TEXAS TECH UNIVERSITY

DEPARTMENT OF CIVIL, ENVRONMENTAL, AND CONSTRUCTION ENGINEERING

Lab Report #6: Impact of a Jet

CE 3105 – Fluid Laboratory

Section:

Team Number:

Instructor:

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Date of Experiment:

Date of Submission:

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THEORY

Fluid often streams into a vane. When it does, its magnitude and direction change. By using Newton's second law, we can derive the impulse momentum principle, which we can use to study these changes. Observe the vane in **Figure 1**.

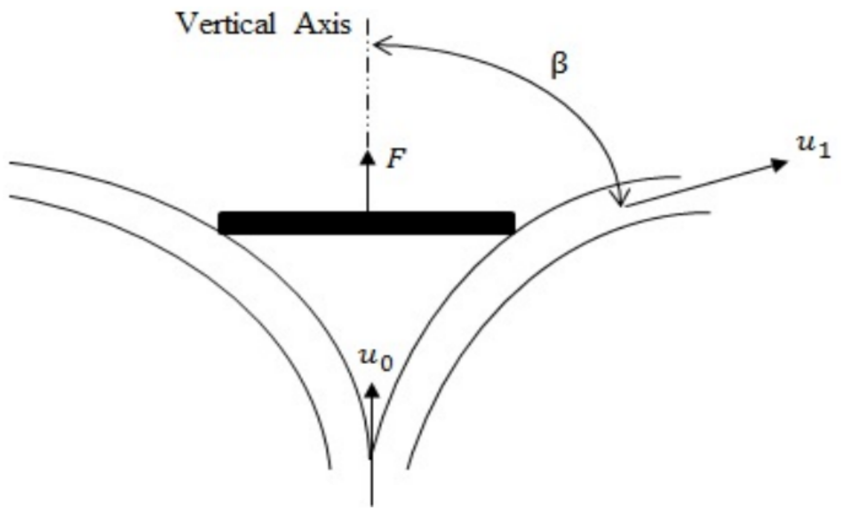

Figure 1: Fluid Jet Striking a Vane. The parameters are discussed in greater detail below.

In **Figure 1**, fluid comes out of the nozzle in a jet. The fluid is travelling vertically and has velocity u. The velocity at which the fluid hits the vane is u_0. The fluid is then deflected at an angle β from the vertical axis, moving at velocity u_1. The mass flow $\dot{m}$ is considered along the vertical axis, and the rate at which momentum enters the system can be expressed as $\dot{m}u_1 cos\beta$. The force exerted by the fluid on the vane along the vertical axis is equivalent to the rate of change of momentum, expressed as:

$$F = \dot{m}(u_0 - u_1 \cos\beta) \qquad (1)$$

$F = force\ exerted\ by\ fluid\ onto\ the\ vane$
$\dot{m} = mass\ flow\ of\ the\ fluid$
$u_0 = velocity\ of\ fluid\ hitting\ the\ vane$
$u_1 = velocity\ of\ fluid\ deflected\ off\ the\ vane$
$\beta = angle\ of\ fluid\ deflection\ off\ the\ vane$

The velocity of the fluid striking the vane can be found if the initial speed of the fluid in the jet is known. The following equation establishes a relationship between these two parameters:

$$u_0^2 = u^2 - 2gs \qquad (2)$$

$u_0 = velocity\ of\ fluid\ hitting\ the\ vane$
$u = velocity\ of\ fluid\ in\ the\ jet$
$g = acceleration\ due\ to\ gravity$
$s = distance\ from\ the\ nozzle\ to\ the\ vane$

If the jet has constant velocity, the force of fluid hitting the vane can be approximated using the following equation:

$$F \approx \dot{m}u_0(1 - \cos\beta) \quad (3)$$

Vanes have different shapes, and these shapes affect the outcome of these equations. The table below shows the different effects of using different types of vanes.

Table A: The Effect of Vane Shapes on Experimental Calculations

Vane type	β	F
Flat plate	90°	$\dot{m}u_0$
Hemisphere	180°	$2\dot{m}u_0$

Please note that **Table A** uses the following assumption:

$$J = \dot{m}u_0 \quad (4)$$

$$J = jet\ momentum$$

To calculate the force on the vane, we use the involved moments. **Figure 2** shows a diagram of the involved moments, including the force of interest F.

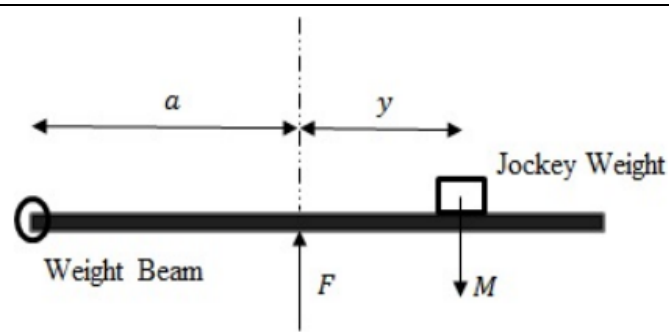

Figure 2: All Involved Moments in Experimental Setup. The parameters are discussed in greater detail below.

For the system in **Figure 2**:

$$F = \frac{Mg(y + a)}{a} \quad (5)$$

$F = force\ exerted\ by\ fluid\ onto\ the\ vane$
$M = downward\ force\ on\ the\ jockey\ weight$
$y = distance\ between\ fluid\ jet\ and\ jockey\ weight$
$a = distance\ between\ pivot\ point\ and\ fluid\ jet$

In our experiment we explored these relationships by using the setups outlined in the APPARATUS section below.

APPARATUS

Below are the images of the jet apparatus used in the experiment. The items not depicted are the small bowl used to help collect the water in the water table to measure the flow rate and the iPhone used to also help measure the flow rate.

Figure 3. Flat-Plane Vane Apparatus. This setup was used for the first portion of the experiment.

Figure 4. Hemispherical Cup Vane Apparatus. This setup was used for the second portion of the experiment.

EXPERIMENT PARAMETERS

1. **Flow Rate (ft^3/s)**

This value comes from dividing the volume by the time it took the apparatus to fill the basin with that volume.

2. **Mass Flow Rate (lb/s)**

This is the flow rate multiplied by the nozzle area.

3. **Density of Water (lb/ft^3)**

The density recorded at the lab was 62.3 lb/ft^3.

4. **Nozzle Area (ft^2)**

This is a given value. The nozzle area is .000845 square feet.

5. **Velocity at Nozzle Exit (ft/s)**

This is the velocity of the water exiting the nozzle before it is deflected.

6. **Velocity Deflected from Vane (ft/s)**

This is the velocity of the water after it is deflected by the flat plate of hemispherical plate.

7. **Vertical Distance (ft)**

This is a given value. The vertical distance is .115 feet.

8. **Force on Vane (lb*ft/s^2)**

This is the force of the jet pushing upwards on the vane.

9. **Mass of Jockey Weight (lb)**

This is another given value. The mass of the jockey weight is given as 1.32 pounds.

10. **Gravity (ft/s^2)**

This is the constant gravity on Earth that is 32.2 feet per second squared.

11. **Horizontal Distance (ft)**

This is the distance y plus the next parameter listed that depends on the distance the jockey weight is from the pivot.

12. **Point of Application of F from Pivot (ft)**

This is the point where the force is applied related to the distance from the pivot. This is given as .5 feet or 15 cm.

RESULTS

Table 1: Data collected during flat plate portion of lab

Below is the data collected from the trials using the flat plate. This includes the distance needed to get the moment created by the jet and the volumes and times used to calculate the flow rate.

Flate Plate			
Trials	**Distance y(mm)**	**Volume V (L)**	**Time t (s)**
1	242	10	22.85
2	225	10	23.94
3	210	10	29.66
4	205	10	33.70
5	182	5	36.51

Table 2 Data collected from hemispherical cup vane portion of lab

Below is the data collected from the trials using the hemispherical cup vane. This includes the distance needed to get the moment created by the jet and the volumes and times used to calculate the flow rate.

Hemispherical Cup Vane			
Trials	**Distance y(mm)**	**Volume V (L)**	**Time t (s)**
1	283	10	18.70
2	247	10	23.41
3	205	10	32.09
4	163	5	21.37
5	155	5	29.97

Table 3: Calculations for the Flat Plate section

The table displays the flow rate, mass flow rate, the flow velocity, velocity at nozzle exit, velocity deflected from vane, rate of delivery of momentum, and the force from the flat plate portion of the lab.

Flat Plate							
Trials	**Flow Rate**	**Mass Flow Rate**	**Distance y (ft)**	***u***	***u_0***	***ṁu_0***	**F**
1	.015	.935	.793	118	118	110	110
2	.015	.935	.738	112	112	105	105
3	.012	.748	.689	135	135	101	101
4	.010	.623	.673	160	160	99.7	99.7
5	.005	.312	.597	299	299	93.3	93.3

Table 4: Calculations for the Hemispherical Cup Vane

The table displays the flow rate, mass flow rate, the flow velocity, velocity at nozzle exit, velocity deflected from vane, rate of delivery of momentum, and the force from the hemispherical cup vane portion of the lab.

Hemispherical Cup Vane							
Trials	**Flow Rate**	**Mass Flow Rate**	**Distance y (ft)**	***u***	***u_0***	***ṁu_0***	**F**
1	.019	1.18	.928	102	102	120	121
2	.015	.935	.810	119	119	111	111
3	.011	.685	.673	146	146	100	99.7
4	.008	.498	.535	177	177	88	88
5	.006	.374	.509	229	229	85.6	85.8

DISCUSSION

Experiment Purpose

The objective in this experiment is to demonstrate that the force on a vane is proportional to the rate of delivery of momentum and show that we can predict the force on a vane from a combination of properties such as its surface shape.

With the results that we achieved in this experiment we managed to calculate the force and compare between the surface property that we changed. We received the same flow rate between the two and concluded that a hemispherical plate receives more upward Force compared to the flat plate.

REPORT QUESTIONS

1. What percentage of velocity compared to that exiting the nozzle is lost as the jet deflects from the Flat Plate Vane?

Using $u_0^2 = u^2 - 2gs \rightarrow u_0^2 = (118^2) - 2(32.2)(.115) = 117.9686$

Then $(118) - (117.9686) = .031 \rightarrow \left(\frac{.031}{118}\right) \cdot 100 = .026\%$

2. What percentage of velocity compared to that exiting the nozzle is lost as the jet deflects from the Hemispherical Cup Vane?

Using $u_0^2 = u^2 - 2gs \rightarrow u_0^2 = (102^2) - 2(32.2)(.115) = 101.9637$

Then $(102) - (101.9637) = .036 \rightarrow \left(\frac{.036}{102}\right) \cdot 100 = .035\%$

3. Compare the coefficient of theoretical force found using the plot in Calculations 6b with the given, typical values for the coefficient of theoretical force on a Flat Plate Vane.

Theoretical Force $(F_t) = (mass\ flow\ rate)(u_0)$

Then plugging in our obtained values $(F_t) = (.935)(118) = 110.33$ lb-ft/s^2

Actual Force obtained by balancing moment about the pivot.

$Fa = W(a + y) \rightarrow F(.5) = (1.32 \cdot 32.2)(.5 + .794) = 110.00$lb-ft/s^2

3a. Compare your values for each trial using difference or some other mathematical comparison.

Table 5: Theoretical Force and Actual Force on Flat Plate

Trial	F_t lb-ft/s^2	F Lb-ft/s^2
1	110.33	110.00
2	104.72	105.02
3	100.98	101.07
4	98.68	99.714
5	93.29	93.25

Using the difference of the Theoretical force vs Actual force we get an average difference of .359.

4. Compare the coefficient of theoretical force found using the plot in Calculations 6b with the given, typical values for the coefficient of theoretical force on a Hemispherical Cup Vane.

For Theoretical $(F_t) = (1.18)(102) = 120.36$

For Actual Force

$$Fa = W(a + y) \rightarrow F(.5) = (1.32 \cdot 32.2)(.5 + .928) = 121.39$$

4a. Compare your values for each trial using percentage difference or some other mathematical comparison

Table 6: Theoretical Force and Actual Force on Hemispherical Plate

Trial	F_t lb-ft/s^2	F Lb-ft/s^2
1	120.36	121.39
2	111.27	111.36
3	100.01	99.71
4	88.15	87.98
5	85.65	85.77

Using the difference of the Theoretical force vs Actual force we get an average difference of .342.

5. If an Angled Plate Vane, with an angle of 30°, was examined using Impact Jets, would you expect the coefficient of theoretical force to be higher or lower than the coefficients of theoretical force for Flat Plate and Hemispherical Cup Vanes?

Coefficient for Flat Plate $\left(\frac{F_t}{F}\right) = 1.003$

Coefficient for Hemispherical Plate $\left(\frac{F_t}{F}\right) = .992$

5a. Justify your answer using data found in this experiment.

At 30° $F_n = (mass\ flow\ rate)(u_0)\sin 3\,0 \rightarrow (.935)(118)\sin 3\,0 = 55.165$lb-ft/s^2

Then Force in upward direction: $F_u = F_n \cdot \sin 3\,0 \rightarrow (55.165)\sin 3\,0 = 27.583$lb-ft/s^2

For hemispherical plate at 30° $F_n = (mass\ flow\ rate)(u_0)\sin 3\,0 \rightarrow (1.18)(102)\sin 3\,0 = 60.18$lb-ft/s^2

Upward Force: $F_u = F_n \cdot \sin 3\,0 \rightarrow (60.18)\sin 3\,0 = 30.09$lb-ft/s^2

We see that the hemispherical plate had a slightly better coefficient value. If angled, we see a drop in upward force compared to flat.

6. Which source of error do you think is most significant in your experiment, and why?

Error that occurs in this experiment would be the losses in between flow and vane. Other sources of error that may arise is the volumetric and friction loss. We calculated the losses and saw the losses experienced were extremely close. Our Actual and Theoretical forces were also nearly identical keeping an average difference of .359 for the flat and .342 for hemispherical.

7. Give an example of a real-life application of the principles and theories explored in this lab.

Exploring the principles behind the jet in this lab can be applied to water turbines. To push these turbines to produce power we need to have a nozzle dispense water into the turbine/blade to spin the turbine. These blades that receive this force must be designed to receive the maximum force it can receive on its surface to efficiently operate the turbine.

DATA APPENDIX

CE3105 Mechanics of Fluids Laboratory Department of Civil Engineering Texas Tech University

Experiment: Impact of a Jet - Data Sheet

Date of Experiment: Name

Temperature of water, T= __ °Celsius Water density, ρ = 1.9355 (~~kg~~ slugs/ft3) Gravity, g= 32.2 (ft/s2

FLAT PLATE			
TRIAL – TEAMS	DISTANCE y (mm)	VOLUME V (L)	TIME t (s)
[illegible]	150 + 92	10 L	22.85
	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]
	[illegible]	10 L	[illegible]
	150 + 32	5 L	36.51

HEMISPHERICAL CUP VANE			
TRIAL – TEAMS	DISTANCE y (mm)	VOLUME V (L)	TIME t (s)
[illegible]	150 + ~~[illegible]~~ 133	10L	18.70
	150 + 97	10L	23.41
	150 + 55	10L	32.09
	150 + 13	5L	21.37
	150 + 5	5L	29.97

Instructor's Signature_

CE3105 Mechanics of Fluids Laboratory Departme

Experiment: Impact of a Jet - Data Sheet

Date of Experiment: _ Nam

Temperature of water, T= _ ◦Celsius Water density, ρ = _______(lb/ft3) Gravity, g= 32.2 (ft/s2

FLAT PLATE (add 15cm)			
TRIAL – TEAMS	DISTANCE *y* (mm)	VOLUME *V* (L)	TIME *t* (s)
Team #1			
Team #2			
Team #3			
Team #4			
Team #5	32	0-5	36.51

HEMISPHERICAL CUP VANE			
TRIAL – TEAMS	DISTANCE *y* (mm)	VOLUME *V* (L)	TIME *t* (s)
Team #1			
Team #2			
Team #3			
Team #4	15	6-[illegible]	[illegible]
Team #5	[illegible]	[illegible]	29.97

Instructor's Signatur

CE3105 Mechanics of Fluids Laboratory Department of Civil Engineering Texas Tech University

Experiment: Impact of a Jet - Data Sheet

Date of Experiment: ______ Name: ______

Temperature of water, T= ___ ◦Celsius Water density, ρ = _______(lb/ft3) Gravity, g= 32.2 (ft/s2

FLAT PLATE			
TRIAL – TEAMS	DISTANCE y (mm)	VOLUME V (L)	TIME t (s)
Team #1			
Team #2			
Team #3			
Team #4			
Team #5	32	0-5	36.51

HEMISPHERICAL CUP VANE			
TRIAL – TEAMS	DISTANCE y (mm)	VOLUME V (L)	TIME t (s)
Team #1	133	10	18.70
Team #2	97	10	23.41
Team #3	55	10	32.09
Team #4	13	5	21.37
Team #5			29.97

Instructor's Sig

ERROR CALCULATIONS

Human error also is present with the timing of the flow rate. We set up a stopwatch to record the time it takes for the fluid to fill a specific volume. For this experiment we used 5 to 10 liters to determine this. The slight human error can be present with accurately stopping the time when the fluid successfully reaches the target volume. Times were measured to the best of our ability.

Finding the average difference $(F_t - F_a)$ for flat plate:

$$\frac{(.33 + .3 + .09 + 1.034 + .04)}{5} = .359$$

For the hemispherical plate:

$$\frac{(1.03 + .09 + .3 + .17 + .12)}{5} = .342$$

Standard Deviation for difference in flat plate:

$$\sigma = \sqrt{\Sigma \frac{1}{N-1}(x_i - \mu)} \rightarrow \sqrt{\frac{1}{5-1}\Sigma\big((.33, .3, .09, 1.034, .04) - .359\big)} = .398$$

For hemispherical plate:

$$\sigma = \sqrt{\Sigma \frac{1}{N-1}(x_i - \mu)} \rightarrow \sqrt{\frac{1}{5-1}\Sigma\big((1.03, .09, .30, .17, .12) - .342\big)} = .393$$

SAMPLE CALCULATIONS

NOTE: These calculations are listed in the order that they were asked for in the lab handout, even though they were actually performed in a different order.

FLAT PLATE

MASS FLOW RATE

Using the equation for mass flow:

$$\dot{m} = \rho Q$$

Because we are working in US units, we want our answer in $^{lb}/_{s}$, so we must multiply by gravity:

$$\dot{m} = \rho g Q$$

We plug in values from trial 1 of the flat plate to obtain:

$$\dot{m} = \left(1.9355 \, ^{slugs}/_{ft^3}\right)\left(32.2 \, ^{ft}/_{s^2}\right)\left(\frac{(10\ L)\left(0.0353147 \, ^{ft^3}/_{L}\right)}{22.85\ s}\right)$$

$$\dot{m} = 0.963 \, ^{lb}/_{s}$$

VELOCITY OF FLUID IN THE JET

By rearranging **Equation 2**, we obtain:

$$u = \sqrt{{u_0}^2 + 2gs}$$

We plug in values from trial 1 of the flat plane to obtain:

$$u = \sqrt{\left(70.8 \, ^{ft}/_{s}\right)^2 + 2\left(32.2 \, ^{ft}/_{s^2}\right)(0.115\ ft)}$$

$$u = 70.8 \, ^{ft}/_{s}$$

VELOCITY OF FLUID HITTING THE VANE

By rearranging **Equation 3** suited for flat plane conditions, we obtain:

$$u_0 \approx \frac{F}{\dot{m}(1 - \cos 90°)}$$

We plug in values from trial 1 of the flat plane to obtain:

$$u_0 \approx \frac{68.2\ lb}{\left(0.963 \, ^{lb}/_{s}\right)(1 - \cos 90°)}$$

$$u_0 \approx 70.8 \, ^{ft}/_{s}$$

FLUID MOMENTUM

Using Equation 4:

$$J = \dot{m}u_0$$

We plug in values from trial 1 of the flat plane to obtain:

$$J = \left(0.963\ {}^{lb}/_{s}\right)\left(70.8\ {}^{ft}/_{s}\right)$$

$$J = 68.2\ lb * s$$

FORCE OF FLUID HITTING THE VANE

Using Equation 5:

$$F = \frac{Mg(y+a)}{a}$$

We plug in values from trial 1 of the flat plane to obtain:

$$F = \frac{(1.32\ lb)\left(32.2\ {}^{ft}/_{s^2}\right)\left(92\ mm\left(0.00328084\ {}^{ft}/_{mm}\right) + 0.5\ ft\right)}{0.5\ ft}$$

$$F = 68.2\ lb$$

FORCE VS. MOMENTUM

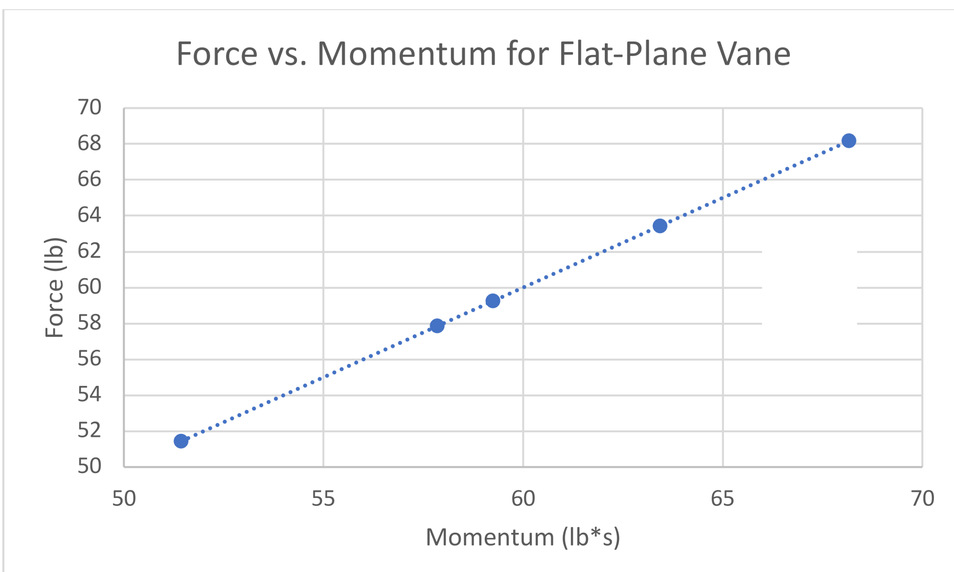

Figure 5: Plot of Force vs. Momentum for Flat-Plane Vane. The values were exactly identical and therefore created a very predictable plot.

HEMISPHERICAL CUP

MASS FLOW RATE

Using the equation for mass flow:

$$\dot{m} = \rho Q = VA$$

We use values from trial 1 of the hemispherical cup to obtain:

$$\dot{m} = \left(1.9355\ ^{slugs}/_{ft^3}\right)\left(32.2\ ^{ft}/_{s^2}\right)\left(\frac{(10\ L)\left(0.0353147\ ^{ft^3}/_{L}\right)}{18.70\ s}\right)$$

$$\dot{m} = 1.18\ ^{lb}/_{s}$$

VELOCITY OF FLUID IN THE JET

By rearranging **Equation 2**, we obtain:

$$u = \sqrt{{u_0}^2 + 2gs}$$

We plug in values from trial 1 of the hemispherical cup to obtain:

$$u = \sqrt{\left(33.8\ ^{ft}/_{s}\right)^2 + 2\left(32.2\ ^{ft}/_{s^2}\right)(0.115\ ft)}$$

$$u = 33.9\ ^{ft}/_{s}$$

VELOCITY OF FLUID HITTING THE VANE

By rearranging **Equation 3** suited for hemispherical vane conditions, we obtain:

$$u_0 \approx \frac{F}{2\dot{m} * (1 - \cos 180°)}$$

We plug in values from trial 1 of the hemispherical cup to obtain:

$$u_0 \approx \frac{79.6\ lb}{2\left(1.18\ ^{lb}/_{s}\right) * (1 - \cos 180°)}$$

$$u_0 \approx 33.8\ ^{ft}/_{s}$$

MOMENTUM

Using Equation 4:

$$J = \dot{m}u_0$$

We plug in values from trial 1 of the hemispherical cup to obtain:

$$J = \left(1.18\ ^{lb}/_{s}\right)\left(33.8\ ^{ft}/_{s}\right)$$

$$J = 39.8\ lb * s$$

FORCE OF FLUID HITTING THE VANE

Using Equation 5:

$$F = \frac{Mg(y+a)}{a}$$

We plug in values from trial 1 of the hemispherical cup to obtain:

$$F = \frac{(1.32\ lb)\left(32.2\ ^{ft}/_{s^2}\right)\left(133\ mm\left(0.00328084\ ^{ft}/_{mm}\right) + 0.5\ ft\right)}{0.5\ ft}$$

$$F = 79.6\ lb$$

FORCE VS. MOMENTUM

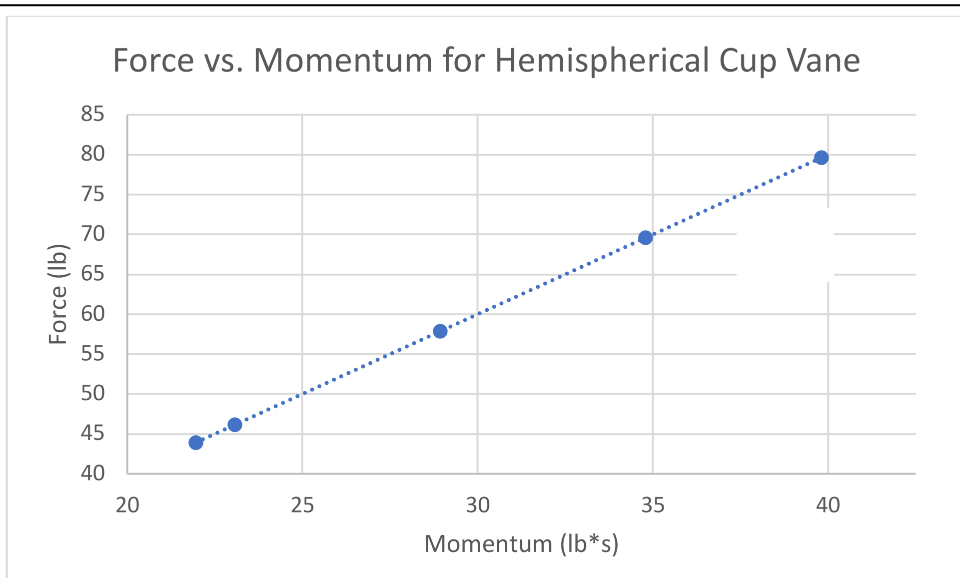

Figure 6: Plot of Force vs. Momentum for Hemispherical Cup Vane. The values of momentum were exactly half that of the values of force. Therefore, the two variables created a very predictable plot.