Tidal Energy Demonstration Channel

Report for TECH 797 Ocean Projects

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Abstract

The tidal energy demonstration channel was accomplished by designing and building a recirculating tank capable of producing sufficiently fast flow in a clear viewing section to rotate a model tidal turbine and power a small generator. A volt meter was set up to read how many volts the generators were producing. The characteristics of two types of hydrokinetic turbines, one with an in-stream horizontal axis and the other with a vertical axis can be demonstrated. The display can demonstrate how the output power increases with an increase in flow velocity, and it can also demonstrate the effect of placing two turbines in an array at variable distances.

The desired fluid velocity in the test section was 2 feet per second achieved using a 380 gallon per minute pump. The system head loss was calculated to be 33 feet. The turbines were made from ABS plastic created in a rapid prototyping machine. The in-stream axis turbines were designed with a tip speed ratio of 3 and the vertical axis turbine was designed with a tip-speed ratio of 2.5.

Contents

Abstract ______ 1
1. Introduction ______ 3
 1.2 Objectives ______ 3
 1.3 How It Works ______ 3
2. Design Calculations ______ .5
 2.1 Tidal Energy Conversion ______ .5
 2.2 Viewing Section Velocity and Flow Rate ______ 5
 2.3 Stilling Tank ______ ..8
 2.4 Contraction ______ 8
 2.5 Diffuser ______ 10
 2.6 Head Loss and Pump ______ ...10
 2.7 Model Turbines ______ 12
3. Construction ______ 20
 3.1 Viewing Section ______ 20
 3.2 Stilling Tank ______ 20
 3.3 Contraction ______ 21
 3.4 Diffuser ______ 21
 3.5 Turbines ______ .22
 3.6 Frame ______ ...22
4. Continuing and Future Work ______ ...23
References ______ .24
Apendix ______ .25

1. Introduction

Over the past decade, there has been a significant increase in environmental awareness. Time and energy was put in to educate the general public about ways they can reduce their carbon footprint. Carpool lanes were designated, more products made recyclable, and new alternative energy technologies received more attention. Solutions for moving away from fossil fuels as the sole source of energy include solar, wind, and hydropower.

Hydropower has been used for centuries; the simplest example would be a water wheel. Compartments on the perimeter of the wheel catch the water as it flowed by and spun the whole device due to the weight displacement. As the wheel rotated it created axial rotation which was used to do work. The concept of creating axial rotation to do work is the backbone of hydropower. Tidal energy is a form of hydropower that converts the kinetic energy in a tidal flow to electricity or other useful forms of energy. Tides are predicted over centuries, making tidal energy conversion into the electrical grid more appealing than other sources such, such as wind or solar energy. Tidal energy conversion is a sustainable, environmentally benevolent way to generate electricity.

Tidal turbines can look similar to underwater windmills. As the tidal current flows through the devices, the blades spin and the axial rotation drives a generator. No matter which way the water is flowing, omni-directional turbines will spin and do not have to be re-orientated for ebbing and flooding tides. Once the current is above a certain cut-in speed, the turbine will spin and produce electricity. Single or an array of turbines are constructed and secured to the seabed in areas of high tidal current velocity areas.

The rotating turbines tend to operate at low speeds, resulting in lower tip speeds, and will not pose a threat to marine wildlife [1]. An in-stream axis turbine installed of the coast in Northern Ireland was designed to only rotate 10 to 15 times per minute [2].

1.2 Objectives

The purpose of our project was to demonstrate how tidal energy conversion works to the general public. This was accomplished by designing and building a recirculating tank capable of producing sufficiently fast flow in a clear viewing section to rotate a model tidal turbine and power a small generator. A volt meter was set up to read how many volts the generators were producing. The characteristics of two types of hydrokinetic turbines, one with an in-stream horizontal axis and the other with a vertical axis can be demonstrated. The display can demonstrate how the output power increases with an increase in flow velocity, and it can also demonstrate the effect of placing two turbines in an array at variable distances.

Part of the design criteria was to make the entire demonstration channel mobile so it can be shown at the Seacoast Science Center and the New Hampshire Children's Museum. With such locations it was important to make the display safe and easy to operate. The material used needed to be high quality to give the final result a museum worthy look.

1.3 How It Works

The system starts with the reservoir. The reservoir was the wooden box where the water was held after flowing through the channel and where the pump draws the water from.
The water was discharged from the pump and enters a PVC pipe. Along this discharge pipe was a y-connector that splits off and siphons some of the flow back to the reservoir. The flow in the

secondary pipe leading back to the reservoir was regulated by a globe valve. This enables the user to control the flow entering the system. Following the flow, the water then entered the stilling tank. The stilling tank was where the flow was reduced and straightened. There was a perforated plate, turning vanes, and a honeycomb to disrupt then straighten the flow. The next component was the contraction. A contraction increases the mean velocity of the flow while always decreasing velocity variations within the flow. Coming out of the contraction the flow travels through a viewing section. The viewing section was a straight rectangular acrylic piece where the turbine display was placed. The water then spilled into a diffuser where the velocity was reduced. At the bottom of the diffuser was the reservoir

2. Design Calculations

2.1 Tidal Energy Conversion

The theoretical kinetic power available in a moving flow was

– (1)

where ρ represents the density of the medium, A was the cross sectional area, and V was the velocity of the medium. A quick example of how tides can produce more power than wind can be done by evaluating Equation 1. Using a turbine with a cross sectional area of 10 meters, a fluid velocity of 3.09 m/s, and varying the fluid density, Equation 1 showed the theoretical power for sea water was $1.51(10^5)$ Watts compared to the 177.63 Watts produced from air.
The power of tidal turbines, or more generally, marine hydrokinetic turbines, was calculated as,

– (2)

where η was the overall conversion efficiency that includes the rotor efficiency and power-take-off efficiency.
The basic relation to calculate flow rate,

. (3)

For convenience, Table 1 shows the common nomenclature used in the equations throughout the report.

Table 1: Common variable nomenclature used in report explained

Variable	Description
V	Velocity
A	Cross Sectional Area
ρ	Density
L	Total Length of Contraction
H_1	Height Before Contraction
H_2	Height After Contraction
G	Gravity
N	Maximum Number of Components

2.2 Viewing Section Velocity and Flow Rate

As shown in the previous section, the power of tidal (hydrokinetic) turbines varies with the cube of the water velocity. However, similar as for wind and wind turbines, the water has to reach a certain velocity, known as “cut-in speed”, before tidal turbines can produce power. Tidal turbines have to produce enough torque to overcome the stall torque of the generators. Miniature generators have small stall torques but high rotation per minute requirements. For a model turbine to spin at a high rpm there needed to be a high flow velocity traveling through the viewing section. Different cross section areas for the viewing section were compared to a range of average flow velocities to calculate pump flow rate requirements. The range used for the cross section area started with a 10 x 6 inch channel and increase by one inch increments to a maximum of a 12 x 12 inch area. Using the areas and velocities, a table was calculated to compare the relative flow rates. To calculate gallons per minute with respect to velocity and area, the equation

$$\frac{}{} \qquad , \qquad (4)$$

was used. The constant 449.47 was to convert cubic feet per second to gallons per minute. Table 2 shows the results from Equation 4

Table 2: GPM for Different Channel Sizes and Different Average Velocities

	Area of Channel [in^2]									
	10x6	8x8	10x7	9x8	10x8	10x9	10x10	10x11	12x10	12x12
Average Velocity [ft/s]	60	64	70	72	80	90	100	110	120	144
0.5	94	100	109	112	125	140	156	172	187	225
1	187	200	218	225	250	281	312	343	375	449
1.5	281	300	328	337	375	421	468	515	562	674
2	375	400	437	449	499	562	624	687	749	899
2.5	468	499	546	562	624	702	780	858	936	1124
3	562	599	655	674	749	843	936	1030	1124	1348

Results in GPM

The blockage from the turbines was also considered when deciding on the channel size. The percent blockage that the in-stream and cross-stream axis turbines would create was calculated by dividing the turbine swept area, by the viewing section cross-sectional area. Table 3 displays the different percent blockage for the various types and sizes of the turbines. It can be seen that at larger cross sectional areas for the viewing channel, much larger turbines can be used. However, this correlates to a higher flow rate. The sought after percent blockage was to be as a high as possible without disrupting the flow. Any blockage around 30% was considered acceptable.

Table 3: Percent Blockage in Viewing Section from Turbines

Percent Blockage

	Diameter of Turbines			**Area of Channel [in^2]**									
				10x6	8x8	10x7	9x8	10x8	10x9	10x10	10x11	12x10	12x12
	In-Stream Axis		**Areas**	60	64	70	72	80	90	100	110	120	144
		2	3.14	5%	5%	4%	4%	4%	3%	3%	3%	3%	2%
		3	7.07	12%	11%	10%	10%	9%	8%	7%	6%	6%	5%
		4	12.57	21%	20%	18%	17%	16%	14%	13%	11%	10%	9%
		5	19.63	33%	31%	28%	27%	25%	22%	20%	18%	16%	14%
		6	28.27	47%	44%	40%	39%	35%	31%	28%	26%	24%	20%
		7	38.48	64%	60%	55%	53%	48%	43%	38%	35%	32%	27%
		8	50.27	84%	79%	72%	70%	63%	56%	50%	46%	42%	35%
		9	63.62	106%	99%	91%	88%	80%	71%	64%	58%	53%	44%
		10	78.54	131%	123%	112%	109%	98%	87%	79%	71%	65%	55%
	Cross-Stream Axis												
Length	**Width**		**Areas**										
3		3	9	15%	14%	13%	13%	11%	10%	9%	8%	8%	6%
4		4	16	27%	25%	23%	22%	20%	18%	16%	15%	13%	11%
5		5	25	42%	39%	36%	35%	31%	28%	25%	23%	21%	17%
6		6	36	60%	56%	51%	50%	45%	40%	36%	33%	30%	25%
7		7	49	82%	77%	70%	68%	61%	54%	49%	45%	41%	34%
8		8	64	107%	100%	91%	89%	80%	71%	64%	58%	53%	44%
9		9	81	135%	127%	116%	113%	101%	90%	81%	74%	68%	56%
10		10	100	167%	156%	143%	139%	125%	111%	100%	91%	83%	69%

It was decided to use a viewing section of 10 x 6 inches because the desired 2 ft/s could be accomplished with 375 GPM and the turbines could be up to 5 inches in diameter, large enough to see the characteristics of the turbine, but small enough to keep the percent blockage to 33%. The overall length of the viewing section was determines by the diameter of the largest possible turbine. Spacing the turbines 5 to 10 radiuses from each other helps diminish the effects of the first turbine. An extra foot was added to the beginning to allow the flow to fully develop before it reached the turbines. The extra foot also enables the demonstration of different turbine spacing. It should be noted that the viewing section was built with 8 inch tall walls to have some freeboard. The rest of the components for the tank were designed off the 80 in^2 area.

2.3 Stilling Tank

The water discharging from the pump needed to be slowed down before it entered the contraction. A stilling tank was designed to reduce the velocity of the water as well as straighten the flow. A 58% solidity perforated plate was put at the bottom of the filling tank right where the water entered. The perforated plate creates turbulence and helps distribute the velocity of the flow. Four cold extruded aluminum turning vanes were installed to guide the water around the 90° bend. After the turning vanes a honeycomb was placed before the contraction to straighten out the flow.

2.4 Contraction

The contraction design was shaped as a 5th order polynomial. 5th order polynomials with an inlet to outlet area ratio of 4:1 have been shown to work well for straightening flows in test channels [9]. The outlet area of the contraction was already determined from the viewing section which meant the inlet area had to be four times the outlet. The overall length was then solved for by multiplying the inlet width by a factor of 1.3, the smallest factor that would still provide straight flow. The 5th order polynomial equations,

– – – (7)

– – – (8)

were solved for in Excel. Equation 7 is the lateral distance measured from the plane of symmetry while Equation 8 is the vertical distance measured from the top of the tank. The variables in both equations were based on the inflection point (xi) and were defined as,

— (9)

— (10)

(11)

(12)

(13)

\- (14)

(15)

The equations were solved for with x broken down in 0.10 inch increments. They were then plotted to have a visual display of what the contraction would look like. Since the demonstration channel had a free surface, the contraction only need to contract on three sides.

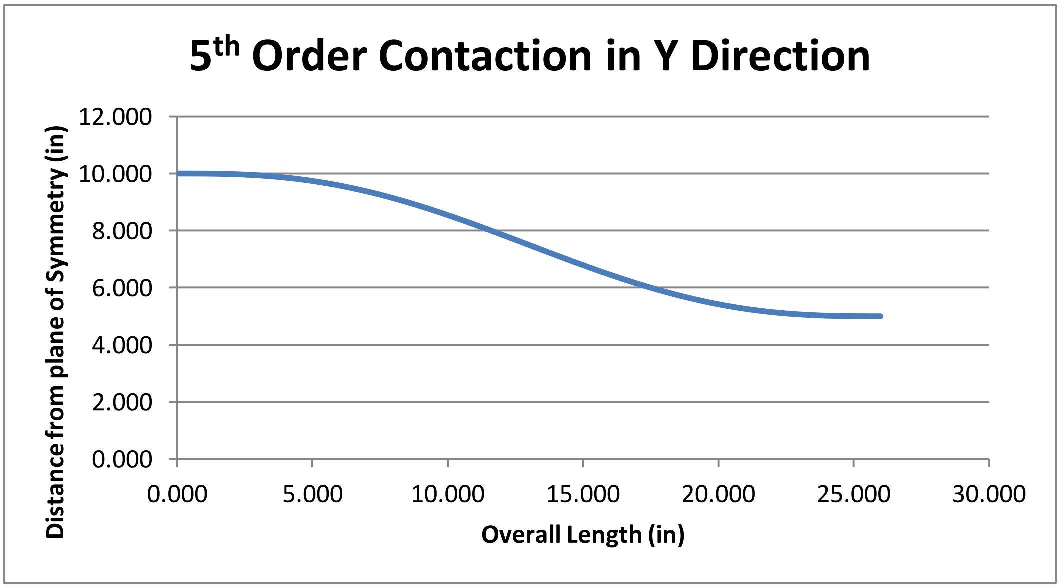


Figure 1: Plot of Contraction Shape in Y Direction

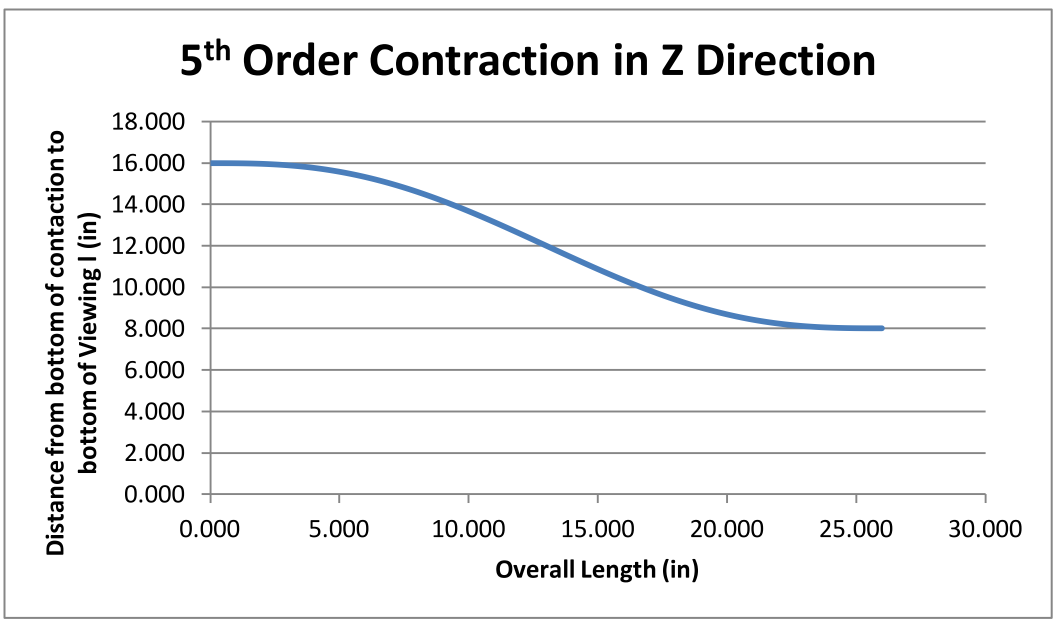


Figure 2: Plot of Contraction Shape in Z Direction

Figures 1 and 2 gave a visual display of what the contraction looked like. The overall length was then broken down into quarter inch increments to know the coordinates for construction.

2.5 Diffuser

After the water exits the viewing section it spills into a diffuser. The diffuser was designed with a 3:1 inlet to outlet area ratio. Turning vanes were installed to compensate for the wide angles of the diffuser. The diffuser was more of an expanding corner due to the turning vanes. A reservoir was built at the bottom of the diffuser to hold the excess water. The pump inlet draws the water from the reservoir and cycles through the system.

2.6 Head Loss and Pump

To select an appropriate pump, and to find the operating point of the pump, the system head loss must be calculated. A centrifugal pump was chosen for its high flow rate at low operating pressures and its compact size to save space. The system head loss for the demonstration channel was calculated using Equation 16, from the Appendix [Head Loss Notes].

(16)

The first summation block is the component's head loss and the second summation block is the friction head losses. *H* is the system head loss, *Q* is the target flow rate, *k* is the coefficient of component head loss, *f* is the coefficient of friction head loss and *L* and *D* are the length and hydraulic diameter of the component being evaluated.

Numerical values for the above variables are needed to calculate the specific head loss. The component head loss, which is the pressure losses due to turns, expansions, screens and flow straighteners was calculated and shown in Table 4.

Table 4: Component Head Loss

Component	k value	Area (ft^2)	velocity (feet/s)	Head Loss (feet)
Pipe Entrance, End Tank	0.5	0.087	9.57	0.71
Diffuser (end tank)	0.56	0.417	2.01	0.03
90° with turning vanes	0.2	2.222	0.38	0.00
90° smooth, PVC Elbow	0.35	0.049	17.02	1.57
90° smooth, PVC Elbow	0.35	0.049	17.02	1.57
90° smooth, PVC Elbow	0.35	0.049	17.02	1.57
90° smooth, PVC Elbow	0.35	0.049	17.02	1.57
Contraction	0.05		2.01	0.00
Honey Comb	1	2.22	0.38	0.00
Screen	1.5	2.22	17.02	6.75
Perforated Plate	3	2.22	17.02	13.50
Expansion into filling tank	0.87		17.02	3.91
Total				31.21

The k-values shown in Table 4 were determined using head loss notes shown in the Appendix [Head Loss]. The velocities were found by dividing the flow rate by the cross-sectional area. The friction losses were calculated for the PVC piping and the viewing section. Table 6 displays the fiction losses and the combined head loss caused from the PVC pipe and viewing sections.

Table 4: Friction Losses

Component	Velocity (feet/s)	Diameter (feet)	Reynolds #	friction factor	Length (feet)	Head Loss (feet)
PVC Pipe	17.02	0.250	404483.9	0.015614	6	1.69
viewing section	2.01	0.909	173263.0	0.017897	3	0.00
Total						1.69

The friction factors were calculated from the Colebrook equation from Appendix [Head Loss],

(17)

where f was the friction factor, L was the length, D_H was the hydraulic diameter and Re was the Reynolds number. This equation was implicit in friction factor f, and needed to be solved iteratively resulting in Equation 18. The hydraulic diameter was calculated for the viewing section because it is not circular in cross section.

(18)

Where P is the wetted perimeter. The Reynolds number was calculated by,

(19)

where v was the kinematic viscosity of the fluid. The total system head loss was found by the sum of all the component and friction pressure losses and displayed in Table 6.

Table 6: Total System Head Loss

System Head Loss		
Component Head Loss	31.21	Feet
Friction Head Loss	1.69	Feet
Total	32.90	Feet

The total system head loss was plotted as a function of flow rate and shown in Figure 3. The correct centrifugal pump would have a pump curve, which is also head loss as a function of flow rate, that would intersect the system head loss curve at our operating flow rate and system head loss.

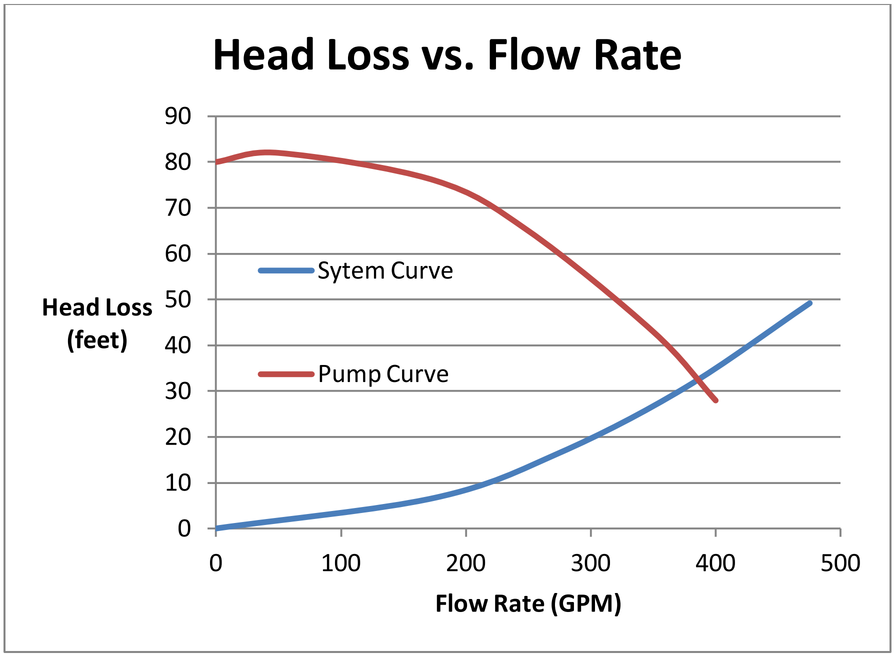


Figure 3: System Head Loss vs. Pump curve

The chosen pump was a Price RC300 stainless-steel pump close-coupled to a 7.5 horsepower motor for easy mounting and maintenance. The intersection point is at 380 gallons per minute at just over 30 feet of head which was where the designed system will operate. The inlet and outlet flow diameters are both 3 inches and the impeller chosen was the largest available at 4.62” in diameter. The largest impeller was chosen to maximize the pumps outlet flow rate at a specific head loss. The pump inlet draws from a reservoir at the bottom of the diffuser which was located within 3 feet of the pump. The pump outlet flow is then split and the main channel will run to the stilling tank while the other “control” channel will run back to the reservoir in the bottom of the exit diffuser. This secondary channel will control the amount of flow that enters the stilling tank. A globe valve will be introduced to the ‘control’ channel so the amount of diverted flow can be controlled. This will help regulate the flow rate through the demonstration channel efficiently and in-expensively. A variable frequency drive is the more user-friendly way of controlling flow rate but is significantly more expensive.

2.7 Model Turbines

To convert the tidal energy, turbines are needed to generate power. Two types of turbines were designed for the tidal energy demonstration channel, a horizontal (in-stream) axis turbine and a vertical (cross-flow) axis turbine. In-stream axis turbines are similar to wind energy turbines you see today , but more robust due to the medium. Tidal energy today is looking towards cross-flow turbines because they can receive the medium equally from any direction, therefore bypassing a device that changes orientation of the turbine due to the medium [5]. Figure 4 shows a section of an in-stream axis turbine blade [6]. Figure 5 shows a cross-flow turbine top-view [7].

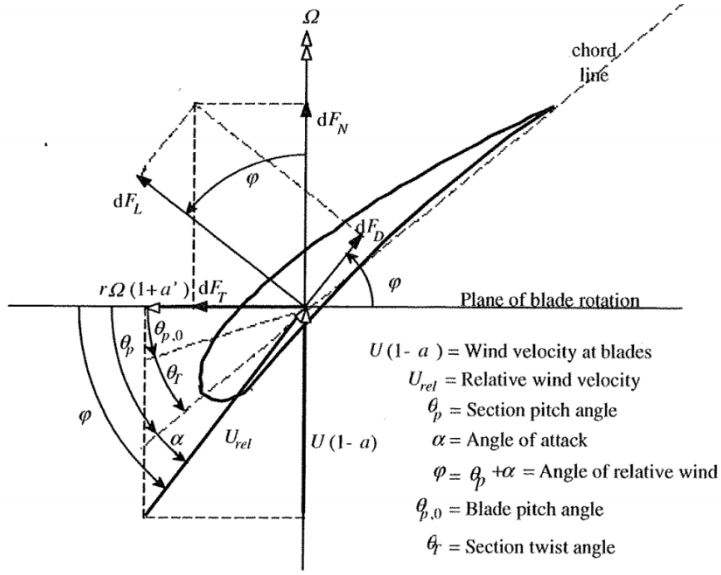


Figure 4: Foil Nomenclature for a Section of an In-stream Axis Turbine Blade

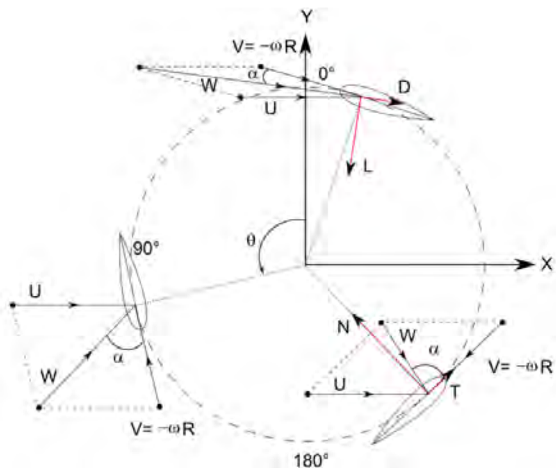


Figure 5: Cross-flow Axis Turbine Top-view

The following power equation was needed to determine the output of the turbine.

– , (20)

was the power and was the overall turbine efficiency By neglecting the orientation of the turbine and the different sections of the turbine blades the range of power was assumed to be between 0.25 Watts to 0.5 Watts. The average torque was then be calculated using the following equation

– , (21)

where was the average torque.

The design of the in-stream axis turbine was considered first. The design of the turbine rotor began by specifying a turbine tip speed ratio. Tip speed ratio was the ratio between the rotational speed of the turbine blade tip and the actual velocity of the medium. A tip speed ratio of 3 was decided as the design tip speed ratio. The turbine rotor had three blades and a radius of 2 inches [5]. The foil for an in-stream axis turbine was a NACA 4421 with a design angle of attack of 7 degrees. The angle of attack was chosen to be 7 degrees because the coefficient of lift divided by the coefficient of drag was highest at 7 degrees. The turbine blade was built in sections based on the tip speed ratio at certain radii. The following equations were needed to build the horizontal turbine blades, where tip-speed ratio was

$$\frac{\quad}{\quad}, \qquad (22)$$

and was the angular velocity and was the overall radius. The local speed ratio in respect to radius was given to be

$$\frac{}{}, \qquad (23)$$

where was the tip-speed ratio at a specific radius, was the design tip-speed ratio, and was the radius throughout the turbine blade. The flow angle can be calculated using tip-speed ratio in respect to a specific radius using the following equation,

$$\frac{\quad}{\quad}, \qquad (24)$$

where was the flow angle in respect to radii. The pitch angle can be calculated from the following equation,

$$, \qquad (25)$$

where was the pitch angle and is the angle of attack. The chord length can be calculated using the following equation

$$\frac{\qquad}{\qquad}, \qquad (26)$$

where was the chord length in inches, was the coefficient of lift, and is the number of blades [6]. Table 7 shows the angle of attack chart produced by javafoil applet for a NACA 4421 foil[8].

Table7: Angle of Attack Chart from Javafoil NACA 4421

α(°)	C_L	C_D	C_L/C_D
0.00	0.57	0.02	25.32
1.00	0.69	0.02	30.32
2.00	0.81	0.02	34.69
3.00	0.93	0.02	38.39
4.00	1.05	0.03	41.36
5.00	1.17	0.03	44.57
6.00	1.28	0.03	45.68
7.00	1.39	0.03	45.88
8.00	1.50	0.03	45.34
9.00	1.60	0.04	43.95
10.00	1.69	0.04	41.91
11.00	1.78	0.05	39.18
12.00	1.86	0.05	36.08
13.00	1.93	0.06	32.76
14.00	1.99	0.07	29.63
15.00	2.04	0.08	26.74
16.00	2.08	0.09	23.96
17.00	2.11	0.10	21.27
18.00	2.13	0.11	18.93
19.00	2.14	0.13	16.76
20.00	2.14	0.15	14.65
21.00	2.13	0.17	12.74
22.00	2.10	0.19	10.92
23.00	2.08	0.22	9.44
24.00	2.04	0.25	8.22
25.00	2.00	0.28	7.15
26.00	1.95	0.31	6.28
27.00	1.89	0.34	5.57
28.00	1.84	0.37	4.95
29.00	1.78	0.40	4.44
30.00	1.73	0.43	3.97

Table 8: In-stream and Cross-flow Axis Turbine Characteristics

Turbine Design	Tip Speed Ratio	Number of Blades	Diameter (in)
In-stream Axis	3	3	4
Cross-flow Axis	2.5	3	5.8

Table 8 was the final characteristics of the model turbines designed.

Table 9: In-stream Axis Turbine Section Blade Specifications

r (in)	$\lambda_{(r)}$	Φ	Θ_p	Chord Length (in)
2.00	3.00	12.53	5.53	0.29
1.50	2.25	16.50	9.50	0.38
1.00	1.50	23.96	16.96	0.54
0.50	0.75	41.63	34.63	0.89
0.25	0.38	60.64	53.64	1.17

The vertical axis turbines do not require any twist in the foil. The foil used for the vertical axis turbine was a NACA 0020 foil with a tip speed ratio of 2.5 and a diameter of 5.8 inches. Table 10 is the average torque calculated for different tip-speed ratios for the in-stream axis turbine, and Table 11 is the average torque calculated for the cross-flow axis turbine.

Table 10: In-stream axis Turbine Average Torque

Tip-Speed Ratio	ω (RPM)	Torque (in-oz)
3	344	1.1
4	458	0.81
5	573	0.65
6	688	0.54

Table 11: Cross-Flow Axis Turbine Average Torque

Tip-Speed Ratio	ω (RPM)	Torque (in-oz)
2.5	198.7	2.3
2	158.1	2.9
1.5	118.5	3.9
1	79.0	5.8

The in-stream and cross-flow axis turbines were drawn using SolidWorks using xyz-coordinates of a scaled NACA 4421 and NACA 0020 according to calculated chord lengths. The turbines were printed in the University of New Hampshire's rapid prototyping machine using ABS plastic Next step was to find a generator that will produce electricity at 344 rpms with 1.1 in-oz for the horizontal-axis turbine and 198.7 rpms with 2.3 in-oz for the vertical-axis turbine.

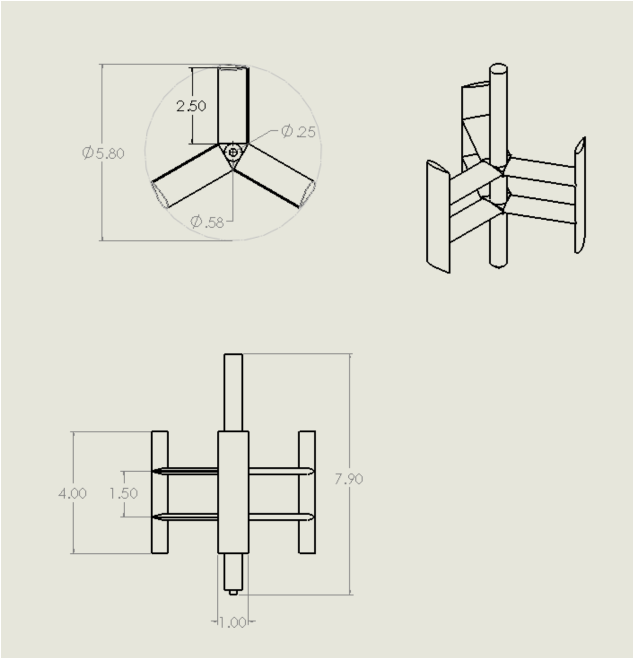


Figure 6: Technical Drawings for NACA 0020 foil

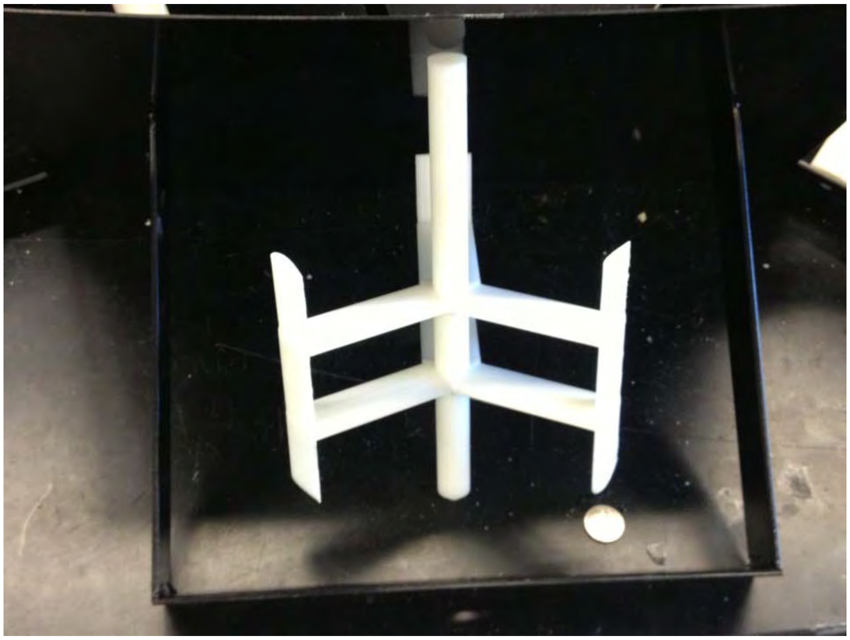


Figure 7: Final Product Vertical Axis Turbine. 5.8 inch diameter, 1 inch chord length, NACA 0020

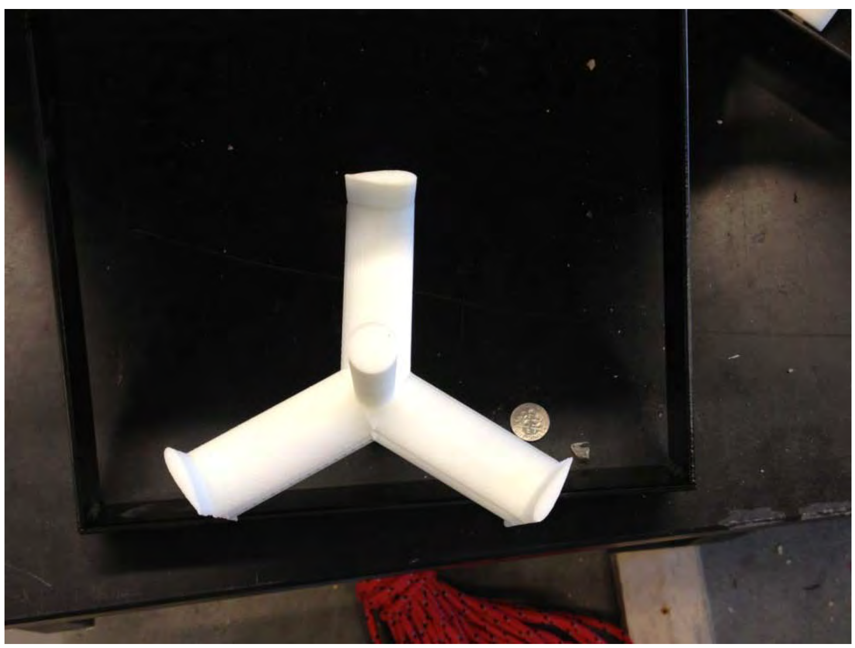


Figure 8: Final Product Vertical-Axis Turbine Top Profile. 5.8 inch diameter, 1 inch chord length, NACA 0020

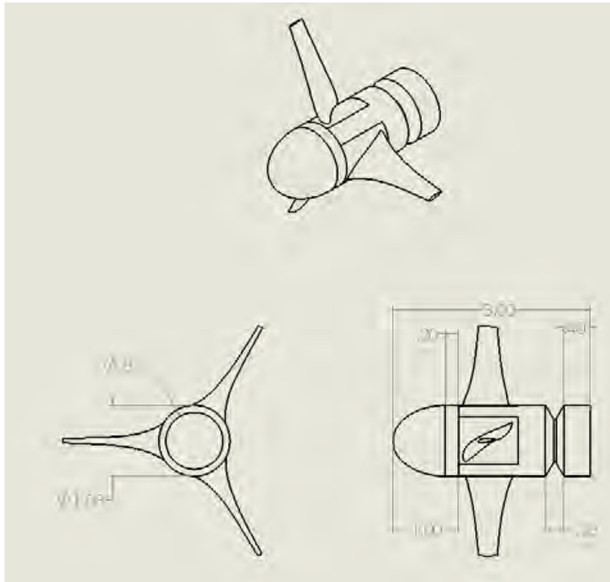


Figure 9: Technical Drawing for in-stream axis turbine. Diameter of 4 inches, NACA 4421 foil

Figure 10: Solidworks model of NACA 4421 foil. Turbine was built as an assemble.

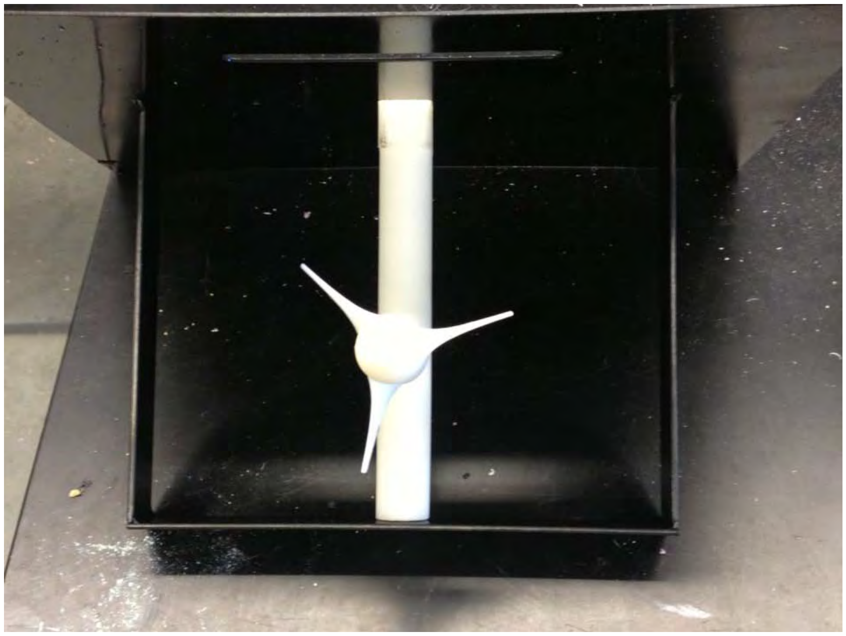


Figure 12: Final Product Horizontal-Axis Turbine. 4 inch diameter, NACA 4421

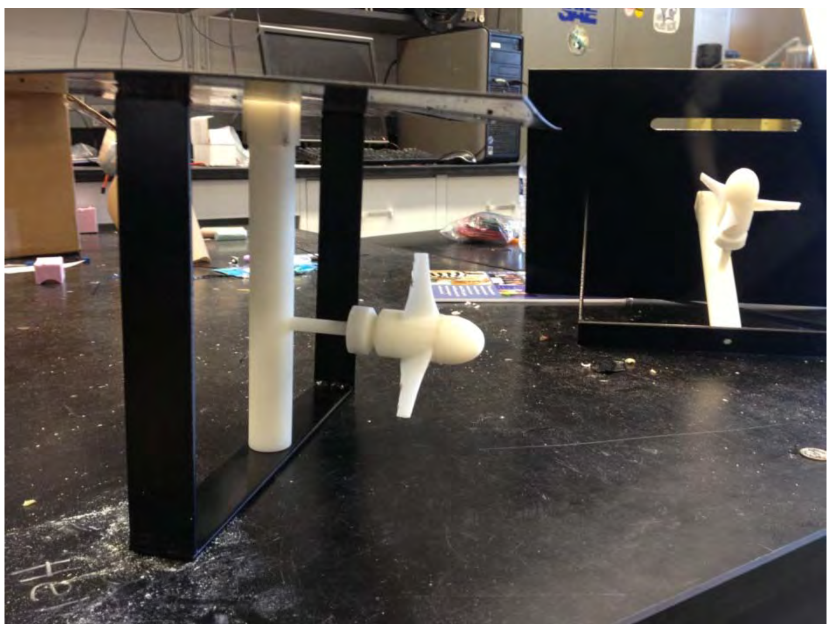


Figure 13: Final Product Horizontal Axis Turbine Side Profile. 4 inch diameter, NACA 4421

3. Construction

3.1 Viewing Section

The viewing section was made of high quality acrylic by Plastic Design Inc. out of North Chelmsford in Massachusetts. This included flanges to attach to the contraction and diffuser and gussets for added strength. The viewing section has 8 inch walls and a width of 10 inches. It measures a total length of 37 inches with flanges on four sides. The flanges have twelve pre drilled holes for attaching to the contraction and diffuser.

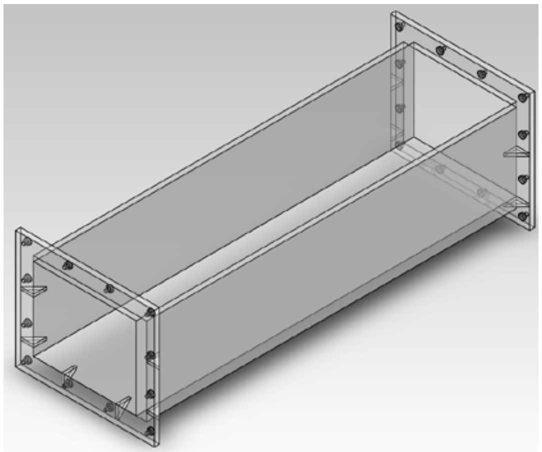


Figure 14: Solidworks Drawing of Viewing Section. Cross Sectional Area of $80in^2$

3.2 Stilling Tank

The stilling tank was constructed of ¾" marine grade plywood. A plywood box was made using 3/8" dados for strength. The box was made with extra-long sides so that a piece of hardwood could be attached to the outside, flush to the walls, to support the box and help hold it together.

Figure 15: Shows dado and overhang with hardwood backing

The stilling tank will be comprised of perforated plates, turning vanes, honeycomb and contraction. They perforated plate and honeycomb was attached to the inside of the box using a small hardwood frame. The turning vanes were attached to aluminum plates that are attached to the inside walls of the tank.

3.3 Contraction

The filling tank will be comprised of perforated plates, turning vanes, honeycomb and contraction. They perforated plate and honeycomb was attached to the inside of the box using a small hardwood frame. The turning vanes were attached to aluminum plates that are attached to the inside walls of the tank. The contraction was made using flexible wood attached to stilts at different highest and angles to give the 5th order contraction shape. The beginning of the contraction was carved into the plywood of the filling tank for a flush fit and to help smooth the flow.

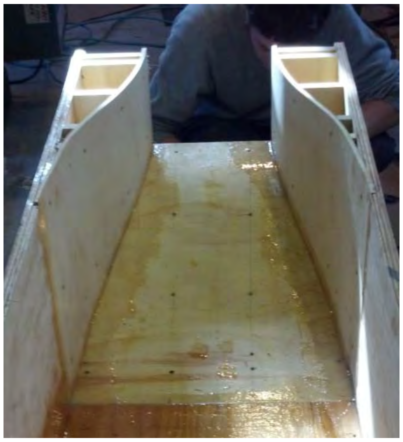


Figure 16: Contraction without top showing construction phase

3.4 Diffuser

The diffuser was made of the same ¾" marine grade plywood with the same dados and hardwood supports. The wide angle of the diffuser was made out of plywood inserts that were glued in place. Turning vanes will be installed to help direct the flow into the bottom of the diffuser known as the reservoir.

Figure 17: Top view of diffuser under construction

3.5 Turbines

The turbines were designed using Solid works were built using ABS plastic in a rapid-prototyping machine. The turbine will be connected to the generator using a pulley system. The turbine-generator system will be rigidly attached to a welded steel frame.

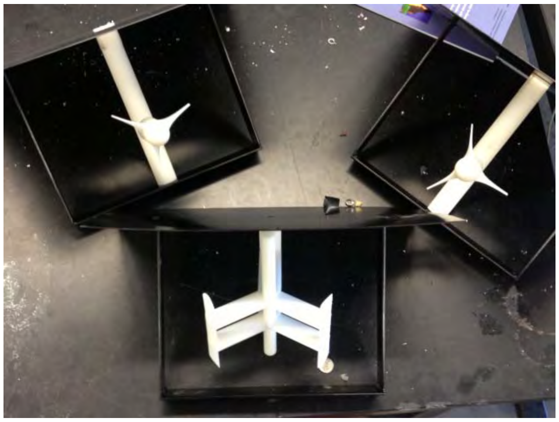


Figure 18: Complete turbine models

3.6 Frame

The frame was constructed out of 8020 aluminum industrial erector set. This is for its lightweight design while still being able to support the weight of the demonstration channel when it is completely full of water. The easy assembly, relatively low cost and large number of accessories made it an ideal choice for the frame.

Figure 19: Frame made of 8020 aluminum

The frame was built out of 1010 and 1020 along with square brackets and connecting plates. The bottom of the frame was made of 2020. 1010, 1020 and 2020 are all specific 8020 parts available online. The frame will also be supported by wheels for easy-handling.

4. Continuing and Future Work

The objective of the demonstration channel was to create a smooth, near laminar flow in the viewing 'test' section. Turbine models attached to mini-generators and a rigid frame will display the amount of output electricity. This output voltage will be recorded at different flow speeds for one vertical-axis turbine, one horizontal-axis turbine and an array of two horizontal axis turbines. These values will be analyzed for turbine-generator efficiency. The flow speed in the viewing section will be controlled by the position of the globe valve.

A laminar flow is a flow where all the fluid particles move parallel to the walls of the fluid channel. There are no pressure losses in a laminar flow, meaning eddies, swirls and other forms of turbulence are non-existent. The only fluid velocity is in the stream-wise direction. Technically, a laminar flow is any flow with a Reynolds number of 2300 or smaller. Since our Reynolds number is significantly higher than this, experimental analysis will have to be performed to profile our flow velocity. The screens, perforated plates, turning vanes, honey comb, contraction and diffuser are all engineered to improve our flow characteristics and decrease the amount of turbulence in the viewing section. This will be determined using food-coloring as a rough estimate and flow measurements at different cross-section positions near the inlet and outlet of the viewing channel. The expected flow velocity will be somewhere in the transitional range between laminar and turbulent.

References

1. "Marine Current Turbines." *SeaGen Technology*. Siemens Energy, n.d. Web. 29 Apr. 2013
2. "Sea Generation Ltd - Strangford Lough." *Sea Generation*. Marine Current Turbins LTD., n.d. Web. 25 Apr. 2013.
3. Fox, Robert W., Robert W. Fox, Philip J. Pritchard, and Alan T. McDonald. *Fox and McDonald's Introduction to Fluid Mechanics.* 8th ed. Hoboken, NJ: John Wiley & Sons, 2011. Print.
4. Idelchik, Isaak E. *Handbook of Hydraulic Resistance*. 3rd ed. Mumbai [u.a.: Jaico Publ. House, 2008. Print.
5. Fancis M. Vanek; Louis D. Albright (January 2008),"Components of a Turbine", *Energy Systems Engineering Evaluation & Implementation.* ISBN 9780071640947
6. Manwell JF; McGowan JG; Rogers AL (2002) Wind Energy Explained: Theory, Design and Application. 1st ed.,Wiley, Sussex, England.
7. "Vertical Axis Wind Turbine." *Wikipedia*. Wikimedia Foundation, 20 Sept. 2007. Web. 29 Mar. 2013. <http://en.wikipedia.org/wiki/Vertical_axis_wind_turbine>.
8. Hepperle, Martin. "JavaFoil-Analysis of Airfoils." *JavaFoil*. Martin Hepperle, 27 Jan. 2007. Web. 29 Apr. 2013.
9. Song, Charles, Joseph Wetzel, Roger Arndt, John Killen, and M. Yuan. *Hydrodynamic Analysis of the HYKAT*. Rep. no. 261. Minneapolis: University of Minnesota, 1987. Print.

Apendix

[Head Loss Notes] courtesy of Professor Diane Foster

We've made the following assumptions for this derivation

- conservation of mass
- incompressible flow
- steady state
- uniform flow over inlet and outlet areas
- impermeable boundary
- a full pipe

Please note, the previous equation is NOT Bernoulli's equation, that is frictionless and based on the momentum equation. This equation has friction and is based on the energy equation.

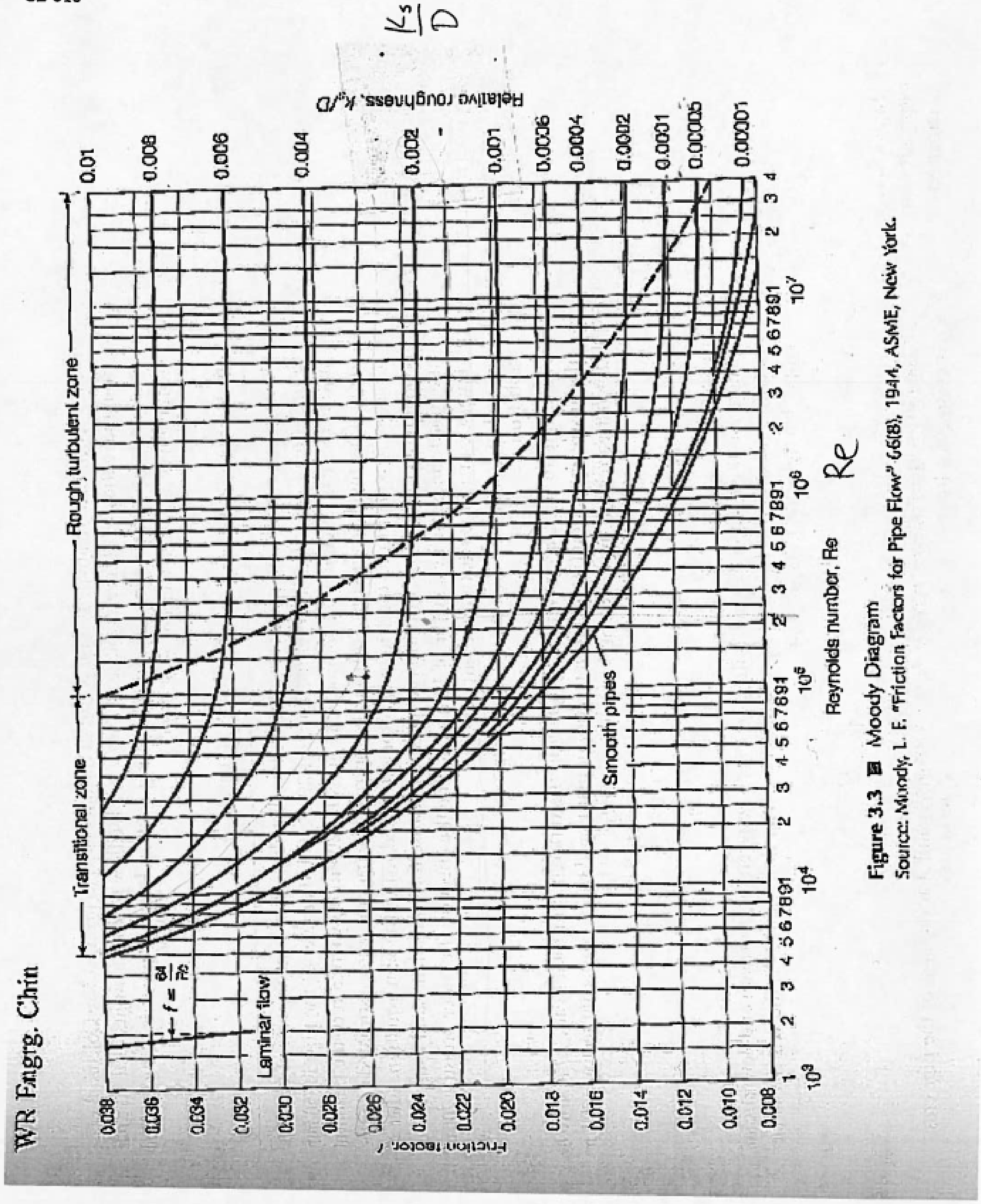
As an aside, recall the Darcy-Weisback for head loss through a single pipe that was derived from the momentum equation (note all minor losses and shaft losses were neglected because we've only considered a single pipe)

$$h_L = h_f = \frac{fL}{D}\frac{V^2}{2g}$$

This term has a similar form to the minor loss term

$$h_{ml} = \Sigma K \frac{V^2}{2g}$$

that implies that we can think of fL/D as a coefficient that represents loss of energy through a pipe.



WR Engrg, Chin
Transitional zone
Rough turbulent zone
Relative roughness, k_s/D
$\frac{k_s}{D}$
Friction factor, f
Laminar flow
$f = \frac{64}{Re}$
Smooth pipes
Reynolds number, Re
Re
0.01
0.008
0.006
0.004
0.002
0.001
0.0006
0.0004
0.0002
0.0001
0.00005
0.00001
0.038
0.036
0.034
0.032
0.030
0.028
0.026
0.024
0.022
0.020
0.018
0.016
0.014
0.012
0.010
0.008
10^3
10^4
10^5
10^6
10^7
Figure 3.3 Moody Diagram
Source: Moody, L. F. "Friction Factors for Pipe Flow" 66(8), 1944, ASME, New York.

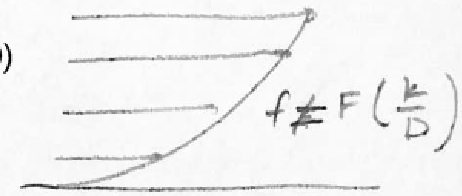
Chin (Fig 2.3)

Estimating the friction factor, f

Prandtl and Von Karman used empiricism (ie. lab experiments) to estimate the friction factor in various flow environments. From their and others results, the friction factor can either be estimated with the below equations or with the Moody diagram (Figure 3.3 in Chin).

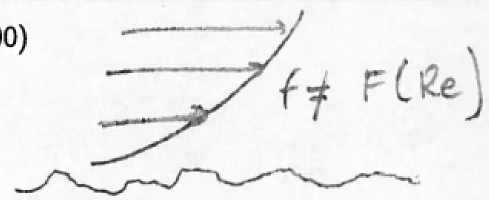
smooth turbulent flow ($k/D \sim 0$, $Re > 4000$)

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{2.51}{Re\sqrt{f}} \right)$$



rough turbulent flow ($k/D >> 0$, $Re > 4000$)

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{k/D}{3.7} \right)$$



laminar flow ($Re < 2000$)

$$f = \frac{64}{Re}$$

Flow that is between these two regimes is considered transitionally rough turbulent flow and is sometimes estimated with the **Colebrook Equation**

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{k/D}{3.7} + \frac{2.51}{Re\sqrt{f}} \right)$$

For a limited flow regime, the Jain equation may be used to estimate the friction factor

$$f = \frac{1.325}{[\ln(k/3.7D + 5.74/Re^{0.9})]^2} \quad \text{if} \quad 10^{-6} < k/D < 10^{-2}, \quad 5000 < Re < 10^8$$

Please note, to use the Jain equation, you must verify that k/D and Re are within the acceptable limits.

WR Engrg. Chin

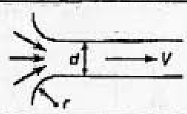
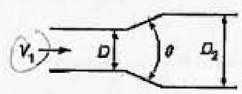
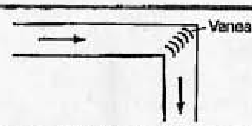
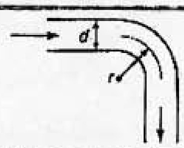
Description	Sketch	Additional Data	K	K
Pipe entrance		r/d	K	
		0.0	0.50	
		0.1	0.12	
		>0.2	0.03	
Contraction		D_2/D_1	K $\theta = 60°$	K $\theta = 180°$
		0.0	0.08	0.50
		0.20	0.08	0.49
		0.40	0.07	0.42
		0.60	0.06	0.27
		0.80	0.06	0.20
		0.90	0.06	0.10
Expansion		D_1/D_2	K $\theta = 20°$	K $\theta = 180°$
		0.0		1.00
		0.20	0.30	0.87
		0.40	0.25	0.70
		0.60	0.15	0.41
		0.80	0.10	0.15
90° miter bend		Without vanes	$K = 1.1$	
		With vanes	$K = 0.2$	
90° smooth bend		r/d	K $\theta = 90°$	
		1	0.35	
		2	0.19	
		4	0.16	
		6	0.21	
Threaded pipe fittings			K	
	Globe valve — wide open		10.0	
	Angle valve — wide open		5.0	
	Gate valve — wide open		0.2	
	Gate valve — half open		5.6	
	Return bend		2.2	
	Tee			
	straight-through flow		0.4	
	side-outlet flow		1.8	
	90° elbow		0.9	
	45° elbow		0.4	

Figure 3.7 ■ Loss Coefficients for Transitions and Fittings

Source: Roberson, John A. and Crowe, Clayton T., *Engineering Fluid Mechanics*. Copyright © 1997 by John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

Chin (Fig 2.7)