

# Low Reynolds Number flow over Airfoils

Seminar Report

by

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# Chapter 1

## Introduction

The performance of airfoils operating at low relative wind speeds (low free stream velocities) has been of interest in modern subsonic aerodynamics. Typical applications where such airfoils can be used are wind turbines, remotely piloted vehicles, sail-planes, human powered vehicles, high altitude devices etc. To characterize flows, the dimensionless Reynolds Number is used. Reynolds number is defined as  $(\rho V L / \mu)$  and gives a measure of the ratio of inertial forces  $(\rho V^2)$  to viscous forces  $(\mu V / L)$  and consequently quantifies the relative importance of these two types of forces for given flow conditions [1]. As Reynolds number is proportional to free stream velocity, the low wind speed flows (low free stream velocity) correspond to low Reynolds numbers. At low Reynolds numbers, the airfoils generate lesser lift, and encounter higher drags, bringing down the performance of the airfoil. This study gives a basic overview of low Reynolds number flows and proposes methods to tackle the challenges of low lift and high drag in such flows.

# Chapter 2

## Low Reynolds number flow effects on an Airfoil

### 2.1 Airfoil

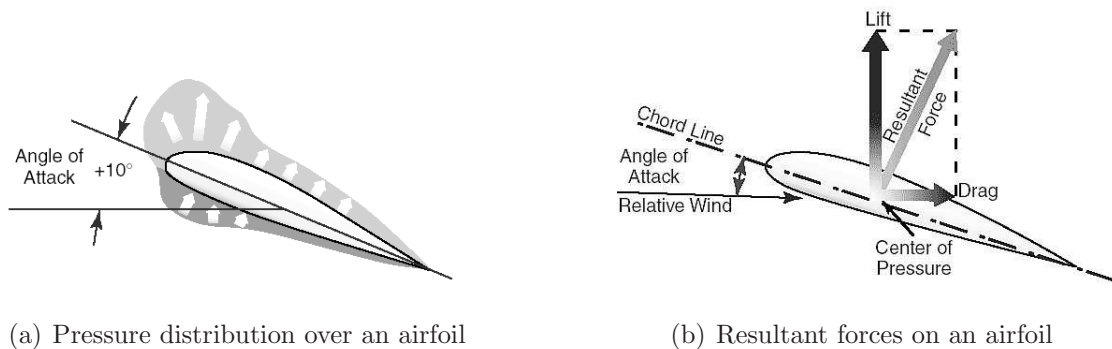


Figure 2.1: Airfoil Characteristics

The aerodynamic cross section of a body such as a wing that creates lift ( $L$ ) and drag ( $F_d$ ) on relative motion with the air is called an airfoil. Lift is defined as force perpendicular to motion of the airfoil. The force parallel to the motion of the airfoil is called drag. As the air flows over an airfoil, the pressure over and under the airfoil changes due to wind speed and circulation. To produce lift, a large part of the region over the wing has lower pressure than on the lower surface. Typical pressure distribution and resultant forces on an airfoil are shown in 2.1(a) and 2.1(b).

For the purpose of analysis of air flow around an airfoil, the flow is divided into two regions: an outer region of inviscid flow, and a small flow region near the airfoil where viscous effects dominate. The region near the airfoil contains slow moving air and

is known as Boundary Layer. The majority of drag experienced by a body in a fluid is created inside the Boundary Layer. The outer inviscid flow is faster moving air and determines the pressure distribution around the airfoil. The outer flow thus determines the Lift force on the airfoil.

## 2.2 Low Reynolds Number flow over airfoil

Low Reynolds number corresponds to low relative wind speed over the airfoil. At lower Reynolds numbers, both lift and drag characteristics are different from high Reynolds number flows:

### 2.2.1 Effect on Lift

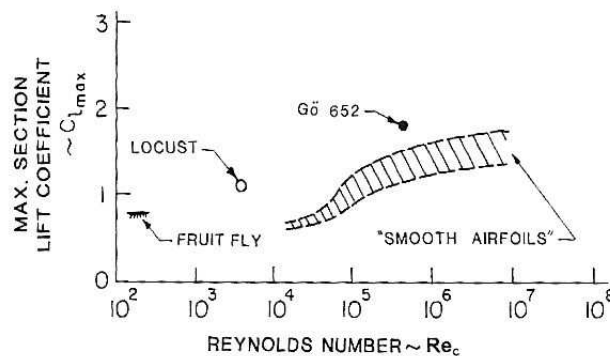


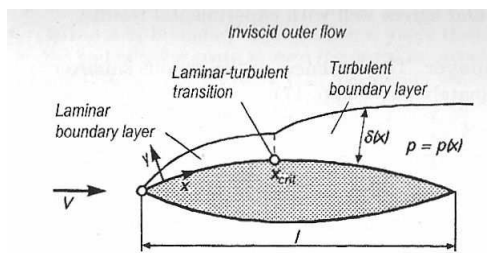
Figure 2.2: Max section lift coefficient for different Reynolds numbers

[2]

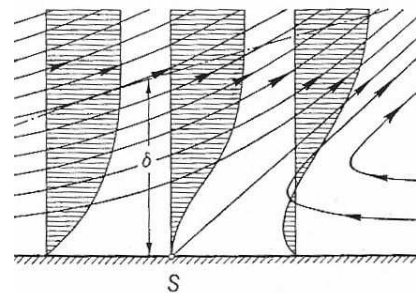
Lift is determined by the pressure distribution around the airfoil. This pressure distribution depends upon the free stream velocity of air around the airfoil. The pressure is related to the velocity distribution as ( $p + V^2/2 = constant$ ). The velocity distribution around the airfoil is a function of the relative velocity of the airfoil. At low Reynolds number flows, the velocity of the flow around the airfoil is lower than high Reynolds number flow, which decreases lift experienced by the foil. Typical coefficient of lift ( $C_L = L/(\rho V^2 A/2)$ ) variation is shown in 2.2.

### 2.2.2 Effect on Drag

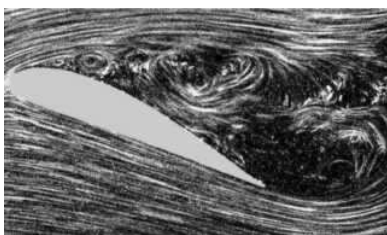
A laminar boundary layer starts forming at the nose of the airfoil. After a certain distance along the airfoil, the flow inside the layer transitions to turbulent flow. At high Reynolds numbers, this transition is quick and the turbulent flow inside the layer is able to effectively overcome the adverse pressure gradient downstream of the minimum pressure. However, for low Reynolds number flows, the boundary layer on an airfoil often remains laminar in the adverse pressure gradient region. When the boundary layer travels far enough against the adverse pressure gradient, the speed of the boundary layer falls almost to zero. This detaches the flow from the surface of the airfoil and takes the form of eddies and vortices which often results in increased drag, particularly pressure drag, which is caused by pressure difference between the front and rear surfaces of the airfoil.



(a) Boundary Layer Formation



(b) Boundary Layer Separation



(c) Eddies and Vortex



(d) Min section drag coefficient for different Reynolds numbers

Figure 2.3: Drag Characteristics

[3] [2]

Drag coefficient ( $C_D = F_d/1/2\rho V^2 A$ ) increases by orders of magnitude when Reynolds number decreases below  $10^5$ . The variation of drag coefficient with Reynolds number is shown in 2.3(d).

### 2.2.3 Aerodynamic Efficiency

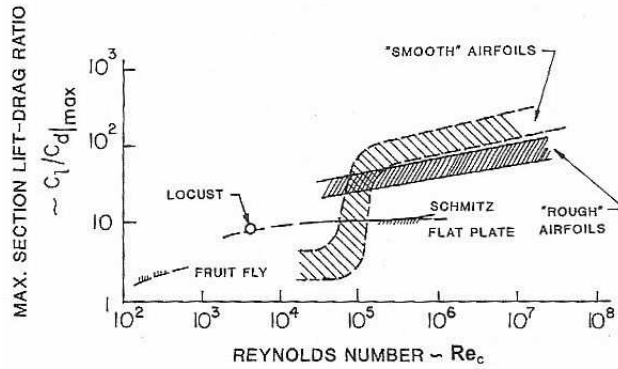


Figure 2.4: Aerodynamic efficiency for different Reynolds numbers

[2]

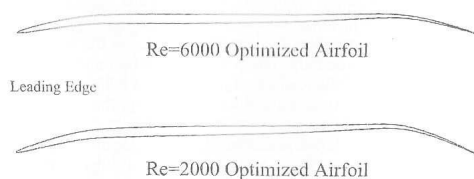
Aerodynamic efficiency is defined in terms of the lift-to-drag ratio. With decrease in Reynolds number, the non-dimensional lift generated by an airfoil reduces while the non-dimensional drag experienced by the airfoil increases. The combined effort reduces the aerodynamic efficiency drastically. 2.4 shows the aerodynamic efficiency as a function of Reynolds number. It is clear from this figure that airfoil performance deteriorates rapidly as the Reynolds number decreases below 10<sup>5</sup>. In the following chapter, methods to increase aerodynamic performance of airfoils at low Reynolds numbers have been discussed.

# Chapter 3

## Approaches to increase aerodynamic performance of airfoils at low Reynolds numbers

The following approaches will be tried to choose or design an optimum airfoil for the Reynolds numbers below  $10^5$ :

### 3.1 Airfoil Shaping



(a) Optimized airfoils for Reynolds numbers 2000 and 6000



(b) Optimized airfoils for Reynolds numbers 50000

Figure 3.1: Optimized Airfoils

[4] [5]

The airfoils used for high Reynolds number flows cannot be scaled down and used in low Reynolds number flows. Newer designs of airfoils for low and ultra low Reynolds number flows have been presented in [4] and [5]. These airfoils have been designed using computational and inverse methods and optimized for a range of low Reynolds number

flow. Some of the parameters to be analyzed and optimized are: maximum thickness of the airfoil, location of maximum thickness, leading edge radius, camber, surface quality etc.

## 3.2 Boundary Layer Control

Flow control through boundary layer manipulation to prevent or postpone separation can significantly reduce the high drag effects of boundary layer at low Reynolds number flow. A variety of methods can be deployed to control the boundary layer:

### 3.2.1 Suction at airfoil surface

The boundary layer formed at the surface of the airfoil is a slow moving layer of air and its depth keeps increasing with the distance from the tip. By sucking in the slow moving air from the airfoil surface, the depth of the boundary layer can be reduced [3] [6]. The outer, faster air comes closer to the airfoil and is able to overcome the adverse pressure better than the slower boundary layer. If the slit is arranged suitably, in certain circumstances, the flow may not separate at all.

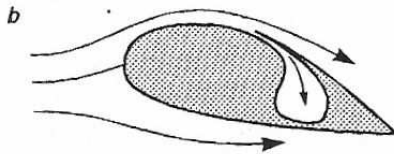


Figure 3.2: Suction Mechanism for Boundary Layer Control

[3]

The pressure in the suction area has to be lesser than that at the slit on the airfoil. The pressure in the sink region can be controlled actively using pumps or passively with a venturi tube like arrangement to reduce pressure. The suction can be tangential through a slit or perpendicular to the surface through a permeable surface.

### 3.2.2 Blowing of high speed air over airfoil

Another method of preventing separation consists of supplying additional energy to the slow moving air in the boundary layer over the airfoil. This can be done by introducing

higher velocity air from inside the body as shown in 3.3(a) and 3.3(b). Directly behind the point of injection, a wall jet profile forms in the boundary layer [3]. The high velocity is able to overcome the adverse pressure easily. If the intensity of the blown jet is high enough, even the lift predicted by potential theory can be surpassed. The pressure inside the body has to be higher than the pressure at the slit on the airfoil. This may be attained through pump or creating higher stagnation pressure inside the cavity.

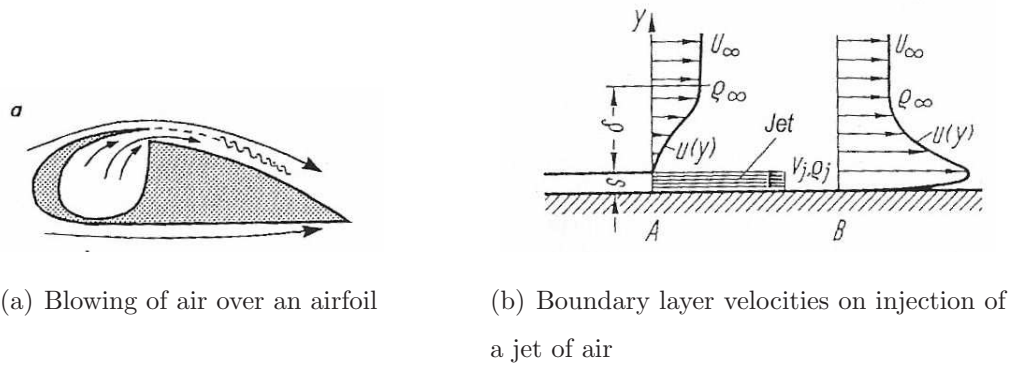


Figure 3.3: Blowing of air over an airfoil

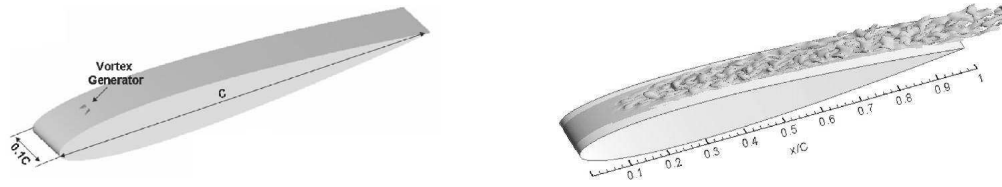
[3]

### 3.2.3 Vortex creators

Vortex creators or turbulators are small vanes attached to the airfoil upstream of the area of separation risk. The vortex creators trip the boundary layer into turbulence, hence giving it more energy. The boundary layer with more energy can overcome greater adverse pressures, so the separation is delayed until a greater magnitude of negative pressure gradient is reached. This effectively moves the separation point further down on the airfoil and may even eliminate separation completely. A consequence of the turbulent boundary layer is increased skin friction relative to a laminar boundary layer, but this is very small compared to the increase in drag associated with separation [7].

### 3.2.4 Heating / Electromagnetic / Acoustic disturbances etc

Extra kinetic energy can be provided to the boundary layer by various other methods like heating the air, active electromagnetic or acoustic disturbances introduced by actuators like micro flaps or MEMS actuators [8] [9]. Active control would require a pressure



(a) Vortex Creators

(b) Turbulent Boundary Layer over Airfoil

Figure 3.4: Turbulators

[7]

probe, an active control circuit, and an electronic actuator system coupled with a control algorithm.

### 3.3 Artificially increase flow speed over the blades

The incoming air can be forced to flow through a narrower area, using nozzles in order to increase the flow speed. The airfoil can be made to operate in the narrower area, thus forcing a higher speed air over the airfoil, which increases the Reynolds number. For wind turbine applications, such a solution would tap the energy of air flowing through a larger area, keeping the size of the turbines small.

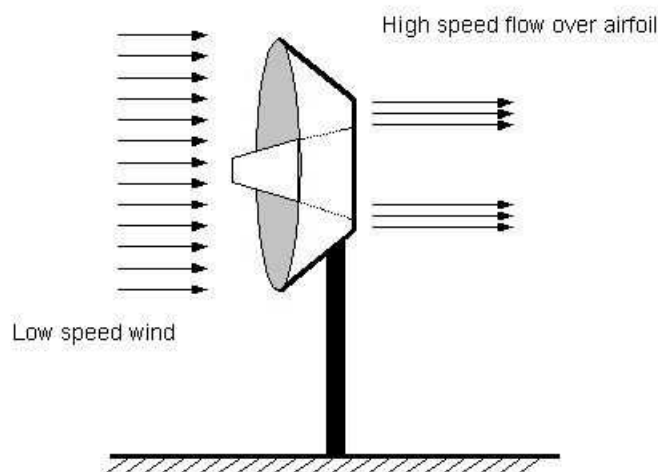


Figure 3.5: Way to increase airflow over airfoil

# Chapter 4

## Future Work

A workable solution would probably require a combination of the methods described in the previous chapter. The aim of the work over next few months is to explore each of these methods, first using CFD tools and then validating the findings experimentally. Initially, each of the methods will be tried in isolation to other methods, to understand the dynamics of each of the methods. Once the understanding of each method is built, a combination of the methods will be tried.

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