Since the heat transfer from the pressurant gas to the liquid will result in a decrease in tank pressure the final pressure after the 96 hours will be significantly less when the tank is pressurized with ambient temperature helium. Therefore, using helium at ambient temperature to pressurize the tank is preferred to pressurizing the tank with helium at the liquid oxygen temperature. The higher helium temperature will also result in less mass of helium to pressurize the tank.

Nomenclature

\[ R : \text{Universal gas constant, 8.314 KJ/Kmol-K} \]
\[ u : \text{Velocity component, m/s} \]
\[ S_c : \text{Source term for continuity equation, 1/s} \]
\[ S_h : \text{Source term for energy equation, W/m}^3 \]
\[ t : \text{Time, s} \]
\[ T : \text{Absolute temperature, K} \]
\[ x_j : \text{Spatial domain variable, m} \]

Greek Letters

\[ \alpha : \text{Mass fraction} \]
\[ \epsilon : \text{Volume fraction} \]
\[ \gamma : \text{Specific heat ratio} \]
\[ \mu : \text{Dynamic viscosity, Kg/m-s} \]
\[ \rho : \text{Density, Kg/m}^3 \]
\[ \nu : \text{Specific volume, m}^3/\text{Kg} \]

Introduction

NASA has initiated an effort to look at a liquid oxygen and ethanol orbital maneuvering (OMS) and reaction control system (RCS) for space shuttle upgrades. Numerous trade studies conducted from 1980 to 1996 have shown that liquid oxygen and ethanol are the two most appropriate fluids for a pressure-fed system. Liquid oxygen and ethanol are clean-burning, high-density propellants that provide a high degree of commonality with other spacecraft subsystems including life support, main propulsion, power, and thermal control. The use of liquid oxygen will reduce the number of different fluids and propellants used on the space shuttle. These propellants will support a variety of reusable launch vehicles (RLV) for future human exploration. Historically most vehicles have used earth-storable propellants for the OMS/RCS, however liquid oxygen combined with passive insulation is suitable for reusable vehicles with up to 30 day on-orbit stay
time; and for longer duration, over years, cryo-
coolers can be used to eliminate the boil-off. Oxygen
also be tapped off the tanks for life support or
fuel cell reactants. The key to this pressure-fed
system is the use of sub-cooled liquid oxygen at
2413.2 KPa (350 psia). In this approach, there is
44.4 K (80 R) of sub-cooling, which means that boil-
off will not occur until the temperature has risen 44.4
K. The sub-cooling results naturally from loading
propellants at 90.6 K (163 R), which is the saturation
temperature at 101.325 KPa (14.7 psia), and then
pressurizing to 2413.2 KPa (350 psia) on the launch
pad. Thermal insulation and conditioning techniques
are then used to limit the liquid oxygen temperature
to a 102.8 K (185 R) maximum to maintain sub –
cooling. Another important factor to consider is the
wide melting point to boiling point temperature range
of ethanol, 159.4 K to 422.2 K (-173 F to +300
F), which can provide heat to gasify the liquid oxygen or
provide a good coolant.

The rationale for using non-toxic propellants are to
improve safety, reduce cost, increase the flight rates,
and improve mission capability. The non-toxic
OMS/RCS design addresses each of these goals. It
reduces ground and flight safety hazards with the
elimination of the current toxic and corrosive
c propane. The cost savings for shuttle ground
operations are estimated to be over $26 million for 8
flights per year, and the savings will increase with
increasing flight rates. Using non-toxic propellants
reduces the serial processing time by 75% during
ground turnaround. This will also support
dramatically higher flight rates. The payload
capability is significantly increased by 1134.0 Kg to
1496.9 Kg (2500 to 3300 lbm) due to increased OMS
e engine performance. By interconnecting the aft and
forward tanks and by adding redundant verniers, the
non-toxic OMS/RCS improves space station reboost
capability by up to 20 nautical miles. The redundant
verniers are added by using dual thrust RCS engines,
which also improves mission success reliability.

**Thermal Stratification**

The issue being addressed in this paper is the extent
of the thermal stratification that could build up while
the space shuttle is docked at the international space
station. During this 96-hr time period, it is desired to
have no venting from the space shuttle's liquid
oxygen tanks. The thermal stratification and resulting pressure rise in the tank during this time
was examined by performing a computational fluid
dynamic assessment of the liquid oxygen tank.
When the shuttle undocks from the space station
there could be a pressure collapse in the liquid
oxygen tank caused by fluid mixing, which results
from the thruster firings.

The liquid oxygen tank was modeled using the
computational fluid dynamic software FLUENT,
created by Fluent, Inc. Running the full 3D model
requires extensive computer memory and time.
Therefore, an axisymmetric 2D model of the tank
was created that gives the opportunity to run different
cases in a reasonable amount of time. The Volume
of Fluid (VOF) technique is used by FLUENT to
model multiphase problems. The fluids share a
single set of momentum equations. For each
additional phase a volume fraction is defined. The
volume fraction of each phase is tracked through the
computational domain. Surface tension effects were
also included.

Mass transfer between the liquid and gaseous oxygen
was not included in the analyses. Previous studies in
microgravity liquid acquisition\(^5,17\) show that when the
tank is pressurized with gaseous oxygen the vapor at
the interface condenses onto the liquid oxygen. The
increase in the heat transfer decreases the surface
tension. However, when the tank is pressurized using
helium no mass transfer occurs at the interface.
Since there is no convection the mass transfer at the
liquid/vapor interface is limited by the diffusion of
oxygen vapor through the gaseous helium, which
proceeds very slowly because of the equality of their
temperatures. Therefore, mass transfer can safely be
neglected in the simulations.

**Analysis**

The following set of equations is solved in the VOF
model. The compressible version of the ideal gas law
is used to calculate the gas density.

Equation of state

\[
\rho = \frac{(P_{op} + P')M}{RT} \tag{1}
\]

where \(P_{op}\) is the operating pressure and \(P'\) is the
pressure update. The operating pressure is a constant
reference pressure and the pressure update is the time
varying pressure. The density variation is
accommodated by the time varying component of the
pressure.
Continuity for the volume fraction of the vapor phase is given by:
\[
\frac{\partial \varepsilon}{\partial t} + u_j \frac{\partial \varepsilon}{\partial x_j} = S_e
\]  
(2)

Momentum equation
\[
\frac{\partial (\rho u_j)}{\partial t} + \frac{\partial (\rho u_j u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_j} + \mu \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) + \rho g_j + F_j
\]  
(3)

Energy equation
\[
\frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho u_j h)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( k \frac{\partial T}{\partial x_j} \right) - \varepsilon_i S_h
\]  
(4)

FLUENT uses the Semi-Implicit Method for Pressure Linked Equations (SIMPLE) to solve the above system of equations. The convergence criterion for all variables except enthalpy is $10^{-3}$. When solving the energy equation a $10^{-6}$ convergence was satisfied. In order to ensure the stability and damp out nonlinearities, small values of underrelaxation were applied to update the parameters. Larger values were needed for faster convergence.

Nine different cases were evaluated to determine the effects of the different parameters on the final tank pressure. The tank is loaded with liquid oxygen at different initial conditions as saturated liquid at 241.3 KPa (35 psi) and 101.325 KPa (14.7 psi) with 85% and 65% fill levels ('fill level' indicates the volume occupied by the liquid phase). These two fill levels were selected as being representative of the liquid quantities that would be remaining in the liquid oxygen tank at the time that the space shuttle docks to the space station. The tank is then pressurized to 2413.2 KPa (350 psi) using helium at two different temperatures, ambient temperature and the temperature of the liquid oxygen. The effect of boundary heating is also evaluated for various heat flux values. In the following section a sample calculation is given for Case 1.

**Evaluation of the initial conditions for Case 1**

In this case the liquid and vapor oxygen are starting at the saturation conditions at a pressure of 241.3 KPa (35 psi). Helium is then introduced into the tank to increase the pressure to 2413.2 KPa (350 psia).

The volume occupied by the liquid oxygen is 85% of the total tank volume and will be referred to as "85% fill level". Boundary heat flux at the wall is 6.31 W/m² (2 BTU/hr-ft²). The properties of the liquid and vapor phases after pressurization are calculated. The liquid phase is pure oxygen whereas the vapor phase is a mixture of oxygen and helium. The fluid properties are obtained from the computer code released by the National Institute of Standards and Technology (NIST). The pressurization process is assumed to be fast enough that we can make an isentropic compression assumption. The following relation is used to obtain the temperature of the vapor oxygen after the pressurization process:

\[
\frac{T_2}{T_1} = \left( \frac{P_2}{P_1} \right)^{\frac{1}{r}} = \left( \frac{350}{35} \right)^{0.48} = 2.110203
\]  
(5)

where $T_1$ is the saturation temperature of vapor oxygen at 241.3 KPa (35 psi). Then $T_2 = 209.733$ K (377.5 R). The volume reduction of the vapor oxygen due to compression can be obtained as:

\[
\frac{V_2}{V_1} = \left( \frac{P_1}{P_2} \right)^{\frac{1}{r}} = \left( \frac{350}{35} \right)^{1/1.48} = 0.2102
\]  
(6)

The ratio of the vapor oxygen volume before and after the pressurization is calculated using the conservation of mass principle:

\[
\frac{m_{O_2}}{V_1} = \frac{V_2}{V_1} \Rightarrow \frac{V_2}{V_1} = \frac{V_2}{V_1} = 0.2102
\]  
(7)

This shows that after He is pumped into the tank 21% of the initial vapor volume is occupied by vapor oxygen and 79% is occupied by helium. To calculate the mixture properties the mass fraction of the gases must be known. First the properties of both gases will be obtained and then using the densities the mass fraction will be computed. After pressurization vapor oxygen has the following properties:

- $T = 209.73$ K
- $P = 2413.18$ KPa
- $\rho = 47.24$ Kg/m³
- $\mu = 15.85e-6$ Kg/m-s
- $C_p = 1017.754$ J/Kg-K
- $k = 0.02071598$ W/m-K

Helium properties are as follows:

- $T = 209.73$ K
- $P = 2413.18$ KPa
- $\rho = 5.45$ Kg/m³
- $\mu = 15.79e-6$ Kg/m-s
- $C_p = 5193.8$ J/Kg-K
- $k = 0.123716$ W/m-K

The mass fraction of helium is given by
Finally, any property \( P \) is calculated based on mass averages.

\[
P = \alpha_{O_2} P_{O_2} + \alpha_{He} P_{He}
\]

The only information that is needed to start the simulation is the liquid oxygen properties, which are the saturation properties at 241.3 KPa (35 psi). The simulation starts after the pressurization period. Therefore, the property values mentioned above are the initial conditions. The initial conditions for all of the simulations are given in Table 1. A 1x10\(^{-5}\) g gravity vector is applied for all the simulations so that the initial position of the liquid is known.

The axisymmetric model, Figure 1, is run to obtain the thermal conditions at the end of the four-day period. Then the data is used to generate a 3D model, Figure 2, by using symmetry. Then the gravity vector is applied in the opposite direction with a magnitude of 1e-2 g, which is believed to be the worst case as far as fluid mixing and thus pressure collapse is concerned. The 3D runs continued until the pressure recovers itself.

<table>
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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9*</th>
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<td>85</td>
<td>85</td>
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<td>Mass fraction of Helium</td>
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<td>0.3</td>
<td>0.488</td>
<td>0.711</td>
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<td>237.607</td>
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<td>6.31</td>
<td>6.31</td>
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</tr>
</tbody>
</table>

Table 1. Initial and boundary conditions for different cases

*The thermodynamic vent system (TVS) is operated continuously to maintain a constant temperature of 80.6 K at the centerline of the tank.

Results

Figure 3 shows the effect that the liquid fill level has on the tank pressure when the tank is loaded with liquid oxygen saturated at 241.3 KPa (35 psi) pressure. In both cases the tank was pressurized with ambient temperature helium (hot helium case). The energy from the vapor region is initially transferred...
to the liquid region until the liquid and vapor at the interface reach an equilibrium temperature. The pressure in the tank decreases during this period. After an equilibrium temperature is reached the environmental heat input causes the ullage pressure and temperature to increase.

Figure 3. Effect of liquid fill level on pressure rise when the tank is loaded with liquid oxygen saturated at 241.3 KPa (35 psi) pressure.

Figure 4 shows the effect of helium temperature on the pressure change when the liquid fill level is at 65%. The hot helium case is when the tank was pressurized with ambient temperature helium. The cold helium case is when the tank was pressurized with helium at the liquid oxygen temperature. In the hot helium case the energy from the vapor region is initially transferred to the liquid region until the liquid and vapor at the interface reach an equilibrium temperature. The pressure in the tank decreases during this period. After an equilibrium temperature is reached the environmental heat input causes the ullage temperature and pressure to increase. In the cold helium case the ullage pressure immediately starts to increase since the liquid and vapor are already at an equilibrium temperature.

Figure 4. Effect of helium temperature on the pressure change when the liquid fill level is at 65%.

Figure 5 shows the effect of the helium temperature on the pressure change when the liquid fill level is at 85% and the tank has suffered a failure in the insulation system. The heat flux has increased to 67.8 W/m² (21.5 BTU/hr-ft²) to simulate the loss of the thermal insulation system.

Figure 6 shows the effect of varying the heat flux on the pressure in the tank at a liquid fill level of 85%. In both cases the tank was pressurized with ambient temperature helium. Two different environmental heat leak values were investigated, 6.31 W/m² (2 BTU/hr-ft²) and 3.15 W/m² (1 BTU/hr-ft²). As expected the pressure recovery occurs faster with a larger heat input.
Figure 5. Effect of helium temperature on the pressure change when the liquid fill level is at 85% and the tank has suffered a failure in the insulation system.

Figure 6. Effect of varying the heat flux on the pressure in the tank at a liquid fill level of 85%.

Figure 7. Ability of the thermodynamic vent system (TVS) to control the tank pressure following the loss of the insulation system. In both cases the tank was pressurized with helium at the liquid oxygen temperature. In the no-TVS case, the ullage pressure immediately starts to increase since the liquid and vapor are already at an equilibrium temperature. The continuous operation of the TVS removes energy from the tank at a rate faster than it is being introduced from the environment, allowing a nearly constant pressure to be maintained in the tank. Even with the much higher heat input resulting from the loss of the insulation system, the TVS can remove sufficient heat to control the pressure in the tank. Under nominal heat input conditions the tank pressure would decrease with TVS operation.

Conclusion

The use of ambient temperature helium to pressurize the OMS liquid oxygen tank was determined to be preferable to introducing the helium at the liquid oxygen temperature. The heat transfer from vapor to liquid will result in a temporary decrease in the tank pressure. The final tank pressure after 96 hrs will be significantly less than the case with cold helium. The higher helium temperature will also result in less mass of helium to pressurize the tank. No significant
thermal stratification was detected in the simulations performed. It was also found that a 5-minute period where the acceleration is increased from $1 \times 10^3$ g to $1 \times 10^2$ g in the opposite direction was insufficient to cause fluid mixing within the tank. With no fluid mixing there would be no pressure decrease even if a significant amount of thermal stratification were present.

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References


