Open Source Design and Analysis of a Rocket Engine Fluid System

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Abstract

Tartarus is a student-led liquid rocket engine development project of the Space Hardware Club, based at UAH. The team has completed the design and fabrication of a test stand for dedicated rocket engine testing. During this process, a series of in-house spreadsheet-based calculators were developed for initial analysis of the fluid system. This process helped ensure selected commercial off-the-shelf (COTS) components were compatible with our designed system. The calculators allowed the team to get an accurate estimate of the required initial pressure needed to supply sufficient flow of propellants to the engine for hotfire. In addition, the calculators aided in getting an estimated figure of the amount of LOx needed to initially cool down the entire system and account for boiloff due to ambient temperature. Furthermore, calculators were used to properly size relief valves, as they are an imperative component in making sure the fluids system does not exceed its Maximum Allowable Working Pressure (MAWP) due to boiloff of LOx or any other possible source of overpressure. The test stand consists of 3 main subsystems: a LOx fluid system, an ethanol fluid system, and the main engine thrust structure. All of these systems were designed in-house, using COTS components for added safety and reliability. Additionally, fluid flow meters were designed and manufactured in-house. These meters use the venturi effect, measuring differential pressure across a custom-machined meter housing. These calculations will be validated this spring through a variety of water flow characterization tests.

I. Nomenclature

h_L	=	head loss (m)
K	=	fluid loss coefficient
ρ	=	density
g	=	acceleration due to gravity on Earth's surface
V	=	flow velocity
f	=	friction factor
L	=	duct length
D_h	=	hydraulic diameter
ε	=	surface roughness
Re	=	Reynolds number
μ	=	dynamic viscosity
Q	=	heat
m	=	mass
C_p	=	pressure specific heat
T	=	absolute temperature

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L_v = latent heat of vaporization
$\dot{Q}$ = heat rate
k = thermal conductivity
$\dot{m}$ = mass flow rate
N_2 = SCFM adjustment constant
C_v = flow coefficient
P_1 = relative upstream pressure
P_2 = relative downstream pressure
SG = specific gravity
A_w = wetted surface area
A_r = required relieving area
Z = compressibility factor
MW = molecular weight

II. Introduction

One of the major challenges for a student team developing a liquid rocket engine test bed is the fluid support systems which are required for static testing. This is complicated even further by the limited familiarity with fluid design and analysis on most student teams and the introduction of cryogenic oxidizers. In order to aid in the analysis of future fluid systems, Tartarus has developed three calculators based upon the standards from the American Society of Mechanical Engineers (ASME), the American Petroleum Institute (API), and NASA. The calculators utilize the CoolProp plugin for Google Sheets and focus on the estimation of cryogenic boil off rates, major and minor loss pressure drops, and relief valve sizing; the development of and access to these calculators will serve as a tool for future fluid design and more rapid iteration.

IEI. Design Requirements

The design requirements for the fluids system are set by the future plans of the propulsion team, guidelines set out by ASNE in the B31.3 Process Piping Guide [1], guidelines defined by ASME in BPVC section VIII [2], and guidelines laid out by NASA in the KSC-SPEC-Z-0008 document. Despite being a student team, adherence to industry level ASME standards is enforced whenever possible to ensure the safety of the system. To satisfy the requirements set by the propulsion team, a maximum allowable working pressure (MAWP) of 1000 psi was defined. To remain in compliance with both the MAWP requirement and ASME B31.3 the system must pass a hydrostatic test at 1.5 times MAWP, or 1500 psi. Manufacturing standards for all tubing present in the system were derived from a combination of NASA KSC-SPEC-Z-0008, ASME B31.3, and fabrication directions provided by Swagelok [4].

IV. Fluid System Layout & Design

Minos is Tartarus' in-house developed mobile test platform built to support and fire a liquid bipropellant rocket engine. Minos is made up of three main modules, those being the Ethanol cabinet, the LOx cabinet, and the Engine Thrust Stand (ETS). Of these components, there are five subsystems with the LOx and Ethanol Cabinet and ETS comprising three of those subsystems. The remaining two subsystems, the Muscle Pressure System and the Nitrogen Purge System, are integrated within the Ethanol and LOx cabinet, respectively. An overview of the general layout and a Full System P&ID can be viewed in Fig.1 and Fig. 2 below. The P&ID is broken down into four main sections: the Nitrogen Blowdown system, the LOx Line, the Ethanol Line, the Muscle Pressure system, and the Nitrogen Purge system. The engine is supplied with pressure provided by the Nitrogen Blowdown System. Each cabinet has a separate K sized nitrogen cylinder,and a component panel to pressurize the fuel and oxidizer for the system. For the ethanol panel, nitrogen is routed through a regulator (PR-X1), which is set to offset any pressure loss caused by the length of the system. After the regulator, a filter (PF-X0) is in place to limit foreign object debris (FOD) entering the system. On the ethanol cabinet panel, a pneumatic valve (PV-X1) is placed between two relief valves (RV-X1, RV-E1, set at 1000 psi) to ensure no trapped atmosphere in the event of overpressure. PV-X1 regulates flow into the ethanol tank; thus opening it will pressurize the system. A pressure transducer is located between the two relief valves to measure the pressure of the N2. A check valve (CV-X1) is placed between the pressure transducer and the second relief valve (RV-E1). Another pneumatic valve (PV-E1) is placed before the run tank to allow N2 to be vented after hotfire. A similar panel is located on the LOx cabinet; a regulator (PR-Y1) and filter (PF-Y0) are in place to set the required pressure and limit FOD. A relief valve (RV-Y1, set at 1000 psi) is placed after. After the relief valve, the pneumatic valve (PV-Y1) will pressurize the LOx system. A pressure transducer and check valve (CV-Y1) are placed before a second relief valve (RV-G1, set at 1000 psi). After the relief valve, a pneumatic valve (PV-G1) is in place to vent N2 after firing. A second pressure transducer is placed over the LOx tank. It is of note that CV-Y1 and RV-G1 are rated to cryogenic temperatures. In the LOx system, all pressure transducers are placed at the end of a stagnation tube to protect them from cryogenic temperatures.

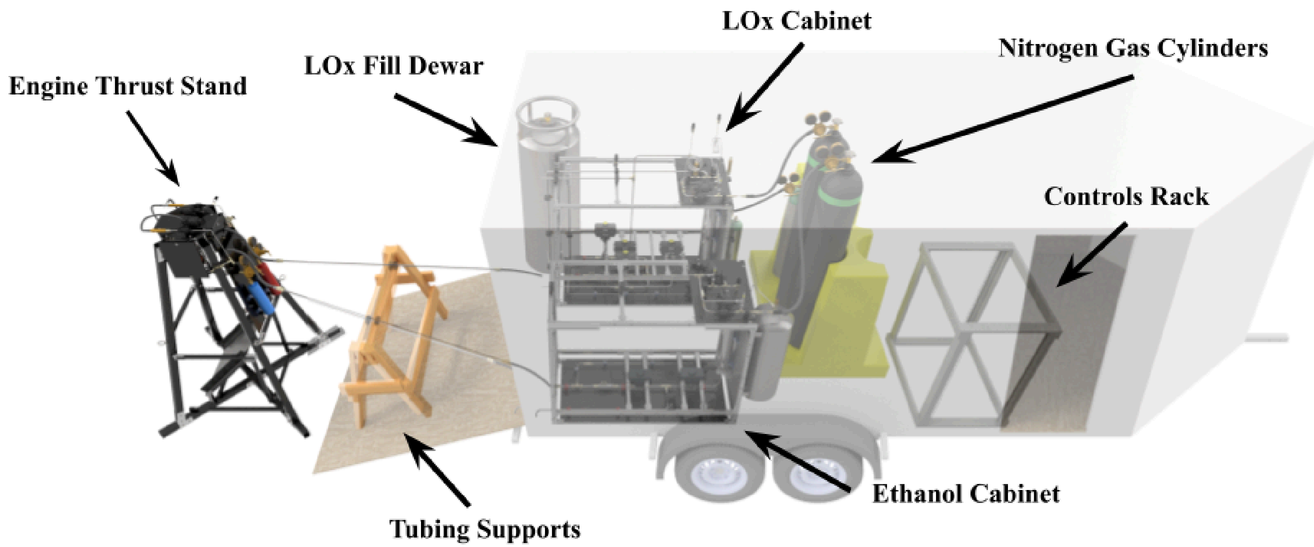

Fig. 1 Top-down view of Minos.

Moving on from the Nitrogen Blowdown system, the LOx Line has four pneumatic valves total, being PV-L02, PV-L01, PV-L03, and PV-L04. Two cryogenically rated relief valves, RV-L00 and RV-L02, are set at 1000 psi. One custom-built venturimeter, VM-L0. To gather data on the LOx Line, the system has a total of six thermocouples and three pressure transducers. Two pressure transducers and one thermocouple will be integrated with the venturimeter. The LOx Line will be supplied from a larger tank to ensure the line is chilled to cryogenic temperatures prior to firing. This tank will be operated manually and isolated once the system is chilled and the run tank for the LOx system, RT-L0, is filled. Two flex lines, FL-L01 and FL-L02, will connect the LOx system to the ETS. The Ethanol Line contains three pneumatic valves, being PV-E02, PV-E01, and PV-E03, and one custom-built venturimeter (VM-E0). Similar to the LOx Line, the venturimeter will have two pressure transducers and a thermocouple integrated with it. In total, the Ethanol Line will have two pressure transducers and two thermocouples. The Ethanol run tank, RT-E0, will be manually filled before hot fire. Two flex lines, FL-E01 and FL-E02, will connect the Ethanol Line to the ETS. The Muscle Pressure System will supply the necessary pressure to operate the pneumatic valves. The Muscle Pressure system will contain two valves, one being a relief valve (RV-M0, set at 125 psi) and a manual valve (MV-M0), and one pressure transducer. An air compressor and accumulator tank will be used to ensure muscle pressure can be maintained continuously. The Nitrogen Purge System will have three pneumatic valves, PV-N31, PV-N32, and PV-N33. PV-N32 will clear residual ethanol from the Ethanol Line and PV-N33 will clear residual LOx from the LOx Line. Check valves CV-N31 (Ethanol) and CV-N32 (LOx, cryogenically rated) will prevent any fluid from flowing into the blowdown system. One pressure transducer and one relief valve (RV-N3, set at 350 psi), as well as the regulator standard with a Q bottle (PR-N3), will be present in the Nitrogen Purge System.

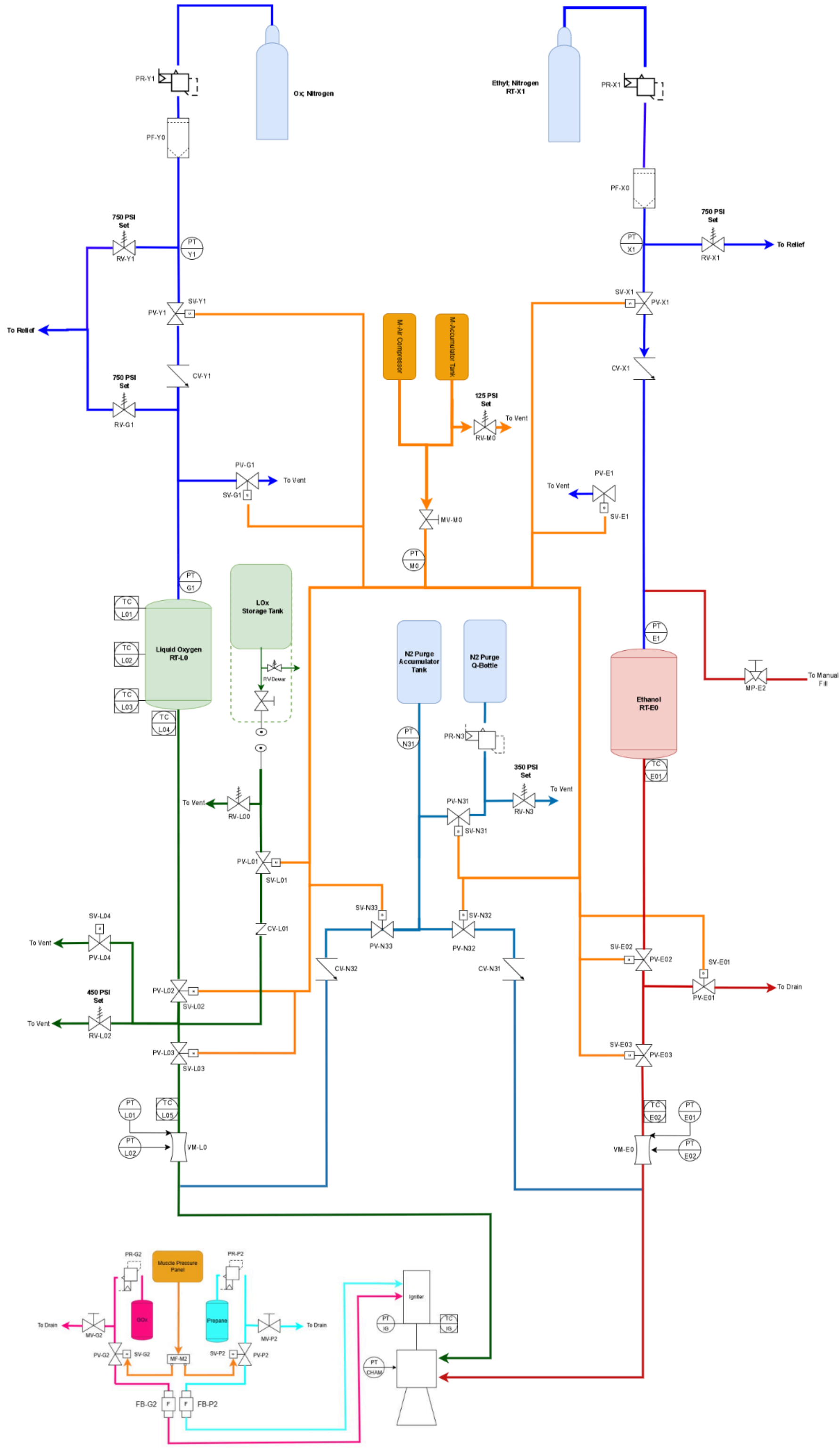

Fig. 2 Minos P&ID.

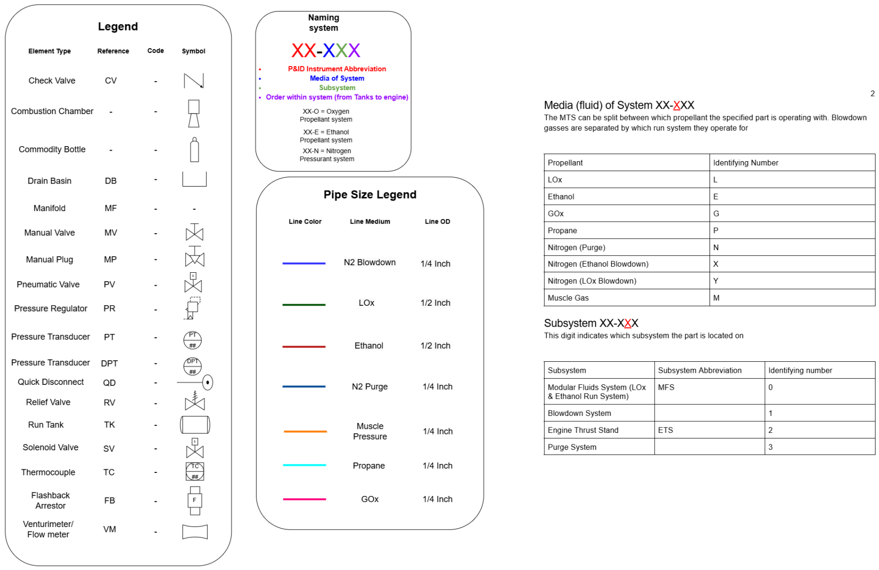

Fig. 3 Minos P&ID legend.

V. Blowdown & Pressure Loss Analysis

The regulated blowdown engine cycle allows for a simpler design and analysis process of the fluid system leading into the rocket engine. The main goal of the test stand is to provide propellants to the test article at a specific pressure and flow rate. In order to ensure that we will set our system pressure correctly, it is required to understand how the regulator will operate, as well as what the pressure losses in the system could be. The main goal of this analysis is to get a rough idea of what pressure the regulator should be to get to the required pressure at the engine inlet. This analysis is required to ensure that regulators, valves, and other components are compatible with the blowdown set pressure. This entire process was done in a single Google Spreadsheet, with CoolProp as a fluid property reference. It is important to note that only steady-state analysis was considered for this system. There is no transient nitrogen filling considered for the blowdown system as the ullage of the run tanks will be fully pre-pressurized before firing.

The first step in conducting this analysis is to determine the analysis regions. Our system will be working with both liquids and gases, which are analyzed differently. For each section of our system, we split the pressure loss analysis into 2 ‘circuits’. One circuit will be the incompressible liquid propellant side (LOx or ethanol), and the other circuit will be the incompressible blowdown gas side. The incompressible assumption is made based on the low calculated fluid flow velocity, negating the compressible for analysis. The ‘terminal pressure’ of this system is the required pressure at the engine inlet. From here, the analysis is conducted for liquids. Propellant mass flow rate, given by the Propulsion Subteam, is a critical requirement for the fluid system.

The first step for the blowdown pressure drop is to establish the fluid parameters. The standard temperature and pressure for this is based on the expected testing location and time of year. Density throughout all calculations is obtained through the CoolProp fluid properties plugin [9]. The liquid in these lines will be operating at very low speeds during engine firing, so it is safe to assume incompressible gas and liquid flow. To determine the expected pressure loss across the first circuit, the delta P can be found as follows [6]:

$$\Delta P = \Sigma h_L \rho g \tag{1}$$

$$\Sigma h_L = h_{L\,Minor} + h_{L\,Major} \tag{2}$$

$$h_{L\,Minor} = \Sigma K_L \frac{V^2}{2g} \tag{3}$$

The minor losses are defined as frictional losses due to components and tube bends in the system. These are characterized by summing the individual component and tube geometry K values. A table of the commonly referenced K values is shown:

Table 1: Fluid Loss Coefficient for each component type.

Component	**K Value**
90˚ Bend	0.9
Union	0.08
Tee (run)	0.9
Tee (branch)	2.0
Ball Valve	6.4875
Venturimeter	0.65

The major losses require the use of the Darcy Friction Factor. The general major head loss equation is shown as [6]:

$$h_{L\,Major} = f\frac{LV^2}{D_h 2g} \tag{4}$$

In order to achieve a higher accuracy, the friction factor was calculated with the Colebrook-White approximation. This equation uses the built-in Google Spreadsheet GoalSeek plugin to solve for the friction factor numerically. Dynamic viscosity is pulled from the CoolProp plugin [9]. The equation for the friction factor is given as [7]:

$$\frac{1}{\sqrt{f}} = -2log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{Re\sqrt{f}}\right) \tag{5}$$

The Reynolds number is calculated both for the Darcy Friction Factor and to determine the flow regime of the fluid. The Reynolds number equation used is as follows [6]:

$$Re_d = \frac{\rho V D_h}{\mu} \tag{6}$$

These all combined allow for the total circuit head loss to be calculated, which can be converted to a PSI.g equivalent number. This pressure loss is added onto the first circuit 'terminal pressure' to get a new 'terminal pressure' for the second circuit. The second circuit that will be evaluated is the blowdown gas side of the system. The flow rate of this circuit is established based on a volumetric flow rate equivalence. It is assumed that the volume of propellant exiting the run tank is equal to the volume of blowdown gas entering the run tank, shown in Fig. 4. This equivalence gives the volumetric flow rate of blowdown gas required, and using the assumed ambient temperature and terminal pressure, the mass flow rate of the gas can be calculated for use in the pressure loss analysis. The pressure loss of the blowdown gas system is evaluated using the same major and minor head loss equations at the propellant circuit. The pressure loss of the blowdown system is then added to the second circuit terminal pressure, and this gives the regulator pressure required for the system to operate. This helps determine regulator characteristics prior to testing, which saves both integration time and cost.

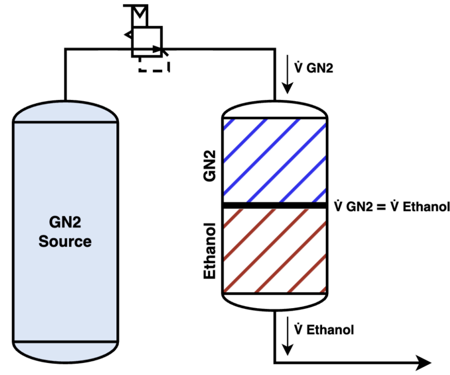

Fig. 4. Ethanol run system volumetric equivalence.

VI. Thermal Analysis

One of the crucial setup steps before hotfiring the Prometheus engine is the LOx "prechill" step. A small amount of LOx is slowly pushed through the LOx run lines to cool the tubing and tank down to near-cryogenic temperatures to minimize any LOx boiloff during hotfire. However, in order to properly cool down the tubing to the desired temperature, the team must know how much LOx needs to be pushed through the lines. A simple model can be used to determine how much LOx will boil off during the "prechill" process. This can be done by relating the heat transferred between the atmosphere and the stainless steel tubing to the heat required to boil off LOx, given its latent heat of vaporization. This was done with Eqs. (7) and (8).

$$Q = m * C_p * \Delta T \tag{7}$$

$$Q = m * L_v \tag{8}$$

Since the density and heat capacity of stainless steel are known, and the volume of stainless steel within our tanks and lines is also known, finding the total mass is a relatively straightforward process. The temperature change was assumed to be the difference between the hottest recorded day in Huntsville, Alabama (46℃) and the boiling point of LOx (-183℃). This calculated heat value can then be plugged into Eq. (8), and since the latent heat of vaporization of LOx is a known value, the mass of gas that gets boiled off due to this heat transfer can be calculated. The resulting mass can then be divided by the density of LOx to find the volume of LOx that ends up getting boiled off. The calculated volume, however, is very idealized, since it assumes that the LOx is in all of the tubing at the same time, rather than being trickled into the lines slowly. This means that the volume of LOx boiled off is an underestimate, and the actual volume of LOx that gets boiled off would be higher. However, calculating a more precise figure is exponentially more tedious, as it would require iterating rates of heat transfer across mass, since the amount of heat transferred changes over time as LOx comes into contact with more stainless steel. Furthermore, an exact value is not needed either, as a more simply calculated value still gives the team a relative idea of how much LOx is needed to fully "prechill" the system. Using this simple method, the team estimated that 0.57 gallons and 1.1 gallons would be required to cool the tubing and the tank down to cryogenic temperatures, respectively. The tank only has a capacity of 1 gallon, so it will need to be refilled continuously during this process.

Furthermore, once the tank is full, there will be a continuous transfer of heat via conduction from the outside atmosphere into the tank, which will result in more LOx boiling off. A rate of heat transfer equation can be used to then relate to Eq. (8) to find a rate of LOx boiloff, assuming the same temperature difference as previously mentioned. Since the tank has semispherical caps, there must be two different equations used; Eq. (9) finds the rate of heat transfer for cylinders, and Eq. (10) finds the rate of heat transfer for spheres.

$$\dot{Q} = \frac{2\pi k L(\Delta T)}{ln(\frac{r_0}{r_i})} \tag{9}$$

$$\dot{Q} = \frac{4\pi k r_0 r_i(\Delta T)}{r_0 - r_i} \tag{10}$$

The *k* value for 316 stainless steel (the material used in our tank and tubing) varies greatly across temperatures, but it is assumed that the tank would be at or near cryogenic temperature, so we chose the *k* value that corresponds to its thermal conductivity at cryogenic temperature, which is about 4 W/(m*K). The two calculated $\dot{Q}$ values can be added to find a total rate of heat transfer in the tank, which resulted in about 38,700 W. This figure can then be plugged into Eq. (8) to find that about 0.042 gallons of LOx boils off per second while the tank is full, which equates to a little over 5 ounces per second. At this rate, the tank becomes fully empty after about 24 seconds, which is crucial information for the team to know.

VII. Relief Valve Selection & Design Safety

Safe design and operation of this test stand is the number one priority of the project. Due to the inherent risks associated with liquid rocket engine testing, many safety measures are required to be implemented in our system. One of the most critical safety devices in any fluid system is the pressure relief valve (PRV). These valves allow for the release of pressure if a system rises above its expected operating pressure. This helps alleviate the risk of an overpressure event in a system and keeps components at their safe operating pressure. Because of the criticality of these components, extensive analysis is required to ensure that the correct valves are chosen and are integrated properly. Sizing guidance is based on the American Petroleum Institute (API) 520 industrial standard. Due to the nature of the team's testing, adjustable relief valves are required. These valves are not ASME code compliant, which requires this more detailed analysis. This is to mimic industry standard guidance on how to use these components, not only ensuring our system will be safe but also giving students exposure to real industrial standards. Additionally, building an in-house calculator acts as a valuable teaching tool for students to understand where code requirements come from.

The process for sizing relief valves begins with determining the required failure cases. This system is focused on 2 relieving emergencies. The first is the case of the pressure regulator failing, allowing full source pressure to enter the system. The second is the thermal expansion due to a fire in the test stand. It is important to note that a separate thermal relief case is not analysed for a trapped cryogenic volume, as the fire case will have a substantially higher vapor flow rate than any ambient evaporation.

During a regulator failure, the full pressure of a high pressure source is allowed to enter the system. The first step for this case is determining the criticality of the flow across the failed regulator. This is important as it governs the equations used for the PRV sizing. This is determined by using the API 520 isentropic critical flow equation as follows [3]:

$$\frac{P_1}{P_2} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \tag{11}$$

Gamma is assumed to be constant as per API 520 recommendation. This is compared against the actual pressure ratio from the tank and relief valve set pressure. This determines whether the choked or non-choked equations are used. Due to our high-pressure system, we have no cases using non-choked flow equations.

The next step is to calculate the mass flow rate of gas that the relief valve needs to handle. This is governed by the internal orifice of the regulator. The mass flow equation based on the supplier-provided Cv is as follows [4]:

$$\dot{m} = 0.471 N_2 C_v P_1 \sqrt{\frac{1}{SGT_1}} \tag{12}$$

The volumetric flow rate is then converted from SCFM into a lb/hr mass flow rate based on the fluid conditions. This mass flow rate is assumed to be constant between the regulator and the relief valve for analytical simplicity. This is now the mass flow rate that is used to determine the sizing requirement of the PRV. The only difference in analysis between the relieving cases is the calculation of the required relief flow rate and relieving pressure. The emergency fire relief case takes into account the possibility of the pressure vessel full of liquid, caught in a fire. The mass flow rate can be calculated using the standard API 520 set of equations as follows [3]:

$$\dot{m} = \frac{Q}{L} \tag{13}$$

$$Q = 21,000 A_w^{0.82} \tag{14}$$

The next step is to back-calculate the orifice area required to relieve this flow rate, and compare that to a chosen COTS relief valve for compatibility. In order to determine the API 520 equations required for determining the orifice size, the flow criticality must be analyzed again. This is done by comparing the results of Eq. (11) with the actual pressure ratio of the RV relieving pressure and atmospheric pressure. Once again, due to the high pressure of the system, only choked flow equations are used. The relieving pressure used is dependent on the relieving case. Based on the API 520 standard, overpressure allowance for regulator failure is 10% of MAWP while the fire case is

21%. Compressibility was obtained using the CoolProp plugin [9].The required area equation is given by API 520 as shown (for SI units) [3]:

$$A_r = \frac{\dot{m}}{CKP_rK_bK_c}\sqrt{\frac{TZ}{MW}} \quad (15)$$

This required area is then compared against the internal orifice area of the PRV given by the supplier. If the required area is less than the PRV orifice area, the relief valve is considered safe.

The last step in ensuring that PRVs are safe for a system is the discharge area accumulation. This is the backpressure that builds up from the exiting PRV gas in any vent lines that can cause resistance against the internal spring mechanism. This process uses flow friction pressure loss equations similar to the blowdown pressure loss analysis. The allowable backpressure comes from API 520 as 10% of the RV set pressure for all cases [3]. Using the friction factor and pressure drop equations from the blowdown analysis, similar results can be obtained. Using measured vent line lengths, a total expected pressure drop can be obtained for the PRV vent lines. As long as this pressure drop is below the allowable backpressure, the relief valve is considered to be integrated safely into the system.

VIII. Instrumentation

For the purpose of measuring mass flow rate, we designed a venturimeter to be manufactured in-house out of 304 stainless steel. An orifice plate could have been used, but the team decided to use a venturimeter instead, since the sudden change in diameter from an orifice plate could cause notable pressure losses. Like any venturimeter, this in-house venturimeter works on an application of Bernoulli's Principle:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 \quad (16)$$

Since the velocity of the fluids in the system never exceeds Mach 0.3, incompressible flow is assumed, and the equation can be rearranged for fluid velocity. This can be used to find the volumetric flow rate, which is given by the product of fluid velocity and cross-sectional area, as shown in the formula below:

$$\dot{V} = \frac{1}{4}\pi D^2 v_1 = \frac{1}{4}\pi d^2 v_2 \quad (17)$$

Rearranging gives the following formula for volumetric flow rate:

$$\dot{V} = \left(\frac{\pi d^2}{4\sqrt{1-\beta^4}}\right)\sqrt{\frac{2(P_1-P_2)}{\rho}} \quad (18)$$

The venturimeter contains ports to put pressure transducers into. These pressure transducers measure the difference in pressure between the inlet and the constricted area. Then, the volumetric flow rate was calculated from this given information. The volumetric flow rate can then be multiplied by the density of the fluid to find the mass flow rate.

The venturimeter was designed with the idea that it could be easily manufactured in-house. The team has access to specific imperial-sized tooling, which means certain geometries, such as the inlet and outlet taper and the constriction diameter, had to be carefully designed to ensure both accurate results and ease of fabrication.

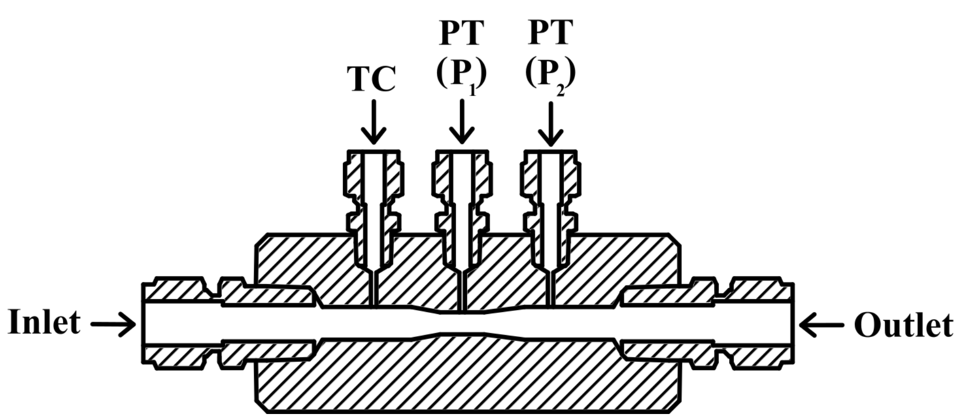

Fig. 5 Cross-section view of in-house venturimeter design.

IX. System Commissioning & Testing

Upon completion of fabrication, Minos was assembled to confirm that all designed components had been properly manufactured and validate that all components could be properly integrated. Once assembly was verified, the test stand underwent a series of “commissioning” tests and procedures to verify component integrity and mitigate specific risks. The first commissioning test was an individual hydrostatic test of every in-house manufactured component. Testing components individually, rather than performing an integrated hydrostatic test with the fully assembled test stand, limits leak identification to a small set of components per test rather than searching for the source of pressure drop across hundreds of elements. Each hydrostatic test with Minos' components was done using a manual hydrostatic pump. The test article is filled with distilled water to a set pressure of 1500 PSIG, which is 1.5x the MAWP of the system, 1000 PSI. The pressure of the test article is recorded at the beginning of the test and again after 10 minutes. If the difference in beginning and end pressure is less than 50 PSIG, the test article passed hydrostatic testing. If the pressure difference exceeded 50 PSIG, the test article failed the test, and the test article was checked for leaks; this process was repeated until the test article satisfied the acceptance criteria.

After passing hydrostatic testing, the components underwent an in-house oxygen cleaning procedure to remove FOD and Volatile Organic Compounds (VOC). Each component was disassembled, and its individual parts were flushed with a 1 to 20 ratio solution of Extreme Simple Green detergent to deionized water. The parts were then flushed with deionized water, followed by a flush with 99% isopropyl alcohol. Each part was dried using a filtered compressed air supply of greater than 100 PSIG and subsequently bagged and labeled as oxygen-cleaned to prevent contamination prior to re-assembly.

Minos is currently being assembled for full integration tests as part of the commissioning process. The first of the fully integrated tests consists of a series of water flow tests, both with and without the propellant injector mounted. These tests verify that the assembled fluid system satisfies design requirements for structural integrity, leak-tight performance, and acceptable pressure losses under controlled flow conditions. Using the recorded mass flow rate, pressure, and temperature data, the coefficient of discharge, C_d is calculated independently for Minos and the propellant injector.

Following the water-flow tests, a cold-flow test is conducted. This procedure is similar to the water-flow test; however, liquid nitrogen (LN2) is filled in the liquid-oxygen system, and the full engine is mounted to the engine test stand (ETS). The purpose of this test is to evaluate the system's behavior under cryogenic conditions without combustion, as cryogenic fluids introduce additional considerations that can impact the system's performance. During the cold-flow test, pressure, temperature, and mass-flow data are recorded to assess the system's stability and verify that instrumentation functions properly at cryogenic temperatures. This test serves as the final verification step before hot-fire operations, ensuring that the fluid system performs as expected under representative operating conditions.

X. Conclusion

The primary goal of the Tartarus project is to serve as a STEM education experience. Providing access to hands-on engineering work is critical for building the next generation of engineers and leaders. Conducting in depth analysis on a pressure system like this allows for students to get a more in depth understanding about why certain components are selected for service. It is also important to acknowledge the limitations of operating as a student team. The main limitations come from funding, time, and knowledge handover. Because of these, a custom method of implementing important standards like API 520 and ASME Section VIII is required. These methods were adapted for a more ‘lightweight’ use on a student team, balancing effectiveness with practical implementation. In addition to this, building out full calculators allow for future customization of more complicated hardware. The next steps for this design will be moving forward with testing and comparing results to real data. In addition to this, further analysis will be completed for liquid flow service, as well as using Fanno flow equations for the relief backpressure calculations.

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References

[1] American Society of Mechanical Engineers, Process Piping: ASME Code for Pressure Piping, B31 (ASME B31.3-2022), ASME, New York, NY, 2022.
[2] American Society of Mechanical Engineers, BPVC Section VIII: Rules for Construction of Pressure Vessels: Division 1, 2025th ed., ASME, 2025.
[3] American Petroleum Institute, Sizing, Selection, and Installation of Pressure-Relieving Devices, Part I—Sizing and Selection, 10th ed., American Petroleum Institute, 2020.
[4] Swagelok Company, "Valve Sizing Technical Bulletin," Tech. Rep. MS-06-84, Swagelok Company, 2007.
[5] Reader-Harris, M. J., "Venturi Meters," , 2011. URL https://www.thermopedia.com/content/1241/, thermopedia.
[6] Hardee, R., "Calculating Head Loss in a Pipeline," , 2015. URL https://www.pumpsandsystems.com/pumps/april-2015-calculating-head-loss-pipeline, pumps & Systems.
[7] Khan, M. K., "Fluid Mechanics," Fluid Mechanics and Machinery, Oxford University Press, 2015, pp. 165–204.
[8] "Conduction Heat Transfer," , n.d. URL https://engineeringlibrary.org/reference/conduction-heat-transfer-doe-handbook, engineering Library, DOE Handbook.
[9] Bell, I. H., Wronski, J., Quoilin, S., and Lemort, V., "Pure and Pseudo-pure Fluid Thermophysical Property Evaluation and the Open-Source Thermophysical Property Library CoolProp," Industrial & Engineering Chemistry Research, Vol. 53, No. 6, 2014, pp. 2498–2508. https://doi.org/10.1021/ie4033999.