Experimental Analysis of Levitation Dynamics of Spheres in An Upward Air Stream: Insights into Drag Force and Turbulence

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Abstract. This paper presents an experimental investigation into the levitation dynamics of spheres with varying weights in a vertical air stream generated by a hair dryer. The experiment aimed to analyze the effects of drag force, turbulence, and Bernoulli's principle by measuring the levitation heights of five spheres with different masses. The findings indicate that heavier spheres exhibited greater stability and smaller deviations from theoretical predictions, while lighter spheres displayed larger fluctuations due to airflow turbulence, highlighting their increased sensitivity to turbulent forces. A key observation was the role of air pressure differences in maintaining levitation, particularly when the airflow direction was tilted. This demonstrates the stabilizing effect of low-pressure zones created by the high-speed air stream. The paper highlights the limitations of manual measurements and proposes improvements, such as using laser-based or electronic height measurements for greater precision. These results provide valuable insights into fluid dynamics and have practical implications for engineering applications, such as improving the aerodynamic stability of drones, levitating devices, and structures exposed to turbulent airflow, thereby contributing to advancements in aerodynamic design and fluid mechanic's research.

Keywords: Levitation dynamics, Drag force, Turbulence, Bernoulli's principle.

1. Introduction

On the most basic level, the question of how objects fall through a vertical air stream has been investigated in fluid dynamics for decades [1-3]. The interaction of drag force, turbulence, and gravitational force has been studied in countless works, attempting to predict the stability and behavior of objects suspended in an airflow [4-5]. A deep understanding of drag force and turbulence principles is crucial for engineers working in various industries ranging from aerospace to environmental science, as these phenomena will happen at many situations and are relevant to the study of natural and artificial systems [6-7].

Numerous studies have investigated the drag force subject to spherical bodies under steady-state and turbulent flows in the past. In Faber it was found that drag coefficient (C_D) is a strong function of Reynolds number and surface roughness. It was also found that less heavy objects are more sensitive to turbulence that can cause oscillatory motion and stability loss [8-9]. In contrast, larger masses achieve consistent heights during levitation because their inertia resists changes in airflow around them better than lighter masses [10-11].

We designed this experiment to understand how spheres of different weights behave in an upward air stream, deepening the understanding of drag force, turbulence and Bernoulli's principle. We measured the levitation height of different spheres, comparing the experimental results with theoretical predictions. Heavier spheres can be particularly more stable in turbulent air and correlated better with theoretical models than lighter spheres, which showed more variability, the study determined. This experiment provides us with deeper insights into the mechanics of drag force in fluid and turbulent conditions. It also strengthens our idea for the applications of drag force and turbulence in fluid mechanics.

2. Experiment

We know that there are several factors that will affect of the height of a sphere in linear upward flow. They are known as the speed of the fluid, the mass of the sphere, and so on. So, in this experiment, we will conduct multiple experiments with different weights of spheres and use the data of different weights of spheres to analyze the levitation of a light sphere in an upward air jet from a" hair dryer," which can help us understand drag force, turbulence, and the Bernoulli principle. This phenomenon can be observed whenever a correctly sized and weighed ball (e.g., a Ping-Pong ball or a foam ball) is suspended in mid-air by a vertical air stream. The balance is achieved when the drag force from the airflow equals the gravitational force acting on the object.

This experiment aims to measure and predict the height at which these spheres levitate in the jet generated by the setup. The results of the study will be compared between experimental data and theoretical models in this lab.

We used five spheres of different weights (2.10 g, 2.44 g, 2.53 g, 2.74 g, and 3.17 ab and applied the same flow conditions to each sphere. To measure the speed of the jet, a hair dryer with a nozzle diameter of 3.8 cm was used to inflate a bag to a volume of 0.117852 m3 which is 0.117852m3. A timer was used to record the time taken to fully inflate the bag, which allowed us to calculate the flow speed for further calculations.

In this experiment, we can measure the jet speed and stability of the ball in the profile and compare our observations to predictions from the drag force calculations. Looking at the applications, levitating various spheres of different weights gives us insight into dragging force across turbulent airflow to create useful properties in fluid mechanics.

balls	mean height(m)	sd	mean deviation	ball weight (*10^-3)
1	0.546	0.0488	0.0377	2.1*g
2	0.33	0.0165	0.00732	2.44*g
3	0.333	0.0106	0.00847	2.53*g
4	0.294	0.0161	0.00815	2.74*g
5	0.257	0.0101	0.00963	3.17*g

Figure 1: Mean height (m), standard deviation (SD), mean deviation, and ball weight (relative to gravitational constant, g) for five distinct balls. Data illustrate that as ball weight increased, the mean height reduce.

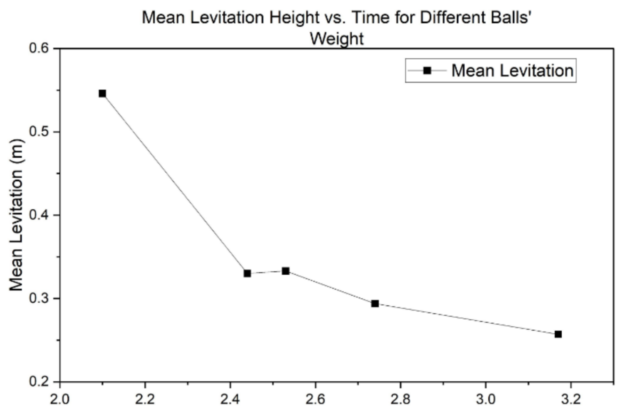

Figure 2: This figure clearly illustrates that an overall increase in ball weight reduces the mean height, except for balls 2 and 3, which may be caused by fluctuations in the flow.

The experiment was performed with five spheres of varying weights (2.10 g, 2.44 g, 2.53 g, 2.74 g, and 3.17 g) under steady state airflow conditions. Initially all spheres were located on the same position in relation to the hair dryer. A ruler was used to check vertical alignment in terms of distance; a check was made that both the spheres and the hair dryer were perpendicular to the ground.

First, each of the spheres was held at one starting point then we turned on the hair dryer. So, the spheres would move in the vertical air stream produced by the hair dryer. The upward force required to keep the spheres at different heights was supplied by the air stream. Eventually, the spheres would stay around at one point. Each spheres' motion in the process was recorded by a camera. This camera footage was analyzed by Tracker software, which tracked each sphere frame by frame. Multisource data of both the spheres' vertical position as a function of time was extracted from the current video frames for further analysis, guaranteeing accurate measurements of levitation height and motion stability.

This approach ensured that all measurements were recorded under identical airflow regimes and that any fluctuations in levitation height were indicative of sphere weight with the airflow manner consistent.

2.1. Airflow rate measurement

Table 1: Experimental Equipment Details

Equipment	Details
Five balls with different weights	A hair dryer
A large garbage bag	A camera (smartphone)
A ruler	Tracker software
A dial caliper	A digital gram scale

Table 2: Weights and Diameters of the Balls

Balls	Weight (g)	Diameter (mm)
1	2.1	57.3
2	2.44	39.5
3	2.53	40.0
4	2.74	40.0
5	3.17	39.6

Table 3: Volume of the Garbage Bag

Item	Volume (cm^3)
Large garbage bag	117,852

To measure the airflow rate, the hair dryer nozzle was connected to a large garbage bag with a volume of 0.117,852 m3. The inflation time of the bag was measured, and it took 8.28 seconds for the bag to fill with air. By dividing the volume of the bag by the recorded time, the airflow rate (U) is equal to 12.55 m/s.

$$U = \frac{V}{t} = \frac{0.117852}{8.28} \approx 12.55 m/s \tag{1}$$

The drag force balance can be calculated as follows:

$$F_{drag} = F_{gravity}$$
$$F_{drag} = \frac{1}{2} C_D \rho U^2 A \tag{2}$$

Where C_D is drag coefficient; ρ is fluid density; U is airflow velocity; A is cross section area of the sphere D is diameter of the ball. R_e can be described as follows:

$$R_e = \frac{\rho U D}{\upsilon} \tag{3}$$

Each sphere was placed in the upward air stream and allowed to stabilize at a consistent height. To estimate both average and maximum heights, we shook the setup slightly to observe how well the spheres maintained their positions in the air stream. Once stable, the height of the ball was recorded.

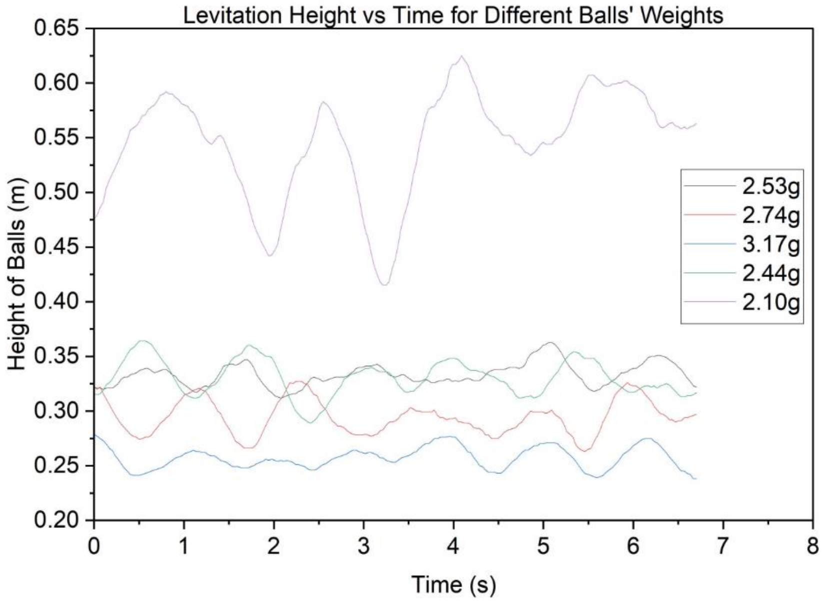

Figure 3: The plot shows fluctuating patterns in levitation height over time, with heavier balls levitating at lower mean heights compared to lighter ones, illustrating the influence of ball weight on both stability and levitation height.

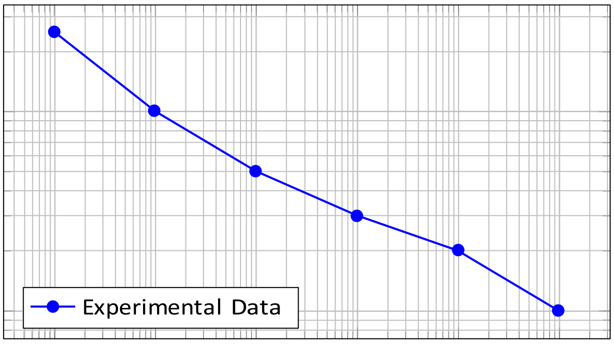

Figure 4: Variation of drag coefficient (C_D) with Reynolds number (*Re*).

Ball number	Theoretical_ Height(m)	Difference (m)	Percentage Error(%)
1	0.45	0.096	21.33333333
2	0.287	0.043	14.9825784
3	0.285	0.048	16.84210526
4	0.274	0.02	7.299270073
5	0.252	0.005	1.984126984

Figure 5: Theoretical height (m), difference between the theoretical and experimental heights (m), and percentage error (y%) for five distinct balls. The data illustrates that the model is more accurate for lower height values overall, as indicated by the decreasing percentage error with smaller theoretical heights.

The software Tracker was used to measure the height of the ball, using the diameter of the hair dryer nozzle as the reference length. As the camera was not fixed, some shakiness was present. To correct this, the movement of the center of the hair dryer was tracked and used as the reference point, eliminating the effect of the camera shake. The bottom of the ball was then tracked for 200 frames to record its levitation height and horizontal movement.

2.2. Data analysis

The measured heights were entered into Excel to calculate the mean values and perform further analysis. Linear graphs were created to illustrate the relationship between sphere weight and the upward thrust achieved for each sphere.

We repeated these steps with each of the five spheres to see how weight affects levitation height.

3. Results

Combining the five spheres, we did an experimental measurement of how high they floated in the constant upward stream of air from a hair dryer. We used a software tracker to measure the height at which each sphere hovered, taking multiple measurements to have enough data to get an average height.

Overall lighter ball tends to levitate higher than heavier ball. There is an exception in our experiment that ball 2 and ball 3 have similar weights as ball 3 is 0.11 gram heavier but levitate 0.003 m higher. This may be caused by fluctuations in the flow. (Fig. 1 and 2)

We observed that lighter spheres tend to move up and down more significantly than heavier ones and have larger standard deviations. This indicates that lighter objects are more influenced by the turbulence in the airflow (see Figure 3).

These heights were then compared to the predicted heights calculated using our model. The difference between our experimental observations and theoretical predictions decreased with the weight of the spheres. This implies that the model was more consistent with the heavier spheres in the air stream.

4. Discussion

We came up with an equation to predict the levitation height of the ball by equating the drag force and the weight of the ball. We calculated the value of the Reynolds number of the airflow and read the coefficient of drag C_D from the plot (see Fig. 4)

$$y = \sqrt{\frac{\frac{1}{8}\rho(5Ud)^2 \pi D^2 C_D}{W}} \quad (4)$$

Where is the levitation height. W is the weight of the object. ρ is the fluid density, $\rho = 1.2$ kg/m^3. $U = 12.55$ m/s and $d = 0.038$ m are the airflow velocity and diameter of the nozzle, respectively. D represents the diameter of the ball. C_D is the drag coefficient, $C_D = 0.47$.

We compared the actual heights we measured to the heights predicted. We found that, as the spheres got heavier, the difference between what we observed in the experiment and what the theory predicted became smaller. This suggests that the heavier spheres behaved more predictably in the air stream. (See Fig. 4 and 5)

When the hair dryer is placed upright, the drag force produced by the high- speed jet is balanced by the weight of the ball. The up-and-down oscillatory movement of the ball may be caused by the turbulence in the stream.

The oscillation in the horizontal axis is much harder to predict and explain. Our ansatz (educated guess) is as follows: any initial instability and turbulence in the airflow could cause the ball to oscillate horizontally. The nozzle is not perfectly uniform, which may introduce initial turbulence, and any asymmetry in the ball's shape can amplify this effect. The heavier the ball, the more resistance it has to turbulence. Hence, lighter balls not only oscillate more vertically but also horizontally.

We also found that when the hair dryer is tilted to a certain angle, the ball does not fall out of the airflow profile. This can be explained using Bernoulli's equation. A high-speed jet issuing out of a nozzle leads to lower pressure in that region compared to the surroundings. Hence, when the hair dryer is tilted, the ball remains in the stream due to the pressure difference. The ball will fall out if the angle is large enough that the weight exceeds the vertical supporting force.

The experiment revealed several notable findings related to the relationship between sphere weight, stability, and their behavior in a vertical air stream. Heavier spheres demonstrated greater stability with less variation in levitation height, consistent with theoretical predictions, as the stronger gravitational pull they experience makes them less sensitive to turbulence. In contrast, lighter spheres exhibited greater fluctuations in their levitation height, with higher deviations from predicted values, likely due to the stronger turbulence effects and instability of the air stream. A key observation related to Bernoulli's principle was that when the hair dryer was tilted, the spheres remained levitated within the stream, held in place by the pressure difference created by the high-speed airflow. This highlighted the importance of low-pressure zones in maintaining levitation. However, some experimental limitations were identified, such as inconsistencies in the air stream from the hair dryer and the manual alignment of the setup, which may have introduced minor discrepancies in sphere positioning and flow measurements.

To address these limitations and improve future experiments, we propose several modifications and additional steps. Firstly, the accuracy of height measurements can be improved by using laser-based or electronic sensors, though this would require access to advanced laboratory equipment. Similarly, more precise airflow speed measurements could be obtained using specialized instruments rather than indirect calculations, providing more accurate data on flow velocity. We also recommend testing a wider variety of object shapes, weights, and materials, as this would provide a more comprehensive understanding of how drag force and turbulence interact across different configurations.

5. Conclusion

This study offers valuable insights into the mechanics of drag forces and turbulence. It demonstrates that heavier objects tend to resist turbulent and random air movements more effectively, staying closer to predicted levitation heights, whereas lighter objects are more susceptible to vertical and horizontal oscillations. These findings are significant not only for advancing fluid mechanics education but also for practical applications, such as improving the aerodynamic stability of drones, projectiles, and other objects subjected to turbulent airflows. Future research could expand this work by considering different geometries, materials, and flow conditions, contributing to the design of more stable structures in aerodynamic and fluid dynamic systems.

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