# Force Produced by Impingement of a Fluid Jet on a Deflector

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## Abstract

An understanding of fluid jets and the forces they can produce are important to engineers in the design of turbines and in fluids flowing through pipelines at elevated pressure. The purpose of this paper is to describe the experimental equipment and its use for measuring the flow rate at which an impinging fluid jet will lift a weighted deflector. The experimental results showed that the calculated jet force ($F_j = \rho Q v$) ranged from 2.4-3.7 $N$ (0.54-0.83 $lb_f$) for flow rates ranging from 2.2-2.8 $\frac{m^3}{hr}$ (9.8-12.2 $\frac{gal}{min}$ or $gpm$). The jet force was 3.5-19.8% higher than the calculated force due to gravity based on the mass of the deflector ($F_g = mg$), indicating that there are experimental errors which need to be corrected.

## Introduction

Engineering has its roots in applied science and mathematics, blending the skills of analytical thinking, design and problem solving. Clearly, engineering students benefit from the "hands-on" aspects of their education such as co-ops/internships, research and undergraduate laboratories. Despite this fact, there has been a pedagogical shift toward classroom and lecture-based engineering education, and away from laboratory education, over the past 30 years.[1-3] Feisel and Rosa[4] attribute this shift to the increasing complexity and cost of laboratory equipment and the change in motivation of the faculty, but also note that that the integration of the computer into the laboratory has been a positive influence.

Fortunately, the trend away from laboratory instruction is reversing, and laboratory pedagogy is now recognized as a fertile ground for engineering research.[1] This is important since a majority of engineering students learn best when exposed to hands-on exercises and activities.[4] Although there have been a variety of approaches for developing hands-on activities, Penney and Clausen[5-15] focused on the development of fluids and heat transfer exercises that can be used in the undergraduate laboratory or as demonstrations of important concepts in the classroom. Just as important, each of these activities can be easily constructed from materials purchased at minimal cost or simply found in most engineering shops.

The purpose of this paper is to describe the experimental equipment and its use for measuring the flow rate at which an impinging fluid jet will lift a weighted deflector. Turbines are often used to recover energy from a fluid. In a Pelton wheel turbine, shown in Figure 1, the energy is recovered by directing the fluid onto veins or buckets. The force due to the impinging fluid rotates the turbine, and this rotation is used to convert the mechanical power into electrical power.[16] The force of the impinging jet of liquid on the veins or buckets needs to be calculated to determine the output of the turbine. Another area of interest to engineers is the force produced by flowing fluids in pipelines. The venting of water from a vessel at 21.8 *kPa* gauge (150 *psig*) could easily produce a water jet velocity of 150,000 $\frac{m}{hr}$ (140 $\frac{ft}{sec}$). This velocity through a 10 *cm* (4 *in*) vent line would have a flow rate of 1249 $\frac{m^3}{hr}$ (5,500 $\frac{gal}{min}$ or *gpm*) and produce a resultant force of 21,000 *N* (4,700 $lb_f$) on a 90° elbow, as calculated by *The Engineering Toolbox*.[17] A force of this magnitude would require careful support of the piping to prevent failure from the bending moment on the pipe.


Figure 1. Pelton Wheel (from G. Dewey, http://www.rhino3d.com/gallery/6/30348)

The specific objectives of this activity as a laboratory experiment in CHEG 3232, Chemical Engineering Laboratory II, were to:

- Experimentally determine the flow rate at which an impinging fluid jet would lift a deflector
- Develop a simple mathematical model to predict the force of the jet
- Compare the predicted force from the mathematical model to the force obtained from the experimental data

## Equipment and Procedures

The following paragraphs describe the equipment and materials, experimental procedures and safety considerations in performing the experiment.

### *Equipment List*

The equipment and supplies used in the experiment were as follows:

- 0.75 *kW* (1 *hp*) regenerative pump, from Atrepo USA, serial no. 82009
- Jet deflector, manufactured from a 0.0038 $m^3$ ( 1 *gal*) PETE, pretzel container, installed with a center pipe
- 1.27 *cm* (½ *in*) copper pipe, threaded at one end, 52.7 *cm* (20.75 *in*) long
- 0-690 *kPa* (0-100 *psi*) pressure gauge, manufactured by Nosha
- Rotameter, Brooks Instrument Division, Emerson Electric Co., Model: 1305D10A3A1A

- 2.5 *cm* (1 *in*) PVC ball valve
- Generic meter stick
- Carpenter's hammer
- 0.019 $m^3$ (5 *gal*) polyethylene pail
- 1.9 *cm* ( $\frac{3}{4}$ *in*) galvanized steel pipe nipple, 5.1 *cm* (2 *in*) long
- 1.3 *cm* (½ *in*) brass pipe nipple, 7.6 *cm* (3 *in*) long, 2
- Aluminum bar for support of copper tube, 2, 15.2 *cm* x 5.1 *cm* x 1.6 *cm* (6 *in* x 2 *in* x 0.625 *in)*
- Stainless steel disk base to support the copper tube in a vertical upright position, 12.7 *cm* dia x 1.6 *cm* thick (5 *in* dia x $\frac{5}{8}$ *in* thick)
- Assorted galvanized steel washers to serve as weights
- Hose clamp
- 1.9 *cm* ( $\frac{3}{4}$ *in*) brass union
- Bushing, 1.9 *cm* male to 1.3 *cm* female ( $\frac{3}{4}$ *in* male to $\frac{1}{2}$ *in* female)
- 1.3 *cm* ( $\frac{1}{2}$ *in*) 90° elbow, galvanized steel, 2
- PVC or Tygon tubing
- Stand for bucket and pump
- Power strip
- Dental floss
- Electrical tape
- Digital calipers
- Laboratory scale

***Experimental Apparatus***

Figure 2 is a photograph of the experimental apparatus, containing the regenerative pump, carpenter's hammer, dental floss, jet deflector, pail, power strip, pressure gauge, rotameter, tubing, stand, ball valve, and yardstick. Figure 3 is a photograph of the jet piping, which includes the all of the fittings, aluminum bars, weight, pipe, and hose clamp. Figure 4 is a photograph of the jet deflector, which was constructed from a 1 *gal* pretzel container, installed with a center tube. The 1.6 *cm* ( $\frac{5}{8}$ *in*) PVC center pipe was 15.2 *cm* (6 *in*) long. All threads (3.2 *mm*-32 or $\frac{1}{8}$ *in*-32) were used as supports. Figure 5 is a photograph of the placement of the washers on the deflector, used to add weight to the container.


Figure 2.  Photograph of the Experimental Apparatus


Figure 3.  Photograph of the Jet Piping

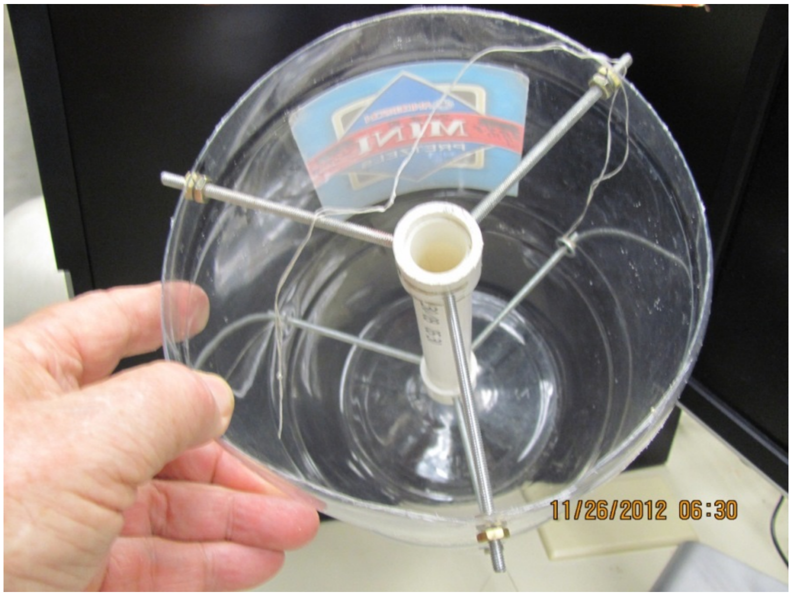


Figure 4. Photograph of the Jet Deflector


Figure 5. Photograph of the Placement of the Washers as Weight

***Experimental Set-up***

The following procedure was used to set up the equipment in preparation for experimentation:

- Measure the dimensions of all of the equipment using the meter stick and digital calipers.
- Weigh the jet deflector and each washer using the laboratory scale.

- Pour water into the 0.019 $m^3$ (5 *gal*) polyethylene pail until it is half full.
- Place the jet piping into the pail.
- Place the jet deflector on the pipe.
- Tie the jet deflector to the pail using dental floss, but leave the floss loose to allow the jet deflector to float.
- Plug the regenerative pump into the power strip and the power strip into a power source.
- Recruit four people to perform the experiment.
  - One person will stand by the pump to turn it off in case of an upset.
  - One person will adjust the ball valve and place washers on the jet deflector.
  - One person will monitor the jet deflector to determine when it begins to float and take the rotameter readings.
  - One person will record the weight of the jet deflector and washers and the rotameter readings.

***Experimental Procedure***

The following procedure was used in conducting the experiment:

- Turn on the regenerative pump.
- Using the carpenter's hammer, adjust the ball valve until the jet deflector floats.
- Record the total weight of the jet deflector and the rotameter reading. In performing the experiment, the students took rotameter readings at the top of the float.
- Add two 1.3 *cm* (½ *in*) washers to the top of the jet deflector and repeat the experiment. Do this several times for a total of six experiments.

***Safety***

As in all laboratory exercises, always wear safety goggles, closed toe shoes and pants throughout the experiment.

**Experimental Results**

Table 1 shows the data from the experiment, shown as the required flow rate for a given total deflector weight. As more weight is added to the deflector, the flow rate of water increases to float the deflector.

Table 1. Experimental Data

| **Total Deflector Weight, *g*** | **Flow Rate, $\frac{m^3}{hr}$** | **Flow Rate, *gpm*** |
|---|---|---|
| 204.8 | 2.2 | 9.8 |
| 239.0 | 2.3 | 10.2 |
| 273.2 | 2.5 | 10.9 |
| 307.5 | 2.6 | 11.4 |
| 341.9 | 2.7 | 11.9 |
| 367.5 | 2.8 | 12.2 |

**Data Reduction**

The force of an impinging jet, which deflects 90°, is given by the equation[18]

$$F_j = \rho Q v \qquad (1)$$

The force due to gravity is given by the equation

$$F_g = mg \qquad (2)$$

The jet deflector will float when the force of the impinging jet, $F_j$, equals the force due to gravity, $F_g$, of the jet deflector plus any added weight.

***Statistical Analysis***

The deviation between experimental force due to gravity, $F_g$, and the jet force, $F_j$, may be calculated by the equation

$$\Delta R_m = \frac{(F_g - F_j)}{F_j} \qquad (3)$$

The coefficient of variance between the force due to gravity and the jet force is found from the equation

$$c_v = \left[\frac{1}{n}\left(\sum \Delta R_m\right)^{0.5}\right] \qquad (4)$$

***Sample Calculations***

Using Run 1 in Table 1 (a deflector weight of 204.8 $g$ allowing a flow rate of 2.2 $\frac{m^3}{hr}$ or 9.8 *gpm*), the calculations of Equations 1-4 were performed. The force of the impinging jet, $F_j$, is found from Equation 1 as:

$$F_j = \rho Q v = (1000\,\frac{kg}{m^3})(2.2\,\frac{m^3}{hr})\left[\left(2.2\,\frac{m^3}{hr}\right)\left(\frac{4}{\pi(0.01422m)^2}\right)\right]\left(\frac{hr}{3600sec}\right) = 2.40\ N$$

where the velocity, $v$, is the flow rate divided by the cross-sectional area of the tube. The force due to gravity is given by Equation 2 as:

$$F_g = mg = (204.8\ g)(\frac{kg}{1000g})(9.8\,\frac{m}{sec^2}) = 2.01\ N$$

where the acceleration of gravity is 9.8 $\frac{m}{sec^2}$.

The deviation between experimental force due to gravity and the jet force, $\Delta R_m$, is calculated by Equation 3 as:

$$\Delta R_m = \frac{(F_g - F_j)}{F_j} = \frac{2.01N - 2.40N}{2.01N} = -0.198$$

Finally, the coefficient of variance, $c_v$, is calculated by summing the deviations using Equation 4.

**Discussion of Results**

Table 2 shows the force due to gravity based on the mass of the deflector and added weights and the calculated jet force as a function of the volumetric flow rate, as well as the deviation between these results. The results are also plotted in Figure 6. As is noted, the jet force was consistently higher than the gravitational force, most likely because the jet did not deflect at exactly 90° and erroneous flow rates were obtained because the rotameter was not calibrated. At the lowest flow rate, there was an error of 19.8% between the two forces. At the highest flow rate, the error was only 3.5 %. The coefficient of variance was 5.2%.

Table 2. Gravitational Force and Jet Force as a Function of Flow Rate

| **Flow Rate, $\frac{m^3}{hr}$ (*gpm*)** | Force, *N* | | $\Delta R_m$ |
|---|---|---|---|
| | Gravitational | Jet | |
| 2.2 (9.8) | 2.01 | 2.40 | -0.198 |
| 2.3 (10.2) | 2.34 | 2.60 | -0.112 |
| 2.5 (10.9) | 2.68 | 2.97 | -0.111 |
| 2.6 (11.4) | 3.01 | 3.25 | -0.080 |
| 2.7 (11.9) | 3.35 | 3.55 | -0.058 |
| 2.8 (12.2) | 3.60 | 3.73 | -0.035 |

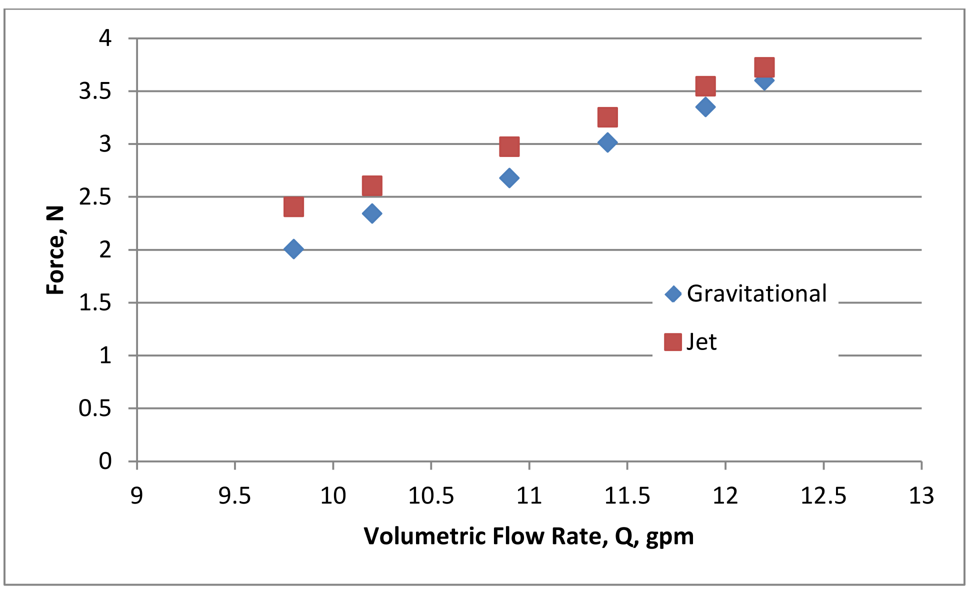


Figure 6. Plot of Gravitational Force and Jet Force as a Function of Flow Rate

**Conclusions**

1. The force due to gravity based on the mass of the deflector and added weights and the calculated jet force matched very well (within 3.5%) at high flow rates.
2. The coefficient of variance was 5.2%, which indicates that there are experimental errors which need to be corrected.
3. The errors in the experiment are most likely due to the jet not being deflected at exactly 90° and inaccurate rotameter readings.

## Nomenclature

| | |
|---|---|
| $c_v$ | Coefficient of variance |
| $F_g$ | Force due to gravity, N |
| $F_j$ | Force due to the fluid jet, N |
| $g$ | Acceleration due to gravity, $m/s^2$ |
| $m$ | Total mass of the jet deflector and all added weight, kg |
| $n$ | Total number of experimental data points |
| $Q$ | Volumetric flow rate, $m^3/s$ |
| $v$ | Velocity of the fluid, m/s |
| $\Delta R_m$ | Deviation between experimental force due to gravity and the jet force |
| $\rho$ | Density of the fluid, $kg/m^3$ |

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