CALCULATION OF THE MAIN PARAMETERS OF STORED-GAS PRESSURIZATION SYSTEM

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Abstract

This paper describes a simple analysis and the calculation methods used to estimate design parameters of pressurization system of pressure-fed liquid rocket engines. The method applies to stored-gas systems without heating, and doesn't take into account the heat transfer between the pressurant and propellants, neither between the fluids and its environments (walls and internal hardware). It is devised for use during the preliminary design of storable propellant systems, although it can be used (with caution) for rough estimates in cryogenic propellant systems. A computational algorithm is also given. Results of the methods applied to a typical Reaction Control System of a launch vehicle illustrate its use in practical situations.

Keywords: Pressurization system, Tank pressurization, Rocket design, Liquid rocket engine, Reaction control system.

1. INTRODUCTION

Planning for launch and space vehicle and mission requirements necessitates continuing optimization of propellant tank pressurization systems. This optimization is realized in an accurate determination of pressurant requirements for any given set of operating parameters, such as tank pressure, inlet gas temperature, liquid outflow rate, and tank size. This knowledge will allow the design of a system that carries only the mass (pressurant gas and associated tankage) necessary to accomplish the mission.

Pressurant gas and total stored-gas requirements for launch and space vehicles may be predicted by different models of the pressurization process. However, preliminary design studies require a fast and reasonably accurate method of predicting without resorting to complex computer programs.

Several simple studies have been made to predict the mass requirements in pressurizing storage vessels. Some studies, as in (Momenthy, 1964), use the *saturation rule*, which usually predicts gas requirements that are 10 to 15% conservative (larger than actually required) if only pressurization and transfer are considered (no hold time).

In more sophisticated studies, improved accuracy generally has been achieved in calculating pressurant mass. Thermal stratification and other thermochemical process inside a propellant tank are considered in some computer programs (Naumov et al., 1999).

The computer program described in (Masters, 1974) is relatively uncomplicated and has been used for numerous trade-study calculations; although never used specifically for propellants other than cryogens, the program is considered suitable for storable-propellant applications. In addition to these computer programs, there have been a number of programs developed for specific applications (these programs are for private use and, therefore, not divulged in open literature).

Although the most accurate method of predicting pressurant requirements is with a computer program that had been adjusted and verified by experiments, it is advantageous to have a fast, reasonably accurate method to determine the total mass of pressurant gas required without resorting to complex computer programs. This type of analysis is necessary in comparison and optimization studies for preliminary design, where the number of possibilities to be considered precludes a detailed computer analysis of each case.

This report presents a discussion of the problem and a simple approximate method for estimation the total required mass of pressurant. The technique to be described here is devised for use in preliminary design analysis, including the optimization calculations on design of pressurization systems. It is extracted from (Oliveira, 2000), where there is a complete analysis and the program listing, and must be used with reserve for situations besides those explicitly cited in the text. Sample cases are included to illustrate the use of this methodology, which is restrict to pressurant models of perfect gas and real gas by compressibility formulae or tables (other gas models could be easily implemented).

2. STORED-GAS PRESSURIZATION SYSTEMS

Stored-gas pressurization systems are widely used. The gas is usually stored in a tank at an initial pressure ranging up to 700 bar (although rarely overcome 250 to 300 bar) and supplied to the propellant tanks at a specified pressure controlled by a regulator. These systems have achieved a high level of reliability.

A commonly used configuration of stored-gas system without heating is shown schematically in Fig. 1. It consists of a high-pressure storage tank, a start and shutdown valve, a pressure regulator, and a thrust chamber. Regulated pressurant gas is dueled directly to the propellant tanks. This has the advantage of great simplicity. However, the mass of the system is relatively high because of the low temperature and mass density of the gas. In some expulsion methods are used metallic (as that depicted on Fig. 1) or elastomeric diaphragms, or inflatable elastomeric bladders. The following discussions will be restricted to configurations like that shown on Fig. 1.

The basic design parameter of a pressurization system is the quantity of gas required to pressurize the propellant tanks. However, the gross mass of the stored gas required for a given system depends also on the system design, on the expansion process during operation, and on the environmental temperature range within which the system must function.

3. DETERMINATION OF PRESSURANT REQUIREMENTS

The physical and chemical processes which take place during the expulsion of a liquid propellant from a tank by a gas or gas mixture are numerous and difficult to analyze. Even the simplest systems require simultaneous, time-dependent modeling of the fluid flow and heat transfer. Applicable experimental data for a selected system are often limited. Thus, the basis for the analytical approach is frequently narrow and uncertain. As a result, the initial design calculations of the quantity of pressurant gas required must be considered approximate until verified experimentally. The refinement of the analytical approach to minimize discrepancies between theoretical predictions and actual test results an art requiring experience and thorough understanding of the physical processes.

The required mass of gas required for accomplish the propellant tank pressurization is a function of the ullage mean temperature at cutoff, which is derived with the gas equation of

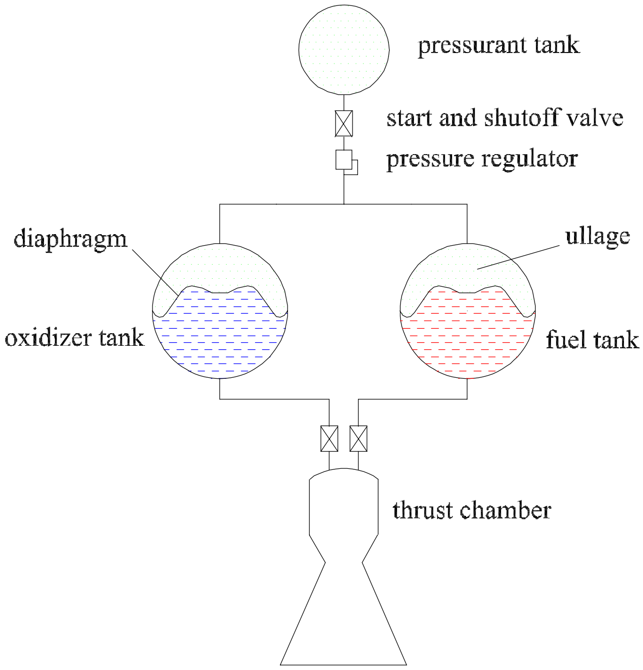

Figure 1: Stored-gas pressurization system without heating.

state and the energetic balance of the process of transformation between the initial and the final states.

If the system operating duration is relatively short, or if the pressurant temperature is close to the propellant and hardware temperatures, heat transfer and pressurant/propellant mass-transfer effects can be neglected. The required pressurant mass in the propellant tanks can then be calculated as follows:

$$m_{\mathrm{uf}} = Z_{\mathrm{uf}} \frac{p_{\mathrm{u}} V_{\mathrm{l}}}{\mathcal{R}_{\mathrm{g}} T_{\mathrm{uf}}} , \tag{1}$$

where: m_{uf} – required pressurant mass in the propellant tanks; p_{u} – propellant tank ullage pressure; V_{l} – volume of propellants expelled; $\mathcal{R}_{\mathrm{g}}$ – gas constant of the pressurant; T_{uf} – mean temperature of entering pressurant; Z_{uf} – compressibility factor of pressurant at ullage end condition.

4. VARIATION IN PRESSURANT TEMPERATURE

4.1 Final Gas Temperature in Pressurant Tank

High pressure gas outflows from pressurant tank, after start/shutdown valve is opened, throttles in pressure regulator up to the feeding pressure, and enters the propellant tanks. The remaining gas in pressurant tank begins to expand, with the corresponding temperature decrease. As a result of gas temperature decrease, occurs heat transfer from tank's wall to the remaining gas in the pressurant tank. But, due to the rather small heat transfer, as a result one can consider a decrease in the gas temperature, or in other words, it takes place a process of polytropic expansion of gas with polytropic exponent n lower than adiabatic exponent k $(1 < n < k)$.

Assuming known the initial gas temperature T_{gi} and pressure p_{gi} at the pressurant tank, the final gas temperature T_{gf} in the pressurant tank can be estimated by use of the equation of a polytropic process of transformation from the initial state $(T_{\mathrm{gi}}, p_{\mathrm{gi}})$ to the initial one $(T_{\mathrm{gf}}, p_{\mathrm{gf}})$:

$$T_{\mathrm{gf}} = T_{\mathrm{gi}} \frac{Z_{\mathrm{gi}}}{Z_{\mathrm{gf}}} \left(\frac{p_{\mathrm{gf}}}{p_{\mathrm{gi}}} \right)^{\frac{n-1}{n}} , \tag{2}$$

where $Z_{\rm gi}$ and $Z_{\rm gf}$ are the compressibility factors of the pressurant gas at the initial and final states in the vessel. Thus, $Z_{\rm gi} = Z_g(T_{\rm gi},\, p_{\rm gi})$ and $Z_{\rm gf} = Z_g(T_{\rm gf},\, p_{\rm gf})$.

The intensity of heat transfer to the pressurant will depend on the operation cycle, on the particular construction of the tank, on the gas nature, and eventually on the existence of heat sources inside the tank.

If a heating source is provided inside the pressurant tank, the expansion process of the gas within would be polytropic ($1 < n < k$) and, depending on the intensity of heat transfer to the gas, isothermic ($n = 1$). For a system without heating inside the storage tank, the expansion process of the gas can be assumed to be isentropic ($n = k$), i.e., no heat is transferred between gas and tank walls. The exponent for the polytropic expansion process, n, is estimated during analytical treatment and verified experimentally.

If a perfect gas model is adopted, then, instead of Eq. (2), the following relation can be used to calculate the final gas temperature in the storage tank: $\frac{T_{\rm gf}}{T_{\rm gi}} = \left(\frac{p_{\rm gf}}{p_{\rm gi}}\right)^{\frac{n-1}{n}}$.

4.2 Final Gas Temperature in Propellant Tank

As a result of gas outflow, its temperature at the pressurant tank decreases continuously from $T_{\rm gi}$ down to $T_{\rm gf}$, as seen above. Before reaches the propellant tank, it passes by start/shutdown valve and pressure regulator (Fig. 1). During the gas throttling in the pressure regulator, the temperature of a real gas usually not remains constant. Particularly for air and nitrogen it decreases, and for helium it increases slightly. Moreover, after entering in propellant tanks, the gas change heat with walls and hardware inside the tanks. It is difficult to calculate theoretically all these temperature changing.

For most analyses, it has been found adequate to assume an adiabatic flow process through regulator and lines. It is a characteristic of this process that the total (or "stagnation") temperature remains constant. Since the gas essentially comes to rest in the propellant tank and no further compression takes place following initial propellant-tank pressurization, it is assumed that the propellant-tank temperature is an average from the temperatures in the pressurant tank.

In order to simplify the consideration of the process of the gas temperature variation inside the ullage volume of propellant tank, it is supposed the following scheme: every gas portion entering the propellant tank has temperature equal to the gas temperature in pressurant tank, at the same moment. So, at starting, the first gas portion arrives to the propellant tank with temperature $T_{\rm gi}$; and the last one, at the end of engine work, with temperature $T_{\rm gf}$. All these portions are mixed up in the tank, so that the average bulk gas temperature in the tank at end of process of propellant expulsion will be in the range from $T_{\rm gf}$ to $T_{\rm gi}$, i.e., $T_{\rm gf} < T_{\rm uf} < T_{\rm gi}$.

Here, in accordance with the above assumptions, the average bulk gas temperature in the tank at end of process of propellant expulsion will be assumed as the arithmetic mean between $T_{\rm gf}$ and $T_{\rm gi}$:

$$T_{\rm uf} = \frac{T_{\rm gi} + T_{\rm gf}}{2}\,. \tag{3}$$

5. DETERMINATION OF STORED-GAS REQUIREMENTS

The main purpose of a pressurization system is to provide the quantity of gas required to pressurize the propellant tanks. However, significant part of the initial pressurant mass remains in storage vessels, feedlines, valves and regulators. So, the total stored-gas requirement must accounts for all these masses. Actually, the gross mass of the stored gas required for a given system depends also on the system design, on the expansion process during operation, and on the environmental temperature range within which the system must function.

Normally, at preliminary design, the main purpose of calculations is to determine the necessary vessel's volume and gas mass supply. Sometimes, at this phase, there is no detailed information about tank configuration, length of feedlines, characteristics of pressure regulators, etc., and it is necessary to assume values for some parameters.

5.1 Initial Data

The following data must be available before initiate the calculations:

- total volume of expelled propellants, V_l, or total volume of fuel and oxidizer tanks, V_t;
- pressure of pressurization, p_u, or propellant tanks pressure, p_t;
- gas constant $\mathcal{R}_g$ and initial temperature of gas in pressurant tank T_{gi}.

The storage pressure, i.e., the initial gas pressure in vessel, p_{gi}, is usually chosen in such way to permit a small and lightweight gas tank design. It is determined by the feeding conditions. It ordinarily ranges between 12 and 35 MPa and is usually 4 to 8 times as high as the propellant tank pressure (Oliveira, 2000).

The final pressure in vessel, p_{gf}, must be greater than ullage pressure at propellant tank, p_u, and the difference must be equal to or greater than the minimum necessary pressure difference on the pressure regulator, Δp_{reg}, for ensure normal work (Oliveira, 2000).

5.2 Mass and Volume Relations

Considers the states of pressurant gas before and after the feeding process. Before feeding, all the gas is stored in the high pressure tank. Then, using the equation of state for the pressurant gas, the initial mass of gas in the vessel, m_{gi}, is given by

$$m_{gi} = \frac{p_{gi} V_g}{Z_{gi} \mathcal{R}_g T_{gi}} \,. \tag{4}$$

At the end of feeding process, part of the gas is in the vessel and part in the propellant tanks. Then, from the equation of state applied to this end condition, the mass of the remaining gas in the vessel can be expressed as

$$m_{gf} = \frac{p_{gf} V_g}{Z_{gf} \mathcal{R}_g T_{gf}} \,, \tag{5}$$

where p_{gf} and T_{gf} are, correspondingly, pressure and temperature of the remaining gas in the vessel at the end of expulsion/feeding process.

The mass of gas in the ullage at the end of feeding process, m_{uf}, is the gas mass which enters the tank up to the shutdown of the system. As seen in **section 3**, it is calculated from the gas state in the propellant tanks at end of feeding process:

$$m_{uf} = \frac{p_{uf} V_l}{Z_{uf} \mathcal{R}_g T_{uf}} \,. \tag{6}$$

Here, V_l is the displaced volume of liquid propellants from their tanks. If the initial ullage and the gas in feedlines are disregarded, and assuming that at end condition the tanks are completely empty, then the end ullage volume is the total volume of propellant tanks, i.e., $V_l = V_t$.

Due to the conservation of the mass of pressurant during the pressurization process, the total mass of gas in vessel and tanks at the end of work is equal to the initial one. Hence, $m_{gi} - m_{gf} = m_{uf}$ and, from these mass relations results:

$$V_g = \frac{p_{uf} V_l}{Z_{uf} T_{uf}} \left(\frac{p_{gi}}{Z_{gi} T_{gi}} - \frac{p_{gf}}{Z_{gf} T_{gf}} \right)^{-1} \,. \tag{7}$$

Taking into account the Eq. (2), the previous equation can rewritten as

$$V_{\rm g} = \frac{Z_{\rm gi} T_{\rm gi}}{Z_{\rm uf} T_{\rm uf}} \frac{p_{\rm uf}}{p_{\rm gi}} V_{\rm l} \left[1 - \left(\frac{p_{\rm gf}}{p_{\rm gi}} \right)^{\frac{1}{n}} \right]^{-1} . \tag{8}$$

This equation shows basically that the vessel's volume is independent on the gas constant of pressurant ($\mathcal{R}_{\rm g}$), and proportional to the pressure ratio $p_{\rm uf}/p_{\rm gi}$, to the temperature ratio $T_{\rm gi}/T_{\rm uf}$, and to the volume $V_{\rm l}$ of expelled liquid propellant. As expected, increasing the ratio $p_{\rm uf}/p_{\rm gi}$, will demand a higher vessel volume. The ratio of compressibility factors $Z_{\rm gi}/Z_{\rm uf}$ indicates that is better to have low compressibility on storage conditions and high compressibility at ullage; but in general this is not the case, as can be seen in (Oliveira, 2000). Fixed all the other parameters, the vessel's volume decreases if is increased the initial pressure $p_{\rm gi}$ and/or the ullage temperature $T_{\rm uf}$. This last effect can be obtained by heating the gas before its entrance in propellant tanks.

Knowing the pressurant tank volume, $V_{\rm g}$, then the initial mass of gas in the pressurant tank, $m_{\rm gi}$, can be obtained from the Eq. (4). However, for further analysis it is interesting to an explicit expression for $m_{\rm gi}$. From Eqs. (4) and (8) results:

$$m_{\rm gi} = \frac{p_{\rm uf} V_{\rm l}}{Z_{\rm uf} \mathcal{R}_{\rm g} T_{\rm uf}} \left[1 - \left(\frac{p_{\rm gf}}{p_{\rm gi}} \right)^{\frac{1}{n}} \right]^{-1} . \tag{9}$$

It shows that the required supply of gas in the bottle $m_{\rm gi}$ is directly proportional to the pressurization pressure $p_{\rm uf}$ and the volume of the displaced liquid $V_{\rm l}$, and inversely proportional to the gas constant $\mathcal{R}_{\rm g}$ and to the ullage temperature $T_{\rm uf}$.

The mass of gas depends from its properties: it is lower for a gas with higher gas constant; so the application of helium instead of air or nitrogen allows to decrease gas mass about 7 times.

To decrease $m_{\rm gi}$ it is also advisable to increase the initial pressure in the bottle $p_{\rm gi}$ and consume the gas to the lowest possible final pressure $p_{\rm gf}$. This latter is usually selected as previously indicated.

The **pressurant use factor**, $f_{\rm p}$, defined as the ratio of stored-gas requirement to the net mass of pressurant utilized in the propellant tank, can be now calculated: $f_{\rm p} = \frac{m_{\rm gi}}{m_{\rm uf}}$.

5.3 Simplifications of Model

In order to simplify the analysis for the influences of different parameters on the pressurant tank volume, it is convenient to rewrite $T_{\rm gf}$ and $T_{\rm uf}$ in more simple ways. Firstly, the temperature of the residual gas in the pressurant vessel can be expresses by

$$T_{\rm gf} = c_1 \, T_{\rm gi} \, , \qquad c_1 = \frac{Z_{\rm gi}}{Z_{\rm gf}} \left(\frac{p_{\rm gf}}{p_{\rm gi}} \right)^{\frac{n-1}{n}} . \tag{10}$$

The value of c_1 depends on the pressure ratio $p_{\rm gf}/p_{\rm gi}$ and on the exponent n, which is determined by heat transfer intensity from vessel's wall to gas. Usually, one can consider values of n in the range (1.15 – 1.33). Analogously, one can assume that the gas temperature in the tank at the end of feeding is proportional to the initial temperature at the vessel:

$$T_{\rm uf} = c_2 \, T_{\rm gi} \, , \qquad c_2 = \frac{1 + c_1}{2} \, . \tag{11}$$

Here, the coefficient c_2 is a factor of proportionality which, for the present simplified model, is obtained from Eqs. (3), (10) and (11).

Taking into account the relationships for initial and the final parameters, as expressed by Eqs. (10) and (11), and assuming perfect gas, then after simple transform of Eq. (7) one can get:

$$V_{\rm g} = c_3 \, \frac{p_{\rm uf}}{p_{\rm gi}} V_{\rm l} \, , \qquad c_3 = \frac{2c_1}{1 + c_1} \frac{1}{c_1 - p_{\rm gf}/p_{\rm gi}} \, . \tag{12}$$

The vessel's volume is proportional to the pressure p_{uf} and the volume V_l of displaced liquid propellant; it decreases with initial pressurant pressure p_{gi} increase, and it is independent on the gas constant of pressurant ($\mathcal{R}_g$).

It is shown in (Oliveira, 2000) that the coefficients c_1, c_2 and c_3 decrease with crescent p_{gi}/p_{gf}.

All the previous equations holds for real gases. In particular, for a perfect gas, c_1 and, therefore, c_2 and c_3 are functions only of p_{gf}/p_{gi} and n. Hence,

$$V_g = V_g\left(\frac{p_{gf}}{p_{gi}}\,,\,\frac{p_{uf}}{p_{gi}}\,,\,V_l\,,n\right)\,, \qquad c_3 = \frac{2}{1-\left(\frac{p_{gf}}{p_{gi}}\right)^{\frac{1}{n}}+\left(\frac{p_{gf}}{p_{gi}}\right)^{\frac{1}{n}-1}-\left(\frac{p_{gf}}{p_{gi}}\right)^{\frac{2}{n}-1}}\,. \tag{13}$$

From the relation for c_3 in Eq. (13), the functional relation (13) and considering that $c_1 < 1$, $c_2 < 1$ and $c_3 > 1$, it is concluded that, for a perfect gas as pressurant, the required storage volume of pressurant increases with higher p_{gf}/p_{gi}, p_{uf}/p_{gi}, n and V_l. An interesting way to represent this relations is a plot of the parametric form $V_g/V_l = c_3\,p_{uf}/p_{gi}$, as shown on Fig. 2, for a perfect gas and $n = 1.2$.

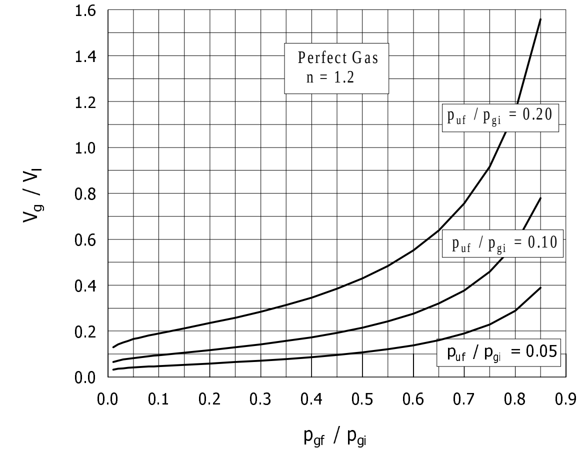

Figure 2: Parametric relations for vessel volume of a perfect gas ($n = 1.2$).

Since the volume of the bottle V_g is known and its shape had been selected, further calculation of the gas-stored system reduces to determining the dimensions and the thickness of the walls of the pressurant vessel, using familiar dependences (Oliveira, 2000).

6. APPLICATION RESULTS

The present methods will be applied to the design calculations of a Reaction Control System similar to the illustrated on Fig. 1 (in reality, there is a bunch of thrust chambers).

The pressurant is compressed nitrogen stored in a spherical aluminum tank of 8 L. The fuel is unsymmetrical dimethylhydrazine (UDMH) and the oxidizer is nitrogen tetroxide (NTO). The propellants are stored in individual aluminum spherical tanks with equal volumes of 25 L, being separated from the pressurant by metallic diaphragms. The pressure difference between the gas and the liquid sides of diaphragm, in each propellant tank, is less than 2 bar. It is necessary to determine the pressurant storage volume and mass for compressed nitrogen for this system.

The nominal pressurant storage pressure is taken as $p_{gi} = 220\,\text{bar}$. The initial gas temperature in the pressurant vessel is $T_{gi} = 285.15\,\text{K}$. The nominal pressure in the liquid cavities of both propellants is $p_t = 13$ bar. Then, considering that the metallic diaphragm introduces a pressure drop of 2 bar, the gas side (i.e., the ullage) must be at $p_u = 15$ bar. It will be disregarded the initial ullage and the gas inside feedlines, valves and regulators. It will be considered as end state the moment when occurs the total expulsion of the propellants; so, the final ullage will

Table 1: Results for the RCS nominal operation.

parameter	value	unit
Pressurant (nitrogen) properties		
$\mathcal{M}_g$	0.0280	kg/mol
$\mathcal{R}_g$	296.940	J/(mol.K)
n	1.200	
Initial condition at pressurant tank		
V_g	6.489	L
p_{gi}	220.000	bar
T_{gi}	285.15	K
m_{gi}	1.686	kg
Final condition at pressurant tank		
p_{gf}	80.000	bar
T_{gf}	240.9	K
m_{gf}	0.726	kg
Final condition at propellant tank		
V_t	50.000	L
p_{uf}	15.000	bar
T_{uf}	263.0	K
m_{uf}	0.960	kg

occupies all the propellant tanks volume: $V_l = V_t = 50\,\text{L}$. The final pressure level in pressurant vessel at the end of propellant expulsion process is taken equal to $p_{gf} = 80\,\text{bar}$.

The main results for the nominal conditions, assuming pressurant as a perfect gas and $n = 1.2$, are presented on Tab. 1. The calculated ullage temperature was $263\,\text{K}$. Ideally, this value should be a little higher than the freezing temperature of NTO ($\approx 262\,\text{K}$). Any way, for pulsed regime of work the calculated value is conservatively a lower limit for the ullage temperature and, so, can be considered that the estimated value satisfies this restriction.

If were used helium as pressurant instead of nitrogen, kept constant all the other conditions, the required mass of pressurant would be $m_{gi} = 0.241\,\text{kg}$. For nitrogen, the estimated value was $m_{gi} = 1.686\,\text{kg}$, a value seven times greater (and equal to the ratio between the molecular masses of nitrogen and helium). The required volume of pressurant would be the same ($V_g = 6.489\,\text{L}$) for both gases, as previously forecasted.

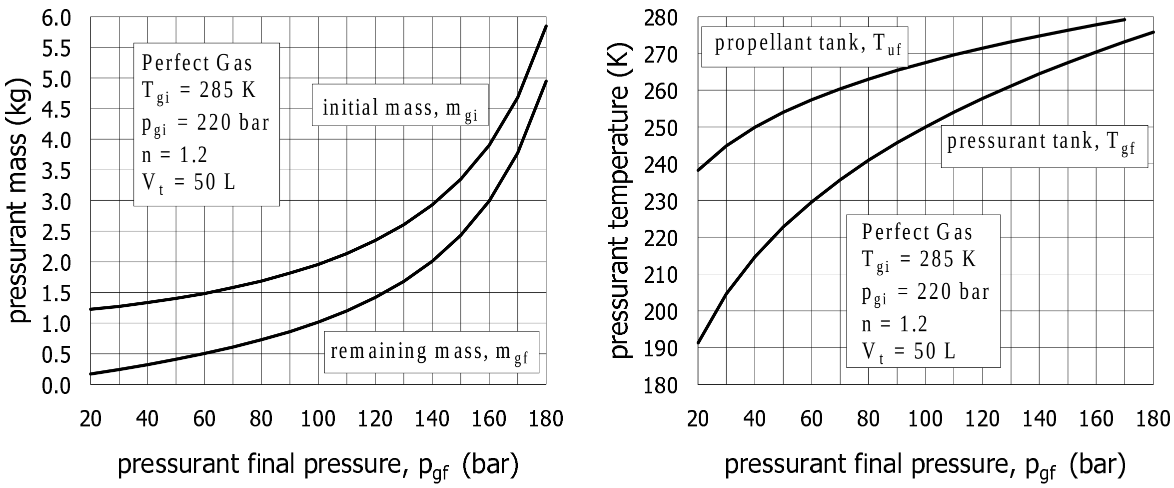

Figure 3: Influence of final pressure of pressurant vessel on gas mass requirement and gas temperature.

Figure 3 show the behavior of the required and residual pressurant mass, and pressurant final temperatures at ullage and vessel, all as function of the final pressure in the pressurant vessel. Obviously, as predicted in previous sections, all these parameters increase with the pressure of remaining gas in the vessel.

The variations on the main parameters due to changes in the pressurant storage pressure (p_{gi}) are presented on Fig. 3. The pressurant storage volume and mass, as well as the other shown parameters, decrease with increasing pressurant storage pressure. Note, in Fig. 3, that the residual mass on the pressurant vessel decreases more quickly than the initial mass, as expected. For the pressure range analyzed, the storage vessel decrease less intensively for high pressures.

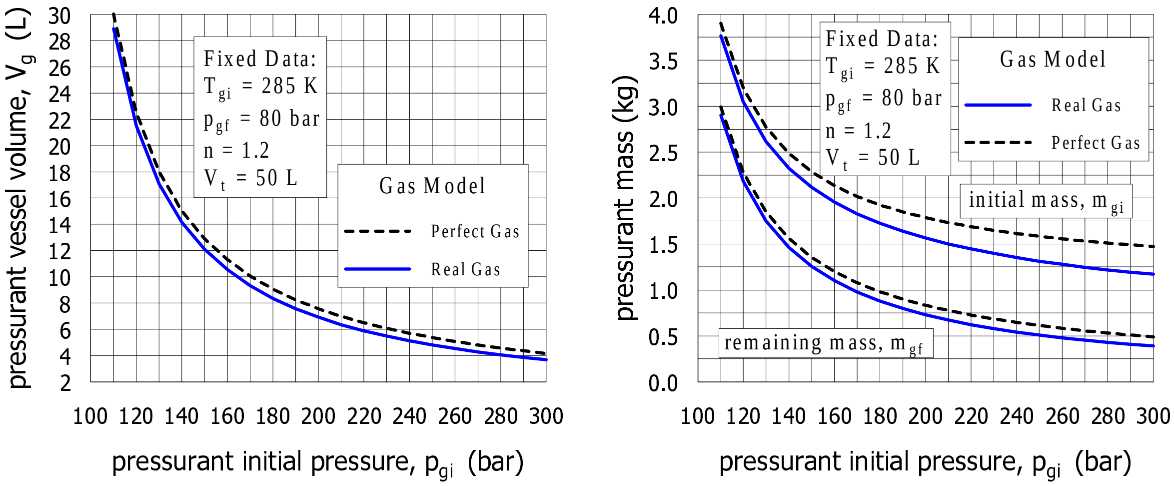

Figure 4: Variations of volume and initial and residual mass of pressurant at different storage pressure for perfect and real gas.

The compressibility effects on vessel's volume and initial and residual masses of pressurant, for different storage pressures, also are shown on Fig. (4). The values computed with real gas model are lower than those ones estimated using perfect gas model. Thus, for the analyzed case, the perfect-gas model gives more conservative results.

7. CONCLUDING REMARKS

This paper presents an analysis to predict the pressurant gas requirements and other design parameters of a stored-gas pressurization system for the discharge of storable liquid propellants from storage tanks. The study deals with the expulsion of the liquid at an uniform pressure (pressure-regulated system) of pressure-fed liquid rocket engines. The model of analysis involves approximations of the final temperature for the tank ullage. It is disregarded the heat transfer between the ullage gas and the tank wall, and also the heat transfer from the ullage to the liquid interface and to the hardware components. Another important simplification is that the heat transfer between the pressurant and the vessel's wall wasn't calculated, and its effect was included in calculations by assuming a polytropic expansion process.

A computational algorithm is also given. Sample case is included to illustrate the use of the described methods. The validity of the analysis presented herein has not been completely verified yet, due to absence of adequate experimental data.

Although prior knowledge of the operating conditions for a fluid system is needed for an analysis, the use of the simple methods resulting from the present analysis do not necessitate that experimental data derived from prototype systems be available. Thus, they are advantageous for preliminary design and optimization studies where the use of detailed computer programs becomes inadequate and sometimes impossible (due to the lack of needed input information).

The analysis cover the models of perfect gas and real gas. In the last case, are used compressibility formulae or tables. An easy extension of this analysis could be the implementation of Peng-Robinson and Redlich-Kwong equations of state in the calculation process.

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Appendix: ALGORITHM OF PRESSURIZATION WITH REAL GAS

Final Gas Temperature in Pressurant Tank (Known: p_{gi}, p_{gf}, T_{gi})

$$Z_{\mathrm{gi}} = Z_g(T_{\mathrm{gi}},\, p_{\mathrm{gi}})\,, \qquad Z_{\mathrm{gf}} = Z_g(T_{\mathrm{gf}},\, p_{\mathrm{gf}})\,, \qquad T_{\mathrm{gf}} = T_{\mathrm{gi}}\,\frac{Z_{\mathrm{gi}}}{Z_{\mathrm{gf}}}\left(\frac{p_{\mathrm{gf}}}{p_{\mathrm{gi}}}\right)^{\frac{n-1}{n}}$$

Average Bulk Temperature at Propellant Tanks

$$T_{\mathrm{uf}} = \frac{T_{\mathrm{gi}} + T_{\mathrm{gf}}}{2}$$

Pressurant Tank Volume

$$V_{\mathrm{g}} = \frac{p_{\mathrm{uf}} V_{\mathrm{l}}}{T_{\mathrm{uf}}}\left(\frac{p_{\mathrm{gi}}}{T_{\mathrm{gi}}} - \frac{p_{\mathrm{gf}}}{T_{\mathrm{gf}}}\right)^{-1}$$

Initial Mass of Gas in the Pressurant Tank

$$m_{\mathrm{gi}} = \frac{p_{\mathrm{gi}} V_{\mathrm{g}}}{Z_{\mathrm{gi}} \mathcal{R}_{\mathrm{g}} T_{\mathrm{gi}}}$$

Gas Mass in Pressurant Tank at End of Propellant Expulsion

$$Z_{\mathrm{gf}} = Z_g(T_{\mathrm{gf}},\, p_{\mathrm{gf}})\,, \qquad m_{\mathrm{gf}} = \frac{p_{\mathrm{gf}} V_{\mathrm{g}}}{Z_{\mathrm{gf}} \mathcal{R}_{\mathrm{g}} T_{\mathrm{gf}}}$$

Final Mass of Gas in the Propellant Tanks

$$Z_{\mathrm{uf}} = Z_g(T_{\mathrm{uf}},\, p_{\mathrm{uf}})\,, \qquad m_{\mathrm{uf}} = m_{\mathrm{gi}} - m_{\mathrm{gf}} = \frac{p_{\mathrm{uf}} V_{\mathrm{l}}}{Z_{\mathrm{uf}} \mathcal{R}_{\mathrm{g}} T_{\mathrm{uf}}}\,.$$