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Prediction of Pressurant Mass Requirements for Axisymmetric Liquid Hydrogen Tanks

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PREDICTION OF PRESSURANT MASS REQUIREMENTS FOR AXISYMMETRIC LIQUID HYDROGEN TANKS

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Abstract

Experimental data from several test series are compared to an existing correlation that predicts the amount of pressurant gas mass required to expel liquid hydrogen from axisymmetric tanks. It was necessary to use an alternate definition of the tank equivalent diameter to accommodate thermal mass in the tank wall that is initially warm and to accommodate liquid residuals in the tank after expulsion is stopped. With this modification, the existing correlation predicted mass requirements to within 14 percent of experimental results. Revision of the correlation constants using a nonlinear least-squares fit of the current experimental data has a minor effect, thus supporting the validity of the original correlation's form, its fitted constants, and the alternate definition of the tank equivalent diameter.

Nomenclature

A	surface area
C	ratio of wall-to-gas effective thermal capacity
CF	collapse factor ($= w_p / w_p^0$)
c_p	specific heat at constant pressure
D_{eq}	equivalent tank diameter
h_c	gas-to-tank wall free convection heat transfer coefficient
m	mass
$p_1 \ldots p_8$	fitted constants
$\dot{q}$	heat flux from ambient to tank wall
Q	ratio of total ambient heat input to effective thermal capacitance of gas
S	modified Stanton number
t	thickness
T_0	pressurant inlet temperature
T_s	saturation temperature of propellant at initial tank pressure
w_p	total pressurant mass
w_p^0	total pressurant mass under conditions of zero heat and mass transfer
w_p / w_p^0	collapse factor
V	volume
ΔV	expelled liquid volume
θ_T	total liquid outflow time
ρ	density

subscripts

exp	experimental
G	gas
lid	tank lid only
pred	predicted
sw	swept by the liquid free surface during expulsion
tank	tank wall excluding lid
w	wall

superscripts

0	at pressurant inlet temperature and tank expulsion pressure

overbars

~	denotes computed value that accommodates variable wall thickness or material

Introduction

The pressurized expulsion of cryogenic fluids from propellant tanks was an active research area during the 1960's and early 1970's as is evident from the large number of publications on this subject. Of interest herein is the cryogenic pressurant requirements correlation developed by Epstein[1] in 1965 and subsequently revised by Epstein and Anderson[2] in 1968. The correlation predicts the collapse factor, a dimensionless pressurant mass, given the following dimensionless

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p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
0.330	0.281	4.26	0.857	1.50	0.312	0.160	0.986

Table 1 — Fitted constants for the Epstein and Anderson[2] correlation for hydrogen propellant.

groups—pressurant-to-saturation temperature ratio, wall-to-gas effective thermal capacity ratio, ratio of ambient heat input to effective thermal capacitance of pressurant, and a modified Stanton Number for gas-to-tank wall heat transfer. The original correlation was developed for cylindrical liquid hydrogen and oxygen tanks pressurized by the propellant vapor or helium. The form of the correlation has a theoretical basis and contains eight constants determined by nonlinear least-squares fitting[1,2]. In the later paper, the correlation was revised with updated constants to include axisymmetric tanks through the use of an equivalent tank diameter. The revised correlation was compared to experimental data from numerous sources and reported to agree to within ± 12 percent, provided the data variables are within specified ranges.

The form of Epstein and Anderson's correlation is:

$$\frac{w_p}{w_p^0} = \left\{ \left(\frac{T_0}{T_s} - 1 \right) \left[1 - \exp\left(-p_1 C^{p_2} \right) \right] \times \left[1 - \exp\left(-p_3 S^{p_4} \right) \right] + 1 \right\} \times \exp\left[-p_5 \left(\frac{1}{1+C} \right)^{p_6} \left(\frac{S}{1+S} \right)^{p_7} Q^{p_8} \right] \tag{1}$$

where

$$w_p^0 = \rho_G^0 \Delta V \tag{2}$$

$$C = \frac{\left(\rho c_p^0 t\right)_w}{\left(\rho c_p\right)_G^0 D_{eq}} \frac{T_s}{T_0} \tag{3}$$

$$S = \frac{h_c \theta_T}{\left(\rho c_p\right)_G^0 D_{eq}} \frac{T_s}{T_0} \tag{4}$$

and

$$Q = \frac{\dot{q} \theta_T}{\left(\rho c_p\right)_G^0 D_{eq} T_0} \tag{5}$$

The quantity w_p / w_p^0 is known as the collapse factor and represents the ratio of actual pressurant consumption to an ideal amount assuming no heat or mass transfer from the pressurant. The heat transfer coefficient in Eq. 4 is obtained from a Nusselt Number correlation for turbulent free convection for vertical planes and cylinders[3]. Table 1 lists Epstein and Anderson's values of fitted constants for liquid hydrogen pressurized by either hydrogen or helium gas.

Since publication of the revised correlation, additional experimental data was obtained at the NASA Lewis Research Center for the pressurized expulsion of liquid hydrogen from spherical and nearly spherical tanks[4-8]. The data series and references are listed in Table 2.

Data Series	Reference	Tank Diameter	Tank Shape	Pressurant Gas
I	Van Dresar & Stochl[4]	2.2 m	Oblate spheroid	GH_2
II	Stochl, et al[5]	4.0 m	Sphere	GH_2
III	Stochl, et al[6]	1.5 m	Sphere	GH_2
IV	Stochl, et al[7]	4.0 m	Sphere	GHe
V	Stochl, et al[8]	1.5 m	Sphere	GHe

Table 2 — Liquid hydrogen expulsion data obtained at NASA.

Variable	Epstein & Anderson	NASA data
Spherical tank diameter [m]	1.5-9.1	1.5-4.0
Wall thickness [cm]	0.25-2.5	0.21-1.3
Pressurant inlet temperature-to-propellant saturation temperature ratio	2-15	8-17
Total outflow time (sec)	200-500	132-1980
Ambient heat flow (W/m^2)	0-32,000	2.3-100

Table 3 — Range of variables for correlation.

A total of 60 data points are available from the sources in Table 2. These data points were obtained using a variety of pressurant gas diffusers. Data obtained with straight-pipe gas injectors were not included as this injector configuration results in high heat and mass transfer rates at the liquid surface† . With a few exceptions, the data variables fall within the ranges specified for the Epstein and Anderson correlation as shown in Table 3. The most significant differences are some data points having longer total outflow time and the low ambient heat flux for the NASA data.

In this work, the Epstein and Anderson correlation is compared to the NASA data and a revision of the correlation is provided.

Comparison of Data to Epstein and Anderson Correlation

Although not stated, the Epstein and Anderson correlation assumes that the tank is completely expelled (i.e., liquid residuals are zero). In the NASA experiments, expulsions were stopped at approximately five percent liquid fill level. Therefore, when comparing the predictions to the data, adjustments were made to correct for the liquid residuals. This correction was achieved by omitting the liquid residual volume and the mass of the corresponding tank wall from the analysis—i.e., the appropriate tank volume does not include the liquid residual volume and the appropriate tank mass does not include the mass of the tank wall that remained wetted at the conclusion of the experiments.

Epstein and Anderson state that their correlation may be used when the initial ullage volume does not exceed 20 percent of the total tank volume. For the present data set, initial ullage volumes were from 5 to 14 percent of the tank volume after correcting for the liquid residual volume.

The correlation further assumes a uniform wall thickness and material. All of the NASA data was obtained in tanks fitted with lids that were thick compared to the tank walls, and in the case of data from references 5-8, the lid material differed from that of the tank. The adjusted tank wall density, wall thickness and wall specific heat capacity were obtained as follows:

$$\tilde{\rho}_w = \frac{m_{tank} + m_{lid}}{V_{tank} + V_{lid}} \tag{6}$$

$$\tilde{t}_w = \frac{m_{tank} + m_{lid}}{\tilde{\rho}_w A_w} \tag{7}$$

and

$$\tilde{c}_p = \frac{m_{tank} c_{p,tank} + m_{lid} c_{p,lid}}{m_{tank} + m_{lid}} \tag{8}$$

The adjusted values obtained from Eqs. 6-8 were then entered into Eq. 3 to calculate the "C" parameter.

† For the present data set, the ratio of total mass transferred across the liquid-vapor interface-to-total pressurant mass ranged from -0.26 to 0.19, where a positive value represents condensation. Although this information is not generally known, one should be careful to apply the correlation in its present form only to conditions where mass transferred across the liquid-vapor interface is no greater than ±25 percent of the pressurant mass. Some cases where this condition is known not to hold are expulsion during liquid sloshing and expulsion of slush hydrogen.

Comparison of predicted and experimental results are shown in Fig. 1. The data points generally fall above the diagonal line representing perfect agreement. Specifically, the Epstein and Anderson correlation predicts a greater collapse factor than the experimentally determined value for all but two points. Errors ranged from -4 percent to +27 percent with a mean error of +15 percent. The root mean squared error is 5.6 percent.

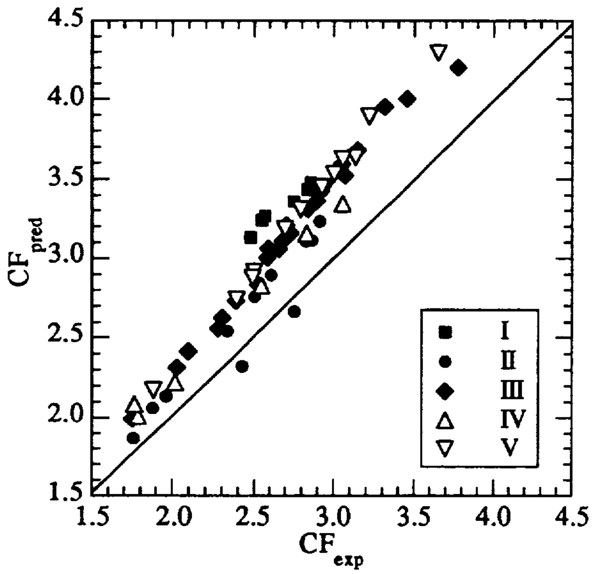

Figure 1 — Correlation results using Epstein and Anderson's definition for equivalent diameter.

Modification of the Correlation

All of the NASA data were obtained with tank hardware having initially warm thermal mass concentrated at the top of the test tanks. It is suspected the major cause of the discrepancy in the above comparison is the inclusion of the warm thermal mass of the upper tank wall, tank neck and lid. This mass is not initially at the cold saturation temperature of the propellant, but at elevated temperatures approaching that of the ambient temperature of the surroundings or of the pressurant gas inlet temperature. In Test Series II to V, the ullage was exposed to warm pressurant gas flow prior to the test during a gas temperature conditioning procedure. In Test Series I, there was no conditioning of the pressurant gas temperature, however, initial lid temperatures were near ambient temperature. Since this upper wall thermal mass is initially warm, it is not expected to absorb much thermal energy from the pressurant gas. Thus, it is reasonable to attempt to modify the correlation by excluding the initially warm thermal mass.

In their paper, Epstein and Anderson defined the equivalent diameter as the "diameter of a cylindrical tank having the same wall surface area and total volume as the tank under investigation." Here an alternate definition for the equivalent diameter is suggested:

$$D_{eq} = \frac{4\Delta V}{A_{sw}} \tag{9}$$

where ΔV is the volume of expelled liquid and A_{sw} is the area of wall surface swept by the liquid free surface during the expulsion process (i.e., the wall surface area initially wetted by the propellant that is exposed to gas at the end of the expulsion). For an initially full tank that is completely expelled, this definition is equivalent to Epstein and Anderson's definition. Otherwise, this definition removes the influence of both liquid residuals and warm tank walls above the initial liquid level. When Epstein and Anderson's correlation form and constants are used with the alternate equivalent diameter, much improved results are obtained as seen in Fig. 2. Errors range from -10 percent to +14 percent with a mean error of +0.6 percent. The root mean squared error is 4.7 percent.

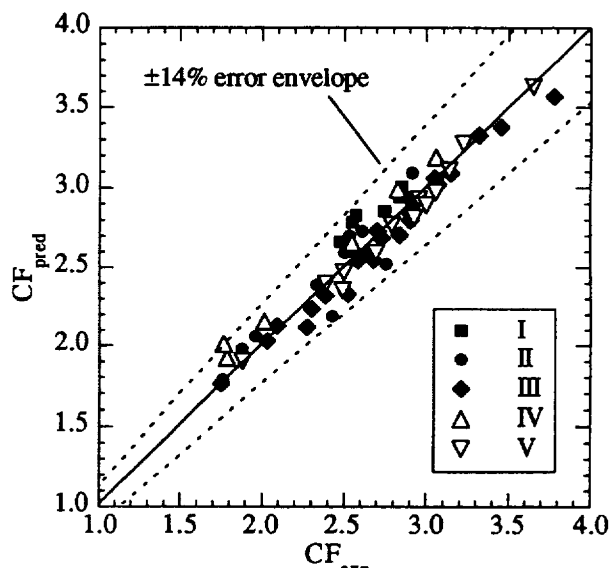

Figure 2 — Correlation with alternate definition for equivalent diameter.

Revision of Fitted Constants

The constants p_1 through p_4 were updated using a nonlinear least-squares fit of the NASA data. Since the maximum ambient heat flow of the NASA data was less than one half of one percent of the maximum from

	p_1	p_2	p_3	p_4	p_5	p_6	p_7	p_8
Epstein & Anderson	0.330	0.281	4.26	0.857	1.50	0.312	0.160	0.986
Revised Constants	0.300	0.291	5.71	0.906	1.50	0.312	0.160	0.986

Table 4 — Comparison of original and revised constants for the Epstein and Anderson[2] correlation for hydrogen propellant.

Epstein and Anderson's work, no attempt was made to update their constants for the environmental heat input (constants p_5 through p_8)[§] . The comparison of predicted collapse factor with the experimental data is shown in Fig. 3 and the revised constants are listed in Table 4 along with Epstein and Anderson's values. The revised constants give a slightly smaller error envelope and root mean squared error. Errors range from -8 to +13 percent with a mean error of +0.5 percent. The root mean squared error is 4.1 percent. Note that the revised constants reduce the error envelope, but only by an incremental amount. This indicates that the use of the alternate definition of equivalent diameter with the original Epstein and Anderson correlation has merit and can be used with confidence.

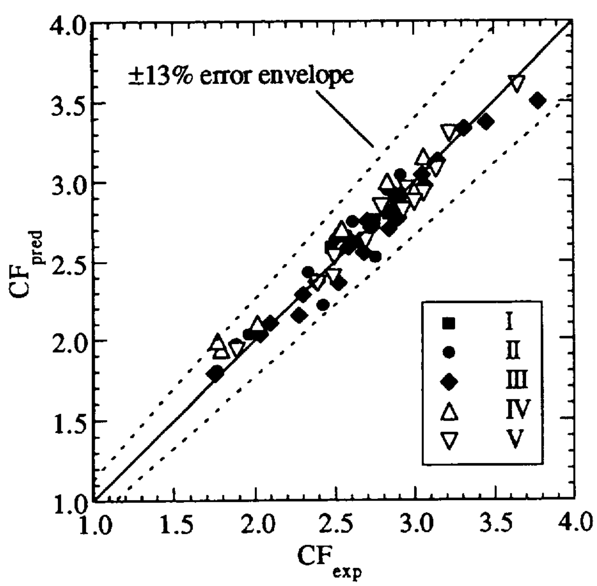

Figure 3 — Correlation with alternate definition for equivalent diameter and revised constants.

§ The exponential multiplier in Eq. 1 containing the "Q" parameter has values ranging from 0.949 to 0.999 for the present data set. Therefore, its impact on the correlation is relatively small.

Recommendations

The correlation of Epstein and Anderson is considered reliable for axisymmetric liquid hydrogen tanks provided one remains within the specified range of variables, the initial ullage space is not more than 20 percent, the liquid is completely expelled, and the tank wall initially above the liquid level is near the saturation temperature.

If the liquid is not completely expelled, or if the upper tank wall temperatures are significantly above the propellant saturation temperature, then the alternate definition of equivalent diameter presented within should be employed. The portion of thermal mass initially at elevated temperatures with respect to the saturation temperature or thermal mass below the final liquid level should be excluded when calculating the "C" parameter (Eq. 3) and equivalent diameter (Eq. 9).

The correlations do not contain dimensionless groups that quantify heat and mass exchange between the pressurant and the propellant. Therefore, the correlations should not be used to predict pressurant mass requirements in systems where these effects are relatively large—e.g., systems with liquid sloshing or slush hydrogen systems.

The ±13 to ±14 percent error envelope of the present work compares favorably with the ±12 percent error envelope reported by Epstein and Anderson. The correlations are useful tools for estimating pressurant mass requirements in axisymmetric liquid hydrogen tanks. The reliability of these correlations may be as good as, if not better than, current computer codes used to predict pressurant mass requirements.

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