Improving the Hydraulic Performance of Centrifugal Pumps using Computational Fluid Dynamics and Fractional Factorial Design of Experiments

Hamzah Al Rashdan
Ira Topp

Department of Engineering and Physics, University of Central Oklahoma

Submitted on May 5th, 2015 to

Adviser: Dr. Abdellah Ait Moussa

Department of Engineering and Physics, University of Central Oklahoma
Executive Summary

Pumps have been used ever since ancient Egyptian times to move buckets of water from lower levels to higher. In 1475, Italian Renaissance engineer Francesco di Giorgio Martin designed the first centrifugal style pump, and Denis Papin developed the “straight vane” centrifugal pump in 1687 [1]. In 1851, John Appold introduced the curved vane centrifugal pump, and improvements & optimizations have been made ever since. Small differences in geometry can lead to significant changes in the performance of these machines.

The subject of this project is to devise an efficient numerical technique that automatically optimizes the geometry of the impeller for maximum hydraulic performance, and seeks to take improvements to the next level by use of computer simulations. The research will combine automatic design of the impeller, computational fluid dynamics (CFD), and fractional factorial design of experiments using orthogonal arrays. The results will be compared, both simulated and experimental, to verify the design improvements of a 3D printed copy of the improved computer simulation, by means of an onsite pump testing station.
## Contents

Executive Summary........................................................................................................ 2

Statement of Problem.................................................................................................... 4

Design Objectives.......................................................................................................... 4

Technical Approach....................................................................................................... 5
  Plan of Action............................................................................................................... 5
  Identifying Customer Needs....................................................................................... 6
  Identifying Target Specifications.............................................................................. 7
  Generating Design Concepts..................................................................................... 7

Project Management.................................................................................................... 18
  Gantt Chart................................................................................................................ 18
  Deliverables............................................................................................................... 18
  Budget....................................................................................................................... 19
  Communication and Coordination with Sponsor................................................... 19
  Team Qualifications................................................................................................. 20

Conclusion.................................................................................................................... 20

References..................................................................................................................... 21

Appendix A: Résumés of Team Members.................................................................... 22
  Hamzah Al Rashdan.................................................................................................... 23
  Ira Topp..................................................................................................................... 24
Statement of Problem

The efficiency of a pump is the ratio of energy delivered by the pump to the energy supplied by the pump shaft. Typical pump efficiencies are 60 to 80 percent, and vary based on impeller design. Typically, for lower powered pumps, the impeller contains 90 degree angles, which are not ideal for high moving fluids, but reduce the costs of manufacturing due to their simple geometric designs. Using computer aided modeling software; we seek to find the ideal geometric design that will enable the fluid to flow with as little restrictions as possible. This research ultimately seeks to produce and verify an impeller and volute that achieve a 10 percent increase on a given pump efficiency, by using Computational Fluid Dynamics (CFD) and fractional factorial design using orthogonal arrays, all in an automated setup. This setup will then be used to generate a geometric design that will be able to be replicated for any centrifugal pump on the market, providing a simple plug-and-play solution for increasing an existing pump.

Design Objectives

Our impeller and volute setup will be designed to increase the overall pump efficiency of an existing pump a further 10%. The pump testing stations will be able to test a 3D printed geometrically optimized impeller and volute, while verifying the existing pump efficiency characteristic curves. An automated safety monitoring system will shut down the system to avoid damage when critical pressures or flow rates are reached, while providing instant visual information for flow and pressure ranges via multicolored LEDs. Pressure and flow rate readings will be automatically recorded to generate pump characteristic curves, and the ability to set pump curve flow rates automatically will be designed into the system. CFX modeling and fractional factorial design will be used to generate an ideal geometric design for an impeller and volute, and the resultant will be 3D printed.

The constraints for our project include economic, manufacturability, ethics, and health & safety. Due to the budget of $250 per person, and because we only have two members, we are restricted to the quality of equipment that can be used. As this method of approach is much less costly than trial-and-error methods of past, this method and design should provide pump manufacturers the ability to provide a new standard of pump efficiencies, reducing their respective customers electrical power costs. Since we are currently limited to the availability of only one pump for benchmarking and testing, the geometric design will be theoretically scalable for any centrifugal pump on the market, and may need to be sent to manufacturing companies for verification.
Technical Approach

Plan of Action

To obtain the optimized impeller geometry that we have set for ourselves, we followed a design process in which we first identified the problem, represented by the industry needs. We determined the specifications that must be met in our design to address these specific needs and designed concepts that met these specifications. Finally, we selected a concept that best fit our specification needs and within our design constraints. We will take further action by testing selected components of the design and verifying that the specifications have been met and then implementing and testing a prototype of the design. We start by creating a mathematical model of the pump in Mathematica. Then transport the mathematic model to solid works and generate the geometric model. From this model, we use ANSYS-CFX to simulate the fluid dynamic inside the pump. Rather than manually iterating design changes until all design requirement are met, wan can work more effectively by automating the design process and using an optimization algorithm to create a final design that meets the particular requirements.

In this study, to achieve optimal performance, we will be facing three parts of work; geometric modelling of impeller and casing geometries, finite element analysis (FEA) and mathematical modeling and programming. Different program files will be developed for each part, and communication between these parts is manipulated by an interface. One of the most interesting features of ANSYS program is the possibility to use it as a mere subroutine of any other external program. Parameters can be either directly passed or exchanged through external files. This flexibility allows us to build an interface between ANSYS and our external algorithm, to be coded in Visual Basic for applications (VBA), where ANSYS is a finite element package capable of calculating the objective function and constraints. The ANSYS-CFX software contains the broad physical modeling capabilities needed for our application. In addition, design updates will be streamed to our cad software “SolidWorks” directly from a mathematical software package known as “Mathematica” where the direct modeling of impeller geometry using non-uniform rational B-spline (NURBS) and Bezier functions will be made and tables of control points identifying the NURBS surfaces of the blades and the respective geometries of the hub and shroud are modeled. Once in SolidWorks, the impeller surface of the blades will be reconstructed, and the remaining device features built including hub and shroud. Most CAD software packages such as SolidWorks have integrated features that allow one to make direct function calls to the application programming interface (API) from VBA macros. The built in macro feature in SolidWorks makes the selection of these functions manageable. The methodology schematics are shown in fig.1.
As the ideal pump blade is determined by using the method described above, we will conduct experimental testing to quantify our numerical result that we gathered. The experimental testing will be held at the designed testing station.

**Identifying Customer Needs**

The needs of the customer are easy for this project, first we need to provide a product easy to install for all consumers who uses the Berkeley BPDH10 pump. Also this product needs to be simple and easy to create for the manufactures, it is not installed incorrectly and defeating the purpose of our product, since the angle at which impeller geometry is critical in the improvement of the efficiency. Also the needs of the consumer is a product in which will improve their current pump performance, and save them money quickly and efficiently so that the payback on our product does not take years to break even.
Identifying Target Specifications

The needs of the consumer are important to us, and we want to strive to provide them with the best product available. The simplification of installation and the payback time on this product are very important. If it is too difficult to install, or takes too long on the return investment, then the product will not be purchased by the end user.

The process for completing the simulation and obtaining a model that provides the maximum value of the efficiency begins with building and accurate model of the pump volute and impeller of Berkeley BPDH10 pump to be tested. This is accomplished using the CAD software Solidworks. Solidworks was chosen as the CAD tool for this project due to its accessibility, ease of use, and its reputation as a professional engineering tool in industry. The specs need to be spot on, and minimal tolerances are used in the CAD modeling. The pump testing station needs to be highly accurate as well, taking into consideration all the theorem of Fluid mechanics and dynamics. The sensors need to be well made, and electronics/programming needs to be within a small tolerance.

Generating Design Concepts

Our basis and starting point of the design process centered on the need for an accurate CAD model of our existing impeller and volute. We had 3 options for modeling: wax model of the vanes, cutting the impeller open and physically measuring all necessary geometry, or obtaining access to a CT or MRI machine for internal imaging. After a few failed attempts at making wax and silicon molds of the interior geometry, and cutting into the only available model not really an option, we decided to call the Radiology Laboratory at The University of Oklahoma Health Science Center. After a few communications, we were able to obtain 0.25 mm resolution planar images of the internal geometry. We then used these images in Solidworks to create a CAD model of the impeller by overlaying lines and splines over images of the cross sectional images. The volute was also designed in Solidworks, which was then mated to the generated impeller design. This completed model will form the basis of the computational fluid analysis.
Figure 2: CT Scan Imaging

Figure 3: Image Layering
Figure 4: Solidworks CAD Development

Figure 5: Solidworks Full Render Mosaic
For our third objective, we have designed a testing station to benchmark the experimental results of our current impeller and volute performance and compare the result with simulated result of the current impeller and volute from Ansys. As shown below from the figures the testing station is consist of pressure sensors, flow rate sensor, control box, and computer box.

The main computer box houses the essential components for functional operation of the pump testing station and safety monitoring system, and the control box houses the switches and LCD screen used for operation and real time data viewing. Quick disconnects for the sensors and boxes were used whenever possible, and the entire setup was professionally soldered for reliability. Components and key components have been labeled for ease of identification, troubleshooting, and display purposes.

The control box was designed to easily control the manual operation of the testing station, while adding a small storage area to the testing station desktop for placement of routinely used items and tools.
Figure 7: Testing station (1: Laptop, 2: Main Computer Box, 3: Control Box, 4: Wattmeter, 5: Berkeley BPDH10 Pump, 6: Pressure Sensors, 7: Flow Meter, 8: Electronic Ball Valve)

Figure 8: Main Computer Box (1: Power Switch, 2: Power Supplies, 3: Voltage Bus Bars, 4: Arduino Uno and Mega, 5: Power Relays, 6: Arduino USB ports, 7: Quick Disconnects, 8: Automated Valve Controls, 9: Pressure Sensor Circuitry)
Figure 9: Main Computer Box

Figure 10: Main Computer Box quick disconnects
Figure 11: Testing Station Isometric View

Figure 12: Control Box and storage area
The safety monitoring system was instituted as a means of rapidly visually and audibly monitoring the pressure and flow ranges, to prevent damage and cavitations from extremely low flow/pressure fluctuations. With an LED strip illuminating in different colors for different pressure range, and an alarm activated upon reaching the lowest range, the system provides an effective solution for monitoring the system from a distance, while keeping the entire setup in check.

The system is checked every 1 second for conditions via LabVIEW, and a signal is sent to the LED strip to display the indicated color range across the strip. Upon reaching the lowest preset range of pressure or flow reading conditions, the LED strip strobes white, and the audible alarm is activated. As seen from figure 12 below, TL: Green indicates Good, TR: Amber indicates Fair, BL: Red indicates Poor, and BR: Strobe indicates Dangerous. Note the changes in flow conditions visible through the clear piping.

![Figure 13: Safety Monitoring System.](image)

Clear tubing and LED strip lighting were implemented to observe the flow patterns, and ensure that the system was internally functioning properly. Reynolds numbers for the low and high flow rates were calculated to be 5800 and 81000 respectively, so the need for a flow straightener became clear. The flow straightener was made from plastic corrugated cardboard, and improved the flow characteristics and readings greatly. While not of ideal build quality, the inexpensive design proved to be useful.
Figure 14: Flow Straightener Mosaic

Figure 15: Clear Piping and LED setup
LabVIEW was an integral part of the design, and was used to facilitate the automation of the pump station, as well as gather, interpret, and utilize data to generate the flow characteristics.

![Figure 16: LabVIEW Front Panel](image1)

![Figure 17: LabVIEW Block Diagram](image2)
The resulting efficiency of the pump was compared to the manufacturers efficiency chart, and similarities were noted. While there is a strong correlation between the 2 resulting characteristic curves, it was noted that the manufacturer’s curves were generated under ideal test conditions, and the pump testing station we developed was not ideal.

![Figure 18: Testing Station Efficiency vs Manufacturers Efficiency](image)

The ultimate impeller design was 3D printed, and will be tested to verify the increased flow rates shortly. Verification should confirm that the new impeller closely matches the resulting CFX scenario, and produce a higher design efficiency and characteristic curve.

![Figure 19: 3D Printed Impeller Mosaic](image)
**Project Management**

**Gantt Chart**

The Gantt chart [Fig. 13] shows the time line of completed tasks as well as those that will be completed in the next semester. Since the team consists of only 2 people, scheduling and communication between the team members was simplified, and the semester objectives were met with relative ease. As the Gantt chart demonstrates, the main objective of this project was to have a completed pump testing station. Time was inherently left for the ordering and receiving of the 3D impeller prints, and problem solving time has been built into the timeline.

![Gantt Chart](image)

**Figure 20**: Gantt chart for the project. The solid bars the tasks that we have accomplished or intend to complete by stated date.

**Deliverables**

The project deliverables are as follows:

1. Produce a CAD model of the current impeller and volute of the pump and isolate the fluid domain bounded inside.

2. Simulate the fluid flow inside the pump and produce a plot of the pump characteristic and hydraulic efficiency using ANSYS workbench (CFX) Software.

3. Design testing station by using instruments to reproduce the characteristics of the pump, benchmark and compare it to the
results obtained from the simulation.

4. Setup safety monitoring procedure for the pump pressure and flow rate.

5. Use the numerical technique authored by Dr. Abdella Ait Moussa and graduate assistant Lin Yunhao, to optimize the geometry of the impeller and volute for the maximum hydraulic efficiency.

6. 3D Print the optimized impeller geometries and run experiment to confirm the improvement of the pump efficiency.

**Budget**

The requested funds are primarily due to the cost of the pump testing station that will be used to validate the manufacturer efficiency ratings, and the simulated results. The pump testing station was designed and constructed to be used by students in the Engineering and Physics department at the University of Central Oklahoma. Cost reduction methods included use of recycled electronic and material components, and promotional items from various manufacturers and distributors.

![Table 1: Generalized Budget Breakdown.](image)

- **Sensors / Controlled Valve**: 64%
- **Pipe Fittings**: 25%
- **Arduino Hardware**: 11%

**Total: $1000**

**Communication and Coordination with Sponsor**

Each member of our group has scheduled a meeting with Dr. Abdellah Ait Moussa every week. Each member is expected to attend the meeting. Group meetings are scheduled on an ‘as needed’ basis.
Team Qualifications

Hamzah Al Rashdan has four years of study in an ABET accredited engineering program at a respected university. Here he has learned the problem solving and critical thinking skills to contribute extensively to this project. The most beneficial areas of study for this project are Thermo System Design, Fluid mechanics and programming as well as knowledge of CAD, FEA and CFX software.

Ira Topp has over four years of study in an ABET accredited engineering program at a respected university. He has been working with vehicle lighting and electronics for over 15 years, and has been an electronics hobbyist for over nearly 25 years. Having spent 8 years in the US Army, he has acquired the ability to work extremely well under pressure, along with a minimal budget.

Conclusion

In conclusion, the design, research, and process that were proposed in this paper were relatively new and innovative. This process will hopefully mark a new advancement in centrifugal pump efficiencies, and bring us closer to the elusive ideal 100% efficiency. The process proposed has been tested and validated in other fields of study, and should yield the ultimate characteristics in impeller and volute design. Although we were unable to fully test the resulting 3D impeller designs, we are optimistic that they will yield a significant increase in the efficiency of the pump. We are striving to be able to produce an industry-wide impeller design that will globally reduce the pump design requirements for everyday consumers, lowering the costs of pump worldwide.
References


Appendix A: Résumés of Team Members

The following pages present one-page résumés of the team members for this project.
Hamzah Al Rashdan
8202 N. Macarthur Blvd
Oklahoma City, Oklahoma 73132
(405)-664-6432, halrashdan@uco.com

**OBJECTIVE**
Engineering position with challenges, responsibilities, leadership, and opportunity for advancement.

**EDUCATION**
University of Central Oklahoma, Edmond, Oklahoma
Bachelor of Mechanical Engineering, Expected Graduation May 2015

**WORK EXPERIENCE**
Research Assistant, UCO, Edmond, OK (August 2014 – Current)
Teaching Assistant, UCO, Edmond, OK (August 2012 – December 2012)
Phillips 66 Gas station manager (January 2012- Current)

**RELEVANT COURSE WORK**
- Engineering Computing
- Dynamics
- Strength of Materials
- Electrical Science
- Thermodynamics
- Finite Element Analysis
- Engineering Statistics
- Computational Methods in Engineering
- Fluid Mechanics
- Heat Transfer
- Material Science
- Signals and Systems
- Mechatronics
- Thermal Systems Design
- Mechanical Engineering Design

**RELEVANT SKILLS**
- SolidWorks
- Matlab
- C#
- Multisim
- Excel Programming
- Ansys (CFD,CFX Mechanical (PDL))
- LabView
- Quick Learner
- Computer Skills
- Well Rounded
- Good People Skills
- Mechanically Inclined
- Mathematica
- Customer Service
- Aerodynamics

**Additional Experience**
Senior Design Project: Centrifugal Pump Efficiency Improvement
Undergraduate Research: Drag Coefficient Optimization for SUV's
Undergraduate Research: Heart Assist Devices Optimization

**HONORS**
Member: American Society of mechanical engineers (ASME)
Member: IEEE
Ira Topp  
5401-D Canyon Dr  
Oklahoma City, Oklahoma 73118  
210-632-1005  
IraTopp@GMail.Com  

EDUCATION  
University of Central Oklahoma, Edmond, Oklahoma  
Mechanical Engineering, Expected Graduation: May 2015  

WORK EXPERIENCE  
Maintenance Technician, NPMA; Oklahoma City, Oklahoma – (Summer 2013)  
Tools and Hardware Associate, Home Depot 3908; Oklahoma City, Oklahoma – (Summer 2012)  
Combat Medic, United States Army (Active Duty); Ft Riley, Kansas – (Spring 2006 - Spring 2009)  
Abrams Tank Mechanic, United States Army (Active Duty); Camp Casey, South Korea – (Winter 2002 - Spring 2006)  

RELEVANT COURSE WORK  
Digital Logic and Design  
Dynamics  
Electrical Science  
Engineering Computing  
Engineering Statistics  
Fluid Mechanics  
Heat Transfer  
Material Science  
Mechanical Engineering Design  
Mechatronics  
Signals and Systems  
Strength of Materials  
Thermal Systems Design  
Thermodynamics  
Computational Methods in Engineering  

RELEVANT SKILLS  
ANSYS Workbench  
Arduino Microcontrollers  
CATIA v5  
Circuit Design  
Electronically Inclined  
Excel Programming  
Good People Skills  
Machine Work  
Mathematica  
Matlab  
Mechanically Inclined  
Microsoft Office Suite  
Multisim  
NI Labview  
Quick Learner  
Solidworks  
Supervisory  
Video Editing  

Additional Experience  
Senior Design Project: Centrifugal Pump Efficiency Improvement  
Personal experience with Provisional Patents  

Honors and Awards  
ASME member  
Combat Medic Badge / Combat Action Badge / Mechanic Badge / Driver Badge  
Army Commendation Medal / Army Achievement Medal x3 / Army Good Conduct Medal  
Afghanistan Campaign Medal / Korean Defense Service Medal