Engineering Notes

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Ullage Mixing Effects on Tank Pressurization Performance

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Nomenclature

a = acceleration
d = jet exit diameter
T = gas temperature
u = velocity
x = axial distance downward from pressurant injector
y = momentum diameter
Z = gas compressibility factor
ρ = density

Subscripts

b,m,u = buoyancy, mixing and ullage, respectively
0 = jet exit

Introduction

A TYPICAL heated gas pressurization system employs a diffuser-type pressurant injector which reduces disturbance of the ullage gas. Buoyancy causes a natural thermal stratification of the ullage, giving a vertical temperature distribution with little radial or circumferential variation. Heat transfer occurs between the gas and the adjacent tank wall. These characteristics are simulated by a one-dimensional model with only vertical profiles of temperature. Several analyses and computer programs of this type have been developed.[1–3] The validity of this approach has been established by correlations with experimental data.[1,4]

The gas inflow, if it is not well diffused, can cause mixing of the surrounding ullage, disrupting the assumed thermal stratification. The effect of this ullage mixing on tank pressurization performance is the subject of the present investigation. Ullage mixing changes the gas temperature profile, which modifies the gas-wall temperature difference and heat-transfer rate. It has been shown[5] that for a given total ullage mass and enthalpy, a uniform ullage temperature will result in the minimum gas-wall heat-transfer rate and pressurant mass inflow rate compared to any stratified temperature distribution. However, the magnitude of this effect must be established with quantitative performance data.

Complete Ullage Mixing

Examples were calculated for identical systems and operating conditions under the two limiting conditions of a perfectly stratified ullage and a completely mixed ullage. The computer program[3] employed in this study is based on the one-dimensional model, uses a volume node finite-difference technique and includes variable thermal properties for the tank wall material and the ullage gas. For the small number of examples, many parameters are held constant. The tank is a cylinder with hemispherical end caps, $L/D = 2$, of aluminum with a uniform wall thickness and no internal hardware. A complete expulsion of propellant from the initial loading to depletion is performed at constant outflow rate, tank pressure and pressurant inlet temperature. All temperatures (wall, liquid, and ullage) are initially uniform at 45.6°R, 185°R, and 535°R for liquid hydrogen, liquid oxygen, and storable propellant, respectively. The gas-wall heat transfer coefficient is 10 Btu/hr-ft^2-°R.

The examples are presented as plots of the collapse factor vs initial ullage volume fraction. These comparisons are for multiple-burn applications in which a range of initial ullage volume fractions may be encountered at individual engine firings during a mission. The collapse factor is the ratio of the actual to the ideal pressurant mass, the latter being the volume of propellant outflow multiplied by the density of incoming pressurant.

Pressurization performance for liquid hydrogen tanks pressurized with gaseous hydrogen at 50 psia is shown in Fig. 1a. The merging of the curves at initial ullage volume fractions greater than about 0.5, and the collapse factor reaching values less than 1.0 are due to the variable specific heats of the tank wall and the propellant vapor, respectively. Figure 1b shows the influence of the tank pressure and Fig. 1c shows the performance obtained with helium pressurant. Ullage mixing improves performance for all systems investigated, but as the ratio of pressurant inlet temperature to initial ullage temperature decreases, this difference in performance decreases. Figure 1d shows the much smaller effect for a typical storable propellant with a gas generator pressurant and higher inlet temperatures. Figure 1e is a final example for liquid oxygen. These examples show it would be beneficial to promote ullage mixing to improve pressurization performance. Additional calculations[5] over a wider range of operating conditions substantiate this conclusion. The liquid hydrogen system is the most promising application.

These calculations illustrate the maximum possible difference in pressurization performance which can be caused by ullage mixing. The improvement in real systems may be smaller because a completely mixed ullage may not be obtained and heat losses to the liquid may degrade performance.

Partial Ullage Mixing

Pressurization tests performed at NASA-Lewis show straight-pipe pressurant injectors to be effective in producing ullage mixing. The data reported by DeWitt et al.[6] were obtained with a stainless-steel, 27-in.-diam, $L/D = 3$ tank, expelling LH_2 at $P = 160$ psia with a GH_2 pressurant inlet temperature of ~525°R. The ullage gas temperature vertical profiles (measured at the tank half-radius) obtained with three different injectors are shown in Fig. 2. Both diffusers result in temperature stratification. The straight pipe injector causes extensive ullage mixing, giving a nearly uniform ullage temperature over much of the tank length. This

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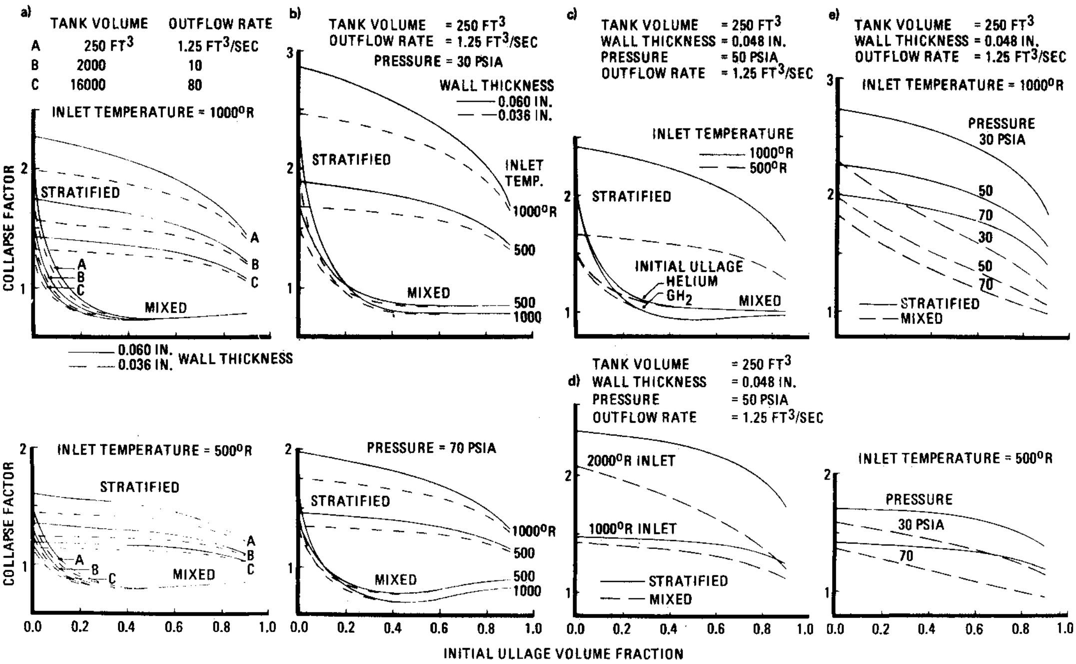

Fig. 1 Expulsion characteristics: a) LH_2/GH_2 expulsion at P = 50 psia; b) LH_2/GH_2 expulsion at 30 and 70 psia; c) LH_2 expulsion by He; d) storable propellant expulsion by gas generator products; e) LO_2 expulsion by He.

behavior suggests a partial mixing model with a mixed zone of uniform properties at the top of the ullage and a lower region of thermally stratified gas undisturbed by the pressurant inflow.

The depth of the mixed ullage zone is set equal to the penetration depth of the pressurant jet. The vertically downward flowing jet is at a higher temperature and lower density than the surrounding ullage and is decelerated by buoyancy. Jet velocity decreases also due to viscous, turbulent mixing with the surrounding gas. The penetration depth, the point at which the jet velocity has decreased to zero, is determined by a pressure balance on the jet centerline. The viscous mixing and buoyant deceleration processes are assumed to be independent and additive.

The variation in gas velocity and temperature on the jet centerline due to turbulent mixing is expressed using the equations of Laufer.[7] The difference between the virtual and actual jet origins can be ignored for the subsonic jet-exit velocities in this application giving

$$u/u_0 = 19.2y/x \qquad x > 19.2y \qquad (1)$$

and

$$(T - T_u)/(T_0 - T_u) = 15.9y/x \qquad x > 15.9y \qquad (2)$$

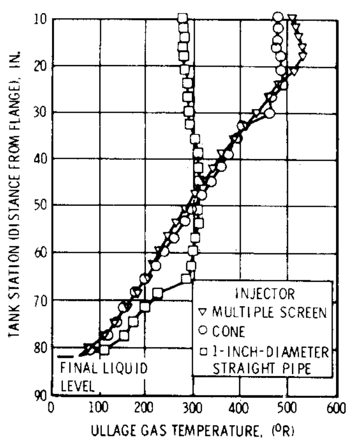

Fig. 2 Ullage temperature profiles for different injector types at end of 130 sec expulsion.[6]

where $y = (\rho_0 d^2/8\rho_u)^{1/2}$ is the momentum diameter. The deceleration of the jet centerline velocity by the buoyancy force is

$$d(u^2) = 2a(1 - \rho_u/\rho)dx \qquad (3)$$

A compressibility factor is included for ρ_u but the warmer jet is assumed to be a perfect gas, giving

$$d(u^2) = 2a(1 - T/Z_uT_u)dx \qquad (4)$$

Since the jet penetration solution is evaluated mostly within the mixed-ullage region, it is valid to replace T_u in Eq. (2) by T_m, the mixed ullage region temperature, giving

$$T = T_m + (T_0 - T_m)15.9y/x \qquad (5)$$

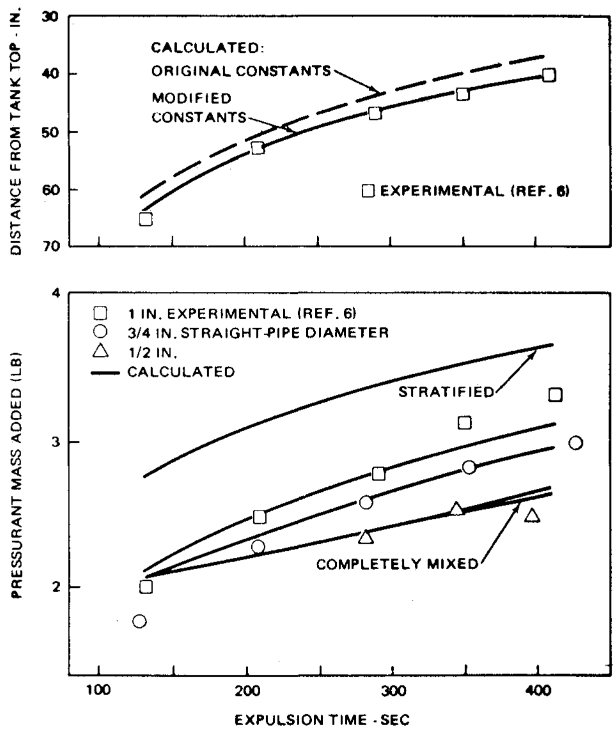

Fig. 3 Depth of mixed ullage zone and pressurant mass added at end of expulsion.

The mixed ullage density is also used in evaluating y. Substituting Eq. (5) into Eq. (4) and integrating from x_1 to x_2 gives

$$\Delta(u^2)_b \Big|_{x_1}^{x_2} = 2a\left[\left(1 - \frac{T_m}{Z_u T_u}\right)(x_2 - x_1) - \frac{(T_0 - T_m)}{Z_u T_u} 15.9y \ln\left(\frac{x_2}{x_1}\right)\right] \quad (6)$$

The velocity-squared decrement due to jet mixing is given directly by Eq. (1)

$$\Delta(u^2)_m \Big|_{x_1}^{x_2} = (u_0 19.2y)^2(x_2^{-2} - x_1^{-2}) \quad (7)$$

The total change is the sum

$$\Delta(u^2) \Big|_{x_1}^{x_2} = \Delta(u^2)_b \Big|_{x_1}^{x_2} + \Delta(u^2)_m \Big|_{x_1}^{x_2} \quad (8)$$

The second term is zero in the velocity core region at the jet exit.

Using this jet penetration analysis in the computer program, the mixed ullage depths were calculated for the NASA-Lewis 1-in. straight-pipe injector tests.[6] Increasing the constants in Eqs. (1) and (2) by 20% to give values of 23.0 and 19.1, respectively, improves agreement with the experimental data. The results are shown in Fig. 3a. The pressurant mass calculated as a function of expulsion time for three straight-pipe injectors is compared in Fig. 3b with the experimental data. The calculated mass of pressurant and the relative influence of the injector diameter both agree quite well with the test results. The deviations are probably influenced by interface heat and mass transfer.

Discussion

The examples in Fig. 1 also illustrate a comparison between the "distributed system" and "lumped system" approach to pressurization analysis. The distributed system includes a spatial distribution of the system variables, along the vertical tank axis in the one-dimensional model; the lumped system uses only average values of the ullage and tank wall temperatures. The lumped model is attractive for its simplicity but the examples show that it can give grossly inaccurate results for a cryogenic propellant with a thermally stratified ullage. Only the one-dimensional analysis should be used for cryogenic applications; however, the lumped model may be suitable for storable propellant applications. The examples also show the importance of using variable gas and wall properties rather than constant average values.

Conclusions

The present analytical investigation and a study of the referenced experimental data has resulted in the following conclusions:

1) Ullage mixing has a significant effect on tank pressurization performance, resulting in a reduction in gas-wall heat loss and pressurant mass requirement. The performance difference is greatest for small tanks, low tank pressures, cryogenic propellants and large initial ullage fractions.

2) The feasibility of improving pressurization performance by causing gas mixing to occur in the ullage has been demonstrated. A reduction of over 50% in the pressurant mass for LH_2 systems is theoretically possible. Significant reductions have been observed experimentally. The straight-pipe injector is effective in causing extensive ullage mixing.

3) The analysis of jet penetration depth and ullage partial mixing agrees well with the available experimental data for straight-pipe injectors.

4) Further study of ullage mixing should include an investigation of gas-liquid interface processes.

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Quenching of Solid-Propellant Rockets by Water Injection

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Introduction

IN other programs, command termination of solid-propellant motors by water quench has been demonstrated in motors having propellant weights up to 8600 kg. However, most attempts to correlate extinguishment data have given questionable results. Three mechanisms have been proposed: 1) rapid cooling of gases causes a dP/dt sufficient for extinction; the water then wets the surface, cooling it to prevent reignition[1]; 2) cooling of the gases below some threshold value lowers heat feedback to the propellant below that necessary for self-supported combustion[2]; and 3) a water film covers the entire surface of the propellant, cooling it below the temperature required for burning.[3,4] The present study was initiated to improve understanding of the quench mechanism and to determine the optimum method of water injection.

The slab-burning window motor used (Figs. 1 and 2) is capable of accepting several different types of water injectors: head-end injectors, multiple injectors impinging normal to the propellant surface, and sheet injectors which lay a thin sheet of water onto the propellant surface. The spray form varied from a fine mist to a solid stream.

High-speed movies were taken during water injection and quenching. To facilitate viewing, a nonaluminized propellant (JPL 540 Mod A) with a polyether-polyurethane binder and ammonium perchlorate oxidizer was used.

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