Experimental Investigation about Drag Force on the Both Icy and Non-icy Airfoils

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ABSTRACT

In this paper, the influence of icy boundary on the drag force is studied experimentally. For this purpose, at first, the drag force on NACA0015 airfoil is measured in a subsonic wind tunnel. The span of airfoil is 15 cm and its chord are 20 cm and the section of airfoil for experiments is 300x450 mm. Then, a cast is designed to produce icy airfoil with the same dimensions of aforementioned airfoil. The drag force of icy airfoil is measured in the same wind tunnel, too. Polyamide is used to make the cast. The results show that the drag force on the icy airfoil is up to 40% less than non-icy one. This reduction is lower for smaller attack angles. Delayed boundary layer separation is the main reason for decrease in drag force. Sublimation of icy airfoil produces the secondary flow accompanying with a new boundary layer under the primary one. The secondary boundary layer is another reason for reduction of drag force. Experiments are conducted at different attack angles between and The Reynolds numbers are between 105 and 2.5×105. The accuracy of experimental instruments is considered and the results are obtained after numerical error analysis.

1. INTRODUCTION

Fluid flow over solid bodies is very important in several engineering fields such as mechanical engineering, marine engineering, aerodynamics and etc. To design solid bodies as airplane and ship, the calculation of forces including both the drag and lift forces acting on these bodies is crucial. The governing equations are complicated and in the most problems, do not have any exact analytical solutions. Numerical and experimental methods are alternative approaches. In this research, an experimental method is employed to measure the drag force on solid bodies.

Zhou et al. [1] investigated the flow around a smooth cylinder and a longitudinally grooved cylinder at Reynolds numbers ranging from 7.4×103 to 1.8×104 experimentally. This paper meant to find an improved understanding of effects of the grooved surface on the drag coefficient and the flow characteristics of cylinder. Gylys et al. [2] presented an analysis of the drag force decrease through the hot spherical and cylindrical bodies movement in the water in contrast with the movement of cold bodies. Effect of 2-phase water–vapor flow on the drag force was studied both experimentally and numerically. The initial consequences of study showed an adequate decrease of drag force for the hot body in relationship to the cold body due to vapor existence. Niknafs and Rad [3] presented a towing tank based experimental study on drag forces for different Reynolds numbers of a special underwater model. This paper discovered drag force and coefficient in a diverse flow direction over the model. Obtained experimental outcomes were clarified. Khaled et al. [4] concentrated on a parametric study of trends in aerodynamic forces. They described aerodynamic force measurements carried out on a basic vehicle model. Experiments were done in a wind tunnel for changed airflow configurations in order to separate the parameters to approve others earlier suspected. Nakamura and Igarashi [5] reached a drag decrease for a round cylinder exposed to the cross-flow by attaching cylindrical rings along its span at an interval of numerous diameters. The Reynolds number based on the diameter of the cylinder ranged from 3000 to 38000 for the tests. The adding of the rings decreased the drag force by 15 % for Re⩾20 000, even though the projected area enlarged. Polidori et al. [6] did skin-friction drag force analysis in the underwater swimming. From a simplified model in a variety of pool temperatures, it was confirmed that whatever the swimming speeds, a 5.3 % discount in the skin-friction drag would happen with growing average boundary-layer.

Mirzaei et al. [7] studied the characteristics of separated bubbles and unsteady features of flow fields around a glazed airfoil. The study was did using both experimental and numerical methods. The experimental measurements were carried out using the hot-wire anemometry at Reynolds number of 0.5×106 and attack angle ranging from 0° to 6°. Koomullil et al. [8] offered a new plan for simulating the flow around iced airfoils. Two different tactics were applied to generate qualified grids over the iced airfoil. Both grids can be categorized as generalized grids since multiple element types were working in each.

Tsao and Rothmayer [9] advanced a viscous–inviscid interaction triple-deck building to define the thermo-mechanical interaction of an air boundary layer with ice sheets and liquid films. Linear stability outcomes were compared with nonlinear triple-deck calculations, and a number of nonlinear simulations of air–water–ice interactions were presented. Kornilov [10, 11] considered the drag of an axisymmetric body of revolution in the incompressible flow experimentally. In other work, he organized some experiments to study the possibility of reducing the net drag force of a flat plate with the usage of streamwise-oriented vertical elements mounted normal to the surface in the incompressible turbulent
flow.

Leontiev and Milman [12] considered the influence of condensing steam flow parameters. The total pressure reduction of steam was upper for the counter-flow. The pressure reduction was calculated with diverse computation schemes. Semenov [13] offered the chief principles and approaches of developing the single-layer monolithic compliant coatings for the turbulent drag force reduction. Rabani et al. [14] studied experimentally and numerically the effect of the crosswind and wagon numbers to the aerodynamic characteristics. Three dimensional incompressible turbulent airflow has been considered for numerical simulation. The consequences presented that the variation of the longitudinal force coefficient (LFC) and side force coefficient (SFC) in the medium wagons is similar. Majumder et al. [15] did an experimental study of the turbulent fluid flow through a rectangular diffuser. Their experiements are done for incompressible 3D turbulent flow with Re=6.2 × 10^4. Fouad et al. [16] studied on the effect of solution velocity in the absence and presence of drag-reducing polymer on the rate of diffusion controlled corrosion experimentally. Natarajan et al. [17] determined the optimum shape for fore body in inviscid supersonic flow with an attached shock constraint numerically.

There are a lot of ways to reduce the drag. In this paper, the influence of icy boundary on the drag force was investigated experimentally.

2. EXPERIMENTAL SETUP AND ACCURACY ANALYSIS

2.1 Wind tunnel

A subsonic wind tunnel is used to measure the drag force on the solid bodies. This tunnel has been shown in Figure 1. The convergent and divergent sections of this tunnel is fabricated from fiber glass and its shape is a hexagon with 300 mm sides. A 5-fins fan is located in the exit of tunnel and is rotated with a motor to produce pressure difference. This pressure difference produced air flow. Wind tunnel properties are displayed in Table 1.

![Subsonic wind tunnel](image1.png)

**Figure 1.** Subsonic wind tunnel which is used to measure the drag force on solid bodies

**Table 1.** Wind tunnel properties

<table>
<thead>
<tr>
<th>wide</th>
<th>0.8 m</th>
<th>Electrical power supply</th>
<th>240 V, 50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>length</td>
<td>2.98 m</td>
<td>Range of drag force</td>
<td>2.5 N</td>
</tr>
<tr>
<td>Test section</td>
<td>300×450 mm</td>
<td>Measurement accuracy</td>
<td>0.01 N</td>
</tr>
</tbody>
</table>

Monometers are used to measure the total and static pressures. Water is used as manometer's liquid. The difference between total and static pressures is calculated from Eq. (1).

\[ P_{\text{total}} - P_{\text{static}} = \rho g \Delta h \]  

(1)

The velocity of air flow is calculated from dynamic pressure with

\[ \rho_{\text{air}} = \frac{P_{\text{air}}}{R_u T_{\text{air}}} \]  

(3)

2.2 Fabricating non-icy and icy airfoils

In the next step, one needs to design and make an icy-boundary solid and non-icy boundary solid. So, a NACA0015 airfoil is fabricated with 15 cm span and 20 cm chord. The three and two dimensional shapes of this airfoil are illustrated in Figure 2.

Then, a cast is made to produce an icy-boundary airfoil with the same dimensions. In order to protect the cast from cracking induced by freezing, the material chosen for the cast should be soft and flexible. This material should not be very flexible because more flexibility leads to mismatch between the icy model and the non-icy one. So, polyamid is selected as the appropriate material for the cast. To produce icy airfoil, mentioned cast is filled with water and then water in cast is frozen in a refrigerator. So, icy airfoil is exited from the cast and is located in a wind tunnel. The three and two dimensional shapes of mentioned cast are shown in Figure 3.
2.3 Experimental methodology

2.3.1 Experiments on the non-icy model

After making the model, the experiments were conducted in the following steps:

- Assembling the non-icy airfoil in the wind tunnel.
- Adjusting the attack angle on a specific attack angle.
- Balancing the initial forces.
- Starting the experiments and changing the velocity.
- Changing the attack angle and repeating the steps above.

2.3.2 The experiments on icy airfoil

At first, the water is filled inside the cast up to calculated height and then it is put inside a refrigerator. The steps aforementioned for a non-icy airfoil are conducted for the icy model. The Reynolds number of flow is defined as

\[
Re = \frac{\rho_{\infty} V t}{\mu_{\infty}}
\]

In the above equation, \( t \) is the thickness of airfoil. In all numerical calculations, error analysis is done to determine the significant digits. For example, to determine the accuracy of calculated Reynolds number, this equation is used

\[
|Re - Re| < \left| \frac{\partial Re}{\partial V} \right| |V - V| + \left| \frac{\partial Re}{\partial \rho_{\infty}} \right| * |\rho_{\infty} - \rho_{\infty}'| + \left| \frac{\partial Re}{\partial \mu_{\infty}} \right| * |\mu_{\infty} - \mu_{\infty}'| \]

In the above equation "*" is used for real value of quantity. Other quantity is obtained with experiments or with numerical calculations. According to accuracy of the experimental instruments, one has
\[ |t| \leq 0.5 \times 10^{-4} \]  
\[ |\mu_{\text{air}} - \mu_{\text{air}}^*| \leq 0.5 \times 10^{-7} \]  

(6)  
(7)

And after an error analysis for density and velocity, one has

\[ |\rho_{\text{air}} - \rho_{\text{air}}^*| = 0.007705898 \]  
\[ |V - V^*| \leq 0.000769097 \]  

(8)  
(9)

So,

\[ |\text{Re} - \text{Re}^*| \leq \left| \frac{1.0 \times 0.200}{184 \times 10^{-10}} \right| + \left| \frac{23.15 \times 0.200}{184 \times 10^{-10}} \right| + \left| \frac{1.0 \times 23.15}{184 \times 10^{-10}} \right| + \left| \frac{1.0 \times 23.15 \times 0.03}{(184 \times 10^{-10})} \right| \times 0.5 \times 10^{-7} \]  

(10)

Hence, the calculated Reynolds number has accuracy of order of $10^4$. The drag coefficient is obtained from the following equation

\[ C_d = \frac{F_d}{0.5 \rho_{\text{air}} V^2 A} \]  

(11)

in which, $F_d$ is the drag force, $\rho$ is the density of air, $V$ is the velocity of air in the wind tunnel and $A$ is the projected area of airfoil on the direction of air flow. In the following, the accuracy of drag coefficient is calculated.

\[ A = C \times h = 0.150 \times 0.2000 = 0.0300000m^2 \]  
\[ |C - C^*| \leq 0.5 \times 10^{-4} \]  
\[ |h - h^*| \leq 0.5 \times 10^{-4} \]  
\[ |A - A^*| \leq \left| \frac{\partial A}{\partial C} \right| \times |C - C^*| + \left| \frac{\partial A}{\partial h} \right| \times |h - h^*| \]  
\[ |A - A^*| \leq 0.015 \times 0.5 \times 10^{-4} + 0.020 \times 0.5 \times 10^{-4} = 0.1075 \times 10^{-4} \]  
\[ C_d - C_d^* \leq 2 \times \left( \frac{-2 \times 0.73}{1.0 \times 8.86 \times 0.0300} \right) \times 0.000763398 + \left( \frac{-0.73}{1.0 \times 8.86 \times 0.0300} \right) \times 0.007705898 + \left( \frac{-0.73}{1.0 \times 8.86 \times 0.0300} \right) \times 0.00001075 + \left( \frac{1}{1.0 \times 8.86 \times 0.0300} \right) \times 0.5 \times 10^{-2} \]  

(12)

In the above equation, $C$ is the thickness and $h$ is the length of span of the airfoil.

Thus, the accuracy of drag coefficient is order of $10^{-1}$. According to obtained accuracy of drag coefficient and its magnitude between 0.04 and 0.63, it can be concluded that in the small drag coefficients, the obtained results for drag coefficient has a considerable defect. Therefore, it causes the drag to be sketched versus the Reynolds number instead of drag coefficient.

3. RESULTS AND DISCUSSION

Experiments are done in a wind tunnel on icy and non-icy airfoils and the Reynolds number and drag force are obtained from experimental data and by using equations 1 to 5. So, drag reduction percent are calculated. These tests are done for different attack angles from $\alpha = 0^\circ$ to $\alpha = 30^\circ$. Results for different attack angles are shown in figures 5 and 6 for icy and non-icy airfoils. Drag force increases when Reynolds number rises. Also drag force increases while attack angle grows.

![Figure 5](image1.png)

Figure 5. Drag force versus Reynolds number in different attack angles in icy airfoil

In Figure 5, it is observed that the drag force increases as the Reynolds number increases. Also, the drag force increases with an increase in the attack angle.

![Figure 6](image2.png)

Figure 6. Drag force versus Reynolds number in different attack angles in non-icy airfoil

Also, the average drag reduction versus the attack angle has been displayed in Figure 7

![Figure 7](image3.png)

Figure 7. Average drag reduction versus attack angle

In Figure 7, it is observed that the average drag reduction increases as the attack angle increases. This indicates that the drag reduction is more significant at higher attack angles.
Results show that the drag reduction is changed from 2% to 40% when attack angle is changed from 0° to 30°. Due to more roughness of icy airfoil, the friction drag is more for icy airfoil. Roughness of icy airfoil converts laminar flow to turbulent flow. Then due to sharp gradient of velocity near the wall, in the turbulent flow, shear stress on icy airfoil is more than non-icy airfoil. Boundary layer separation is delayed because of turbulent flow. So boundary layer separation happens later in icy airfoil. This event has two effects. First one is increase in the shear stress and second one is decrease in the pressure drag force. Boundary layer separation causes a high pressure part before separation point and a low pressure part after that. As a result, force on the front part of airfoil is more than the back part of airfoil and this effect produces asymmetric pressure distribution or a strong pressure drag force. According to mentioned reasons, pressure drag force on icy airfoil is less than non-icy airfoil. At low attack angles, friction drag and pressure drag are important but at high attack angles, large part of drag force is the pressure drag force. So low pressure drag leads to a low pressure drag force.

Given that pressure drag is less for icy airfoil, total drag force is less, too, especially in a high attack angle. Formation of secondary boundary layer in the icy airfoil is another reason for the drag force reduction. This boundary layer is created under the main boundary layer because of sublimation of ice.

4. CONCLUSION

In this paper, an icy airfoil has been conveyed and its drag force has been compared with that of a non-icy airfoil. This study has done in a subsonic wind tunnel experimentally. Results have showed that drag force of icy airfoil is less than non-icy one. This reduction which is function of attack angle, increases when attack angle rises. This reduction is from 2% to 40%.

REFERENCES


