Development of a Gaseous Oxygen-Gaseous Propane Torch Igniter for a Sub-Scale Bipropellant Liquid Rocket Engine

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Tartarus, the student liquid rocketry program of The Space Hardware Club of the University of Alabama in Huntsville is currently working towards the creation of a subscale rocket engine. For the purpose of ignition, an igniter to allow for the combustion of propellants is required. To achieve this, a torch igniter with gaseous propellants will be manufactured. The igniter will be produced out of parts manufactured in-house and from commercial vendors such as a billet of copper material for the chamber of the igniter. The torch igniter will use gaseous propane as its fuel and gaseous oxygen as its oxidizing agent for their high heat of combustion as is necessary for a cryogenic liquid engine. This is capable of being modeled to ensure that ignition occurs within the igniter before reaching the chamber of the engine. The ignition method for the igniter will be a commercial spark plug as there is a low power requirement for the propellants selected. Propane has been chosen for being readily available while gaseous oxygen was chosen for being easy to handle as well as their high heat of combustion. The igniter is placed within the manifold with a parallel flow to the propellant injector face. This is to not change the point of impingement or the momentum of the flow of the propellants for the engine and allows for the avoidance of wall compatibility issues against the chamber walls. This paper will focus on the requirements of ignition and the creation of a gaseous propellant torch igniter.

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I. Introduction

The Tartarus project is the liquid rocketry project of The University of Alabama in Huntsville's Space Hardware Club. The project has the final goal of developing, manufacturing, and testing a subscale liquid rocket engine dubbed "Prometheus." This engine will be 6 inches in length, 5 inches in diameter, and made of copper. Before the engine can be designed and manufactured, the team must demonstrate the ability to design, manufacture, and safely operate an ignition system that meets the target required power estimations. To achieve this, an ignition system needs to be created and then tested to validate simulation and confirm combustion is achieved for the engine to ensure ignition is achieved.

In order to create the ignition system, the scope of the project must first be understood. As a student-led project, criteria can be defined as capabilities to ignite, repeated firing and reusability, ease of manufacturing, and cost. For this, a power requirement and output must be derived to base the design on, as ignition will be the greatest concern. With this the temperature of combustion can be found, allowing for the selection of a material that falls within the budgetary and melting point constraints. Finally, the team is then able to model and simulate the igniter such that it

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can be manufactured within the team without the need for external sources, as everything is machined and assembled in-house, which then allows for the testing and validation of modeling done by the team. To this end, Tartarus' propulsion subteam has researched existing empirical models for the validation of power and developed numerical methods to allow for the simulation of the igniter's behavior in MATLAB. This will then be tested and later validated by the team which will cause any needed iterations in design as well as prove the dependability of the modeling for future designs.

II. Design Constraints

Igniter performance is the first consideration of the design as without an ignition there cannot be performance from an engine. The igniter shall produce the energy required for ignition, which is estimated at 62.8 kW [1] after applying a factor of safety of 2.0 and accounting for vaporization. The igniter must meet these requirements to be considered successful and operational for use within the "Prometheus" engine.

As a student project sharing a budget with other projects within the rocketry program, cost is a prioritized constraint for Tartarus. The igniter will be reusable for repeated firings of the engine to allow for validation of simulation data and allow for efficient use of materials such that a repurchasing of items between every firing should be minimized. This will also decrease the time between firings due to any delays or waiting periods as a result of ordering and shipment. The igniter should be affordable and easy to manufacture, as simplicity and data collection is the key focus of the subscale engine. The geometry of the igniter is limited to the manufacturing abilities of the project as everything is produced by the team apart from parts or pieces of material that will be machined to comprise the igniter.

Safety concerns also limit design criteria. The igniter will allow for avoidance of a hard start, where a significant amount of propellant pools in the chamber before ignition, causing a detonation wave that can damage or destroy the engine. It will also allow for the avoidance of wall compatibility issues and other failure criteria. The igniter should minimize risk from thermal, structural, and chemical considerations. The igniter should also support easy and safe integration of instrumentation such that data can be measured and recorded for the purpose of modeling validation.

III. Igniter Trade Study

A variety of ignition systems were considered to determine which one would be ideal for the engine. Evaluation criteria for this system include safety, reliability, reusability, manufacturability, and documentation in academic literature. Systems such as ignition via spark plug, glow plug, or ignition coil were initially considered but ruled out as they are unable to meet the minimum power requirements outlined above. The use of a hypergolic ignition system was initially considered as well due to their ease of combustion. Hypergolic fuels spontaneously combust when in contact with each other, which allows the system to achieve ignition of the fuel-oxidizer mixture easily and rapidly. In addition, hypergolics can be stored as liquids at room temperature, which greatly simplifies storage relative to other potential propellants. However, the hypergolic ignition system comes with its own issues of dangerous properties. Hypergolics are known to be toxic, carcinogenic, and extremely corrosive, which increases the hazards involved with handling such fuels [2]. Seeing as the "Prometheus" engine is designed to be a subscale engine whose main purpose is to validate modeling, both used and created by the team, using a hypergolic ignition system adds unnecessary risk to the project which can otherwise be avoided with a simpler design that doesn't jeopardize the system.

Ignition of fuels can also be achieved by igniting a solid rocket motor and routing its exhaust to the liquid rocket engine's combustion chamber. This solid motor cartridge ignition system, as seen in Figure 1, is a relatively simple alternative that has been used in other amateur student-led subscale liquid engine efforts such as Half Cat Rocketry or Georgia Tech, with proven success and reliability. As these solid rocket motors are widely used in hobby rocketry, they can be sourced from trusted vendors with relative ease. In addition, implementing such a system into a liquid rocket engine's design is straightforward, and these motors nearly guarantee combustion. However, the implementation of such a system, as well as any further testing or usage, requires the purchase of new motors which can cost upwards of $100 for every engine test fire. The burn time of most hobby rocket motors is short as well, which adds risk and complexity to the engine's ignition sequence by decreasing the time the engine's fuels have to begin combustion. Because this system involves routing rocket motor exhaust gases into the combustion chamber, issues regarding wall compatibility and flow disruption may arise when done in any direction with the exclusion of parallel with the flow of the propellants. Due to the size of the subscale engine, there is a limited amount of room on the injector face, adding to more compatibility issues when integration with the system is discussed the solid motor's combustion byproducts have the potential to deposit onto the inner walls of the engine, thus negatively impacting performance and increasing the difficulty of modeling flow simulations. In addition, although several amateur liquid rocketry programs have reported success with this method, there is somewhat of a lack of documentation and theoretical calculations regarding the simulation of solid motor performance in academia. The nature of this project requires that the validation of potentially implemented systems rely primarily on theoretical simulations as opposed to trial-and-error; as such, this project cannot depend on repeated testing to validate the performance of the ignition system. This lack of academic documentation inhibits the creation of robust models that can be relied on to provide accurate results, thus increasing the uncertainty of the solid motor ignition system's performance and negatively impacting its prospects as a potential ignition system. Below is a preliminary design created by the team to showcase the possibility of a slug igniter's usage.

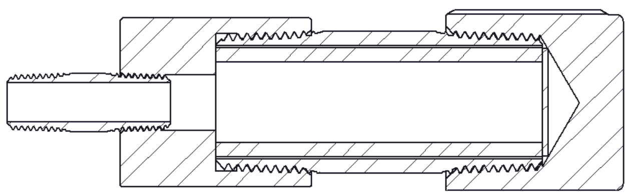

Fig. 1 Theoretical Slug Igniter

The torch ignition system, as pictured below in Figure 2, was another potential candidate that is more widely used in subscale liquid rocket engines. This system involves mixing and igniting gaseous oxygen and gaseous fuel in a separate prechamber, then subsequently using the thermal energy released to ignite the fuel-oxidizer mixture in the main engine combustion chamber. As opposed to other proposed systems, the torch igniter is also fully reusable, requiring only additional fuel and oxidizer replenishment. This system is designed to be as simple as possible and utilizes only gaseous fuel and oxidizer, thus making it especially reliable. Simple and reliable subscale ignition methods such as a spark plug are more than enough to combust the torch igniter's gaseous fuel/oxidizer mix. Torch igniters are potent systems and can generate more than enough heat flux to facilitate ignition in the main engine. Most importantly, this method has a larger amount of academic literature behind it and is more well-documented than other alternatives due to its prolific use in liquid rocketry. This abundance of academic discourse facilitates a relatively easy characterization of the torch ignition system's performance metrics. Consequently, the use of a torch ignition system allows for the creation of more accurate models and simulations, greatly increasing confidence in its ability to reliably facilitate combustion in the main engine. However, this system is slightly more complex than other methods and thus may require more effort in terms of design and integration into the main engine. Finally, verification of the torch igniter function may be difficult without opening run valves, resulting in a potential increase in risk and failure points.

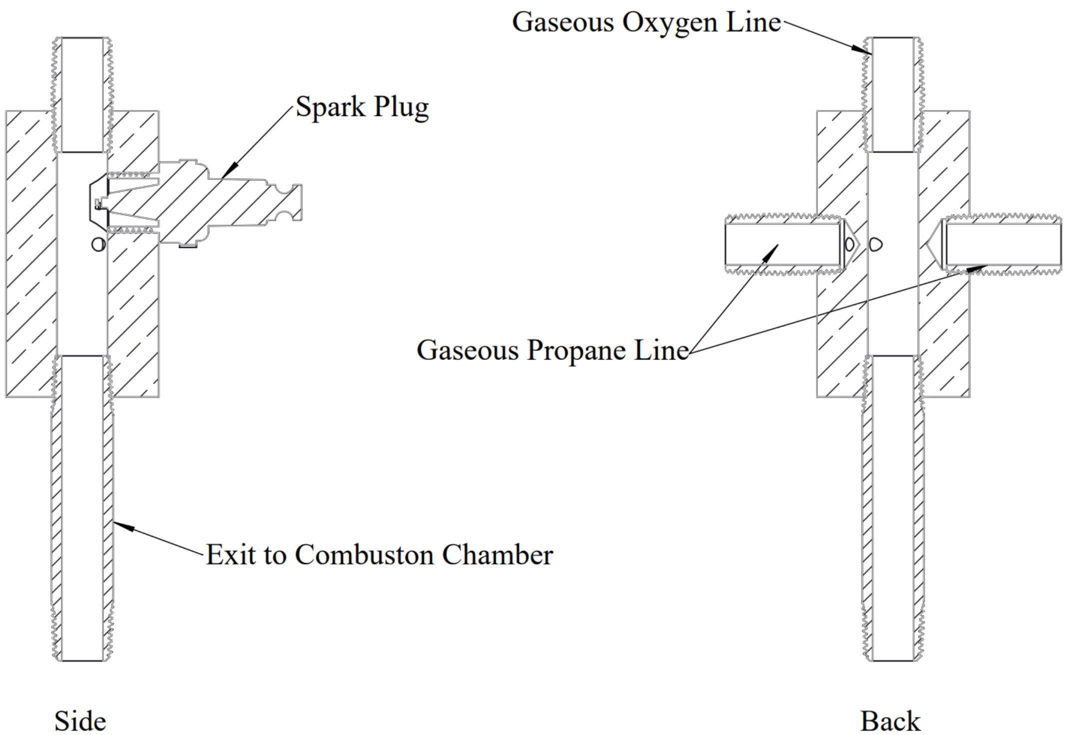

Fig. 2 Current Torch Ignition Design Sectional View

IV. Propellant and Material Selection

To select the propellant and material to manufacture the igniter, multiple candidates were researched from other teams, both through direct discussion and academic papers, and from in-house experience. A wide variety of different propellant mixtures for both fuel and oxidizer were considered for the igniter. Among the fuels researched were MAPP gas, methane, and propane. MAPP gas is a trademarked mixture of gases including methylacetylene, propadiene, and propane commonly used for welding applications [3]. However, no group has used MAPP gas as an ignition fuel and being a mixture of gases makes calculations and modeling increasingly difficult. Another choice for fuel was methane. Methane is common among other torch igniters used in student liquid rocketry teams however methane is difficult to obtain in a pure concentration on top of being expensive compared to alternatives. Propane is less commonly used for torch ignition systems but is cost effective and easy to obtain being used for multiple consumer applications in other industries.

The selection of gaseous oxygen (GOx) was almost unanimous due to GOx being easy to work with and easy to obtain as well as its extremely well recorded among academia in addition to usage among other student teams of a similar nature. Nitrous oxide was also considered as an oxidizer as nitrous oxide is slightly easier to ignite. Nitrous oxide in gaseous form is not cryogenic thus requires less energy to ignite and receives extra heat as it is heated from exothermic decomposition. Even with these benefits however, nitrous oxide was ruled out due to being far more expensive and being extremely hazardous as the exothermic decomposition can cause a runaway effect from any heating before ignition [4]. This theoretical event also played a part in Tartarus previously moving away from using nitrous oxide in its liquid state as an oxidizer selection for the engine.

The injector will be machined out of the alloy copper 110 due to its high thermal conductivity melting from 1338-1356 kelvin and annealing from 748-1023 kelvin [5]. This will allow for the heat to disperse from the walls of the igniter due to the lack of any cooling system in a simple design like the one selected. The igniter is not designed to fire for more than 20 seconds per firing meaning the copper will never reach the temperature requirements to melt or anneal. As compared to many variants of stainless steel, which have a higher melting point, the risk of hotspots occurs due to the lack of aforementioned cooling for the igniter. The tradeoff of selecting a material where a cooling system, such as a cooling jacket, instead makes copper more favorable.

V. Igniter Integration with System

The igniter design will employ the use of a spark plug, a device that uses internal combustion to create a spark via a source of high voltage, to achieve ignition of the gaseous propellants within the igniter. The spark plug igniter is going to be incorporated with the manifold parallel to the injector face so that the propellants are shot straight down the igniter shaft as opposed to on the walls as to avoid any possible wall compatibility issues that would arise from the propellant reacting with the material of the walls. The spark plug will be attached perpendicular to the GOx inlet, which will flow in from the top of the igniter, and perpendicular to the two propane inflow pipes on the sides as seen in Figure 2. Due to GOx being a strong oxidizer, it is much safer to have the oxygen spray straight down, decreasing the chance of the liquid getting on the walls and reacting with the igniter. To further mitigate the risk of oxidation, the igniter body will be made of copper, which resists oxidation well, and the pipes used to bring the GOx and propane into the igniter body will be made of steel, which similarly has a low oxidation rate.

The NGK 5812 CM-6 spark plug was chosen as it had the desired size and can reach the required power output needed to ignite the gas within the engine. The energy required to ignite the propane and LOX is low due to the gasses being extremely combustible when mixed within the chamber of the igniter. The spark plug will be powered by a 10kV power supply at 30 amps, connected to the spark plug via an alligator clip, due to this method being self-contained separate to the controls of the engine and easier to manage than other ignition systems for the purpose of the igniter.

For the purpose of testing and studying the igniter, two thermocouples will be applied to the igniter manifold to record the temperature data of the igniter as it heats up and is fired. A thermocouple is a device consisting of two metals that, when experiencing a temperature change, produce a voltage that is measured and correlated to the change in temperature of the surroundings. The thermocouple that will be used in the igniter is the Super Omegaclad XL Thermocouple Probes, as it can handle up to 1600 K [6], which is above the 1500 K the igniter will reach. In addition, these thermocouples have a longer lifespan than others that can survive the temperatures that the igniter will reach. Due to these high temperatures, the pressure transducers available cannot be used, so pressure will therefore not be measured and included within igniter data. All coupling will use national pipe thread size ⅛ inch as that pipe size is the largest that can reasonably fit through the propellant manifold for the main combustion chamber.

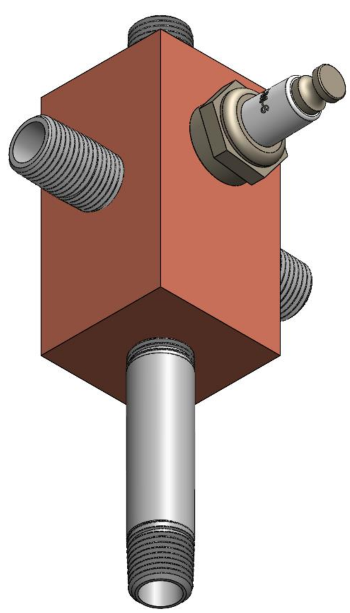

Fig. 4 Current Torch ignition Design

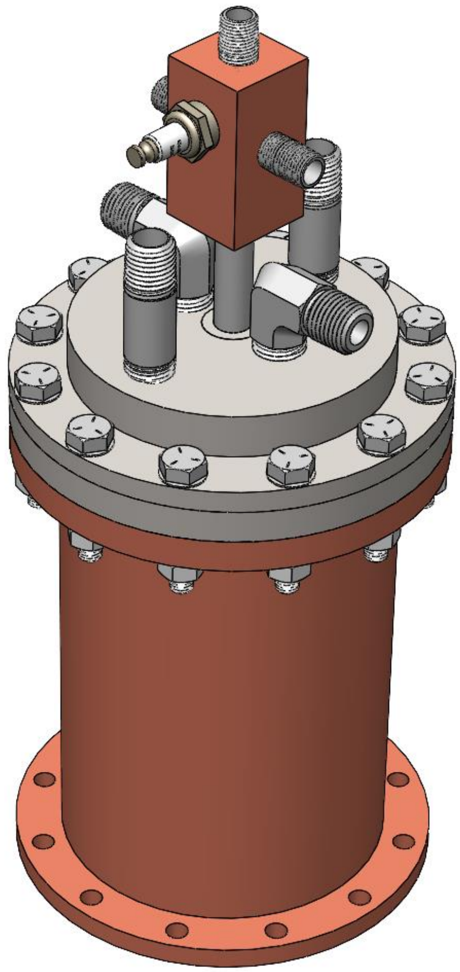

Fig 3. Igniter Integrated with the "Prometheus" Engine

VI. Script Modeling in MATLAB

In order to estimate the required parameters of an ignition system, first the required ignition power for the chosen propellants had to be calculated. This was done within MATLAB, using the open-source plugins CoolProp and Cantera for calculation of fluid thermodynamic and transport values and for chemical equilibrium analysis, respectively [7, 8]. First, CoolProp is used to determine the mass-specific enthalpy difference between the fuels at injection conditions and at auto-ignition, accounting for the latent heat of vaporization required to vaporize the fuels. Per Mitu et. all, autoignition of ethanol occurs at 323℃ in pure oxygen, or 400℃ in air [9]. For this analysis, that value was roughly averaged for safety for a target ignition temperature of 365℃, or 6 For each fuel, this produces an enthalpy difference of 1.607 MJ/kg for ethanol and 0.74 MJ/kg for liquid oxygen. To average for the sum propellant mixture, a mass average enthalpy is produced according to the OF ratio of the propellant mixture.

$$h_{mix} = \frac{1}{OF+1}(h_{fuel}) + \frac{OF}{OF+1}(h_{ox}) \quad (1)$$

According to this equation, a combined specific energy of 1.2 MJ/kg is required to bring the propellant to ignition conditions. However, not all this needs to come from an igniter, as combustion is a chain-reaction process which becomes self-sustaining after a certain amount of propellant is ignited. For the purposes of this analysis, chain-reaction combustion is assumed to be attained once a certain mass fraction x of propellant releases enough energy via combustion to bring the remaining fraction $1 - x$ to combustion. Thus, if I is ignition energy in kj/kg and C heat of combustion, then the following relation is derived:

$$(C - I)x = (1 - x)I$$
$$\rightarrow (C - I)x + Ix = I$$
$$\rightarrow Cx = I$$
$$x = \frac{I}{C} \tag{2}$$

Thus, the mass fraction of propellant needed to be ignited to begin self-sustaining combustion is estimated to be the ratio of ignition energy to combustion energy. Using Cantera and the PCRL ethanol mechanism, combustion energy can be calculated as the difference between the mass-specific chemical potential energies of the pre- and post-combustion mixtures, assuming an adiabatic combustion process without bulk kinetic effects [10, 11]. For the given OF ratio and propellants, this produces a combustion energy of 27.025 MJ/kg. Thus, using Eq. (), the percent of propellant mixture that must be ignited is 4.44%. To convert to a required power, the ignition energy is multiplied by the ignition fraction and the propellant mass flow rate, ṁ:

$$P_{ig} = \dot{m} \cdot x \cdot I \tag{3}$$

For the given propellant flow of 0.5985 kg/s, this produces an igniter power of 31.385 kW. To account for non-ideal heat transfer conditions and inefficiencies, a factor of safety of 2 is applied, finally producing the previously cited required power of 62.8 kW. To find the needed igniter propellant flow to achieve this, first the combustion energy of the igniter fuels must be calculated in the same manner as the prior combustion calculation. First, an assumed max temperature of 1600 K was set to ensure safe operation of the igniter for its max firing of 5 seconds. Using Berkely's GRI-3.0 mechanism, an OF ratio of 1.15 or propane-oxygen was found to produce a flame temperature of 1522 K, within assumed safe parameters, with a combustion energy C_{ig} of 22.57 MJ/kg [12]. From this, the required mass flow rate can be calculated as follows:

$$\dot{m} = \frac{P_{ig}}{C_{ig}} \tag{4}$$

With the given values, this arrives at a total igniter mass flow rate of 2.8 grams/s, or 1.3 grams/s of propane and 1.5 grams/s of oxygen, providing a performance metric to design towards.

VII. Finite Element Analysis Integration

To examine how thermal generation during the ignition process would affect the temperature disturbance in the chamber of the igniter, an FEA model was produced using Marc. The thermal properties of 110 copper material were utilized, and the coefficient of thermal expansion and specific heat was adjusted to scale with temperature using values obtained from sources mentioned above. Thermal boundary conditions were set to normal air convection conditions for the external walls of the igniter, while the interior walls thermal boundary conditions were sourced from the MATLAB simulations. Assuming a total firing time of 5.0 seconds, as is planned with the burp test of the igniter, a thermal heat analysis was run with the results shown below:

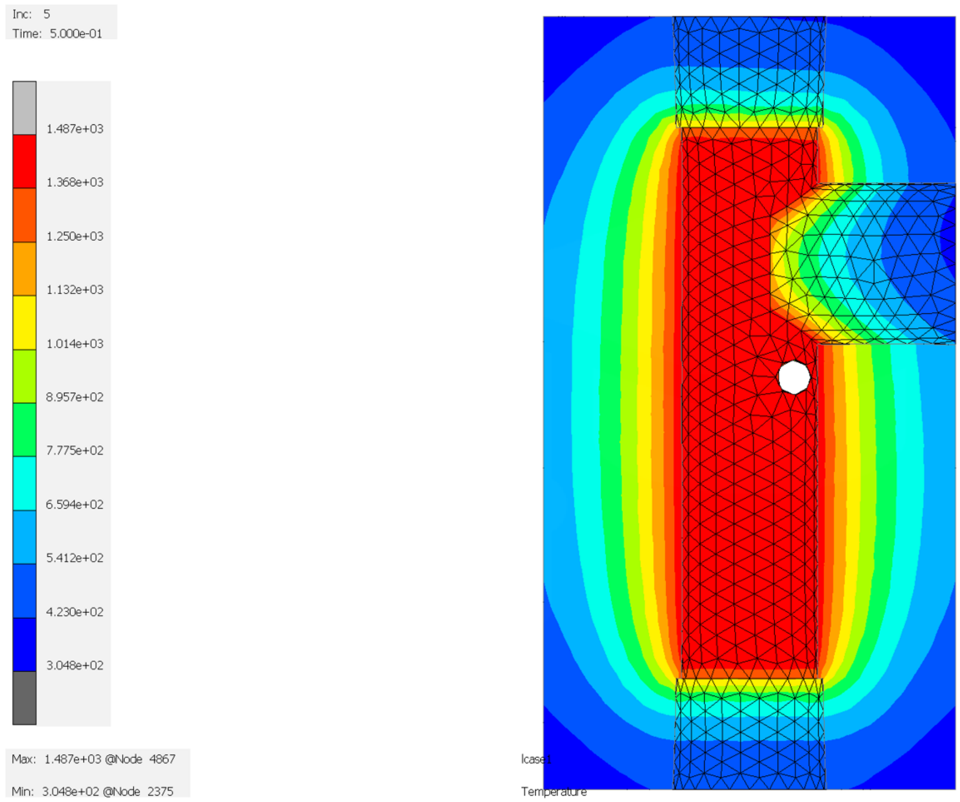

Fig. 5 Thermal distribution from a transient study at 5.0 seconds

As seen in Figure 5, the igniter will reach a relatively high temperature that will surpass the melting point of 110 copper within the igniter however due to the high thermal conductivity of the copper as stated earlier the heat will disperse along the body of the igniter preventing any permanent damage to the igniter. The future testing of the igniter will allow for validation of this modeling and its reliability moving forward for the team.

VIII. Future Model Validation

To validate the selections for propellant, ignition, modeling both mathematically and logistically, and igniter geometry, an igniter test fire independent of the engine will be conducted. The igniter will be mounted to a test stand as designed by the team and fired at a maximum of 10 seconds. The igniter will have a temperature sensor and pressure sensor mounted inside the body of the igniter to validate the finite element analysis performed by the team. A camera will be placed perpendicular to the test stand to record high speed footage of the exhaust flame. In addition, markings on the mount will be provided so that the length of the flame can be measured such that wall compatibility issues with the igniter can be avoided depending on the mixture and flow rate of the propellants. Before engine hotfire there will also be a test of the igniter while it is integrated with the rest of the engine setup but not firing the rest of the engine, referred to as a cold flow test which will allow validation of the igniter that will not damage the engine or its components during firing.

IX. Conclusion

This research will contribute to other student-led liquid rocketry programs by providing a basis upon which to build new ideas and experimentation. Through this study, such liquid rocketry projects will be able to more easily and more accurately predict how an engine design will work and should work. Along with this, student liquid rocketry projects will be able to iterate and improve upon designs, directly benefiting this project as it moves forward with the development of more hardware for their capabilities external to solely the engine. Having the capabilities to simulate and validate the torch igniter, which holds similarities to a small gaseous engine, will give Tartarus, as well as other teams, greater chances of having successful engines and fulfilling mission requirements.

This remains only a step forward for Tartarus, further proving the capabilities of the team to model, simulate, and improve in the future, further advancing student liquid rocketry programs. It will continue to drive further designs at a higher fidelity moving forward. This knowledge can and will be shared with other amateur student liquid rocketry teams such that growth may be seen as a collective and for the field of liquid rocketry.

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