

Levitational Dynamics: Analyzing the Performance of Lightweight Objects over a Vertical Jet

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Abstract. This paper explores the phenomenon of aerodynamic levitation, concentrating on the performance of various lightweight objects as they are positioned over a vertical air jet emitted by a standard household hair dryer. The study meticulously analyzes levitation, which is achieved by balancing gravitational pull with aerodynamic forces that act counteractively, utilizing objects of different masses, volumes, and geometric shapes. The experimental framework is crafted using easily accessible household items, which include a hair dryer for generating air jets and various lightweight objects. The process involves video recording to meticulously track and analyze the stability and altitude of these objects while they levitate. To interpret the experimental data, the study integrates mathematical calculations and fundamental physics theorems. Results from the experiments indicate that the shape of an object is a critical factor influencing its stability and effectiveness in levitation scenarios. Spherical and ellipsoidal objects exhibit superior levitational characteristics and maintain stability more effectively compared to angular-shaped objects such as cubes and pyramids, which display a propensity to be displaced from the jet stream due to their less aerodynamically favorable shapes.

Keywords: Levitation, Aerodynamics, Stability.

1. Introduction

Aerodynamics and levitation are subjects grounded in complex physics principles and extensive experimentation. Among these, aerodynamic levitation stands out for its intriguing application in balancing objects in midair without mechanical support, primarily through air jets. Historically, phenomena like levitating a ping-pong ball with a hairdryer have not only fascinated physics classes globally but have also demonstrated fundamental aerodynamics and fluid mechanics principles [1]. These principles dictate the behavior of objects when exposed to forces such as air jets, where both the shape and material of the object play crucial roles in determining the outcome of levitation experiments.

Current research in aerodynamics frequently utilizes advanced simulations and real-world experiments to explore fluid dynamics under varied conditions [2]. In educational and research settings, simple yet effective experiments using everyday items like hairdryers provide valuable insights into the dynamics of airflow and its interaction with different objects. The performance of these objects when levitated by air jets is contingent on multiple variables, including the speed of the airflow and the physical characteristics of the objects themselves. Such experiments help in understanding the stability, altitude, and behavior of various objects in levitated states, contributing to broader applications in technology and industrial design.

This paper focuses on the experimental analysis of lightweight objects levitated by a vertical jet from a hair dryer, exploring how different shapes and masses respond to aerodynamic forces [3]. Using a simple setup involving a hairdryer with two speed settings and objects of varied geometrical shapes, the study investigates the stability and altitude of levitation achieved under controlled conditions. Mathematical models and physical laws such as Bernoulli's principle and the drag coefficient are employed to analyze and predict the behavior of these objects during levitation. The findings highlight significant differences in performance between spherical and non-spherical objects, with spheres showing greater stability and consistency in levitation compared to angular shapes like cubes and pyramids, which are prone to displacement due to their unfavorable aerodynamic properties.

2. Experiment Preparation

2.1. Equipment and Tools

Due to the reason that this experiment is simplified and conducted with daily articles, the equipment and tools should be highly accessible. One of the issues that is not under control is the rotation of the lightweight objects. Ideally, the experiment should physically restrict the rotation of the object or simply assume the object does not rotate. The intention of the act is to guarantee an almost constant projected area of the object [2]. This is not easily achievable under the current experimental set up. Therefore, the flow speed of the jet is limited so that the lightweight can gain relatively higher stability during their levitations

A hair dryer with two speed modes to provide vertical jet. A plastic bag of known volume for the hair dryer's flow rate calculation. A regular spherical object (a pingpong ball) of diameter 4 centimeters and weighs 2.7 grams. A regular ellipsoid with 5.5 centimeters on the major axis and 4.5 centimeters on the minor axis. It weighs 3.5 grams. A regular cube with side length 4 centimeters and weighs 1 gram. A regular triangular pyramid with side length 4 centimeters and weighs 0.5 grams. Tracker software developed Open-Source Physics [3].

2.2. Experimental Methods

The experimental method states the overall routine, introduces experimental variables and demonstrates specific strategies to this experiment. In this experiment, the mass, diameter, shape of the objects are determined to be independent variables. Dependent variables, the values that are expected to vary, are the levitation altitude and stability of the objects over the jet. The experiment is conducted inside a closed space, which means that there are no external factors, such as wind, affecting the objects.

First of all, a hair dryer is fixed onto a table with its air outlet pointing vertically upward. The hair dryer has two speed modes: Both are used during the experiment. Next, the hair dryer is switched on and produces a vertical jet. Objects are separated into two groups. In the first group, two objects—a regular spherical object (a pingpong ball) of diameter 4 centimeters, and a regular ellipsoid with 5.5 centimeters on major axis and 4.5 centimeters on minor axis—are placed over the jet in order to find their levitation height and stability. In the first run of simulations, the speed mode of the hair dryer is set to high, and the second run uses low speed mode. Second group consists of two irregular objects: a regular cube with side length 4 centimeters and a regular triangular pyramid with side length 4 centimeters. They are placed over the jet to achieve the same intentions as the first group. Low speed mode is used when experimenting with the second group, since they are made from A4 paper and are relatively lighter than two objects in the first group. As show in the fig.1 and fig. 2.

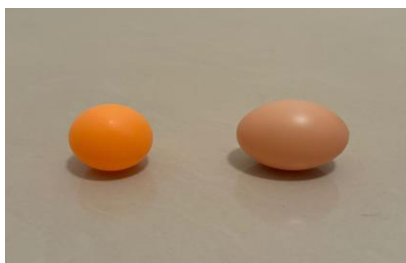


Figure 1. The sphere and the ellipsoid (Photo credit: Original).

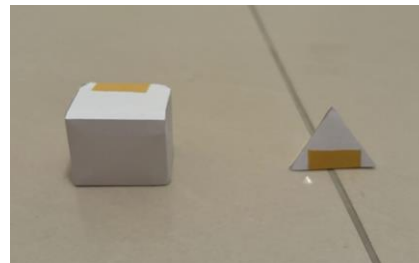


Figure 2. The cube and the triangular pyramid (Photo credit: Original).

2.2.1. Flow rate

The flow rate of the hair dryer can be obtained by calculating time taken to completely fill up a plastic bag of a known volume when fully inflated. To achieve this, a plastic bag's opening is taped around the barrel of the hair dryer so that no air is able to escape during the inflation. Use a timer to start timing when the hair dryer is switched on low-speed mode, and stop timing when the bag is fully

inflated. The same process is repeated for high-speed mode. The flow rate of two speed modes can be calculated by dividing the plastic bag's volume by the time taken by the corresponding speed mode.

2.2.2. Experimenting with objects' levitation performances

For the first group, the hair dryer is switched on with high-speed mode first, and, sequentially, two objects are placed over the jet produced. Both levitations are recorded by taking a video using a mobile phone. Next, the speed mode of the hair dryer is set to low. Two objects are again placed over the jet, and videos are recorded. As show in the fig.3 and fig. 4.



Figure 3. The sphere over a vertical jet (Photo credit: Original).



Figure 4. The ellipsoid over a vertical jet (Photo credit: Original).

For the second group, the hair dryer is set to low-speed mode throughout. The cube and the triangular pyramid are placed, in order, over the vertical jet. Both levitations' videos are recorded. As show in the fig.5 and fig. 6.



Figure 5. The cube over a vertical jet (Photo credit: Original).



Figure 6. The triangular pyramid over a vertical jet (Photo credit: Original).

2.2.3. Using Tracker software for numerical and graphical analysis

After getting all of the video records, they are uploaded into the Tracker software for tracking and analysis. The scale of measurement is calibrated first before every tracking. A coordinate system, which contains X and a Y axis, is constructed, with its original point located at the midpoint of the diameter of the hair dryer's air outlet. The X axis is horizontally aligned with the air outlet; thus, the Y axis is vertically aligned with the chord of the hair dryer. In every tracking, the center of mass of the object is located in every frame of the recording. By doing this, the changes in the objects' position in the coordinate system over time can be identified and plotted into graphs. As show in the fig.1 and fig. 7.

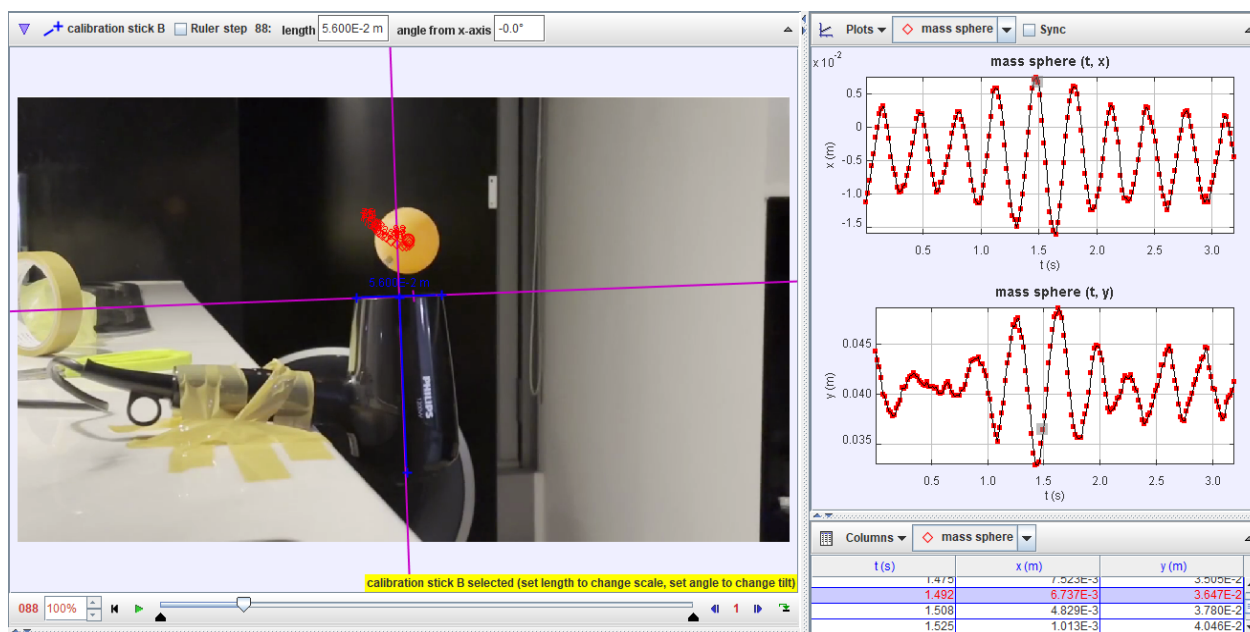


Figure 7. The Tracker software set up for the sphere levitation experiment (Photo credit: Original).

3. Experiment Results and Discussion

3.1. Numerical Results

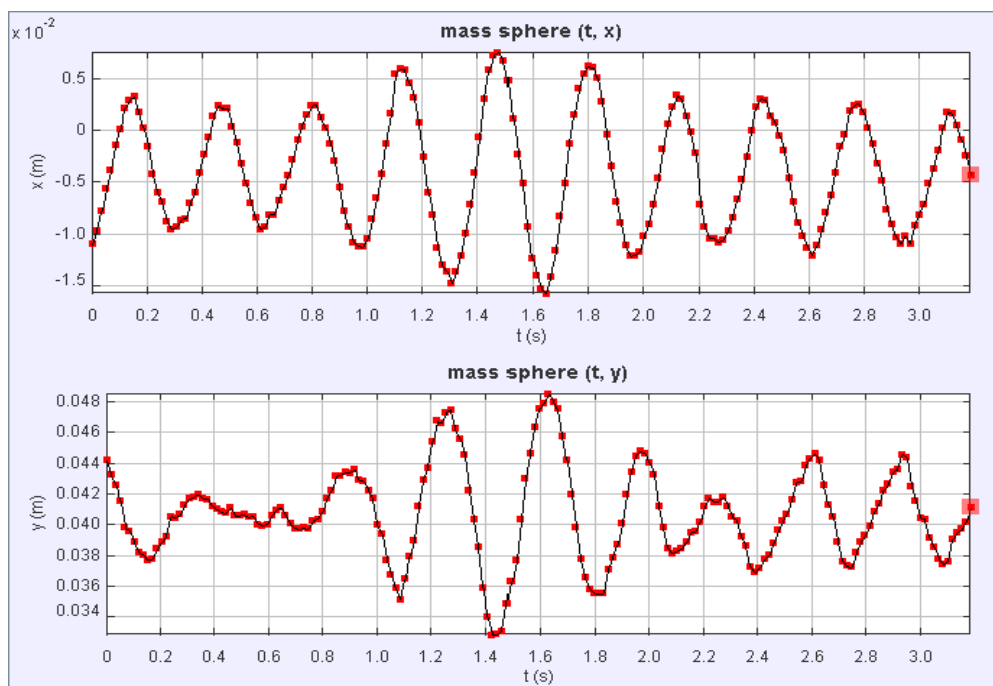


Figure 8. The graph of the sphere's motion in x,y axis during its levitation over a jet of high speed mode (Photo credit: Original).

As show in the fig.8. The speed mode of the hair dryer is set to high. The Fig. 7. demonstrates the regular sphere's motion on the x and the y axis, which represent horizontal and vertical directions, during the 3.2 seconds of its levitation. The range of X direction movement is from -1.6 cm (left of the X axis) to 0.75 cm (right of the X axis). The height of the levitation, which is illustrated in the Y and t graph, varies between 3.3 cm to 4.9 cm. The mean levitational altitude was 4.1 cm above the air outlet.

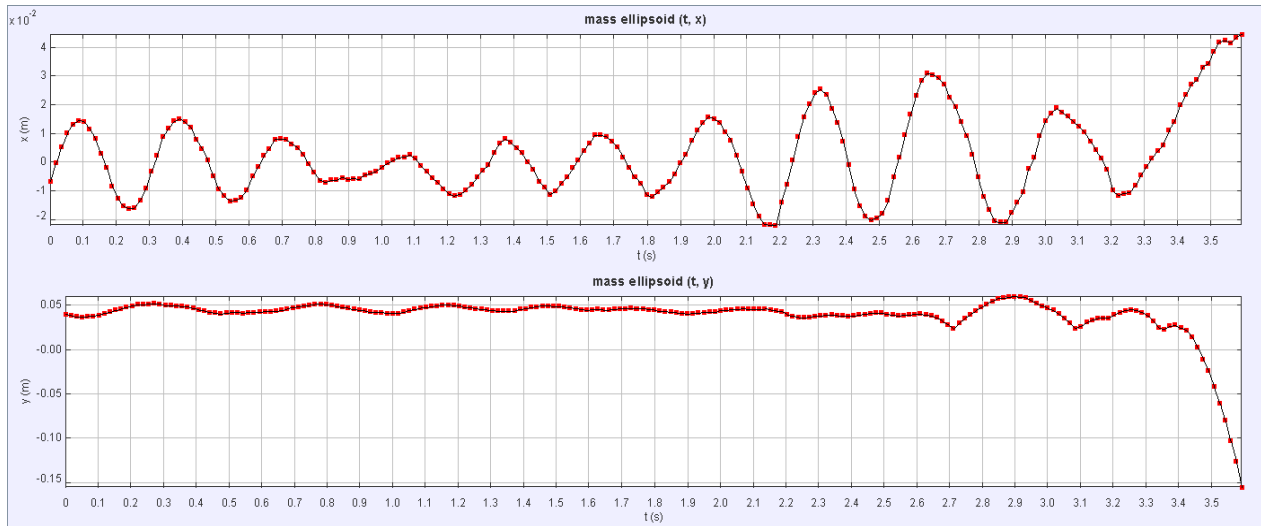


Figure 9. The graph of the ellipsoid's motion in x, y axis during its levitation over a jet of high-speed mode (Photo credit: Original).

As show in the fig.9. During the levitation of the ellipsoid, it performed relatively stable at first, but eventually fell off at the end. During its stable levitation, the mean altitude of levitation was 4.5 cm above the air outlet. However, it only lasted for 3.1 seconds. For horizontal movement, the ellipsoid reached -2.2 cm minimum and 3.1 cm maximum.

Then the speed mode of the hair dryer is set to low, both sphere and ellipsoid are placed over the jet again. As show in the fig.10.

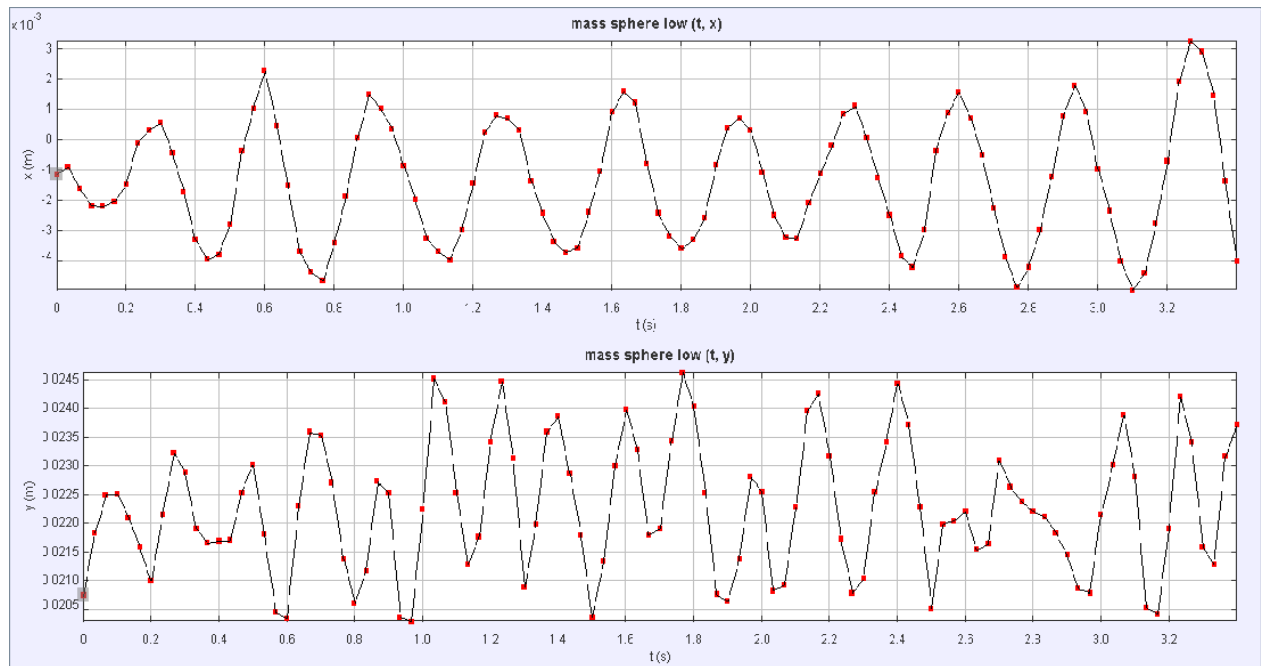


Figure 10. The graph of the sphere's motion in x,y axis during its levitation over a jet of low speed mode (Photo credit: Original).

During the sphere's 3.4 seconds levitation, the minimum value and maximum value in X directions were -0.5 cm to 0.3 cm correspondingly. The mean levitational altitude was 2.2 cm. As show in the fig.10.

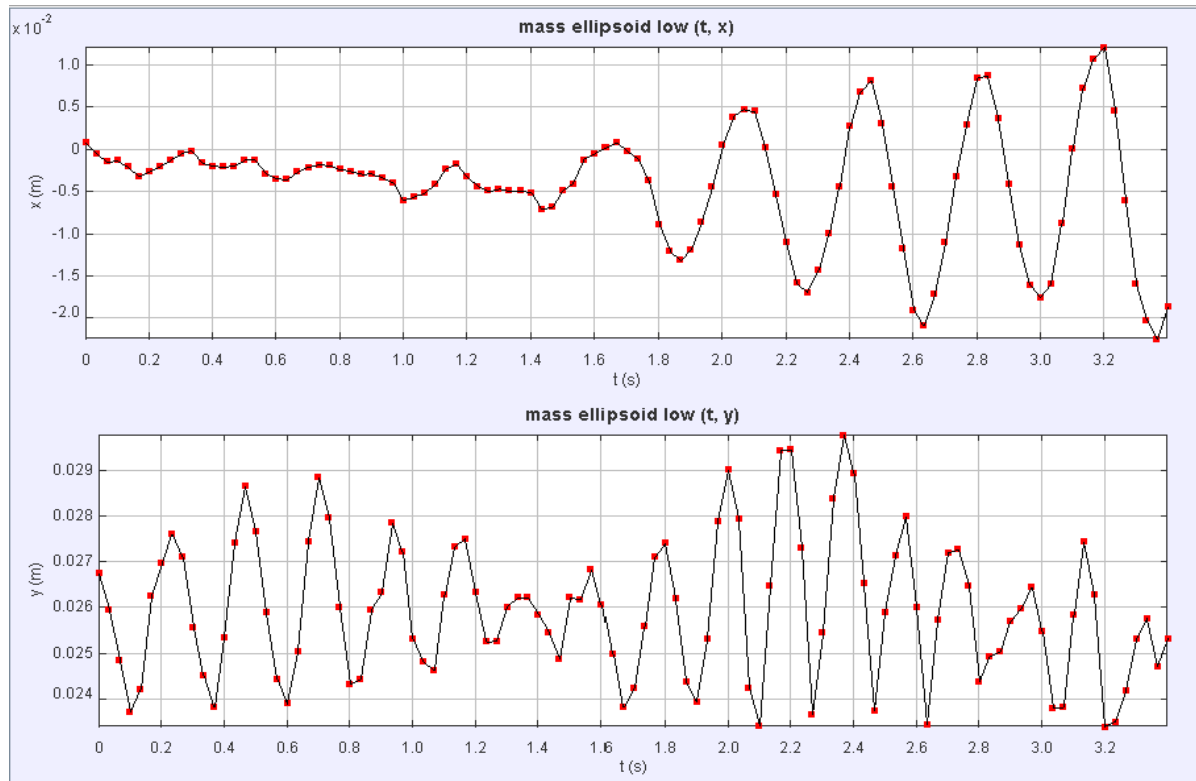


Figure 11. The graph of the ellipsoid's motion in x,y axis during its levitation over a jet of low speed mode (Photo credit: Original).

As show in the fig.11. When putting the ellipsoid over the low speed, the Y direction movement was relatively stable in comparison to its movement on X direction: It's levitating at a mean altitude of 2.6 cm above the air outlet. For its X direction movement, the ellipsoid is initially maintained at the center point of the air outlet. However, it started traveling in a circle around the edge of the air outlet, and eventually fell off.

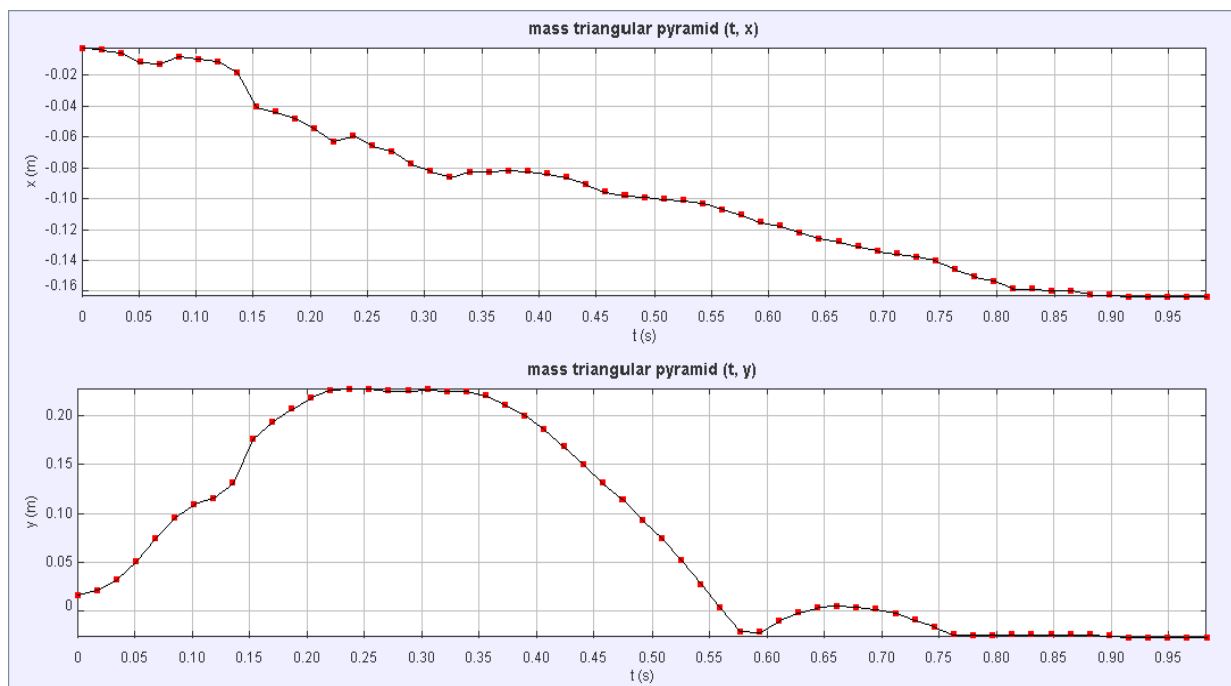


Figure 12. The graph of the triangular pyramid's motion in x,y axis during its levitation over a jet of low speed mode (Photo credit: Original).

As show in the fig.12. The triangular pyramid couldn't maintain in levitation however; When it was placed over the vertical jet, it got instantly pushed away by the jet and landed somewhere else.

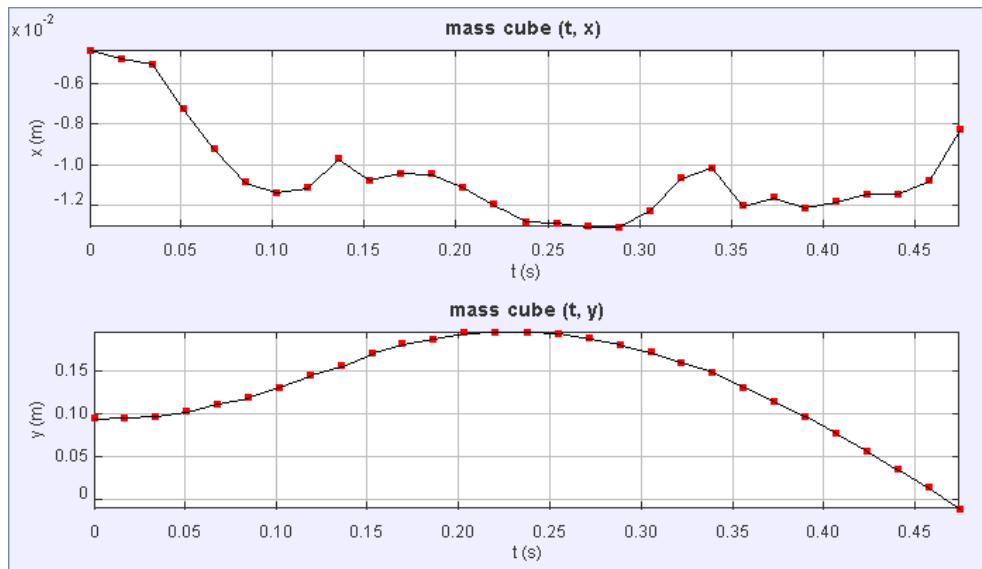


Figure 13. The graph of the cube's motion in x,y axis during its levitation over a jet of low speed mode (Photo credit: Original).

As show in the fig.13. Similar to what happened to the triangular pyramid, the cube couldn't suspend above the jet: It was pushed up by the jet at the instant of release and landed elsewhere.

3.2. Results Analysis

In all of the four objects in the experiment, only the sphere and the ellipsoid were able to maintain in levitation for a period of time. For the triangular pyramid and the cube, they both failed to suspend. Comparing the graphical data of when the sphere was over a high-speed mode jet with when it's over a low-speed mode jet, sphere over a low-speed mode jet has higher stability in both X and Y directions: The range of variation in X direction was 0.8 cm under low-speed mode but 2.4 cm when under high-speed mode. In the Y direction, the range of variation was 0.4 cm under low-speed mode and 1.4 cm when under high-speed mode. The phenomenon can be explained using Bernoulli's principle. When the sphere is exactly above the jet, the airstreams surround the sphere, and as they flow through the sphere, they attach to the curved surface of the sphere [4]. By seeing the airstream and the sphere as a 2D diagram demonstrated in Fig. 14., the airstreams can be seen as symmetric lines about the axis of symmetry which is a vertical line passing through the center of mass of the sphere

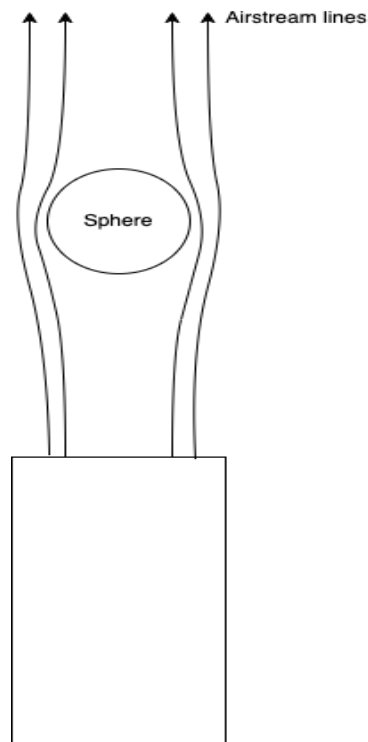


Figure 14. The symmetric air flow around the sphere shown in a 2D diagram (Photo credit: Original).

Bernoulli's principle states that an increase in speed leads to a decrease in the pressure [5]. However, when the sphere is exactly in the middle of the jet, the pressure exerted by the airstream on both sides of the sphere are identical. Also, since the sphere has constant surface area no matter of perspective, therefore the area covered by airstreams on both sides are also the same. In this case, there are two forces of same magnitude by opposite direction exerting on the sphere, resulting in the sphere maintaining an equilibrium position in horizontal direction. Even if the sphere tends to move towards any direction, the unbalanced pressure will keep making corrections and move the sphere back to the center of the jet. For the vertical direction, the equilibrium position is where the buoyant force provided by the jet and the sphere's weight are equivalent in terms of magnitude, and the equilibrium position varies with the flow speed of the jet. Therefore, when there is no resultant force acting on the sphere from horizontal nor vertical direction, the sphere is able to levitate over a jet with good stability.

For the ellipsoid, the same phenomenon is observed. The ellipsoid spinned above the low-speed jet much faster than when it was over the fast speed jet; However, even though it was fast spinning, it was steadily suspending over the jet. When the ellipsoid wasn't spinning fast like when it was over the high-speed jet, it eventually fell into a circular tracker and then fell off. This phenomenon is explainable when the ellipsoid characteristics are contrasted with the sphere's: The surface area on two sides of the sphere are always identical, no matter how much it spins. Whereas for the ellipsoid, its two sides' surface area is constantly changing as it spins, more specifically, the sides keep switching their shapes between a circle and an oval. This would create unbalanced pressure on two sides; But this time the pressure difference cannot be corrected, as the surface area is always different at any time. Eventually, this unbalance of pressure pushes the ellipsoid to the edge of the air outlet. While the ellipsoid is on the edge, there is no airstream flowing through the outer side, which then creates a pressure difference that drags the ellipsoid back towards the center of the jet. With all the previous explanation, it is no surprise that the ellipsoid circled around the circumference of the air outlet and eventually fell off

For the irregular shaped objects, the triangular pyramid and the cube, they both failed to achieve levitation. The reason behind may be their constant variation in projected area, leading to an uneven spread of drag force exerted by the jet. In addition, both the cube and the triangular pyramid have

sharp edges, meaning that no laminar flow can be formed around the object like the sphere. The force provided by the jet exerts forces on planes that are of different inclinations, creating movements not only in vertical direction, but also in horizontal direction. Finally, they are pushed away from the center of the jet and fly too somewhere else.

3.3. Theoretical Comparisons

Despite conducting the experiment to Fig. out the levitational altitude of different objects over a jet, the altitude can also be mathematically calculated with help from physics theorems. Since the sphere was the only object that performed relatively stable compared with other objects, the theoretical calculations will only focus on the levitation of the sphere.

Since the hair dryer's flow speed is already known, the U , flow speed of air can be calculated using the equations, where Q is the flow rate of the jet, V is the volume of the plastic bag, t is the time taken to fill up the bag and d is the diameter of the hair dryer's air outlet.

$$Q = V/t \quad (1)$$

$$U = \frac{Q}{\frac{1}{4}\pi d^2} \quad (2)$$

By tying the opening of the plastic bag to the barrel of the hair dryer, the plastic bag expands into a sphere-like object. Therefore, the volume of the plastic bag is modeled as a sphere with radius 15 cm, which is 0.15 m.

$$V = \frac{4}{3}\pi(0.15)^3 = 0.1414 \text{ m}^3 \quad (3)$$

The time taken to fill up the plastic bag was 1.51 seconds and 1.35 seconds for low-speed mode and high-speed mode respectively.

$$Q_{low} = \frac{0.01414}{1.58} = 0.008949 \text{ m}^3\text{s}^{-1} \quad (4)$$

$$Q_{high} = \frac{0.01414}{1.35} = 0.01047 \text{ m}^3\text{s}^{-1} \quad (5)$$

Then, we can further calculate the initial flow speed of air for the two modes. The diameter of the hair dryer's outlet is 5.2 cm, or 0.052 m.

$$U_{low} = \frac{0.008949}{\frac{1}{4}\pi(0.052)^2} = 4.214 \text{ ms}^{-1} \quad (6)$$

$$U_{high} = \frac{0.01047}{\frac{1}{4}\pi(0.052)^2} = 4.932 \text{ ms}^{-1} \quad (7)$$

When an object is able to suspend over a jet, the resultant force acting on it is none, meaning the drag force provided by the jet has the same magnitude as the object's weight. The drag force can be represented by equation, where F_D is the drag force, ρ is the air density, S is the projected area and C_D is the drag coefficient [6].

$$F_D = mg = \frac{1}{2}\rho U^2 S C_D \quad (8)$$

Since it doesn't matter how a sphere spins, its projected area is always the circular area with the sphere's radius, regardless of from which perspective the sphere is observed. Therefore, the equation can be expressed as.

$$F_D = \frac{1}{2}\rho U^2 (\frac{1}{4}\pi d^2) C_D = \frac{\pi}{8}\rho U^2 d^2 C_D \quad (9)$$

$$mg = \frac{\pi}{8}\rho U^2 d^2 C_D \quad (10)$$

When a jet is emerging from a nozzle, its speed is at maximum at its central axis [7]. The air flow speed u can be expressed in the function.

$$u(x, 0) = U_{max} = \frac{5U_0d}{x} \quad (11)$$

Where U_0 is the initial speed of the air flow. In this calculation model, the sphere is designated to suspend vertically above the center of the air outlet. Thus, U_{max} will be taken as the air flow speed in further calculations.

To determine drag coefficient C_D , the concept of Reynold's number has to be involved.

$$Re = \frac{\rho U_0 d}{\mu} \quad (12)$$

In this specific case, the linear dimension is determined to be the hair dryer's air outlet. Re stands for Reynold's number, μ is the air viscosity.

Connecting with U_0 obtained from previous calculation, the Reynold's number for two air flows can be obtained by the equation below. At room temperature of 28 celsius, the air flow from the hair dryer has the approximately identical temperature, meaning its density is around 1.172 kgm^{-3} and its viscosity is around $1.863 \cdot 10^{-5} \text{ kgm}^{-1}\text{s}^{-1}$ [8].

$$Re_{low} = \frac{(1.172)(4.214)(0.052)}{1.863 \cdot 10^{-5}} \approx 13785 \quad (13)$$

$$Re_{high} = \frac{(1.172)(4.932)(0.052)}{1.863 \cdot 10^{-5}} \approx 16134 \quad (14)$$

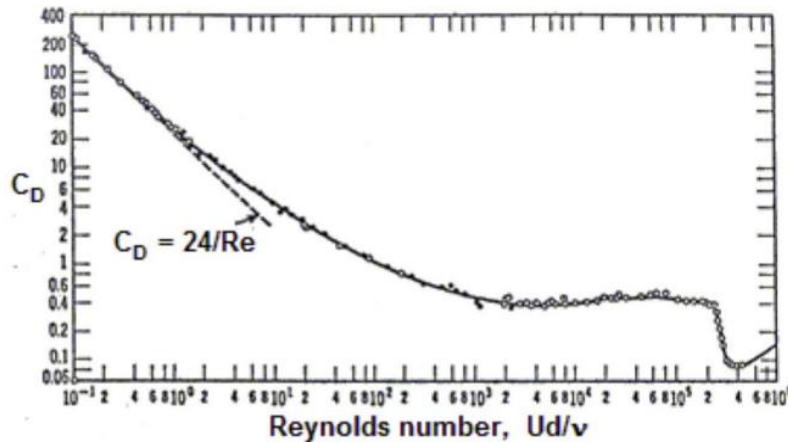


Figure 15. Drag coefficient as a function of Reynolds number for a sphere. Origin from [9].

From Fig. 15, plugging in two obtained Reynolds numbers into the graph, the drag coefficient for the sphere over the low-speed jet is 0.4. For the sphere when over the high-speed jet, drag coefficient is also 0.4.

Inheriting the derived equation from the previous, the levitational altitude of the sphere over jets of different flow speed can finally be determined. First, substitute U with the expression for U_{max} . The equation now contains x , the levitational altitude above the starting point of the air flow.

$$mg = \frac{\pi}{8} \rho \left(\frac{5U_0d}{x} \right)^2 d^2 C_D \quad (15)$$

Rearrange the equation to make it in terms of x

$$x = 5U_0d^2 \sqrt{\frac{\pi \rho C_D}{8mg}} \quad (16)$$

The x for low flow speed and high flow speed can be calculated

$$x_{low} = 5(4.214)(0.052)^2 \sqrt{\frac{\pi(1.172)(0.4)}{8(0.0027)(9.81)}} = 0.1502 \text{ m} \quad (17)$$

$$x_{high} = 5(4.932)(0.052)^2 \sqrt{\frac{\pi(1.172)(0.4)}{8(0.0027)(9.81)}} = 0.1758 \text{ m} \quad (18)$$

However, this is not the final answer. When the air is blown out from the hair dryer, the fan, which is seen as the starting point of the nozzle, locates inside the barrel of the hair dryer, meaning the starting point of the air flow is somewhere inside the hair dryer. Usually, a virtual origin is set to assume a starting point of an air flow [10]. The distance from this virtual origin to the nozzle is modeled as

$$x_0 = \frac{5}{2}d \quad (19)$$

Where d is the diameter of the nozzle. In this case of hair dryer, the distance from the virtual origin to the air outlet is

$$x_0 = \frac{5}{2}(0.052) = 0.13 \text{ m} \quad (20)$$

To obtain the actual levitational altitude measuring from the center of the sphere to the air outlet of the hair dryer, this distance from the air outlet to the virtual origin is deducted from x_{low} and x_{high} .

$$x_{low \text{ final}} = 0.1502 - 0.13 = 0.0202 \text{ m} = 2.02 \text{ cm} \quad (21)$$

$$x_{high \text{ final}} = 0.1758 - 0.13 = 0.0458 \text{ m} = 4.58 \text{ cm} \quad (22)$$

As the final answer of the theoretical calculations, 2.02 cm should be the levitational altitude for the sphere to suspend over the low-speed jet, and 4.58 cm for the high-speed jet. Comparing these two values with previous experimental results, 2.2 cm and 4.1 cm, the percentage errors are 8.9% and 10.5%. Considering many steps in the experiment are designed as a simplified model, the percentage errors are acceptable.

3.4. Challenges Identified

There are many challenges in this whole experiment. Firstly, the model of jet spreading out from a nozzle is simplified and doesn't necessarily represent real life situations. In real life, whether the jet follows the model is highly dependent on the quality of the hair dryer. There are many uncontrollable and undesirable factors affecting the hair dryer's performance: For example, an unconstant rotation of the fan may affect the speed of the jet produced. Secondly, some measurements are relatively inaccurate. For instance, the plastic bag used for measuring the flow rate may have a high volume than 0.1414 m^3 ; But since it is really hard to measure the exact volume of an irregularly shaped plastic bag, the approximation model has to be taken. Lastly, it is not easy to obtain irregular lightweight objects. The cube and the triangular pyramid are made from a sheet of A4 paper, and this is the reason why they are very light and not suitable for this experiment.

4. Conclusion

By conducting physical experiments and calculating numerical results using physics principles, a few conclusions can be drawn from this experiment. Regular shaped curved objects do have better performance in levitation than irregularly shaped objects. The stability of the object's levitation relies heavily on their projected area, which is the area facing the jet. If the rotation of the object is not controlled, an object that has a constant projected area, no matter how it rotates, owns the best stability over a jet, in this case, the spherical objects. However, if the object doesn't have a curved surface, laminar airstream flow will not be formed along the surfaces. Therefore, reaching stable levitation for objects like the cube and the triangular pyramid is not very likely. Some improvements can be done to improve the experimental results' accuracy. For example, using more precise and accurate measurement apparatus would increase the reliability of results obtained; Some models such as the

volume of the plastic bag and the jet nozzle can be refined in order to make numerical values more precise, which helps to reduce uncertainties in the overall calculation

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