Control of the Thermodynamic State of Space-Stored Cryogens by Jet Mixing

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The departure from equilibrium of the thermodynamic state of space-stored cryogens results in mass penalties that are minimized by the use of mechanical mixers. Jet mixing concepts are superior to other candidate mixer concepts when evaluated with respect to weight, flow characteristics, duty cycles, simplicity, and state-of-the-art development. Detailed evaluation of jet mixers indicates that bulk fluid mixing can be readily obtained under space conditions by compact, electric-motor-driven, vane-axial fans with a few watts of power consumption. Analytical methods of evaluating jet mixers are developed and experimentally verified and criteria for design determined. Although buoyancy effects on mixing were observed in 1-*g* space simulating mixing test, buoyancy effects are negligible under actual low-*g* conditions.

Nomenclature

a = acceleration
A_v = liquid surface area in contact with vapor
b = slope at which axial turbulent jet spreads
c_{ps} = constant pressure specific heat of vapor
c_v = constant volume specific heat of vapor
D_b = bubble diameter
D_0, D_t = nozzle exit and tank diameter
f_v = vapor void fraction
g_c = dimensional conversion factor, 32.2 ft-lb$_m$/lb$_f$ sec^2
g_0 = acceleration due to Earth gravity, 32.2 ft/sec^2
h_{fg} = heat of vaporization
h_m = jet penetration above liquid/vapor interface
I_{mi} = initial energy integral, $1 - (T_s - T_m)/(T_s - T_b)_i$
k = thermal conductivity
L = cylinder length
N = dimensionless number, $4b^2N_i^*(I_{mi} - I_{mi}^2)/(1 + 2I_{mi})$
N_{Bo} = Bond number, $L^2\rho a/\sigma g_c$
N_i^* = $a\beta(T_s - T_b)_i Z_i^3/(V_0 D_0)^2$
N_{Pr} = Prandtl number, ν/α
N_{Re} = Reynolds number, $V_0 D_0/\nu$
P = pressure
P_b = bulk fluid vapor pressure
P_i = initial pressure
r, r_t = radial distance, tank radius
T_b, T_M = nozzle exit, mean fluid temperature
T_s = surface temperature
V_c, V_0 = centerline, nozzle exit velocity
$\dot{V}_a$ = annulus-like region flow rate
$\dot{V}_j$ = volume flow rate of jet
V_R = radial velocity
V_v = vapor volume
V_Z = axial velocity
Z = distance from nozzle to dye interface
Z_{di} = initial distance from nozzle to dye interface
Z_i = initial distance from nozzle to bottom of stratified layer or liquid depth above nozzle
α = thermal diffusivity, $k/\rho c_p$
β = coefficient of thermal expansion
β_p = slope of saturation pressure vs temperature
δ = stratified layer thickness for conduction
δ_j = axial-jet half-thickness
Δ = stratified layer thickness for free convection
θ = time after mixer turned on
θ_j = time for jet to transit from nozzle to stratified layer
θ_1 = time after surface temperature begins to drop
ρ, ρ_l = density, liquid density
σ = surface tension
ν = kinematic viscosity

Introduction

MIXING to thermal equilibrium provides a convenient means of controlling thermal stratification in a stored cryogenic fluid, thus reducing the mass penalties associated with the conventional propellant settling/venting techniques to relieve tank pressure. Well-mixed fluid is also required for the proper operation of an advanced thermodynamic vent system.[1] This study investigated, with 1-g experimental verification, means of controlling thermal stratification in space-stored cryogens.

A stratified layer in the vicinity of the liquid/vapor interface supports a tank pressure higher than the equilibrium (mixed) pressure. Removing this stratified layer by mixing results in a decrease in tank pressure to near equilibrium. Mixing the fluid to thermal equilibrium approximates the minimum tank pressure history since the tank pressure is in equilibrium with the liquid/vapor interface vapor pressure. This is especially important in the case of liquid hydrogen because a 0.3°R temperature increase will result in a vapor pressure increase of approximately 1 psi. In addition to the weight penalty reductions gained during static fluid storage conditions, there are also weight penalty reductions gained by selective mixing during propellant acquisition and transfer. Fluid mixing to eliminate boiling at tank drain region heat shorts permits satisfactory operation of propellant acquisition systems that use surface tension, fluid retention devices.

The thermal stratification must be predicted before mixing performance is predicted, since the extent of the stratification affects the required mixing. The analysis of stratification can be accomplished by either numerical or analytical methods, depending on the degree of detail desired in the solution. The simpler analytical models were considered to provide an adequate description of the stratification development and were used extensively in the study.[2–5]

After stratification is predicted, a method of mixing the stratified fluid is selected. Although numerous methods are available, for this study jet mixers were selected as the most desirable. The mixing performance of this system is defined in terms of mixing time, fluid power requirements, and cycle time.

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Thermodynamic State Prediction

In the study the thermodynamic state of a stored fluid (pressure, temperature, and fluid phase) was evaluated by establishing the magnitude of temperature stratification, since the temperature distribution in the tank serves as a basis for evaluation of tank pressure (the tank pressure corresponds to the vapor pressure of the warmest fluid in the tank).

The prediction of thermal stratification is accomplished conveniently by the use of analytical models which consider 1) thermal conduction, 2) ullage heating (no evaporation or condensation), 3) free-convection boundary layer[2,6] (with and without ullage heating effects), and 4) heat-short boiling. The description and development of these models is presented in another paper.[5]

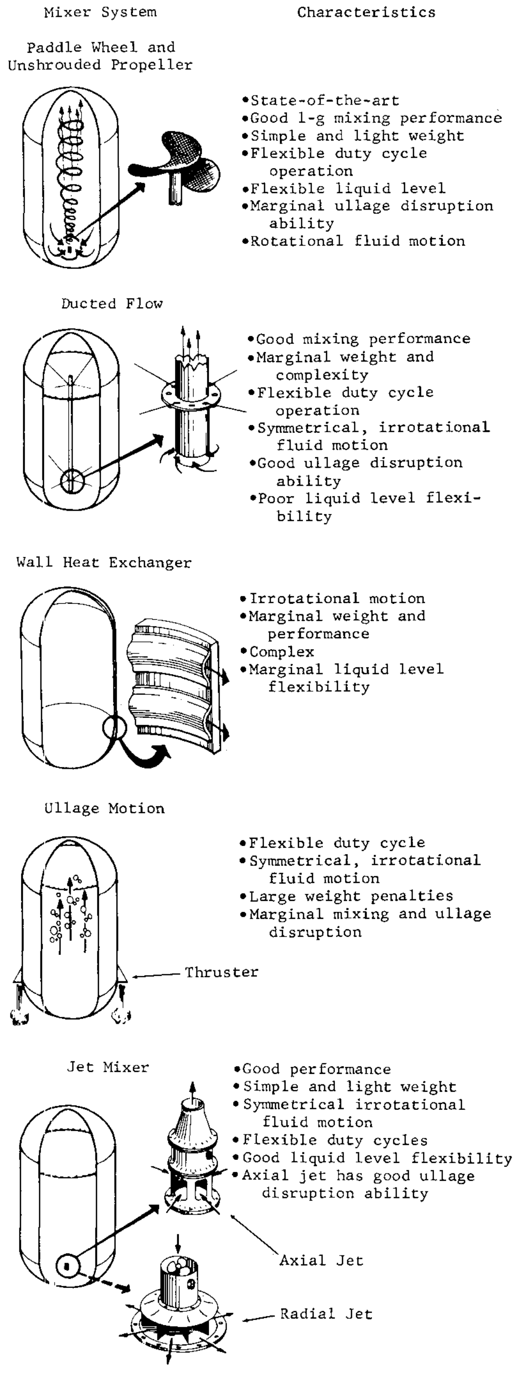

Fig. 1 Mixer system characteristics.

Mixer Concept Selection

Numerous mixer concepts are available for possible utilization in low-g storage tanks. A summary of the principal characteristics of the various mixer systems studied[2-4] is given in Fig. 1. In the evaluation of these mixers to determine the best choice for low-gravity application, the following factors are considered to be desirable: 1) good mixing performance, 2) low-system weight and compactness, 3) production of nonswirl motion and exertion of symmetrical forces on the tank wall, 4) flexible with respect to mixer duty cycle, 5) state-of-the-art development, 6) ability to disrupt ullage, and 7) independent of liquid level.

A complete evaluation of the candidate systems based on these criteria is beyond the scope of this study. However, it is possible to reject most of the proposed systems on the basis of one or more of the criteria. For example, the paddle wheel system produces swirling motion and has little ability to disrupt the ullage if required (the desirability of ullage disruption is discussed in the section entitled Jet Mixing). The ducted flow system required a fixed fluid level to operate and lacks good mixing performance and weight characteristics. The use of ullage motion to provide mixing is not suitable because of the severe weight penalty and performance limitations. Wall heat exchanger concepts require continuous operation and lack simplicity and ease of installation. The performance of the wall heat exchanger is also degraded by a change in the liquid level. The radial jet concept is excellent in all respects except when disruption of the ullage is desired. The axial jet is superior in all respects to the other concepts. Superiority with respect to weight, flow characteristics, duty cycle, and liquid level flexibility are combined with simplicity and good state-of-the-art development. These traits are shared with the radial jet. The ability of the axial jet to disrupt the ullage if necessary is the only significant difference between the two jet concepts. Consequently, the axial jet was selected for further analysis and technology development.[2]

Jet Mixing

Jet mixer design guidelines were established by a detailed evaluation of the effects of 1) buoyancy on bulk-fluid mixing, 2) ullage size and location on mixing, and 3) bulk-fluid mixing on a tank pressure response. Available 1-g jet mixing investigations[7-9] do not treat many of the special low-g mixing phenomena. The additional problems encountered in analyzing a mixer for operation in a low-g environment include 1) variable ullage location, 2) ullage breakup, 3) ullage encapsulation of mixer, and 4) boiling at heat shorts.

Ullage Effects

Ullage-location/mixer-location effects

Under high-g conditions the ullage is positioned by large buoyancy forces and is easily predicted. The absence of these buoyancy forces results in uncertainty of the location and distribution of the ullage. Under 1-g conditions good mixing is achieved by locating the mixer in the liquid region. However, under low-g conditions it may be desirable to locate the mixer in either the liquid or the vapor, depending on the tank vapor fraction. For large void fractions, ullage disruption due to liquid mixing results in three undesirable situations 1) liquid dispersal complicates the fluid acquisition necessary for draining, 2) liquid impingement on hot vapor region surfaces increases the liquid heating, and 3) tank-c.g. variations induced by fluid sloshing increase the demand on the attitude control system.

Jet mixer application to large void fraction, low-g storage conditions requires care in the selection of mixers that will implement proper mixing without disrupting the vapor.

Vapor region mixing for large ullage, low-g storage conditions implements interfacial liquid motion and eliminates ullage region stratification. The pressure response is expected to be slower for vapor region mixing and complete mixing is not considered possible. Near thermodynamic equilibrium conditions cannot be approached without the use of vapor venting, e.g., the operation of a thermodynamic vent system located in the vapor region. The number of vent system duty cycles will be increased if effective intermediate nonvent mixing is not possible.

Ullage breakup

Ullage breakup during mixing typically reduces a single vapor region to a number of much smaller vapor pockets dispersed throughout the liquid, promotes mixing, and generally reduces the rate of restratification. For large tanks, ullage breakup during mixing is recommended only for small void fraction (5–15%) storage conditions. The mixer-outlet momentum requirements for ullage breakup are limited to mixers located in the liquid region.

For large Bond numbers ($N_{Bo} > 10$), the jet momentum parameter, $V_0 D_0$, required for ullage breakup is derived[2] from a balance of the jet inertia forces and the body forces caused by acceleration:

$$V_0 D_0 \geq (L - h_m)(h_m a/g_0)^{1/2} \quad \text{and} \quad h_m \approx D_b \qquad (1)$$

For liquid hydrogen, stored in the Nuclear Propulsion Module (NPM) Mars Braking Stage, the required $V_0 D_0$ is shown in Fig. 2 by the solid line as a function of tank acceleration.

For low Bond numbers (less than 10), the jet momentum parameter $V_0 D_0$ required for ullage breakup is obtained by a jet inertial surface-tension force balance, yielding

$$V_0 D_0 \geq (g_c \sigma Z/\rho)^{1/2} \qquad (2)$$

or, for liquid hydrogen

$$V_0 D_0 \geq (Z)^{1/2}/30, \ (Z = L - D_b) \qquad (3)$$

For the NPM Mars-Braking-Stage, a value of $V_0 D_0$ of about 0.2 ft^2/sec is calculated and shown in Fig. 2 by the dotted lines for bubble diameters of 15 and 21 ft. The necessary value of $V_0 D_0$ is less than 1 ft^2/sec for both low and high Bond number conditions and can be handled by a conventional vane axial electric-motor driven mixer.

Ullage encapsulation of mixers

The maximum mixing efficiency occurs when 1) at least one mixer (located at each end of the tank) remains in the liquid during mixing and 2) the ullage is disrupted. Conventional axial jet mixers operating under low-g conditions will have more than adequate power to disrupt the ullage if at least one mixer remains in the liquid region or if at least one of the mixers that is encapsulated can, by operating in a vapor, cause the vapor to be removed from the mixer (vapor de-encapsulation). The ullage de-encapsulation situation is of interest only for small void fraction conditions in which it is desirable to disrupt the ullage.

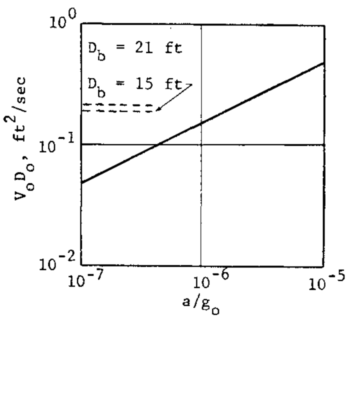

Fig. 2 Mixer momentum parameter $V_0 D_0$ for ullage disruption.

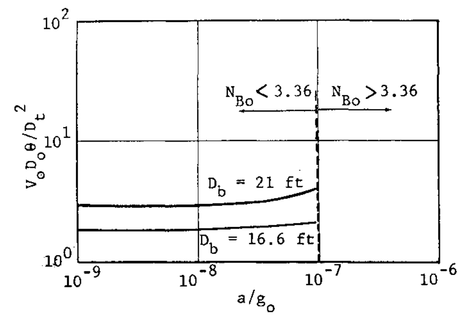

Fig. 3 Mixing time for ullage de-encapsulation of a mixer.

Ullage encapsulation is a problem only if $|N_{Bo}| < 3.36$, because one of the mixers will be free of vapor if $|N_{Bo}| > 3.36$. The worst case occurs when one-half of the ullage is located at each end of the tank, thus encapsulating each mixer. For the Mars-Braking-Stage example considered here, the bubble diameter for one-half the maximum ullage is 16.6 ft. Figure 3 shows the dimensionless time required to remove the bubble from one of the mixers as a function of tank acceleration. The prediction is based on the vapor jet impulse (on a bubble interface) required to move the bubble a distance of one bubble diameter. The product $V_0 D_0$, related to the jet vapor momentum, is chosen to be 1.5 ft^2/sec, a typical value for a conventional vane axial, electric motor driven fan. The total time that the fan is operated must include the time required to de-encapsulate a mixer.

A comparison of a.c. and d.c. electric motors to drive the mixer indicates that the more desirable speed-up characteristic of d.c. electric motors when vapor is ingested produces higher jet vapor momentum (for the same liquid jet momentum) than the essentially constant speed a.c. motors. The higher momentum of the jet vapor from the d.c. motor driven fan results in more rapid vapor de-encapsulation of the mixers.

Boiling suppression

Heat-short induced thermal stratification is found to have a high probability of occurrence under low-g conditions. The heat-transfer process is dominated by thermal conduction and interfacial phase change. Stratification is estimated by a first-order approximation (neglecting the change in energy of the vapor) by use of a thermal conduction model. The heat short heat-transfer rate is assumed to be conducted to the liquid through the available liquid/vapor interfacial area.[5]

During mixer operation, thermal stratification is effectively destroyed in the liquid/vapor interfacial regions of high jet impingement velocities, whether these regions are at the heat short or elsewhere. For example, high jet impingement velocities occur along the tank centerline for an axial jet as shown in Fig. 4. In the stagnant tank regions shown, vaporization (because of the pressure decay during mixing) at the heat shorts cools the stagnant region liquid. Stagnant regions can be eliminated by the use of a mixer at each end of the tank.

Bulk fluid mixing

Jet bulk fluid mixing, characterized by fluid set in motion by jet entrainment, is instrumental in accomplishing pressure decay and ullage disruption, boiling suppression, etc. Three

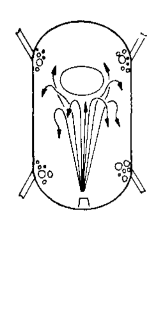

Fig. 4 Boiling at heat shorts during jet mixing.

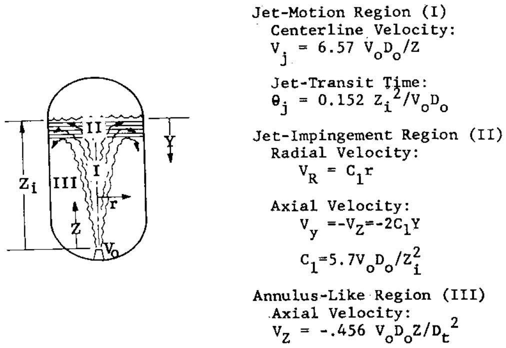

Fig. 5 Characteristic velocities for regions I and II.

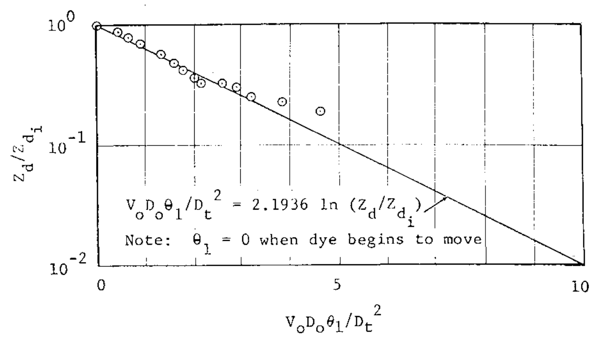

Fig. 7 Correlation of experimental axial jet dye layer motion for region III.

regions (shown in Fig. 5) of forced fluid flow that characterize bulk-fluid mixing are (I) the jet, (II) the impingement, and (III) the annulus-like region motion.

Turbulent-jet flow phenomena (without buoyancy effects) of Region I is described in Schlichting.[10] The liquid/vapor-impingement region (II) is described by the use of potential-flow theory. The annulus-like region flow (III) is described by slug flow, whose velocity is determined by the mass continuity relation between Regions I and III.

In Region I, the time required for a fluid particle leaving the jet nozzle to reach the interface was found by experiment to be twice the steady-state time based on the center-line jet velocity.[3] The mathematical expression for the transition time is given in Fig. 5. No pressure decay or reduction in stratification near the interface can occur until the mixer has been operated at least this length of time. Under 1-g conditions, even a longer period of time is required because of buoyancy effects.

The impingement region plays the most significant role in the bulk-mixing process, since the flow in this region sweeps away the stratified layer that develops in the vicinity of the liquid/vapor interface. Potential flow is assumed in the impingement region that extends downward from the interface a distance of one-half the jet width. The velocity distribution in the radial and axial directions given in Fig. 5, is required to calculate the pressure decay during mixing. Except for natural convection induced stratification, the stratified layer is considered to be thin, e.g., less than δ_j, and is immediately swept away from the interface, resulting in an essentially uniform temperature (T_b) in the impingement region. For a thick stratification layer ($\Delta \gg \delta$), the temperature of the impingement region responds more slowly than for a thin stratification layer, as shown in Fig. 6.

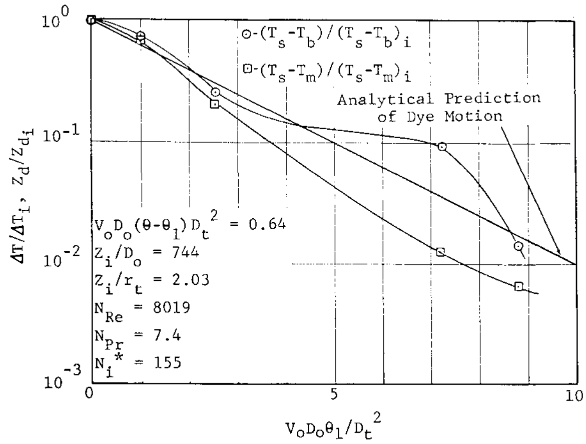

Fig. 6 Experimental bulk temperature mixing fraction of initial temperature difference.

The annulus-like region slug-flow assumption, verified by experiments,[3] permits the downward velocity to be predicted, based upon the jet-upflow velocity. The jet volume flow rate, given by Schlichting,[10] is

$$\dot{V}_j = -\dot{V}_a = 0.404(\pi/4)^{1/2}V_0D_0Z \tag{4}$$

Neglecting the jet area, the downward particle velocity for the cylindrical section of the tank is

$$dZ/d\theta = 0.456V_0D_0Z/D_t^2 \tag{5}$$

Integrating the above equation from an initial position at the base of the impingement region ($Z_i - \delta_j$) to any point Z results in

$$V_0D_0\theta/D_t^2 = 2.194\ \ln[(Z_i - \delta_j)/Z] \tag{6}$$

The dimensionless time $V_0D_0\theta/D_t^2$ is the time required for a warm particle of fluid to move from the vicinity of the liquid/vapor interface to a position Z. In order to evaluate the dimensionless cylindrical section mixing time, Z is chosen as the distance to the bottom bulkhead. Similar expressions[3] have been obtained for particle movement in nonconstant cross-sectional area regions. The form of the preceding equation is identical to that obtained experimentally by Fosselt and Prosser.[8] A dimensionless mixing time of 9 was reported in that work. The prediction of the fluid particle motion is compared in Fig. 7 with dye motion, flow visualization tests.[3]

Buoyancy-retarded bulk mixing

The buoyancy effects that resist the upward jet flow of fluid into a warm fluid region under high-g conditions are negligible under space storage conditions. However, the buoyancy effects have been observed in all 1-g experimental tests conducted to verify that thermally stratified regions may be eliminated by jet mixing. As a result, essentially all of the 1-g experimental mixing performance data obtained during this study correlate well with a buoyancy parameter N:

$$N = 4b^2N_i^*(I_{mi} - I_{mi}^2)/(1 + 2I_{mi}) \tag{7}$$

The dimensionless time required for the surface temperature to drop to one-tenth of the initial temperature is plotted in Fig. 8 as a function of N for various tests, demonstrating the effect of buoyancy on mixing time. Results are shown for both large and small tank tests in which water was used as the fluid. Analytical predictions based on the same buoyancy parameter exhibit the same trend. Buoyancy effects must be taken into account in a similar manner when future large scale mixer system qualification tests are conducted under 1-g conditions in order to properly interpret the low-g mixing performance.

Tank pressure response

A delay in the pressure response induced by settled bulk fluid mixing has been predicted analytically and observed experimentally.[1-3] The tank pressure response for settled bulk

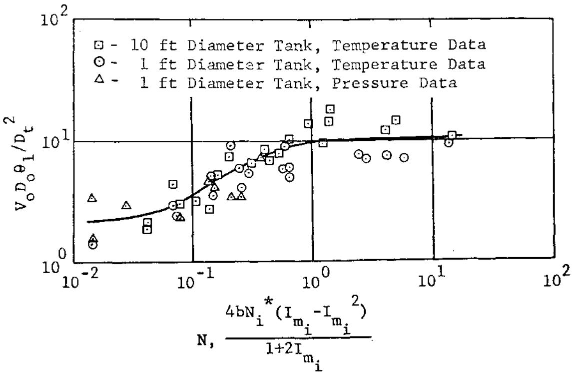

Fig. 8 Mixing time for stratification to drop to 10% of its initial value.

fluid mixing represents the worst case condition because of the more vigorous vapor/liquid interaction in the ullage disrupting case. The qualitative investigation is limited to the settled ullage case, since it is more amenable to analysis and to 1-g experiments.

The initiation of bulk fluid mixing results in the sweeping away of the warm fluid in the vicinity of the interface. In order to maintain thermodynamic equilibrium of the phases at the liquid/vapor interface, condensation of the vapor takes place. A corresponding lowering of the tank pressure results.

The tank pressure response analysis consists of a mass and energy balance in the ullage region and in the interface region, along with flowfield predictions in the bulk fluid. The resulting equation for the pressure response is given in Fig. 9.

This analysis assumes that the stratification layer is thin (on the order of the jet half-width δ_j) and that the stratified layer is immediately swept away from the interface, exposing the interface to liquid whose temperature is T_b. The condensate layer forms immediately and serves to support the temperature difference $T_s - T_b$ (T_s corresponds to the tank pressure). A slightly modified analysis is required when the stratified-layer thickness is large and the fluid temperature under the condensate layer is also varying with time in the manner shown in Fig. 6.

As an example, the equations given in Fig. 9 are used to calculate the pressure response for the NPM Mars-Braking Stage, with an initial stratified-minus-mixed-pressure difference of 10 psi, and mixer V_0D_0 of 1.5 ft²/sec. The tank pressure, shown in Fig. 10, reaches a mixed pressure after about 0.4 hr ($V_0D_0\theta/D_t^2 = 2.1$) after the stratified layer is swept away.

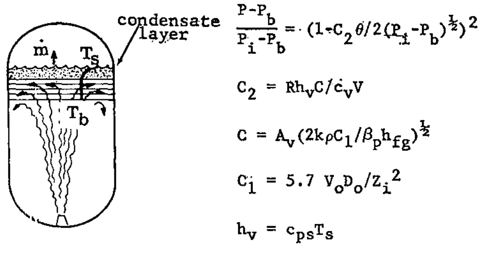

Fig. 9 Pressure response for thin stratified layer mixing.

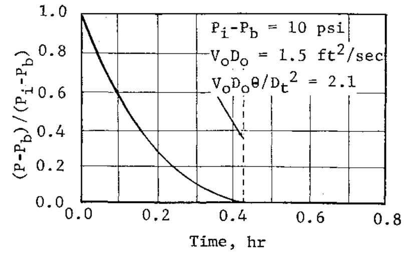

Fig. 10 Pressure response during mixing for the Mars-braking stage.

The total mixing time depends on other factors such as the time required for the jet flow to reach the interface and mixer de-encapsulation time.

Conclusions

The results of the analytical and experimental investigations conducted to assess the requirements for and evaluate the performance of jet mixers in reducing thermal stratification in cryogenic fluids stored in a low-g environment demonstrate that 1) cryogenic propellant thermodynamic conditions will depart sufficiently from thermal equilibrium to warrant the use of a mixer during typical storage modes, 2) jet mixing is superior to other mechanical mixing concepts for low-g application, and 3) jet mixers are capable of mixing a stratified tank in 1-g tests simulating low-g storage, even though buoyancy forces in large-scale 1-g mixing dominate the jet mixing process, but can be neglected for low-g mixing.

References

[1] Stark, J. A., et al., "Study of Zero-Gravity Vapor-Liquid Separator, Second Monthly Progress Report," Rep. 584-4-4, Sept. 9, 1966, General Dynamics, Convair Div., San Diego, Calif.

[2] Poth, L. J., et al., "A Study of Cryogenic Propellant Stratification Reduction Techniques, Annual Report," Rept. FZA-419, Sept. 15, 1967, General Dynamics Fort Worth Div., Fort Worth, Texas.

[3] Poth, L. J., et al., A Study of Cryogenic Propellant Mixing Techniques, Final Report," Rept. FZA-439, Nov. 1, 1968, General Dynamics Fort Worth Div., Fort Worth, Texas.

[4] Van Hook, J. R., et al., "Study of Cryogenic Fluid Mixing Techniques, Final Report," Rept. FZA-450, Sept. 15, 1970, General Dynamics Fort Worth Div., Fort Worth, Texas.

[5] Poth, L. J. and Van Hook, J. R., "Thermal Stratification of Cryogens Stored in a Low-Gravity Environment," *Proceedings of the Institute of Environmental Sciences*, Institute of Environmental Sciences, Vol. 1, April 1971, pp. 244–254.

[6] Harper, E. Y., et al., "Analytical and Experimental Study of Stratification in Standard and Reduced Gravity Fields," *Proceedings of the Conference of Propellent Tank Pressurization and Stratification*, NASA/MSFC, Vol. 1, Jan. 1965, pp. 207–244.

[7] Fox, E. A. and Gex, V. E., "Single-Phase Blending of Liquids," *American Institute of Chemical Engineers Journal*, Vol. 2, 1956, pp. 539–544.

[8] Fossett, H. and Prosser, L. E., "Application of Free Jets to the Mixing of Fluids in Bulk," *Proceedings of the Institute of Mechanical Engineers*, Vol. 160, No. 2, 1949, pp. 224–232.

[9] Sterbacek, Z. and Taush, P., *Mixing in the Chemical Industry*, Pergamon Press, London, 1965, pp. 229–234.

[10] Schlichting, H., *Boundary Layer Theory*, McGraw-Hill Co., New York, 1960, pp. 607–609.