**Experimental Analysis of Flow Separation on Model Geometry**

Christopher R. White

MWG: David Bedding, Jorge Godoy, Samuel Hordeski, Kevin Myers, Justin Sandler

Department of Mechanical Engineering

Lafayette College

Easton, PA 18042

**Abstract**

The study of aerodynamics is important when developing products that interact with moving air and the behavor of the flow is influenced by geometry, surfacing, and orientation. The purpose of this experiment was to validate the use of AEROLAB Educational Wind Tunnel by determining the coefficient of drag for several spheres in order to analyze the behavior of flow separation for a Clark-Y airfoil. The coefficinets of drag were determined for 3 smooth spheres (dia: 3.81 cm, 7.62 cm, 10.16 cm) from 4.5 - 45m/s and were compared to the Morrison[] smooth sphere correlation based on the Schlichting smooth sphere data[]. **The results displayed that the smooth sphere data was accurate between Reynolds numbers of \_\_\_\_\_ to \_\_\_\_\_\_\_\_\_\_\_\_. Turbulent flow was observed for coefficient of drag for the 10.16 cm sphere with turbulent trip and a standard golf ball. The lift and drag coefficients for the Clark-Y airfoil model were determined at angles of attack of -6 to +20° at 40 m/s and compared to published data for \_\_\_\_ \_\_\_\_\_\_\_ \_\_\_\_\_\_\_\_\_ and the data was accurate between angle of \_\_\_\_\_\_\_ and \_\_\_\_\_\_\_\_\_\_.**

**Introduction and Methods**

Aerodynamics are an important part of the design process for developing products for various industries, from cars, to planes, to sports equipment. An efficient, economical way of developing a product is by designing and testing scale models to determine the optimal design before increasing the scale of the prototype. Wind tunnels provide insight into the flow behavior as it develops a boundary layer and moves around solid model surface. This behavior can be predicted for the dimensions of the full scale prototype through the Reynolds number, which is a dimensionless quantity that correlates flow profile behavior based on the ratio of inertial forces to viscous forces and is expressed as

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where is the flow velocity, L is the reference length, is the density of the fluid, and is the viscosity coefficient approximated at the fluid temperature. The Reynolds number can be used to determine whether the flow is laminar, transitioning, or turbulent. In order to use determine the Reynolds number with the wind tunnel, the velocity of the air was required. Pressure mesurments were determined using the static pressure ring and a simplified version of Bernoulli’s principle equation expressed as

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where is the static pressure, is the density of the fluid, is the fluid velocity. The hydraulic head term was ignored due to the following assumptions: no heat transfer, no work, and incompressible flow. Therefore static pressure was measured within the test section and used in Eq. (2) to determine the wind tunnel velocity.

The mechanics of flow across an object can be modeled using Bernoulli’s equation, which asserts that aerodynamic lift is the result of the angle of attack and is due to lift and drag component forces. With the wind tunnel testing section, the model is attached to a balance sting equipped with load cells that measure axial and normal forces exerted on the model. The component equations for drag and lift are expressed as

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where FN is the normal force, FA is the axial force, and α is the angle of attack with respect to horizontal axis. This is not true for spheres due to the symmetrical geometry, angle of attack is zero and therefore the air only exerts drag force on the sphere. the coefficient of drag was determined by measuring axial force using load cells within the sting balance at an angle of attack of zero. Since the spheres are symmetrical, there is no angle of attack and therefore axial force is the drag force. Utilizing the dynamic pressure term of Bernoulli’s principle equation, the lift and drag forces can be non-dimensionalized coefficients and can be expressed as

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where FL, D is either lift or drag force, is the density of air at fluid temperature, is the velocity of the air, and is the planform area of the airfoil. The coefficients of lift and drag can be compared between models. Due to the differences in geometry, the coefficients of lift and drag for airfoils is determined using lift line theory. Using lift line theory, coefficient of lift and drag for airfoils with a theoretically infinite aspect ratio can be expressed as

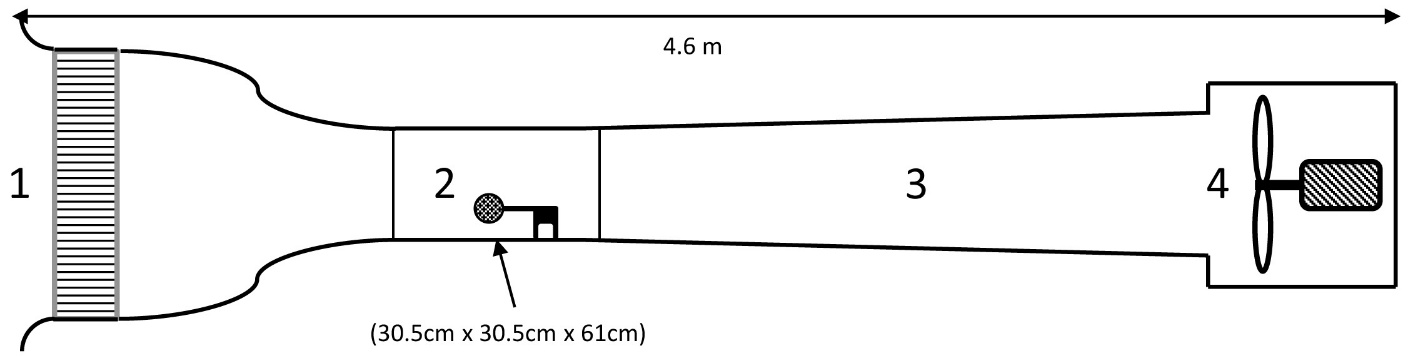
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where AR is the wing aspect ratio calculated using the equation , where b is the wing span, S is the planform area, and is the Oswald efficiency number which is a correction factor for non-elliptical planform wings ( for elliptical wings, and for rectangular planforms.)

In the current study the coefficents of lift and drag were experimentally determined for several models and compared to published data to test the effectives of the experimental procedures.

The experiments were performed by applying a known air velocity on models attached to the sting balance test section. In order to determine the effects of geometry, surface finish, and angle of attack on lift and drag forces. It was assumed that the experiments were conducted at room temperature. Experimental set up displayed in Figure 1. It was assumed that the fluid was incompressible and temperature fluctuations were minimal.



**Figure 1: AEROLAB Educational Wind Tunnel: (1) ENTRANCE: honeycomb attenuates parallel laminar flow, the contraction area due to Bernoulli’s equation reduces variations of mean axial velocity due to incompressible flow. Creates uniform flow, thin boundary layers, and negligible losses (2) TEST SECTION: pressure instrumentation and models are attached to a sting balance that equipped with load cells to measure axial and normal force. The sting balance can be adjusted to angles of attack between -6 and +20 degrees. Data is displayed on instrumentation readouts. (3) TRANSITION REGION: fluid flow leaving test section transitions to laminar flow. (4) DRIVER: fan that drives the flow from the entrance to the exit attached to a 7.5 KW electric motor.**

**Results and Discussion**

Three experimental set ups were considered: (1) airflow over 3 smooth spheres (dia: 3.81 cm, 7.62 cm, and 10.16 cm), (2) tripped airflow for 10.16 cm sphere and standard golf ball, and (3) airflow over Clark-Y airfoil model at various angle of attack.

For the airflow over the 3 smooth spheres, the coefficient of drag was determined by measuring axial force using load cells within the sting balance at an angle of attack of zero. The readouts were zeroed to negate the effect of gravity on the models. Axial force was measured at flow speed intervals of 2.5m/s from 4.5 - 45m/s and was used to determine drag force using Eq. (3). The drag coefficients were determined using Eq. (5) and are displayed in Figure 2. The results were compared to coefficient of drag for smooth spheres data published by Schlichting [5].

The effects of transitioning to turbulent flow on coefficient of drag was determined for the 10.16 cm sphere with turbulent trip and the standard golf ball. The 10.16 cm sphere was tripped using an approximately 0.5” thick ring of tape attached to the surface of the sphere facing the entrance of the wind tunnel. The drag force was determined using Eq. (3) and the coefficient of drag was determined using Eq. (5). The resulting coefficients of drag was computed and is displayed along with the smooth spheres and Schlichting data in Figure 2. Fog was emitted into the entrance of the wind tunnel using a SAFEX Fog Generator and a 1W GaN 445 nm Laser was used to enhance the visualization of the fog streamline crossections.

The behavior of flow separation for the Clark-Y airfoil model was tested at 40 m/s at 2° increments from -6 to + 20° in respect to the horizontal axis. Before testing began, axial and normal forces to get a full spectrum of the component forces without the loads induced by flow. These measurements were used to correct the axial and normal force data. The behavior of the fluid flow was observed and recorded for future use. Tape tips were attached to the top surface of the airfoil and it was noted that the tape tips began flapping at – 1° and complete separation occurred at 20°. It was also noted that it took longer for the flow to reconnect with the airfoil as it did not reconnect until the airfoil was returned to an angle of 13°.

Expecting error bars in final version.

**Figure 2: Coefficient of Drag vs Reynolds Number for Smooth Spheres & Tripped Spheres**

Figure 2 displays the results of the smooth spheres and tripped spheres experiments compared to the data from the Schlichting smooth sphere experiment. When airflow hits transition flow the coefficient of drag rapidly decreases until it transitions to turbulent flow where it stays at a steady, low coefficient of drag value. Larger spheres had more surface area and therefore achieved a larger range of higher Reynolds numbers displaying the transition to turbulence more clearly and were most similar to Schlichting data. Note that the distinct transition to turbulence can be seen for the golf ball at a Re = 7x104, whereas this is not true of the 10.16 cm tripped sphere. However it is clear that the tape had an effect since the 10.16 cm tripped sphere has a lower coefficient of drag compared to the 1.5” sphere and the smooth 10.16 cm sphere. Therefore this indicated that transition to turbulence occurred very early. For the smooth 10.16 cm sphere, the transition to turbulence is seen occurring at a Re = 2.49x105 which is approximately the same point at which the Shlichting data transitions to turbulence. Furthermore due to the small size of the sphere, larger velocities that exceed the velocity range of the wind tunnel would be required. Further testing is required to make definitive conclusions for the 1.5” sphere and the 10.16 cm turbulent tripped sphere.

In order to test the validity of the smooth sphere experiment, a correlation for coefficient of drag for smooth spheres determined by Morrison [1] was used to compare the experimental data, published data, and model data. The Morrison sphere correlation was used to determine the coefficient of drag over a range of Reynolds numbers and is expressed as

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where the drag coefficient and Re is is the Reynolds number. Due to the nature of the curve fit equation, the curve was identical for all sphere sizes since the equation only depends on Reynolds number.

In regards to the Clark-Y airfoil model, the resulting data required correction since Eqs. (6 and 7) are for lifting line theory for infinite aspect ratios. Since the actual model has a finite the 2D calculations for lift and drag and the infinite aspect ratio does not capture the wing tip vortecies, the lift and drag coefficients had to be corrected. This was accomplished by using Prandtl’s lifting line theory to relate the planform area of the airfoil to 3D Lift coefficients using the following equations

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Where is determined by using Eq. (5) with AR = and using AR = 2.86 the 3D corrected coefficients are displayed in Figure 4.

The experimental airfoil data was compared the 4 following data sets: 3D lifting line model, NACA Data, and Xfoil for two Reynolds numbers for since the experimental data fell between both Reynolds numbers data sets. The experimental data was most similar to the NACA data, since lift force decreases at 17° and the drag force begins to increase because there is a greater frontal area. More of the flow is hitting the bottom of the airfoil and is being converted into drag rather than lift force, since there is a significant surface area creating a large pressure differential. This is the same for experimental and the NACA data for drag coefficient, which both deviated from the rest of drag force profiles at 0° by increasing. Note that the The 3D lift line model does not account for stalling. The experimental data and the NACA lift coefficients correlate at stalling at an angle of approximately 17°.

**Conclusions**

**Figure 4: Airfoil Performance, Experimental vs Theoretical Lift & Drag**

The purpose of this experiment was to analyze the effects of flow separation for various model geometries due to variations in flow speed and model orientation with an AEROLAB Educational Wind Tunnel. The smooth sphere coefficient of drag results as a whole were similar to the results in the Schlichting data. Model surfacing was studied by determining the coefficient of drag for the 4” sphere with turbulent trip and a standard golf ball. Even though the 4” sphere did not display a distinct transition to turbulence, the coefficient of drag was lower than the smooth 4” sphere and the 1.5” sphere. The effects of orientation were studied by determining the coefficient of lift and drag with a Clark-Y model at varying angles of attack. Separation was observed and the coefficient of drag and lift forces were most similar to the NACA data. Recommended course of action would be to continue the wind tunnel testing to acquire more conclusive results.

**References**

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Fog airfoil

18.8 deg – stalling

15 deg – recovery

Lifting line doesn’t take into consideration the pressure gradient