Thermal Effects during Pressurization of Vehicle Gas Tanks from Reservoir Tanks

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Two theoretical methods of analyzing the process of filling vehicle-borne, high pressure gas tanks from gas reservoirs are presented. The first method assumes that a given weight of gas at ambient temperature and a specified pressure is required in the vehicle tank and selects a tank volume to exactly accommodate these conditions. The second method assumes the vehicle tank has a given volume and then predicts the temperature overshoot that results from loading a fixed weight of gas to a predetermined pressure and, thereafter, the final gas pressure after the vehicle tank and its contents have returned to ambient temperature. In addition, a means is presented for predicting to what pressure the vehicle tank must be loaded such that, after returning to ambient temperature, it will contain at least the desired weight of gas at the desired pressure.

Nomenclature

B	= universal gas constant = 1546 (ft-lbf/mole °R)
C_P	= gas specific heat at constant pressure (Btu/1bm °R)
C_V	= gas specific heat at constant volume (Btu/1bm °R)
J	= 778.26 (ft-1bf/Btu)
k	= specific heat ratio C_P/C_V
M	= number of moles of a gas
$\bar{M}$	= molecular weight of a gas
N	= the number of moles of a gas contained in volume, V
P	= pressure (psi, psf, or atm)
Q	= quantity of heat (Btu)
Q_c	= heat transferred between the vehicle tank gas and the tank walls during the fill process (Btu)
R_G	= specific gas constant for gas, G (ft-1bf/1bm °R)
T	= temperature (°R)
V	= volume (ft^3)
W	= weight of gas (1bm)
Wk	= work done on or by gas (ft-1bf)
μ	= the Joule-Kelvin Coefficient (°C/atm or °R ft^2/1bf)

Subscripts

1	= reservoir conditions (assumed constant)
2	= vehicle tank conditions at end of fill process
3	= vehicle tank conditions after the filled gas has returned to T_3 (usually ambient temperature)
A	= air
H	= helium
m	= gas mixture
S	= maximum permissible value

Introduction

SUPPLIES of helium at relatively high pressures are often required in sounding rockets for such purposes as pressurizing liquid fuel and oxidizer tanks or for attitude control jet systems. Pressures in vehicle tanks of the order of 3500 psi introduce safety problems that necessitate loading as closely as possible to launch time. Experience has shown that the vehicle helium tanks often display an appreciable increase in temperature as the reservoir gas is allowed to flow into the tank. The result is that the fill process is drawn out in time by the need to fill to a predetermined pressure, allow the gas to cool to ambient temperature, and then add more gas. This often-repeated "topping-off" method might take as much as an hour to assure that the final conditions of pressure and temperature in the tank are such that the required energy is available during flight.

The work reported here attempts to derive an approximate analysis of the thermodynamic effects for the purpose of devising a faster and simpler pressurizing gas tank loading procedure. The applicability of the theory used (thus, the conclusions) must be confirmed by experiment because of the fundamental assumptions with respect to the thermodynamic processes involved.

Assumptions

The following assumptions are made for this analysis: 1) the entire fill process is adiabatic in that no heat is assumed to flow from the gas (loaded into the vehicle tank) to or from the tank walls until after the fill process is complete. Although this assumption is clearly incorrect, the magnitude of the error can only be determined by experiment. In any case, the error results in an underprediction of the weight of gas loaded; 2) Eqs. (2) and (6) assume that the expansion from reservoir to vehicle tank conditions is adiabatic and isentropic; 3) Eq. (7) (correctly) assumes a "constant volume" change of conditions from "end-of-fill" through "return to T_3" (usually T_{ambient}); 4) the fill process is so regulated that the gas flow never approaches sonic velocity. If experimental evidence indicates that there is substantial heat transfer, Q_c, between the vehicle tank gas and the tank walls during the fill process, then this heat can be accounted for by adding it to Eq. (4)

$$\Delta T = (Q + Q_c)/C_P W$$

where Q_c is positive for heat flowing from the tank walls to the gas.

Theory

The problem is illustrated schematically in Fig. 1. The reservoir containing gas, G, at pressure, P_1, and temperature, T_1 (ambient), is assumed to contain sufficient mass of the gas to permit the loading of the vehicle tank to desired conditions with no more than negligible effect upon P_1 and T_1. The loading process consists of merely opening the valve and permitting the gas to flow into the vehicle tank until some predetermined value of P_2 is reached. At this point, the valve is closed and the vehicle tank gas will return, in time, to ambient temperature and some pressure (P_3) below that which existed in the vehicle tank at the end of the fill process (P_2).

The field problem involves getting a specified mass (W) of gas into the vehicle tank at a predetermined pressure, P_3, and

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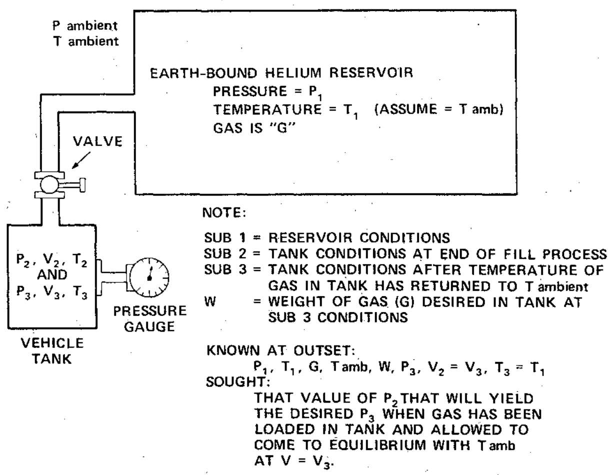

Fig. 1 Schematic sketch of the problem.

anticipated operating temperature, T_3, such that the required energy (work potential) will be provided by the tank gas. Translated into the terms of Fig. 1, the data known at the onset are G, P_1, T_1, V_2, V_3, P_3 and T_3. The unknown quantity is the pressure (P_2) to which the vehicle tank must be raised in order to attain the required value of P_3 after the vehicle tank gas has come to thermal equilibrium with its surroundings.

The first calculation seeks the volume, V_1, of the desired weight, W, of the gas, G, at P_1 and T_1 (reservoir conditions). It is obtained from

$$V_1 = WR_G T_1 / P_1 \tag{1}$$

Next, the work done on the gas in expanding from reservoir to vehicle tank conditions is determined. This process, assumed to be adiabatic and isentropic ($n=k=C_P/C_V$), yields

$$Wk = (P_1 V_1 - P_2 V_2)/(k-1) \tag{2}$$

The heat equivalent of this work is

$$Q = Wk/J \tag{3}$$

and the resulting change in temperature of the gas is

$$\Delta T = Q/WC_P \tag{4}$$

or the final (end of fill process) temperature in the vehicle tank is

$$T_2 = T_1 + \Delta T \tag{5}$$

The vehicle tank pressure (P_2) at end-of-fill is

$$P_2 = P_1 [V_1/V_2]^k \qquad \text{(adiabatic, isentropic)} \tag{6}$$

in which $k=(C_P/C_V)$ for gas, G. Finally, the pressure, P_3, to which the gas, G, in the vehicle tank will come when the temperature (T_2) returns to T_3 (where T_3 is usually taken as T_{ambient}) is obtained from

$$P_3 = P_2 T_3 / T_2 \qquad \text{(constant volume)} \tag{7}$$

In the preceding work it is assumed that the volume of the vehicle tank is fixed (and, of course, known). It is possible, knowing the values of W, P_1, T_1, and the required value of P_3, to obtain that volume ($V_2 = V_3$) of the vehicle tank which will contain W pounds of G at T_3 and P_3 from

$$V_2 = V_3 = (WR_G T_3 / P_3) \tag{8}$$

First Method

If the value of V_2 is predetermined from Eq. (8) and this volume is used in Eq. (2), it will be found that the net work done on the gas is zero. This results in $\Delta T = 0$ so at the conclusion of filling the vehicle tank, the gas in this tank will weigh W pounds and will be at $T_2 = T_{\text{ambient}}$ and P_2 (the required pressure). Since $T_2 = T_3$, then $P_2 = P_3$. Moreover, if the thermodynamic assumptions [adiabatic, isentropic for Eqs. (2) and (6), constant volume for Eq. (7)] are valid, then one can decide upon the P_3 and T_3 for any arbitrary W in order to have the correct available energy, solve Eq. (8) for V_2 ($=V_3$) and then design the vehicle tank to have this exact volume. The tank, in this case, can be filled in one continuous operation without appreciable temperature overshoot. The method has the weakness that, if the energy requirements change, a new tank would have to be designed or the second theoretical method substituted for the "preselected volume" method.

Second Method

The second method assumes that the tank volume will be predetermined but will not conform to the definition of V_2 from Eq. (8). This is tantamount to assuming that the vehicle tank is already designed and built when the energy level required by the gas is determined. An examination is made here to define that pressure to which the vehicle tank must be over-pressurized (in excess of the desired P_3 value) during the fill process to assure that when the gas has slowly returned to ambient temperature (T_3), the desired P_3 value with the appropriate weight of gas is obtained. The relation between P_2 and P_3 is obtained from Eq. (7). Note that T_3 will usually have the value of $T_1 = T_{\text{ambient}}$ but the subscript 3 is retained such that any arbitrary value may be assigned.

$$P_2 = P_3 (T_2 / T_3) \tag{9}$$

Putting this value into Eq. (6), get

$$P_3 (T_2/T_3) = P_1 [(V_1/V_2)]^k \tag{10}$$

in which all but T_2 are specified. Note that here P_2 is the value to which the tank must be pressurized in order to yield the desired P_3 after T_2 returns to T_{ambient}. From Eqs. (2-4)

$$\Delta T = \frac{P_1 V_1 - P_2 V_2}{(k-1)\ C_P W_G J} \tag{11}$$

or, with Eq. (5)

$$T_2 = T_1 + \frac{P_1 V_1 - P_2 V_2}{(k-1)\ C_P W_G J} \tag{12}$$

Combining Eqs. (10) and (12)

$$P_2 = \frac{P_1 V_1}{V_2} - \left\{ \frac{P_1 T_3 \left[\frac{V_1}{V_2}\right]^k - P_3 T_1}{V_2 P_3} \right\} C_P W_G J (k-1) \tag{13}$$

in which P_2 is the appropriate end-of-fill pressure.

Discussion

If tests should demonstrate that the assumptions yield reasonable estimates, then two design procedures are available: 1) preset the volume of the vehicle tank [Eq. (8)] for each application and build the tank with exactly that volume. This design results in a system which can be filled all at once to the desired final pressure without temperature overshoot; and 2) design the vehicle tank to have a volume slightly larger

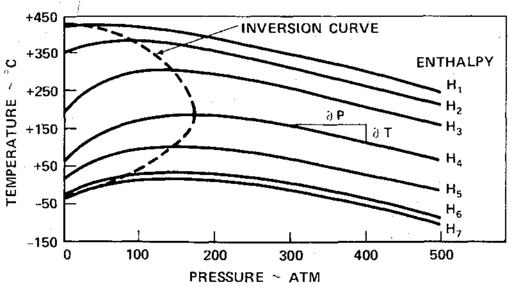

Fig. 2a Typical isenthalps on *T-P* diagram.

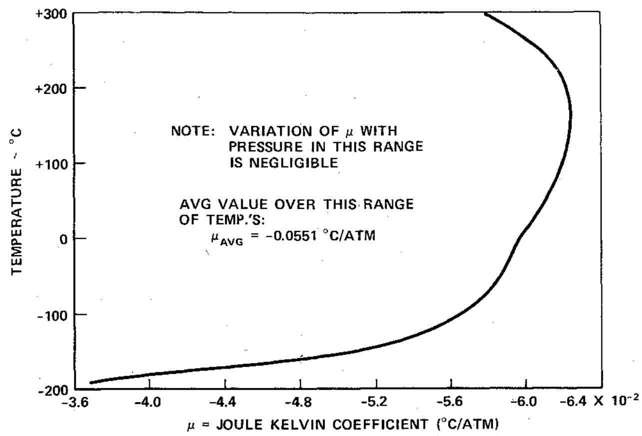

Fig. 2b Joule-Kelvin Coefficient vs temperature. [1]

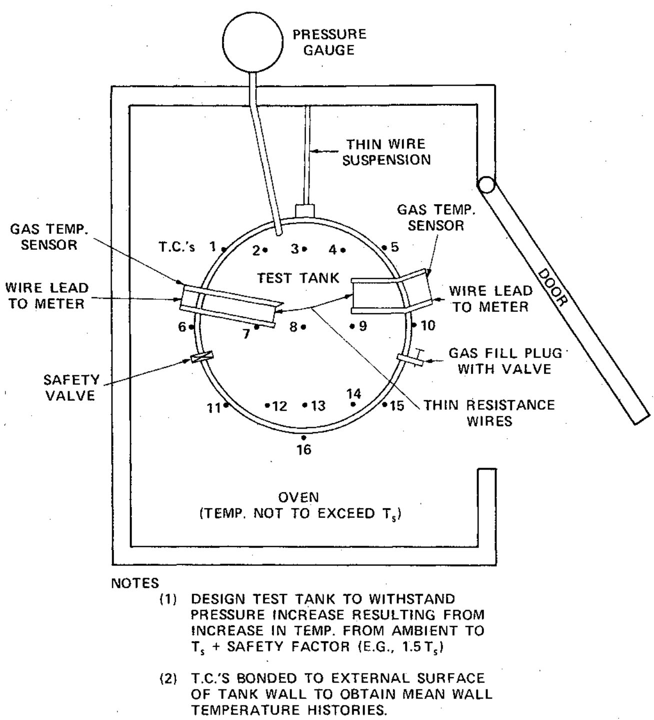

Fig. 3 Schematic sketch of test equipment for heat transfer from tank walls to the gas in the tank.

than that indicated by Eq. (8) and then calculate [Eq. (13)] that pressure (P_2) to which the gas in the tank must be raised in a single-shot fill process such that, upon cooling to an arbitrary final temperature (T_3), the tank will contain not less than the required weight of gas at the required temperature and pressure. This process requires that the vehicle tank be "over-pressurized" to accept the pressure overshoot required by the temperature overshoot associated with the filling process.

A factor which must be accounted for in either case is the possibility of additional heating of the vehicle tank after completion of the fill process but before use of the gas (e.g., aerodynamic heating). There is particular danger in this form of heat addition if the vehicle tank is of the structurally integral type. If the primary purpose of the gas is to pressurize the vehicle liquid propulsion system tanks, then normally a sufficient amount of gas is used prior to any aerodynamic heat input (while the vehicle is lifting off and accelerating through Mach 1) that a pressure rise in excess of the tank capacity is practically impossible. If, however, the heat source is either of solar origin or is internal (nonaerodynamic in origin) or if no part of the gas is used until after the heat is input (as might occur in the case of a liquid fueled second stage pressurizing gas tank), then the vehicle tank must be either protected by insulation or designed to withstand the resulting overpressure.

The magnitude of the overpressure which results from heat sources is difficult to predict without tests on the specific configuration. Equations (4, 5, and 7) can be used to predict the pressure overshoot from the fill process and, indeed, can include the effects of added heat if the magnitude of the heat that can actually get into the gas (not just the tank walls) is known. This latter heat that is received by the gas can be estimated for each individual case by means of extrapolated or interpolated data from heating tests such as that suggested in paragraph A of the Appendix.

The need to consider all possible sources of heat input (which is common to all pressure tank design problems) does more or less tie in with the second analytical method in that some design over-pressure may be required by either the fill process or later heat input. Thus, the increasing of the tank strength satisfies both needs.

Attention is called to the fact that heat transfer from the vehicle tank wall to the gas within is ignored during the fill process only. Tests should be run (using some system similar to the test tank of Fig. 3) to measure the validity of this assumption. In general, for the case for which the second analysis applies (V_2 actual is greater than required – hence temperature overshoots), the heat loss to the tank wall will result in slight overfilling of the vehicle tank. Thus, provided that this overfilling does not create dangerous pressures from subsequent heat input, the energy level in the vehicle tank will be greater than that calculated. At the end of the fill process, the pressure will be correct, the temperature slightly lower than anticipated but the weight of gas loaded will be a slight amount greater than that originally planned.

Sample Problems

As a means of illustrating the use of the methods discussed, a sample source reservoir is hypothesized. The gas is helium and the reservoir is assumed to have sufficient volume to permit removal of W (lbm) of helium without significantly changing the reservoir pressure and temperature. The reservoir conditions are

$$P_1 = 6000\ (\mathrm{psi}) = 864{,}000\ (\mathrm{psf})$$
$$T_1 = 540\ (^\circ\mathrm{R}) = 80\ (^\circ\mathrm{F})$$
$$R_{\mathrm{He}} = 386\ (\mathrm{ft\text{-}lbf/lbm}\ ^\circ\mathrm{R})$$
$$k_{\mathrm{He}} = C_P/C_V = 1.658$$
$$C_{P_{\mathrm{He}}} = 1.25\ (\mathrm{Btu/lbm}\ ^\circ\mathrm{R})$$

The desired final conditions in the vehicle tank are

$$W = 5.0\ (\mathrm{lbm})$$
$$P_3 = 3500\ (\mathrm{psi}) = 504{,}000\ (\mathrm{psf})$$
$$T_3 = 540\ (^\circ\mathrm{R}) = 80\ (^\circ\mathrm{F})$$

Case 1

For the first case, the vehicle tank volume is selected such that it holds exactly 5.0 lbm of helium at 3500 psi and 540°R.

To do this, the volume is obtained from Eq. (8) and is 2.068 ft^3. From Eq. (1), the volume of 5.0 lbm of helium at reservoir conditions is 1.206 ft^3. The work done on the gas in going from V_1 to V_2 is [Eq. (2)] zero. Thus, since no work is done on the gas, then $T_1 = T_2$ or there is no temperature overshoot. This suggests that the tank can be filled directly to the desired pressure and the helium weight will automatically be the 5.0 lbs that was used to obtain V_2. (Caution must be taken to assure that the filling process does not involve supersonic flow at any time.) These results do not account for the Joule-Kelvin effect which is estimated (in a later section) to be small-to-negligible in this case.

Case 2

This case is the same as Case 1 but, instead of predetermining the V_2 value by means of Eq. (8), it is arbitrarily given the value of 2.5 ft^3. The applicable conditions are

$V_1 = 1.206$ ft^3, $T_1 = 540°$R
$V_2 = 2.5$ ft^3, $P_2 = 3500$ psi $= 504{,}000$ psf
$W = 5.0$ lbs of helium

Now the work done on the gas is no longer zero. From Eq. (2) the work is $-331{,}000$ ft-lbf and the heat equivalent is 425.3 Btu so ΔT is 68.1°R or $T_2 = 148°$F. The tank was filled to the desired pressure (3500 psi) but the helium temperature "overshot" by 68°F above ambient. After the temperature returns to ambient (540°R), the tank will have a pressure of [Eq. (7)] 3108 psi. This clearly results in available helium energy (work potential) definitely less than the design requirement. Accordingly, it is of interest to calculate the pressure to which the vehicle tank must be pressurized in a single-step fill operation in order to end up with the desired 5.0 lbs of helium at 3500 psi and 540°R in the tank. This calculation utilizes Eq. (13) to get $P_2 = 755{,}630$ psf (5247 psi). Using the assumption of a constant volume process to determine whether or not this pressure will reduce to the desired 3500 psi, the work is [Eq. (2)] 1,287,000 ft-lbf from which the heat equivalent is -1654 Btu (note that if Wk = negative, ΔT is positive) and $\Delta T = 265°$R or $T_2 = 805°$R which temperature with the calculated P_2 value from Eq. (7), yields $P_3 = 3522$ psi. This figure is within 0.6% of the anticipated value (3500 psi) so the analysis is apparently valid in theory and lacks only experimental verification of the assumptions. Note, however, that in order to assure a final pressure of 3500 psi, it has been necessary to load the 2.5 ft^3 tank with an excess amount of gas – in this case about 6.08 lbs instead of 5.0 lbs. If exactly 5 lbs of helium is to be loaded, the tank volume must be predetermined. If the total energy and tank pressure are the governing factors and only a minimum gas weight is specified, the above method is valid. In either case the pressure overshoot must be predetermined to avoid a catastrophic explosion on the one hand or failure to provide the required energy on the other.

Case 3

It is now of interest to consider the same conditions as Case 2 but to remove the assumption of a vehicle tank which has been evacuated of air prior to the filling process. Instead, the tank is assumed (initially) to contain air at one atmosphere pressure and ambient temperature. For this case, the following initial conditions apply to the air

$P_A = 2116.2$ psf
$V_A = V_2 = V_3 = 2.5$ ft^3
$T_A = T_{\text{ambient}} = 540°$R
M_A = number of moles of air in V_A
B = universal gas constant = 1546 (ft-lbf/mole °R)

The number of moles of air is

$$M_A\ (P_A V_A / B T_A) = 0.0063 \text{ moles (air)}$$

The number of moles of helium is

$$M_H = (P_H V_H / B T_H) = 1.2484 \text{ moles (helium)}$$

So the number of moles of mixture is

$$M_M = M_A + M_H = 1.2547 \text{ moles (mixture)}$$

The temperature of the mixture after adiabatic loading of helium on top of the air is

$$T = (P_M V_M / M_M B) = 649.6°R$$

The temperature of the helium (assuming the tank was evacuated of air prior to the filling with helium) is

$$T_H = (P_2 V_2 / M_H B) = 652.9°R \tag{14}$$

Therefore, accounting for air left in the vehicle tank changes the post-loading temperature by only about (3.3°) 0.5%. In any case, the tank would probably be purged of the air to eliminate moisture or other contaminants so, leaving the purging helium in the tank, the theoretical temperature change would be less than that shown above. Although the use of only one equation of state to calculate T_M and T_H is not strictly correct, it is used here solely to demonstrate that the air in the tank prior to fill can reasonably be ignored. As a matter of interest, the basic assumption that the gases behave as perfect gases is not correct but in the region examined it does not introduce large errors. (In the present case, the equation $PV = N\bar{M}RT$ was substituted for $PV = RT$ resulting in a 2.5% decrease in the post-fill temperature if the vehicle tank is assumed to start out full of air at ambient conditions as opposed to being evacuated. $\bar{M}$ is the molecular weight of the gas and N is the number of molecular weights of gas in volume, V.)

Case 4

The only other case of immediate interest is the case in which the predesigned vehicle tank has a volume which is less than the volume obtained from Eq. (8). Assume all values are identical to those of Case 2 except $V_2 = 1.5$ ft^3 instead of 2.5 ft^3. In this case, the work equation [Eq. (2)] yields $WK = 421{,}300$ ft-lbf and the heat equivalent is 541 Btu. Then $\Delta T = -87°$R and $T_2 = 453°$R. Notice that if the negative work of Case 2 indicates work done on (hence heat into) the gas, then the positive work indicated here requires that work has been done by the gas so the resulting ΔT must be negative. The case is actually a trivial one, however, because at the desired P_3 and T_3 the 1.5 ft^3 tank will not satisfy the energy requirements exactly. The above T_2 will rise to $T_3 = T_{\text{ambient}}$ and the pressure will be higher than intended. That is [Eq. (7)], $P_3 = 4172$ psi. This pressure is considerably above the desired 3500 psi but if the 3500 psi is held at T_3 in the 1.5 ft^3 tank, the energy requirement will not be fulfilled. The obvious conclusion to this case is that no tank having a volume which is less than that indicated by Eq. (8) should be used.

Joule-Kelvin Effect

The Joule-Kelvin (or Joule-Thompson) effect is a phenomenon of real gases which (in certain temperature and pressure regions) causes the gas temperature to increase with decrease in pressure for a throttled process. The Joule-Kelvin Coefficient is defined as

$$\mu(\partial T/\partial P)_H \tag{15}$$

which is nothing more than the slope of an isenthalp plotted on a $T-P$ diagram. Isenthalps plotted on $T-P$ diagrams have regions of positive and of negative slopes. The locus of zero slopes on a large number of isenthaps for any gas is called the "inversion curve" for that gas and serves as the line of separation between the plus and minus slopes (see dashed line of Fig. 2a). For all points lying to the left of the inversion curve, a decrease in pressure will cause a decrease in temperature. For all points to the right of the inversion curve (or "outside" the curve), decrease in pressure will cause an increase in temperature. An isenthalpic process is assumed, of course. Thus, adopting an appropriate sign convention to conform to the above changes in temperature with pressure, the temperature change is defined as

$$\Delta T = \mu(\Delta P) \tag{16}$$

The value of μ (Ref. 1) for helium in the range shown in Fig. 2b is virtually independent of pressure except at the extreme lower end of the temperature scale – the region beyond the interest of the present study. Accordingly, a conservative estimate of μ (averaged over the entire range of Fig. 2b) is: $\mu \approx -0.0551°C/atm$. This value covers the range $1 \text{ atm} \leq P \leq 200$ atm and $-175°C \leq T \leq +300°C$. For the case of sample problem 2: $P_I = 408$ atm, $P_3 = 213$ atm, and $\Delta P \approx 200$ atm. So

$$\Delta T = \mu(\Delta P) = 0.0551 \times 200 \approx 11°C$$

The actual pressures in the sample problem are appreciably higher than those of Fig. 2b because no data was available for $P \approx 400$ atm. However, the small rise in temperature calculated suggests that, inasmuch as the temperature range of interest is considerably above the (−175°C) of the Ref. 1 lower limit, the Joule-Kelvin effect will not grossly affect the temperature overshoot estimates for the fill process.

Source Material

The Joule-Kelvin effect is discussed in some detail for general gases in Chap. 14 of Ref. 2, Chap. 9 of Ref. 4, and specifically applied to helium in Ref. 1. A convenient summary of gas laws for constant volume, constant pressure, constant temperature, reversible adiabatic (isentropic) and polytropic processes is found commencing on p. 293 of Ref. 3.

Conclusions

The following conclusions have resulted from the work reported here: 1) the first and most urgent conclusion is that the assumptions upon which the analytical procedures are based must be verified by experiment before attempting to apply them to an actual vehicle case. Subsequent conclusions are predicted on the assumption that this verification has been completed; 2) if the weight of gas (to be stored in the vehicle tank at specific temperature and pressure conditions) is known, the vehicle tank can be predesigned to have that exact volume which will prevent temperature overshoot during the fill process such that the tank can be loaded in a single, continuous flow from the reservoir; 3) if the more general case (in which the tank has a volume greater than that specified in number 2, above) is considered, a single fill process can still be used if the tank has sufficient strength to accommodate an appreciable pressure overshoot. That is, the tank can be filled to a pressure which lies somewhere between the desired final pressure and the reservoir pressure. This excess pressure offsets the effects of the temperature overshoot (caused by the work done on the gas) and the final pressure and temperature in the vehicle tank will be as required; 4) the temperature overshoot effects arising from the Joule-Kelvin effect for helium in the regions of pressure and temperature of interest in most sounding rocket applications are relatively small and are not expected to have significant effect upon the fill process; 5) the entire fill process (if large pressures, e.g., 3500 psi, in the vehicle tanks are required) may be assumed to be independent of whether or not the air is evacuated from the vehicle tank prior to fill; and 6) once the required P_3, T_3 and W are defined, the vehicle tank should never have a volume which is less than V_2 as defined by Eq. (8).

Appendix

Two specific tests are suggested as a means of 1) establishing the degree of applicability of the assumed adiabatic nature of the fill process; and 2) demonstrating the degree of accuracy with which the temperature overshoot can be predicted and, ultimately, how closely it is possible to achieve the final conditions of gas weight and pressure at (usually) ambient temperature by means of the "pressure overshoot," single-fill-process implied by Eq. (13). The same equipment can be used to test the validity of the preselected volume method of the first sample problem (Case 1).

A. Tank Wall-To-Gas Heat Transfer Test

The basic equipment required to derive mean rates of heat transfer from the test tank wall to the stored gas is shown in Fig. 3. Notice that the system shown provides the means of obtaining average heat rates between the tank wall and the stored gas. The parameters which should be varied are the tank wall temperatures and the gas pressures (original amount of gas loaded into the tank at ambient temperature – prior to placing tank in oven). The 16 temperature sensors shown bonded to the tank outer surface, the two internal (thin wire resistance) gas temperature sensors and the test tank pressure should all be recorded continuously. Various values of the oven temperature (T_S) should be used and the history of all measurements recorded until equilibrium is reached.

B. Check Fill Process Theory

If the test tank is removed from the oven and a pressure source (reservoir) attached to the gas fill plug, the equipment can be used to measure the conditions for Cases 1 and 2. Such tests would utilize corrections in the "adiabatic fill process" assumption if the oven tests so indicate. Notice that a single test tank can be used for numerous tests of Case 2 by merely varying the total weight of the gas to be loaded in the calculation of V_I in Eq. (1). For each value of W in Eq. (1), a different pressure and temperature of the gas at the end of the fill process will result.

Case 1 is simulated by selecting W such that $P_I V_I$ equals $P_2 V_2$ (or the work done on the gas is zero). This value of W is $W = V_2 P_2 / R_G T_I$ in which $P_2 = P_3 =$ the final desired pressure and V_2 is the actual test tank volume. This value of W is used in Eq. (1) to get the applicable V_I for use in Eq. (2). If the theory of Case 1 is followed using the above W, this W should be in the tank after it is pressurized to P_3. (This can be confirmed by comparing the empty and filled weights of the tank.) Also, the temperature should be $T_3 = T_I$ at the conclusion of the fill process. Note that tank weighing to confirm the amount of gas loaded should always be done where practicable.

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