Electric Propellant Feed-System for Amateur Class High Altitude Sounding Rockets

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Liquid propellant rockets engines, with their high impulse density, offer a path to the attainment of extreme altitudes at apogee for university class sounding rockets. The majority of student and amateur groups working with liquid propulsion use heavy pressure fed systems. By contrast, commercial class turbopumps, in addition to their significant engineering complexity, offer little in the way of mass ratio improvements for small launch vehicles. A mechanical engineering senior capstone team at Portland State University has developed a small, high head, low flow DC-motor driven centrifugal pump for rocket applications.

Nomenclature

PSAS	=	Portland State Aerospace Society
EFS	=	Electric Feed-System
BLDC	=	Brushless DC Motor
SLA	=	Stereolithography
DMLS	=	Direct Metal Laser Sintering
LOX	=	Liquid Oxygen
NPSH	=	Net Pressure Suction Head
NPSHa	=	Net Pressure Suction Head Available

I. Introduction

Portland Space Aerospace Society (PSAS) is a student aerospace engineering group at Portland State University with the mission of building low-cost, open-source rockets that feature some of the most sophisticated amateur rocket avionics systems in the world. The group's inspirational 'horizon goal' is to orbit a 1 kg nanosat with their own launch vehicle.[1] One of PSAS's current projects, Launch Vehicle 4 (LV4), is designed to breach the so-called von Kárman 100 km above sea-level. To reach these altitudes, the LV4 design incorporates active attitude control, a light-weight carbon-composite airframe and propellant tanks, and liquid bi-propellant rocket propulsion.[2]

Since the 1940s, turbopumps have been the industry standard for generating the required pressure head in large liquid fuelled engine rockets. Groups in amateur rocketry, however, do not typically have access to the budgets or infrastructure required to develop turbopumps. These groups usually opt for the simpler pressure fed systems for the fuel/oxidizer tanks. Unfortunately, this requires tanks rated for very high pressures (in excess of 1500 psi in some cases). Tanks rated to these pressures are extremely heavy, which is detrimental to the mass ratio of the rocket.

To overcome the challenges and limitations presented by these designs, PSAS has chosen to explore alternative feed-system concepts. Owing to recent improvements in battery energy density and brushless DC (BLDC) motor technology over the past several years a new type of feed-system has become feasible: an electric feed-system. In the 2016 academic year a senior capstone team at Portland State University rapidly

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prototyped such a system, likely the first ever to be built by undergraduate students. Per PSAS's open-source mandate, the electric pump project deliverables (including CAD assemblies, impeller sizing scripts, and CAM scripts) are available on GitHub.[3] It is hoped by the authors that both acadamia and private industry will leverage this work in the furtherance of aerospace endeavour as a whole.

II. Design

A. Impeller

Table 1: Example computational output numbers for a theoretical 6 vane LOX impeller

LOX Impeller	
RPM	20000
Blade number	6
Flowrate [GPM]	11.57984
Head Rise [ft]	754.324
Specific speed	472.594
Fluid Power [kW]	1.87631
Required Motor Power [kW]	4.69077
Specific Diameter [in]	0.184903
Impeller Diameter [in]	2.13375
Throat Diameter [in]	0.177869
Eye Diameter [in]	0.42981
Impeller Eye Area [in^2]	0.570073

In typical pump design and selection the choice of impeller type is a straightforward result of the pump sizing process. The impeller type is determined from the specific speed, a value calculated from the requirements of the system (for reference, the venerable Huzel and Huang[4] give a good overview of the conventional pump sizing methodology). However, the small size of PSAS's 2.2 kN development engine, having relatively high head and low flow rate requirements, led to a specific speed that falls outside of the range offered by common impeller types.

This forced the design process to take a radical departure from the typical options found in pump design documentation. Literature review outside of the normal canon of rocket pump design led to the suggestion of a Barske design impeller;[5] an unorthodox, straight vane radial impeller design suitable for low flow, high head, and low specific speed requirements. This impeller type also has an inherent geometric simplicity which is attractive for its maneuverability. The sizing calculations were done using *Python* in a *Jupyter Notebook* which can be viewed on GitHub.[3] Some figures of merit for the pump are presented in Table 1.

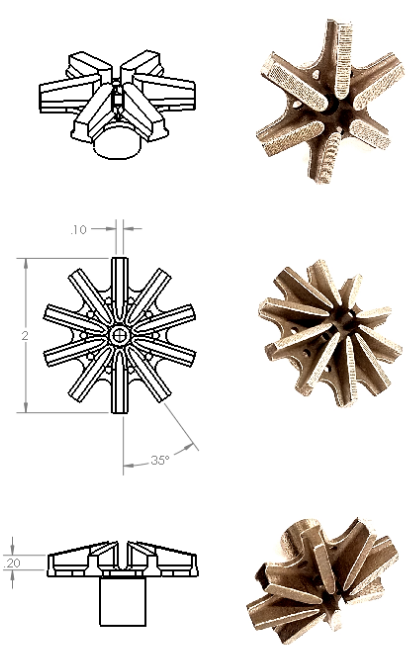

Figure 1: Solidworks CAD of the test impellers and the Stainless steel DMLS printed final product

B. Housing

Another major decision was the housing type to be used for the initial prototype and water testing. A simple option for an impeller housing is a concentric bowl design, which is the easiest to manufacture but may reduce efficiency. Higher performance housing options could include an expanding volute or the addition of a cutwater to the concentric design.

In the interest of developing a prototype to validate theory (before hitting performance targets), a concentric volute housing was chosen to simplify manufacturing. The first prototype test is intended to prioritize isolating the influence of factors represented in the pump sizing theory used for fundamental design calculations. In particular, impeller diameter, height, blade number, inlet size, and outlet size are critical dependant variables. Fortunately, many of these variables are colinear, and a test regimen does not need to independently manipulate each variable. Introducing housing design as a dependant variable at this stage, however, dramatically complicates the testing required without providing clear validation of the theory used in the design.

III. Results

Performance testing of the EFS prototype as a complete system is an involved and ongoing process. Pump tests are based on standardized testing procedures[a] relating to the characterization of centrifugal pumps. This requires the production of several standardized plots to determine the characteristics and operating performance of a particular pump. In order to produce these plot a testing platform and series of designed experiments were developed. These plots include flow rate (Q) vs. head (H), Q vs. net pressure suction head (NPSH), Q vs. efficiency, and a system curve describing the friction losses of the particular system. Preliminary test results show that the pump outperforms expected results in several key performance measures. Shown in Figure 2, are the standard performance curves for the 10 blade impeller at 16500 RPM.

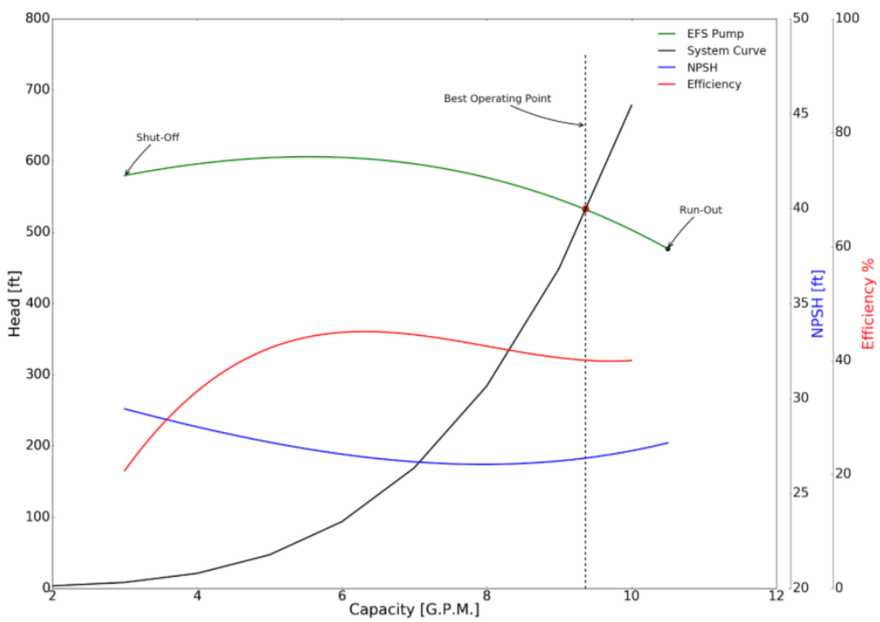

Figure 2: Graph of performance characteristics for 10 blade impeller & 8 degree diffuser at 16500 RPM.

From early pump performance runs, the EFS is on track to meet key performance targets. Although data analysis is in progress for higher RPM testing, discharge pressure and flow rates exceeding requirements have been witnessed in preliminary testing. Current data analysis shows maximum outlet pressure of 284 psi for a 10 blade impeller at 16500 RPM. The optimal rotational speed for the conceptual design was predicted at 22000 RPM. Challenges with battery performance inhibited full testing at these speeds. Future iterations of this project with revised power supply are expected to exceed design requirements for outlet pressure delivery.

In addition, performance of individual subsystems were evaluated prior to pump performance testing. Due to extremely tight tolerances and clearances, large pressure differentials, and high rotational speeds, the verification of component dimensions and clearances was done extensively before the final assembly of

[a]Hydraulic Institute Test Standard (ANSI/HI 14.6)

the pump to lower the risk of catastrophic system failure. For example, manufacturing difficulty involved in producing sufficient surface finish for diffusers led to a decision to 3D print the diffusers on a high precision Stereolithography (SLA) resin printer. Due to the lack of information available about the proprietary material used, there was some concern about the durability and strength of the printed parts. To verify the SLA resin diffusers, a test rig was built. This experimental set up tested various diffuser geometries at static pressures of up to 500 psi without leakage or failure. In addition, diffusers were flow tested prior to pump testing at 100 psi without damage.

Overall, the mechanical subsystem performed well in preliminary testing. The selected off the shelf seals within the pump housing were able to withstand high rotational speeds and pressures without failure or leakage. Off the shelf bearings were able to handle the large forces and torques present in the system and did not show visible wear after preliminary testing. The in-house manufactured shaft and coupling maintained concentricity at high RPMs without unwanted vibrations or rubbing.

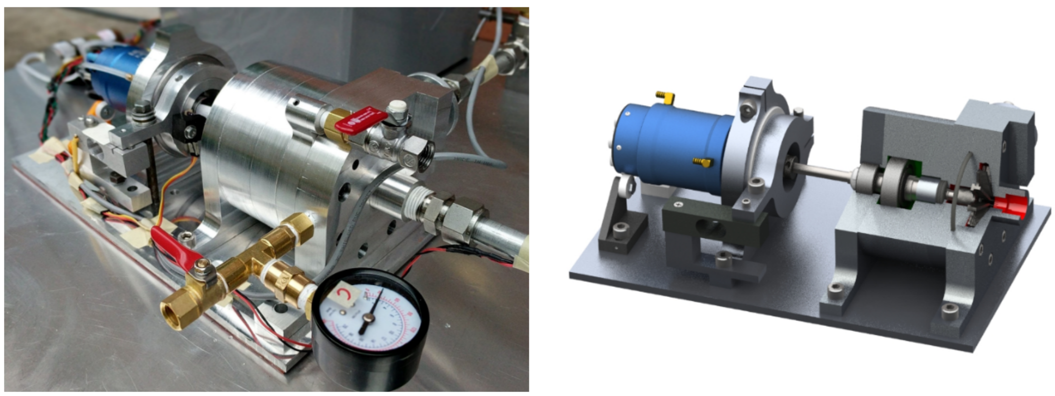

Figure 3: The completed EFS pump with tap outs for priming the system and a quarter section Solidworks rendering of the pump design

The flow loop and measurement subsystems of the test stand have also performed well. Due to the unique features of the EFS, some sensors were designed and manufactured by the team to provide accurate performance characterization. For example, a custom dynamometer was designed and manufactured to measure torque. The motor drives a torque arm into a small load cell calibrated to measure force. By collecting data from the load cell, the measured force and known arm length are used to calculate torque. This torque measurement was critical in creating the system performance curves.

IV. Conclusion

The EFS team successfully designed and built a test water pump to meet the needs of PSASs 2.2 kN rocket engine. Key conceptual design developments included the design of an unorthodox barske style impeller, diffuser, and pump volute of the hydraulic subsystem to meet the hydrodynamic requirements necessary to deliver fluid at the specified flowrate and pressure of 12 gpm and 300-400 psi, respectively. A flow loop subsystem was designed and manufactured to meet the flow and pressure requirements of the pump in performance testing. A mechanical subsystem was designed and manufactured to include involved a high speed shaft, shaft coupling, and bearing and seal system required for the pump to operate at its design rotational speed of 20000 rpm. The power subsystem was sized to provide a motor and battery pair that can successfully to meet the pumps power requirements. Finally, a measurement subsystem was successfully implemented for continuous data acquisition of sensors, which measure flow rate, inlet and outlet pressures of the pump, and rotational speed of the pump.

Next steps for the EFS project include full testing and characterization of the pump at design conditions. Further testing is required to achieve a complete characterization of the system, including experiments where impeller blade number and diffuser angle combinations are investigated. Future iterations of this design should include modifications of the mechanical system to meet the rigors of cryogenic temperatures. Modifications include selection of cryogenic seals, selection of liquid oxygen compatible materials for pump housing, and manufacturing considerations for single piece volute and diffuser design. The power supply to the motor should also be re-evaluated for more robust testing.

Acknowledgments

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References

[1] "Portland State Aerospace Society," .

[2] Tucker, J., Dib, T., Rice, T., Schmidt, E., Travis, K., and Viggiano, B., "Development of a Small Bipropellant Rocket Engine Utilizing Additive Manufacturing Processes," in "AIAA SPACE 2016," p. 5405, 2016.

[3] "Electric Feed System Github," .

[4] D. K. Huzel, . D. H. H., *Design of liquid propellant rocket engines*, 1971.

[5] V. S.Lobanoff, . R. R. R., *Centrifugal pumps: design and application*, 1985.