The potential of using superhydrophobic surfaces on airfoils and hydrofoils: a numerical approach

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Abstract: Fluids at their interface with ordinary solids are motionless. This condition is referred to as no-slip condition. On superhydrophobic surfaces, fluids have slip velocity which is quantified using Navier’s slip length definition. On a superhydrophobic surface, slip velocity can be as large as 50% of the free-stream’s velocity. We have studied the potential of using superhydrophobic surfaces to improve the performance of airfoils. For that, National Advisory Committee for Aeronautics (NACA) 4412, 4418, and 4424 were studied numerically. The chord-based Reynolds number was approximately 5,000. We found that increasing the slip from 0 to 50% results in up to 66% increase in the lift, and 45% decrease in the drag force when angle of attack is small (i.e., < 5°). For larger angle of attack values (i.e., > 5°), using superhydrophobic airfoil is still worthy, but its effectiveness becomes smaller. The less efficacy of superhydrophobic airfoils is explained by the laminar separation bubble phenomenon which can have an adverse effect on lift and drag. For small angle of attack values, by increasing the slip from 0 to 50%, the bubble length becomes smaller which is favourable and explains the well-behaviour of superhydrophobic airfoils at small angle of attacks. However, for larger angle of attack values, by increasing the slip, bubble’s length grows which results in less efficacy of superhydrophobic airfoils at larger angle of attack values.

Keywords: airfoil; superhydrophobic; lift; drag; laminar separation bubble.


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1 Introduction

Recently, there has been a great interest in ways of reducing aerodynamic and hydrodynamic drag. Decreasing the drag force could improve the velocity of ships and airplanes, and reduce the fuel consumption. So far, different techniques for reducing drag are proposed. Among them are using permeable walls (Nikitin and Pavel’ev, 1998), riblets (Horsten, 2005; Saravi and Cheng, 2013; García-Mayoral and Jiménez, 2011; Bechert et al., 2000; Friedmann and Richter, 2010; Dean and Bhushan, 2010; Dean, 2011; Peet et al., 2007; Kramer et al., 2010), polymer injection (Usui et al., 1988; McComb and Rabie, 1982), bubble injection (Sanders et al., 2006; Elbing et al., 2008; Ceccio, 2010; Murai, 2014), creating air layer, Leidenfrost effect (Biance et al., 2003; David, 2013; Gottfried et al., 1996; Song et al., 2010), and using superhydrophobic surfaces (Murai, 2014; Truesdell et al., 2006; Daniello et al., 2009; Ming et al., 2011). Permeable walls and riblets align the turbulent velocity near the surface and limit the vortex interactions, but they are useful only in a specific range of Reynolds numbers. Polymer and bubble injections require constant upstream injection. Also, maintaining the bubbles and polymer downstream is challenging. Furthermore, polymers degrade at high strain rates. Creating the air layer and Leidenforst effect and maintaining the air film on a moving object is not easy. Using superhydrophobic surfaces may open a great alternative for reducing the drag force. Superhydrophobic surfaces can also be combined with other methods [e.g., with riblets (Barbier et al., 2014)].

Superhydrophobic surfaces are surfaces with large contact angles (> 150°) and small sliding angle (< 5°). There are a few examples of superhydrophobic surfaces in nature, e.g., lotus leaves, taro leaves, paddy leaves, butterfly wings, water strider legs, tulip tree, eucalyptus. These surfaces show self-cleaning (Nun et al., 2002), anti-corrosion (Hu et al., 2012), anti-icing (Hejazi et al., 2013; Susoff, 2013), and low friction drag properties. As such, they have potential applications in different industries.

Regarding the evolution of manufacturing the artificial superhydrophobic surfaces, it should be mentioned that chemical coating a surface can increase the contact angle up to nearly 120°. For further increase of the contact angle, surface should be roughened.
(Wenzel, 1949). This roughness should be within a proper range (100 nm to 10 μm). Depending on the roughness dimensions and chemical deposition, water may or may not penetrate into the troughs. For larger textures, the stability of the air pockets may be lost (Garc, 2014). By changing the pattern design, the air pocket can be sustained longer (Wang et al., 2014). To have small sliding angles which is the second condition for having a perfect superhydrophobic surface, water should not penetrate into the roughness. This state is referred to as Cassie-Baxter (or Fakir) state (Cassie and Baxter, 1944; Cassie, 1948, 1944), and the other state which represents the penetrated case is the Wenzel (1949) state. It should be noted that roughness should be such that wetting stays in Cassie-Baxter state otherwise friction drag may not necessarily decrease.

In 1933 Nikuradse showed that in laminar regime, roughness does not affect the friction coefficient and friction coefficient is only a function of Reynolds number (Yang and Joseph, 2009). Also, in turbulent regime, increasing the roughness results in friction coefficient increase. However, the order of magnitude of the roughness that he looked at was not sub-micron. As such his conclusion may not be necessarily valid for superhydrophobic surfaces. In Cottin-Bizonne et al. (2003), using molecular dynamics, for a fluid slab confined between two parallel solid walls (Couette flow) with nano-scale periodic (square shaped) patterns, for the first time, it was shown that surface friction may be reduced by increasing the surface roughness.

The trapped air between the surface asperities on a superhydrophobic surface has a lubricating effect (Busse et al., 2013). The fluid-air interface can be treated as a stress-free boundary [or low stress boundary with considering the negative impact of the meniscus curvature of the liquid into the troughs (Bolognesi and Pirat, 2014)]. As such, unlike conventional surfaces, fluids on superhydrophobic surfaces slip. To characterise the degree of slip, slip length is defined as the distance between the top wall position and the depth at which the extrapolated velocity profile reaches the zero velocity (β in Figure 1).

**Figure 1** Slip length (β) on a superhydrophobic surface for a Couette flow is shown (see online version for colours)

![Figure 1](image)

Navier was the first to propose a relation for slip. However, the relation was originally for Knudsen numbers equal to or greater than one where the continuity assumption is lost. The same equation may be used for fluids on superhydrophobic surfaces even where fluid is still continuous (Panton, 2013):
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\[ \beta = \frac{u_s}{\frac{du}{dy}} \]  

where \( \beta \) is the slip length (m), \( u_s \) is the fluid velocity on the solid surface (m/s), and \( \frac{du}{dy} \) is the velocity gradient on the surface (1/s). On regular surfaces, slip length is less than 1 nm, but on superhydrophobic surfaces slip length can be as large as 400 \( \mu m \) (Lee and Kim, 2009). Large slip length corresponds to large slip velocity on the surface and small friction drag.

To find an upper limit for drag reduction of a laminar flow on a superhydrophobic surface, Busse et al. (2013) modeled a superhydrophobic surface as a fixed air layer with constant thickness, and found that the friction drag can be reduced as large as 80%. However, this 80% drag reduction is not achievable as modelling the whole solid-liquid interface as a stress-free boundary condition is not correct (Bolognesi and Pirat, 2010). Battiato (2014) proposed a continuum-scale model for flows over micro-patterned surfaces by modelling the micro-patterned surface as a porous medium, and coupling Brinkman equation for flow in porous media and Reynolds equation for flow on the micro-patterned surface. He found a closed-form solution for skin friction coefficient in terms of the Reynolds number and geometry of the micro-structure. For a laminar flow on a superhydrophobic surface with slip length of 25 \( \mu m \), slip velocity can be as large as 60% of the ambient velocity and in this case friction drag can be reduced by up to 40% (Ou et al., 2014). This drag reduction is much larger than drag reduction using riblets and shark skin effect (Bhushan and Nosonovsky, 2010).

There are contradictory statements when it comes to experiments. Cheng et al. (2014) fabricated three types of superhydrophobic coatings and applied them on ship models and found depending on the superhydrophobic coating, ships may travel faster and slower. Based on that they claimed superhydrophobic coating is not always useful in reducing the friction drag. However, their statement is not valid as a surface with large contact angle is not necessarily superhydrophobic (roll-off contact angle should be small as well). Large contact angle along with large roll-off angle means that wetting is in Wenzel state and may cause an increase in friction drag. In Daniello (2009) it is debated that the drag reduction in laminar flow is small and drag reduction is observable only in turbulent regime. However, they used particle image velocimetry (PIV) and pressure drop measurement for calculating the slip length and slip velocity without mentioning that PIV is not very accurate for this scale.

For the above reason, most of the studies on drag reduction are in turbulent regime (Barbier et al., 2014; Daniello, et al., 2009; Battiato, 2014) and for flows in a channel and only few studies are on curved surfaces (Gogte et al., 2005; Shirtcliffe et al., 2009) and/or in laminar regime [Shirtcliffe (2009) studied superhydrophobic spheres and cylinders and observed up to 30% drag reduction; and Gogte et al. (2005) studied a superhydrophobic Joukovsky hydrofoil and observed 18% drag reduction].

In turbulent flows, a thin viscous-dominated sublayer (which is similar to the laminar regime) exists near the wall to this height:
where $y^+$ is the dimensionless length from the wall, $y$ is the vertical distance from the wall, $\tau_w$ is the shear stress on the wall, $\rho$ is the liquid density, and $\nu$ is the kinematic viscosity. As such, friction drag in turbulent regime can be analysed similar to that in laminar regime (Cheng et al., 2014). The similarity is valid until the viscous sublayer thickness approaches the scale of superhydrophobic asperities which occurs only at very large Reynolds numbers. For instance, in Gogte et al. (2005), the viscous sublayer thickness was in the order of 1 mm and the surface texture was 8–10 μm.

In this study, the potential of using superhydrophobic surfaces for improving the potential of airfoils is investigated. As the first step, National Advisory Committee for Aeronautics (NACA) 4412, 4418 and 4424 are numerically studied in laminar regime. Medium is air and its velocity is 1 m/s (i.e., chord-based Reynolds number, $Re$ is approximately 5,000). The effect of slip velocity is studied at different angle of attacks. Lift and drag forces and their components are analysed to see if using superhydrophobic airfoils is beneficial or not.

2 Methods

The modelling and meshing is performed in Gambit (see Figure 2) and 2D models are analysed in ANSYS Fluent 14. Mesh sensitivity analysis is performed and 354,120 cells are found to be optimum number of mesh cells (Table 1). Cells near the wall are smaller and in total 712 nodes are on the airfoil wall. The cells near the wall are 1 μm in height, and $y^+$ is 0.76.

Figure 2 (a) Geometry of NACA 4412, 4418, and 4424 is shown (b) The domain used for modelling is shown (see online version for colours)

Notes: Inset shows the meshing in gambit.
Inlet velocity is 1 m/s and outlet pressure is 1 atm.
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Figure 2  (a) Geometry of NACA 4412, 4418, and 4424 is shown  (b) The domain used for modelling is shown (continued) (see online version for colours)

Notes: Inset shows the meshing in gambit.

Inlet velocity is 1 m/s and outlet pressure is 1 atm.

The numerical model solves the Navier-Stokes equations using the finite volume method and applying the Reynolds average theorem. Convergence is checked using the dependent parameters. With increasing the Reynolds number and/or increasing the angle of attack, the laminar separation bubble (LSB) emerges. The growth of LSB results in drag increase and lift decrease. In other words, with increasing the angle of attack, the stall phenomenon becomes more probable. The following transition models are suggested for this problem: $k-\omega$ SST (Menter et al., 2006) and $k-k_L-\omega$ (Walters and Leylek, 2005).

Table 1  The effect of grid size on drag coefficient is shown

<table>
<thead>
<tr>
<th>Grid size</th>
<th>$y^*$</th>
<th>Coefficient of drag</th>
</tr>
</thead>
<tbody>
<tr>
<td>196,000</td>
<td>8.5</td>
<td>0.0142</td>
</tr>
<tr>
<td>354,120</td>
<td>0.76</td>
<td>0.0144</td>
</tr>
<tr>
<td>544,122</td>
<td>0.15</td>
<td>0.0144</td>
</tr>
<tr>
<td>784,000</td>
<td>0.025</td>
<td>0.0144</td>
</tr>
</tbody>
</table>

Note: Re = 60,000, angle of attack 0.

The $k-\omega$ SST model is based on intermittency equation (which is used to trigger the transition) and the momentum thickness equation (which is forced to follow the experimental results). The $k-\omega$ is most accurate near the wall, and $k-\varepsilon$ is better for far-field. The SST model combines the advantage of the two and uses the $k-\omega$ near the wall and as it gets away from the wall $k-\varepsilon$ becomes activated. The SST also captures the separation more accurately. The $k-k_L-\omega$ model includes turbulent kinetic energy, laminar kinetic energy, and specific dissipation rate. The former model (i.e., $k-\omega$ SST) is easy to implement and accurate for the airfoil geometry. As such, $k-\omega$ SST with the following settings is used in this study. Solution is steady, simple, at low Reynolds number, and medium is air at 25°C. The second order upwind discretisation is used. For
modelling the slip condition, instead of no-slip boundary condition, ‘moving wall’ along with the following developed UDF is used.

One of the two governing equations of the numerical model is mass conservations for an incompressible flow in laminar regime:

\[
\frac{\partial}{\partial x_j}(\rho u_j) = 0
\]  

(3)

where \( u_j \) is velocity of the medium; and the other governing equation is linear momentum for an incompressible flow in laminar regime:

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j u_{i,j} \right) = -P_{,i} + \mu \left( u_{i,j} + u_{j,i} \right) - \rho \bar{u}_i \bar{u}_j
\]  

(4)

where \( P_{,i} \) is the gradient of pressure, and \( \mu \) is medium viscosity. It should be noted that equation (4) is for a laminar flow, and for a turbulent flow, momentum conservations is:

\[
\rho \left( \frac{\partial u_i}{\partial t} + u_j u_{i,j} \right) = -P_{,i} + B_i + \mu \left( u_{i,j} + u_{j,i} \right) - \rho \bar{u}_i \bar{u}_j - \frac{\mu_T}{\rho} \frac{k}{\delta_{ij}}
\]  

(5)

where \( B_i \) is volume force and the last term is found using Boussinesq model:

\[
-\rho \bar{u}_i \bar{u}_j = 2\mu_T \left( \frac{u_{i,j} + u_{j,i}}{2} \right) - \frac{2}{3} \rho k \delta_{ij}
\]  

(6)

where \( \mu_T \) is turbulent viscosity and is found using the \( k-\omega \) SST model with low Reynolds number assumption; \( k \) is the kinetic energy and \( \delta_{ij} \) is Kronecker delta.

For verification of the numerical results, drag and lift coefficient of NACA4418 are compared with the results of XFOIL at (http://www.airfoiltools.com) and less than 1% relative error was observed. It should be noted that the validation was done at \( Re = 50000 \) to model a worse case.

**Figure 3** Cartesian and normal-tangent coordinates on an airfoil are shown
According to equation (1), slip velocity is equal to the slip length ($\beta$) times the gradient of the velocity near the wall and in the normal direction to the wall $\left(\frac{du}{dy}_{\text{wall}}\right)$. The challenge for curved surfaces compared to flat plates is that the direction of slip velocity (which is tangent to the airfoil) and velocity gradient (which is normal to the airfoil) both change along the airfoil’s surface (see Figure 3).

The procedure of developing the UDF (user defined function) is as follows. The velocity gradient normal to the airfoil surface can be found as:

$$\frac{\partial U_s}{\partial n} = \hat{n} \nabla U_s$$  

(7)

where $n$ is a unit vector normal to the airfoil and $\nabla U_s$ in Cartesian coordinates is:

$$\nabla U_s = \left( \frac{\partial U_s}{\partial x}, \frac{\partial U_s}{\partial y}, \frac{\partial U_s}{\partial z} \right)$$  

(8)

Assuming flow is 2D, using some geometry and trigonometry relations, one has:

$$U_s = U \cos \theta + V \sin \theta$$  

(9)

where $U$ and $V$ are the velocity components in $\hat{i}$ and $\hat{j}$ directions, accordingly; and $\theta$ is the angle between the tangent to the airfoil and horizontal line and a point on the airfoil. The advantage of this form of writing is that $U$ and $V$ can be found at each point in the domain, using the software. For finding the $\theta$ at each point on the airfoil, a 6th order polynomial is fitted to the top half and another 6th order is fitted to the bottom. Tangent to the polynomial at each point can provide the value of $\theta$. It was also found that the maximum absolute error at each point using the 6th order polynomial is less than $10^{-4}$m. Using the polynomial fit, at each point on the foil, the unit vector normal to the foil can be found as:

$$\hat{n} = -\sin \theta \hat{i} + \cos \theta \hat{j}$$  

(10)

Using equations (7) to (10) one has:

$$\frac{\partial U_s}{\partial n} = -\sin \theta \frac{\partial}{\partial x} (U \cos \theta + V \sin \theta) + \cos \theta \frac{\partial}{\partial y} (U \cos \theta + V \sin \theta)$$  

(11)

The $\frac{\partial}{\partial y}$ derivatives can be converted to $\frac{1}{\tan \theta} \frac{\partial}{\partial x}$ using the Chain rule. The value of $\frac{\partial U_s}{\partial n}$ in equation (11) can be found by knowing the 6th order polynomials used to fit the airfoils, the values of $U$ and $V$, and their derivatives.
Figure 4  Velocity contour on top of the foil for (a) Slip boundary condition (b) No-slip boundary condition and pressure contour on top of the foil for (c) Flip boundary condition (d) No-slip boundary condition are shown on NACA 4418 at 0 angle of attacks (see online version for colours)

Note: medium is air and its velocity is 1 m/s. flow is laminar and Reynolds number is approximately 5,000.
Figure 4  Velocity contour on top of the foil for (a) Slip boundary condition (b) No-slip boundary condition and pressure contour on top of the foil for (c) Flip boundary condition (d) No-slip boundary condition are shown on NACA 4418 at 0 angle of attacks (continued) (see online version for colours)

Note: medium is air and its velocity is 1 m/s. flow is laminar and Reynolds number is approximately 5,000.

3 Results

To have a better understanding of the effect of applying superhydrophobic surfaces on the surface of airfoils, the drag and lift forces are calculated independently. Superhydrophobic surfaces create slip on the surface of foils [see Figure 4(a)]. The slip boundary condition can affect the pressure distribution across the airfoil [Figure 4(c)].

The lift force has two components: pressure lift and viscous lift. As shown in Figure 5, total lift is almost equal to the pressure lift as viscous lift is negligible. This is true for all three airfoils, at different angle of attacks ($\alpha$) and slip velocities.

As shown in Figure 5(a), increasing the slip on the wall (form 0 to 50%), results in lift increases [Figure 5(c)]. For NACA 4418, by replacing the no-slip airfoil with 50% slip airfoil, the total lift increases by up to 66% for $\alpha = 0$. For larger $\alpha$ values, using 50% slip airfoil is still promising but not as efficient. For example, when $\alpha = 15^\circ$, total lift increase by 31% [see Figure 5(c)]. It should be noted that 50% slip velocity on the wall is easily achievable on a superhydrophobic surface (Daniello, 2009).

As expected and shown in Figure 5(a), by increase of $\alpha$, pressure lift increases [the same trend is observed for viscous lift, see Figure 5(b), and total lift, see Figure 5(c), accordingly]. This trend stops at a specific angle called stall point. Further increase of $\alpha$ from stall point does not result in lift increase (or may also deteriorate the situation). It was found that applying slip velocity on the wall (or using superhydrophobic airfoils) slightly delays the stall occurrence. For instance, by increase of $\alpha$ from 10° to 15° for NACA 4418 with no-slip [Figure 5(c)], pressure lift remains unchanged which means that stall has occurred. However, for the same airfoil with 50% slip, by increasing $\alpha$ from 10° to 15°, pressure lift slightly increases which means that $\alpha = 10^\circ$ is not a stall point.
Figure 5  The (a) Pressure lift (b) Viscous lift (c) Total lift on NACA 4418 at different angle of
attacks (α) and different slip velocities on the wall are shown

Note: Medium is air and its velocity is 1 m/s. flow is laminar and Reynolds number is
approximately 5,000.

Drag components (i.e., pressure drag, and viscous drag) are studied independently.
Similar to the lift force, as shown in Figure 6, pressure drag is the dominant component in
the total drag. By increasing α, pressure drag [Figure 6(a)] and the total drag increase
[Figure 6(c)], but viscous drag (which has a small contribution in total drag) decreases
[Figure 6(b)].

By increasing the slip, at small α values (i.e., < 5°), all of the pressure drag
[Figure 6(a)], viscous drag [Figure 6(b)], and total drag [Figure 6(c)] decrease. For α = 0,
the total drag decreases by 45%. But for larger α values (i.e. > 5°), increasing the slip
length results in the drag increase which is not what we are looking for. For instance for
α = 15°, 50% slip results in 11% increase in the drag force [Figure 6(c)].
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Figure 6  (a) Pressure drag (b) Viscous drag (c) Total drag on NACA 4418 at different angle of attacks ($\alpha$) and different slip velocities on the wall are shown

Note: Medium is air and its velocity is 1 m/s. flow is laminar and Reynolds number is approximately 5,000.

4 Discussion

As shown in Figure 6(c), using superhydrophobic airfoils increases the lift force and delays the stall occurrence. Using superhydrophobic foil also decreases the drag force at small $\alpha$ values [Figure 6(c)]. Increasing the lift and decreasing the drag are the two objectives of designing better airfoils. Therefore, using superhydrophobic airfoils, may potentially open a new avenue in designing more efficient airfoils. Figure 7 shows the ratio of lift to drag at different slips and angle of attacks. The potential usefulness of superhydrophobic airfoils vanishes as the angle of attack increases.
The incompetency of superhydrophobic airfoils at larger $\alpha$ values is explained by laminar separation bubble (LSB) phenomena. LSB is the region between separation and reattachment points. Occurrence of LSB has adverse effect on the performance of airfoils. Within the LSB, the direction of the flow (or shear stress accordingly) becomes reversed. As such, separation and reattachment points can be distinguished as points with zero shear stress on the wall. Previous studies on LSB have found that the length of the bubble should decrease with increasing the Reynolds number. Also, increase of $\alpha$ should slightly move the bubble forward with small or no effect on the length of the bubble (Genç and Kaynak, 2009; Haggmark et al., 2000). As expected and shown in Figures 8(a) to 8(c), increase of $\alpha$ does not change the bubble’s length of a no-slip NACA 4418. However, when there is 50% slip on the wall, increase of $\alpha$ results in increasing the bubble’s length [see Figures 8(d) to 8(f)]. This can explain the adverse behaviour of 50% slip airfoils at large $\alpha$. Comparing Figures 8(a) and 8(d) reveals that for small $\alpha$ values (i.e., $\alpha = 0$), the bubble’s length decreases with increasing the slip on the wall. This explains the promising behaviour of superhydrophobic airfoils at small $\alpha$ values. In other words, for small $\alpha$ values, slip condition on the wall results in smaller shear strain (or low friction) which itself is responsible for increasing the momentum. Excessive momentum in competition with adverse pressure gradient and viscosity effect can delay the separation point [compare Figures 8(a) and 8(d)]. For larger $\alpha$ values, the excess in momentum cannot overcome the pressure and viscous effects; therefore, using superhydrophobic airfoils is not that promising for $\alpha$ values greater than $5^\circ$.

**Figure 7** The ratio of total lift to total drag on NACA 4418 at different angle of attacks ($\alpha$) and different slip velocities on the wall are shown.

Note: Medium is air and its velocity is 1 m/s. flow is laminar and Reynolds number is approximately 5,000.
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Figure 8  Shear stress on the top wall of a NACA 4418 airfoil is shown at (a) $\alpha = 0$ (b) $\alpha = 5^\circ$ (c) $\alpha = 10^\circ$ with no-slip on the wall (d) $\alpha = 0$ (e) $\alpha = 5^\circ$ (f) $\alpha = 10^\circ$ with 50% slip on the wall.

Note: Medium is air and its velocity is 1 m/s. Flow is laminar and Reynolds number is approximately 5,000.
It should be noted that making the whole airfoil surface superhydrophobic may not necessarily provide the best option performance or be economically feasible. Therefore, selective superhydrophobising the airfoil can be the next step. In Mastrokalos et al. (2015) for supressing the Karman vortex street (which may lead to structural fatigue in cooling towers, and heat exchangers) partial superhydrophobising the cylinder rather than making the whole surface superhydrophobic is suggested.

5 Conclusions

The potential of using superhydrophobic airfoils is studied numerically and in low chord-based Reynolds number (i.e., ~5,000). Despite normal surfaces, on superhydrophobic surfaces fluids have slip motion. The slip motion can be as large as 60% of the free-stream. It was found that for NACA 4412, 4418 and 4424, 50% slip on the airfoil’s surface results in up to 66% increase in lift, slightly delays the stall and decreases the drag by 45%. The promising performance of superhydrophobic airfoils decays as the angle of attack increases. The root cause of the lower effectiveness of superhydrophobic airfoils at larger contact angles (i.e., > 5°) is the creation of LSB. At larger angle of attack values, the LSB grows. The LSB growth results in lower lift and higher drag. As such, using superhydrophobic airfoils is suggested for small angle of attacks (i.e., < 5°).

Acknowledgements

The authors would like to thank the national elites’ foundation of Iran for their financial support.

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