Optimizing Partial Emission Pump Performance

Jacob Abrogar, Patrick Daly, Gabriela DiMauro, Shivaani Gopal, Keith Mesecher

Our Team

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Mechanical Engineering

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Mechanical Engineering

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Mechanical Engineering

Shivaani Gopal
Mechanical Engineering

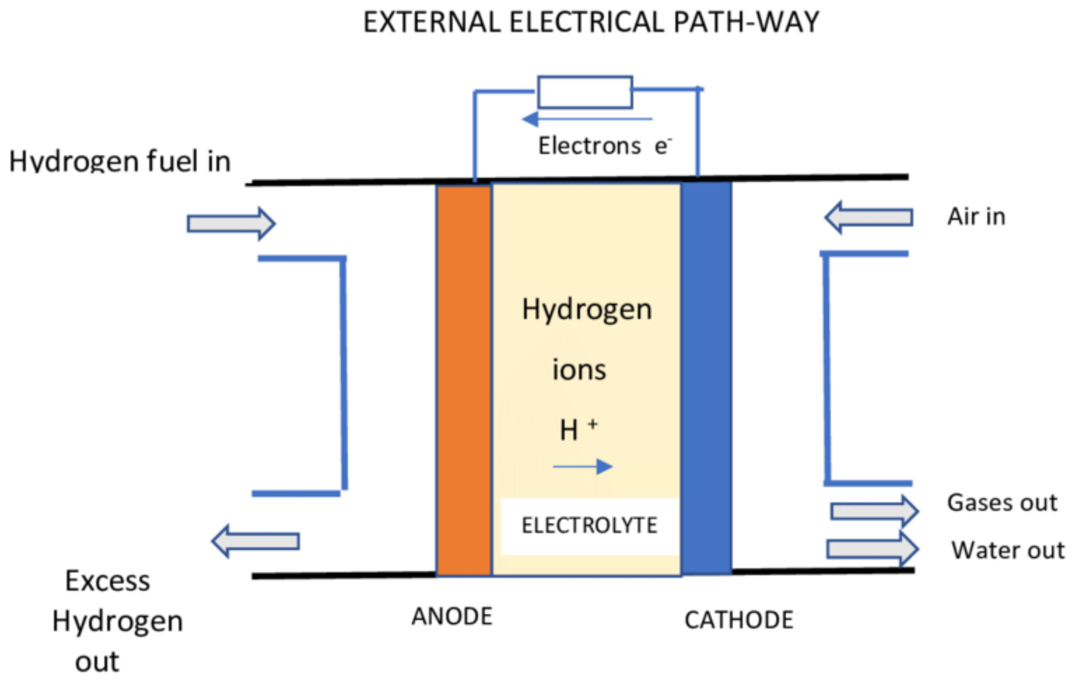
Keith Mesecher
Mechanical Engineering

Introduction

What problem is our project addressing?

What is Hydrogen Fuel Cell Technology?

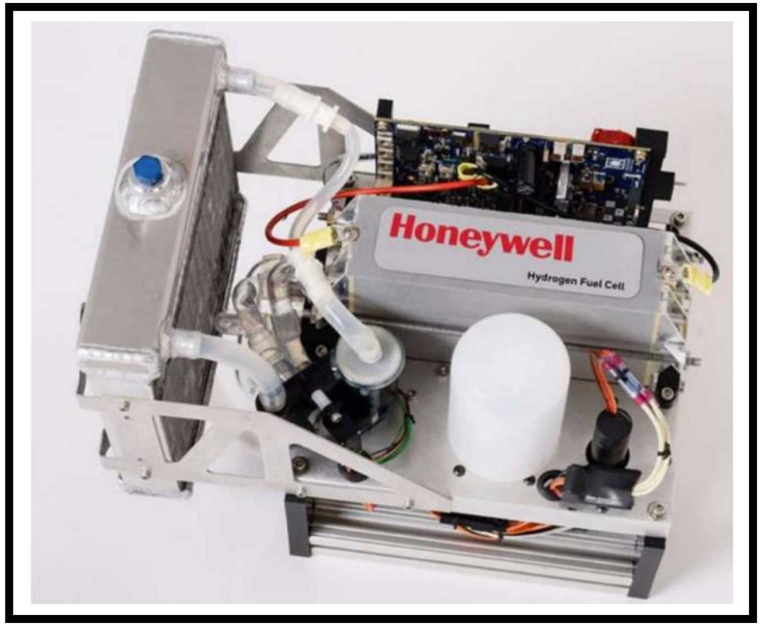
- Alternative cleaner energy source
- Electricity is generated through an electrochemical reaction

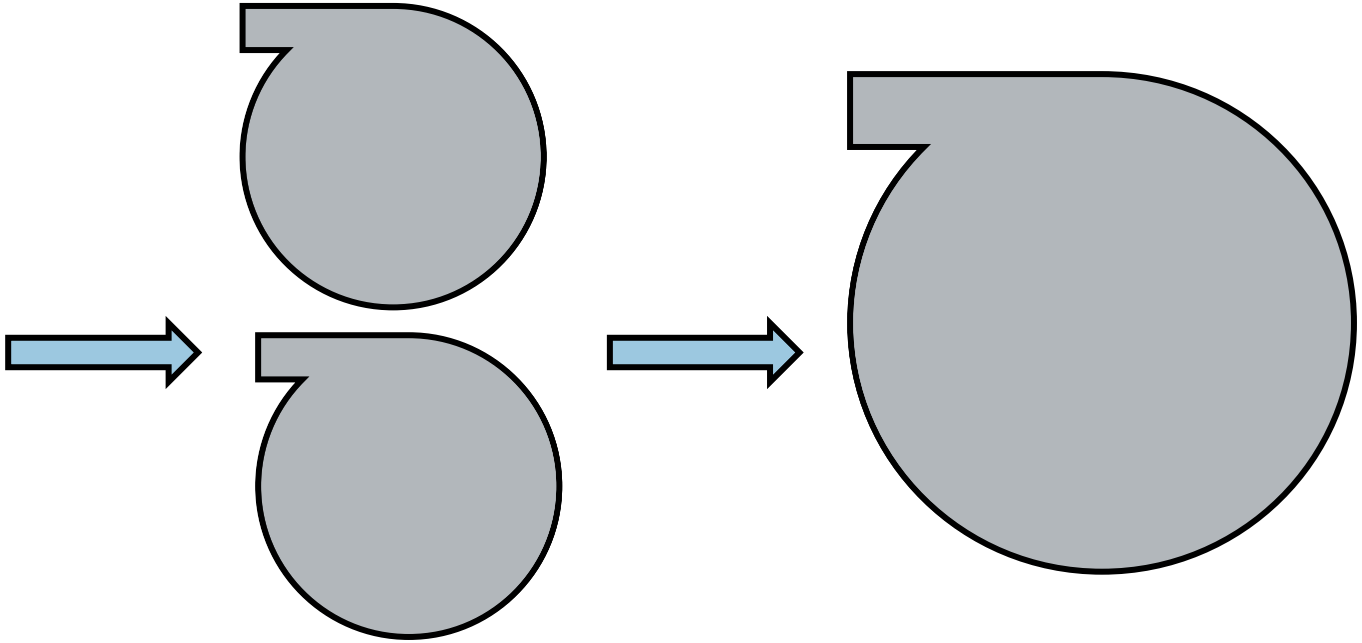


Murray-Smith, D. (2019). *External Electrical Pathway* [Image]. Research Gate. https://www.researchgate.net/figure/Schematic-diagram-of-hydrogen-fuel-cell_fig1_337991572

Project Problem

- Double the 600 watt hydrogen fuel cell stack
- Optimize a large pump to account for the total 1200 watt stack





1. Honeywell International Inc. (2022). MQP Projects
2. Stock Images from Microsoft 365

Problem Definition

Optimize PEM pump performance for scaling hydrogen fuel cell systems to power larger UAVs efficiently.

Background

What are PEM pumps? How do we analyze them?

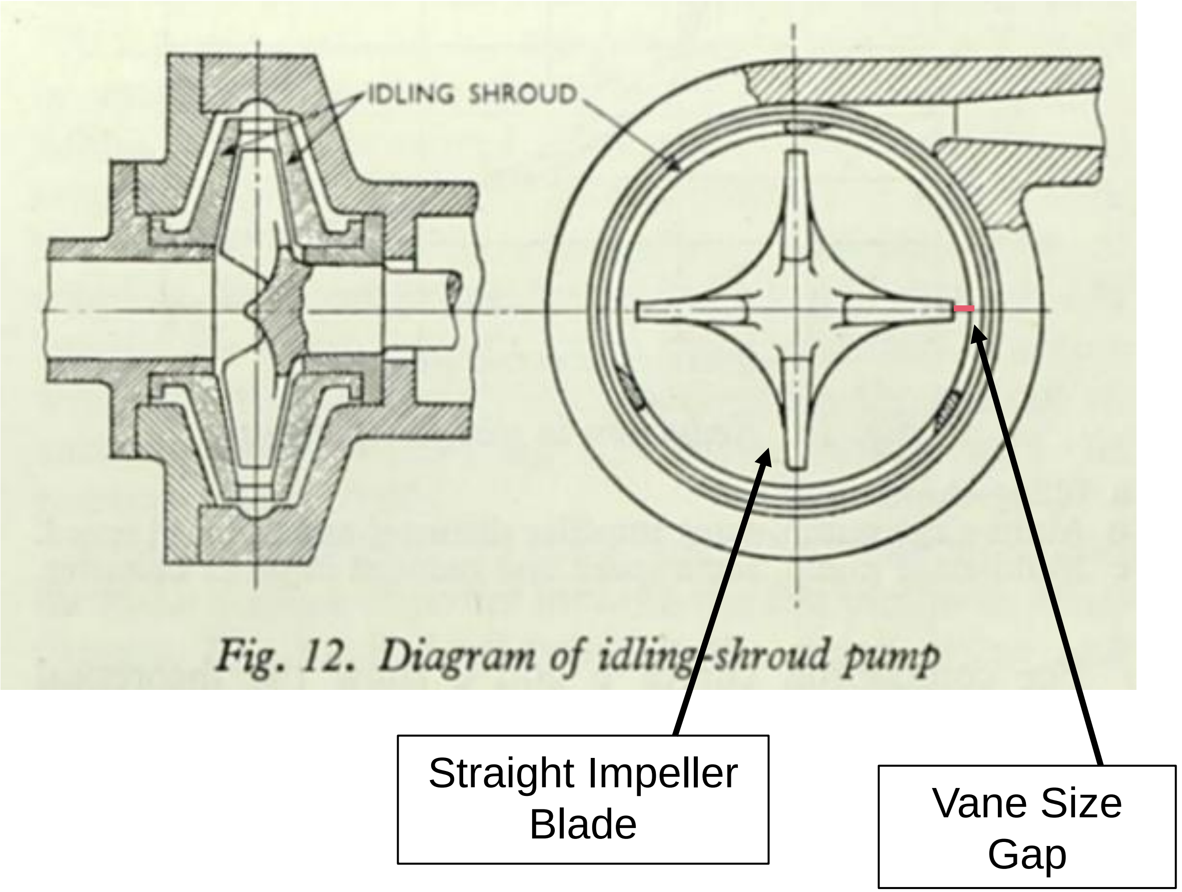
What are Pumps?

- Mechanical systems:
  - Uses energy to move fluid ⟶ affects several output parameters
- How they work:
  - Uses a mechanism (i.e. impeller) to drive fluid from inlet to outlet
- Used in several applications:

Stock Images from Microsoft 365

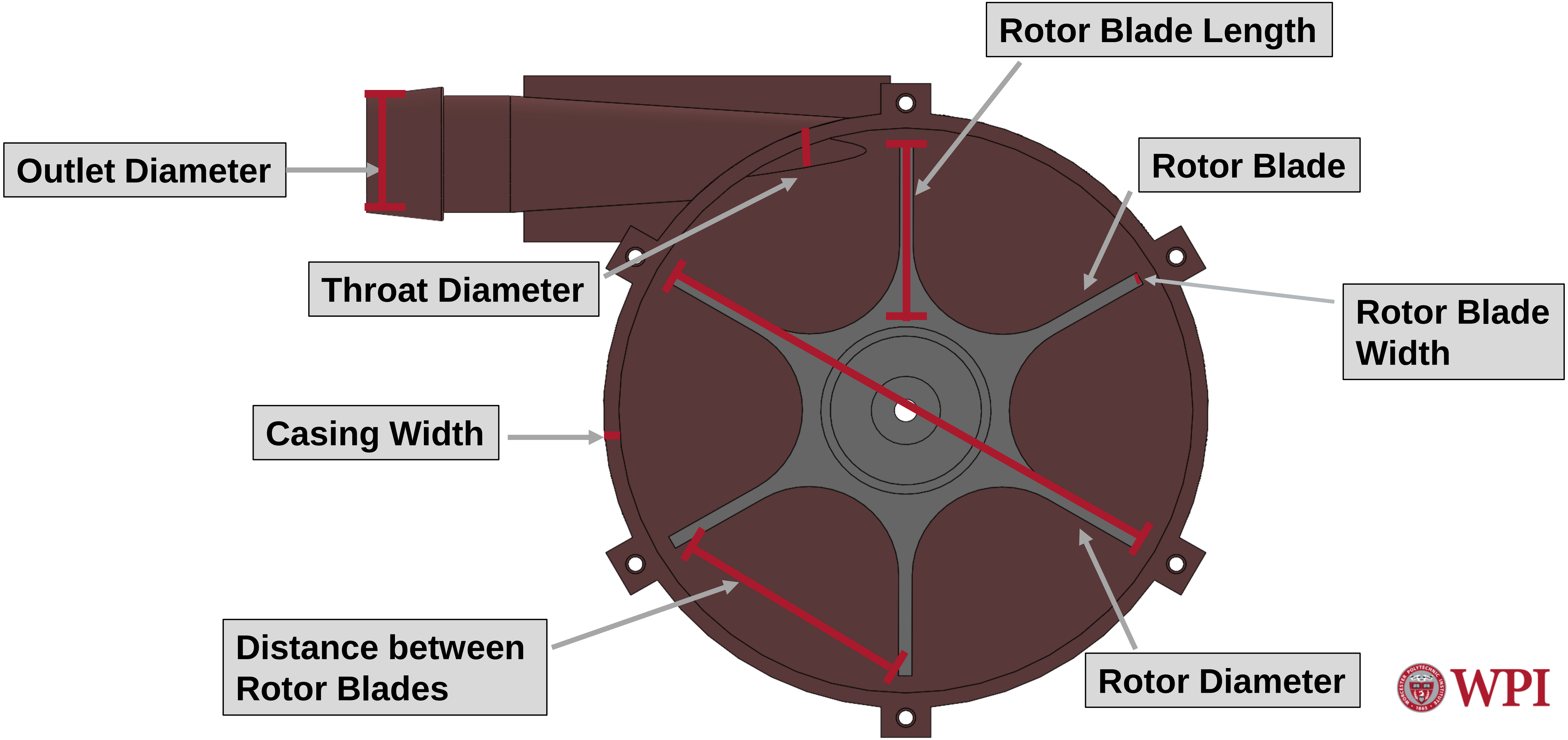
PEM Pump Research

- Centrifugal Pumps ⟶ PEM Pumps
- Produce low flow and high head
- Development is credited to U.M. Barske
- Limited research on PEM Pumps



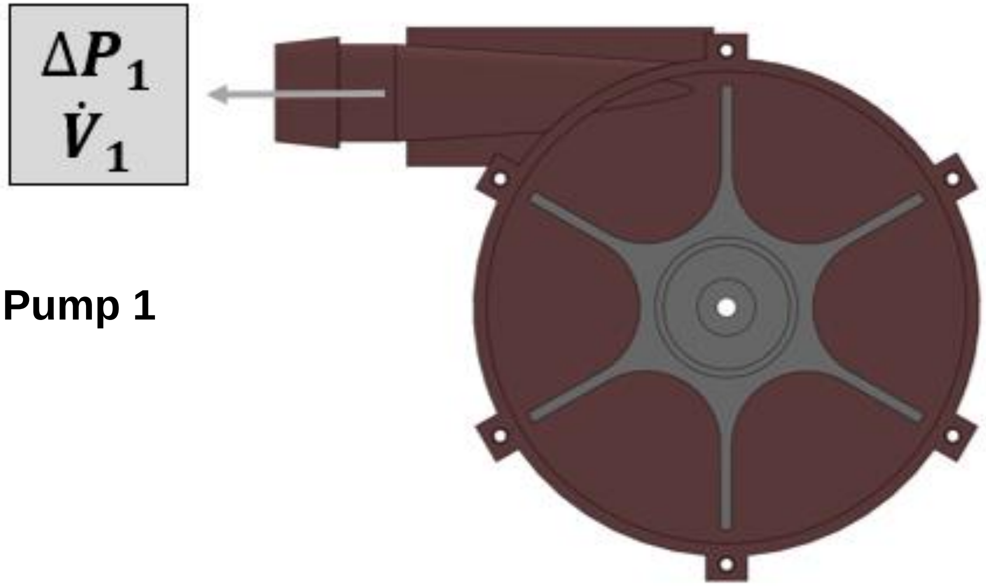
Barske, U. M. (1960). Development of some Unconventional Centrifugal Pumps. Institution of Mechanical Engineers

PEM Diagram

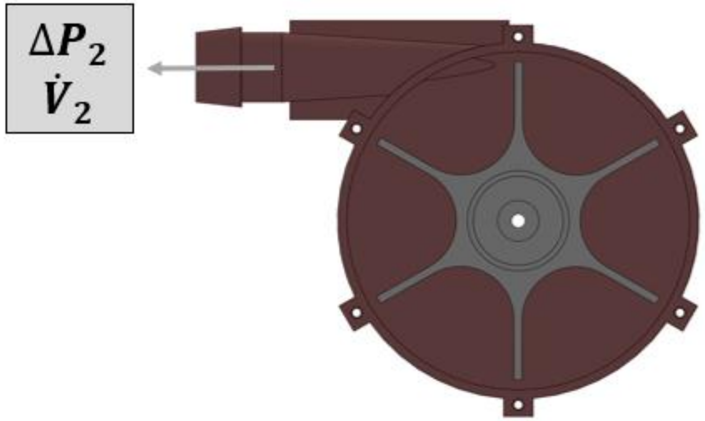


Rotor Blade Length
Outlet Diameter
Rotor Blade
Throat Diameter
Rotor Blade Width
Casing Width
Distance between Rotor Blades
Rotor Diameter

Nondimensional Variables

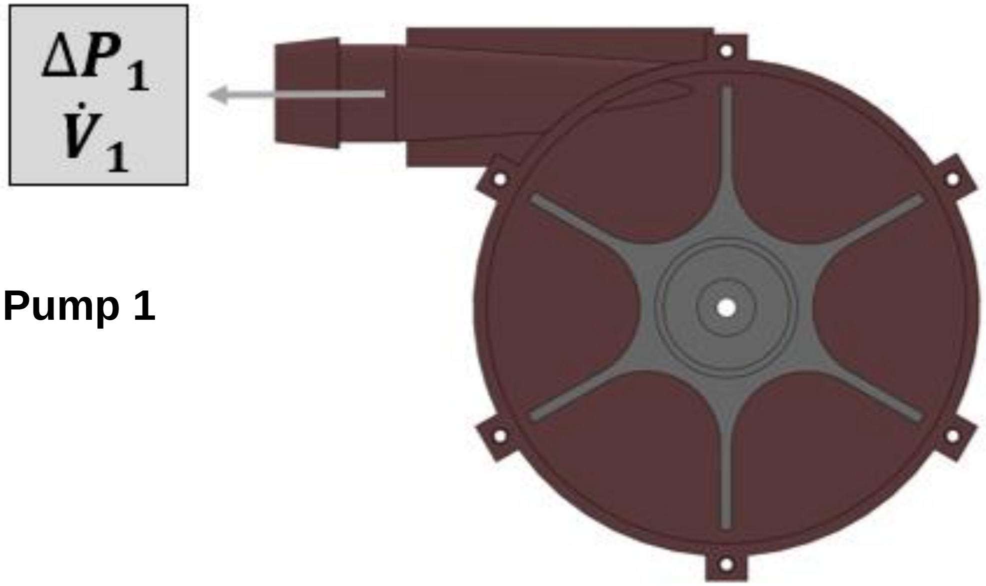


Pump 1

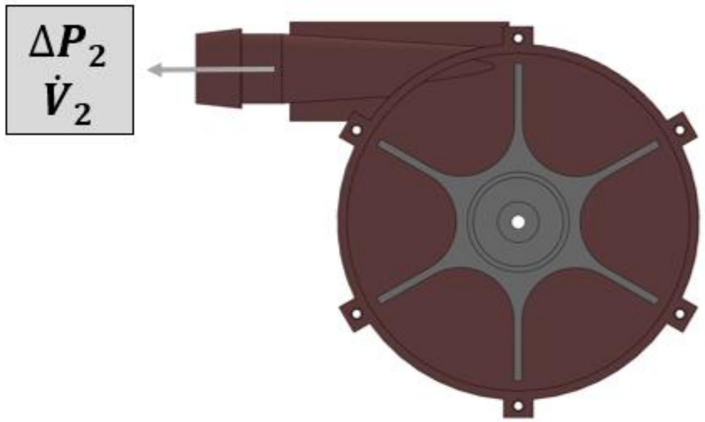


Pump 2

Nondimensional Variables



Pump 1

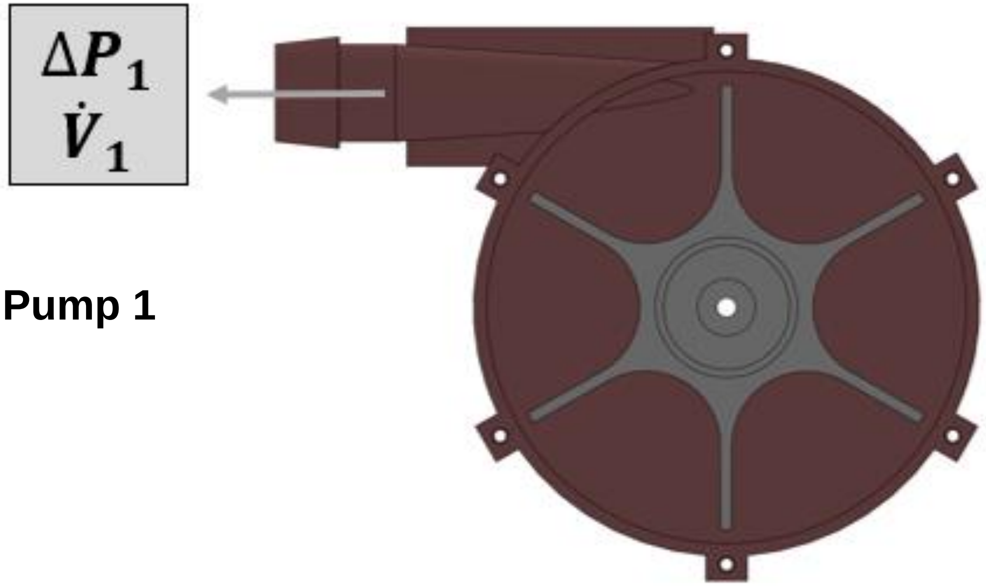


Pump 2

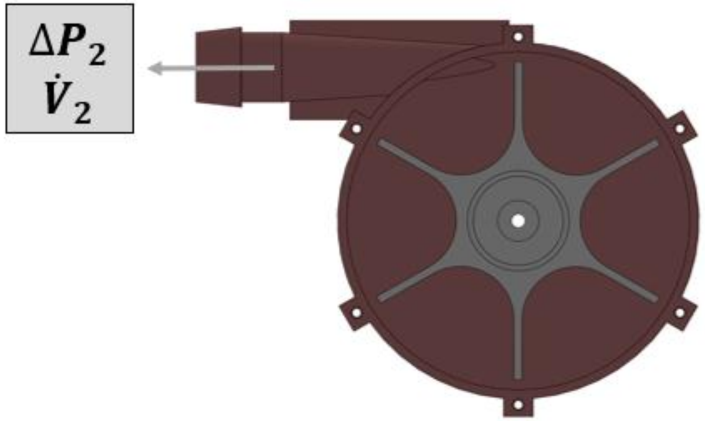
Dimensional Parameters

$$\omega_{rotor} \quad D_{rotor}$$
$$D_{throat} \quad \rho_{fluid}$$

Nondimensional Variables



Pump 1



Pump 2

Dimensional Parameters

$$\omega_{rotor} \quad D_{rotor}$$
$$D_{throat} \quad \rho_{fluid}$$

Nondimensional Parameters

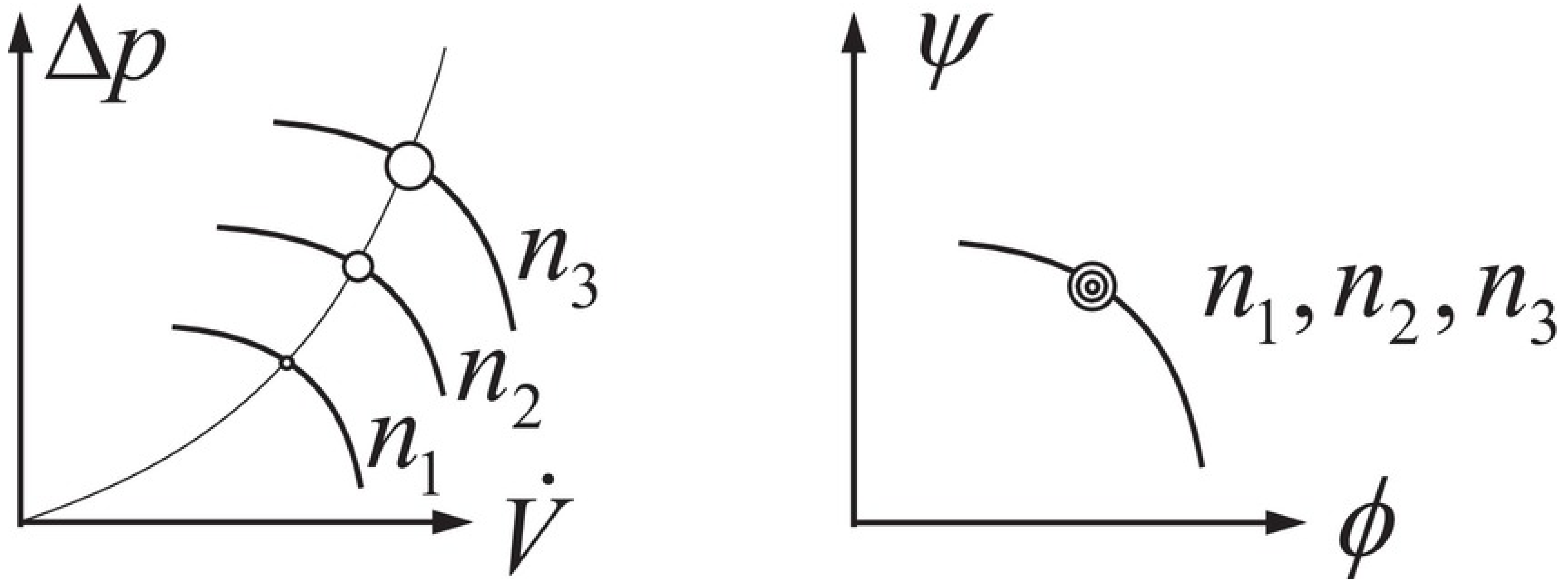
$$\phi, \varphi$$

OR

$$n_s, d_s$$

Nondimensional Variables

- Dimensional Curves collapse onto one dimensionless curve

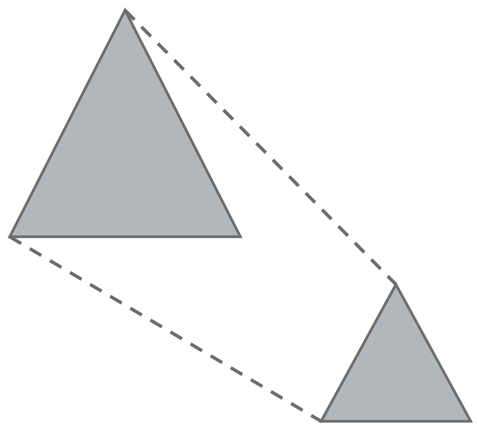


Casey, M., & Robinson, C. (2021). *Radial flow turbocompressors: Design, analysis, and applications*. Cambridge University Press.

Similarity Requirements

Similarity Requirements

Geometric Similarity



Chemloul, N.-E. S. (n.d.). *Dimensional analysis and similarity in Fluid Mechanics*. O'Reilly Online Learning.
https://www.oreilly.com/library/view/dimensional-analysis-and/9781786305961/c03.xhtml

Similarity Requirements

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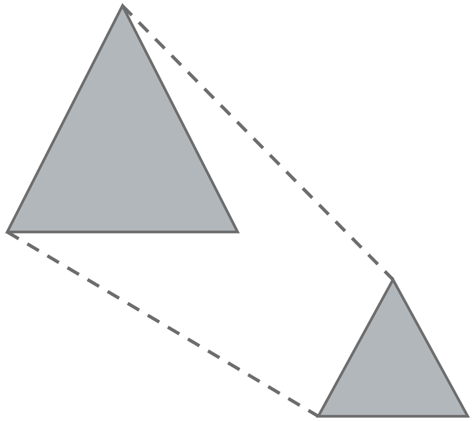
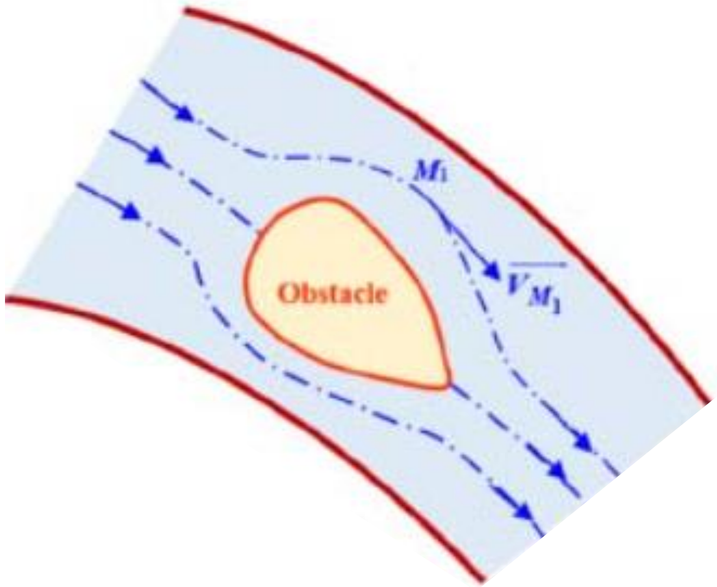


Fluid Dynamic Similarity



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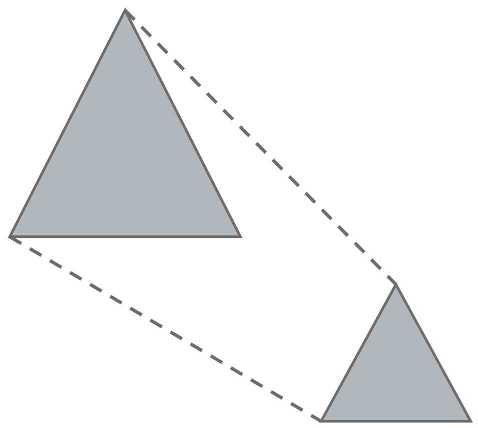
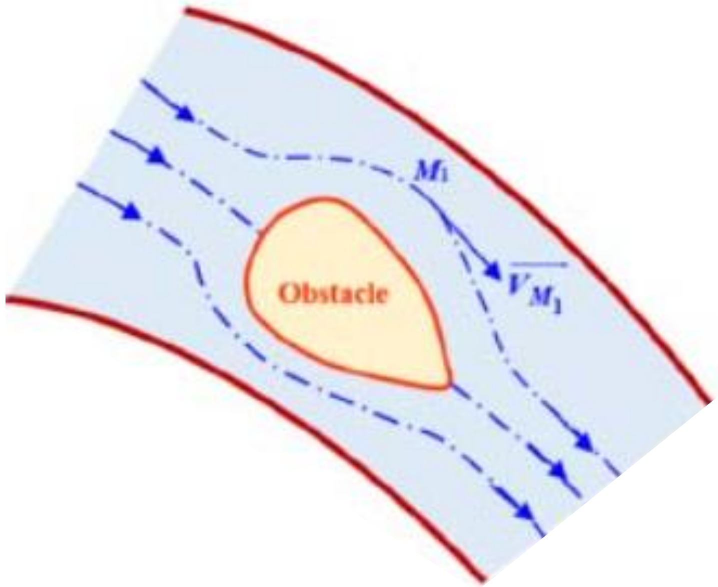
Geometric Similarity



Fluid Dynamic Similarity



Thermodynamic Similarity

$$PV = nRT$$

Chemloul, N.-E. S. (n.d.). *Dimensional analysis and similarity in Fluid Mechanics*. O'Reilly Online Learning.
https://www.oreilly.com/library/view/dimensional-analysis-and/9781786305961/c03.xhtml

Specific Speed and Specific Diameter

Specific Speed and Specific Diameter

$\underline{Specific\ Speed}$

$$\boldsymbol{n_s} = \frac{\omega\sqrt{\dot{V}}}{(Hg)^{3/4}}$$

The **rotational speed** at which a geometrically similar pump would operate if it were delivering **one unit of flow rate** and developing **one unit of head.**

Balje, O. E. (1981). Turbomachines: A Guide to Design, Selection and Theory.

Specific Speed and Specific Diameter

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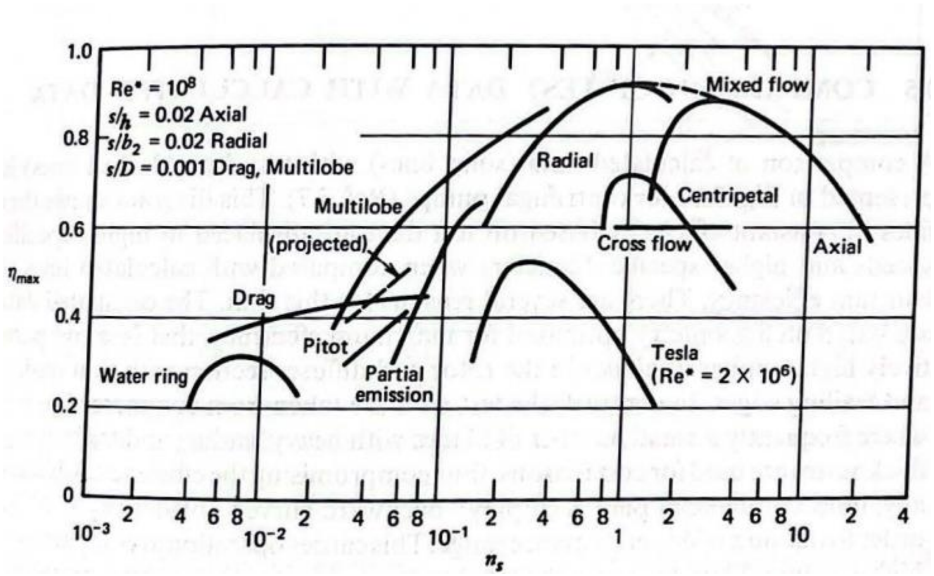

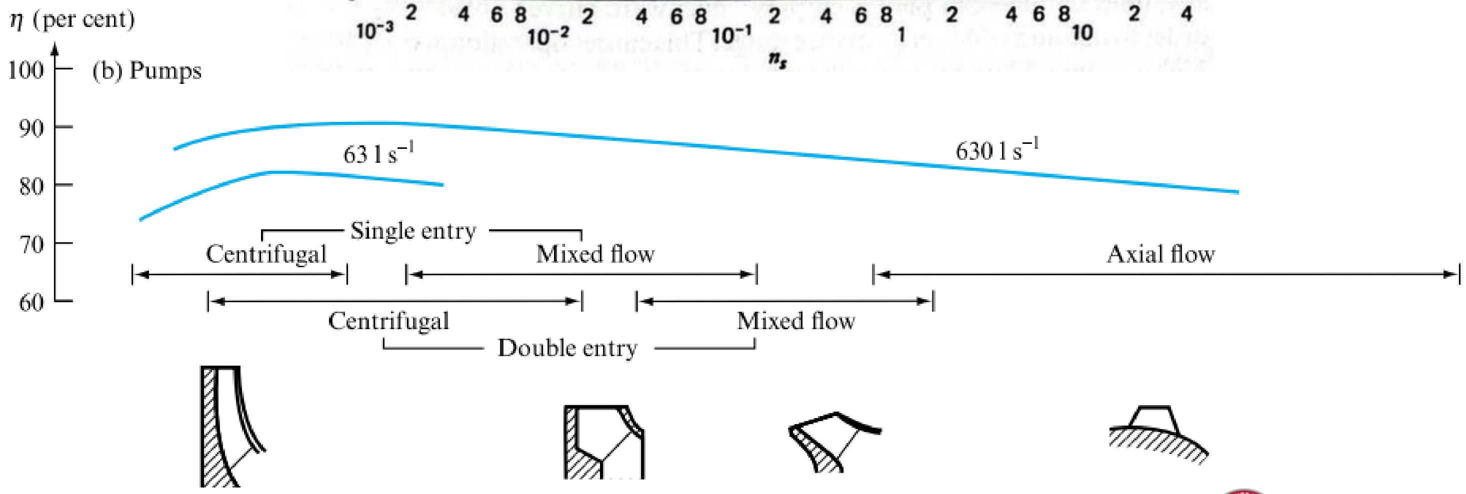

Balje, O. E. (1981). Turbomachines: A Guide to Design, Selection and Theory.
Douglas, J. F. (2007). *Fluid mechanics*. Pearson.

Specific Speed and Specific Diameter

The **rotor diameter** of a geometrically similar pump that would deliver **one unit of flow rate** while developing **one unit of head.**

$$\underline{Specific\ Diameter}$$

$$\boldsymbol{d_s} = \frac{D_{rotor}(Hg)^{1/4}}{\sqrt{\dot{V}}}$$

Balje, O. E. (1981). Turbomachines: A Guide to Design, Selection and Theory

Specific Speed and Specific Diameter

Specific Speed

$$\boldsymbol{n_s} = \frac{\omega\sqrt{\dot{V}}}{(Hg)^{3/4}}$$

Specific Diameter

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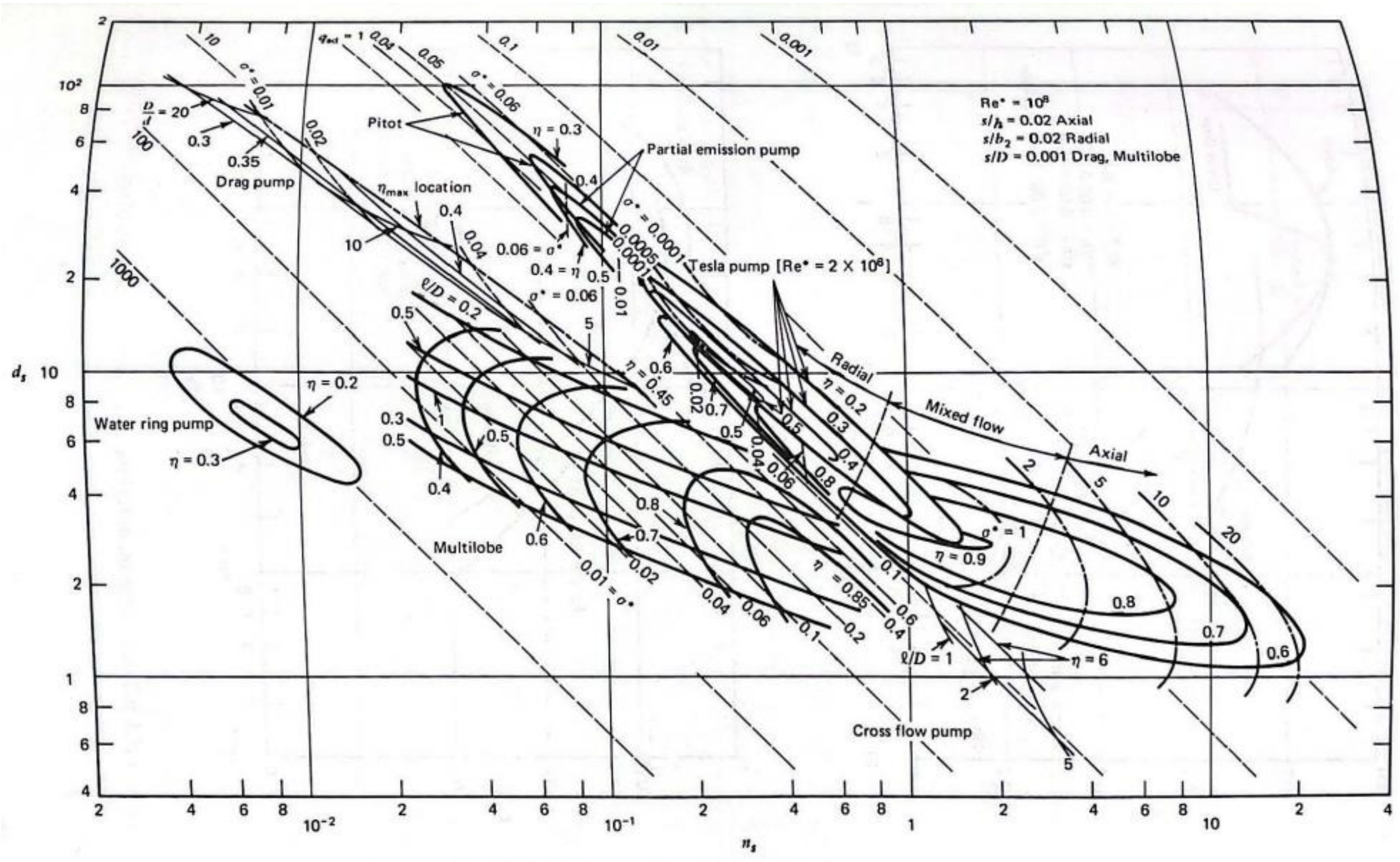

FIGURE 3.8 $n_s d_s$ diagram for single stage pumps.

Balje, O. E. (1981). Turbomachines: A Guide to Design, Selection and Theory [Image].

Specific Speed and Specific Diameter

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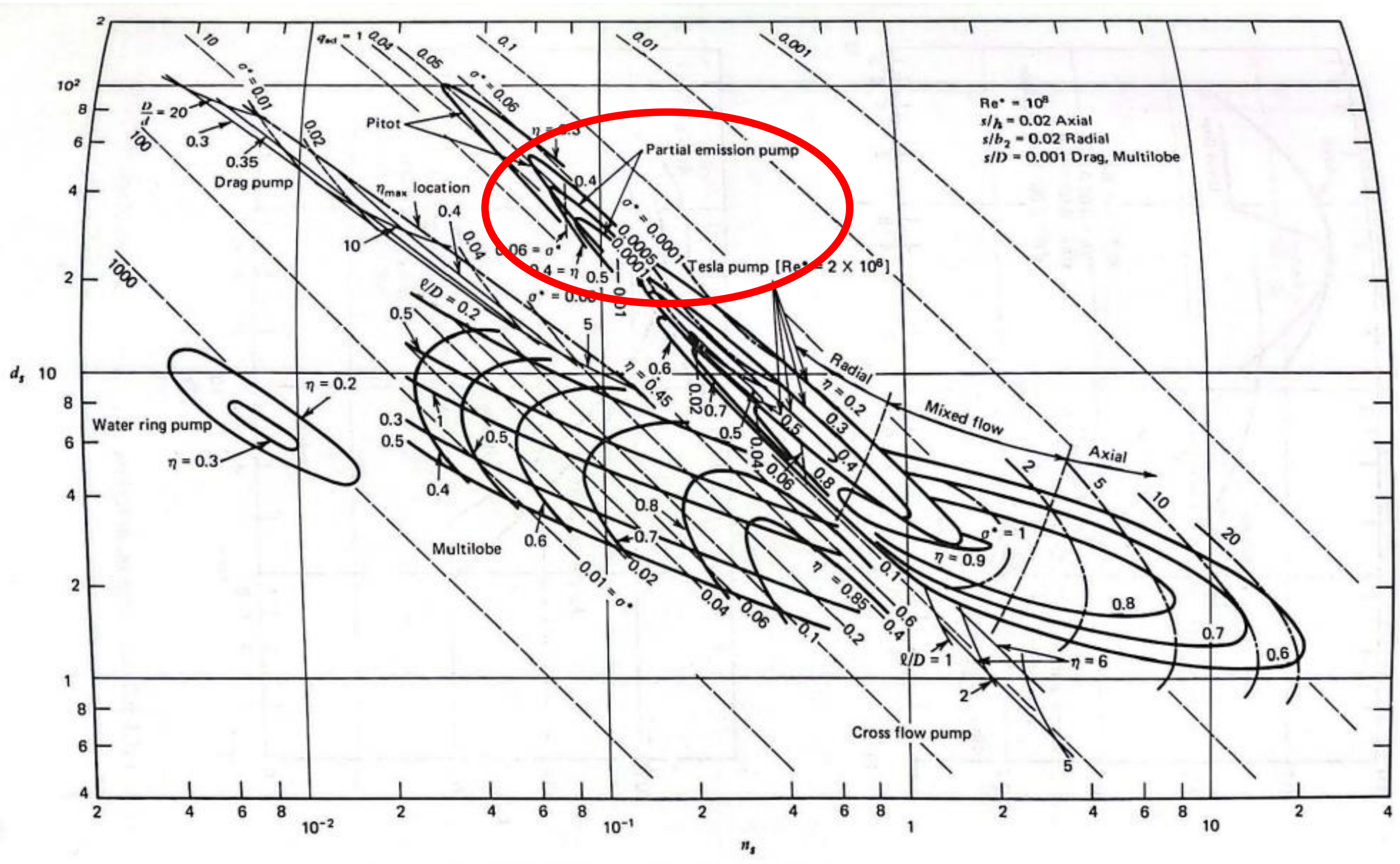

FIGURE 3.8 $n_s d_s$ diagram for single stage pumps.

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Pressure and Flow Coefficients

Pressure and Flow Coefficients

$$Pressure\ Coefficient = \boldsymbol{\psi} = \frac{\Delta\,\mathrm{p}/\rho}{U^2}$$

The **ratio** of the **pump pressure rise** to the **dynamic pressure of the fluid flow.**

$$U_2 = \pi \cdot n \cdot D_{rotor}$$

Martin, J. L., & Mahoney, J. (2007). (tech.). *Turboblower Optimized for Man-Portable Fuel Cells*. Broomfield, Colorado: Mesoscopic Devices, LLC.

Pressure and Flow Coefficients

$$Pressure\ Coefficient = \boldsymbol{\psi} = \frac{\Delta p/\rho}{U^2}$$

The **ratio** of the **pump pressure rise** to the **dynamic pressure of the fluid flow.**

$$Flow\ Coefficient = \boldsymbol{\phi} = \frac{v_{out}}{U}$$

The **ratio** of the **throughput component of the velocity** to the **blade tip speed**.

$$U_2 = \pi \cdot n \cdot D_{rotor} \qquad v_{out} = \frac{\dot{V}}{\frac{1}{4}\pi \cdot D_{diffuser}^2}$$

Martin, J. L., & Mahoney, J. (2007). (tech.). *Turboblower Optimized for Man-Portable Fuel Cells*. Broomfield, Colorado: Mesoscopic Devices, LLC.

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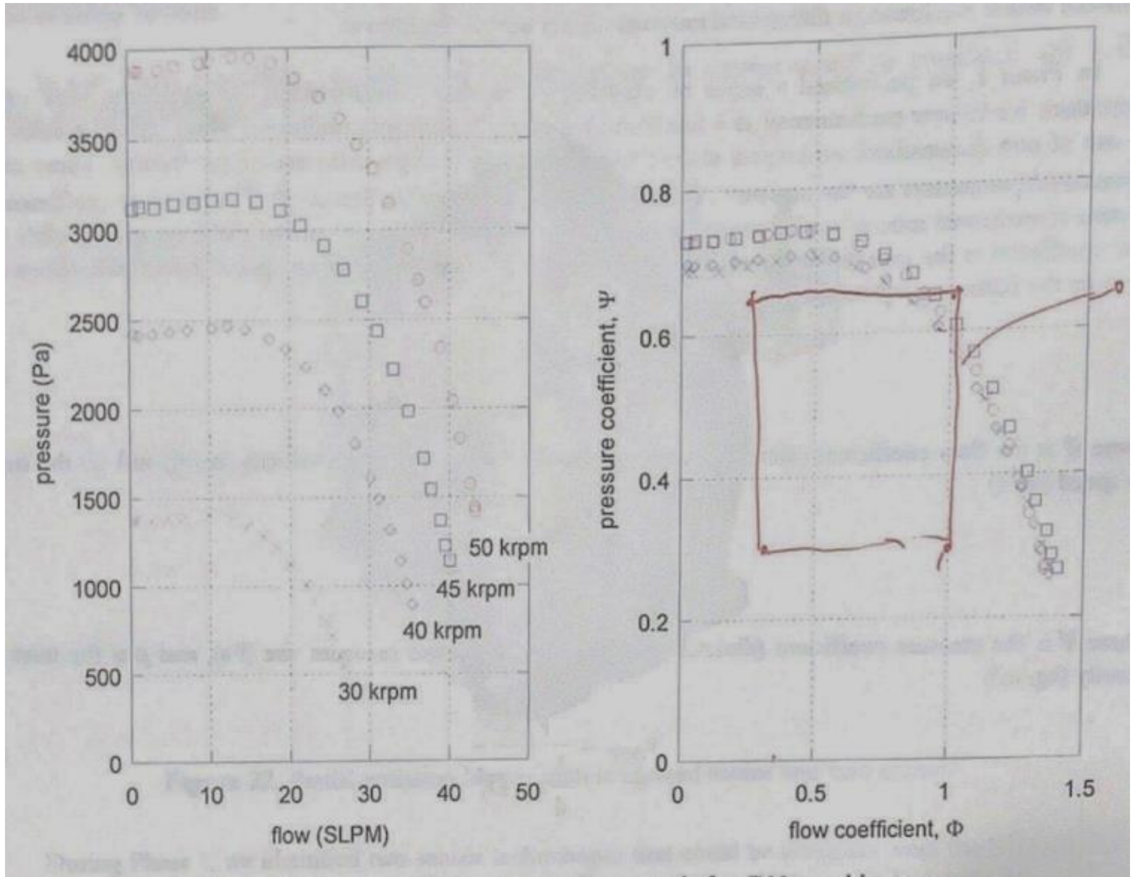


Figure 23. Pressure-flow curves at four speeds for Ø30 mm blower.
Left: dimensional data, right: non-dimensional data.

Martin, J. L., & Mahoney, J. (2007). (tech.). *Turboblower Optimized for Man-Portable Fuel Cells*. Broomfield, Colorado: Mesoscopic Devices, LLC.

Project Objective

Develop an **empirical model** that accurately **captures the performance characteristics of PEM pumps** under diverse operating conditions.

Methodology

How did we reach this objective?

Methodology Overview

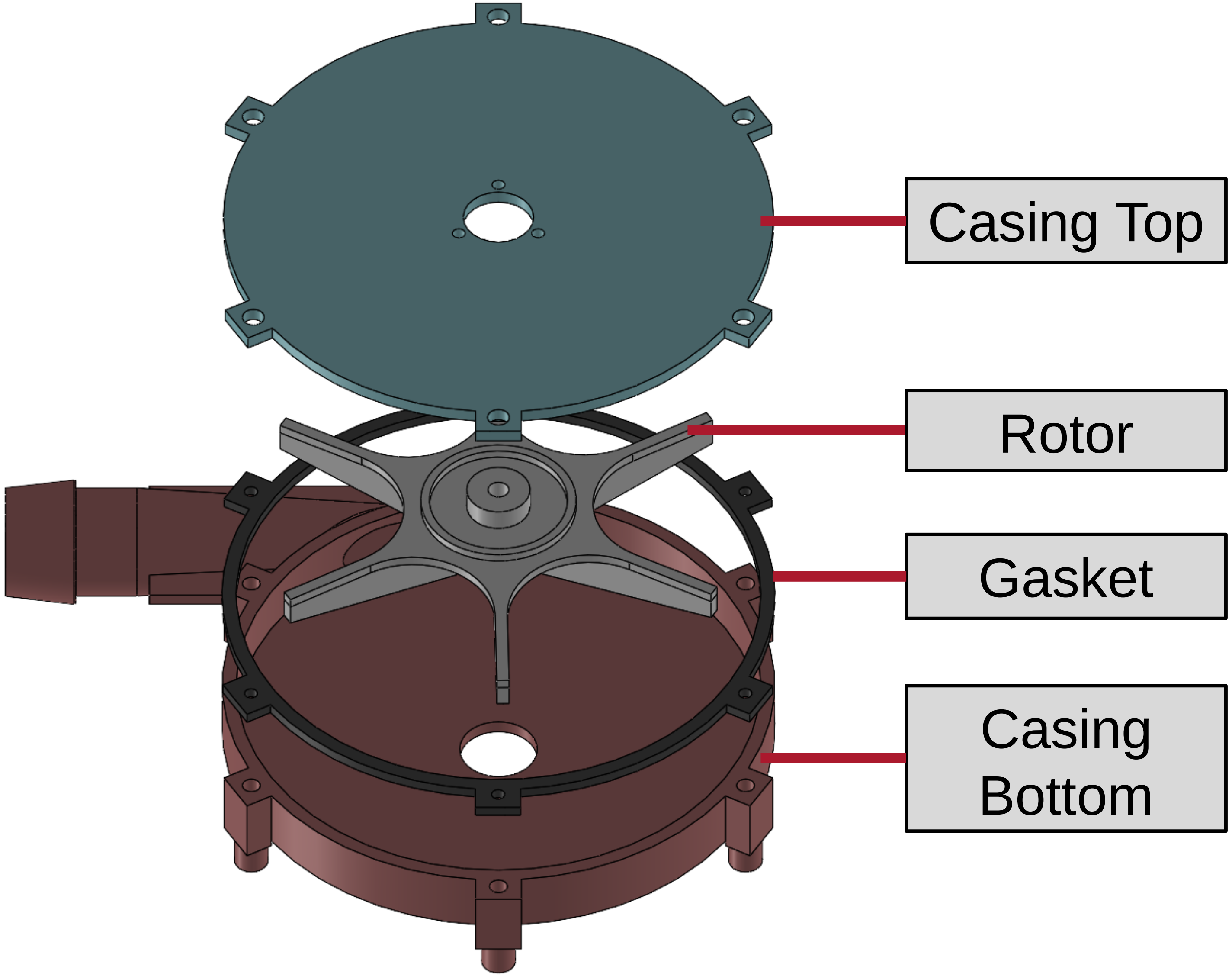
Build geometrically similar pumps

Build experimental test setup

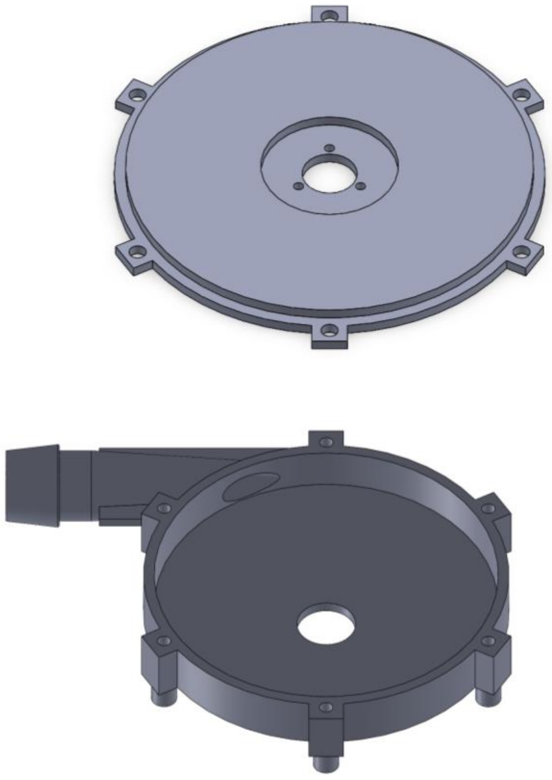
Collect experimental data to formulate nondimensional variables

Create empirical model with experimental data

Building the Pumps

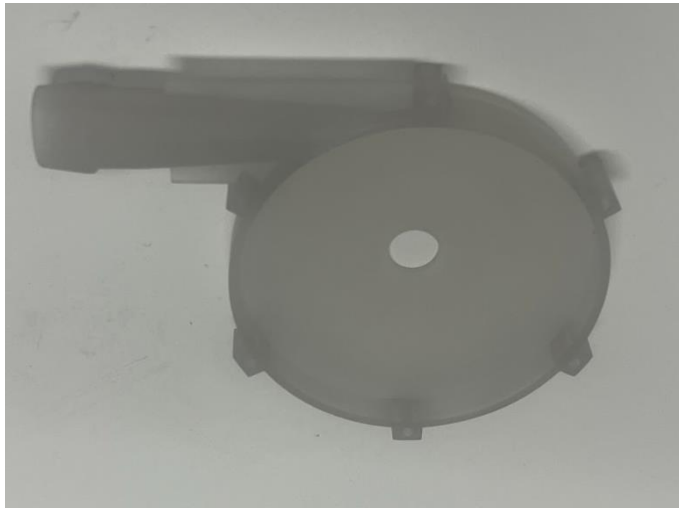


Casing Design and Manufacturing



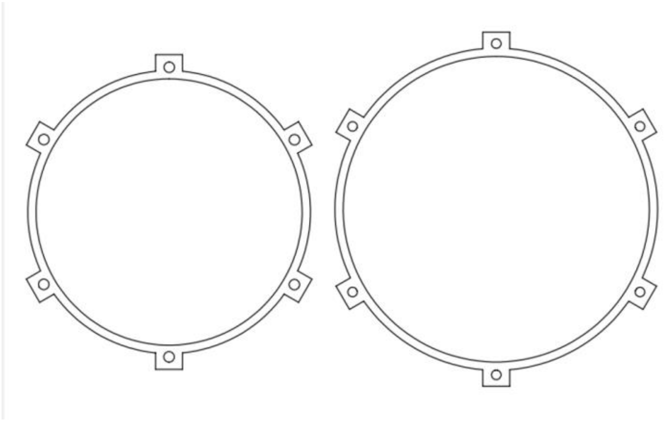
Models for each rotor size were created in CAD software

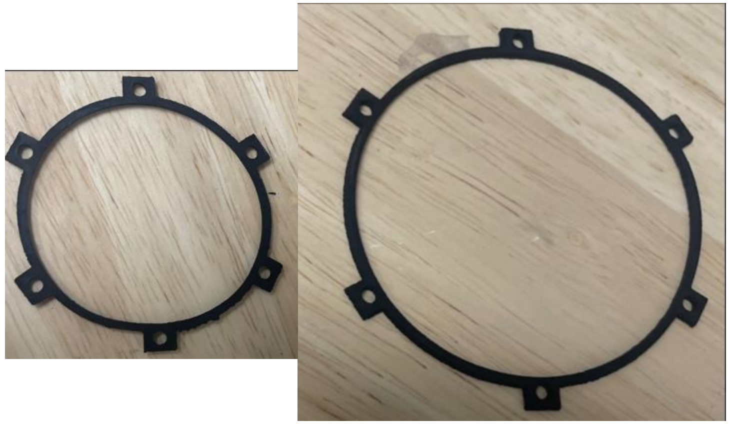
Prototypes were 3D printed in PLA



Final casings were 3D printed in resin

Gasket Design and Manufacturing



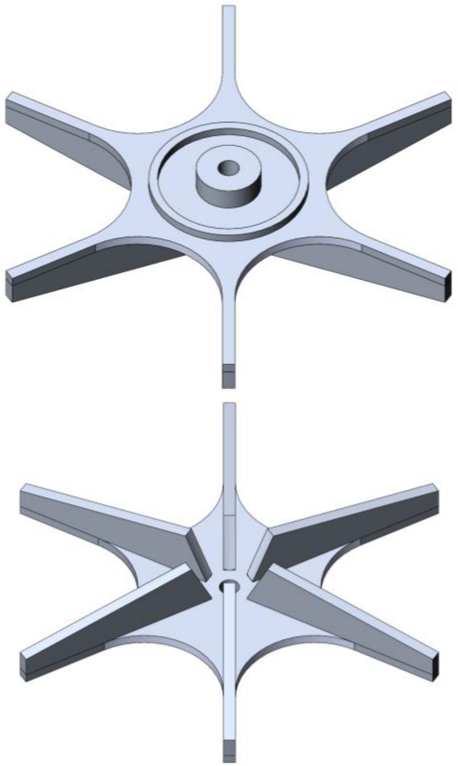


Drawings were created in CAD software

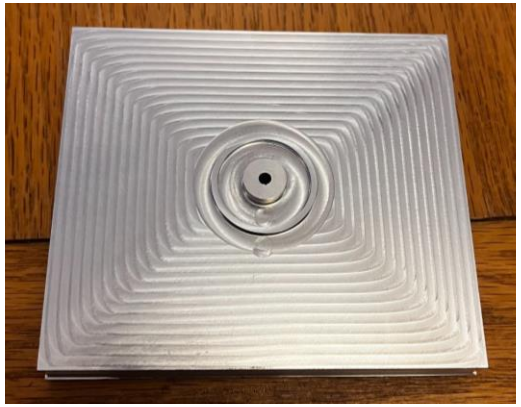
Drawings were uploaded to laser cutter and gaskets were cut out of rubber sheets

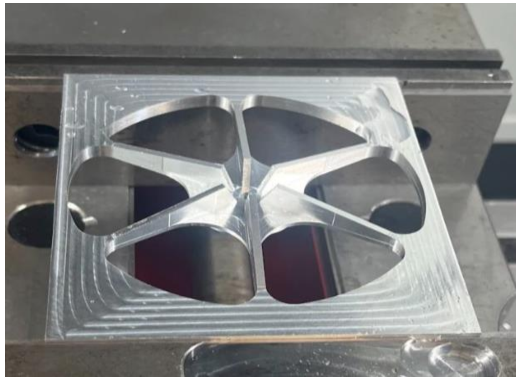
Finished gaskets for 40 and 60 mm diameter pumps

Rotor Design and Manufacturing (70 mm)



Blades extended to 70 mm & CAM developed for both sides



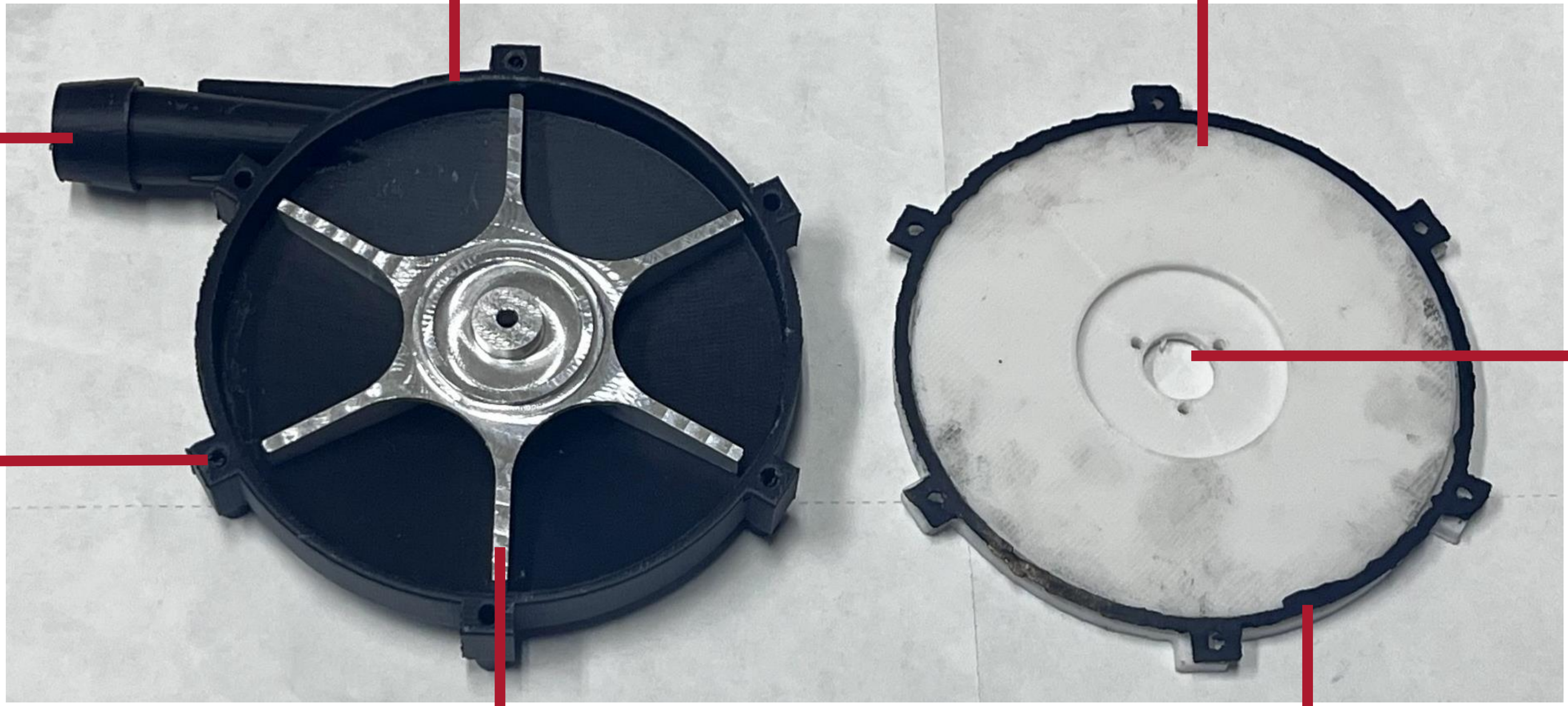


Both sides were CNC machined out of aluminum stock

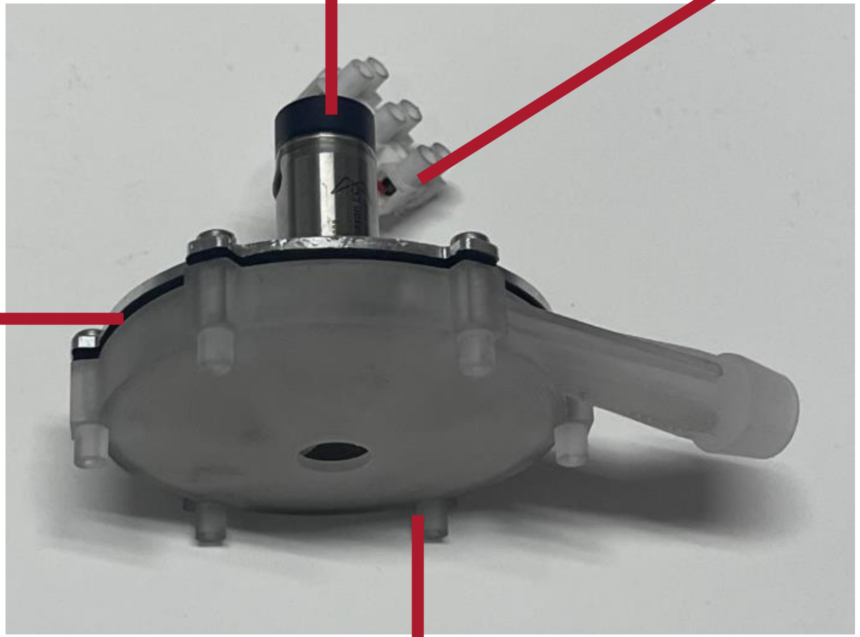
Rotor was cut out of stock & sanded

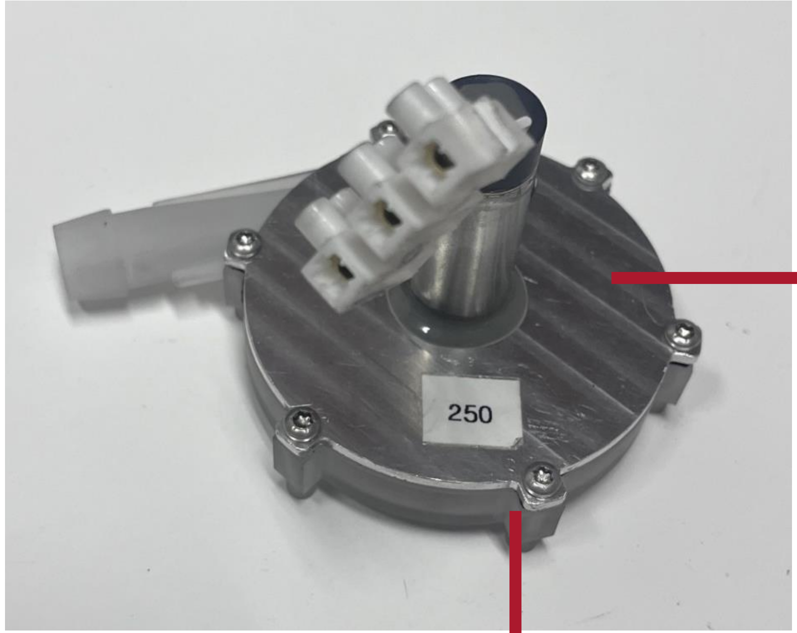
WPI

Prototype Pump Assembly

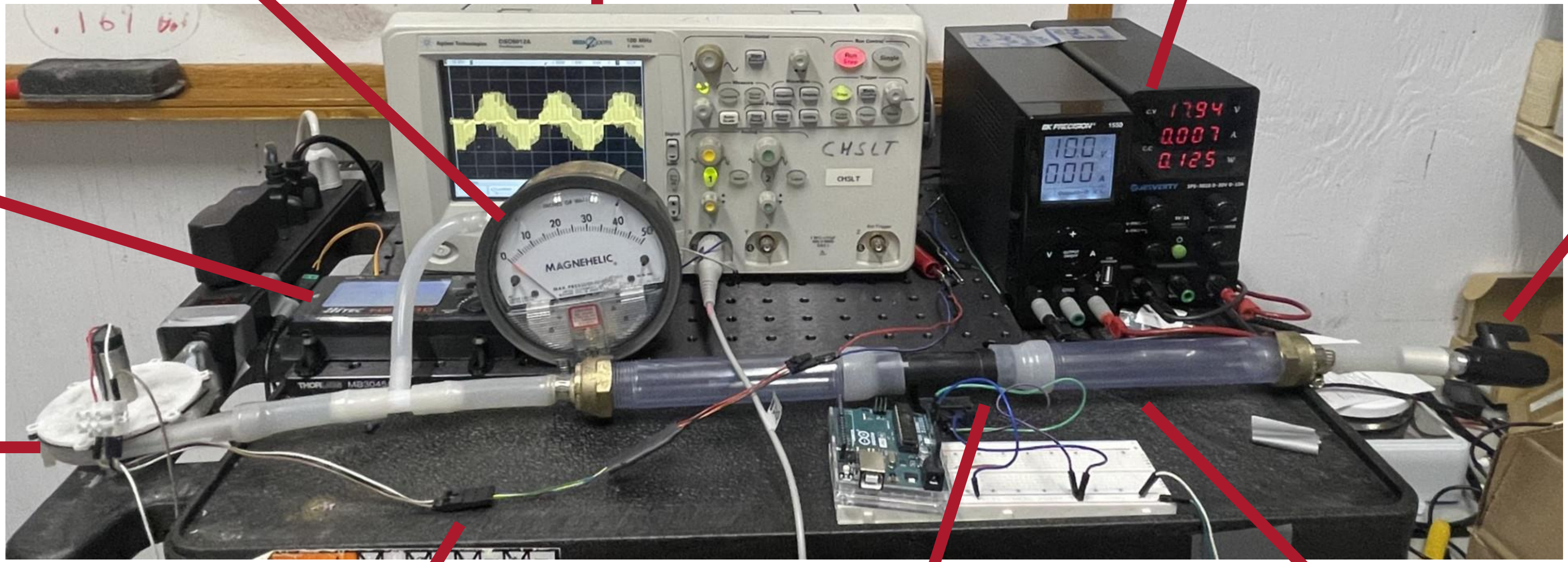


Final Pump Assembly with Motor



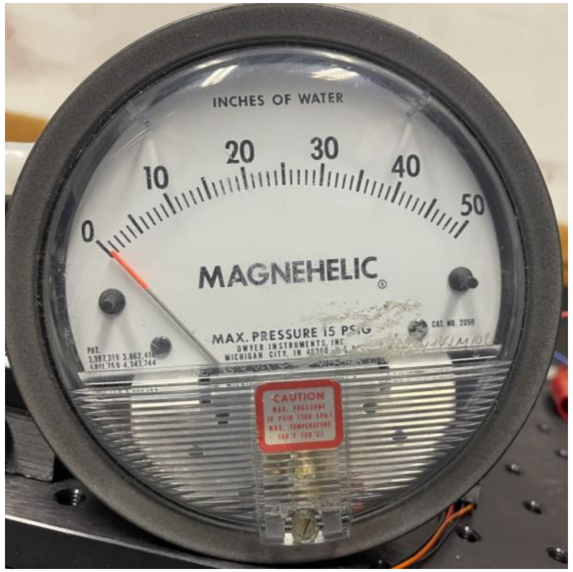


Experimental Setup

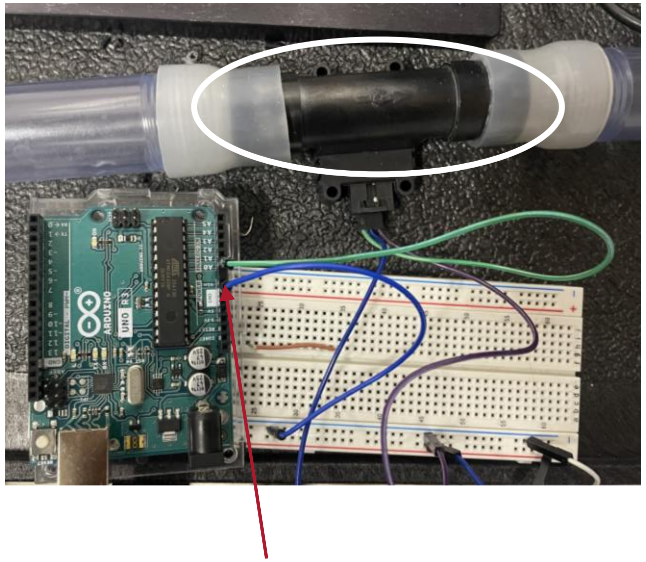


Measuring Paramters

Pressure

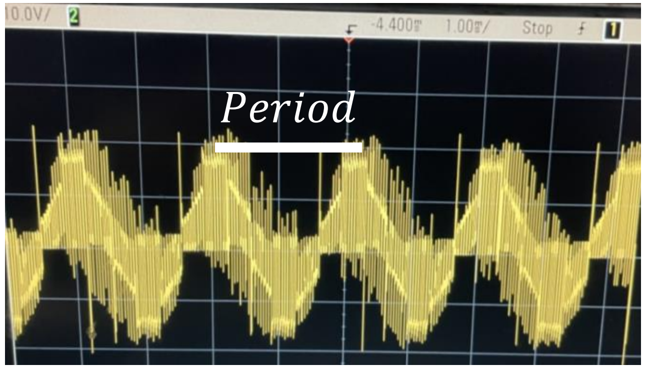


Flow



$$Flow = f(voltage)$$

Rotational Speed

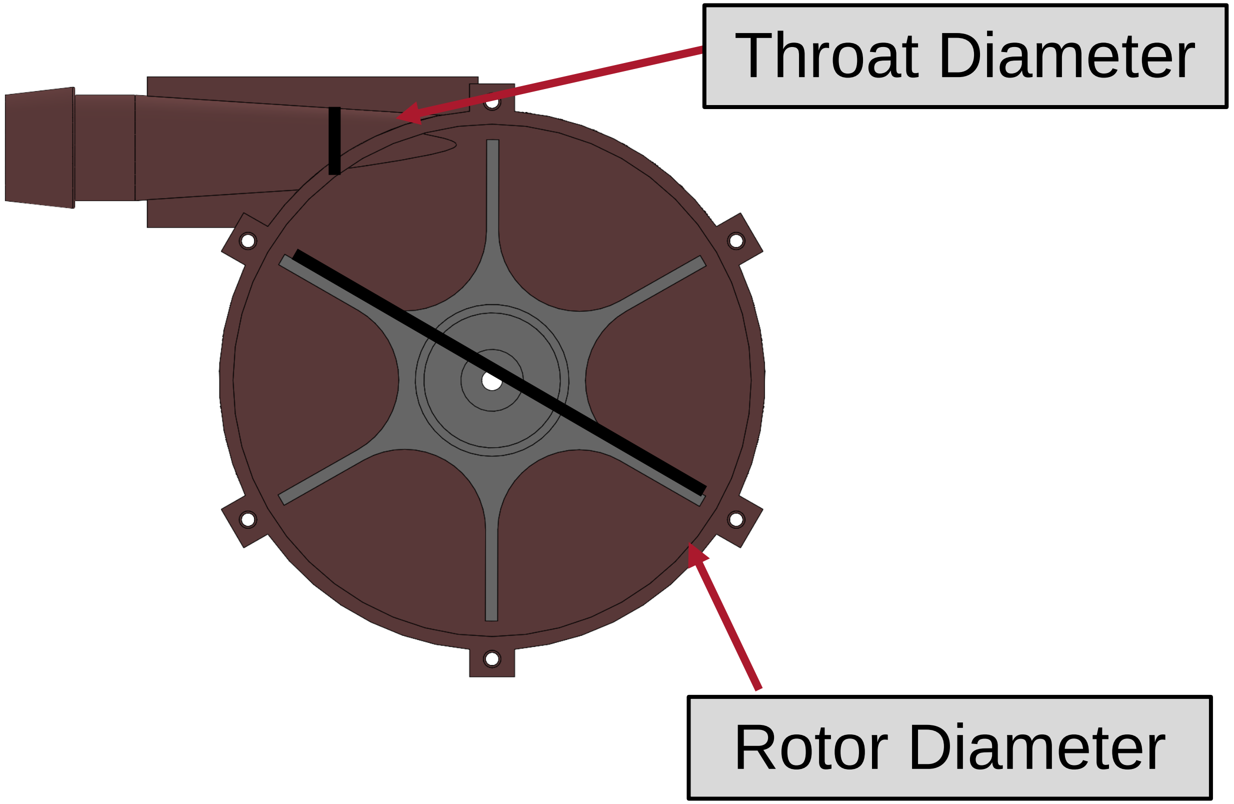


$$Frequency\ \ f_s = \frac{1}{Period}$$

$$\omega = \frac{120 f_s}{no.of\ poles}$$

Measuring Rotor Parameters

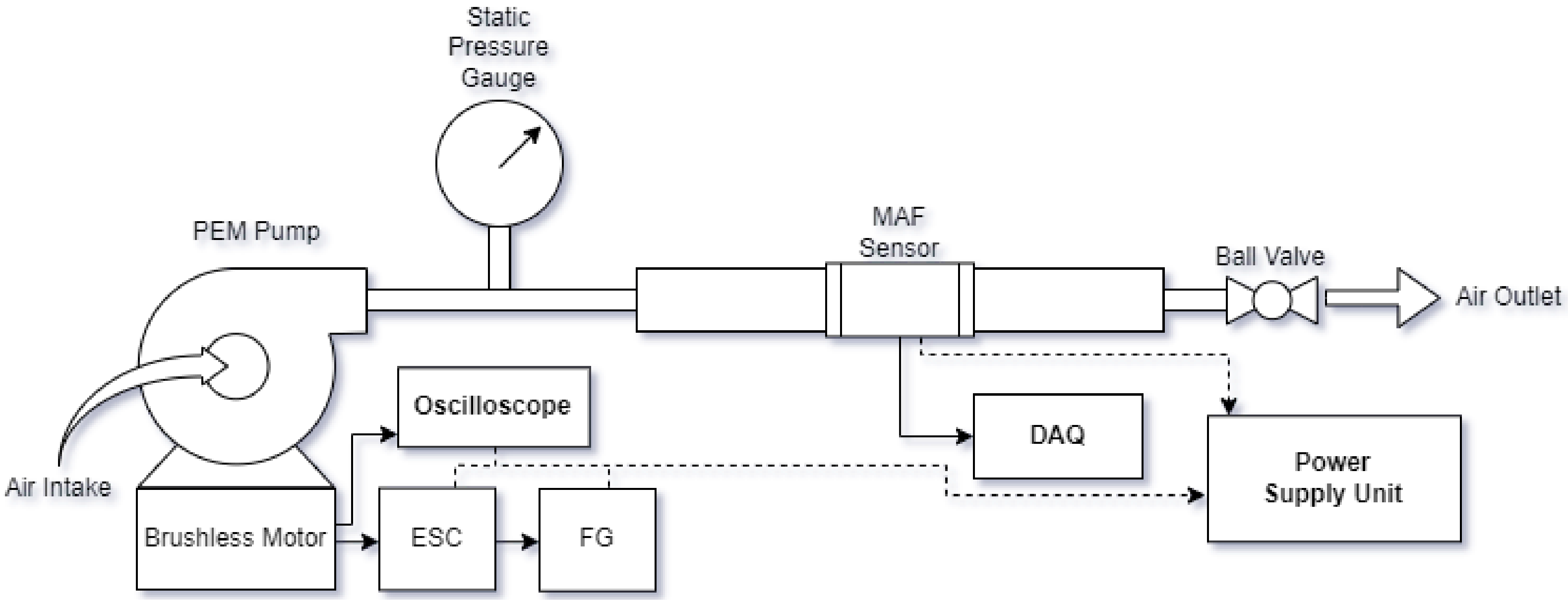
Rotor and Throat Diameter



Power

Experimental Setup

- Parameters Measured:
  - Pressure
  - Flow
  - Rotor Speed
  - Throat Diameter
  - Rotor Diameter
  - Power



Creating Non-Dimensional Values

- Pressure Rise (Pa)
- Rotor Speed (RPM)
- Rotor Diameter (m)
- Throat Diameter (m)
- Flow (SLPM)

$$\psi = \frac{\Delta p/\rho}{U^2}$$

$$\phi = \frac{v_{out}}{U}$$

→ $\psi = f(\phi)$

→ $\phi = f(\psi)$

$$d_s = \frac{D_{rotor}(Hg)^{1/4}}{\sqrt{\dot{V}}}$$

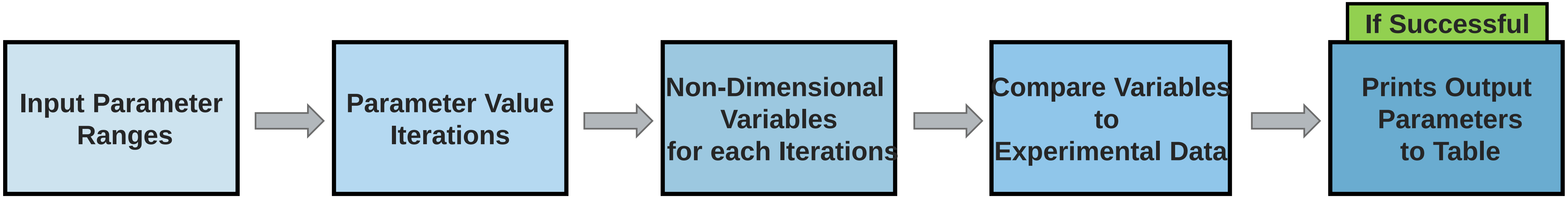
$$n_s = \frac{\omega\sqrt{\dot{V}}}{(Hg)^{3/4}}$$

→ $d_s = f(n_s)$

→ $n_s = f(d_s)$

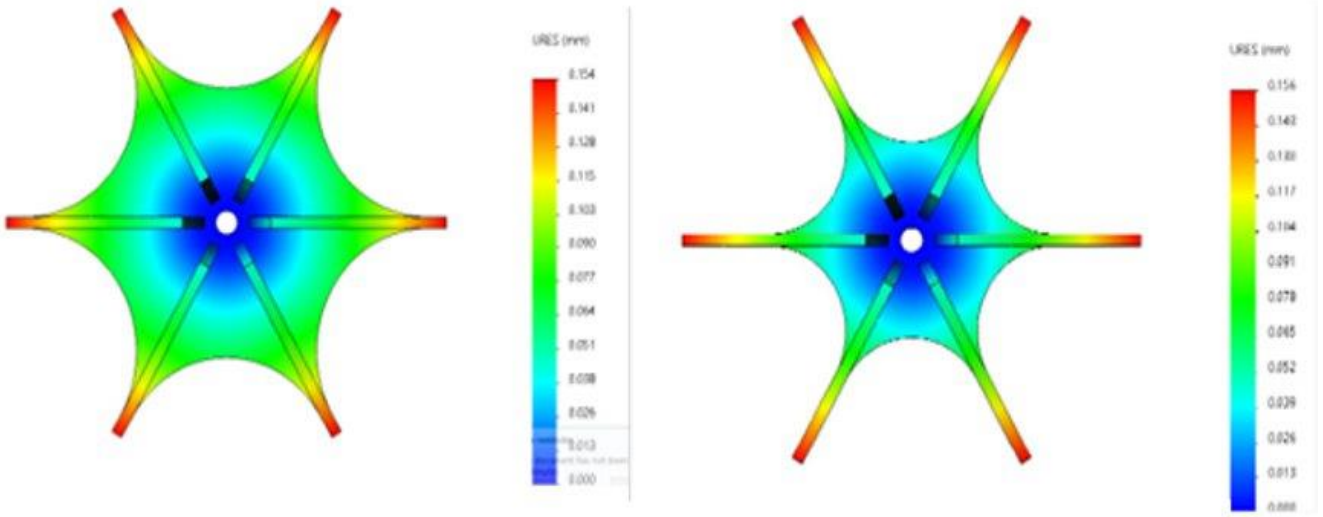
Model Creation

- An empirical model on MATLAB was developed to optimize the desired parameters of the pump
- A curve fit was created from experimental pressure and flow coefficients to develop equations for an output value from the input values



Rotor Deflection

- Blades of non-metal impellers experience a deflection effect from centrifugal forces
- Simulations were developed in SolidWorks and used to test different impeller parameters

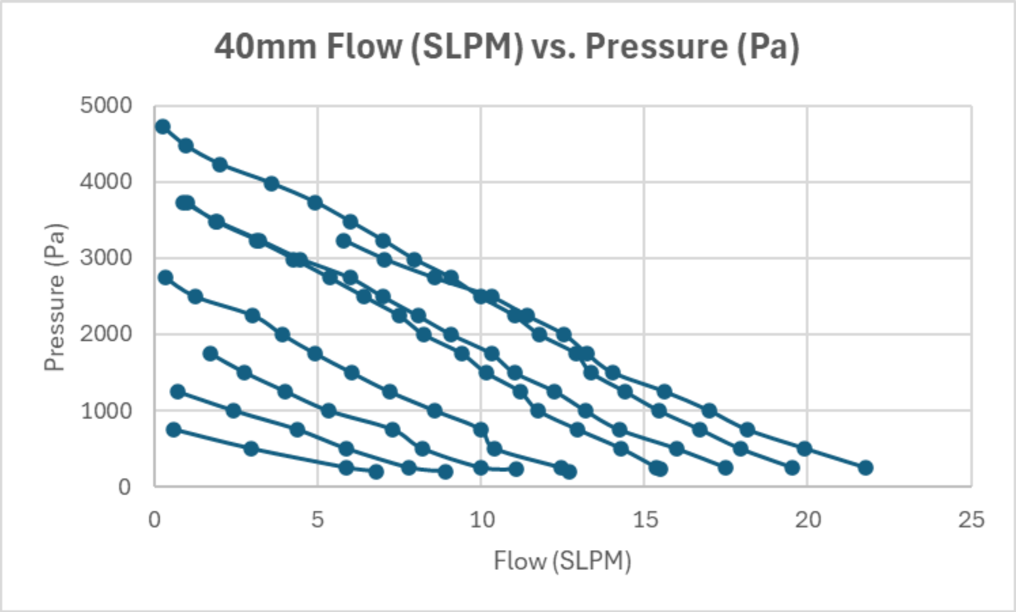


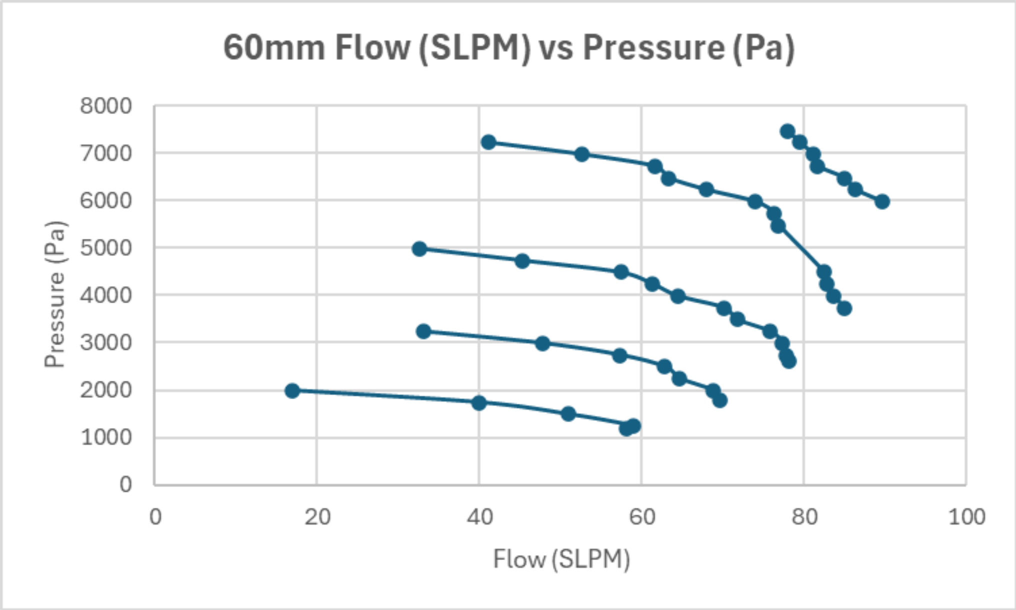
Results

What did we find?

Experimental Setup Results

- Measured performances of 40 mm, 60mm PEM pumps





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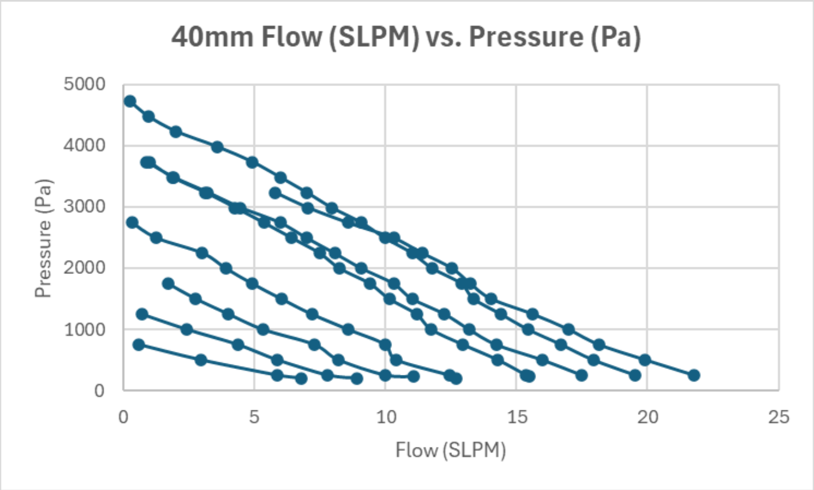
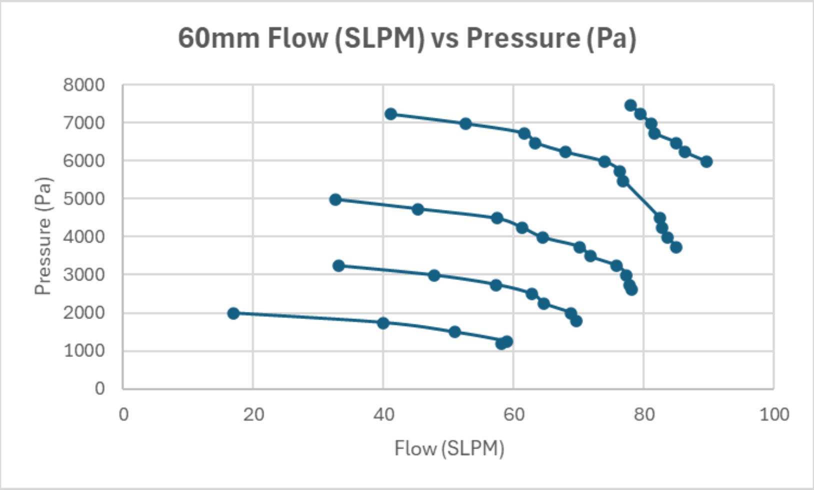
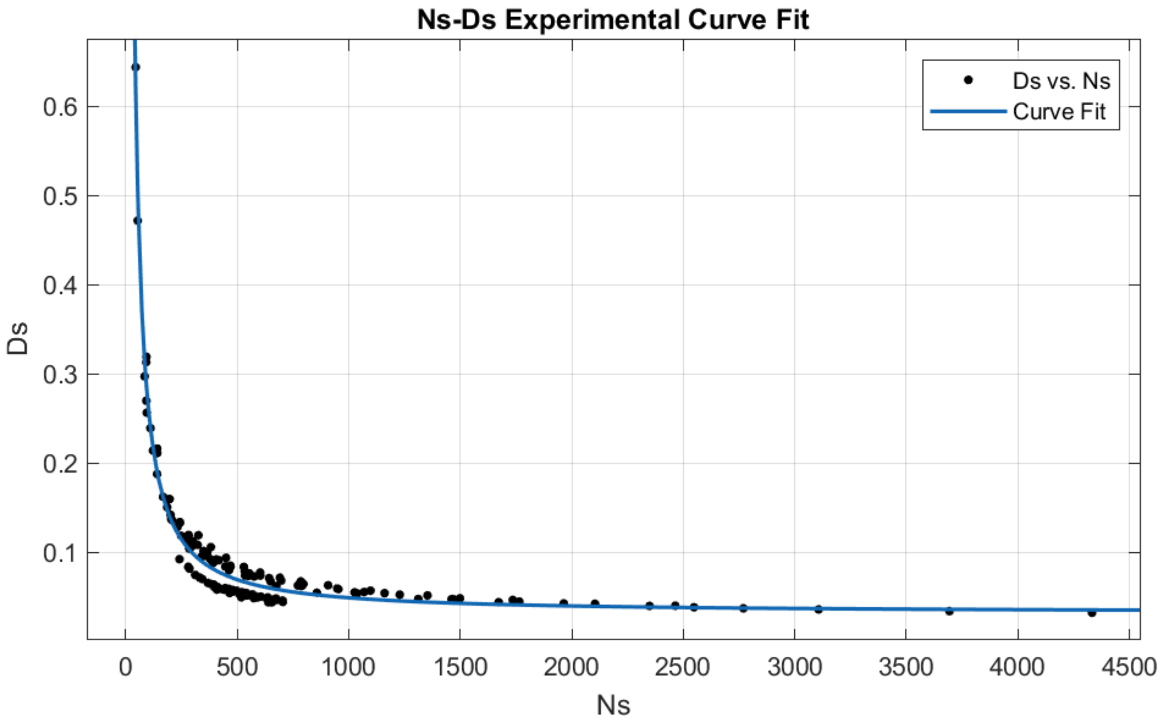
Experimental Setup Results

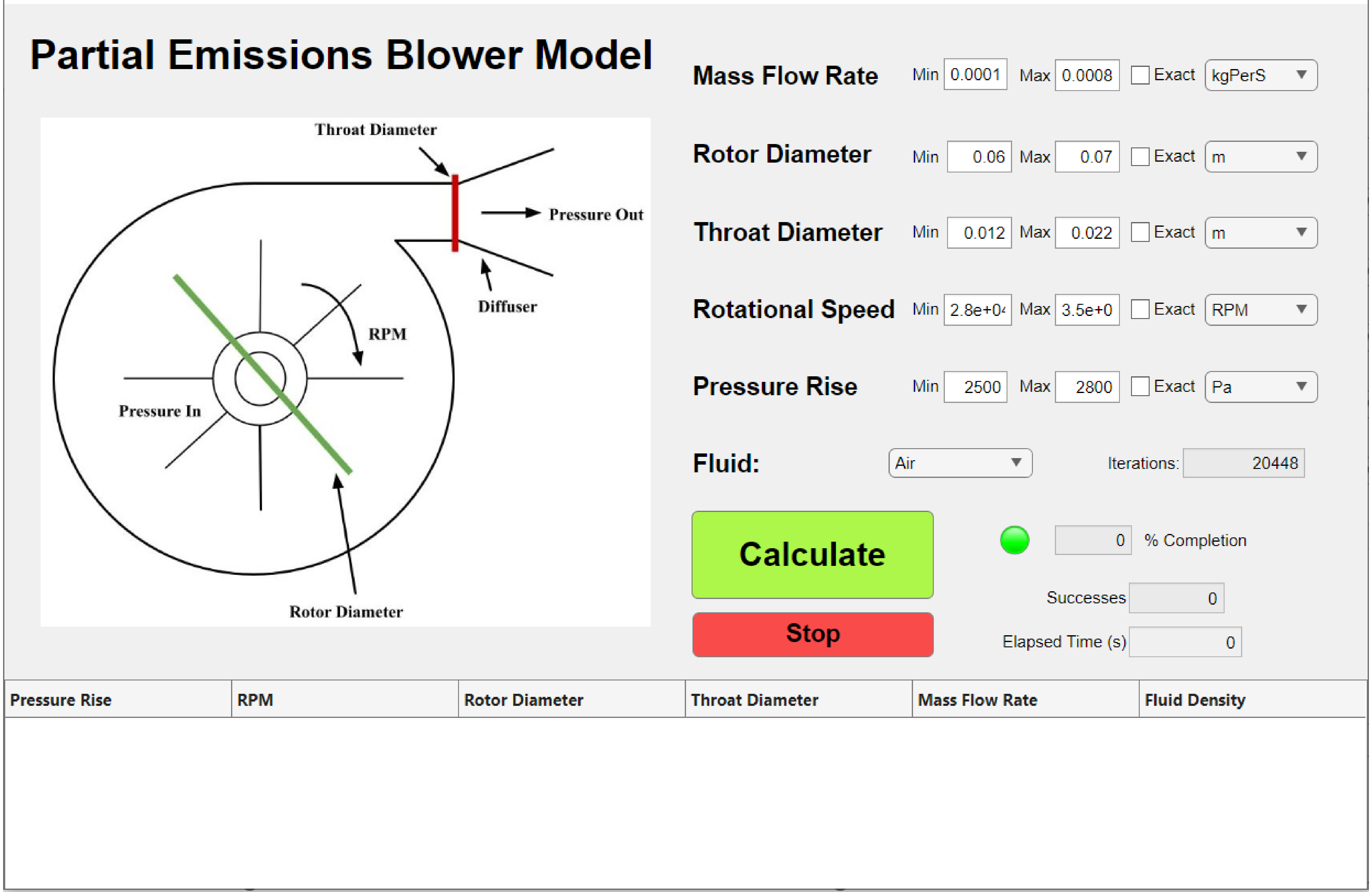
- Developed non-dimensional curve fits based off experimental results



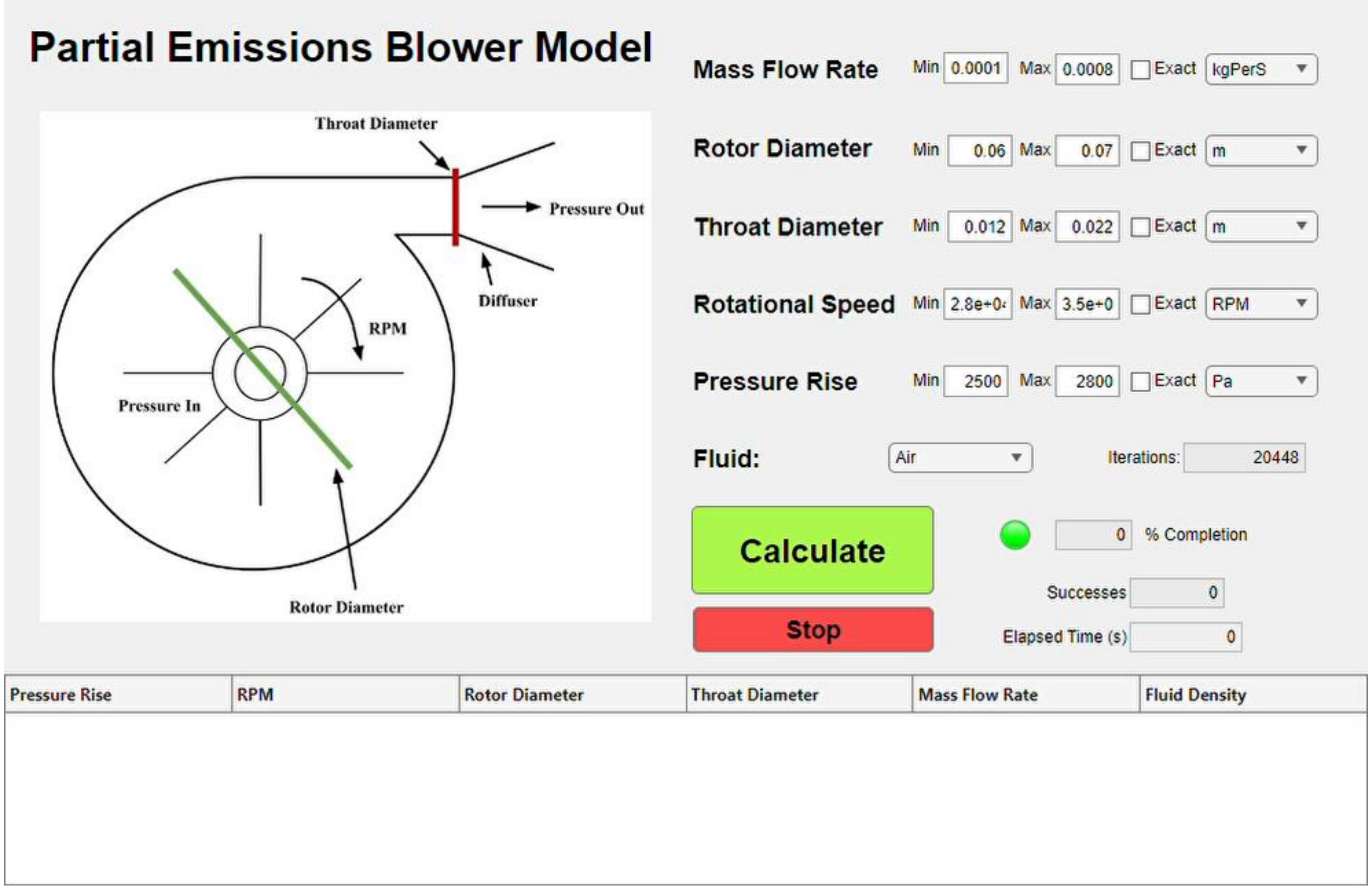




$$D_s = 46.308 N_s^{-1.1473} + 0.0324$$


Partial Emissions Blower Model
Throat Diameter
Pressure Out
Diffuser
RPM
Pressure In
Rotor Diameter
Mass Flow Rate Min 0.0001 Max 0.0008 Exact kgPerS
Rotor Diameter Min 0.06 Max 0.07 Exact m
Throat Diameter Min 0.012 Max 0.022 Exact m
Rotational Speed Min 2.8e+04 Max 3.5e+0 Exact RPM
Pressure Rise Min 2500 Max 2800 Exact Pa
Fluid: Air
Iterations: 20448
Calculate
Stop
0 % Completion
Successes 0
Elapsed Time (s) 0
Pressure Rise
RPM
Rotor Diameter
Throat Diameter
Mass Flow Rate
Fluid Density

Model Features



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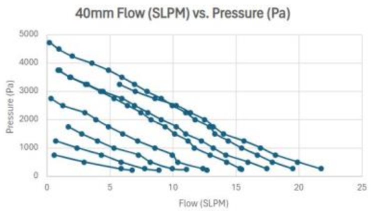
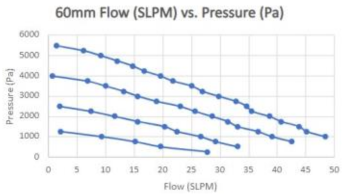
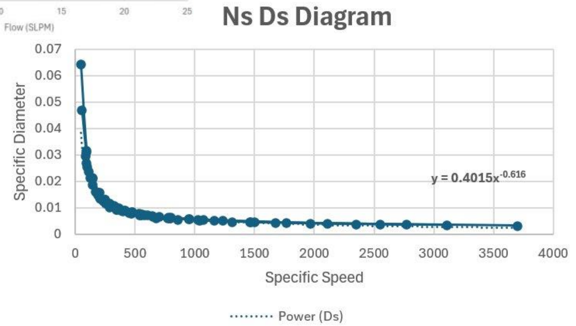
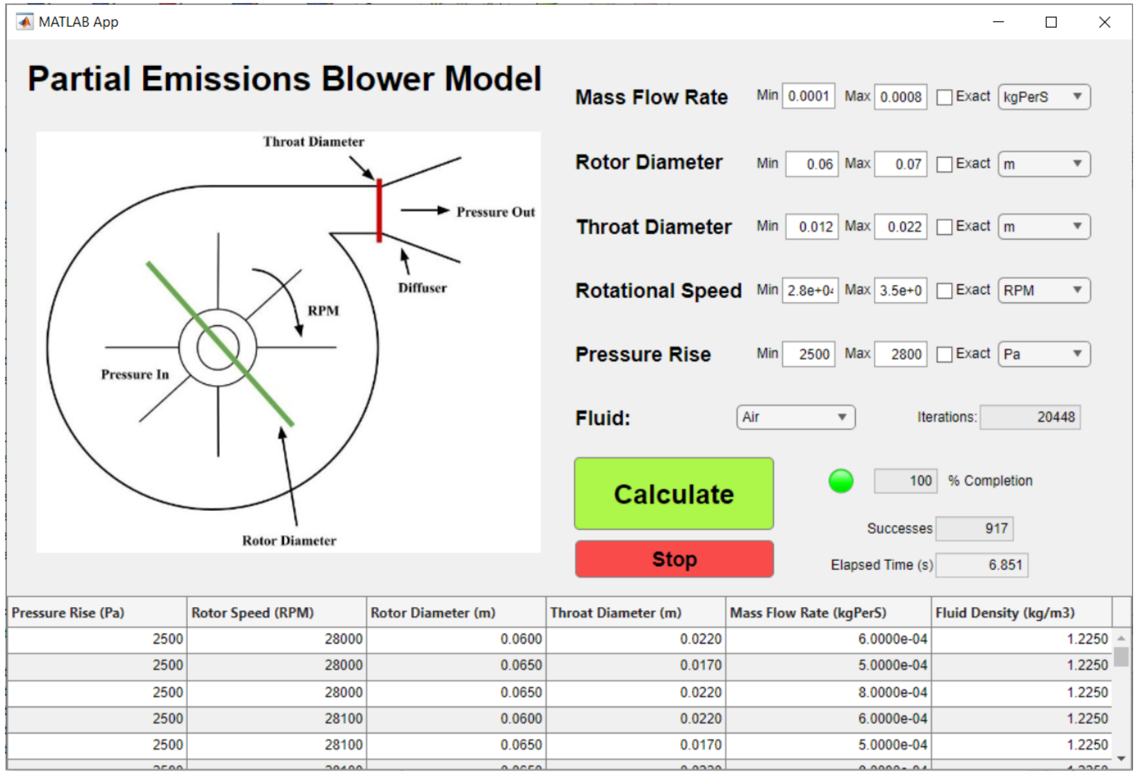
Model Features - Customizability

- Model Strength Based on Data
- Customizable tolerances, units, iteration step sizes



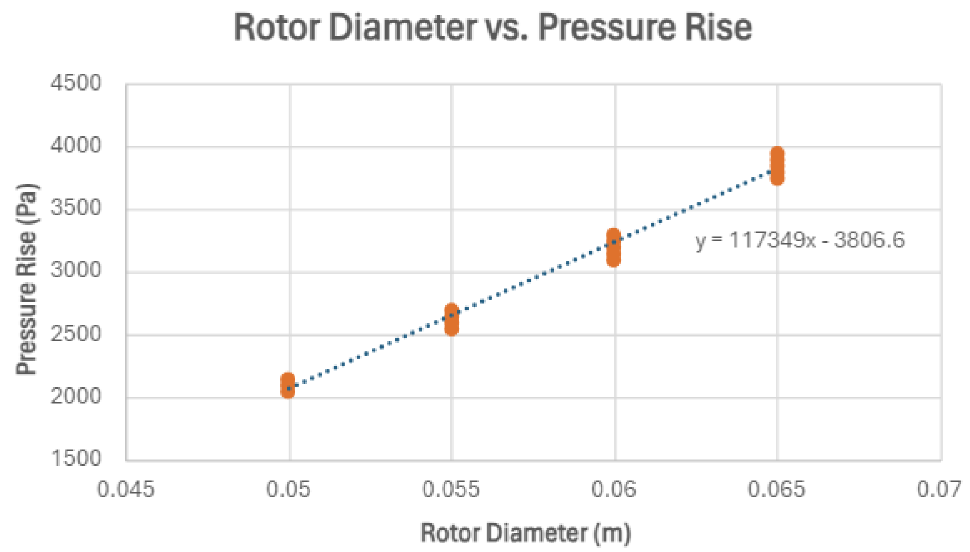


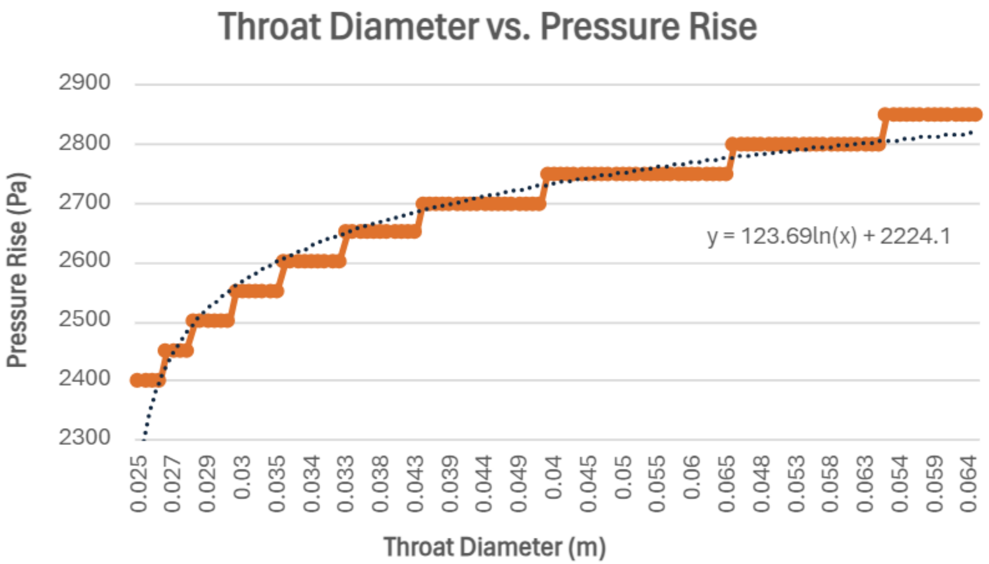




WPI

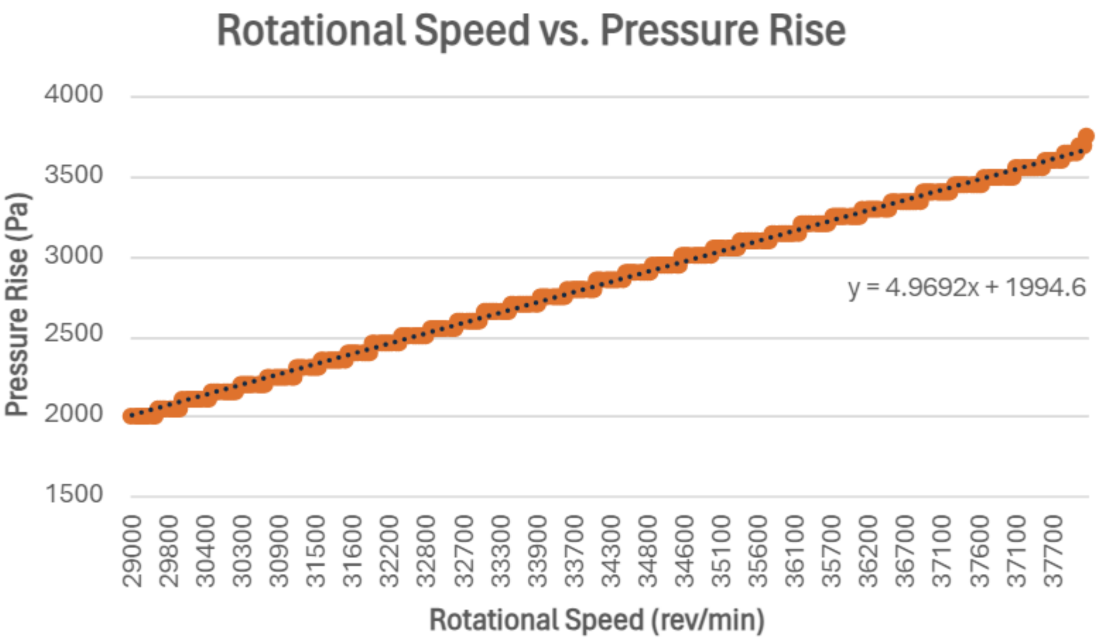
Analysis and Trends - Pressure



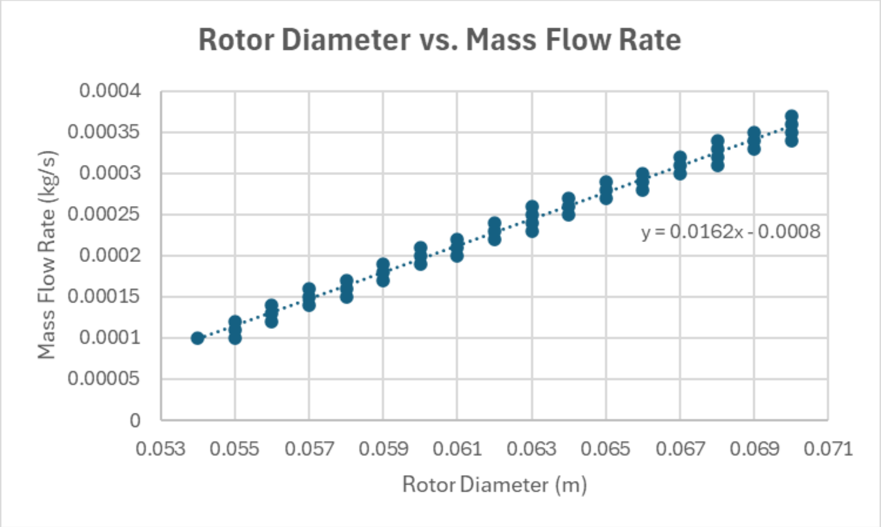


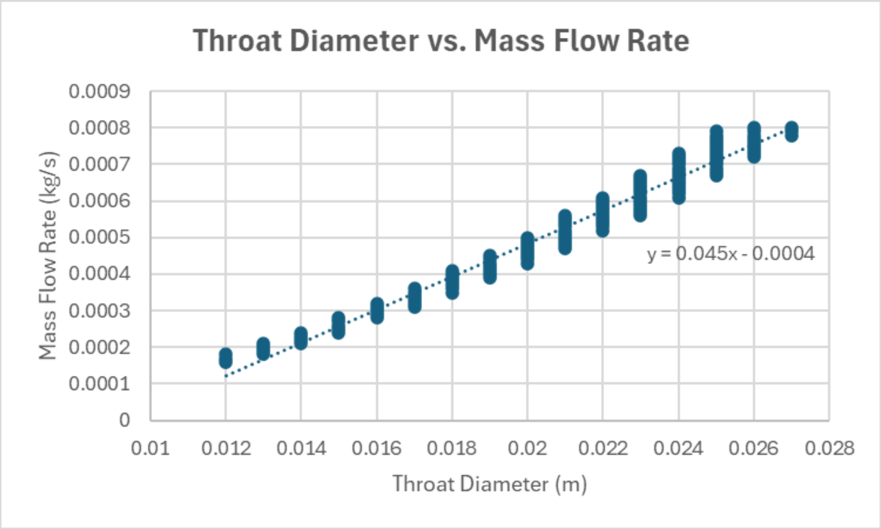
1. **Linear relationship** between **rotor diameter, speed** and **pressure rise**

2. **Slope** becomes **more steep** in relationship between **throat diameter** and **pressure rise**

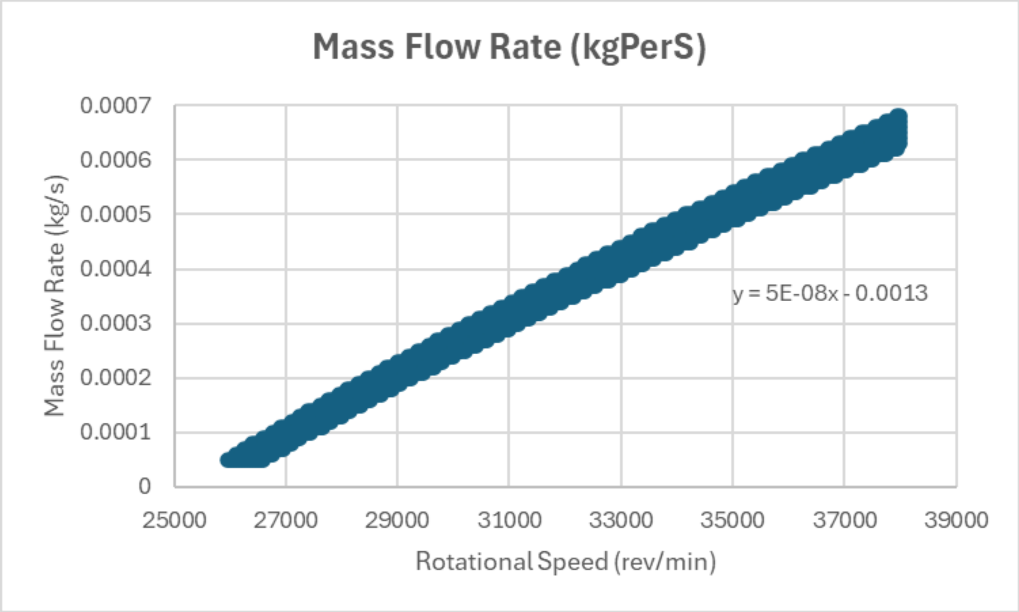


Analysis and Trends – Flow



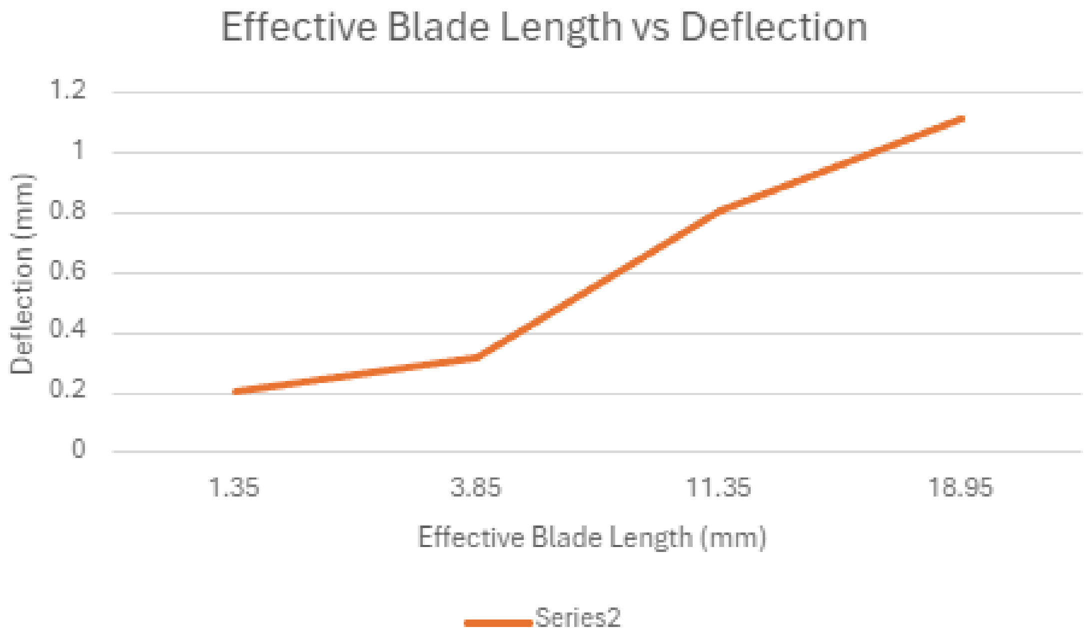


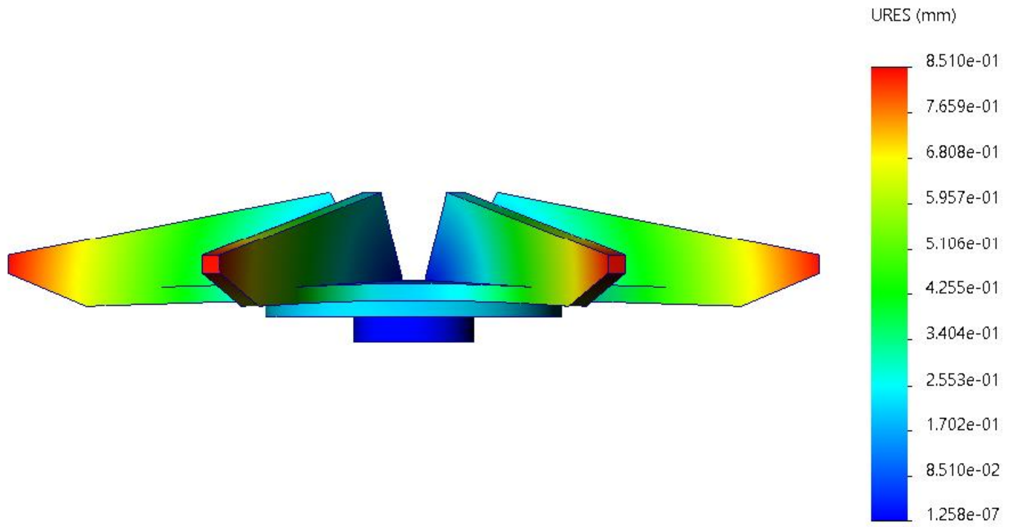
Linear relationship between **diameters**, **speed** and **mass flow rate**



Deflection Results

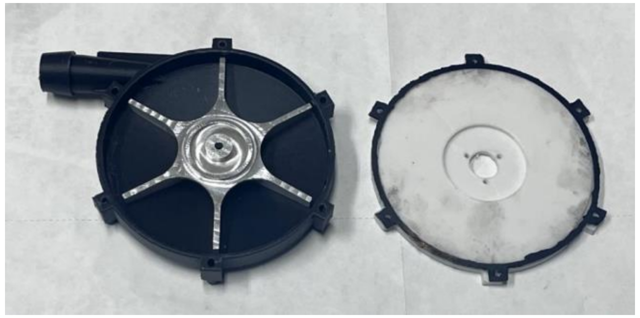
- Found that the parameter that had the greatest effect on deflection was blade length
- Finalized on a redesign that would attempt to change the location of the max deflection felt rather than the overall value of it

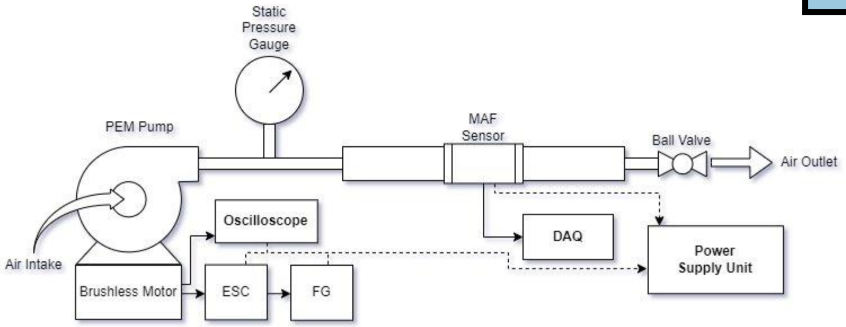


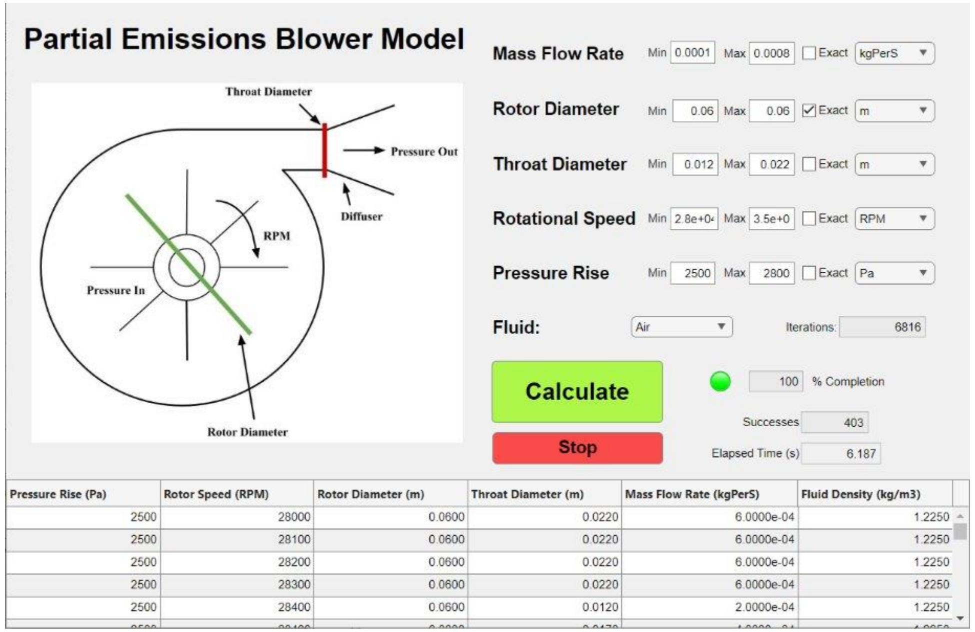


Summary

- Primary Goal: Develop a tool that helps to explore several design parameters that affect pump characteristic outcomes and can suggest an effective pump design
    - Alternative to manufacturing pumps – reduced time in costs; manufacturing

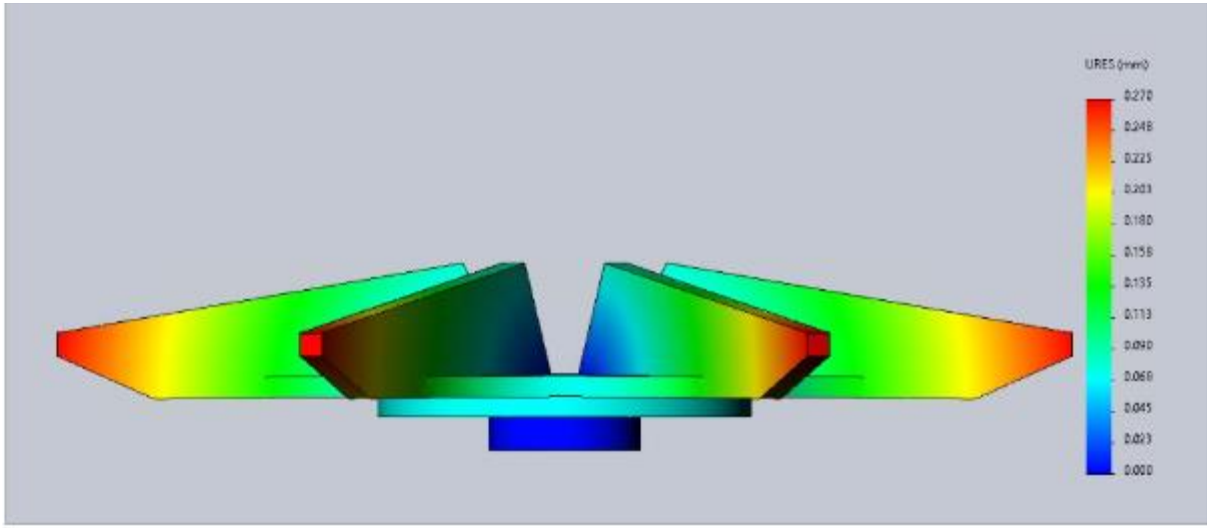






Summary

- Secondary Goals
  - Determine an effective method for manufacturing impellers that can be used at different scales
  - Determine an effective design change to mitigate blade deflection in non-metal impellers



Recommendations and Future Work

- Strengthen curve fits with 70mm data, additional data
- Look into other models to scale up pump
  - Geometrically similar, dissimilar pumps
  - Different diffuser geometry
- Test rotor deflection design change experimentally

Questions?

Sources

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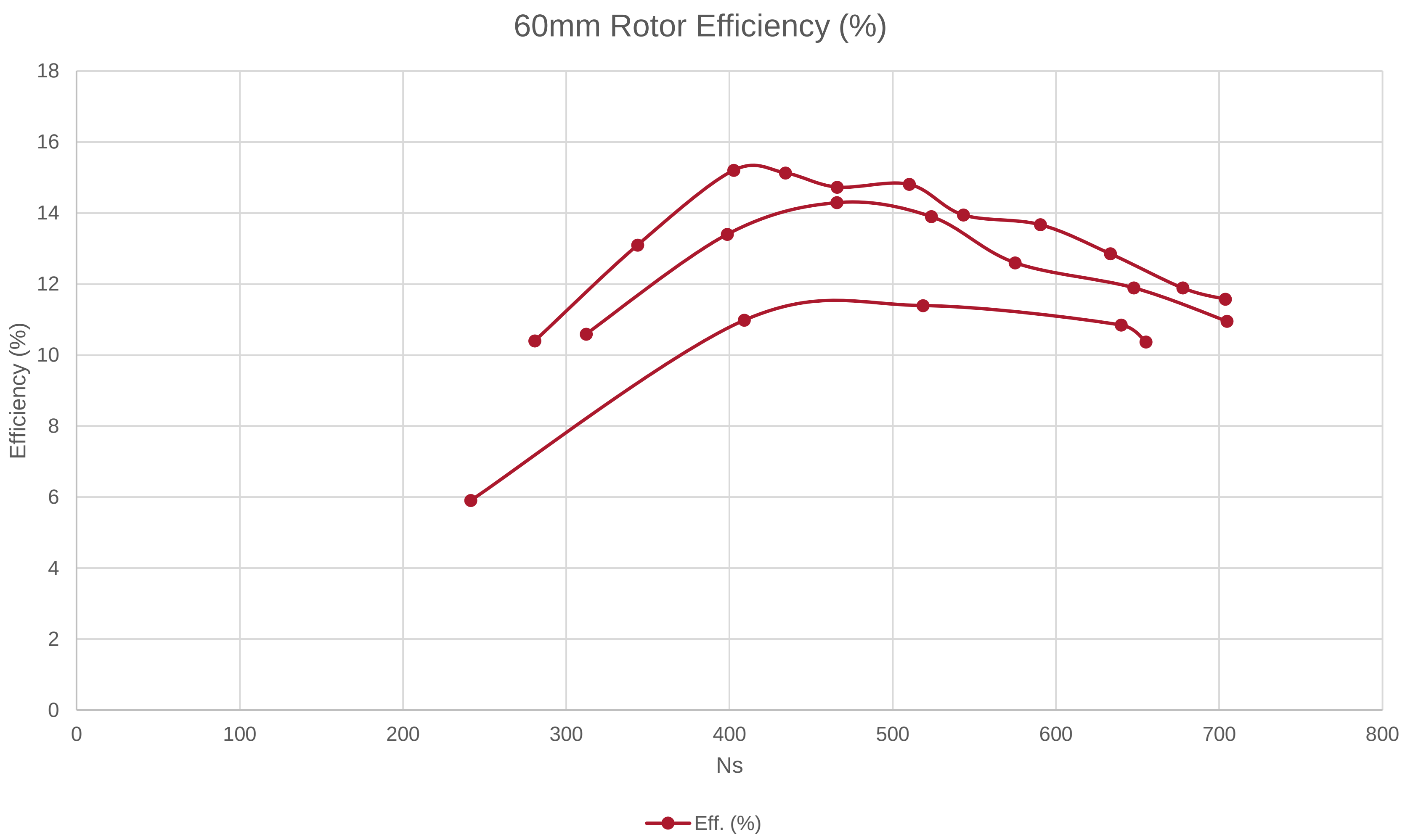
PEM Diagram


60mm Rotor Efficiency (%)
Efficiency (%)
18
16
14
12
10
8
6
4
2
0
0
100
200
300
400
500
600
700
800
Ns
Eff. (%)