Ted Ankara Collage Foundation High School

Behavior of Drag Force Depending on the Shape of an Object

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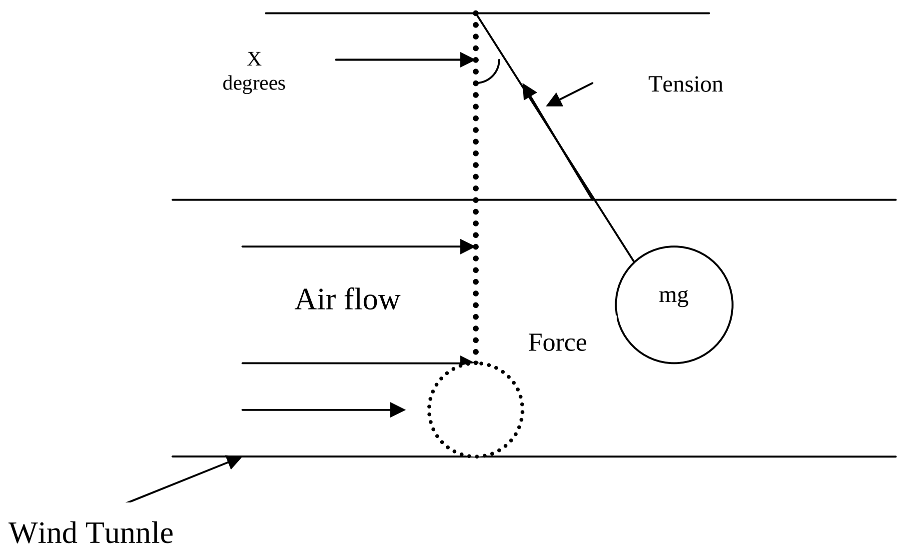
Abstract:

The objective of this essay is to analyze the data, gathered from the relevant experiments, in order to find if drag force depends on the shape of the objects. In this essay, we will be looking at different shaped and sized objects and how the drag force reacts to these differences in shape. For this research, these differences in shape can be classified as their differences geometric shape, mass and cross-sectional area.

In order to reach the answer of our research, unique experiments were conducted for each difference in shape. Each object was hung in a contraption that consists of a cardboard wind tunnel, created by myself, that generated linear air flow via a hair dryer for the objects. Below you will find the diagram. The X angles, made possible by the forces, were used to find the drag forces. The angle is determined by an optical system, by the shadow of the string that the object hangs from the drag forces will be under the scope. These forces were compared with different shaped objects such as, sphere, cube and cylinder, in order to answer the question ''How do drag forces exerted on an object differ by geometric shape?''.



At the end of the trials and calculations, it was clear that the drag force that was applied to the spherical objects were smaller when compared with the other shapes and that as the cross – sectional area increases also the drag force increases. Additionally it was seen that as mass increased the angel decreased.

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Appendix

Part I. Introduction

The term “aerodynamics” is defined in most dictionaries as "the branch of science dealing with the forces exerted by air or other gases in motion”, or “a branch of dynamics that treats of the motions of air and other gaseous fluids and one of the forces acting on bodies in motion relative to such fluids”. More scientifically, aerodynamics is a quantitative science that applies mathematical equations and experimental measurements to improve the lift and drag performance of a shape.

Now, if we extend the term shape that is mentioned above; the shape isn’t literally a circle or a triangle. The shape that is mentioned here is the object that is effected by the lift and drag forces. With the proper measurements, aerodynamics prepares this object to give maximum performance when it is in the air. This essay concentrates on those measurements. The measurements and research along with the experiments in this essay all are focused to understand the behavior of the drag force, and how it differs when the object differs in shape.

Thus the explanation of the terms lift and drag are needed. The example of an airplane will be given to explain the forces. The relative wind acting on the airplane produces a certain amount of force which is called the total aerodynamic force. This force can be resolved into components, called lift and drag, as shown in Figure 1.

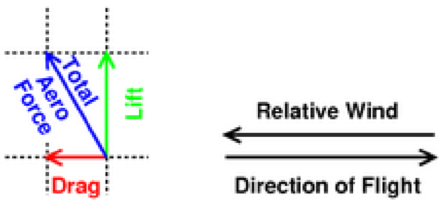


Figure 1: Total Aerodynamic Force = Lift + Drag

- Drag is the component of aerodynamic force parallel to the relative wind. The drag force can also be labeled as air friction.

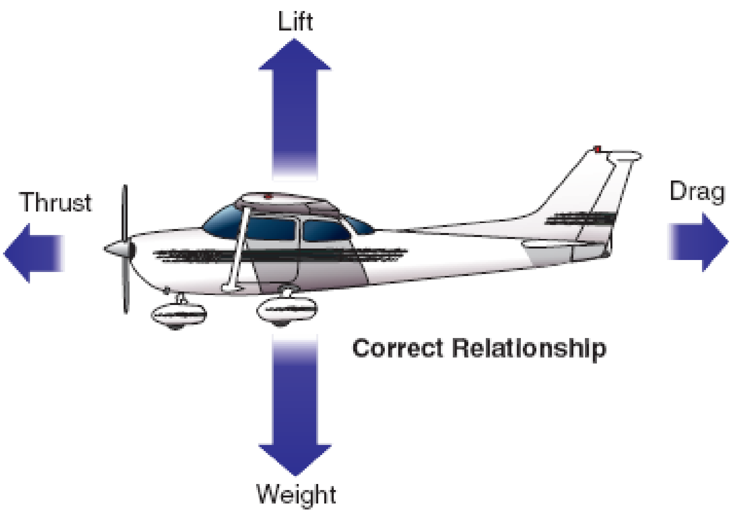
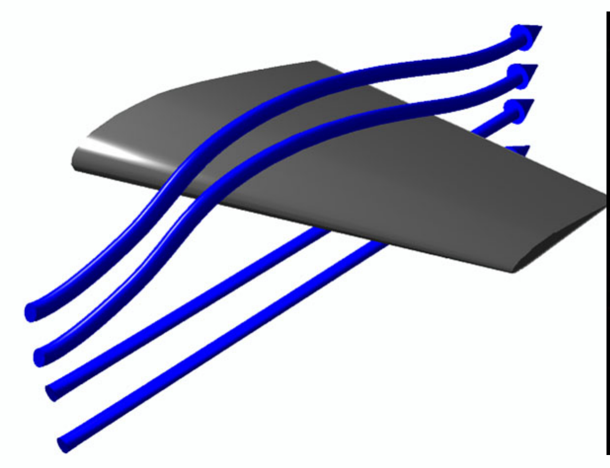


Figure 2: Relationship of forces acting on an airplane

Experimental measurements of the aerodynamic forces acting on a vehicle are carried out primarily in wind tunnels. The wind tunnel itself is an aerodynamic device: It is a machine designed to produce in the laboratory a well-defined, smooth, uniform flow of a gas (usually air) in which a model of a flight vehicle is placed for the purpose of measuring lift, drag, and other parameters. Over the years, the primary focus for many researchers was, and in some cases still is, the aerodynamics of the wind tunnel itself. Also, as we shall see, often knowledge of the details of a flow field around a flight vehicle is required if one is to calculate the aerodynamic forces.

To begin this explanation of aerodynamics for my experiment, consider the flow of air over the body shown in Figure 3. The motion of the air over the body (an airfoil, i.e. a section of an airplane wing) is shown by four streamlines, sketched above and below the airfoil. These streamlines trace out the paths of small parcels of air as they move through the flow field. Figure 4 shows a photograph of the streamlines over an airfoil, made visible by injection of small jets of smoke into the airflow ahead of the airfoil. Tile streamlines shown in Figures 3 and 4 can be thought of as the streamlines that would be observed if a body were stationary and air were flowing over it (such as occurs in a wind tunnel) or as the streamlines that would be observed if a body were moving into stationary air, with the observer moving along with the body. Plane wings and bodies are specifically designed so that they would minimize drag force. This aerodynamic property is related to the question ‘’How do drag forces exerted on an object differ by geometric shape?'' Experimenting on drag force in aerodynamics is crucial for safety in planes and for maximum performance in machinery. Figure 3 can be a diagram of a plane wing which can be classified as an aerodynamic object as the drag force is close to minimum.



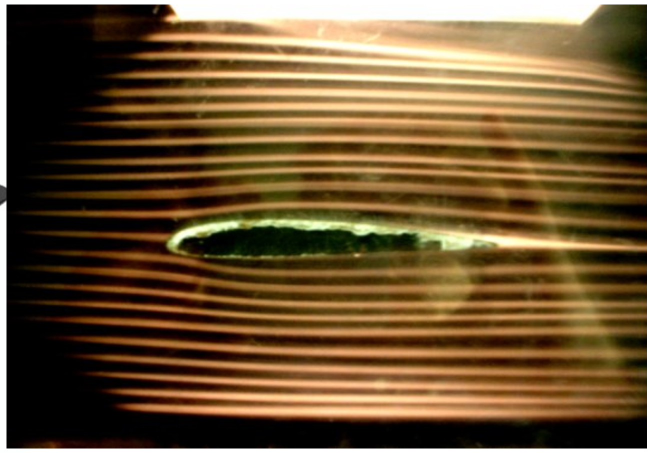
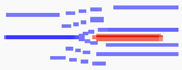
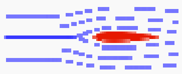
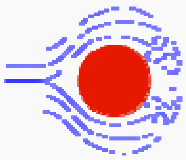
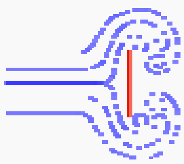


Figure 3: Streamlines over a body immersed in a flow

Figure 4: Smoke photograph of the flow over an airfoil

Shape and flow	Form drag	Skin[1] friction
	0%	100%
	~10%	~90%
	~90%	~10%
	100%	0%

As it can be observed, the air molecules hover over the body in figure 3. I hypothesize that this would not be possible if the object that was exposed to the air flow was flat, like a wall. The air molecules would strike the wall perpendicularly if the linear air was uniform to the streamlines in figure 3. If the molecules would do so strike the wall in that fashion, the air friction applied would increase when compared with figure 3. This is better explained in figure 5 which was obtained from research done in the name of air friction.

We see that the skin friction (the friction caused by the sides) is at maximum and the drag force is at minimum when the shape of the object is parallel to the air flow and completely opposite when perpendicular. In the third row of the figure we also see that a spherical shape has an effect on altering the skin and air friction. In addition, the sphere has the smallest surface area with respect to its volume, so it can be concluded that the air friction of an object depends on its shape and cross- sectional area. This essay condenses on the question; what shape and cross- sectional area causes what amount of drag force? As it was emphasized before, drag force is a force against the thrust. Minimizing this drag force, results in lower need of thrust. This issue is important as thrust is gained from fuels and natural resources.

[1] http://en.wikipedia.org/wiki/Turbulence

Air friction, in my experiment is velocity dependent. This experiments' velocity is the air force blowing at a steady object. Since it is difficult to observe a mobile object, it was easier to have the air come to the object. For high velocities and large objects, the frictional drag is approximately proportional to the square of the velocity:

$$f_{drag} = -\frac{1}{2} C \rho A v^2$$

Where ρ is the air density, A the cross-sectional area, and C is a numerical drag coefficient. From this we can see that the cross sectional area is effective in the calculation of the drag force. It is important to notify that the negative sign in the formula indicates that the force works against the velocity

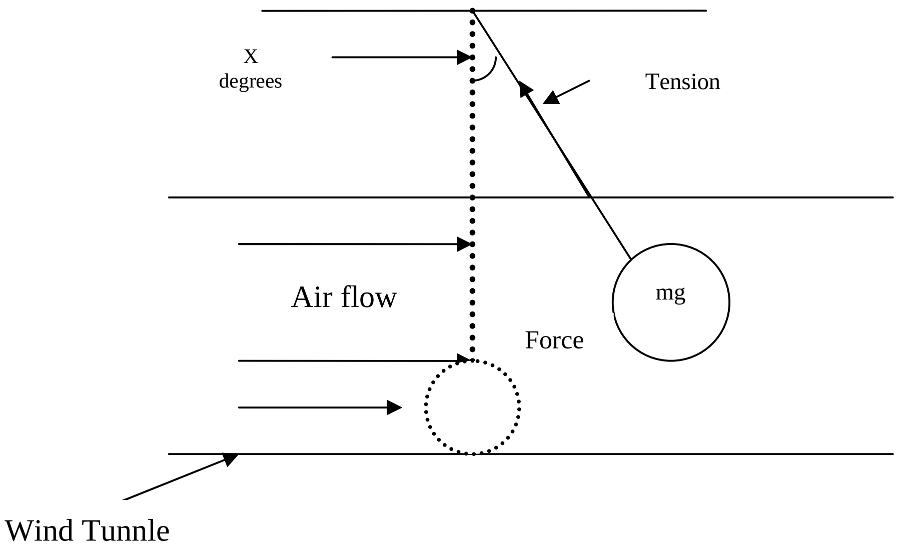
The numerical drag coefficient is a value that is used by aerodynamicists to bond many dependencies such as shape, drag and insulations.

Drag Coef = D / (A * 0.5 * r * V^2)[2]

Where D is the drag force, A is the cross – section area and V is the velocity of the object (r is another coefficient). In wind tunnels these drag coefficients are calculated. According to the data above, the drag coefficient is dependent to the velocity that is why it was kept constant in all sectors of my experiment.

[2] http://www.grc.nasa.gov/WWW/K-12/airplane/dragco.html

My experiments are based on the drag force. In order to do that, my calculations all revolve around the angle shown in the diagram



As we look at the diagram again, it can be deduced that;

$Sinx * T = F_{drag}$

$Cosx * T = F_{mg}$

So, $Tanx * F_{mg} = F_{drag}$

From these calculations it can be concluded that, if we keep the mass constant we can compare the drag forces of objects.

Part II. Understanding the Experiment

a) Materials (The parenthesizes by the materials indicate how the materials were provided for this experiment)

- String
- Tunnel (85cm long Cardboard tube) (diameter of 12,2 cm)
- Needles
- A light source (Mag-Lite brand Flashlight)
- Duck Tape
- Blank sheet of paper
- One aerodynamic object (a styrofoam ball)
- One non-aerodynamic object (a Styrofoam cube)
- A Marker
- An air source (Slone Pro brand Hair dryer 2600W)
- Knife and Scissors

b) The Method

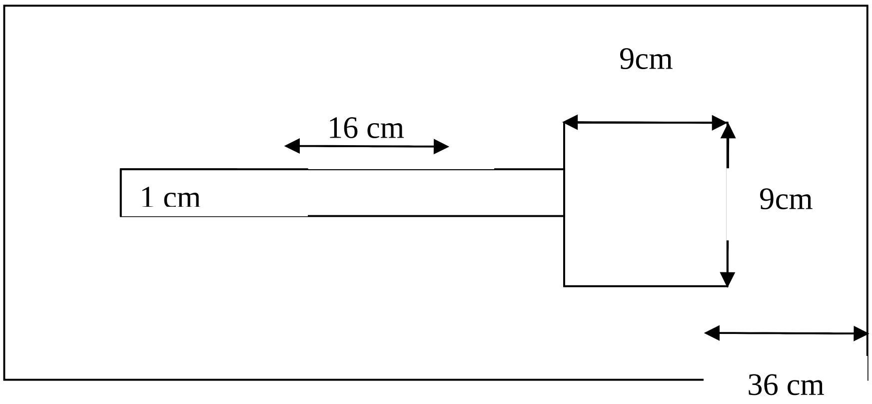
The main idea in this experiment is to figure out the force exerted on the objects by air. Measuring the drag force by throwing the objects seems highly unlikely. However exposing the objects to the air's pushing force and measuring that is reasonable

The way this was done is as follows (each object was treated the same. The objects were taken into observation one by one):

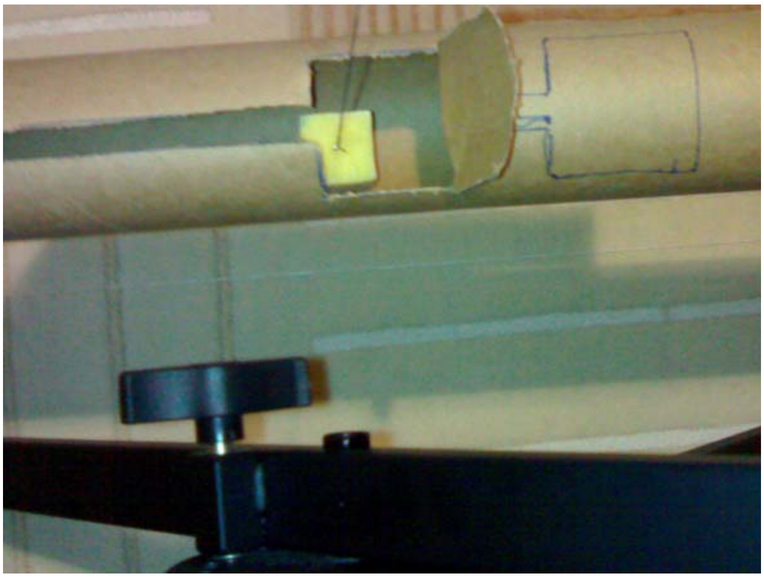
- The object was taken and a needle was driven inside it. A string (the string was chosen from the lightest material, so that it wouldn't affect the experiment) was tied on the other end of the needle. This object is later going to be hung.

- The cardboard tunnel was cut from the top by a knife. The cutting was made so a 9 cm x 9 cm square shape would form 36cms away from the left end of the tunnel. Additionally a rectangle with dimensions of 16 x 1cms from the right end of the tunnel was created. This modified tunnel was later hung from 7.7 cm from the left and right of its ends to a pipe so it would "float". To maintain balance it was also tide to the ground from the same place it was tied to the pipes. To sum up the final position of the tunnel stood 30.15 cm from the ground.

A viwe over the wind tunnel and the modification plans



- The soon to be hung object was granted entrance to the tunnel through the 9x9 cm square. Once inside the tunnel, the object was tried to be placed at the very center of the tunnel. When this was achieved the string was tied to another pipe just above the system and then cut from its source.



- After these steps the air source was used. Since the air source used in this experiment was a hair dryer with a diameter of 5.3 cm, it was able to fit inside the tunnel through the left end.
- Then a light source was duck taped to a table. The main idea in using a light source concerned that its rays must cause a shadow of the string that the object was hung from. Finally a blank sheet of paper was hung with strings (from all corners) so that it would “float”. The paper was placed so that the string’s last position was between the light source and the paper. These three objects were parallel to each other and perpendicular to the ground.

This is how the experiment’s system was created. The reasons why some of these materials were used in the way they were in the experiment and how the experiment was operated is explained below:

c) Tunnel: The main reason that a tunnel was used came from the experience of my own trial and error. In the primitive stages of the experiment a tunnel was not present. When the air source was turned on it was observed that the objects (especially the non-aerodynamic one) were swinging in random directions. After seeing this it was understood that the air passing around and acting on the object were coming at complete random directions. It was because of this that the objects were behaving in an unbalanced manner. In order to focus the air molecules on the objects, the tunnel was added to the experiments.

d) Light Source and Blank Sheet

As mentioned before a quantitative analysis would be preformed. The light source and the blank sheet were used as a tool in order to get the data for this analysis. The experiment was done in a dark medium. When the light source was operating, while the air source wasn't, the shadow of the string that was perpendicular to the ground was visible and sketched on the empty sheet. After the air source was turned on the air force pushed the object thus the string that was tied to it also had to advance. The string passed through the thin rectangle cut on top of the tunnel. Approximately a minute had to be waited until the aerodynamic object reached a balancing point (that area will be covered later on in the essay). Since the string's other end was tied to a pipe (a steady area) the string made an angle with its original position. Since the light source operated through out the experiment the shadow of the advanced string could also be sketched.

Notice the shadow of the string, this is the starting point of the object, all calculations concerning the angles will be made with respect to this *start point*

e) The Objects

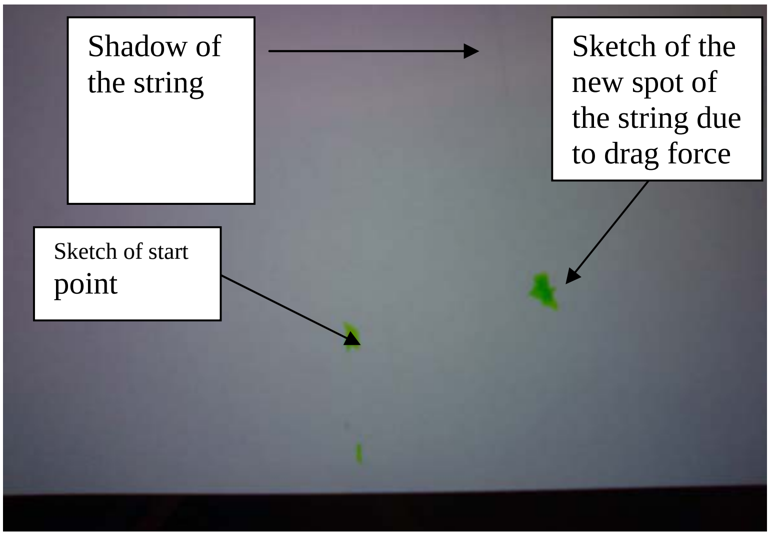
The objects were in different shapes and different masses but in the same density. To do this all objects were carved out of a dense Styrofoam. The picture were taken inside the tunnel

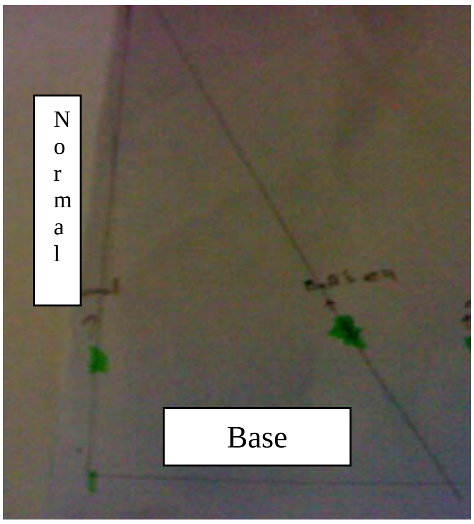
Part III Operating the Experiment

a) Understanding the Calculations

The following segment is just a tutorial to show how data was collected in the experiments. This segment shows the method of all calculations that were done all throughout the experiment. This tutorial only consists of the two objects with the masses of 440g that were taken into the experiment. This is NOT the complete experiment

1) The Sphere: The sphere was placed inside the tunnel and the airflow was operated. The projection on the sheet was recorded.





Notice the shadow of the string on top of the page.

Then a triangle was formed from taking a point on the sheet and drawing two lines from it to a base line. The angle between the two lines will be labeled by the letter “x”. The angle’s degree will be calculated to make a relation between the forces that are exerted on the objects. This procedure is not reserved for only the sphere. The same procedure will be followed with the cubic object as well. The angle will not be measured directly. The newly formed triangle will have a tangent (since one of the lines is perpendicular to the “ground”). From there the angle is calculated in degrees.

The Triangle is created by drawing two lines that derive from a random point that is on the same x-axis as the normal line (the line that was formed from the shadow of the string at its resting moment). The second point is the point where the objects reach their balance points in the tunnel.

Length (cm)	Normal ± 0,2 cm	Base ± 0,2 cm
	17.4	6.8

Tanx = 6.8∕17.4=0.39

If Tanx= 0.39 then x=21.31° (calculations were done by ‘’TI-84 Plus’’)

2) The Cube:

The cube will be observed three different parts. Due to its geometric shape, it had difficulty getting to its balance point in the tunnel. The maximum and minimum value that the angle reached was recorded additionally to the angle that it had when it was balanced.

Firstly the minimum value will be observed:

Length (cm)	Normal ± 0,2	Base ± 0,2
	17.4	9.8

Tanx = 9.8/17.4=0.56

If Tanx= 0.56 then x=29.25°

From this we can say that even the minimum angle value of the non aerodynamic object is larger then the sphere's balanced angle value.

The maximum value:

Length (cm)	Normal ± 0,2	Base ± 0,2
	17.4	15.0

Tanx = 15.00/17.4=0.86

If Tanx= 0.86 then x=40.69°

The maximum and minimum value was shown to emphasize the factor of turbulence

<u>The Balance value:</u>

These are the values when the ball reached complete balance inside the tunnel.

Length (cm)	Normal ± 0,02 cm	Base ± 0,02 cm
	17.40	12.10

Tanx = 12.1/17.4=0.69

If Tanx= 0.69 then x=34.61°

*Please note that from now on any angle value will be the value of balance.

This experiment was done for a number of trials to get the right answer for what effects drag force. The dense styrofoam that was used earlier to explain the process of the experiment was used all through out the experiment to carve out geometric shapes in equal masses and equal cross sectional areas.

b) Same masses different geometric shape

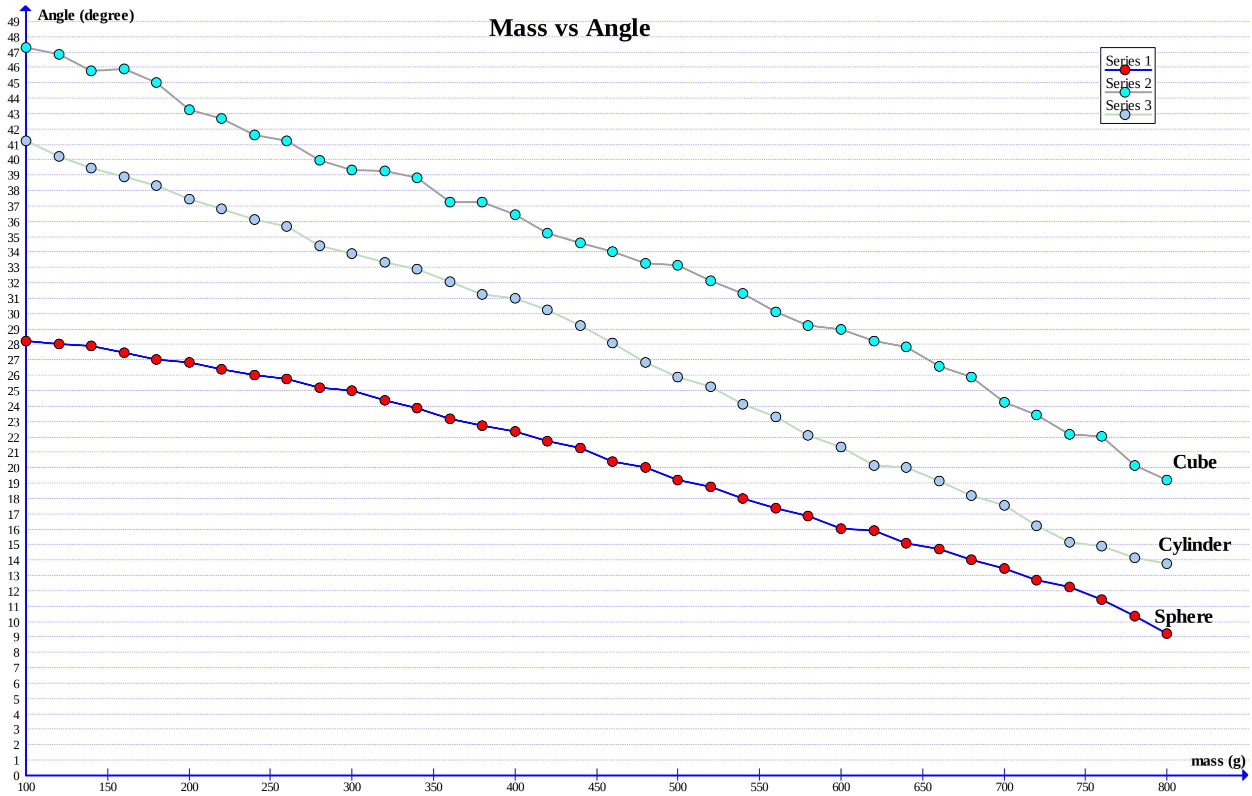
For this experiment a sphere a cube and a cylinder were used each in equal masses and the same procedure was followed while collecting the data of angles. On the next two pages it is possible the data in both graph and table format.

Mass (grams) ± 0,01	Angle of Sphere (degree) ± 0,01	Angle of Cube (degree) ± 0,01	Angle of Cylinder (degree) ± 0,01
100	28.22	47.31	41.23
120	28.03	46.85	40.23
140	27.92	45.77	39.45
160	27.44	45.89	38.89
180	27.00	45.01	38.34
200	26.83	43.25	37.45
220	26.41	42.68	36.78
240	26.01	41.60	36.12
260	25.78	41.25	35.68
280	25.22	39.98	34.41
300	24.97	39.36	33.89
320	24.40	39.25	33.34
340	23.89	38.84	32.87
360	23.20	37.23	32.10
380	22.74	37.25	31.25
400	22.33	36.44	30.99
420	21.74	35.23	30.21
440*	21.30	34.61	29.24
460	20.41	34.00	28.11
480	20.02	33.25	26.85

500	19.20	33.12	25.89
520	18.74	32.12	25.25
540	18.00	31.33	24.12
560	17.34	30.12	23.27
580	16.87	29.26	22.11
600	16.02	28.99	21.32
620	15.88	28.22	20.12
640	15.11	27.87	19.99
660	14.69	26.56	19.11
680	13.99	25.89	18.21
700	13.45	24.25	17.52
720	12.69	23.41	16.23
740	12.25	22.15	15.12
760	11.44	22.02	14.87
780	10.33	20.12	14.12
800	9.24	19.21	13.78

Table 1: Data collected from the same mass different shape experiment

The controlled variables were the masses, densities, air flow force & room conditions. The only condition that showed change was the shape of the objects.



Graph 1: Mass vs Angle

c) Same Cross - Sectional Area, But Different Geometric Shape

For this experiment a sphere and a cylinder was used each in equal masses and with the same Styrofoam. Since only half of the sphere is exposed to the air flow, half of its complete surface area is what we need to equal the base of the cylinder. Since the base of the cylinder is the part of the cylinder which is exposed to air in this experiment.

The masses were tried to be kept constant by matching the spheres' mass by either increasing or decreasing the height of the cylinder (via 3,14 * r *r /4)

Cross-Sec Area (cm^2)	Angle of Cylinder (degree)	Angle of sphere (degree)
49,97	32,55	24,97
60,38	29,23	22,32
70,12	26,11	19,23
79,20	22,32	16,02
87,76	17,23	13,45

The controlled variables were the masses, densities, air flow force & room conditions. The only condition that showed change was the cross- sectional areas of the objects.

Part IV. Conclusion

When we look at the experiment, the objects are both under the effect of three forces. The gravitational force, tension and the drag force. If we do not mind the tension, there is only one force acting on the x-axis thusly making the angle possible (as the gravitational force pulls the object perpendicular to the ground (or x-axis). So we can say that the angle is created by the "drag" force of the air flow. From this we conclude that if there is a larger angle present there is a larger grater force applied on the object by the air flow.

When we look at the results obtained from the experiments we see that the spherical object's string makes the smallest angle with the normal (with respect to the ground) when compared with any of the results that were obtained from the cubic and cylindrical object. Thus since the smallest angle belongs to the spherical object it can be derived that the drag force exerted on that object is the smallest.

As explained earlier the spherical object is aerodynamic. Since the aerodynamic object made the smallest object we can finally say that the aerodynamic object was under less drag force then the cubic one.

a) Evaluation of the Same masses different geometric shape experiment

We can see that despite the change in mass still the spherical object is the object that is less affected by the air's force. This has a direct link with the geometric, surface area shape and cross sectional area.

Let us compare the sphere and cube. Since the density and the masses are the same each shapes' volumes must be equal. Let us assume that the equal volume is 27000cm cube.

Volume of cube is equal to (let one side be a cm) a*a*a

Then a= 30cm

According to this, in perfect conditions, the area of the section that is exposed to the air force is 900cm cube.

Volume of the Sphere is $4/3\pi r^3$

From this we can deduce that r is equal to 18.61cm and since only half of the sphere is exposed to the air force, that area is calculated to be 544.047cm2

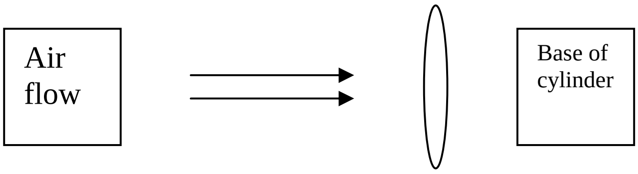
So it can be said that provided that they are under the same volume the sphere has a smaller surface area. In our experiment the density and the mass thusly the volume was kept constant. It can be concluded that surface area is a reason why the drag force differs on objects. As the area that is exposed to air molecules increases the drag force increases.

The graph on page 16 reassures us that for every mass value the angles, thusly the drag forces can be compared as $f_{sphere} < f_{cylinder} < f_{cube}$. Additionally, there is an important note. As it can be noticed, the graph of the cubes' values is more edgy when compared with the other to. This is because of the fact that the cube was the most difficult geometric shape to control due to turbulence. This will be discussed in the following segments.

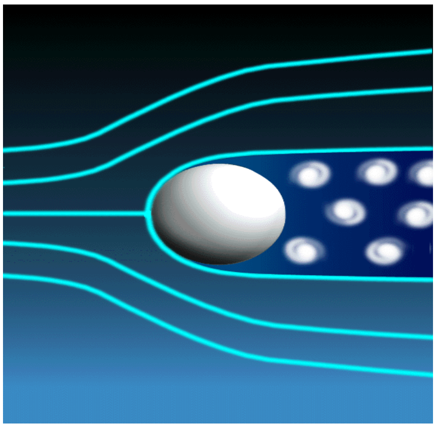
b) Evaluation of the Same Cross - Sectional Area, But Different Geometric Shape Experiment

It is clear that the spheres make smaller angles when compared with the cylinders. Even though they had the same surface area, the spheres have such a geometric shape that they turn some of the head on air friction to skin friction. While the cylinder has takes the air molecules perpendicularly having no skin friction what so ever

In this experiment all is constant except for the geometric shape. The shapes have different ways of greeting the linear air flow. Where the cylinder greets it perpendicularly,



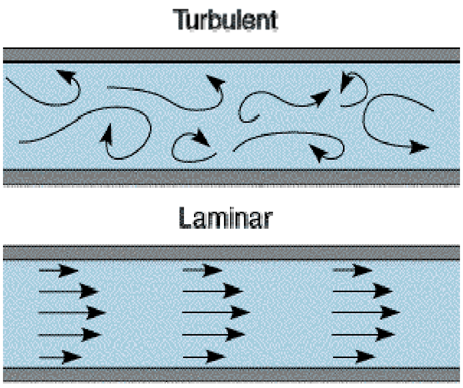
the sphere turns some of the drag force to skin friction mentioned earlier in the introduction by scattering and making the molecules slide over its geometric shape.



As it is seen in the experiment, the drag force of the sphere is smaller because of this exact reason. It is important to add that the reason for the lack of data for this experiment is that carving the same cross section area and mass of a sphere and cylinder was very difficult.

c) Sources of Error

1) In the evolution of the experiment there was great difficulty in controlling the objects. Obtaining clear data was out of the question. In researching this problem the reason was found. This problem was caused because the air flow was turbulent instead of laminar. Laminar flow happens when the forces acting on the object come at it in a neat and parallel manner. Turbulent flow is seen when the forces coming at the objects are unpredictable.



(Figure 9) figure 9: flows

The irregularity of the flow in this experiment is caused mostly because of two things.

Firstly the shapes of the non-aerodynamic object invited turbulence to happen. The second reason is that when the air source was turned on it is distributed not in a direct strait line but in every direction.

So when the forcing air molecules reach the object it reaches it in a turbulent manner. It was because of this reason why a cardboard tunnel seemed a priority in the experiment's construction. With this tunnel the goal was to minimize the irregularity of the airflow as much as possible.

The data would be healthier if the experiment was redone in a closed wind tunnel where the air flow is much less turbulent.

2) In the ‘’Same Surface Area Different Geometric Shape’’ experiment keeping the masses equal was difficult. This is a source of error as we saw in the first experiment;

As the mass increases by 20g the angles are measured differently. So mass affects the angle from which we derive the drag force. As keeping the mass constant is difficult the data gathered was limited. If there was access to a wider range of materials the data would be much stronger.

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