Tank Ullage Dynamics & Self-Pressurization

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## Introduction to Pressurization

The pressures seen in the combustion chamber of a rocket, especially the backpressure on the injector plate, are often exceptionally high. Even when operating on the student-scale as Tartarus does, megapascals of chamber pressure are by no means unheard of. As a result, rockets need some means of forcing propellants into the high-pressure combustion chamber. In rocketry this is referred to as an engine cycle. For commercial applications, this most often takes the shape of turbopumps, in which some propellant is tapped off and combusted, driving a turbine which then drives either an axial or centrifugal pump, generating high enough downstream pressure to force fluid into the chamber. However, these methods are often exceedingly complex, often requiring an entire engineering team dedicated solely to pump design.

Instead, many smaller rockets (this project included) use a “pressure-fed cycle”, where the propellant tanks themselves are pressurized to a pressure high enough to produce an acceptably high chamber pressure. In commercial applications, this requires tanks to be too heavy and bulky to be practical, but on the small student-scale the simplicity of this method is exponentially more practical than any turbopump, or even electric pumps.

Traditionally, pressure-fed rockets apply some inert gas such as nitrogen (for affordability) or helium (for weight savings) to the top of the liquid propellants in the tanks in order to produce the desired pressure. There are a couple of different forms this often takes on this scale: firstly, an onboard tank of ullage gas will provide constant ullage pressure to the propellant tanks, governed by a pressure regulator. This method is heavy and bulky, but provides fairly constant thrust throughout firing. While not technically the correct terminology, often this project will refer to this method as “blowdown gas” pressurization.

The second method is a large portion of the tank is emptied, often up to ~50%. Then, inert gas is fed from the ground station, pressurizing the void volume, or non-liquid volume, up to some desired pressure. Then, the inert gas feed is cut off. The amount of inert gas within the tank remains constant, and as the liquid level drops, the void volume expands, meaning pressure decreases throughout firing, assuming ideal gas behavior. This is a particularly common method used on student projects for its high degree of simplicity and light weight. However, this method still has notable drawbacks in the form of thrust decreasing over time and requiring large portions of the tank to be void of propellant. While also not technically industry-standard terminology, methods such as these will often be referred to within this project as “supercharging” or “supercharge” pressurization.

## Vapor Pressure, Two-Phase Fluids & Self-Pressurization

Any given fluid in a liquid state has a vapor pressure at some given temperature. Often the vapor pressure of some fluid can be extracted from a thermodynamic table by hand, or from software such as CoolProp[A]. If a liquid is stored such that it is exposed to air or gas, it will exist in what is known as a “two-phase mixture”. A two-phase mixture is characterized as a fluid which contains both liquid and vapor components. For example, a two-phase mixture of hot water flowing through a pipe might see the bottom half populated by liquid and the top half populated by steam or water vapor.

How much of the mass of a two-phase mixture is vapor or gas (or the vapor quality *Q* or *x*) is largely dependent on the density of the fluid - that is, how small of a volume some unit mass is confined within. So, expanding it won’t create a void, but instead more liquid will evaporate until the entire remaining volume is filled by vapor at the vapor pressure. Similarly, compressing it will force some of the vapor to condense into the liquid until enough has left the vapor phase to decrease pressure back to vapor pressure.

Most liquids have a very low vapor pressure at room temperature (e.g. water), meaning very little vapor is produced and therefore the vapor component is often neglected, treating the substance as a single-phase liquid. However, some substances can exist as liquids with very high vapor pressures at room temperature - such as nitrous oxide and ethane. In the context of rocketry, this means that a tank might be filled up to a liquid fill level of 85% tank volume, leaving 15% of the tank volume for ullage gas. Instead of requiring an inert gas within the void volume to provide ullage pressure, the vapor continuously evaporating off of the liquid propellant itself will provide enough ullage pressure to force propellant into the chamber. This is a pressure-fed configuration known as “self-pressurization”. While self-pressurization yields much higher pressure throughout draining than a purely supercharged propellant, it is worth noting that as the propellant drains and “expands” up into the tank, temperature and subsequent vapor pressure drops over time will be observed.

Full self-pressurization is not the only application of high vapor pressure propellants. For example, another noteworthy characteristic of vapor pressure is that vapor pressure is the *partial* pressure of vapor at two-phase equilibrium. To put it simply, the liquid phase of the mixture will continue to evaporate until a partial pressure of its vapor pressure is achieved. So, if at some temperature the vapor pressure of nitrous oxide is 650 psi, then even if you place it in a pressurized vessel initially populated by 200 psi of nitrogen, then the nitrous oxide will continue to evaporate regardless until the vessel is filled with a *partial* pressure of 650 psi of *just* nitrous oxide - this means the vessel will experience 650 psi of nitrous oxide *and* the initial 200 psi of nitrogen, for a total pressure of 850 psi.

In practice, this means that a self-pressurizing propellant can be used to significantly reduce the amount of inert gas required to hold a constant pressure - in order to hold a tank at a constant 800 psi, and at the end of the burn the vapor pressure of the nitrous oxide in the tank is expected to be 600 psi, only enough nitrogen to fill the tank with 200 psi of nitrogen may be needed as opposed to enough to fill the tank with 800 psi of nitrogen.

Most commonly, however, self-pressurized propellants are augmented by an inert gas supercharge. In the case of nitrous oxide, this is done to aid with chemical stability, but in many other cases it might be done to provide a means of pressurization which is not a function of propellant temperature, or to provide an initial “kick” thrust at the beginning of the burn and a lower-thrust burn throughout the rest of the flight.

## Modeling of Ideal Gas Ullage

Before delving into mathematical models of self-pressurization, an exploration of ideal gas pressurization may serve as a much simpler starting point. For constant-pressure systems, calculation of pressure as a function of tank draining is not necessary as the pressure is constant. However, for inert gas supercharge pressurization, control-mass modeling must be considered.

There are a few valid equations which can be used to determine inert gas pressure as a function of void volume. For particularly short drain times with little heat transfer from the propellant to the gas, an adiabatic relation between pressure and volume, as shown by equation 3-9 in Sutton[1], shown in Equation 1 here.

(1)

Where:

* is the ratio of specific heats of the gas
* is initial supercharge pressure
* is the initial supercharge void volume
* is the ideal gas pressure at volume
* is the independent variable void volume

The resulting ullage pressure can then be expressed as a function of ullage volume or of propellant liquid volume, initial ullage volume, initial supercharge pressure, and specific heat ratio of the gas, shown in Equation 2.

(2)

However, for longer drain times or when a propellant vapor is introduced (see following sections), an isothermal relation may be desired - a constant temperature may be assumed to be that of the propellant, the initial temperature, ambient temperature, etc… In the case the temperature is assumed to be constant at the initial value, the resulting equation can be expressed via the ideal gas law as shown in Equation 3.

(3)

(4)

(5)

However, if the temperature is assumed to be that of the propellant, or changes to some other arbitrary value, then the equation can still be derived from the ideal gas law, shown in Equation 6.

(6)

(7)

(8)

Again, these equations assume ideal gas behavior, and therefore are not always applicable to certain cases or gasses with very low molecular weight such as helium or neon.

## Modeling of Self-Pressurized Blowdown

The assumption behind self-pressurization is that the propellant will continue to evaporate until it reaches vapor pressure. Therefore, one might assume that the ullage pressure is constant. However, this is not quite the case. As the liquid component of the propellant flows out of the tank, a certain amount of enthalpy within the liquid phase leaves the tank as well. Therefore, the total amount of enthalpy within the two-phase mixture within the tank decreases over time as the tank drains. Furthermore, as mass flows out, the amount of mass within the fixed tank volume decreases, decreasing the density in turn. The result is both heat loss from the system within the tank *and* an “expansion” of the two-phase mixture within the tank.

The “expansion” of the propellant into the tank causes the propellant temperature to drop over time, which in turn causes the vapor pressure to drop over time. As a result, the ullage pressure and temperature drop steadily as the propellant drains. Several analytical methods have been proposed, but the simplest (and evidently closest to experimental data) is the Single Node Equilibrium model seen in Kardas[2]. The single-node equilibrium model treats both phases of the saturated propellant as a single node, with a uniform temperature, total density, and specific enthalpy between them. The SNE model is characterized by a simple pair of differential equations (assuming we neglect heat flow into the propellant from the tank wall), shown in Equations 9 and 10.

(9)

(10)

Where:

* is the constant tank volume
* is an infinitessimal change in density
* is an infinitesimal change in enthalpy per unit volume
* is an infinitesimal change in time
* is the enthalpy per unit mass of the liquid phase

The system can be integrated across finite time steps in a means similar to an Euler method to yield the enthalpy and density of the node over time. Multiplying both sides of Equations 9 and 10 by *dt* to eliminate time dependent terms yields Equations 11 and 12. Since thermodynamic tables will be in terms of mass specific enthalpy rather than volumetric enthalpy, Equations 13 and 14 express the change in enthalpy in terms of mass specific rather than volumetric specific enthalpy, from initial enthalpy *h0* to final enthalpy *h1*.

(11)

(12)

(13)

(14)

After a finite time step *dt* has been selected, the change in mass *dm* over the time step can be calculated by calculating mass flow rate as per injector flow modeling and multiplying by *dt*[B]. After a new value of density and are calculated, they can be fed into thermodynamics tables such as CoolProp to retrieve a new value for propellant temperature and vapor pressure. These can then be fed back into mass flow rate calculations, which then feed Equations 11 and 14, and so on…

Again, in the case of self-pressurizing systems, if inert pressurization gas is applied, then the ullage pressure at each time step will be the *sum* of the vapor pressure of the propellant *and* the ideal gas pressure of the inert gas.

## References and Sources

[1] [Sutton, Rocket Propulsion Elements](https://drive.google.com/file/d/1muyScRo6bWxT6AzNZnpIaxudrqsAPFAy/view?usp=sharing)

[2] [Kardas, Novel Model for Emptying of Nitrous Oxide Tank](https://drive.google.com/drive/u/1/folders/1rtMTDnJylXlQQApa5ANx0DKBsVjKrJ2a)

## Related Documentation

[A] [CoolProp Documentation](https://docs.google.com/document/d/1SwY_JbAcMK3dY37hVzANKK0KHyNtMjkAvfUAsUOoy1Y/edit?usp=sharing)

[B] [Injector Flow Modeling](https://docs.google.com/document/d/1EwtdHJscOhw51d0kd1JRHDjzPgklcJx-H6rjGxaLMqE/edit#)