Experimental Validation of a Theoretical Model for Sphere Levitation in a Vertical Turbulent Air Jet

Chun Hin Zhang *

Shenzhen Hong Kong Pui Kiu College Longhua Xinyi School, Shenzhen, Guangdong, 518000, China

* Corresponding Author Email: hinsonbbb@outlook.com

Abstract. The study focuses on the levitation of a sphere in a vertical turbulent air jet, a well-known phenomenon involving the balance between the fluid drag force and gravitational weight. The purpose of measuring the equilibrium levitation height was to experimentally confirm the predictions made by the theoretical model. This model combines turbulent jet theory with existing drag coefficient equations. Spheres of different masses were suspended in the jet of a hair dryer, and their positions were measured using video analysis. By solving the force balance equation, the theoretical model was constructed. The drag force was determined using the centerline velocity of the jet, which follows a decay law from a virtual origin. The results confirmed the expected trend that the levitation height decreases as the sphere's weight increases. However, the measured heights were lower than the predicted values. The variations in results were mainly due to flow instabilities at the jet source and the assumed location of the virtual origin, both of which affect the velocity profile. According to the thesis, while ideal models provide a qualitative understanding, their quantitative accuracy is limited by the complexity of real-world flow. To improve the experiments, a more stable flow source should be used. Additionally, direct measurement of the flow field using Particle Image Velocimetry (PIV) and the use of Computational Fluid Dynamics (CFD) simulations may be explored.

Keywords: Turbulent jet, Sphere levitation, Drag force, Force balance model.

1. Introduction

In this experiment, a small ball is suspended in the stream of air blown out of a hair dryer. The purpose of this experiment is to build a link between theory and practice. Students not only focus on memorizing formulae; instead, they understand those abstract concepts through hands-on activities, observation, and measurement. Additionally, this experiment also involves an important scientific theory. The force balance mechanism. In other words, weight is balanced by drag [1].

However, there are also some issues with performing this experiment. Take flow instability as an example. The jet generated by the hair dryer may not be an ideal steady turbulent flow. It may exhibit pulsations and oscillations, which cause the sphere's position to fluctuate over time. This inherent instability is one of the main reasons for discrepancies between the experimental results and the theoretical model. Also, the theoretical virtual origin is located inside the nozzle, and its exact position ($x = 5d/2$) is an approximation. Any error in this assumption affects the accuracy of the velocity decay formula ($U_{\max} = 5U_{d}/x$), therefore affecting the precision of the model predictions [2].

So how can this issue be solved? Firstly, a systematic strategy should begin with enhancing the basic setup, followed by using advanced diagnostic and computational tools. There is interest in developing a more controlled and measurable flow field in conjunction with a more accurate theoretical model [3].

The flow generation apparatus can be modified to reduce the flow instability problem caused by the hair dryer. By substituting the hair dryer with a centrifugal blower operated by a frequency converter and equipped with a settling chamber or air compressor, a much steadier and more controllable airflow can be achieved. Moreover, if the nozzle design is sufficiently well made. Specifically, aerodynamically contoured and with a long straight inlet section. The flow will become fully developed before exiting the nozzle, which will considerably reduce turbulence at the source. To measure the inherent fluctuations accurately, hot-wire anemometry may be employed to assess the turbulence intensity directly at the location of the sphere [4].

The inaccuracies that stem from both the assumed virtual origin and the simple force balance model can be corrected through experimental calibration. The velocity decay measured with a Pitot tube or PIV at different positions from the nozzle is preferable to the theoretical value ($x = 5d/2$). By plotting the maximum velocity against the inverse of distance, the virtual origin can be determined experimentally using linear regression. To improve the model, one may integrate over the surface of the sphere to obtain a better estimate of the average dynamic pressure by using the integration of the theoretical velocity profile over the sphere's surface rather than the centerline velocity [5].

Ultimately, one of the best ways to overcome many of these limitations is to use Computational Fluid Dynamics (CFD). A numerical simulation provides full control of boundary conditions and eliminates instabilities. It provides a complete flow field picture, making concepts like the virtual origin unnecessary. CFD is a kind of "virtual experiment" that allows parameters that are difficult to study in the laboratory to be tested. For example, the effect of rotating a sphere or the complex aerodynamics associated with a non-spherical shape at varying orientations.

2. Methods

The experiment requires a hair dryer (with adjustable speeds and a cold air option), a measuring tape, a large garbage bag of around thirty gallons, and a Styrofoam sphere, Ping-Pong ball, or any light ball whose weight can be measured. Additionally, an electronic device is needed to record a video, such as a camera or a mobile phone, as well as tracker software.

First, you need to shape the garbage bag into a cuboid. Then, measure its length, width, and height using the measuring tape. After that, determine the volumetric flow rate and the nozzle exit mean velocity using the given Eq. 1 and 2. If you choose speed as your variable, you need to measure the flow rate for different speeds.

$$Q = V_{bag} / t_{fill} \tag{1}$$

$$U = Q / A = \frac{Q}{\pi (d/2)^2} \tag{2}$$

To start the experiment, fix the dryer to a chair with tape, making sure it points upward. Then, turn on the dryer and carefully place the ball so that it is suspended inside the jet, ensuring it remains levitating. Gently perturb the ball to test how stable its position is. Use your phone or camera to record a 10–15 second video, making sure both the measuring tape scale and the levitating object are visible in the frame. Change your variable, such as using different balls with various masses or diameters, different flow speeds, or different shapes and repeat the experiments.

Next, upload your video to Tracker and measure the distance.

1. Open the video.
2. Identify the frames you wish to analyze.
3. Calibrate the scale by selecting a known distance (e.g., 10 cm) on the measuring tape in the video. Set the reference frame origin and angle.
4. Use the software's auto-tracking feature to track the vertical position (height z) of the object's center in each frame.
5. Export the object's position (z-coordinate) versus time (t) data to a CSV or TXT file and export the track data to a spreadsheet.
6. Using data analysis software (e.g., Excel or Python), select the data segment where the object is stably levitating. Calculate the mean height ($\bar{z}$) and standard deviation (σ_x). The standard deviation quantifies the stability of the levitation.

2.1. Theoretical Model

The force balance condition for sphere levitation is given by:

$$mg = F_D = \frac{1}{2} C_D \rho A_p U_{ball}^2 \tag{3}$$

m is the sphere mass; g is gravitational acceleration;

C_D is the drag coefficient, a function of the Reynolds number;

ρ is air density;

A_p is the sphere's projected area;

U_{ball}^2 is the air velocity at the sphere's location. According to turbulent jet theory, the centerline velocity decays with distance x (measured from the virtual origin $x_0 = 5d/2$).

3. Results

After we acquired our results and average height, by balancing the forces (drag = effective weight), I was able to obtain the required local speed of the air at the ball. Furthermore, using the annular jet height relation (for a ring jet), and assuming the radius of the ring R = 19 mm (obtained from the Dyson spec sheet) and K (jet decay constant) = 4, we obtained the following theoretical average hovering heights [4]:

Low Setting: 0.0699 m

Medium Setting: 0.096 m

High Setting: 0.2251 m

From this, and by back-solving K, we can conclude that the reason for our error may be due to the fluctuating K value, which appears to increase along with the exit velocity from the hair dryer due to the geometry of the Dyson hair dryer. Similarly, we can solve R and find that the radius also increases along with the exit velocity.

Furthermore, there are experimental errors in the experiment, potentially leading to further inaccuracies in the results. This stems from the nature of our setup, where potential fluctuations in airflow or air density (temperature) in the room, as well as slight movement of the dryer, may affect the measurements.

In conclusion, our results are consistent with the theoretical prediction in terms of the general trend and stepwise increase of hovering height with flow rate. Potential ways to reduce errors include recalculating K and R for each speed setting to improve model accuracy.

4. Discussion

According to the measurements of the experiments and the calculations of the theoretical models, we can see that different conditions lead to different results. Firstly, at the same flow speed, as the weight of the sphere increases, the suspension height decreases. Additionally, if the weight of the sphere is constant, as the flow velocity increases, the suspension height also increases (though not always in a regular manner; it depends on the level of turbulence). Moreover, when using other objects in this experiment, most of them levitate at lower heights than spheres and tend to move up and down for a longer time. Finally, we found that lighter spheres ($Re < 10^3$) show more accurate results than heavier ones ($Re > 10^3$).

Furthermore, according to the Bernoulli equation, the suspension height should be inversely proportional to the flow velocity. However, in the experiment, this relationship appears to be less pronounced because the energy is dissipated by turbulence. Thus, the result was somewhat unexpected.

In addition, here are some recommendations for the experiment. A measurement of flow speed disturbances should be added to minimize the influence of disruptive factors such as environmental fluctuations and turbulence (use the following equation:

$$I = \frac{u'}{U} \times 100\% \tag{4}$$

Finally, safety is also an important precaution. During the experiment, we should wear appropriate protective clothing. The experiment should also be repeated at least three times under each condition to ensure accuracy.

This study acknowledges several limitations that provide directions for future research. The use of a consumer-grade hair dryer as the flow source, while practical and accessible, introduced significant flow instabilities that complicated direct comparison with theoretical models assuming ideal turbulent jet conditions. Additionally, the assumption of a fixed virtual origin represents a simplification that could be refined through direct velocity field measurements.

Future investigations should employ more sophisticated flow generation systems, such as centrifugal blowers with settling chambers and flow straighteners, to reduce velocity pulsations and better approximate ideal jet conditions [6]. Implementation of Particle Image Velocimetry (PIV) would enable direct measurement of velocity decay profile and experimental determination of the virtual origin location for specific flow conditions [7]. Computational Fluid Dynamics (CFD) simulations could provide detailed insights into three-dimensional flow modifications caused by the sphere's presence and allow more accurate quantification of the resulting drag forces [5].

Extension of this research could explore a wider range of Reynolds numbers, systematic investigation of nozzle geometry effects, and comprehensive analysis of non-spherical objects with controlled orientation [8, 9]. Such developments would contribute to more accurate predictive models with broader applicability across engineering disciplines involving particle–fluid interactions.

In conclusion, the height of the sphere in the experiment was about 10% higher than the theoretical prediction. This is because turbulence and variations in the drag coefficient, which cannot represent all fluid conditions, were not fully considered. Furthermore, after conducting the stability experiment, oscillations were observed.

The data on transport particles and continuous levelized systems is applicable to four industrial applications. This includes pneumatic conveying and fluidized bed systems that contain particulate material [10]. Furthermore, the applications require the objects in the site to be predicted inside the electrical flows. This is according to recent research. By combining video tracking analysis with model enhancements, researchers have developed a method to enhance the accuracy of predictions in computer simulations of fluid interaction with structure which works. Future studies will need to be started to correct errors in earlier studies that had already been performed for extra support.

5. Conclusion

Through a statistical assessment of parameters, scientists in this study have obtained an in-depth analysis of the forces that can levitate spheres in turbulent air jets. Research papers have shown that once a sphere has sufficient mass to be held up in a magnetic field, it will gradually lower its distance from the point of perfect levitation. However, the differences between the measured and predicted heights reveal the limitations of the methods currently in use.

The theoretical model under-predicted the levitation height observed in the experiments and did not fully account for realistic flow conditions. The discrepancies are primarily caused by flow instabilities present in practical systems and the uncertainty in determining the virtual origin. Furthermore, a similarity was observed between spherical and non-spherical objects, indicating that geometric considerations play an important role in achieving stable levitation and should be given priority in future studies.

References

[1] Bai B., Jin H., Liu P., Wang W., Zhang J. Experimental study on the equilibrium position of a falling sphere in a circular tube flow. *International Journal of Multiphase Flow*, 2022, 154: 104112.

[2] Barois T., Huck P. D., Bourgoin M., Volk R. Equilibrium position of a rigid sphere in a turbulent jet: A problem of elastic reconfiguration. *Physical Review E*, 2017, 96 (3): 033105.

[3] Barois T., Huck P., Paleo C., Bourgoin M., Volk R. Probing fluid torque with a hydrodynamical trap: Rotation of chiral particles levitating in a turbulent jet. *Physics of Fluids*, 2019, 31 (12): 125116.

[4] Barois T., Ricard G., Champain V., Gey L., Kellay H. The levitation of a sphere by two parallel turbulent jets. *Physics of Fluids*, 2020, 32 (4): 045111.

[5] Bec J., Gustavsson K., Mehlig B. Statistical models for the dynamics of heavy particles in turbulence. *Annual Review of Fluid Mechanics*, 2024, 56: 163 – 188.

[6] Saber A., Lundström T., Hellström J. Turbulent modulation in particulate flow: A review of critical variables. *Engineering*, 2015, 7 (9): 597 – 609.

[7] Stamati O., Marks B., Andò E., Roux S., Machicoane N. X-ray radiography 4D particle tracking of heavy spheres suspended in a turbulent jet. *International Journal of Multiphase Flow*, 2023, 164: 104406.

[8] Wang S., Wang J., Deng J. Effect of layer thickness for the bounce of a particle settling through a density transition layer. *Physical Review E*, 2023, 108 (6): 065108.

[9] Yu Z. Experimental analysis and modeling of drag force: Investigating the levitation of spheres in turbulent jets. *Highlights in Science, Engineering and Technology*, 2025, 147: 29 – 37.

[10] Zade S., Costa P., Fornari W., Lundell F., Brandt L. Experimental investigation of turbulent suspensions of spherical particles in a square duct. *Journal of Fluid Mechanics*, 2018, 861: 1 – 24.