Preliminary Design of a Centrifugal Pump for a Turbopump-fed Liquid Rocket Engine

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ABSTRACT

State of the art industry rocket engine architectures use turbomachinery to power orbital launch vehicles. Many undergraduate level rocketry teams utilize liquid rockets with a simple pressure-fed system. However, a more complex turbopump-fed system was designed to propel the Z-1 liquid rocket engine of Cal Poly Pomona's Liquid Rocket Lab (LRL). A major component of a turbopump system is the impeller, which generates the required pressure to the thrust chamber of the rocket. Typical turbopumps consist of a centrifugal pump that utilizes the conventional radial impeller design with backward curved vanes, which has been widely accepted in the liquid rocket propulsion industry. On the other hand, there exists literature that suggests that some applications are better suited for the employment of a Barske impeller, a radial impeller with straight vanes. Aspects to consider when comparing the two impeller designs are efficiency, axial thrust, and impeller diameter. Using the data leveraged from pump performance parameters and pump geometry calculated in MATLAB, a trade study was conducted to determine that a conventional radial impeller was best suited for the design.

SYSTEM LEVEL REQUIREMENTS AND DESIGN CONSTRAINTS

The design process of a centrifugal-flow pump requires the definition of system level requirements (SLR) as well as design constraints. These requirements primarily flow down from the thrust chamber requirements as well as the chosen fluids and build materials.

Table 1: SLR and Design Constraints [2]

Requirement/Design Constraint	Description
Fluid Properties	The chosen fluids for the fuel and oxidizer will determine the fluid properties such as density and vapor pressure. These properties will directly influence pump parameters such as mass/volumetric flowrate and available net positive suction head (NPSH).
Pressurant Tank Pressure	The chosen pressurant tank pressure, with an assumed feed line pressure drop, will effectively determine the inlet pressure of the pump.
Chamber Pressure	The chosen chamber pressure will effectively determine the desired discharge pressure for the pump.
Pump Efficiency	Since the efficiency of the pump cannot be determined before testing, this value is assumed using empirical data such as Figure 5. It will directly affect the fluid power of the pump.
Rotational Speed	The chosen pump rotational speed will effectively determine the size of the pump.
Material Properties	The chosen build materials will effectively determine the inner radius geometries.

IMPELLER GEOMETRY DESIGN

After defining the system level requirements and design constraints, the next step is to select an impeller type. To select an impeller type, the first step is to calculate the dimensionless parameter Specific Speed. This will determine which type of impeller is the best design choice in terms of efficiency. Based on our calculated Specific Speed of 401, the impeller type that would suit our design is a radial impeller.

The impeller inner geometries are determined using the torque and shaft material properties. This approach was developed from a paper titled "Hydrodynamics Design and Analysis for an RP-1 Pump for Liquid Rocket Engines" by Cresson Chetty.

The next step is to determine the impeller outer geometry using specific speed and the pump head coefficient. This is done using the method outlined in the "Pump Handbook" by Igor J. Karassik.

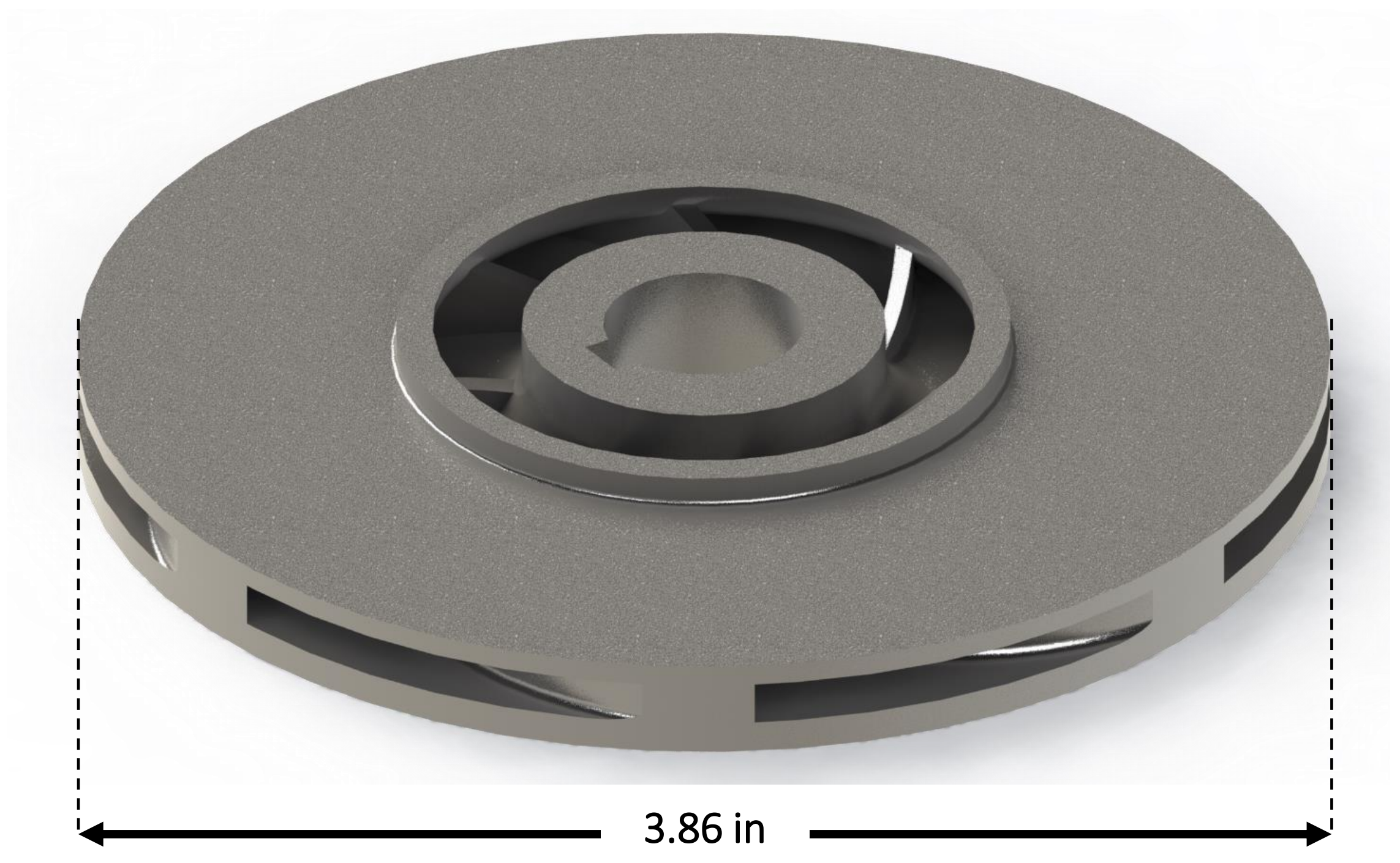

Figure 1: Solidworks Model of the Fuel Impeller

Based on the intended application and design for Cal Poly Pomona's Liquid Rocket Lab, the following table of inputs were considered:

Table 2: Inputs to Calculate Performance and Geometry Outputs

Parameter	Value
Fluid	Ethanol
Overall Efficiency	0.45
Rotational Speed	22,000 RPM
Mass Flow Rate	5.30 lbm/s

Utilizing MATLAB, the following performance and geometry outputs were calculated for the fuel impeller:

Table 3: Performance Outputs

Parameter	Value
Volumetric Flowrate	48.32 GPM
Brake Horsepower	59 hp
Fluid Horsepower	27 hp
Developed Pressure	945 psid
Developed Head	2,765 ft
Inlet Pressure	95 psia
Discharge Pressure	1,040 psia
Specific Speed	401
Suction Specific Speed	2595
Pump Axial Thrust	7,304 lbf

Table 4: Geometry Outputs

Parameter	Value
Impeller Diameter	3.86 in
Impeller Inlet Radius	0.80 in
Impeller Outlet Radius	1.93 in
Impeller Hub Radius	0.73 in
Shaft Radius	0.41 in

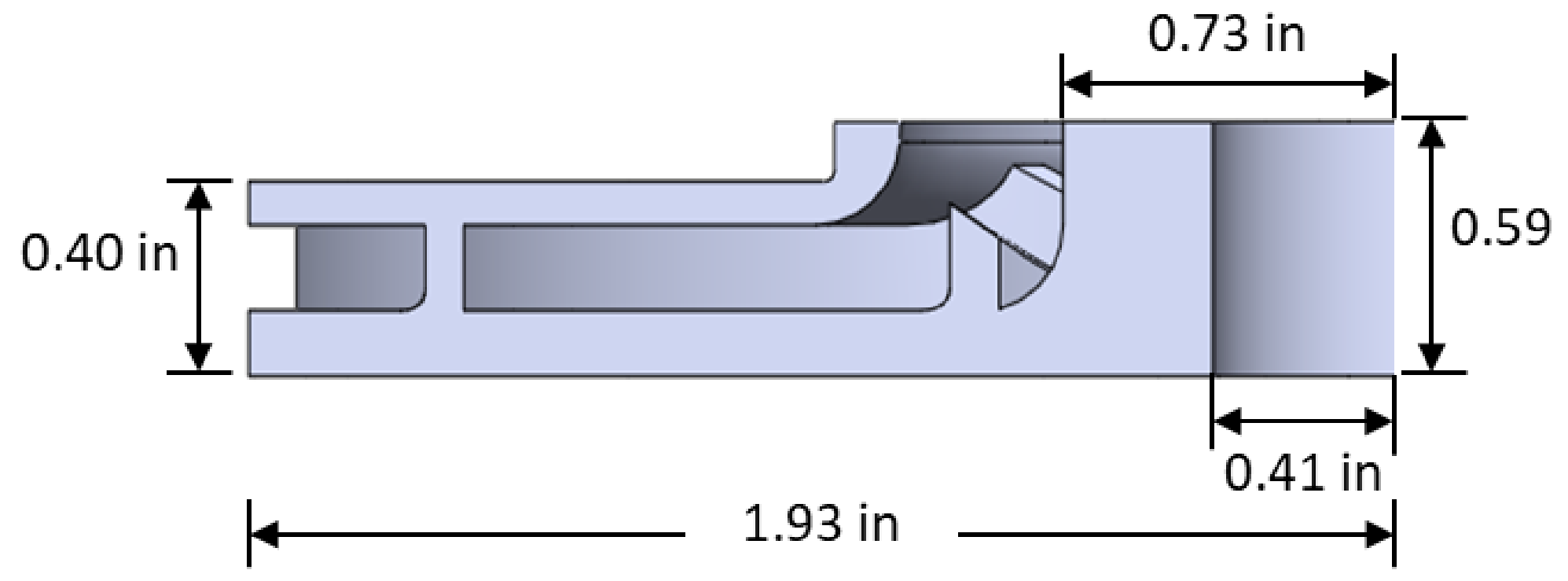

Figure 2: Cross-Section of Fuel Impeller

IMPELLER TRADE STUDY

Based on our design constraints and application, it was determined that a radial impeller was best suited for this project. A trade study was conducted to compare two architectures. The two competing designs for this study are the conventional radial impeller with backward curved vanes and the Barske impeller with straight vanes. Efficiency, axial thrust, and impeller diameter were figures of merit that were examined.

Architecture #1: Conventional Impeller

Attributes:
1. Lower efficiency at low Specific Speeds
2. Medium to hard design complexity
3. Lower radial load

Architecture #2: Barske Impeller

Attributes:
1. Higher efficiency at low Specific Speeds
2. Easy to medium design complexity
3. Higher radial load

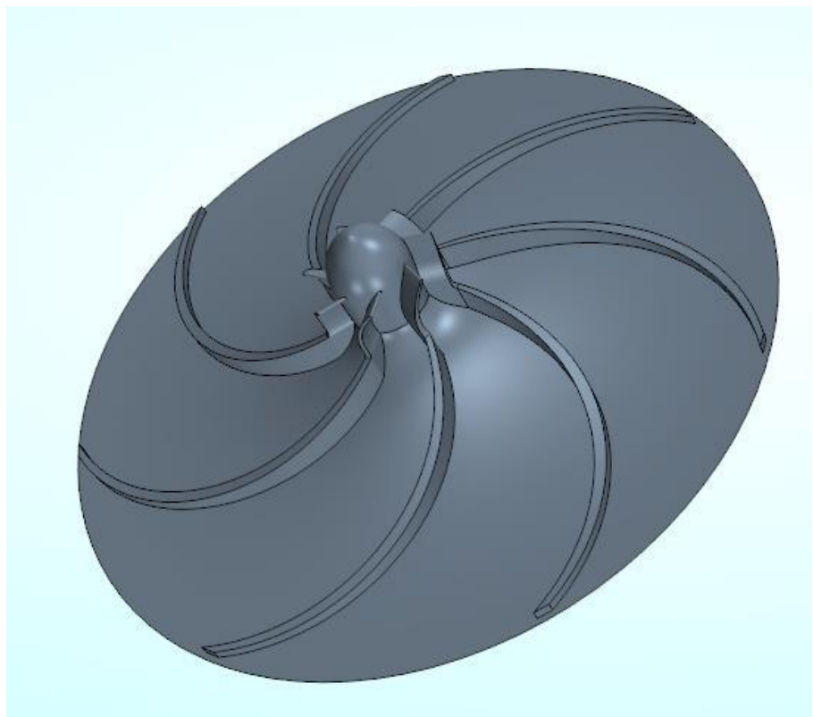

Figure 3: Conventional Impeller Example [1]

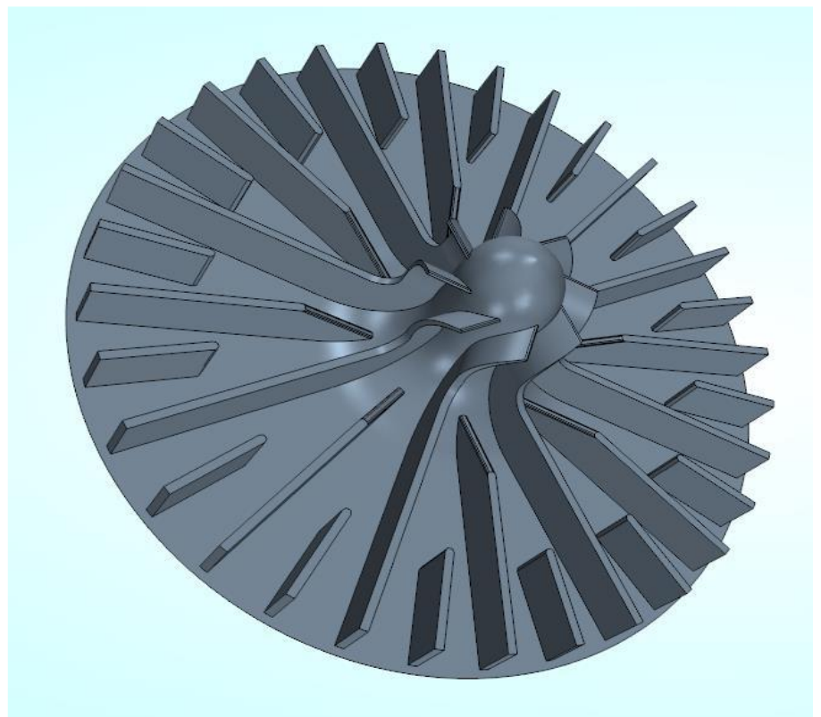

Figure 4: Barske Impeller Example [1]

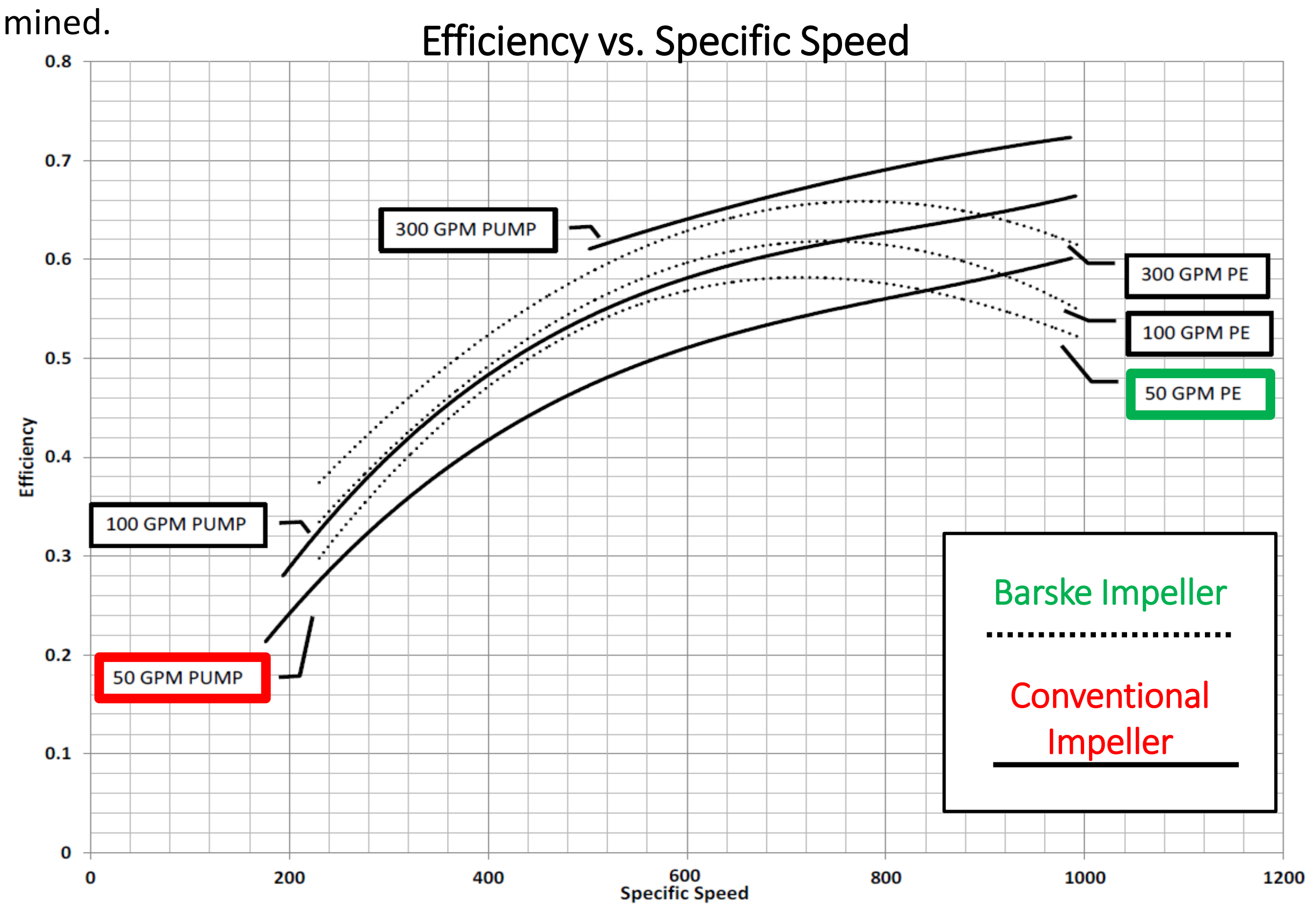

Figure 5: Comparison of Convention and Barske Impeller Efficiencies from Empirical Data [4]

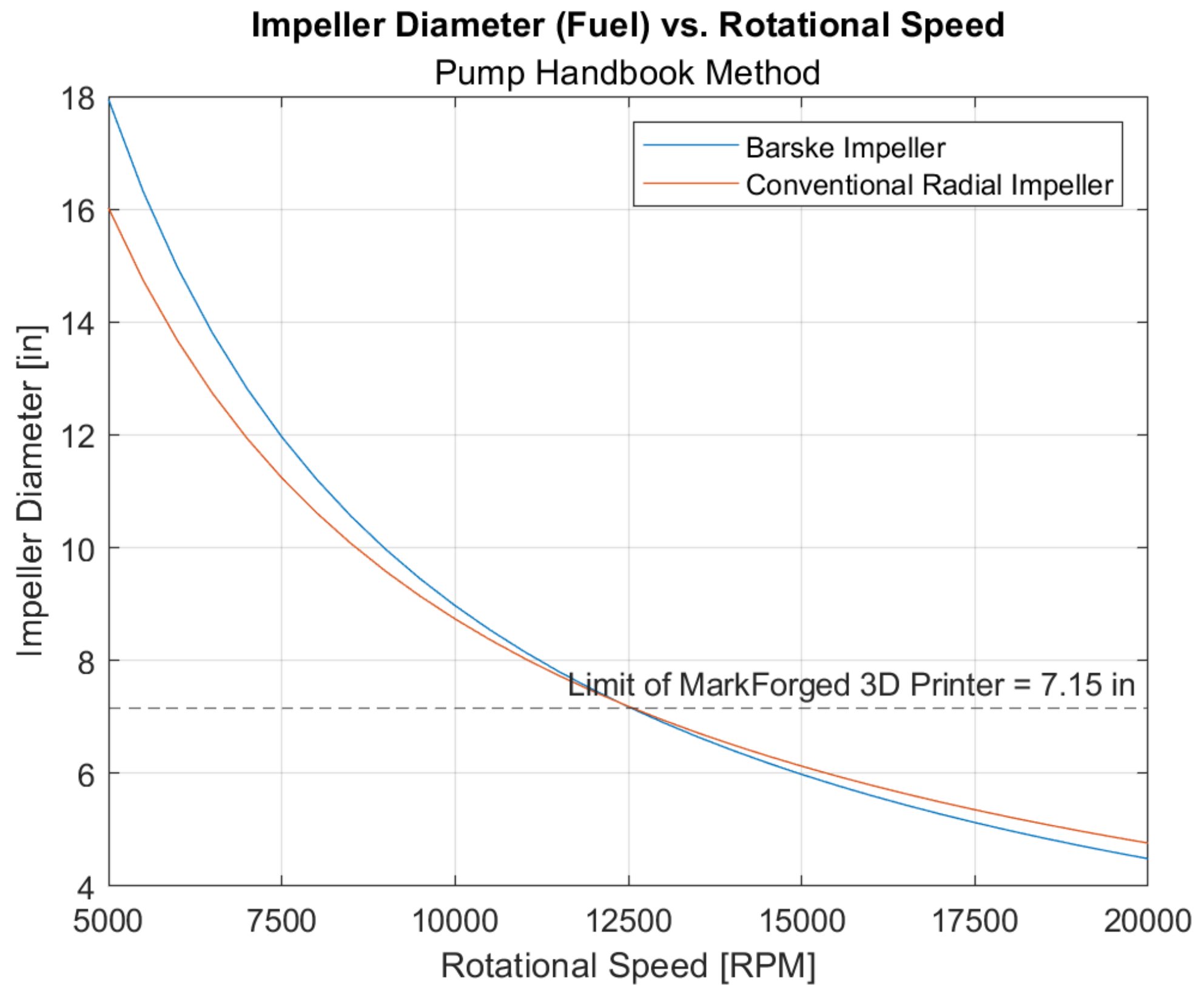

Figure 6: Comparison of Impeller Diameters with Design Constraint of 3D Printer

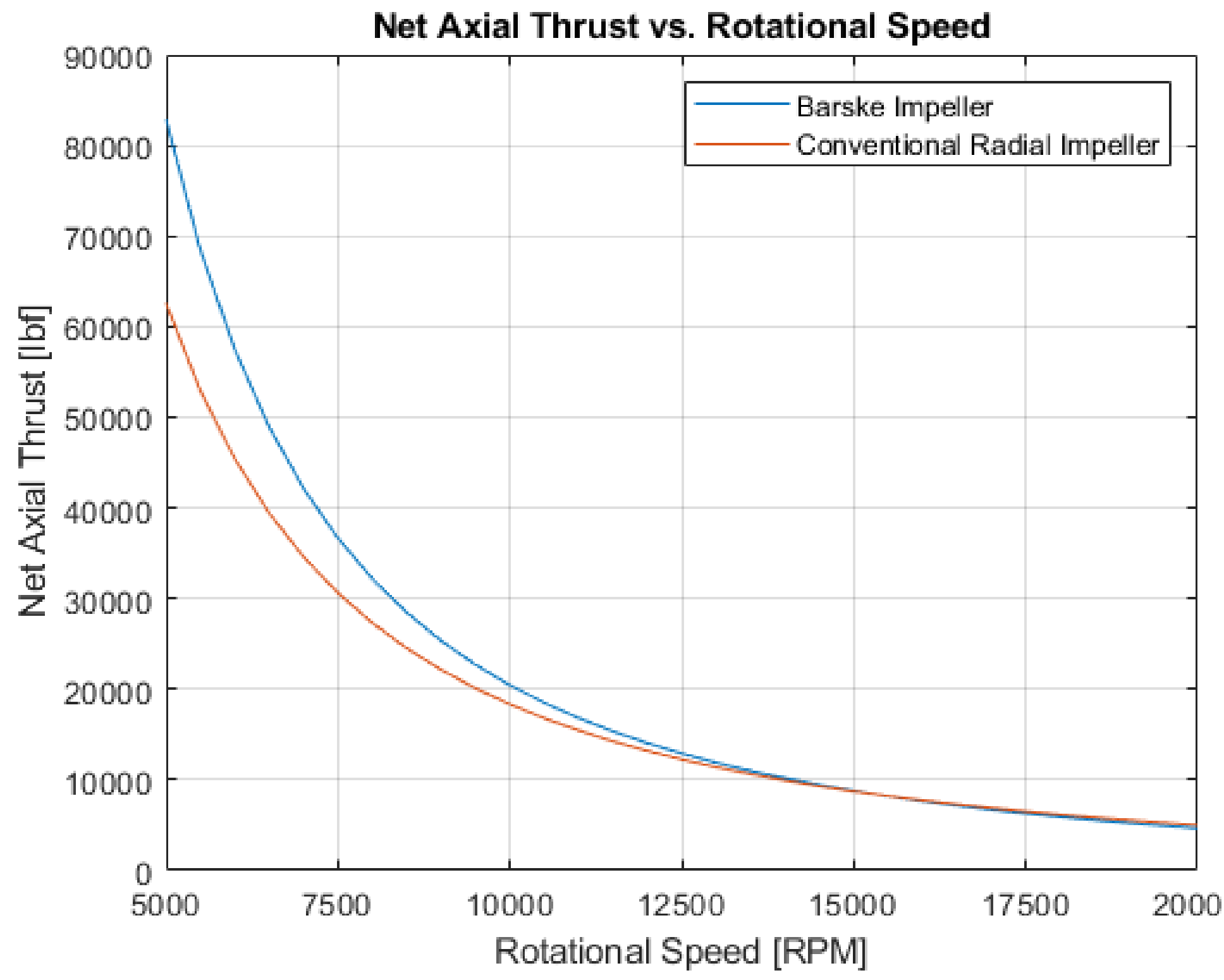

Figure 7: Comparison of Net Axial Thrust for Barske and Conventional Impeller

Based on the trade study, it was determined that the conventional radial impeller would be the best architecture to achieve the project goals. A major factor was a Computational Fluid Dynamics (CFD) analysis, conducted by a team member, that determined, for our application, the efficiency of the conventional radial impeller was significantly larger than that of the Barske impeller.

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