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

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**Abstract**

The study of aerodynamics is important when developing products that will interact with moving air, since the geometry, surfacing, and orientation of an object directly correlates to flow behavior. The purpose of this experiment was to investigate flow separation for several spheres culminating in the analysis of a Clark-Y airfoil model. The testing procedure was validated by subjecting several models to air flow velocities from 4.5 - 45m/s with an AEROLAB Educational Wind Tunnel. The coefficient of drag was determined for 3 smooth spheres (dia: 3.81 cm, 7.62 cm, 10.16 cm) and 2 turbulently tipped spheres (10.16 cm sphere and golf ball) over a range of Reynolds numbers between 1.3x104 and 3.0x105. The results were compared to the Morrison smooth sphere correlation based on coefficient of drag data published by Schlichting [1]. The regions where the 3 smooth spheres correlated to the Morrison model occured at Reynolds numbers below 9.1x104, 2.2x105, and 6.8x104 repectively. The tripped 10.16 cm sphere and golf ball demonstrated that the Morrison model is accurate for rough spheres at Reynolds numbers below 6.7x104. 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. The results were compared to a model utilizing Prandtl’s lifting line theory [2] correlated between the angles of -6 to 18.2. The coefficient of drag and lift resulted in uncertainties of 0.0033 and 0.0125 at a 95% confidence interval respectively.

**Introduction and Methods**

Wind tunnel testing is essential for industries specializing in the development of products that interact with moving air at speeds that can lead to poor aerodynamic performance. Automotive and aerospace companies use wind tunnels to evaluate the aerodynamics of potential designs in a cost effective manner by testing small scale models. The behavior of the air flow can be predicted for the same design regaurdless of scale through the Reynolds number, a dimensionless quantity that correlates fluid movement based on the ratio of inertial forces to viscous forces. The equation for the Reynolds number 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 characterizes the boundary layer profile that develops on solid surfaces in one of the following types: laminar, transitioning, or turbulent flow. However, the velocity of the air cannot be directly measured from the wind tunnel due to the inaccuracy of the velocity mesurements. Therefore the static pressure ring in the test section was used to measure static pressure, which was used to determine velocity with a simplified version of Bernoulli’s 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.

The fluid streamlines interacting with the geometry result in drag force, which is comprised of pressure and friction drag. Based on the shape of the object, aerodynamic lift can develop as the result of the angle of attack and is composed of lift and drag component forces. Models are attached to a sting balance equipped with load cells that measure force exerted on the object in the axial and normal directions. The drag and lift forces are determined from axial and normal forces and 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. For symmetrical geometries, the angle of attack is zero and therefore the air only exerts drag force. In order to compare the aerodynamic properties of various models the drag and lift forces are expressed as dimensionless coefficients. Utilizing the dynamic pressure term of Bernoulli’s principle equation, the coefficients of lift and drag are 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. While coefficients of lift and drag can be used to compared simple geometries, there are more refined models for complicated geometries such as airfoils. Prandtl’s lifting line theory is used to determine the coefficients of lift and drag by modeling distributed vortecies for airfoils. The coefficinents for airfoils with a theoretically infinite aspect ratio are expressed as

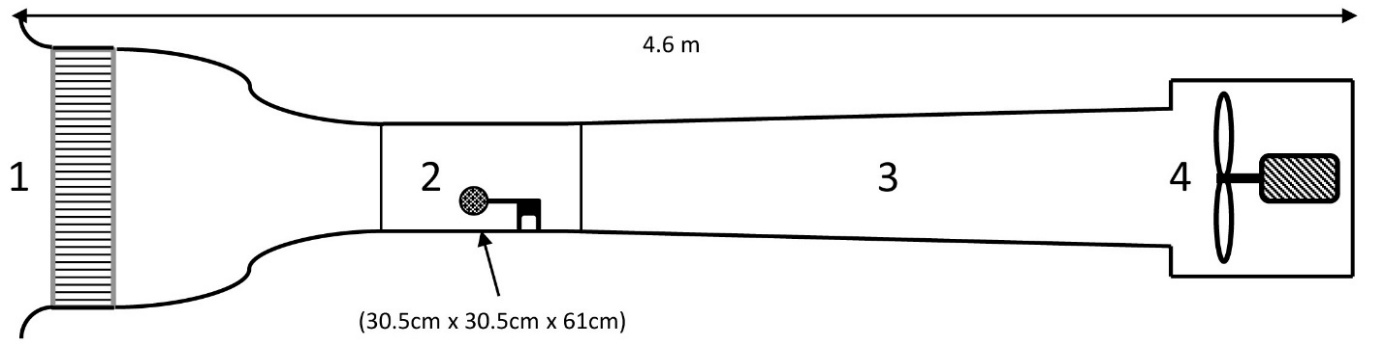
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where AR is the wing aspect ratio calculated using the equation , where b is the wing span, S is the planform area, and is the Oswald efficiency number which is a correction factor for non-elliptical planform wings ( for elliptical wings, and for rectangular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

The experiments were performed by applying air flow of 4.5 to 45m/s on several models while measuring the resulting axial and normal forces with the sting balance. The coefficient of drag was determined for three smooth spheres and two tripped spheres in order to validate the wind tunnel testing procedure. The effects of orientation were studied for the Clark-Y airfoil model by determining the coefficnet of lift and drag. The wind tunnel experimental set up is displayed in Figure 1.



**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 flow for 10.16 cm sphere and standard golf ball, and (3) flow over Clark-Y airfoil model at various angle of attack.

For the smooth sphere testing, each model was mounted to the sting balance at an angle of attack of zero and readouts were zeroed to negate the effect of gravity. The axial force and static pressure was measured at a flow speed range of 4.5 - 45m/s at intervals of 2.5m/s. The static pressure data was used to calculate velocity using Eq. (2) and the Reynolds number was determined using Eq. (1). The coefficient of drag was determined using Eq. (5) and plotted against Reynolds number for each smooth sphere in Figure 2. with the Morrison correlation and the Schlichting data [5]. The uncertainties between the smooth spheres and the Morrison correlation at 95% confidence interval for the 3.81 cm, 7.62 cm, and 10.16 cm were 8.78x10-7, 1.47x10-7, and 7.14x10-7 respectively.

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

and published NACA airfol data [2]