Design of a High-Pressure Fluid System for a Bipropellant Liquid Rocket Engine

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The object of this paper is to design a high-pressure fluid system for a liquid rocket engine project called Tartarus, which is a Space Hardware Club project at the University of Alabama in Huntsville. This system will supply Ethanol and Liquid Oxygen (LOx) from the fuel tanks to the engine. Such a system will be rated to withstand up to 1000 psi of operational pressure which allows for a high range of engine variants to be tested in the future. This system will be fitted into a trailer for easy transport to test locations. Due to our use of cryogens, the LOx side of the system will have to be pre-chilled. We will also not be able to use check valves for the LOx portion of the system. If check valves are used the rapidly moving metal components could create a spark and lead to an uncontrollable rupture. In addition, all LOx lines will also have to be insulated. Without insulation, there is the possibility of LOx boiling in the lines which will cause a rapid pressure buildup with Gaseous Oxygen leading to an explosion. The system must also include instrumentation to measure pressure and temperature to ensure that the system is operating safely within the established limits. If safe limits are exceeded all valves should fail to their predetermined failure state to prevent further damage to the fluid system. There will also be multiple vents and burst disks to alleviate pressure from the propellant lines. This paper will further explore the design and manufacturing of a fluid system that can safely operate at up to 1000 psi.

I. Nomenclature

A = area
D = diameter
$\frac{e}{D}$ = relative roughness
f = friction factor
h_L = major head loss
k = loss coefficient
L = total length of straight pipe
$\dot{M}$ = mass flow rate
P = pressure
Q = volumetric flow rate
$\overline{V}$ = average velocity
μ = dynamic viscosity
Re = Reynolds number
ρ = density
Subscripts =
E = Ethanol
LOx = Liquid Oxygen

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II. Introduction

The fluid system described in this paper is in support of Tartarus, a project of the Space Hardware Club at the University of Alabama in Huntsville(UAH). The original goal of the project was to compete in the Spaceport America Cup however, after many years with no attempts to hot fire, all of the original team graduating, and a review by faculty at UAH it was determined that the project needed a rescope. One of the major issues with the previous engine was the test stand that accompanied it. This stand was large, heavy, cumbersome, and had to be disassembled for transport and reassembled at the test location. This led to valuable time being wasted during test days. Because of this when the rescope was proposed one major component was an overall of the test stand. The new test stand would be made inside a trailer, this would allow for mobility as the trailer can be hooked up to a car or truck and taken anywhere for a test. Since the new test stand will have an integrated fluid system there is no need to disassemble and reassemble it every time a test is to be conducted.

III. System Requirements

One of many considerations when designing this fluid system is the ease of setup. Our old system took several hours to assemble on-site with the possibility of weather or some other unforeseen circumstances delaying or possible stopping that days tests. The purpose of integrating the new system into a trailer is to eliminate the need to disassemble and assemble the system for every test and in doing so reduce setup time drastically. To ensure that the system can grow with the aspirations of our project it has been designed to accommodate not only our current engine but allows for the possibility of testing more powerful engines in the future. With this growth in mind, the maximum pressure that the system will be rated to was chosen at 1000 psig although for the current engine, the operating pressure will be 300 psig. While this difference in rated pressure and fired pressure does allow for a large factor of safety instrumentation will be included to monitor the system at all times. Should the instrumentation detect a failure it will direct all valves to their pre-determined fail states to ensure the safety of anyone nearby.

IV. System Design

Due to the combustible nature of the propellants (Ethanol and LOx*)it make sense that they should be stored on opposite sides of the trailer to minimize the damage that could be done should one of the propellants spontaneously combust.

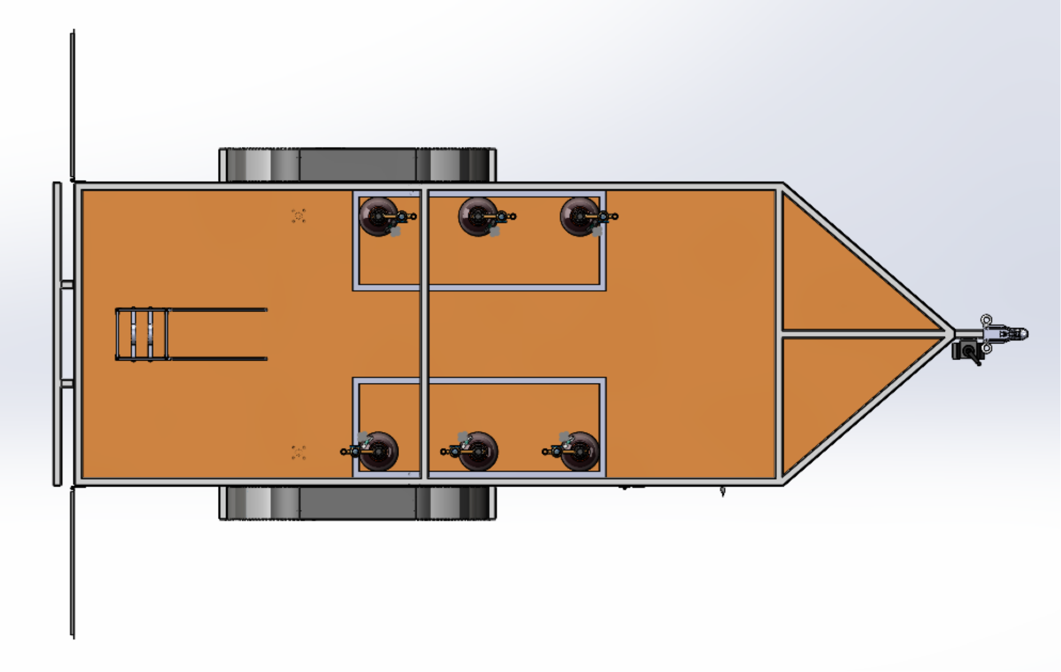

Fig. 1 Trailer Floor Layout

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*Liquid Oxygen

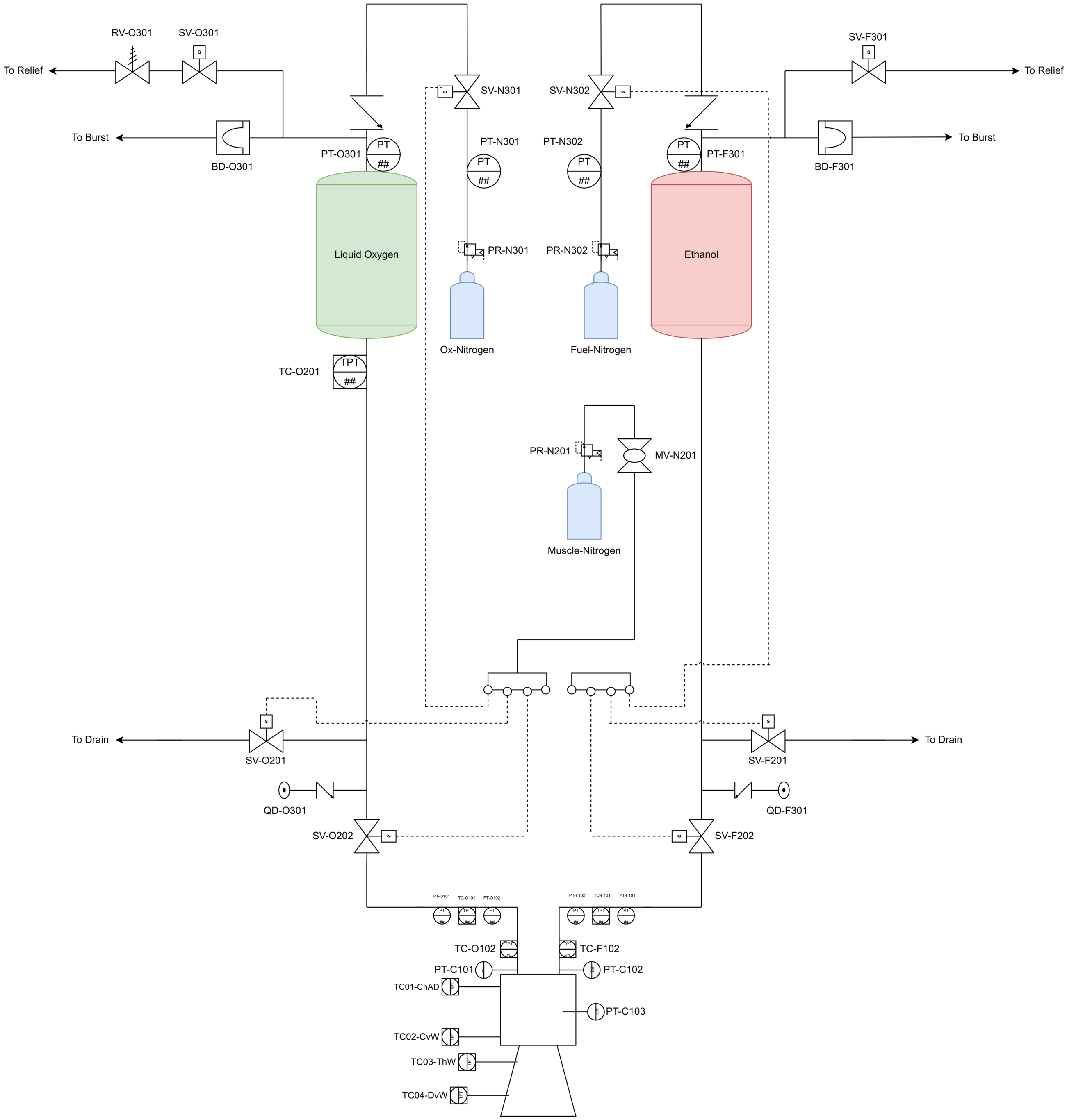

Fig. 2 Fluid System P&ID

Due to this layout the length of pipe required should be approximately the same as both sides of the system should be a mirror of the other. This combined with the fact that the propellants have similar viscosities of $\mu_E = 22.43 * 10^{-6}\ {}^{Lbf*s}/_{\text{ft}^2}$[1] and $\mu_{LOx} = 12.17 * 10^{-6}\ {}^{Lbf*s}/_{\text{ft}^2}$ [2] means that any pressure loss ΔP will be similar for both sides of the system and therefore both sides should use the same diameter pipe. This pressure loss something that needs to be minimized because if it is too great then the engine will not be able to preform at optimal levels because it is being starved of fuel. This ΔP can be calculated using the following equation:

$$\Delta P = \frac{128\mu L Q}{\pi D^2} \tag{1}$$

Because this equation being used to find an optimal pipe diameter the length of the pipe is being approximated to $L = 1\text{ft}$. This is because the length of the pipe only acts as a scalar and does not affect the behavior of the graphs. As this is one of the first calculations made $\overline{V}$ is not yet known so values from $10 - 1000\ ^{ft}/_{s}$ and the following plots were made.

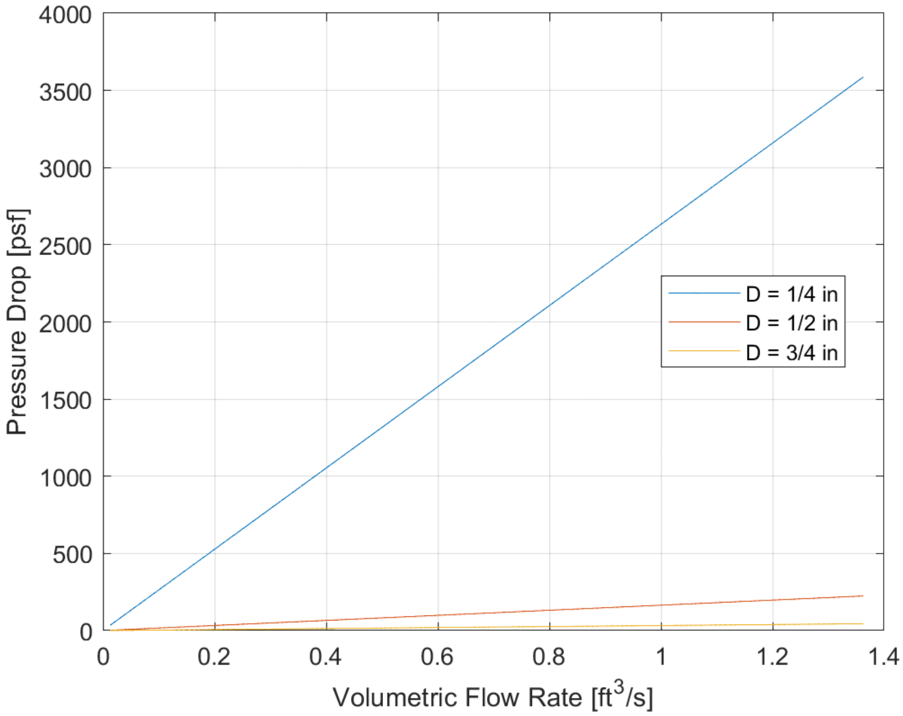

Fig. 3 Flow Rate Vs. Pressure Drop (LOx)

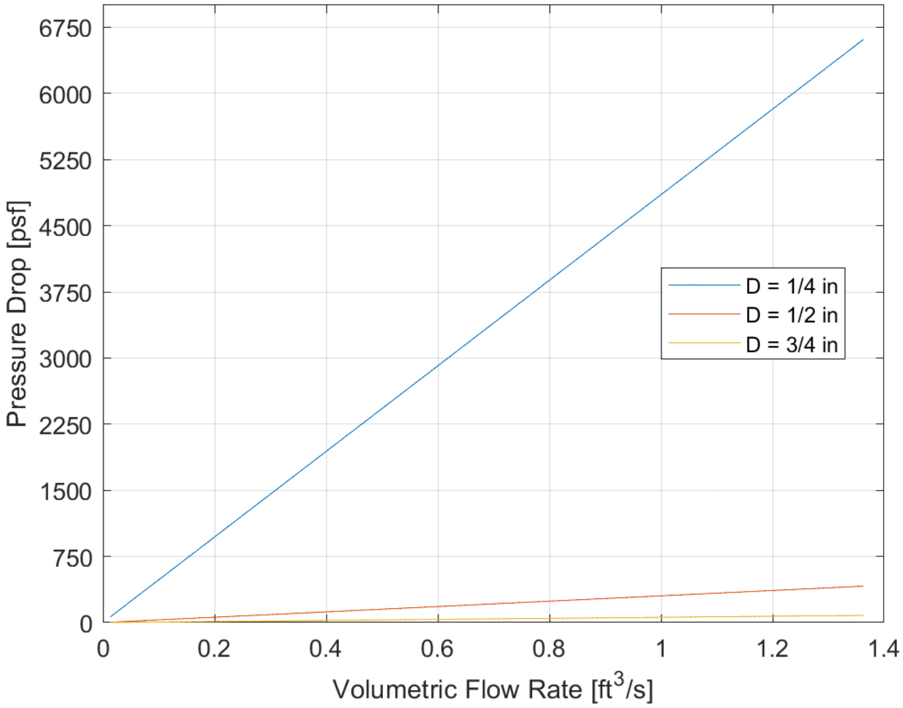

Fig. 4 Flow Rate Vs. Pressure Drop (Ethanol)

ΔP decreases by an order of magnitude when the pipe diameter decreases from 1/4" to 1/2" and, it does decrease further if the diameter is again increased this time to 3/4". This is consistent with Equation 1 that shows the strong influence of diameter on change in pressure. While the further decrease in ΔP is desirable the difference between the 1/2" pipe and the 3/4" is only a few hundred pounds per square foot. This relatively minimal reduction in ΔP is not worth the price difference when dealing with cryogenic valves. Another critical feature that must be known is the head loss of which there are two types, major and minor. Before major head loss can be computed first the average velocities and Reynolds numbers in both sides of the system must be known. Beginning with $\overline{V}$ the equation is as follows:

$$\overline{V} = \frac{\dot{M}}{\rho A} \tag{2}$$

This can be used with the following $\dot{M}_E = 0.01522\ ^{slugs}/_{\text{s}}$ and $\dot{M}_{LOx} = 0.01096\ ^{slugs}/_{\text{s}}$. This will yield average velocities of $\overline{V}_E = 7.339\ ^{ft}/_{\text{s}}$ and $\overline{V}_{LOx} = 47.202\ ^{ft}/_{\text{s}}$. Using the densities for the propellants $\rho_E = 1.521\ ^{slugs}/_{\text{ft}^3}$ [3] and $\rho_{LOx} = 2.487\ ^{slugs}/_{\text{ft}^3}$ [4] the Reynolds number can be calculated using the following equation:

$$Re = \frac{\rho \overline{V} D}{\mu} \tag{3}$$

This will yield values of $Re_E = 2.073 * 10^4$ and $Re_{LOx} = 4.019 * 10^5$ which in combination with Figure 8.13 in the Introduction to Fluid Mechanics [5] the value of f can be found. Since f is a function of Reynolds number and relative roughness so this value will be the same for both propellants. The relative roughness will change overtime with use but since at the construction of the system all pipes will be brand new it is assumed to be the same for all pipes. The assumed value for this is $\frac{e}{D} = 1 * 10^{-6}$. This gives the friction factors of $f_E = 0.025$ and $f_{LOx} = 0.014$. Now that the average velocities and friction factors are known the major head loss can be determined for both sides of the system using the following equation:

$$h_L = f\frac{L\overline{V}^2}{2Dg} \tag{4}$$

When plugging in values of $h_{L-E} = 0.501$ ft and $h_{L-LOx} = 11.624$ ft are calculated. Minor head loss must also be considered but this depends on the valves used throughout the system that are in the path of the flow. Using table

8.4 in the Introduction to Fluid Mechanics[5] combined with Figure 2 the minor head loss due to each valve can be computed. Since the type of valve in the path of flow is the same on both sides the loss coefficient $k = 0.2$ is the same.

$$h_{Lm} = k\frac{\overline{V}^2}{2g} \tag{5}$$

The minor head loss is $h_{Lm-E} = 0.0167$ ft and $h_{Lm-LOx} = 6.919$ ft. This means the total head loss of the system is $h_{L-E-total} = 0.069$ ft and $h_{L-LOx-total} = 18.544$ ft.

Throughout the whole system temperature and pressure data must be recorded. The purpose of gathering this data is to ensure the safety of the system and anyone around it. It is incredibly important that this data is accurate because it is what is relaying all information to our data recording system. If the system receives a reading that is outside of a safe range, it will actuate all valves to their predetermined failure states which entails closing run and check valves while opening drains. Burst disks have also been placed on both sides of the system as a mechanical fail safe for if the other safety measures fail. This fail safe is especially important on the LOx side because the price of cryogen rated pressure gauges is outside of the project budget. This has caused us to search for a method of insulating a standard pressure gauge. The method which has been devised is to apply thermal paste to the interior of the gauge. This is just one of several additional things to consider when using LOx that do not apply to Ethanol.

Due to LOx being a cryogen, it has a low boiling point of $-297°$F steps must be taken to ensure that the injector and the LOx are at relatively the same temperature at the beginning of tests where the injector will be at approximately 68°F. To prevent this temperature difference all LOx lines will be pre-chilled by bottom filling the run tanks, effectively filling all lines with LOx prior to the start of the test. Once LOx is in the system it will chill the lines and the injector. In addition to pre-chilling the lines, they will also be insulated to maintain the reduced temperature throughout testing. These are the measures that are being taken to prevent a BLEVE[†] event however, a BLEVE event is not the only type of explosion that is possible when using LOx. LOx can spontaneously combust when in contact with a piece of metal moving rapidly such as would be present in a check valve. Because of this, no check valves will be included in the LOx lines and the lines must use a combination of changing elevation and pressure differentials to ensure that the LOx only flows in the intended direction.

V. Construction

To construct these lines 316 Stainless Steel [6] was selected due to it's resistance to harsh conditions and low coefficient of thermal expansion. These lines will be anchored to the walls and floor of the trailer to increase rigidity. Any place with lines on the floor of the trailer will be covered by pipe covers to prevent injury to both the lines and trailer occupants when testing is occurring. The sections of these lines that are on the walls will be covered with a clear plexiglass to both protect the lines from any accidental interference while still allowing for visual inspection to ensure the safety of the system.

Acknowledgments

The authors would first and foremost like to thank Dr. Gang Wang for his mentorship to The University of Alabama in Huntsville's Space Hardware Club. We would also like to thank Dr. Xu for representing AIAA at The University of Alabama in Huntsville. We are also very grateful to the MAE department at UAH and Mr. Jon Buckley in particular for the use of their machine shop. The Alabama Space Grant Consortium, University of Alabama in Huntsville, and Blue Origin has graciously given us the resources necessary to fund this project through the Space Hardware Club. Finally, we would like to thank all members of Tartarus for their continued support and dedication to the project.

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