**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 occurred at Reynolds numbers below 9.1x104, 2.2x105, and 6.8x104 respectively. The tripped 10.16 cm sphere and golf ball demonstrated that the Morrison model is an appropriate correlation 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 experimental coefficient of lift was compared to a model utilizing Prandtl’s lifting line theory [2] and correlated between the angles of -6° to 18.2°. The experimental coefficient of drag correlated to the model at angles -6° to 12°. The coefficient of drag and lift 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 regardless 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 measurements. 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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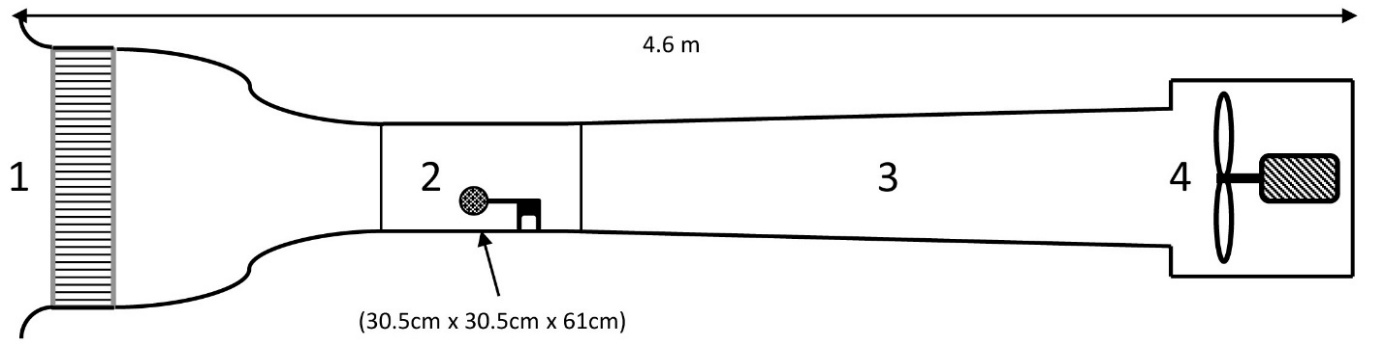
where FL, D is either lift or drag force, is the density of air at fluid temperature, is the velocity of the air, and is the planform area of the airfoil. While coefficients of lift and drag can be used to compared simple geometries, there are more refined models for complicated geometries such as airfoils. Prandtl’s lifting line theory is used to determine the coefficients of lift and drag by modeling distributed vortices for airfoils. The coefficients 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 coefficients 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 coefficient 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 1.27 cm thick ring of tape attached to the surface of the sphere facing the entrance of the wind tunnel. 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 coefficient of drag for each sphere was determined using Eq. (5) and are displayed along with the smooth spheres, Schlichting data, and Morrison model in Figure 2. The uncertainties between the tripped spheres and the Morrison correlation at 95% confidence interval for the 10.16 cm sphere and golf ball were 6.46x10-7 and 3.18 x10-6 respectively.

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

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 tape tips attached to the top surface of the airfoil were observed as orientation changed. It was noted that the tape tips began flapping at – 1°, indicating flow separation. 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 coefficient of drag and lift was determined at each interval using Eq. (6 and 7). It was noted that stalling occurred at 18.8° and recovery at 15°. The coefficients of lift and drag are displayed in Figures 4 and 5 respectively.

**Figure 4: Airfoil Performance, Experimental vs Theoretical vs Published Coefficients of Lift**

Figure 2 displays the coefficients of drag for the smooth and rough spheres compared to the Schlichting sphere data and the Morrison correlation. The Morrison model is a curve fit based on the coefficients of drag from the Schlichting experiment and is expressed as

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where the drag coefficient and Re is is the Reynolds number.

Experimental error was evaluated by determining the error bars for each sphere through propagation of error based on the uncertainty of the coefficnet of drag and sphere area. The results in Figure 2 are interpreted by identifying the regions in which the error bars overlap the Morrison model curve. The natural transition of the Schlicting data displays laminar flow at Reynolds numbers below 2.5x105 characterized by a constant coefficient of drag of 0.46. Transition to turbulent flow occurs between 2.5x105 and 4.2x105 displayed by a steep decreasing slope of -2.48x105. Turbulent flow occurs beyond Re=4.2x105 and a low coefficient of drag of 0.09 is maintained at a steady state. Regardless of the sphere surface, the error bars at Reynolds numbers below 6.7x104, correlated with the Morrison model. However this may be attributed to the fact that the flow speed was not fast enough for accurate static pressure ring measurements due to a low sampling rate. The 3.81 cm, 7.62 cm, and 10.16 cm smooth spheres correlated to the Morrison model at Reynolds numbers below 9.1x104, 2.2x105, and 6.8x104 respectively. Note that the distinct transition to turbulence can be seen for the golf ball at a Re = 7x104, whereas this is not true for the 10.16 cm tripped sphere. The early transition to turbulence is due to the dimpled surface of the golf ball, which induces turbulent flow early by disturbing the viscous region of the boundary layer. The 10.16 cm tripped sphere did not display a distinct transition to turbulent flow and it maintained a coefficient of drag that was lower compared to the smooth 3.81 cm and 10.16 cm spheres. Therefore this indicated that either transition to turbulence occurred early or there was a significant pressure build up on the front of the sphere, resulting in a high pressure differential. 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 Schlichting data transitions to turbulence.

**Figure 5: Airfoil Performance, Experimental vs Theoretical vs Published Coefficients of Drag**

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 for coefficient of lift is displayed in Figure 4 and is compared to the following curves: 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 visually correlated with the both the lifting line theory and the NACA data as they correlated between attack angles of -6° to 18.2°. However the lifting line model does not display stalling at 18.2°, because it does account for the adverse pressure gradient that develops within the boundary layer. Stalling occurs due to flow is hitting the bottom of the airfoil , resuting in a high drag force and a low lift force. The uncertainty at 95% confidence interval between the experimental coefficient of lift and the lifting line model is 0.0125. Figure 5 displays the experimental coefficient of drag data compared to 3D lifting line model, NACA data, and the two Xfoil data sets. Visually, the experimental data correlates with the NACA data at attack angles of -6° to 12°.The uncertainty at 95% confidence interval between the experimental coefficient of lift and the lifting line model is 0.0033

**Conclusions**

The purpose of this experiment was to analyze the effects of flow separation for various model geometries culminating in the analysis of a Clark-Y airfoil model. The sphere testing validated the use of the AEROLAB Educational Wind Tunnel for studying the coefficient of drag, supported by the smooth spheres correlated to the Morrison model occurred at Reynolds numbers below 9.1x104, 2.2x105, and 6.8x104 respectively. The tripped spheres demonstrated the validity of the experiment, since the tripped 10.16 cm sphere and golf ball correlated to the Morrison model 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 experimental coefficient of lift was compared to a model utilizing Prandtl’s lifting line theory [2] correlated between the angles of -6° to 18.2°. The experimental coefficient of drag correlated to the model at angles -6° to 12°. The coefficient of drag and lift uncertainties of 0.0033 and 0.0125 at a 95% confidence interval respectively.

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