THE BLACK HOLE SCIENCE INTERNSHIP PROGRAMME 2025

DESIGN OF A WIRTZ PUMP

Project Report

Submitted by:

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1. Introduction

In today's world, inaccessibility to water is a persistent issue as the world grapples with sustainable management of resources, driving the need for innovative pumping technologies. In 1746, Andreas Wirtz, a Zürich pewterer, invented a novel design for a water-lifting pump, now commonly known as the Wirtz Pump [1]. The earliest known published description of this pump was written by J. H. Ziegler in 1766, describing a stream-wheel used to raise water for a nearby dye house just outside Zürich. Although little is known about the circumstances surrounding the creation of this pump, it is probable that Wirtz combined his knowledge of existing technologies such as the Archimedes' screw and Persian wheel with his own skills as a pewterer to build this spiral pump [2].

The Wirtz Pump comprises a coiled pipe mounted on a rotating wheel. Its structure is such that the outermost loop of the pipe serves as an inlet to scoop plugs of water as the pump rotates while partially submerged in a water body. The innermost loop of the pipe serves as the outlet that pumps water to greater elevations than the pump itself, unlike the Archimedes' screw and Persian wheel. Inside the pipe, the alteration of the plugs of air (low density fluid) with plugs of water (high density fluid) is essential to the working of the pump: the displacement of the high-density fluid by the low-density fluid generates a pressure difference which is conveyed through a rotatory fitting to a delivery pipe to pump water to greater heights. Therefore, this pump works only when it is submerged at times in water and at times in air.

The design of the Wirtz Pump falls into two categories: helical pump, in which the radius of the pipe remains constant throughout the arrangement, and the spiral pump, in which the radius of the pipe successively decreases with each turn. For pumping to low heads, this pump is satisfactory as it does not require fuel; it can function independently in flowing streams and rivers, be hand-turned, or even driven by external power such as a motor, which shall be investigated in this report.

Historically, this pump is reported to have been successful. In 1784, a machine in Archangelsky was recorded to have raised "a hogshead of water in a minute to an elevation of seventy-four feet, through a pipe seven-hundred-sixty feet long" [2]. However, with the advent of modern steam engines, these slow turning pumps have become largely obsolete, though it is still useful in demonstrating principles of hydrostatics and hydrodynamics.

This report will explore the modelling of a helical Wirtz pump, the effects of varying key design parameters and conclude with a summary of our findings on its performance and efficiency. Figure 1 below shows an early schematic drawing of the pump.

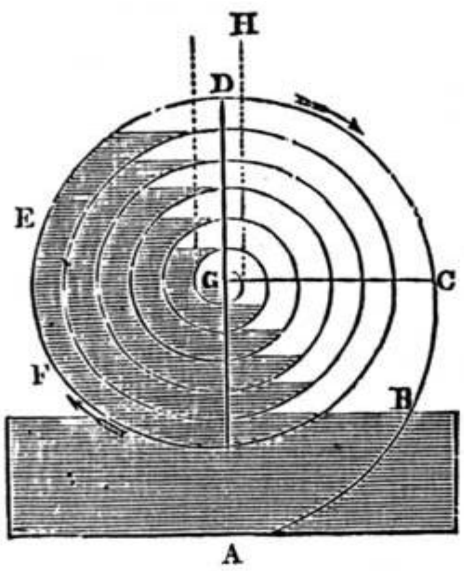

Figure 1: A drawing of Wirtz Pump from 1842 [2].

2. Experimental setup

The Wirtz pump constructed in this project is shown in Figure 2 below. For the purpose of this experiment, a metallic stand of dimensions 38.0 cm × 31.0 cm × 31.0 cm was used as a platform to support a plastic tank measuring 37.5 cm × 24.0 cm × 11.0 cm wherein the Wirtz pump was placed. A custom wooden stand was constructed and affixed to the outer end of the metallic stand with the help of binding wires. A 12 – 18 V DC motor, powered by twelve 1.5 V batteries, was mounted on this stand. Two wooden blocks were attached parallel to the motor to hold it in place, and further stability was ensured by nailing binding wires onto the wooden stand that go around the motor.

The shaft of the motor supports a lightweight metallic wheel of 30.0 cm diameter. A flexible plastic pipe having internal diameter 5.78 mm and outer diameter 8.75 mm was fixed around the circumference of the wheel using zip-lock ties. A 3-D printed elbow fitting for the plastic pipe was attached near the centre of the wheel to allow the outlet to rotate without tangling with the motor's shaft.

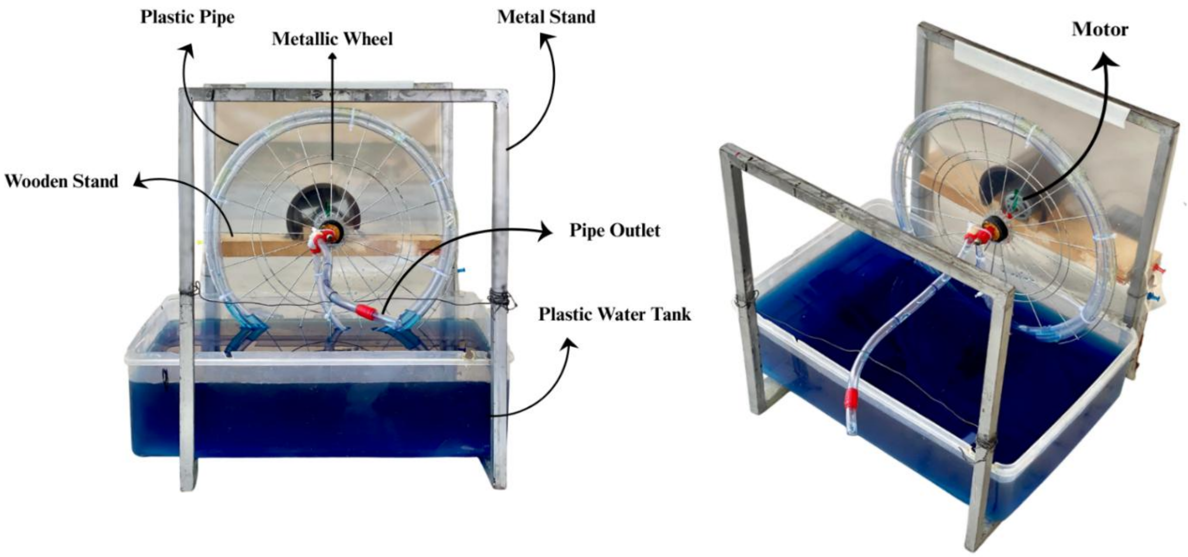

Figure 2: Front and trimetric views of the constructed Wirtz pump.

3. Results

The plastic pipe was attached along the outer circumference of the metallic wheel such that the wheel's diameter measures 30.0 cm, giving it a circumference of 94.2 cm. The motor was powered by twelve batteries of 1.5 V each connected in series, producing a net EMF of 15.85 V. The vertical height of the water in the tank, as measured by a metre rule, was 7.0 cm, and was kept consistent during each parameter variation. The water from the pump's outlet is ejected horizontally and collected in a beaker placed on top of an electronic balance. The mass of the beaker was tared in order to measure the mass of the pumped water only.

3.1. Parameter variation

3.1.1. Standard setup: no funnel and no external resistance

The rotation of the motor's shaft causes the wheel to turn at 27 r.p.m. and pump collects discrete plugs of water from the plastic tank into the collection vessel (beaker). Under these conditions, the readings for the mass of water being collected with respect to time elapsed are shown in Table 1.

Table 1: Mass of water pumped using the standard setup with respect to time

Time (s)	Mass of water (g)
0.00	0.00
5.43	0.95
10.25	1.74
15.31	3.00
20.25	3.46
25.29	4.51

These readings are plotted as a function of time in Figure 2.

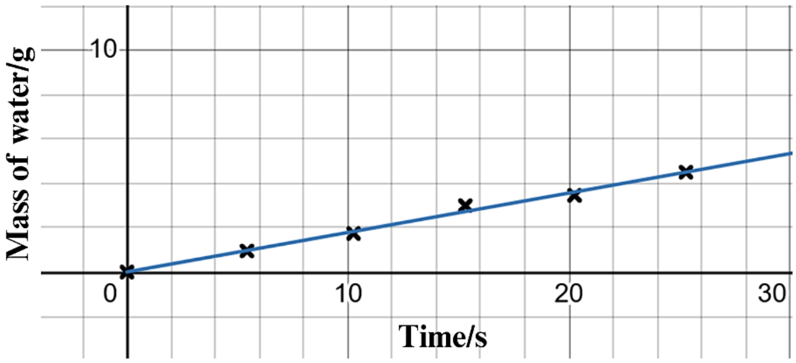

Figure 3: Graph depicting flow rate for the standard setup.

The flow rate of water can be obtained using a linear regression described by the equation:

$$y = 0.178129x + 0.00463321 \quad \text{where } x \geq 0 \qquad (1)$$

The gradient of the graph represents the flow rate of water which is 0.178 g/s.

3.1.2. Modified setup: funnel attached

In this experiment, a plastic conical funnel of diameter 22.23 mm measured by vernier callipers and side length 5.6 cm measured by a metre rule was attached to the inlet of the pipe in order to increase the water intake. All other parameters were kept constant. Readings for the mass of water collected with respect to time elapsed under these conditions, are displayed in Table 2.

Table 2: Mass of water pumped using the modified setup (funnel attached).

Time (s)	Mass of water (g)
0.00	0.00
5.50	16.51
10.55	35.20
15.32	51.04
20.93	75.07

Figure 3 shows these data plotted as a function of time.

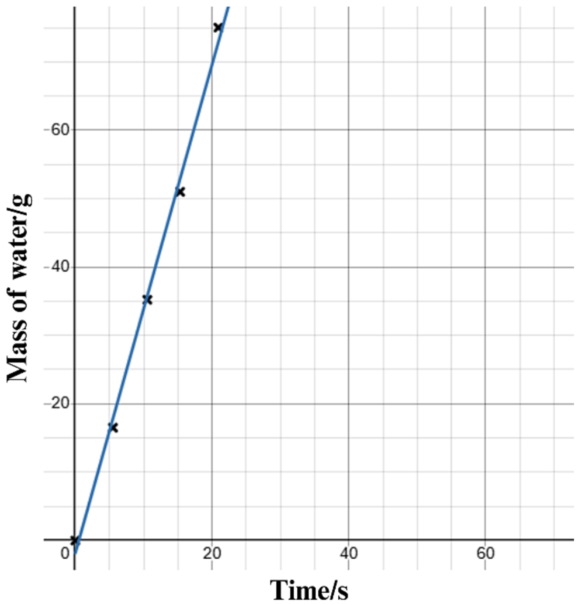

Figure 4: Graph depicting flow rate for the modified setup (funnel attached).

The above graph of the flow rate of water follows a linear behaviour described by the equation:

$$y = 3.57117x - 1.81446 \qquad \text{where } x \geq 0 \tag{2}$$

The gradient of the graph represents the flow rate of water which is approximately 3.6 g/s. Increasing the intake volume through the funnel clearly increases the intake volume and hence the efficiency of the pump.

3.2. Pump efficiency

The efficiency of a pump is defined as the ratio of the hydraulic or output power to the input power. For a fixed interval of time, this is equivalent to the ratio of the output and input energies. The input power is $P_{in} = VI$, where V is the voltage of the battery stack and I is the current through the motor. Power losses due to friction and air resistance have been ignored. To calculate the output power, the gain in kinetic and potential energy of a single plug of water over a fixed time interval is calculated. This is repeated for several plugs of water and the average values considered in the energy calculations. The average EMF and current measured by a multimeter are 15.76 V and is 4.7 mA respectively.

To calculate the kinetic energy, a distance of $d = 6\ cm$ was marked on the outlet pipe as shown in Figure 5 below. The time t taken by a single plug of water to travel this distance was measured using the *VisualEyes* software. The experiment was repeated 5 times and the average value calculated. Average time taken by a water plug to travel 6.0 cm on the outlet pipe. The speed of the water ejected from the pump is given by:

$$v = \frac{d}{t} \tag{3}$$

Using the values for the average mass and the average speed of the water plug, the kinetic energy of the stream was obtained by:

$$E_K = \frac{1}{2} m v^2 \tag{4}$$

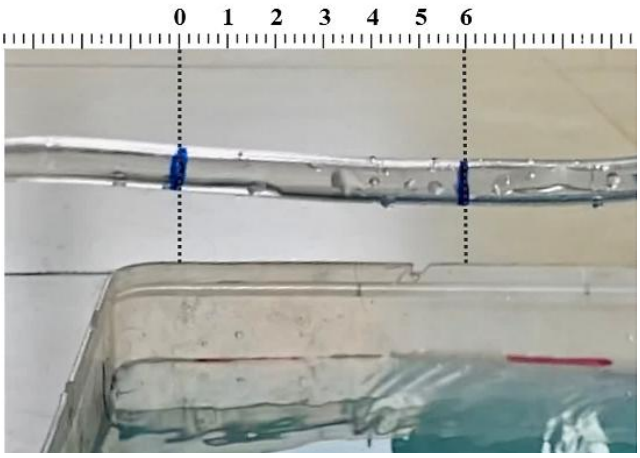

Figure 5: An image of the markings on the outlet of water made to measure the kinetic energy of the ejected water plug.

The gravitational potential energy is given by:

$$E_P = mgh \tag{5}$$

where m is the mass of the water plug, g is the acceleration due to gravity and $h = 12.0\ cm$ is the height of the pipe outlet above the level of water in the plastic tank.

The input energy is calculated as the product of the input power $P_{in} = VI$ multiplied by the time t in which the water plug traverses the distance d:

$$E_{in} = VIt \tag{6}$$

3.2.1. Efficiency calculation for standard setup

In the standard setup, the motor rotates the pump at 27 r.p.m, and the average mass of a single plug of water is 0.23 g, as measured by an electronic balance. The time t as measured by *Visualeyes* software was $0.161\ s$. This gives the speed of the ejected water plugs as:

$$v = \frac{0.060\ m}{0.161\ s}$$

$$v\ = 0.373\ m/s$$

Using the values for the mass and speed of water, the kinetic energy of the water plug is:

$$E_K = \frac{1}{2}(0.23 \times 10^{-3}\ kg)(0.373\ m/s)^2$$

$$E_K = 1.60 \times 10^{-5}\ J$$

The gravitational potential energy is:

$$E_P = (0.23 \times 10^{-3}\ kg)(9.81\ m/s^2)(0.12\ m)$$

$$E_P = 2.71 \times 10^{-4}\ J$$

Thus, the total output energy becomes:

$$E_{out} = E_P + E_K \tag{7}$$

$$E_{out} = 2.71 \times 10^{-4}\ J + 1.60 \times 10^{-5}\ J$$

$$E_{out} = 2.87 \times 10^{-4}\ J$$

Using eqtn. 6, the electrical energy input in the 0.161 s taken by the water plug to travel across the 6.0 cm distance is:

$$E_{in} = (15.76\ V)(4.7 \times 10^{-3}\ A)(0.161\ s)$$

$$E_{in} = 0.0119\ J$$

Finally, the efficiency η of this design of the pump is calculated as:

$$\eta = \frac{E_{out}}{E_{in}} \times 100\% \qquad (7)$$

$$\eta = \frac{2.87\times10^{-4}\,J}{0.0119\,J} \times 100\%$$

$$\eta = 2.41\ \%$$

Several losses in the Wirtz Pump affect its efficiency. In the delivery pipe, fluid flow resistance and air lift slippage are major sources of energy loss [3]. The low efficiency indicated that the pump design needs to be improved and one way of doing that is to increase the water intake as done in the following experiment.

3.2.2. Efficiency calculation for modified setup with funnel

Using the above methodology, efficiency is calculated again for the modified setup. With the funnel attached the pump slightly slows down to 21 r.p.m. because of the additional weight. In this case, the average mass of a single plug of water is 10.3 g. The average time taken for a water plug to travel $d = 6.0\ cm$ in the outlet pipe is 0.180 s, as recorded by the *VisualEyes* software. Therefore, using eqtn. 3, the speed of the water ejected from the pump is calculated as:

$$v = \frac{0.060\ m}{0.180\ s}$$

$$v = 0.333\ m/s$$

Using eqtn. 4 and the values for the mass and speed of water, the kinetic energy of the water plug is calculated as:

$$E_K = \frac{1}{2}(10.3 \times 10^{-3}\ kg)(0.333\ m/s)^2$$

$$E_K = 5.71 \times 10^{-4}\ J$$

Using eqtn. 5, the potential energy of the water ejected is calculated as:

$$E_P = (10.3 \times 10^{-3}\ kg)(9.81\ m/s^2)(0.12\ m)$$

$$E_P = 0.0121\ J$$

Using the previously obtained values, the total energy output of the stream is calculated as:

$$E_T = 0.0121\ J + 5.71\ \times 10^{-4}\ J$$

$$E_T = 0.0127\ J$$

In this experiment, the battery voltage $V = 17.06\ V$ and the current $I = 5.7\ mA$. In the 0.180 s taken by the water plug to travel across distance d the electrical energy input is calculated as:

$$E_E = (17.06\ V)(5.7 \times 10^{-3}\ A)(0.180\ s)$$

$$E_E = 0.0175\ J$$

Finally, the efficiency of this design of the pump with funnel η_f is given as:

$$\eta_f = \frac{0.0127\ J}{0.0175\ J} \times 100\%$$

$$\eta_f = 72.6\ \%$$

Comparing the efficiencies with funnel (η_f) and without funnel (η), it is found that $\eta_f \approx 30\eta$.

4. Discussion

The experiments above demonstrate that connecting a funnel at the outlet of the Wirtz pump is imperative to improving the efficiency of the pump, as the small nozzle of the inlet proves to be inadequate in scooping a considerable mass of water on its own. Although the funnel slightly reduces the r.p.m. of the pump, it collects much larger plugs of water which results in a substantial increase in the flow rate of the pump from 0.18 g/s to 3.6 g/s, as evident in the steeper slope of the graph in Figure 4 as compared to Figure 3. This design choice appears to be consistent with the earlier illustrations of the pump, such as Figure 1, where the inlet is visibly wider than the inner coils, which could be designed to maximize the water intake. It is important to note that the Wirtz Pump does not continuously pump water; the flow rate accounts for the intermittent nature of pumping as it includes the time taken by the pump to rotate partially in air and partially in water.

Certain improvements could also have been incorporated into the experiment and apparatus to enhance accuracy. The difference in the EMFs across different trials could have a considerable impact on the r.p.m. of the pump which was unaccounted for and attributed solely to the difference in the mass of water pumped. A more accurate approach would have involved the use of a constant voltage source to ensure uniform voltage throughout the experiment.

Furthermore, experiments had been conducted in both indoor and outdoor settings. It can, therefore, be assumed that there could be an influence of wind resistance on the rotation of the pump in certain trials which has been ignored. Additionally, when the funnel is attached to the inlet, the greater weight of the water inside the pipes causes it to turn more slowly inside water as compared to its rotation in air. The effect of this non-uniform circular motion on the efficiency of the pump has not been considered which may have introduced additional variability. Furthermore, although the 3-D printed elbow fitting was positioned near the geometric centre of the metallic wheel, it was still not perfectly aligned with the centre. This slight offset caused the pipe outlet to undergo, additional circular motion albeit minor. Since the rotational kinetic energy of the outlet pipe was not accounted for in the calculations, the actual output energy may have been slightly higher than what was reported above.

5. Conclusion

This experiment has been successful in constructing an operational Wirtz Pump and yielded reliable results. This report aimed to investigate the working of the pump using electrical equipment such as a battery and motor to ensure the self-regulation of the pump. A few design parameters were also varied and their effect on the functioning of the pump were analysed to obtain optimum performance. It was found that a funnel-like opening to the inlet is increased the efficiency of the pump by a factor of 30 by substantially increasing the mass of water collected.

With further improvements in its design parameters, this pump can emerge as a low-cost alternative to lift water from streams in rural areas particularly where there is no or unreliable supply of electricity.

6. References

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