VLH Turbine Project

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Conceptual Design Document

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Conceptual Design Document (CDD)

Design Methodology and Application (ENME 538 / ENMF 512)
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1.0 Project Information

1.1 Project Title and Acronym

Optimization of a Very Low Head Turbine (VLHT) is a project that involves optimizing key operational aspects of a very low head water turbine.

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1.4 Useful Definitions and Acronyms

VLHT – Very Low Head Turbine
CFD – Computational Fluid Dynamics
EFD – Experimental Fluid Dynamics
CAD – Computer Aided Design
University – University of Calgary

2.0 Conceptual Design Summary

With public environmental awareness increasing daily, renewable energy sources such as hydro-power are becoming more important. The Very Low Head (VLH) Turbine is a water turbine that is designed to be as low impact as possible while still outputting a useful amount of energy. In order for it to be installed in North America, several key performance questions have to be answered.

This document outlines how our team plans to go about answering two of those key performance questions, which in this document are referred to as our team objectives. The two objectives are:

1) Find the effect of approach geometry on turbine power
2) Find the effect of turbine installation angle on turbine power

The document describes the five conceptual testing methods which our team came up with, as well as the conceptual requirements and feasibility criteria on which each concept would be scored. After comparing the five conceptual testing methods, two stood out as having a higher score than the others. The two highest scoring concepts were:

- Running tests on a 300mm scale model using a small flume
- Performing analysis using CFD

The system architecture of the scale model tests using the small flume is outlined, and the feasibility of the two concepts listed above is examined in detail. Tests that could be run to validate certain assumptions made when scoring these two concepts are described, and the resources and costs associated with all concepts are estimated. The cost of performing tests on a 300mm scale model using the small flume is estimated to be $3700, while the cost of using CFD is free at the University.

3.0 Background

The Very Low Head Turbine is a variable speed water turbine designed for heads ranging from 1.4 to 3.2 meters and low flow conditions from 10 to 30 cubic meters per second. The turbine is installed on a lifting cable system. This allows for variable angles of operation as well as complete removal from the sluice passageway for maintenance, or during high flow conditions.

While the VLH Turbine has been tested in France, Coastal Hydropower Corporation is investigating installing these turbines in several locations throughout North America. These turbines are ideally installed where infrastructure such as weirs, canals or dams already exist.

The VLH Turbine is considered an economical source for green power generation. Because it is installed where current infrastructure exists, it reduces environmental impact and resources required that are common with other power generation systems. As well, the flow conditions and low rotational speed of the turbine make it fish friendly.

4.0 Functional Objectives and Requirements

4.1 Functional Objectives

This project has two top-level functional objectives, each which three requirements for those objectives to be met. Both objectives will evaluate the power generated by the turbine for a range of situations.

Table 1: Top-Level Functional Objectives

Objective	Description	Verification Method
FUNC.1:	Effect of Approach Geometry on Turbine Power	Analysis completed on Flat, Step, Carsland and Lock 25 approach profiles
FUNC.2:	Effect of Installation Angle on Turbine Power	Analysis completed at installation angles of 90°, 70°, 55°, 40°, and 30°

Table 2: Top-Level Requirements

Requirement	Description
SPC.1:	Results are easily obtained
SPC.2:	Results obtained are accurate
SPC.3:	Results obtained are useful to sponsor

5.0 Concept Combination Tables

Five concepts have been generated to address the two top-level functional objectives that were listed in Table 2. Each concept is a method that would be used to meet each objective. A detailed description of these concepts can be found in section 6.0.

Table 3: Concept Combination Table

Top-Level Concept	Func.1	Func.2
1) Large Flume Tests with existing model	- Measuring power with a 900mm VLH turbine model	- Measuring power with a 900mm VLH turbine model
2) Small Flume Tests scaled model	- Measuring power with a 300mm scaled model	- Measuring power with a 300mm scaled model at various angles
3) Small Flume Tests with Turbine Substitute	- Conducting dye visualization tests - Conducting pressure profile tests	- Measuring pressure drop over the turbine substitute
4) Potential Flow Analysis	- Constructing each approach geometry and conducting pressure profile analysis	- Analyzing the pressure profile upstream and downstream at various angles
5) CFD	- Conducting pressure profile analysis with a moving mesh representing the turbine - Conducting pressure profile analysis with a stationary pressure drop representing the turbine	- Analyzing the pressure profile with a moving mesh representing the turbine at various angles - Analyzing the pressure profile with a stationary pressure drop representing the turbine at various angles

6.0 Overview of Conceptual Solution Alternatives

This section describes each of the concepts listed in Table 3, along with their advantages and disadvantages. In addition, each concept from Table 3 was scored on a scale from 0 to 3 representing how strongly each of the top-level requirements from Table 2 is met. The scores were added and the total scores for each concept are shown below in Table 4. Scores were given for each objective as it is very possible that one concept could be used to satisfy Objective 1 while another concept is used for Objective 2. A more detailed summary of how these numbers were calculated can be found in Appendix A.

Table 4: Concept Total Scores for Objective 1 and 2

Concept Number	Objective 1 Score	Objective 2 Score
(1)	11 (F)	11 (F)
(2)	12	12
(3)	12	8
(4)	12	4 (F)
(5)	13	12

Note that the (F) beside some of the values in Table 4 signify that this concept scored a zero for one of the criteria, and therefore would most likely not be used no matter what the total score is.

6.1 Large Flume Tests

6.1.1 Description

This method would involve performing tests on a 900mm model of the VLHT which had previously been tested at the hydraulic machines laboratory (LAMH) at Laval University. For upstream geometry tests the profiles would be built and installed in the flume and the power generated by the turbine would be recorded using a dynamometer. For the installation angle tests the angle of the turbine would be varied and the power would be recorded.

Refer to Figures 1 and 2 in Section 7.0 for diagram of possible experimental setup.

6.1.2 Advantages

Performing tests on the 900mm model using the large flume, provided it could be modified to accommodate the test parameters, would meet both objectives' requirements very well. You could vary the flow rate and several other parameters to get the desired power curves. The 900mm model is also within the minimum size for a scale-model of a turbine to meet Model Standards. Data obtained from these tests would be of most value and accuracy.

6.1.3 Disadvantages

Unfortunately, the University does not currently have a laboratory equipped to test turbo-machinery. The large flume in the Civil Engineering laboratory does not supply high enough flow rates to perform tests with, and the flume and its foundation were not structurally designed for large loadings. The time and budget required to remediate these issues seems to be not feasible within the scope of the fourth year design project, and therefore these tests do not seem possible at this point in time.

6.2 Small Flume Tests

6.2.1 Description

This method would involve the design, construction and assembly of a 300mm (approximately one foot) model of the VLHT for the same tests that are described in Section 6.1.1, but using the small flume in the Civil Engineering laboratory at the University.

Refer to Figures 1 and 2 in Section 7.0 for a diagram of possible experimental setup.

6.2.2 Advantages

Much like the tests on the 900mm model, tests run on the 300mm model would yield the power generated given specific conditions. Unlike the large flume tests, where many modifications would have to be made in order to run the tests properly, the small flume in the Civil Engineering laboratory is the proper dimensions and could provide adequate flow for the tests (see Appendix C for details).

6.2.3 Disadvantages

While constructing and assembling the 300mm model of the VLHT would be considerably cheaper than modifying the large flume, the cost is still significant (estimated at $3700, see Appendix B for details). In addition to this, the group does not currently posses drawings of the VLHT, which would be required for accurate design. As well, a 300mm size turbine is not within the minimum size to meet modeling standards and the results obtained from these test would require more investigation. Results would have to be used at the client's discretion.

6.3 Small Flume Tests with Turbine Substitute

6.3.1 Description

This method would involve using the same apparatus as the one outlined in Section 6.2 but simulating the 300mm turbine with a potential drop. This could be done many ways, and has yet to be investigated closely. The pressure profile of the flow just upstream and downstream of the turbine would then be measured for various approach geometries and "turbine" installation angles. The pressure values and pressure profile uniformity would be used to infer the relative power outputs of the various conditions. Qualitative dye mixing tests could also be run to gain better understanding of the flow profiles.

Refer to Figures 1 and 2 in Section 7.0 for a general idea of what the experimental setup would look like. The turbine in Figure 2 could be replaced by a pressure drop such as a fine steel mesh.

6.3.2 Advantages

The small flume tests with a turbine substitute allow us to run experimental tests on a reasonable budget. Although exact power measurements will not be obtained, the results could still be interpreted and found to be useful.

6.3.3 Disadvantages

The obvious disadvantage of using a turbine substitute is it would not be possible to get actual power measurements at various flow rates, and would therefore be impossible to get a turbine efficiency curve. In addition to this, finding a suitable turbine substitute would take serious investigation, and taking downstream measurements would be difficult and the results would be questionable.

6.4 Potential Flow Analysis

6.4.1 Description

This method would involve creating a 2D representation of the water flow approaching the turbine, and possibly downstream of the turbine as well, using a combination of basic potential flows (sources, sinks, vortices, etc). From this representation you could find the dynamic pressure at various points in the flow for different approach geometries and turbine angles.

6.4.2 Advantages

Using potential flows in this way can give a very good basic understanding of what is going as the flow progresses over a given geometry. Once you have it set up, it is very easy to get information for the behavior of the flow over a large area. Potential flow modeling would be suitable for validation of results and to increase the understanding of the basic flow profile.

6.4.3 Disadvantages

Setting up the potential flow model would require many assumptions, and unfortunately this would have a negative effect the accuracy of the results. In addition to this, potential flows don't handle turbulence very well (no flow can cross over a stream-line) so the results would only be applicable if the flow was laminar. In addition to this, because of its 2D nature, a potential flow model could not represent the swirl induced in the flow by a turbine. In summary, a potential flow model could be useful for enhancing the understanding of the problem, but would probably not yield useful results as a stand-alone method.

6.5 Computational Fluid Dynamics

6.5.1 Description

This method would involve creating a 3D mesh model of the turbine system using a CFD package such as Fluent, CFX, or FloWorks. The turbine could either be represented by a constant pressure drop, or a moving mesh could be used to more accurately simulate the turbine behavior. A computer would be used to solve the system for various approach geometries, turbine installation angles, and flow conditions.

6.5.2 Advantages

If set up properly, CFD modeling could produce useful information. Moreover, the model could be a very accurate representation of how the actual system works, and it would be possible to get actual power measurements from the simulation.

6.5.3 Disadvantages

At the moment the licensing for the CFX and Fluent software at the University has not yet been updated. FloWorks should be available, but as a simpler software package with limited capabilities. Even if CFX and Fluent became available for our usage, setting up CFD meshes and running the simulations can be time consuming. Time would also be required to learn advanced CFD methods.

7.0 System Architecture

Proposed system architecture for Concepts 1 through 3 is shown below.

Figure 1 is a system diagram of the flume, pumps, and water basins. The water would be pumped at the desired flow rate by either a single pump or a series of pumps. It would then travel through a pipe to a large inlet tank, where the flow would be removed of all of its turbulence. It would enter the flume as a uniform, laminar flow, and then exit into a large reservoir, from which it would be pumped back into the system.

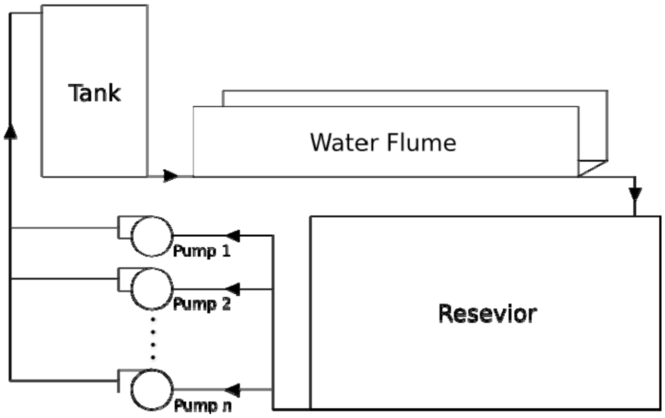

Figure 1: Flume system flow diagram

Figure 2 shows a closer look at the configuration of the apparatus in the flume. The water would inlet from the left and flow over the approach geometry before passing through the turbine and exiting the flume on the right. As you can see in the diagram, there would be some mechanism for changing the angle of the turbine so multiple installation angles could be tested. For Concept 3, the turbine would be replaced by a variable potential drop.

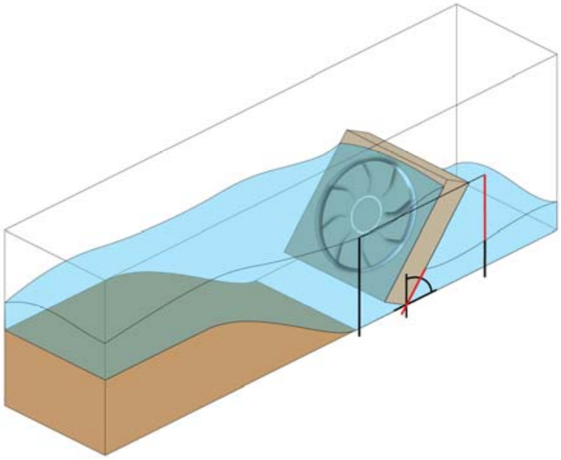

Figure 2: Flume apparatus configuration

8.0 Feasibility

Since it is very possible for us to use more than one of the concepts listed in Table 3, the feasibility of multiple concepts was investigated. These feasibilities were weighed against the strength of each concept as detailed in (Section 6.0) to help make a decision on the final concepts to pursue. The feasibility of conducting tests on the small flume as well as using CFD are presented below as they scored the highest score in our decision making process (See Appendix A). Note that the small flume tests with the 300mm scale model and with the turbine substitute are contained under small flume tests.

The feasibility of the concepts is examined under three main criteria:

- Total monetary cost of concept
- Time to implement concept
- Resources required for concept

The organization of the "Small Flume Tests" section differs from that of the CFD section as we looked at the small flume test feasibility on a sub-concept level.

8.1 Small Flume Tests

8.1.1 Effect of Approach Geometry on Turbine Flow Conditions

All three testing methods on the small flume will require the fabrication of the three different approach flow profiles, which are described in the "General Model Configuration Profile" drawing distributed in the first sponsor meeting. The profiles would most likely be constructed with a wooden frame and use a water-proof fabric to form the profile. The cost of fabrication of all three profiles would be approximately $100 and would take no longer than 16 hours.

8.1.1.1 Measuring Power with a 300mm Scale Model

Fabrication of the 300mm model would require a budget of approximately $3700 (detailed in Appendix B), which would need to be provided by the sponsor. The design, fabrication and assembly of the 300mm model would take approximately two months from the time detailed drawings are obtained. These detailed drawings of the turbine, which are necessary to complete the 300mm model drawings, have not yet been obtained. In addition to this, a dynamometer would be required to measure the power output of the turbine, which would either have to be purchased or borrowed from the Civil Engineering Lab. The validity of conducting power tests on such a small scale model would have to be investigated via similitude relationships. After all of the aforementioned concerns are addressed, we believe testing would take around 2 weeks.

8.1.1.2 Conducting Dye Visualization Tests with a Turbine Substitute

Choice of an appropriate turbine substitute would require some investigation and testing. The cost of an appropriate substitute is currently unknown. The cost of dye would be under $50, and a high speed camera to capture the flow profile could be borrowed for little to no cost. Once an appropriate turbine substitute is found, testing would take no longer than 16 hours.

8.1.1.3 Conducting Pressure Profile Tests with a Turbine Substitute

As mentioned in Section 8.1.1.2, choice of an appropriate turbine substitute would require some work. To take the pressure in the flow, Pitot tubes (or an alternative pressure sensor) and associated instrumentation would have to be purchased or borrowed. The cost of purchasing such equipment is roughly estimated to be around $750. The time spent testing the pressure profile would depend on the number of points that it is deemed will properly describe the pressure profile. This precision could be developed from the dye visualization tests described in Section 8.1.1.2. Testing should take about 2 weeks.

8.1.2 Effect of Installation Angle on Turbine Flow Conditions

8.1.2.1 Measuring Power with a 300mm Scale Model

The fabrication process and other concerns associated with the 300mm model are described in Section 8.1.1.1. Assuming these are all addressed, a mechanism to test the turbine at multiple angles would have to be designed and implemented before testing could commence. After this is done, testing should take about 2 weeks.

8.2 Computational Fluid Dynamics

8.2.1 Resources

Resources for Computational Fluid Dynamics Analysis are limited. The only two commercial software packages with fluid analysis capabilities available to students are ANSYS and SolidWorks. Both of these packages are currently installed in all laboratory computers in the Mechanical Engineering Building.

8.2.1.1 ANSYS Fluid Dynamics (CFX and FLUENT)

The licenses for the ANSYS fluid analysis tools (CFX and FLUENT) are currently unavailable. The Schulich School of Engineering IT group (SSE IT) is currently contacting the ANSYS license administrator in order to resolve this issue. For modeling the fluid flow, it is probable that ANSYS Fluid Dynamics will have the capabilities needed to give insight in answering the questions regarding the VLH turbine.

8.2.1.2 SolidWorks Flow Simulation (FloWorks)

The SolidWorks software has a CFD module “add-in” which allows fluid flow simulation and analysis. There is no missing license for this software. However, SolidWorks Flow Simulation may not have the same level of capabilities as ANSYS Fluid Dynamics. If ANSYS Fluid Dynamics licenses cannot be obtained, SolidWorks Flow Simulation is the best feasible option.

8.2.2 Time

Time will be needed to learn how to use the CFD Analysis tool before any modeling for the VLH Turbine project can be made. The amount of time needed depends on the complexity of the software being used. Software such as ANSYS Fluid Dynamics may require longer than SolidWorks, which requires only a few weeks. Help from Dr. David Wood’s graduate student may reduce the time needed to learn ANSYS Fluid Dynamics, and likewise with Dr. Xue for the Flow Simulation in SolidWorks.

Additional time for ANSYS Fluid Dynamics will be needed to acquire necessary licensing and installation before any learning can begin. The amount of additional time is unknown, as the SSE IT group is still waiting for a response from ANSYS regarding the licensing. The time feasibility for SolidWorks Flow Simulation is better than for ANSYS Fluid Dynamics.

8.2.3 Cost

Purchasing CFD software is a feasible option, however this will only be done if licensing for ANSYS Fluid Dynamics is unavailable, and if SolidWorks is incapable of modeling any kind of fluid flow useful for the VLH Turbine project. The cost for CFD software will range in the hundreds of dollars, while using ANSYS Fluid Dynamics and SolidWorks will have no cost.

8.2.4 Summary

SolidWorks Flow Simulation is the most feasible option at this point in time. It is readily available to use, easier to learn, and has no cost attached. ANSYS Fluid Dynamics requires more time to learn and use, and is also missing necessary licensing.

9.0 Testing and Verification

Below is an outline of some tests that could be performed prior to the actual gathering of data to verify that our concepts will give good results. As the two strongest concepts, the small flume tests and CFD will be analyzed.

In order to verify the results of the actual experiments or analysis, the use of multiple concepts on the same objective is recommended. An example of this would be using potential flows to verify the pressure field obtained using pitot tubes in the small flume tests.

9.1 Small Flume Tests

Simple flume characteristics such as the flow rate could be tested by setting it to a given flow rate and recording the mass of water that flows into a bucket in a period of time. If the turbine substitute tests are pursued, rigorous testing will have to be performed on the potential drop across the substitute. If possible, the swirling behavior of the substitute should be examined as well. This could be done by placing the substitute in the flume and dying a short burst of water to see if it swirls as it passes through the turbine substitute.

9.2 CFD

The methodology of obtaining results from CFD could be tested by attempting to model a very simple system using CFD to which an accurate analytical solution is known. A good example of this would be getting the pressure profile of laminar flow through a pipe.

10.0 Required Engineering Expertise

Table 5: Required Expertise

Technical Area	Team Member Responsible	Level of Expertise
CFD	Colin, Jamie, Matias	Ability to use of CFX, Fluent or FloWorks
EFD	Brenda, Alex, Matias, John	Ability to use laws of similitude to design experiments and interpret results
CAD	Colin, John	Ability to design scale model of VLHT using Solidworks and produce drawings for a machine shop
Potential Flow Analysis	Alex, Matias	Ability to generate simple geometries and analyze pressure profiles
Project Management	Brenda, Colin	Ability to use management tools such as Gantt charts to keep the project on schedule
Communication	All	Ability to use written and verbal communication to effectively translate knowledge internally and externally
Construction	John	Ability to construct geometry profiles, flume modifications, and turbine components

11.0 Resources and References

11.1 Facilities

The facilities required for each concept are summarized in Table 6 below. Refer to Section 5.0 for a description of which concept number corresponds to which concept.

Table 6: Facilities Required for each Concept

Concept Number	Facilities Required
(1)	- Structurally sound large flume - Hardware required for testing such as approach geometries - Dynamometer - Pump capable of delivering up to one 1 m^3/s flow rate - 900mm model
(2)	- Small flume - Hardware required for testing such as approach geometries - Drawings of the VLHT - Dynamometer - 300mm model
(3)	- Small flume - Hardware required for testing such as approach geometries - Suitable turbine substitute - Pressure measuring device such as a pitot tube
(4)	- No facilities required
(5)	- Usable CFD software such as Fluent, CFX, or FloWorks

11.2 Additional Advisors

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11.3 Funds

The estimated costs associated with each concept are listed in Table 7 below. See Appendix B for a description of where the estimated costs come from.

Table 7: Estimated Cost of each Concept

Concept Number	Estimated Cost
(1)	$42,000
(2)	$3700 (not including dynamometer)
(3)	$750
(4)	$0
(5)	$0

The project course supplies $300-$500 per project. The additional funds would be made available by the project sponsors – Projects Canada and Coastal Hydropower.

Appendix A – Concept Evaluation

Each of the concepts were given a mark out of three for how well it met the three requirements (as listed in Table 2), as well as how feasible it was (as described in Section 8.0). The values were then summed to come up with the final concept strength. Tables 8 and 9 below, show how well each concept scored for all six categories for both objectives. Note that R01 to R03 are the requirements and F01 to F03 are the feasibility criteria.

Table 8: Concept Strength for Objective 1

Concept Number	R01	R02	R03	F01	F02	F03	Total
(1)	3	3	3	0	2	0	11
(2)	3	3	2	1	2	1	12
(3)	3	3	2	2	1	1	12
(4)	3	3	1	3	1	1	12
(5)	3	2	2	3	2	1	13

Table 9: Concept Strength for Objective 2

Concept Number	R01	R02	R03	F01	F02	F03	Total
(1)	3	3	3	0	2	0	11
(2)	3	3	2	1	2	1	12
(3)	2	1	1	2	1	1	8
(4)	1	0	0	3	0	0	4
(5)	2	2	2	3	2	1	12

Appendix B – Cost Estimates

Table 10: Cost summary for Concept 1

Item	Estimated Cost
Apparatus hardware – new walls, supports, waterproofing, etc.	$500
Plumbing – 12” (or greater) diameter pvc pipe	$500
Pump – max flow of around 1 m^3/s	$20,000
Dynamometer	$20,000
Testing Standards – IEC 60193 (describes procedures for conducting tests on hydro turbines)	$300
Total	$41,300

Table 11: Cost summary for Concept 2 (excluding dynamometer)

Item	Estimated Cost
Materials for 300mm Model	$500
Machining Cost (at $35/hour)	$1500
Other mechanical components (bearings, etc)	$1000
Wood for frame and approach geometries	$200
Other Supplies (silicone, water-proof paint, dye, rotating mechanism)	$200
Total	$3700

The cost for Concept 3 was generated from the wood and other supplies cost plus an additional $450 for the turbine substitute.

Appendix C – Similitude Relationships

It seems like the model at Laval University took into account Reynold's number and Froude's number in terms of similitude. In hydro mechanical experiments, one must always be aware of Reynold's number, Froude's number, and Weber's number.

Reynold Number Similitude

There were two main dimensionless numbers that were used to scale down the model scale Reynold's number:

$$Q_{11} = \frac{Q}{D^2\sqrt{H}}$$
$$N_{11} = \frac{ND}{\sqrt{H}}$$

The targeted nominal design points were $Q_{11} = 0.7\frac{m^3}{s}\ and\ N_{11} = 105rpm$. These numbers seem to be an average for the range of design parameters for the actual VLH turbines. Therefore, we should continue with this reasoning.

In our small flume in the civil lab, the width of the channel is about 0.3 m and the height is about 0.6 m. If we assume that the runner diameter will be just under 0.3 m, we should be able to get about 0.5 m of head. So from the targeted nominal design points,

$$N = \frac{N_{11}\sqrt{H}}{D} = \frac{105\sqrt{0.5}}{0.3} = 247.5\ rpm$$
$$Q = \frac{Q_{11}D^2}{\sqrt{H}} = 0.7 * \frac{0.3^2}{\sqrt{0.5}} = 0.045\frac{m^3}{s} = 44.5\frac{L}{s}$$

Considering we have at least 42L/s of capacity in our civil lab, we should be OK in terms of water flow rate.

Froude Number Similitude

$$Froude's\ Number = \frac{V}{\sqrt{gD}}$$

Where:
v = mean axial velocity
G = gravity
D = runner diameter

Since the head is proportional to the velocity squared, if the head scale factor follows the diameter scale factor, then Froude similitude will be respected. In other words,

$$\frac{H_p}{H_m} \leq \frac{D_p}{D_m}$$

$$\frac{H_p}{D_p} \leq \frac{H_m}{D_m}$$

Using average values from the ranges given in papers for the prototype,

$$\frac{2.3m}{4.575} \leq \frac{H_m}{D_m}$$

$$0.5 \leq \frac{H_m}{D_m}$$

For Laval, $\frac{H_m}{D_m} = 1.5$. Therefore Froude similitude was satisfied. In our case, assuming H=0.6 and D=0.3, we get $\frac{H_m}{D_m} = 2$. It should be noted that the Laval model had a cylindrical outlet pipe to reach 1 m head. This was needed because proportions between runner diameter and head weren't respected. We may have to do something similar to obtain our correct proportion.

Weber Number Similitude

Weber's number was considered, but it seems that this shouldn't play a major factor in our open surface type flows that we are dealing with.

The ASME provides a guide called "The Guide to Hydropower Mechanical Design" which outlines the most useful relationships when it comes to similitude:

1) $\frac{Q_1}{N_1 D_1^3} = \frac{Q_2}{N_2 D_2^3}$

2) $\frac{P_1}{N_1^3 D_1^5 \rho_1} = \frac{P_2}{N_2^3 D_2^5 \rho_2}$

3) $\frac{D_1 N_1}{\sqrt{g_1 H_1}} = \frac{D_2 N_2}{\sqrt{g_2 H_2}}$

4) $\frac{Q_1}{D_1^2 \sqrt{g_1 H_1}} = \frac{Q_2}{D_2^2 \sqrt{g_2 H_2}}$

$$5)\ \frac{P_1}{(g_1 H_1)^{1.5} D_1^2 \rho_1} = \frac{P_2}{(g_2 H_2)^{1.5} D_2^2 \rho_2}$$

Equations 3 and 4 are derived from Reynold's dimensionless number, and they are used in Laval's scaling calculations. We should continue to verify that our experiments obey similitude laws, and one of the steps would be to confirm that we are obeying the rest of the equations that ASME recommends.