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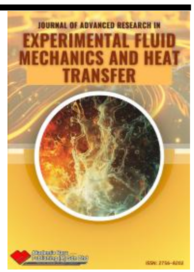

Visualization Analysis of Flow with Smoke on Airfoils and Flaps

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ABSTRACT

Flow visualization using smoke over airfoils and flaps provides valuable insights into the aerodynamic behavior of these surfaces, particularly in identifying flow attachment, separation, and wake characteristics. This study explores the interaction of airflow with clean airfoils and configurations involving deflected flaps, employing smoke as a tracer in a controlled wind tunnel environment. The investigation focuses on analyzing laminar-to-turbulent transition, boundary-layer behavior, flow reattachment, and the formation of vortices and wake patterns. Results demonstrate the influence of flap deflection angles on lift, drag, and flow separation, highlighting the role of slots in mitigating separation and enhancing aerodynamic performance. This approach offers a practical methodology for optimizing airfoil and flap designs in applications requiring efficient lift-to-drag ratios and delayed stall conditions.

1. Introduction

The study of airflow behavior around airfoils and flaps is a fundamental aspect of aerodynamics, critical for understanding and optimizing the performance of aircraft and other aerodynamic surfaces. Flow visualization techniques, such as the use of smoke, provide a clear and practical means of examining complex flow phenomena, including boundary layer development, flow attachment, separation, and wake formation. These visual methods are particularly valuable for identifying critical flow features that influence lift, drag, and overall efficiency [1,2].

Airfoils and flaps play a central role in generating lift and controlling the aerodynamic performance of wings. While a clean airfoil surface can achieve efficient airflow under certain conditions, the deflection of flaps such as trailing-edge or slotted flaps, which is often required to enhance lift, particularly during takeoff, landing, or maneuvering. However, these modifications significantly alter the flow field, introducing challenges such as increased drag, flow separation, and vortex formation. Understanding these effects is crucial for improving airfoil designs and achieving optimal performance [3-5].

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This paper investigates the behavior of airflow over clean airfoils and airfoils equipped with deflected flaps using smoke-based flow visualization. The primary objective is to analyze the impact of flap configurations on the flow field, including changes in boundary layer characteristics, wake development, and the interaction between laminar and turbulent regions. The study aims to provide insights into improving airfoil and flap design, ensuring enhanced aerodynamic performance while mitigating adverse flow effects such as separation and drag [6-8].

2. Methodology

2.1 Test Model

The approach used to assess the airfoil involves visualizing airflow by utilizing smoke produced from a liquid mixture. The experiments were conducted on a 3D model of test. Figure 1 displays the components airfoil the NACA 4412 model [9,10]. The airfoil test model was built using a flexiglass structure, with its surface coated in epoxy resin. The model was created according to the geometric dimensions provided in Figure 2. The chord length (C) is 151.52 mm, the span (S) is 300 mm, and the maximum thickness (t) is 19.18 mm.

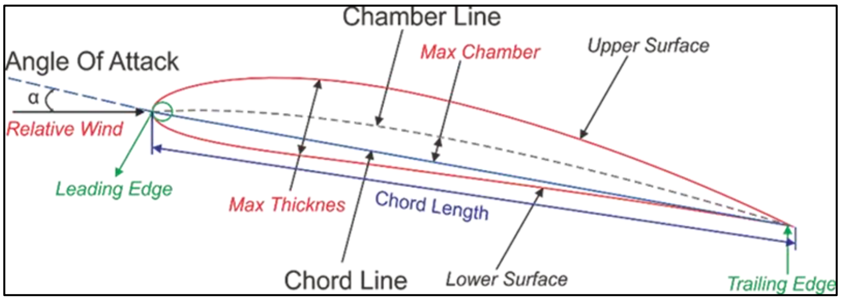


Fig. 1. The test model

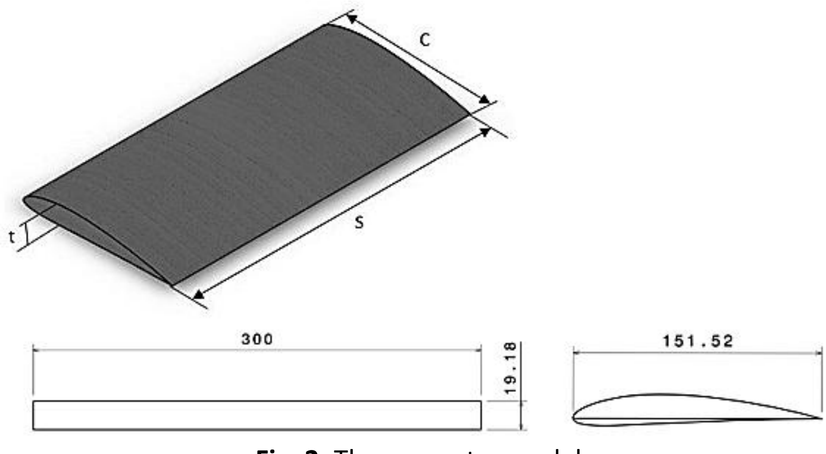


Fig. 2. The geometry model

The Aerodynamics, Aeroelasticity, and Aeroacoustic Laboratory's low speed wind tunnel served as the experiment's location (see Figure 3(a)). The test portion of this wind tunnel is 300 mm by 300 mm square, and its top speed is 25 m/s. The angle of attack (α) was set to 0°, 5°, 10°, 15°, and 20° during testing, while the wind speeds were set to 5 m/s, 10 m/s, 15 m/s, and 20 m/s. The fluid for the testing was a liquid mixture (glyserin:glycol:water=2:2:1). The experiment was conducted again with different setups, maintaining the same ambient temperature and pressure (P = 1 atm, T = 27°C).

For flow visualisation studies, a 3D model of the NACA 4412 aerofoil was placed in the test section (Figure 3(b)) [11,12].

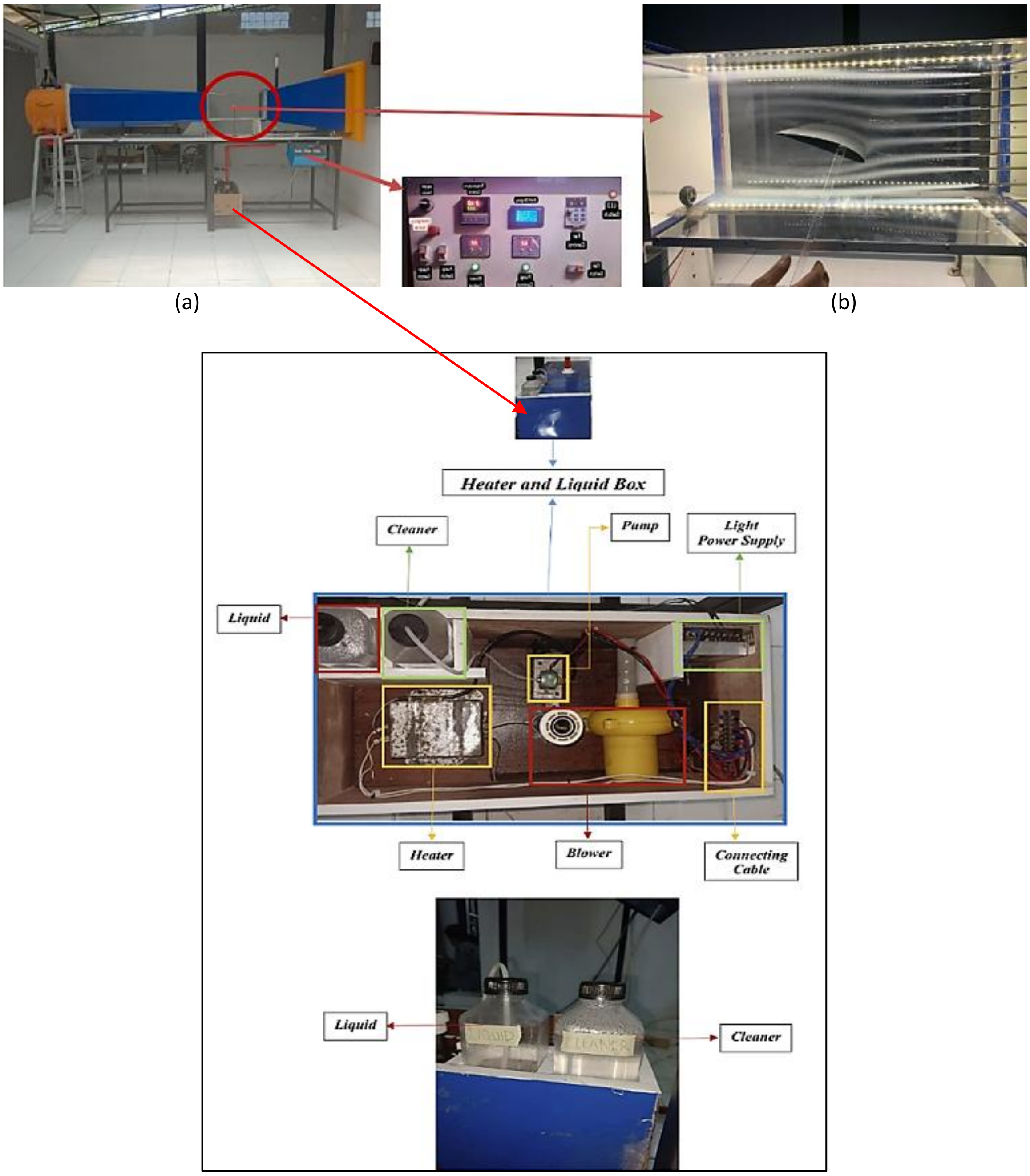
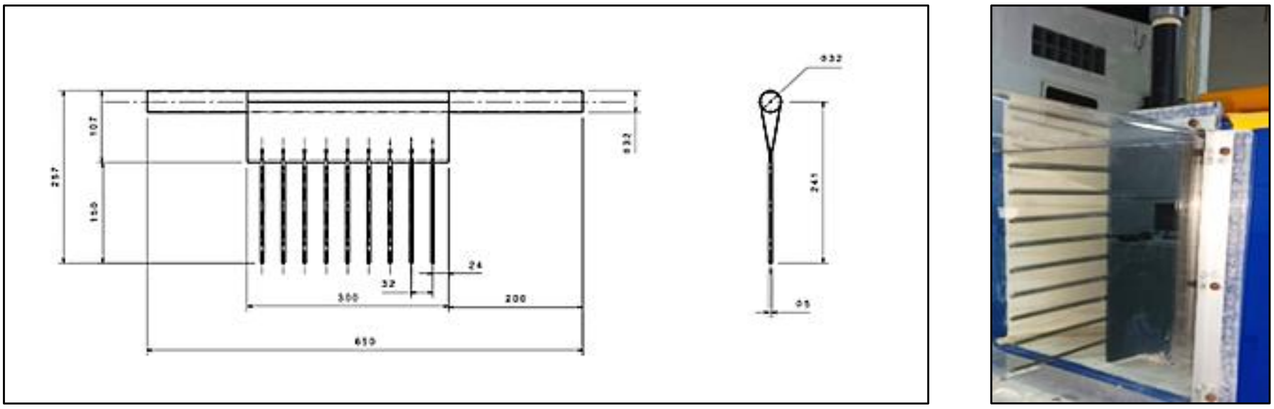


Fig. 3. Low speed wind tunnel (a) Wind tunnel with smoke generator (b) Test model placement

2.2 Smoke Channel

The smoke lines are illustrated in Figure 4. The SC-1 system produced denser and thinner smoke lines compared to SC, with clearer visual flow patterns. SC had a 3 mm injection port, which led to a more disrupted smoke path, but the SC-1 system generated denser smoke lines and produced more consistent flow patterns (Table 1).



(a) (b)

Fig. 4. Smoke channel (a) Smoke cannel design (b) Installed SC smoke channel

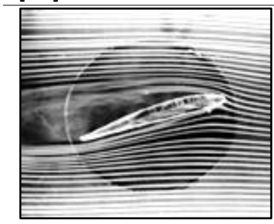
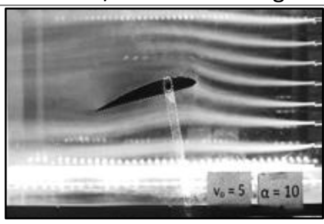
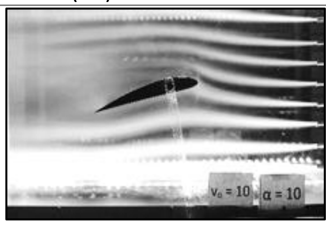
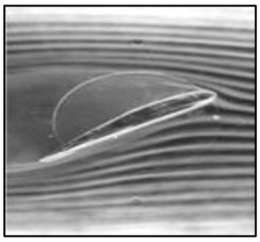
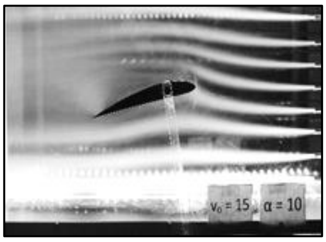
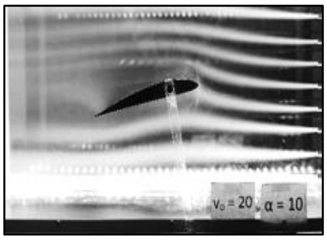
Table1
Smoke channel geometry

Smoke channel	Smoke line thickness	Smoke lines number	Gap between smoke lines
SC	5.0 mm	9	32 mm

2.3 Comparison with Previous Research

The findings of the flow visualisation simulation must be verified against experimental data under the same circumstances in order to guarantee their accuracy. In this study, Jurnal *et al.*,'s [13] experimental data and modelling results were compared [14-16]. Additional trials were carried out at speeds of 5 m/s, 10 m/s, 15 m/s, and 20 m/s. The validation method involved comparing data at the same angle of attack and wind speed (Vo) of 10 m/s. The simulation results and experimental results using smoke-rake SC are compared in Table 2.

Table 2
Comparison of the experimental results of Jurnal *et al.,* [13] with the results of Research SC

Experiment of Jurnal *et al.,* [13]	Findings from studies conducted at 5 m/s, 10 m/s, 15 m/s, and 20 m/s with a 10° angle of attack (SC)	
		
		

3. Results

The flow from the results of flow visualization experiments on the NACA 4412 airfoil, when compared with experimental data and numerical simulations [17], is shown in Figure 5. Whereas, the comparison of the experimental results of Jurnal *et al.,* [13] with the results of Research SC (flap change), is shown in Table 3.

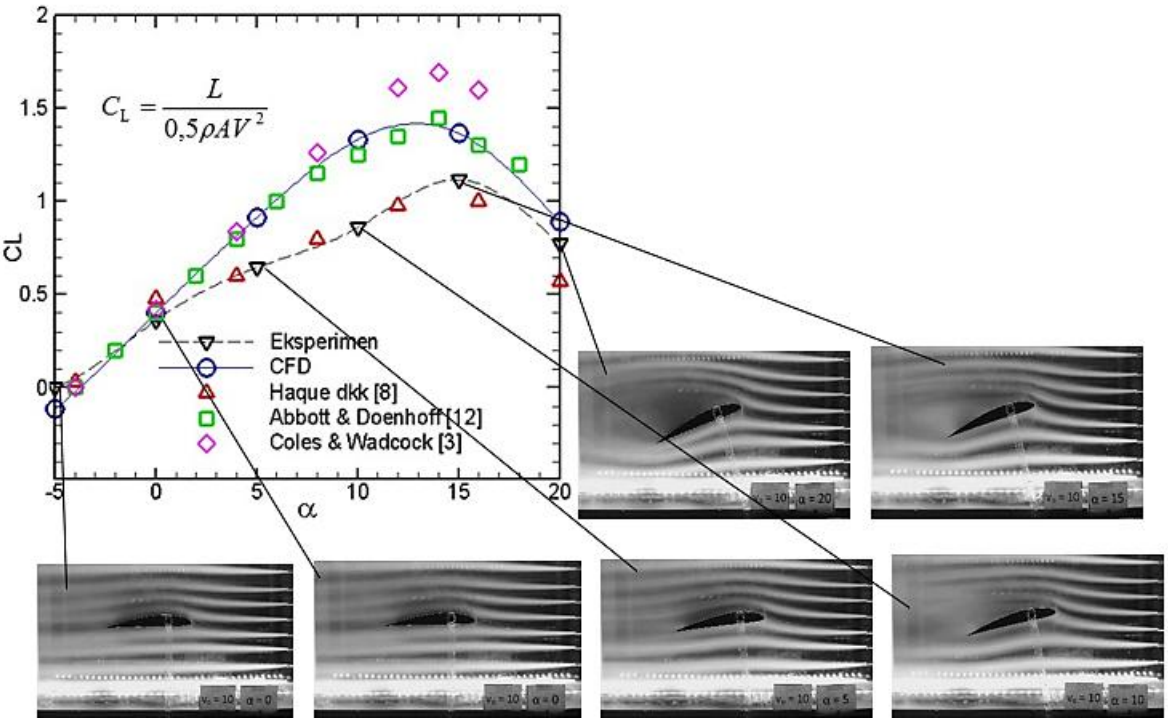
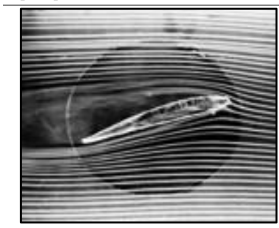
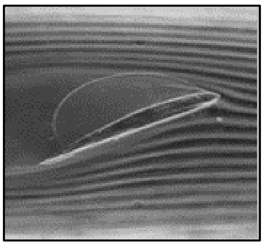
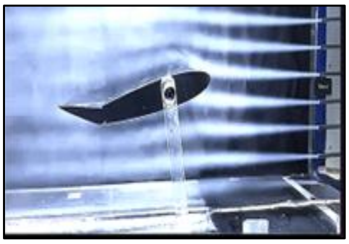
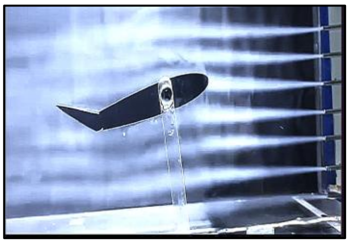


Fig. 5. Numerical experiments and flow

Table 3
Comparison of the experimental results of Jurnal *et al.,* [13] with the results of Research SC (flap change)

Experiment of Jurnal *et al.,* [13]	Findings from studies conducted at 10 m/s on airfoil 10° and flaps -5°, 0°, 5°, 10°	
		
		

The research was continued at angles of attack of -20 degrees and 25 degrees with changes in the flap angle, is shown in Table 4 and Table 5.

Table 4
The research was continued at angles of attack of -20^0 with changes in the flap angle

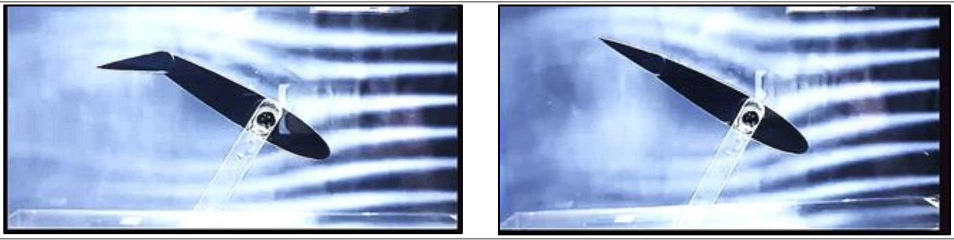
Findings from studies conducted at 10 m/s on airfoil -20° and flaps -10°, 0°


Table 5
The research was continued at angles of attack of 25^0 with changes in the flap angle

Findings from studies conducted at 10 m/s on airfoil -25° and flaps -5°, 0°, -15°


4. Conclusions

Flow visualization using smoke over airfoils and flaps provides a clear understanding of aerodynamic phenomena such as boundary layer behavior, flow separation, and wake formation. The study demonstrates that flap deflection significantly affects the flow field by altering lift and drag characteristics, with higher deflection angles leading to increased flow separation and turbulence. However, the inclusion of features such as slots in flaps can delay separation and improve flow reattachment, enhancing aerodynamic efficiency.

This research highlights the importance of analyzing airflow interactions in both clean and modified airfoil configurations to optimize performance. The insights gained from smoke-based visualization offer valuable guidance for improving airfoil and flap designs, particularly in applications requiring high lift-to-drag ratios and minimized stall risks. Future studies could expand on these findings by integrating computational fluid dynamics (CFD) with experimental techniques to further refine aerodynamic performance.

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