FM Lab Experiment-2: Force Measurement from Jet Impingement

ME351: Mechanical Engineering Lab-I

Prof. Uddipta Ghosh **Prof. Jaichander Swaminathan**

Group-2

20110130	Dishant Patel	patel.dishant@iitgn.ac.in
20110065	Ekansh Somani	ekansh.somani@iitgn.ac.in
20110068	Gaurav Sharma	sharmagaurav@iitgn.ac.in
20110133	Shubham Patel	patel.shubham@iitgn.ac.in
20110169	Rohan Naika	rohan.naika@iitgn.ac.in
20110176	Sachin Bhardwaj	sachin.bhardwaj@iitgn.ac.in
20110032	Ayush Singh Kushwah	ayush.kushwah@iitgn.ac.in

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1. Answers to the questions posed in essential background

Q. Why are liquid jets important? Briefly discuss any 3 applications of liquid jets.

A jet is a stream of matter having a more or less columnar shape. They occur in an incredibly wide range of contexts, covering a wide range of physical length ranges. Jets occur on both cosmic scale and on subatomic length scales and have gained interest for their probable practical usefulness and their heuristic interest, showing some important phenomena of physics and applied mathematics.

In addition to advancing and optimizing liquid jet propulsion, diesel engine technology, manufacturing, agricultural sewage and irrigation, powder technology, ink-jet printing, medical diagnostics or DNA sampling, and nuclear fission, jets are crucial for understanding and explaining the large-scale structure of the universe and the support of galaxy clusters. Jets are also a part of our everyday surroundings, including bathrooms, kitchens, showers, medicine sprays, and cosmetics. They are also employed for fun and security, such as to support firefighters or inflate airbags.

Q. Read up on the Reynolds transport theorem (RTT). How is momentum conservation expressed in this theorem?

The General form of Reynolds Transport Theorem is given by

$$\frac{dB_{sys}}{dt} = \frac{d}{dt}\int_{CV} \beta\rho dV + \int_{CS} \beta\rho(\boldsymbol{V_r}\cdot\hat{\boldsymbol{n}})dA \quad *$$

The momentum equation is found by substituting momentum in for **B**. From this, **β** is found to be velocity. The time rate of change of momentum (now the left hand side of the equation) is, from Newton's second law, equal to the net force

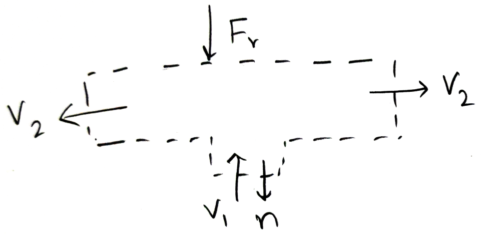
$$\frac{d(m\vec{V})_{sys}}{dt} = \frac{d}{dt}\int_{CV} \rho \vec{V}\, dV + \int_{CS} \rho \vec{V}(\vec{V}\cdot \hat{n})\, dA$$

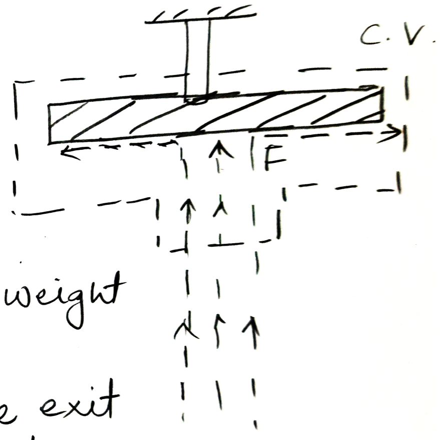
$$\sum \vec{F} = \frac{d}{dt}\int_{CV} \rho \vec{V}\, dV + \int_{CS} \rho \vec{V}(\vec{V}\cdot \hat{n})\, dA$$

Q. Can you compute the force exerted by a liquid jet impinging on a flat surface, using the RTT?

From Reynolds Transport Theorem

$$\Sigma F = \frac{d}{dt}\left(\int_{CV} V\rho \, dV\right) + \int_{CV} \rho V (V \cdot n) \, dA$$





Assuming plate has negligible weight

velocity near vane = velocity at the exit of nozzle

At steady state: $\frac{d}{dt}\int_{CV} (\rho V) \, dV = 0$

$$\Rightarrow -F_r = \int_{CV} \rho V_1 (V_1 \cdot n) \, dA$$

$$= -\rho V_1 (V_1) A$$

$$F_r = \rho A_1 V_1^2 \quad ----(1)$$

Q, Other Equations used in the report

CALCULATIONS

1. Moment Equation: consider, W_1 = Primary balancing weight.
W_2 = secondary balancing weight.
W_3 = Weight of the steel rod + weight of vane

l_1 = length between primary balancing weight and the vane
l_2 = length between vane and Hinge.
l_3 = Length between secondary balancing weight and hinge.

and, F_w = Force exerted on the vane by the liquid jet.
M = moment due to weight of steel scale about the hinge

Now, for moment calculation :-

$$F_1 \cdot (l_1+l_2) + F_3 (l_2) - F_2 (l_3) - F_w \cdot (l_2) + M = 0$$

$$\Rightarrow F_w = \frac{F_1 \cdot (l_1+l_2) + F_3 (l_2) - F_2 (l_3) + M}{l_2}$$

where ; $F_1 = W_1 * g$.
$F_2 = W_2 * g$.
$F_3 = W_3 * g$.

Now, for error calculation we would have ;

$$\Delta F_w = F_w \cdot \left[\frac{\Delta F_1 (l_1+l_2) + F_1 (\Delta l_1 + \Delta l_2) + \Delta F_3 (l_2) + \Delta F_2 (\Delta l_3) + \Delta M}{F_1 (l_1+l_2) + F_3 (l_2) - F_2 (l_3) + M} \right] + F_w \cdot \left(\frac{\Delta l_2}{l_2} \right).$$

Here $\Delta l = 0.1$ cm [Least count error]

2. Rate of Water Flow

$$q = [\,(R_2 - R_1) * A\,] / t.$$

Here we have R_2 = Final level of water tank.
R_1 = Initial level of water tank.
t = time taken water level to fall
A = Area of cross section of tank.

Now by error calculation: $\frac{\Delta Q}{Q} = \frac{\Delta (R_2 - R_1)}{R_2 - R_1} + \frac{\Delta t}{t}$.

Here, we have $\Delta t = 1s$ [Error due to human reaction]
$\Delta l = 0.1cm$ [error due to least count]

3.) Velocity of Water Jet

$$V = Q/A_n$$

where, Q = Rate of flow of water.
A_n = Cross sectional area of the nozzle.

4.) Force due to water jet on a flat plane vane (Theoretical)

$$F_t = \rho * A_n * v^2 \quad \text{[equation (1)]}$$
$$= \rho * A_n * [Q/A_n]^2.$$

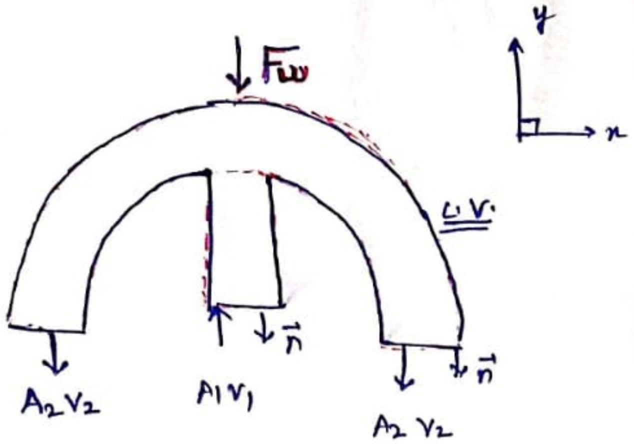
Here error calculation $\Delta F = F.\left[\frac{2\Delta Q}{Q} + \frac{2\Delta r}{r}\right]$

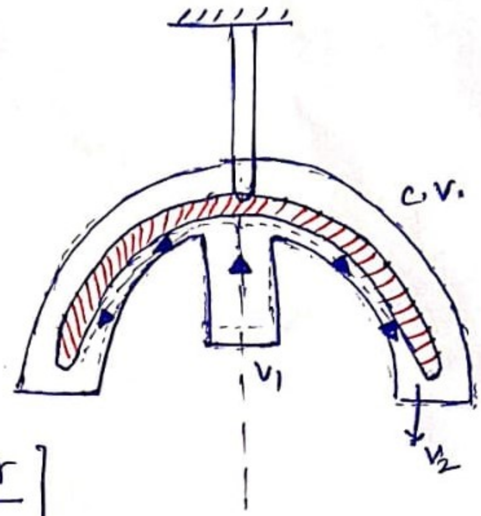
where r is the radius of the nozzle.

5.) Force due to water jeet on hemispherical vane (Theoretical)

Assumptions to consider:
(1.) $A_2 \approx A_1 \therefore V_1 \approx V_2$
(2) velocity near the vane = velocity at the exit of nozzle.
(3) negligible weight of vane

From RTT we would have:
$$-F_w = \int_{cs} \rho v (v n) dA = \rho v_1 (-v_1) A_1 + (\rho \cdot v_2 (v_2) A_2) * 2$$
$$\Rightarrow F_w = \rho v_1^2 A_1 + \rho A_1 v_1^2$$
$$F_w = 2 \rho A_1 v_1^2$$



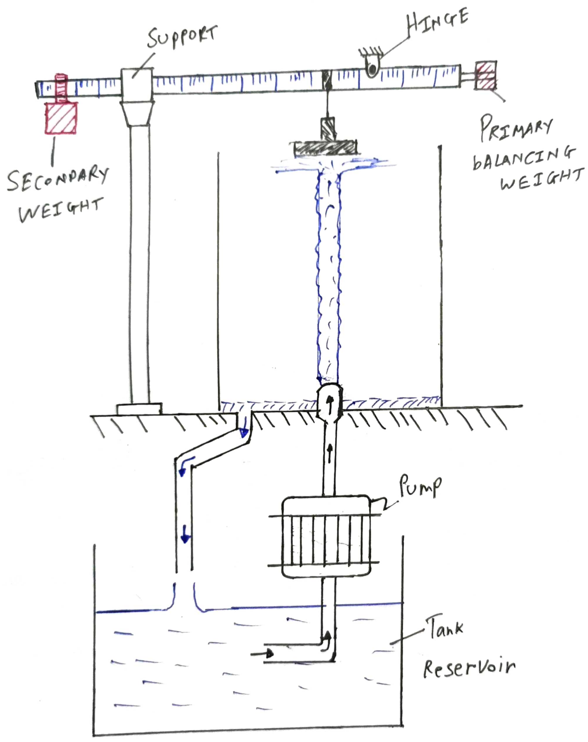


Error calculation :

$$\Delta F = F_o \left[\frac{2\Delta \theta}{\theta} + \frac{2\Delta r}{r} \right]$$

where, r is radius of nozzle.

2. Schematic of the experimental set up along with a photograph



3. Outline of experimental procedures

- Initially, set all the valves closed.
- Gradually ON the pump and open the valve of the jet.
- On opening the valve, the liquid jet from the nozzle strikes the vane at a constant force.
- Keep adjusting the distance of the primary weight to balance the moment created due to the jet.
- The next major step is to measure the flow rate. the water strikes the vane and gets collected in the secondary tank.
- Closing the outlet valve increases the water level and the time required for the same can be calculated.

4. Experimental Observations

Some Essentials

$W_{3,flat} = 346g$ → Weight of Steel Rod, Flate Plate Vane and ALuminium Disc

$W_{3,hemispherical} = 468g$ → Weight of Steel rod, Hemispherical vane, and Aluminium Disc

$W_2 = 960g$ → Secondary Balancing Weight

l_2 = 21 cm → Length between Vane and Hinge

$l_{3,Hemispherical} = 26cm$ → Length between Hinge and Secondary Weight for Hemispherical Vane (Varied for Flat Vane as given in table)

$\rho = 998Kg/m^3$ → Density of water

$A_n = 2.82 * 10^{-5}m^2$ → Cross-Section Of Nozzle

$A_t = 0.0885m^2$ → Area of Cross Section of Tank

$M = 1.48N.m$ → Moment of steel scale

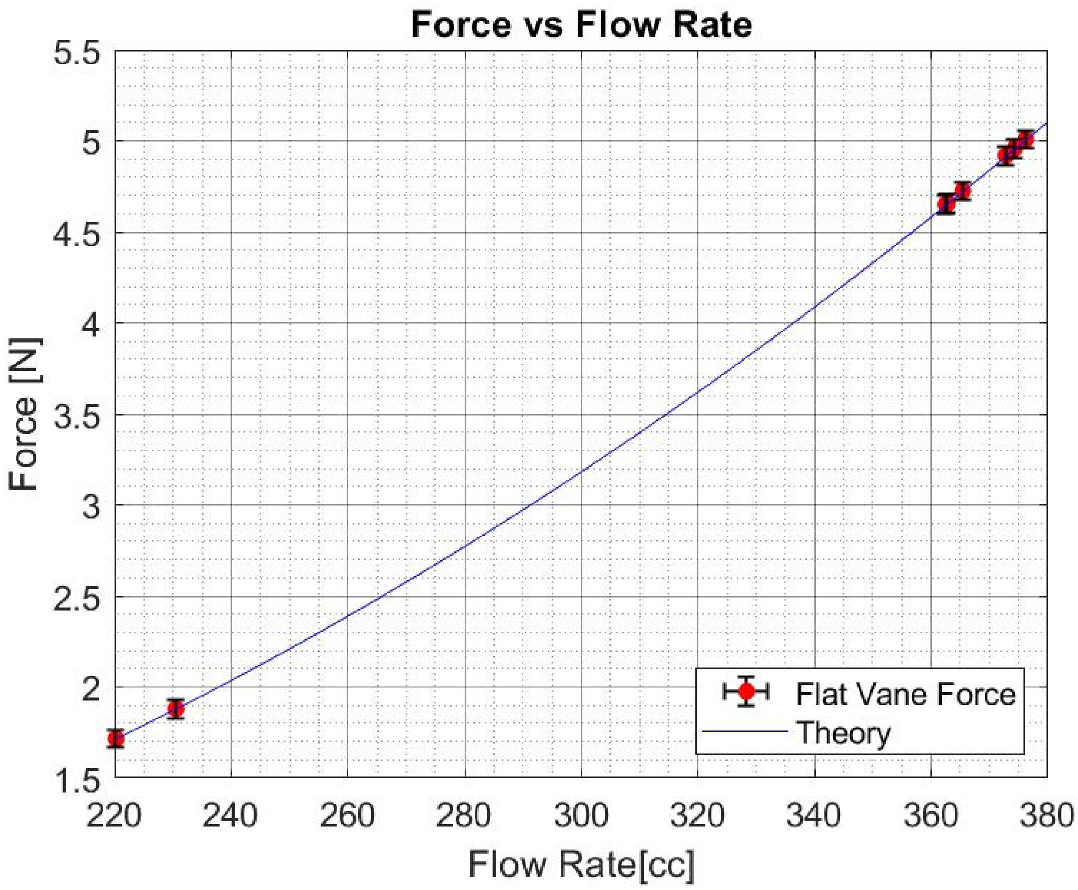
Flat Vane

SI NO	L1(cm)	L2(cm)	Time(sec)	Area(cmxcm)	Volume(cc)	Q(cc/s)	Q error (cc/s)	Q Avg(cc/s)
1	7	12.1	12.01	88500	4425	374.3205	31.24079834	367.4076
	15.5	20.5	12.11	88500	4425	365.3925	30.24586958	
	19	24	12.21	88500	4425	362.5098	29.76208427	
2	15.2	20.2	12.2	88500	4425	362.7386	29.80521985	370.5894333
	21	25	9.5	88500	4425	372.8521	39.3408025	
	14.8	18.8	9.41	88500	4425	376.1776	40.07040997	
3	19	24	20.1	88500	4425	220.2232	11.00042275	227.0791667
	12	22	38.4	88500	4425	230.5143	6.026027993	
	11.2	16.2	19.2	88500	4425	230.5	12.05130833	

Flow Rate

SI No	L1(cm)	L3(cm)	W1(g)	Force(mN)	error(±mN)
1	24.6	28.8	362.2	5209.6653	27.4
	24.7	28.8	362.2	5226.568	27.5
	24.8	28.8	362.2	5243.4707	27.4
2	33.4	20.9	160.2	5112.2487	35.2
	33.3	20.9	160.2	5104.7727	35.2
	33.2	20.9	160.2	5097.2967	35.3
3	24.1	30.1	254.3	2271.1493	16.2
	24	30.1	254.3	2259.282	16.3
	23.9	30.1	254.3	2247.4147	16.2

Force



For flat vane. (The errors were minimal and thus are not visible in the graphs. Due to the large scale, some of the points overlapped and are thus not visible)

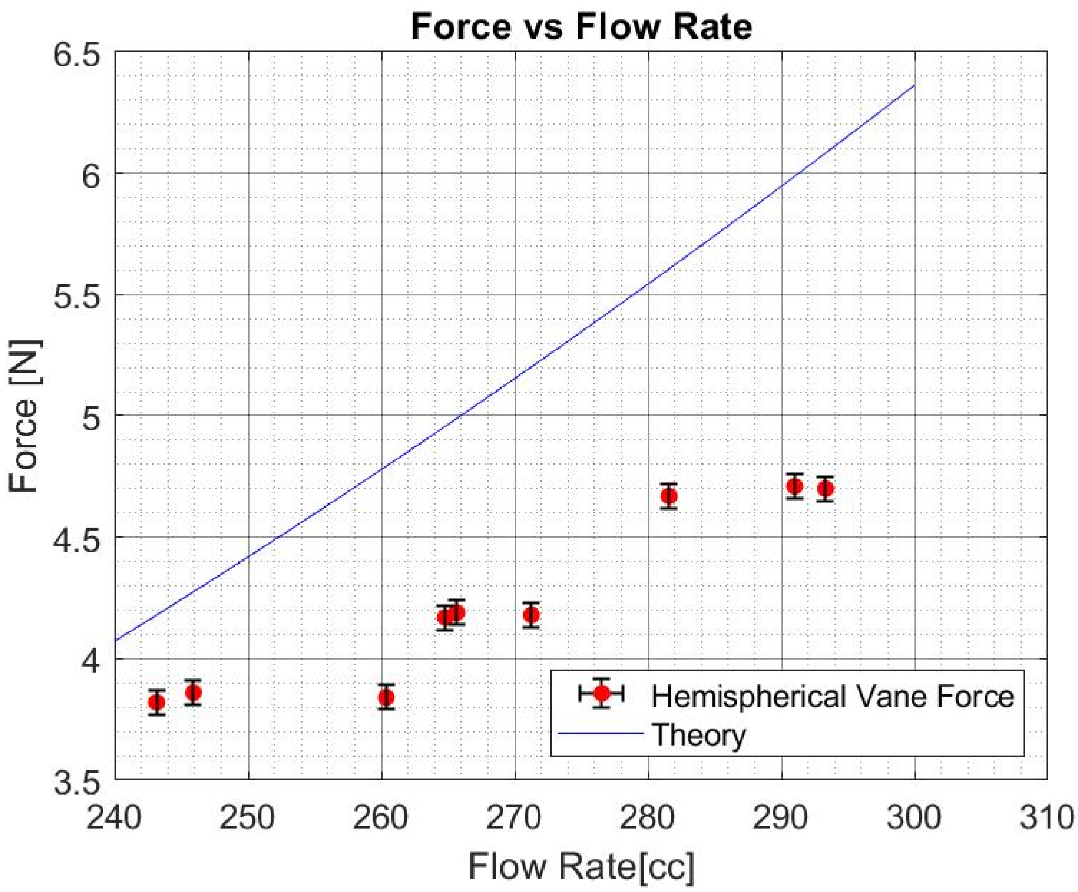
Hemispherical Vane

SI NO	L1(cm)	L2(cm)	Time(sec)	Area(cmxcm)	Volume(cc)	Q(cc/s)	Q error (cc/s)	Q Avg(cc/s)
1	16	21	17	88500	4425	260.3689	15.36789143	249.8063
	11	16	18	88500	4425	245.91	13.71084867	
	14.5	19.5	18.2	88500	4425	243.14	13.40796866	
2	21	26	15.21	88500	4425	291.0127	19.19118742	288.6414333
	13	18	15.09	88500	4425	293.33	19.49736713	
	21	26	15.72	88500	4425	281.5816	17.96863184	
3	14	19	16.71	88500	4425	264.7923	15.89929598	267.2336667
	12	17	16.31	88500	4425	271.26	16.68576641	
	18	23	16.66	88500	4425	265.6487	15.99842986	

Flow Rate

Sl no	L1 (cm)	W1 (g)	Force (mN)	Error (±mN)
	25.3	235.2	3839.774667	21.9
1	25.5	235.2	3861.726667	22
	25.1	235.2	3817.822667	21.9
	33.2	235.2	4706.878667	25.2
2	33.1	235.2	4695.902667	25.1
	32.9	235.2	4673.950667	25.1
	28.3	235.2	4169.054667	23.1
3	28.4	235.2	4180.030667	23.2
	28.5	235.2	4191.006667	23.2

Force



For Hemispherical Vane

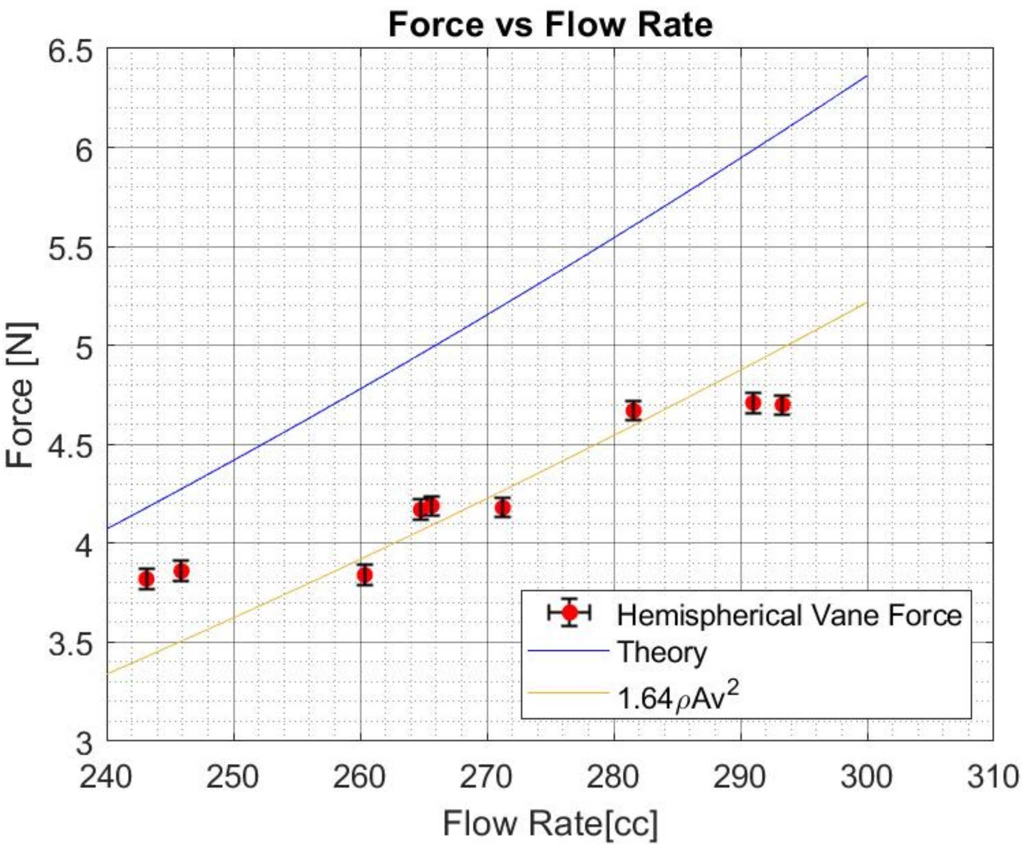
5. Observations and Conclusions

There seems to be minimal descrepancy in case of flat vane. It confirms the working of experimental setup and the precision of our readings. It also confirms that the assumption that we made regarding the flow were all true.

But when we compare the theoretical and experimental for hemispherical vane, it's clear that some of the assumption we made were wrong. The one primary assumption that could justify such large deviation is that we assume in our theory that water doesn't gets deflected back at the same velocity as it came. There might be high frictional losses over there too.

Other Possible reasons for the deviation include as follow:

1. For the first reading in hemispherical vane, we can see that flow rate differed widely from 240 cubic centimetre per second to 260 cc/sec. The same is seen for the other readings in the hemispherical phase. This indicates that motor wasn't able to give a steady supply in later phase. (Possibly because it had already been running for a long time.)
2. If we evaluate force as $F = 1.64\rho A v^2$, we see that the line more closely resembles the data. This gives us 2 possibilities. Either the hemispherical vane deflected the water back at 80% of the incoming velocity. Or it only deflected back 64% of the water at v, the rest fell at the flat surface. This lead us to conclusion that hemispherical vane wasn't completely round and 36% of the jet area ($1.015 * 10^{-5} m^2$) was actually flat.



The combination of above 2 reasons successfully explains the deviation.