AM5820
Wind Tunnel and Numerical Experiments

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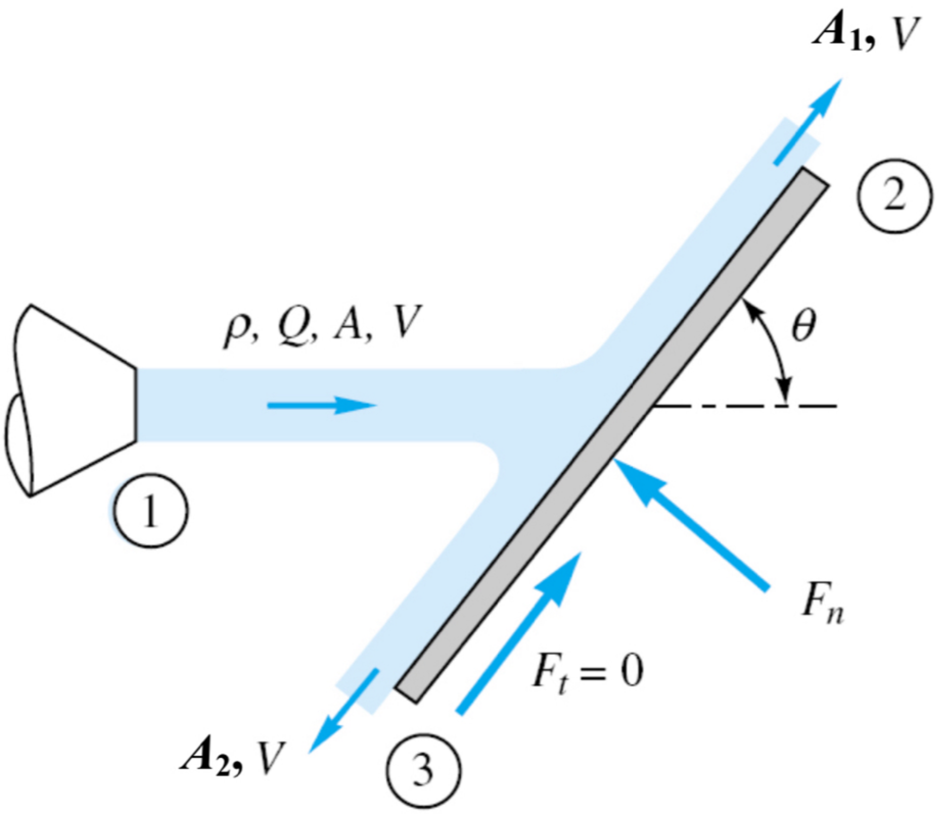
Impact of jet



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Objective

The aim of the experiment is to find out the force exerted by a fluid jet on following surfaces:

1) Horizontal flat plate
2) Hemispherical shell

Introduction

In solid mechanics, Newton's second law of motion states that a mass that is accelerated requires a force that is equal to the product of the mass and acceleration. The analogy to Newton's second law in fluid mechanics is known as the Impulse momentum theorem. According to Impulse momentum theorem, the impulse applied to an object will be equal to the change in its momentum

When a jet of fluid strikes a solid surface at any angle it will not rebound and rather move over the surface tangentially, which causes a change in linear momentum. This change in linear momentum results in the water jet exerting a force on the surface it is impacting.

By applying the Impulse momentum theorem, the components of this force can be resolved. To apply this theorem, following conditions needs to be satisfied:

- The fluid should be incompressible
- The surface tension forces are negligibly small
- The flow is steady
- The velocity distribution across the cross-section is uniform.

Practical Applications

It is very useful to analyse the impact forces of fluid jet when it comes to the application of turbomachinery & hydraulic equipment's.

Steam water turbines are widely used throughout the world to generate power. By allowing fluid under pressure to strike the vanes of a turbine wheel, mechanical work can be produced. Rotational motion is then produced by the force generated as the jet strikes the vanes.

Water jet momentum in civil engineering is used in water dams (to move the water turbines and generate electricity) and in water pressure test in building piping system (Hydraulic pressure test). One of the common types of water turbines is Pelton wheel.

In this type of water turbine, one or more water jets are directed tangentially on to a vanes or buckets that are fastened on the rim of the turbine disc. The impact of the water on the vanes generates a torque on the wheel causing it to rotate and to develop power.

Equipment description

The apparatus consists of a crystal-clear acrylic cylinder. It is so clear that we can see the impinging of the water jet on the surface & how it is deflecting back from the surface. There is a nozzle attached to the center of the bottom of the cylinder through which we can pass the fluid jet. There are holes at the bottom of the cylinder which acts as outlets. At the top of the surface a stem is attached. In that stem a weighting pan is inserted on which different number of weights can be placed in order to counterbalance the fluid force. Also, at the top of the cylinder there is a pointer which helps to locate the equilibrium position. Here, we have an equipment called rotameter which will measure the flow rate (liters per hour) that is coming through the jet by the inlet control valve.

Fig. Apparatus for Impact of jet experiment

Experimental procedure

Remove the top plate and transparent cylinder from the equipment by releasing the knurled nuts and measure and record the nozzle's exit diameter. Screw the flat plate onto the end of the shaft and replace the cylinder. Attach the inlet tube to the bench's quick-release connector. Replace the clear cylinder's top plate, but do not tighten the three knurled nuts. Change the feet to level the cylinder using the spirit level attached to the top plate. Replace the three knurled nuts, then tighten them in order until the top plate is horizontal. The top plate would be damaged if the knurled nuts are overtightened. The nuts can only be tightened to the point that the plate is even. Determine that the stem is free to move and that the spring under the weight pan is supporting it. Change the height of the level gauge until it aligns with the datum line on the weight pan when there are no weights on the weight pan. By gently oscillating the pan, you can ensure that the location is right.

Flat plate

Switch on the pump & slowly increase the flow rate by adjusting the inlet valve. As, we increase the flow rate the rotameter head will move upward. The top head of the rotameter will give the value of corresponding flow rate. Fix the flow rate at a known value.

Now, we can see that the fluid jet coming from the center of the bottom of the cylinder is hitting the flat plate. As a result, the stem is pushed upward because there is no counterbalancing force for the force exerted by fluid jet on the flat plate. We can press the stem by our hand and bring it to the equilibrium position. Our goal is to find the force exerted by the hand and compare it with the theoretical value of the force. In order to find out this force we will add known number of masses one by one. The stem and the weighting pan also possess some dead weight which we have to add to the total weight while calculating the net force. As we keep adding the weights the weighing pan will fall. We might have to adjust or rotate the weighting pan little bit to check if it has reached equilibrium. If the weighing pan going below equilibrium (pressing the spring), then we have added more weight than force exerted by fluid jet. Now, we have to remove the last weight put on the weighing pan & check for smaller weights. By this trial-and-error method we can find the exact weight. By adding all the weights & multiplying with acceleration due to gravity we can find the equivalent force experimentally.

To calculate the theoretical force, we know the jet diameter & the flow rate. By this we can calculate the velocity, & from equations we can calculate the theoretical force. Then we can compare the theoretical & experimental value of forces.

Hemispherical shell

Now, replace the flat plate with a hemispherical shell & repeat the procedure exactly as we did for the flat plate as specified above.

Raw data & Results

$Water\ with\ following\ properties, is\ assumed\ to\ be\ the\ working\ fluid\ for\ both\ the\ cases$

$$\rho = \frac{1000kg}{m^3},\ \ \mu = 8.9 \times 10^{-4} Pa.s$$

Flat plate

$Dead\ weight = 76gm$

$Diameter, d = 6mm$

$Area, a = \left(\frac{\pi}{4}\right) d^2$

$\Rightarrow Area, a = \left(\frac{\pi}{4}\right) (6mm)^2$

$\Rightarrow Area, a = 28.2743mm^2$

S. No.	$Flow\ rate,$ Q (litres/hr)	Total mass (kg)	$Velocity,$ $v = \frac{Q}{a}\ (m/s)$	$F_{exp}(N)$	$F_{th}(N)$	$Reynolds\ Number,\ Re$	$\frac{F_{exp}}{1/2\,\rho a v^2}$
1	800	0.157	7.85951278	2.28573	1.7465584	52985.4794	2.61741034
2	900	0.207	8.84195188	2.77623	2.21048797	59608.6643	2.51187072
3	1000	0.257	9.82439098	3.26673	2.72899749	66231.8493	2.39408794
4	1200	0.392	11.7892692	4.59108	3.92975639	79478.2191	2.33657232
5	1350	0.482	13.2629278	5.47398	4.97359793	89412.9965	2.20121533
6	1400	0.507	13.7541474	5.71923	5.34883509	92724.589	2.13849554

Hemispherical shell

$Dead\ weight = 76gm$

$Diameter, d = 8mm$

$Area, a = \left(\frac{\pi}{4}\right) d^2$

$\Rightarrow Area, a = \left(\frac{\pi}{4}\right)(8mm)^2$

$\Rightarrow Area, a = 50.2655mm^2$

S. No.	$Flow\ rate$, Q (litres/hr)	Total mass (kg)	$Velocity$, $v = \frac{Q}{a}$ (m/s)	$F_{exp}(N)$	$F_{th}(N)$	$Reynolds\ Number, Re$	$\frac{F_{exp}}{1/2\,\rho a v^2}$
1	1000	0.293	5.52621137	3.61989	3.07011743	49673.8101	4.71628865
2	1200	0.444	6.63145365	5.1012	4.4209691	59608.5721	4.61545863
3	1400	0.623	7.73669592	6.85719	6.01743016	69543.3341	4.55821825
4	1600	0.738	8.8419382	7.98534	7.85950062	79478.0962	4.06404447
5	1800	0.863	9.94718047	9.21159	9.94718047	89412.8582	3.70420142
6	2000	1.185	11.0524227	12.37041	12.2804697	99347.6202	4.02929539

Sample Calculation

Flat plate

The jet of water striking the plate will move along the plate, perpendicular to the initial direction because the plate is kept at right angle to the jet i.e. $\theta = 90^o$.

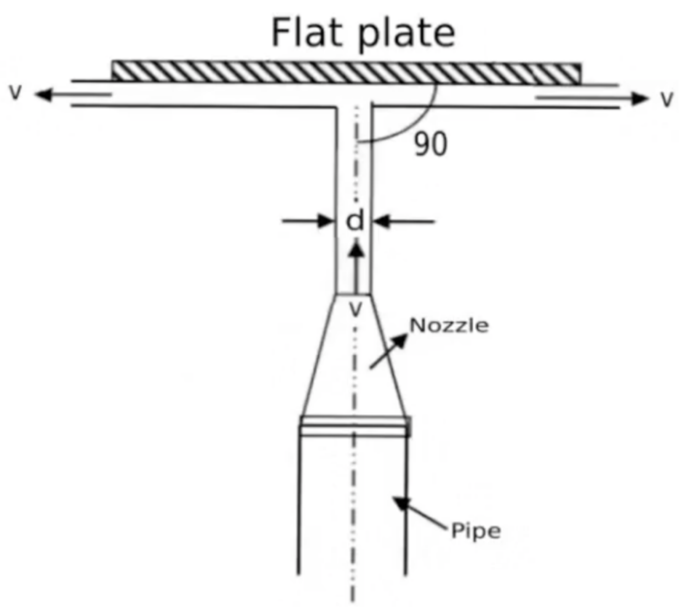


Fig. Impact of jet on a flat plate

Force exerted by the jet on the flat plate in the direction of jet (along x-direction) is calculated as follows:

$$F_{th} = \text{mass rate of flow} \times (\text{initial velocity} - \text{final velocity})$$

$$\Rightarrow F_{th} = \rho av(v - 0)$$

$$\Rightarrow F_{th} = \rho a v^2$$

$$\Rightarrow \boxed{F_{th} = \rho Q v}$$

F_{th} is theoretically calculated force equivalent to the reaction force from the flat plate to attain an equilibrium position.

Impact velocity can be calculated as $v = Q/a$

$$Net\ weight = Total\ weight + Dead\ weight$$

$$\boxed{F_{exp} = Net\ weight \times g}$$

F_{exp} is experimentally calculated force equivalent to the reaction force from the flat plate to attain an equilibrium position.

<u>Hemispherical shell</u>

After striking the vane the jet gets divided and glides over the surface and leaves the vane tangentially with same velocity v

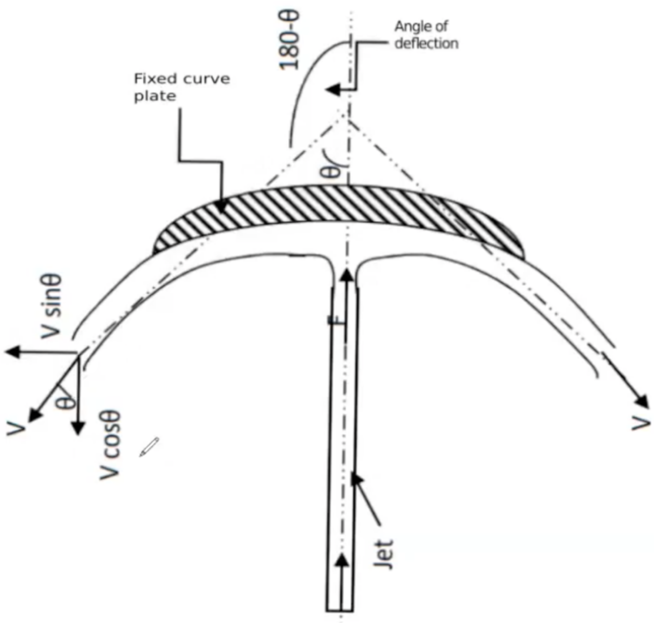


Fig. Impact of jet on hemi-spherical vane

- The velocity at the outlet of the plate can be resolved into two components, one in the direction of the jet and the other perpendicular to the direction of the jet
- Component of velocity in the direction of the jet is given by $-v\cos\theta$
- Component of velocity perpendicular to the jet is given by $v\sin\theta$

- Force exerted by the jet in the direction of jet is given by

$$F_x = \rho a v\big(v - (-v\cos\theta)\big) = \rho a v^2(1 + \cos\theta)$$

- Similarly, the force exerted by the jet in the direction normal to the jet direction is given by

$$F_y = \rho a v(0 - v\sin\theta) = \rho a v^2 \sin\theta$$

- When $\theta = 0$, the vane became hemi-spherical and $\cos 0 = 1, \sin 0 = 0$. So, the value of the forces will become

$$F_x = \rho a v^2(1 + 1) = 2\rho a v^2 = 2\rho \mathrm{Qv}$$

$$F_y = 0$$

We know,

$$F_{th} = \sqrt{{F_x}^2 + {F_y}^2}$$

$$\Rightarrow \boxed{F_{th} = 2\rho \mathrm{Qv}}$$

F_{th} is theoretically calculated force equivalent to the reaction force from the hemispherical shell to attain an equilibrium position.

Impact velocity can be calculated as $v = Q/a$

$$Net\ weight = Total\ weight + Dead\ weight$$

$$\boxed{F_{exp} = Net\ weight \times g}$$

F_{exp} is experimentally calculated force equivalent to the reaction force from the hemispherical shell to attain an equilibrium position.

where,

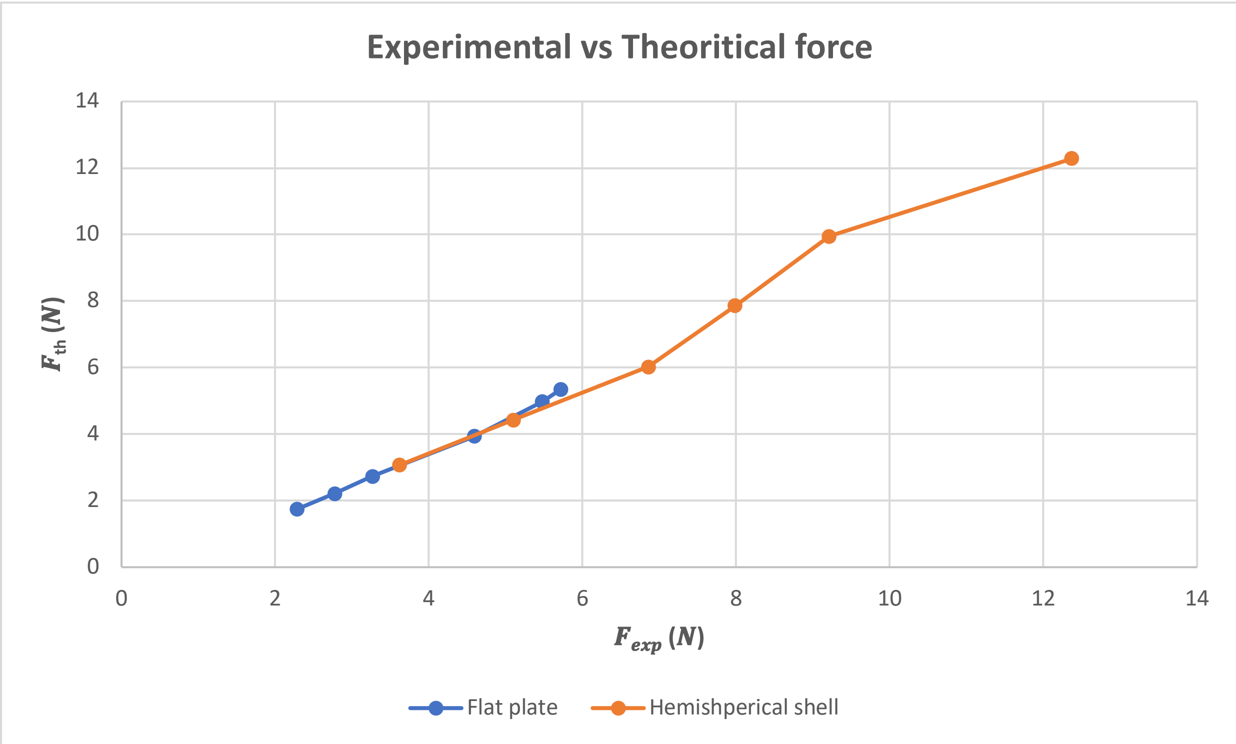
$Q\ is\ the\ volume\ flow\ rate\ of\ the\ jet$

$a\ is\ the\ area\ of\ cross\ section\ of\ the\ jet$

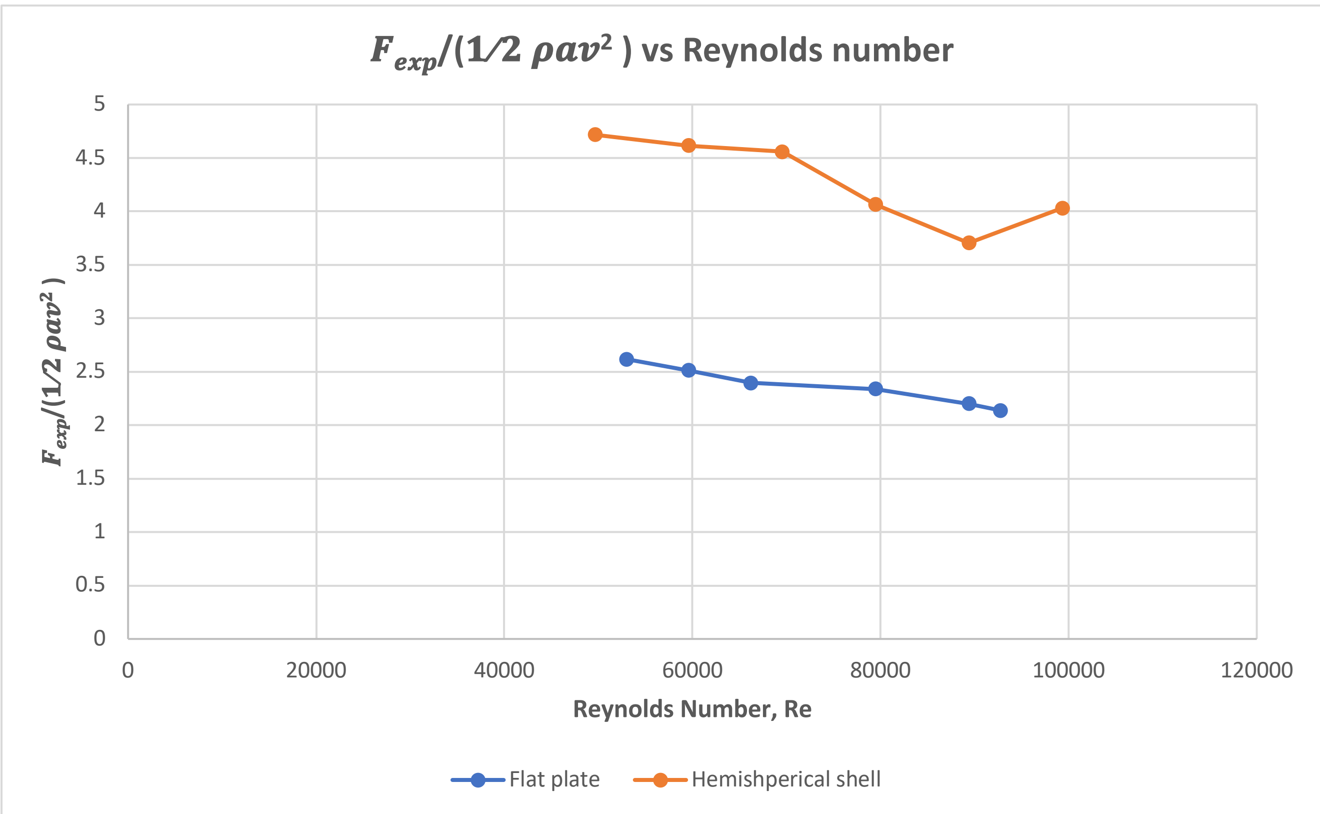
$g\ is\ acceleration\ due\ to\ gravity$

Plot

- Comparative graph of F_{exp} vs F_{th} is plotted as follows



- We know, $Reynolds\ Number, Re = \frac{\rho v d}{\mu}$
- Comparative graph of $\frac{F_{exp}}{1/_2 \rho a v^2}$ vs Reynolds number is plotted as follows



Conclusion

From the first graph it can be seen that for impact force for hemispherical shell is more than for flat plate. The second graph shows that drag coefficient decreases with increase in Reynolds number for both the cases. Also, the value of ratio $\frac{F_{exp}}{1/_2\rho a v^2}$ is lower for flat plate case as compared to hemispherical shell case.

Remarks

a) Why is the force independent of the area of the plate/shell?

Ans: According to the impulse-momentum principle, the net force acting on a fluid mass is equal to the rate of change of momentum of flow in that direction. This rate of change on momentum depends only on the mass flow rate of the fluid & velocity of the fluid. Hence, the impact force is independent of the area of the plate/shell

b) What is the slope of the F_{exp} vs F_{th} plot? What should the ideal value of this slope be? If the slope is different from the ideal value, why is it different?

Ans: For flat plate case slope is 1.0106 & for hemispherical shell case the slope is 1.0292.

The ideal value of this slope should be 1 for both the cases.

The slope is different from ideal value due to several errors made during the experiment:-

- Parallax errors could have occurred due the differences in eye level of the experimenter leading to a result that is higher or lower than the ideal results
- Losses such as frictional losses were not considered
- The viscosity effects were not included in the calculation of the theoretical value

c) What is the significance of the variation of Reynolds number that you observe from your experiments?

Ans: As the variation of the plot of $\frac{F_{exp}}{1/_2\rho a v^2}$ vs Reynolds number for the two cases is almost similar, therefore we can say that at lower values of Reynolds number (less than 10^5), the shape of the body doesn't have a major influence on the impact force