

## Flow Visualization Around Airfoils

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**Abstract** This work presents visualization of low Reynolds number flow around airfoils, *NACA0012* and *NACA23012*, using Hele-Shaw apparatus. The study focuses on the variation of stream surface contour as it moves past airfoils at different angles of attack and pressure heads. For each airfoil, at the stalling angle, the genesis of a bubble has been captured. The bubble size evolution indicates gradual growth for symmetric airfoil, whereas higher growth is associated with asymmetric case with increasing angle of attack as well as Reynolds number. Considering the formation of bubble as a benchmark, the existing procedure may be effectively utilized for stall characterization of airfoils, where laminar boundary layer prevails.

**Keywords:** Hele-Shaw flow, stream surface, airfoil, stalling angle, bubble

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### 1 Introduction

Flow visualization is a powerful tool in Fluid Mechanics to obtain qualitative and quantitative results. One of the most influential works, at the end of the 19<sup>th</sup> century, was the conception of a device called Hele-Shaw cell by Henry Selby Hele-Shaw. The apparatus consists of two parallel plates separated by a small gap, which ensures a planar flow-field. Since, the inviscid flow airfoil theory allows predicting the lift characteristics of an airfoil at low-to-moderate angles of attack [1], experiments based on Hele-Shaw flow can be more appropriate to simulate it. In other words, pressure-driven viscous flow between closely spaced stationary parallel plates can produce potential-line and streamline patterns similar to a two-dimensional ideal flow [2]. So, the present investigation focuses on visualization of flow past airfoils in a Hele-Shaw apparatus.

### 2 Experimental method and measurement techniques

Figure 1 shows schematic of the experimental setup with proper dimensions. The plates are separated by a gasket sheet of thickness 0.05cm. Uniform velocity in the test section is ensured by maintaining constant head ( $h_p$ ) in the overhead tank attached to the apparatus, Fig. 1. The respective velocity in the test section was determined by measuring the volumetric flow rate for different datum heads. Distilled water has been utilized as the test liquid. To ensure 2-D flow around the body, the airfoil is perfectly sandwiched between the plates. A stopper device that acts as a gate valve ensures a smooth initial flow, which is crucial for precise simulation of flow past bodies. In order to avoid gravitational effect, the apparatus is oriented horizontally.

Two airfoils *NACA0012* and *NACA23012* made out of propylene were tested. The present investigation considers liquid velocities ( $U_\infty$ ) 1.4 cm/s, 2.2 cm/s and 3.6 cm/s. For a chord dimension of 5cm, the corresponding Reynolds numbers are 690, 1100 and 1800. To characterize the stalling behavior, experiments were performed at different angles of attack ( $\alpha$ ). Flow visualization utilized a white-colored diffuser plate for uniform background illumination by a 1000W spotlight, and thereby a good contrast for the transparent object plane was achieved. The recording was carried out with a CCD camera (*Sony XCD-X710 B/W*), which has a maximum acquisition rate of 30 frames per second, with a spatial resolution of 1024 x 768 pixels. The exposure time is 1ms. A standard C-mount lens of focal length 25 mm was used throughout the investigation. To track the temporal progression of the stream surface, appropriate image enhancement was carried out in *MATLAB*.

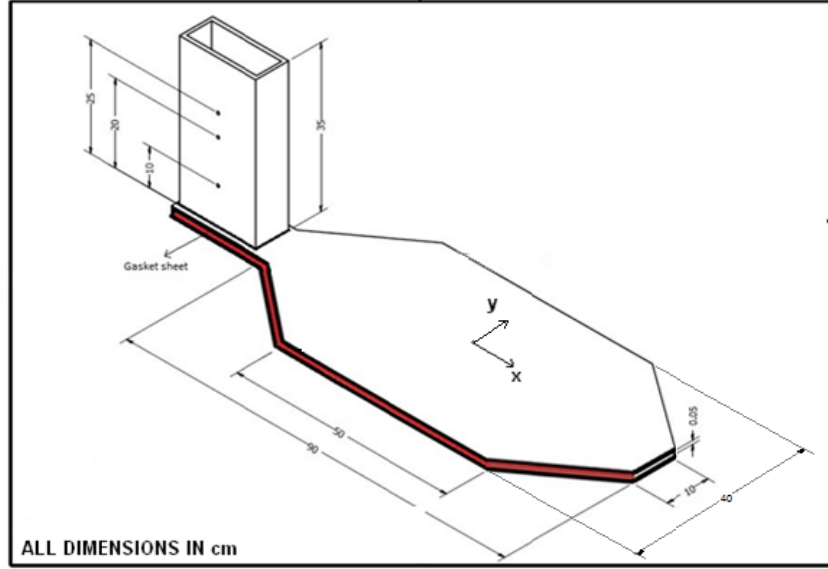


Fig. 1 Hele-Shaw apparatus

### 3 Results and discussion

Typical images of flow around airfoils, *NACA 0012* and *NACA 23012*, are shown in Figs. 2 to 5. Visualization studies were carried out at different angles of attack ( $\alpha$ ), for the specific Reynolds number of 1100. Figures 2 and 3 illustrate the flow behavior for *NACA 0012* at the corresponding angles of attack  $9^\circ$  and  $10^\circ$ . Angles were selected in accordance with the established stalling characteristics of the airfoil that enables to minimize testing conditions [3], [4]. The image sequence of consecutive frames, Figs. 2a and 2b, depicts a smooth passage of advancing stream surface at the trailing edge. However, as the angle of attack reaches the stalling region of the airfoil, the free-stream curls around and then separates to form a bubble attached to the tip as exemplified in Figs. 3a and 3b. In a similar manner, the genesis of bubble associated with *NACA 23012* under stalling conditions were extracted, Figs. 4 and 5. Formation of the bubble can be attributed to the air trapped by the curling water front as the flow approaches the trailing edge. The following section deals with bubble area ( $A_b$ ) characterization based on image processing.

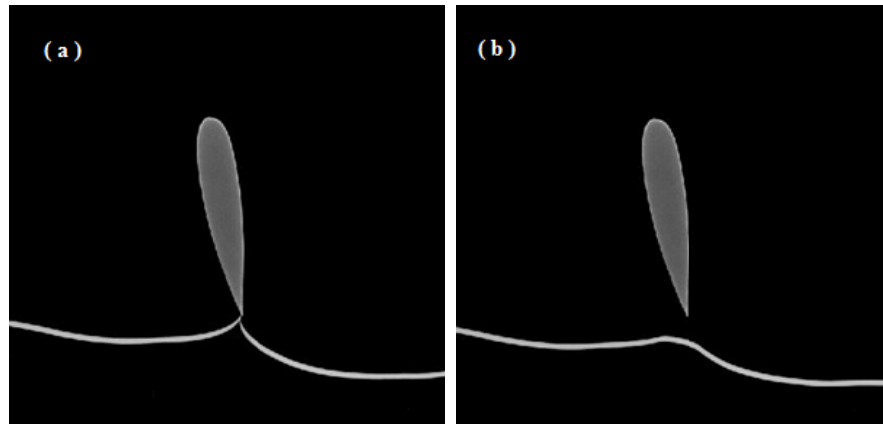


Fig. 2 Image sequence of flow past *NACA 0012* ( $\alpha = 9^\circ$ ,  $U_\infty = 2.2$  cm/s): (a)  $t = 1.57$  s; (b)  $t = 1.6$  s

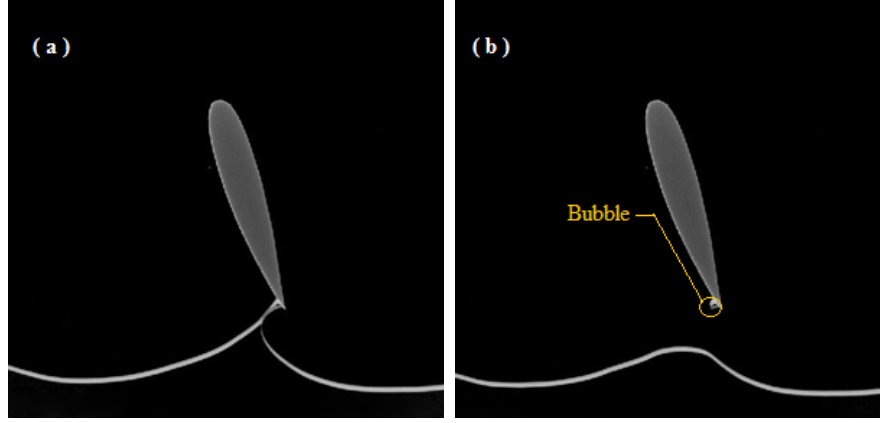


Fig. 3 Image sequence of flow past *NACA 0012* ( $\alpha = 10^\circ$ ,  $U_\infty = 2.2$  cm/s): (a)  $t = 1.87$  s; (b)  $t = 1.9$  s

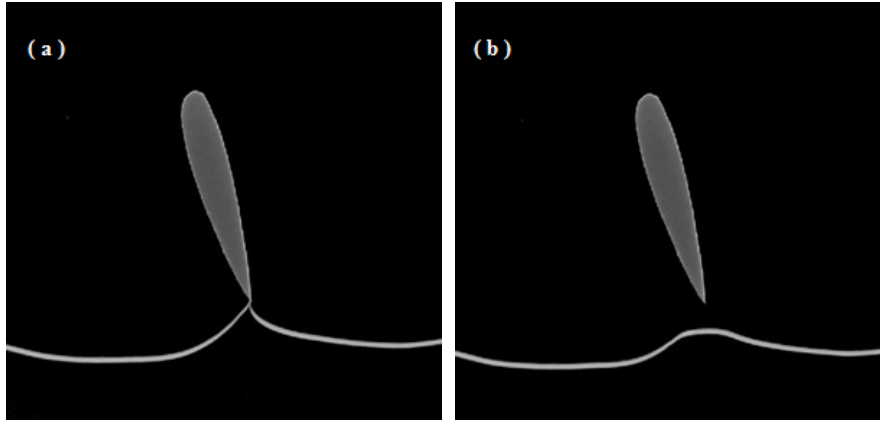


Fig. 4 Image sequence of flow past *NACA 23012* ( $\alpha = 8^\circ$ ,  $U_\infty = 2.2$  cm/s): (a)  $t = 2.10$  s; (b)  $t = 2.13$  s

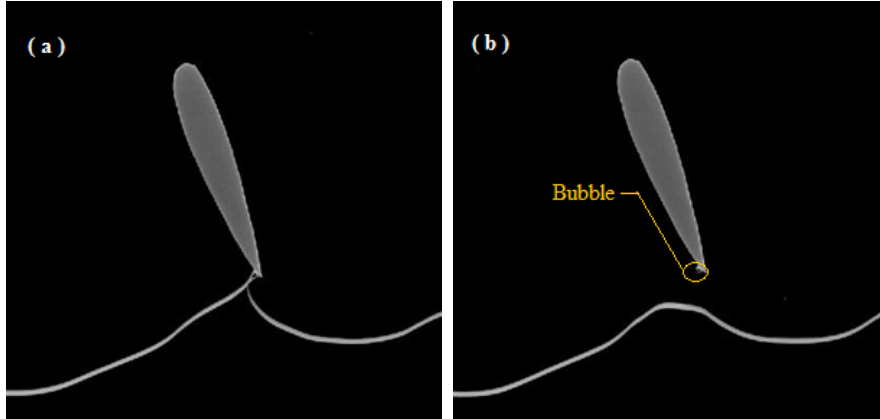


Fig. 5 Image sequence of flow past *NACA 23012* ( $\alpha = 9^\circ$ ,  $U_\infty = 2.2$  cm/s): (a)  $t = 2.10$  s; (b)  $t = 2.13$  s

Since the camera observed the object plane at a certain angle, distortion in the recorded images needs to be extracted. In other words, the associated scaling factor for the respective cases was obtained from the known dimension of the airfoil in the particular frame. Subtracting the bubble image from the image prior to its formation allows in extricating exact bubble portion for the subsequent area measurements. In order to perform the calculation, any singularities or dark patches inside the bubble should be removed by appropriate filling. Figures 6 and 7 depict bubble area ( $A_b$ ) as a function of angle of attack ( $\alpha$ ) and pressure head ( $h_p$ ) for *NACA0012* and *NACA 23012* respectively. From the results, it can be inferred that a gradual increase in area with angle of attack is associated with the symmetric airfoil, Fig. 6, whereas there exists a steep increase in

area for asymmetric configuration, Fig. 7. For both cases, bubble size increases with rise in pressure head also. The observed trend can be attributed to enhanced velocity gradient in the span-wise direction ( $y$ -axis) with increasing angle of attack, as well as pressure head. Higher velocity gradient implies stronger curling of the stream surface that may result in larger bubble area.

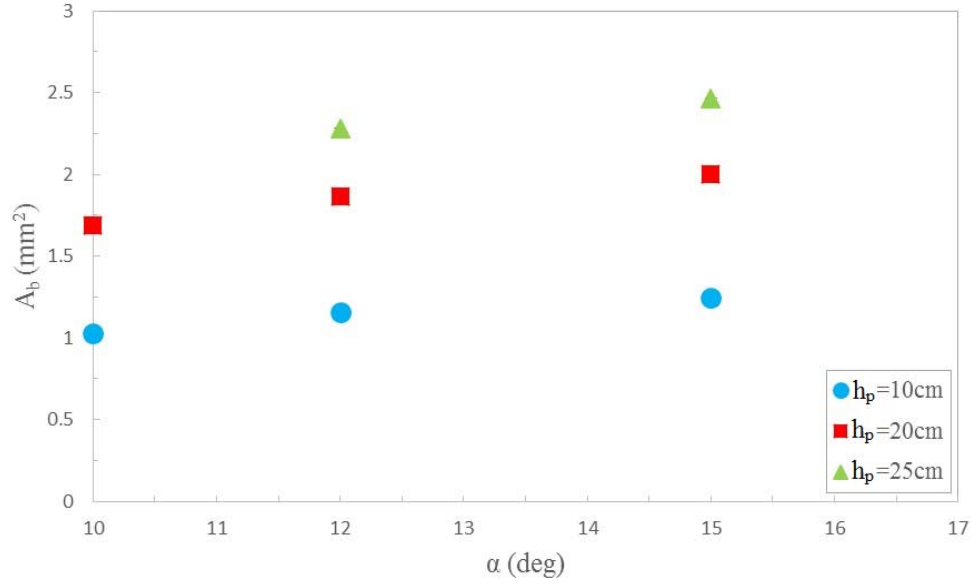


Fig. 6 Area of bubble as a function of angle of attack for different pressure heads (*NACA 0012*)

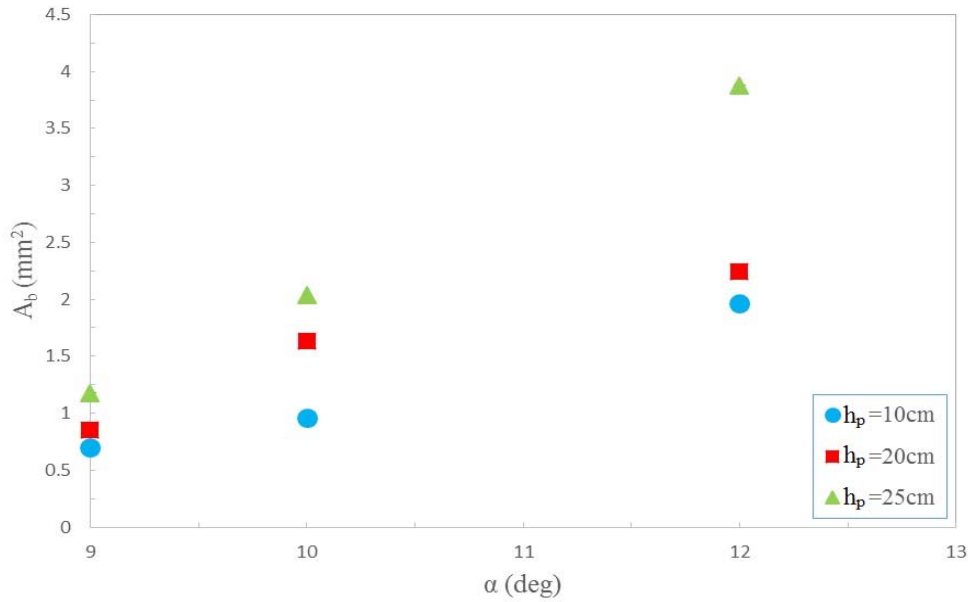


Fig. 7 Area of bubble as a function of angle of attack for different pressure heads (*NACA 23012*)

#### **4 Summary**

The present simulation of flow around *NACA* series airfoils with Hele-Shaw apparatus demonstrates the viability of extracting the respective stalling characteristics. That is, capturing the genesis of bubble at the critical angle of attack with flow visualization provides an elegant and simple procedure, which may find applications in laminar airfoils. Quantifying the bubble-growth with increasing angle of attack as well as Reynolds number may offer a reliable data-bank for future analytical formulation of flow past bodies.

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