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Effect on Terminal Velocity with Changing Hole Diameter

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Abstract

The idea for this paper was to notice how air resistance acts on a body of the same mass, with different diameter holes. I did this by dropping the hand-made cubes from an equal height of 3.7 metres and checking their terminal velocity. Using softwares such as Tracker and Logger Pro, I came to the conclusion that the drilled holes within the different cubes (made with styrofoam) caused a significant amount of change in the final velocity of the cubes which can be enhanced even further in the bigger picture.

Keyword: Terminal Velocity, Drag, Fluid mechanics, Acceleration, Density

Introduction

Ever since I was a child, I have always been very much involved in sports, especially racket sports. It has always fascinated me how aerodynamics works. Just a little topspin over the top of a ball changes its trajectory completely and makes an entirely different feel to it. Even having an interest in cars and noticing that faster cars tend to have more streamlined and open shapes which helps in fast manoeuvers. After taking up physics in my school, I developed more and more interest in the functionality of aeromechanics and my teachers helped me open up a creative portal through which I derived a question. A question to check how air resistance acts upon an object of the same mass with varying diameter holes. In this study, my aim was to check whether or not air resistance is a major factor in falling objects with different cross-sectional areas for it to act on. The initial thought of the use of this study was directed toward engineering applications. For example, in automotive design, understanding how the presence and size of perforations affect air resistance can aid in optimising the design of vehicles for improved fuel efficiency. Even in the sporting industry, seeing how rackets are designed with strings. So this study will help to figure out what the thickness or weight of the added strings should be to make sure it is playable.

Theory

As the size of the hole diameter increases, the value of terminal velocity also increases. Terminal velocity is proven to be proportional to the hole diameter as shown in Fig: 3 and in Table: 2 shown later in the paper. This result is similar to past studies and findings related to this experiment, where it states that the amount of air drag acting on an object increases with the increase in the area of cross-section. The reasoning behind this is attributed to the intricate dynamics of aerodynamics and fluid flow. When falling through the air, the cubes react to air resistance resulting in decreased acceleration acting on the body. Weight is constant for all cubes and air resistance, mathematically is proportional to velocity, or sometimes proportional to the square of velocity. So as velocity increases, so does the air resistance. Here in this case, the drag force acting is on the vertical (y-axis) component of the fall.

According to Newton's second law of motion, Force(F) = Mass(m) x Acceleration(a), which means $a\ (Acceleration) = \frac{Force(F)}{Mass(m)}$

The net external force is given by (W – D) where W is weight and D is drag force. The acceleration then becomes

$$a\ (Accelaration) = \frac{(W - D)}{m}$$

So if drag equals the weight then the acceleration becomes 0 hence, we have reached terminal velocity and that is what the experiment is based on.

The way drag applies to a falling body depends on the density of the fluid. However, in our case, the air resistance acting has a constant density so the change in acceleration or terminal velocity is impossible. The formula to calculate drag is given by the formula:-

$$D = Cd\ \frac{V^2 rA}{2}$$

Where D(Drag) equals Cd (drag co-efficient) time half of V^2 (velocity square) times r (air density) times a reference A (area) on which the drag co-efficient is based.

Through the above formula, it is quite evident that Drag changes with the change in surface area acting on the body. It is directly proportional, so the more the area, the more the drag acts on the body, and similarly to our experimental observation, decreasing the surface area that comes in contact with the air particles throughout the 6 cubes has a changing effect reaction to drag. Drag evidently decreases and hence increases the terminal velocity that acts on the body as shown by our results.

If talking about the direct proportionality of velocity square with drag, the reason for that to occur is that as the velocity increases, the object falling through the air comes in contact with more air particles per unit times so this, hence, increases the drag acting on the body. Again in this situation, due to the lack of presence of some amount of area taken out from the cubes, there is less area for the particles to come in contact with.

The velocity as a function of time for an object falling through a non-dense medium, and released at zero relative-velocity $v = 0$ at time $t = 0$, and at terminal velocity is roughly given by a function involving hyperbolic tangent at a limit (terminal velocity):-

$$v_t = \sqrt{\frac{2mg}{pAC_d}}$$

Where m is mass, g is gravitational pull, p is the density of fluid, A is relative area and C_d is drag-coefficient.

This formula too clearly indicates that terminal velocity is inversely proportional to the relative area(A). In terms of the other variables, the density of air remains constant and the coefficient of drag is found out using the formula above. Using that formula we can figure out that the coefficient of drag decreases with the increase in area, and when the coefficient of drag decreases, the terminal velocity increases. Hence, the terminal velocity again increases as the area of contact decreases i.e. hole diameter increases.

Methodology

To create the objects, I used a material called styrofoam. The reason to use styrofoam was because it has the perfect density of about 1.00g/cm^3. The density is just enough for it to react with air resistance without making it negligible. Firstly, 3x3 cm squares of this were cut, and a total of 6 squares made one cube. The total thickness of the cube was also 3cm to the overall volume of the initial cube was 3x3x3 = 27cm^3 (except when later holes of different diameters were drilled). There were a total of 6 cubes used for the experiment.

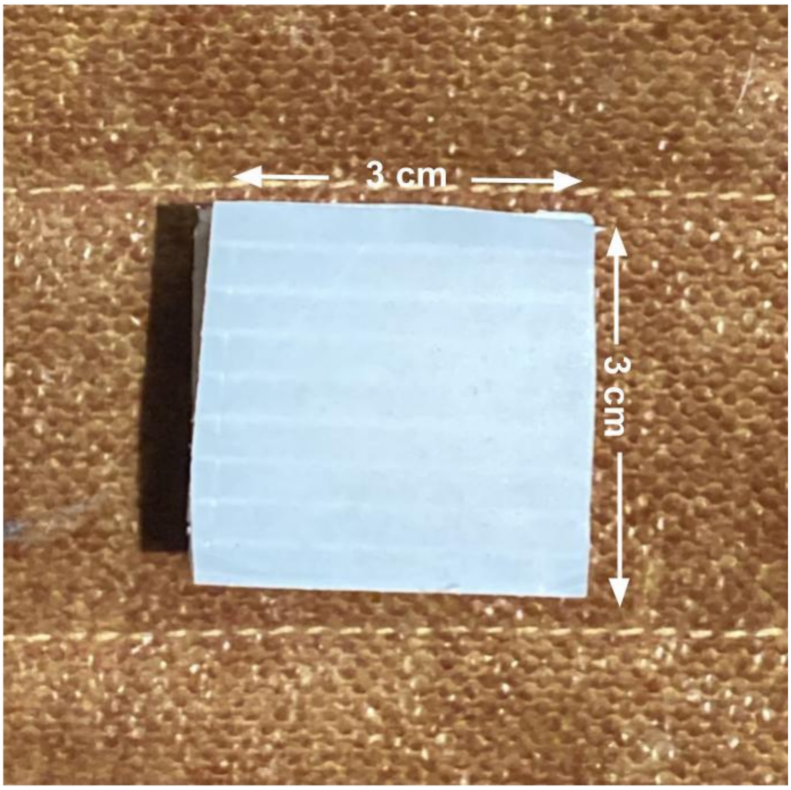

Fig 1: The Cube and its dimensions used for the experiment.

To make the holes, drills of different diameters were used to create gaps in the cubes. Since a total of 6 cubes, 5 of them had holes in an increasing order of diameter and one had no hole within and was an absolute solid. The table below provides the data required.

Cube number	Diameter of the hole(mm)
1.	0.0
2.	5.0
3.	10.0
4.	15.0
5.	22.5

6.	24.0

Table 1: Cube number and the hole diameter used.

The minimum hole is technically 0 mm but the second cube having the actual minimum hole diameter is about 16%, then the maximum diameter of 24 mm is 80% of the area of the square.
As per the weight, to ensure that the weight of all the cubes was the same without disrupting the shape and final volume of the cubes, I used fevi-glue as an option. An extremely thin layer of fevi-glue was used to evenly spread on the sides of the cubes to ensure that the final weight equals the weight of the 1st cube with 0 mm diameter. Note that the change was not brought to the initial cube since that was the aim to be achieved for the final weight. The weight for all the cubes individually was 3.62 grams. To ensure the accurate weight, a jeweler's weighing machine was used which read weight up to 3 decimal places.

As per the dropping of the cubes. A height of 3.7 meters or 370 cm was used. The dropping tools were tongs. This was done to ensure that when dropped, the chances of a tilt or added/subtracted acceleration wouldn't be present. Also using threads as a tool to drop caused massive abruptions in the weight and was nearly impossible to adjust them without changing the shape or how air drag acts on them.

To record the fall, a phone camera was used which was set up using a stand of about 1.7 meters. The video was shot in slow motion which was approximately 240 FPS (Frames Per Second). There were a total of 5 trials for each cube so 30 videos in total were shot.
To measure the Terminal Velocity of each fall, software like Tracker and Logger Pro were used. Tracker gave all the data points and coordinates including the time and rate in reference to the diameter and mass of the object. Those values were then plotted into logger pro and using the formula of:-

$$s = ut + \frac{1}{2}at^2$$

This formula helped me derive the acceleration of each cube.

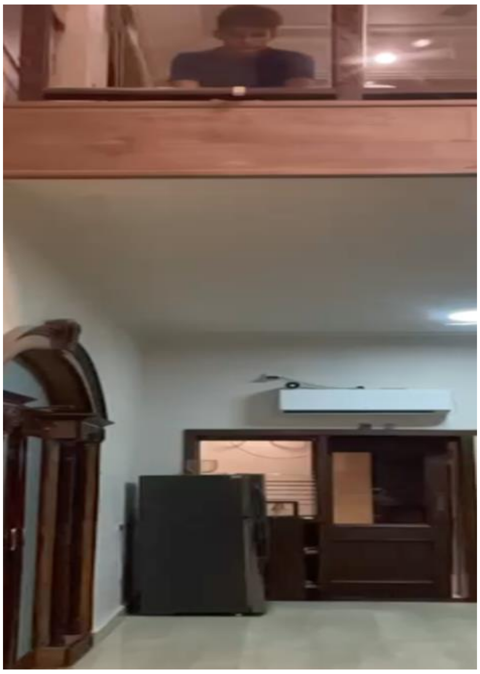

Fig.2: Experimental Setup.

Data

The first set of data was the drill sizes (diameter of the cubes).

Following are the terminal velocity derived from each fall, their mean, and the uncertainty achieved.

Terminal Velocity of cube m/s^2								
S.NO	Hole Diameter (m)	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Mean	Uncertainty
1	0	4.67	4.84	4.78	4.89	4.98	4.8	0.2
2	0.005	5.13	5.12	5.23	5.07	4.87	5.1	0.2
3	0.01	4.98	5.22	5.28	5.18	5.15	5.2	0.2
4	0.016	4.91	5.33	5.36	5.27	5.19	5.2	0.2
5	0.0225	5.52	5.42	5.12	5.28	5.35	5.3	0.2
6	0.024	5.45	5.25	5.21	5.71	6.05	5.5	0.4

Table 2: Change in Terminal Velocity in accordance with the Hole Diameter.

Now looking at the table above shows us evidently that there is certainly a change in the terminal velocity after looking at the Mean of all trials for 6 cubes. This would be expected given the theory presented before.

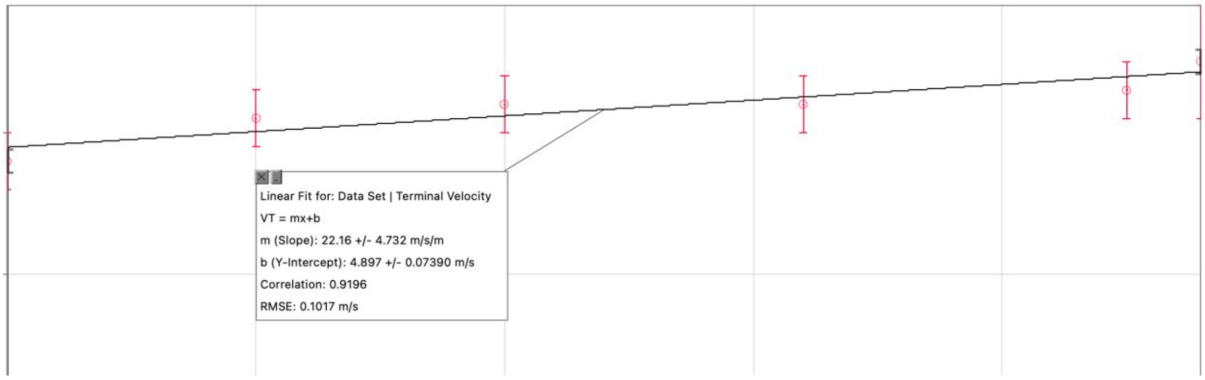

Fig 3: Graph of Hole Diameter against terminal velocity in accordance with uncertainty.

The graph above is the Terminal Velocity of each cube in reference to its hole diameter. This graph was also based on the uncertainty caused and as shown by the table earlier, uncertainty shows no connected pattern with the hole diameter similar to the graph. Here we can see that there is a linear graph present with an upward slope. The slope has a value of 22.16 with +/- 4.73 m/s which means that the value of terminal velocity can be changed up to 20 times the related hole diameter. The slope also brings forth a point that the size of terminal velocity will increase with the increase in hole diameter. Hence, proves that the effect on terminal velocity will be present with changes present due to the hole diameter.

A link to an Excel sheet including all the values and points derived using the software 'Tracker' is attached below. This contains the above table, graph, and all the data points used to attain the graphs for acceleration which were plotted in the software 'Logger Pro'.

Conclusion

Considering the result from the value tables, graphs, and data points, it is evident that the change in terminal velocity is present. The difference in hole diameter affects the speed or terminal velocity of the objects in all cases, always. These changes will grow to become massive as the size of the experiment increases. Especially in application of it in real life when creating automobiles and engineering structures. The reason for this, however, mentioned in the theory section, states that since the objects are of the same density and mass, the effect of air resistance is immense on the hole diameter changes due to the light density of air. Note that this was also done on a smaller scale. On a bigger scale as mentioned, incredibly bigger changes may be shown.

In conclusion, I would say that the effect of drag on the hole diameter of objects with the same mass and area will be negligible and does not exist for real-life scenarios.

Error Evaluation

Possible errors made in this experiment are listed below:-

1. **Straight blocks of the cube -** While making the cube using styrofoam squares, fevi-quick was used and there is a possibility that the shape of the cube wasn't exactly 'blocky' since cutting the pieces and joining them together by hand can cause extremely minor disturbances. Any improvement needed can be made if proper machines were used to cut straight squares instead of cutting them by hand to provide sharper edges.
2. **Dropping the cubes -** Since tongs were used as the device for dropping, during one or two of the drops the cube may have tilted by a few degrees on the left or right but considering the number of trials per cube and a number of cubes, these small tilts wouldn't have led to any major changes in value. Maximum changes can be will 2 decimal points. If there was a chance of improvement then maybe the release device could be changed to something more feasible.
3. **Drilling the holes -** The hole drilling can be improved to provide a pin-point measurement of the place of the hole on the cube. To improve this, maybe a larger surface can be used so it is easier to exactly locate the center and drill without any disturbances.

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