Electric Propellant Feed System for Amateur Class High Altitude Sounding Rockets

Jordan S. Roland[1], Rawand M. Rasheed[2], James Luce[2],

Mimi G. Shang[2], Johnny C. Froelich[2], and John D. Talik[2]

Portland State University Maseeh College

of Engineering and Computer Science,

Portland, Oregon, 97201

I. Extended Abstract

Portland State Aerospace Society (PSAS) is a student aerospace engineering group at Portland State University. Its mission is to intends to build low-cost, open source rockets that feature some of the most sophisticated amateur rocket avionics systems in the world. By being completely open source, PSAS strives to enable other amatuer aerospace engineering teams across the world to design, manufacture, and launch rockets. The current project, titled Launch Vehicle 4 (LV4), attempts to design and build a rocket Capable of achieving altitudes of over 100 kilometers, above the Von Karman line, and into space. To reach these altitudes to deliver the payload, LV4 requires a liquid fuel engine specified as a regeneratively cooled liquid oxygen (LOX) and ethanol bipropellant rocket engine. A DMLS 3D printed rocket engine was developed and prototyped by a past PSAS group [1] (Tucker et al. 2016). For successful delivery of LOX and ethanol from the fuel tank to the engine, an electric pump feed system is proposed.

Since the early days of rocketry, turbo-pumps have been the industry standard for generating the pressure head required to deliver propellants to the combustion chamber in most liquid fuelled

[1] Student deptartment of Mechanical and Materials Engineering Portland State University, Portland, Oregon, AIAA student member since 2016

[2] Student deptartment of Mechanical and Materials Engineering Portland State University, Portland, Oregon

engine rockets. To deliver large mass payloads to orbit, extremely large rockets use turbine driven pumps as the most efficient method of delivering the required pressures to the combustion chamber. Groups in amateur rocketry, with small payloads, do not typically have access to the budgets or infrastructure required to develop turbo-pumps, nor do they require the extremely high pressures that make turbomachinery exclusively required, thus resorting to different methods of propulsion systems. As a result, these amateur groups opt for simpler pressure fed systems. Unfortunately, this requires tanks rated for very high pressures (in excess of 1500 psi in some cases). Tanks rated to these pressures are inherently heavy, which is detrimental to the mass ratio of the rocket, and as a result are detrimental to achieving high altitudes. The concept of an electric pump feed system (EFS) is one that has gained attention in recent years as an alternative feed system for small rockets. An EFS utilizes an impeller driven by a DC motor powered by high density batteries to pump liquid fuel and oxidizer from their respective tanks to the combustion chamber. Fig. 1 provides a block diagram of an EFS. In Rachov et al. 2010 [1], the feasibility of an EFS for liquid propelled rockets is explored. Such a feed system was concluded to not only be feasible, but to also provide advantages over traditional pressure fed systems in the ability to throttle the pump, accessibility due to the use of COTS parts, and a lowered inert mass. Trajectory simulation analysis shows that throttling back near burn out allows for the production of a more optimal vehicle due to the ability to reduce acceleration. When comparing an electric pump feed system to other forms of propellant delivery, a 2013 research paper lead by D. Spiller states that an EFS offer a great advantage over gas-pressure fed systems in terms of inert mass [2]. The EFS reduces the inert mass by dramatically reducing the required pressure of the fuel tanks, thus the tanks can be constructed utilizing lightweight materials and construction techniques. In recent years, advancements in battery and DC motor technology have also led to improved performance and decreased inert mass. As a result, this innovative design helps attain vertical distances far beyond the typical range of an amateur rocket.

Design considerations revolving around an electric pump feed system are complicated due to

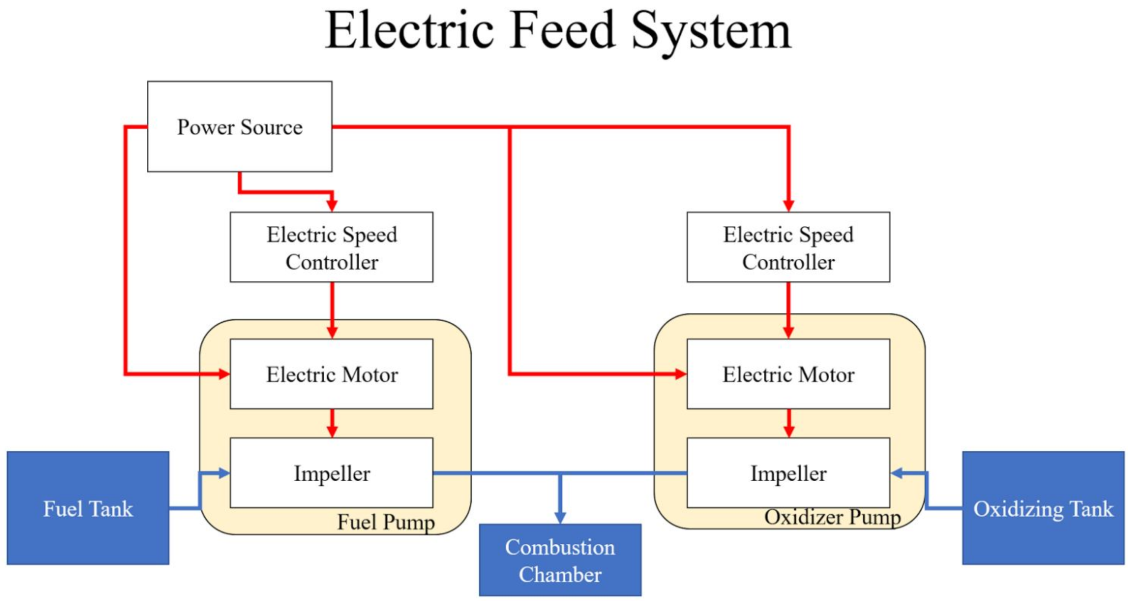

Fig. 1 An overview of the proposed solution to address propellant pressurization by using an electric feed system (EFS). The electric feed system has the potential to greatly reduce the weight of the rocket over other methods of propellant delivery.

the use of cryogenic fluids. Liquid oxygen used in this application poses material compatability issues, as well as issues with component design for cryogenic temperatures. Parts of the design that are complicated due to extremely low temperatures of cryogenic fluids include, but are not limited to, design of the impeller, pump casing, seals, bearings, joints, and fittings. PSAS has

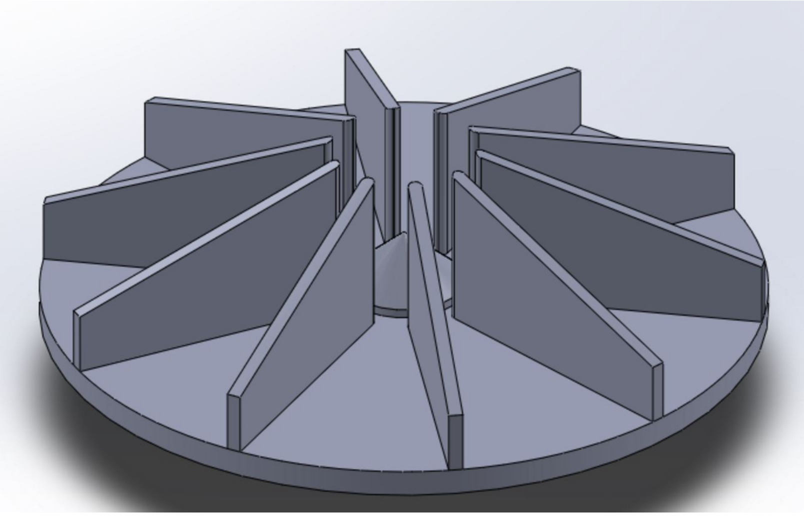

Fig. 2 CAD design of a Barske impeller.

completed preliminary pump sizing calculations [7] to demonstrate the theoretical feasibility of an EFS required to generate a head rise of 1090 ft for the fuel pump and 754 ft for the oxidizer pump, and to deliver propellant at a required flow rate of 13 GPM for fuel and 11.5 GPM for oxidizer to the existing Liquid Fuelled Engine (LFE) [5]. The pump will be constructed utilizing commercial off-the-shelf (COTS) electric motor and motor control system with a custom-designed 3D printed pump. Investigation and testing of impeller design is currently underway. Preliminary calculations favor a Barske impeller design to meet the high head and low flow requirements of the fuel pump (See Appendix A for sample calculations and figures). In addition, the simplicity of the Barske design promotes future for prototype and testing iterations with relative ease. A CAD model of the Barske design is down in Fig. 2. This design has potential to offer a rapid iterative engineering approach to fine tune the most appropriate impeller for this particular application.

Fig. 3 Aquastar T20 3T 730KV/1280KV Water Cooled Brushless DC Motor.

An EFS prototype will be completed and tested as a senior capstone project at Portland State University by June 9, 2017. The first prototype will use an Aquastar T20 3T 730KV/1280KV brushless DC motor, shown in Fig. 3, to achieve the required RPM of the pump [8]. This off the shelf motor will be controlled using it's compatible Turnigy Aquastar 240A Water Cooled ESC [9]. This prototype will be tested first using water, and then using cryogenic fluids. Results of these tests will dictate the feasibility of using an EFS in a flight ready rocket. The focus of the first prototype will be to achieve constant discharge pressure of the pump. Initially, control of the discharge pressure will be assessed using the selected COTS ESC. If necessary, further feedback and control will be added to the system.

Further challenges include mechanical analysis of vibrations in the motor shaft at high RPMs. Preliminary calculations show a maximum shaft torque of approximately 2 kN-m (Appendix B). Shaft diameter of the selected motor is 8mm, which creates challenges in selecting a material and design which can withstand both the torque of the motor and the thermal stresses and strains resulting from contact with cryogenic fluids. Designs will be tested, and evaluated, including cold flow and cryogenic flow testing on PSAS's existing Liquid fuelled engine test stand (LFETS) system.

Appendix

PE impeller calculations:

Theoretical head rise (H') is given as the following:

$$H' = \frac{u_2^2 - u_1^2}{2g} + \frac{u_2^2}{2g}$$

Experimental results of static pressure measurements determine that this equation reduces to the following:

$$H' = \frac{u^2}{2g} + \frac{u^2}{2g} = \frac{u^2}{g}$$

Where u is taken to be the impeller tip speed. The actual head rise becomes:

$$H = \psi \frac{u^2}{g}$$

Impeller tip speed is defined as:

$$u_2 = \pi D_2 N$$

Subsequently the pump specific speed is defined from the flow rate (Q), Head rise (H), and input RPM.

$$N_s = \frac{NQ^{0.5}}{H^{0.75}}$$

Some substitutions:

Substituting u into the equation for head rise (H):

$$H = \psi \frac{(\pi D_2 N)^2}{g}$$

Similarly for the output flow rate (Q):

$$Q = \phi(\pi D_2 N)A_1 = \phi \pi^2 D_2 N d_1^2$$

This means that the specific speed(N_s) then becomes:

$$N_s = \frac{\phi^{0.5} g^{0.75} d_1}{\psi^{0.75} \pi^{0.5} D_2}$$

$$d_1 = (\frac{Q}{\phi \pi})^{0.5} (\frac{\psi}{Hg})^{0.25}$$

$$D_2 = (\frac{1}{\pi N})(\frac{Hg}{\psi})^{0.5}$$

Acknowledgments

Special thanks to PSAS for supporting this endeavor

References

[1] Rachov, P., Tacca, H., Lentini, D. *Electric Feed Systems for Liquid Propellant Rocket Engines*. 2010. Research Report.

[2] Spiller, D., Stabile, A., Lentini, D. *Design and Testing of a Demonstrator Electric-Pump Feed System for. Liquid Propellant Rocket Engine*. Aerotecnica Missili & Spazio, Journal of Aerospace Science, Technology and Systems, 2013.

[3] NASA, Pline. A. (2016, July). *About the Human Exploration and Operations Mission Directorate*. `https://www.nasa.gov/directorates/heo/about.html`

[4] Portland State Aerospace Society Websire `http://psas.pdx.edu/`

[5] Tucker, J., Dib T., Ricey T., Schmidt E., Travis K., Viggianoz B. Development of a Small Bipropellant Rocket Engine Utilizing Additive Manufacturing Processes. AIAA Space 2016.

[6] Rocketlabs Rutherford Engine `https://www.rocketlabusa.com/latest/rutherford-engine-qualified-for-flight/`

[7] Schmidt E. Electric Feed System Pump Size Estimates. `https://github.com/psas/electric-feed-system/blob/master/Analysis/electric_pump_calcs/pump_sizing.ipynb`

[8] Huzel, D. K., & Huang, D. H. (1971). *Design of liquid propellant rocket engines*. Washington: Scientific and Technical Information Office, National Aeronautics and Space Administration.

[9] Lobanoff, V. S., & Ross, R. R. (1985). *Centrifugal pumps: design and application*. Abington Publ.

[10] Budynas, R. G., Nisbett, J. K., & Shigley, J. E. (2011). *Shigley's mechanical engineering design*. New York: McGraw-Hill.

[11] NASA-SP-8119. *Liquid Rocket Disconnects, Couplings, Fittings, Fixed Joints, And Seals*. (1976).

[12] NASA-SP-8109. *Liquid Rocket Engine Centrifugal Flow Turbopumps*. (1973)