EXPERIMENTAL FLOW VISUALIZATION ALONG TWO-DIMENSIONAL AIRFOILS FOR AN UNMANNED AERIAL VEHICLE

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Abstract: *This paper presents the collection of the fluid flow pattern along a 2D NACA 2415 airfoil and four modifications of this one. Results allowed to obtain the location of the separation and reattachment point in some cases for different angles of attack by means of experimental visualization techniques such as oil and smoke. The experiments were held at a Reynolds number of 10000. Finally, experimental results were compared with numerical references and found to be in good agreement.*

INTRODUCTION

Most of the flow visualization methods provide interesting qualitative information on particular flow patterns. This investigation is part of the development of an airfoil for unmanned aerial vehicle with internal propulsion system. The main objective of this work is the observation and analysis of the flow pattern past a two-dimensional airfoil of the NACA four-digits family and four modifications of this one. The vizualization techniques employed were by means of oil and smoke, Tests were performed at a Reynolds number of 100000 which means a velocity of 7,7 m/s according to the climatic conditions of the measurement days. The angle of attack was set from 0 to 16 degrees with an increment of 4 degrees, the experiments were held in the Laboratory of Fluid Dynamics at the Czech Technical University in Prague. The results obtained in this investigation were compared to numerical results from references in [5] and found in good agreement. The whole process is described in the following sections.

OIL VISUALIZATION OF FLOW

Surface oil flow visualization is a very fast and simple method for the observation of separation and reattachment points of the flow past an airfoil. The principle is based on the observation of changes in a thin film of oil which is painted on the surface of the model; where the flow is separated from the wing then it cannot take effect on the oil film. After the reattachment point, the flow will be in contact with the oil and it can take effect on the oil film.

For a successful experiment it is very important to have an adequate viscosity of the oil because when the viscosity is too low, the oil flows down the wing before running the experiment and when the viscosity is too high, it is not possible to observe any change in the oil film because the oil cannot be moved by the flow. Another factor to be considered when performing this experiment is the thickness of the film; it has to be so that the air flow can exert enough effect to produce significative changes. It was used motor oil which was diluted with kerosene in a ratio 5:1. Fig. 1 shows a scheme of the experiment setup and all its components.

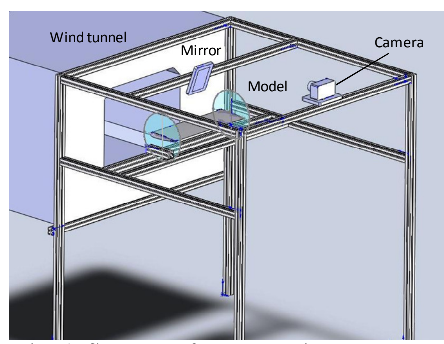


Fig. 1. Schema of the experimental setup for oil flow visualization.

The experiment proceeded as follows. The oil is applied with the tunnel stopped. The crew then leaves the tunnel, turns on the motor, and brings the tunnel up onto the test condition. When the surface oil flow streaks are properly established, the tunnel is stopped, and then photographs of the streaks are quickly taken, in this case for 0, 4, 8, 12 and 16 degrees of angle of attack. The oil must be applied with the correct thickness so that it generates a streak of some meaningful length, but does not pool when the tunnel is stopped. Therefore, skill and experience is needed to obtain meaningful data.

SMOKE VISUALIZATION OF THE FLOW

In engineering and research, white smoke streams are commonly used to visualize air flow patterns so that they can be seen and photographed easily. Nowadays smoke generators are commercially available, these are based on the vaporization of mixtures of concentrated chemicals [3]. However the method of making smoke streams by heating a wire has shown good results in many investigations. It is simple, non toxic, clean, cheap and easily controlled these are the reasons why this latter method was selected for the investigation.

The set of the experiment consists of a nickel chrome wire 0,5 mm in diameter and 0,6 m long which is placed in a circuit and fixed vertically in the middle of the wind tunnel test section as seen in Fig. 2. Liquid glycerin which is an organic compound, clear and colorless is applied to the wire and when this one is heated a highly visible white smoke is produced. In order to produce streaks and to keep the glycerin attached to the wire, helix bends were formed by twisting a pair of wires. Visibility was possible with 2 to 4 V; however this can be enhanced increasing the voltage carefully for not heat the wire too much. Halogen lamps were used to increase the contrast and make the smoke more visible. The camera was placed perpendicular to the air flow. The model was placed beyond a distance of 50mm from the wire to avoid the buoyancy effect developed by the heat generated as reviewing in [4]. The glycerin was spread on the wire with a brush and produced clearly visible white smoke for approximately 30 seconds duration.

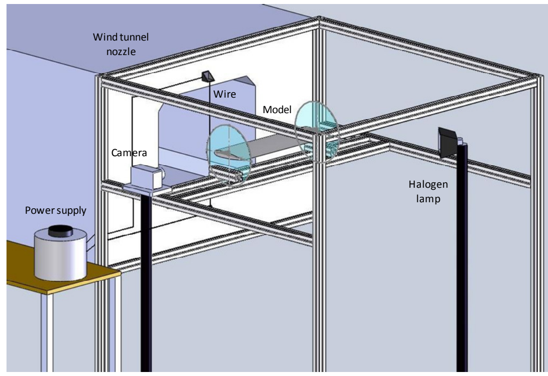


Fig. 2. Schema of the experimental setup for smoke flow visualization.

AIRFOILS TESTED

A NACA 2415 airfoil (Fig. 3), which has become increasingly popular on ¼ scale pylon racers [1], was tested and also four modifications of this one. The modification is based mainly on the creation of an abrupt step on the suction side of the original NACA airfoil. This step simulates a blowing propulsive outlet of the wing in normal flight conditions. Four different configurations where designed which involved the location of the step at different strategical points chordwise. These points are:

- At the location of the maximum thickness: 30% of the chord. (2415-3).
- At the location of the maximum camber: 40% of the chord. (2415-4).
- Before the transition point (at 0 AOA): 50% of the chord. (2415-5).
- Passed the transition point (at 0 AOA): 60% of the chord. (2415-6).

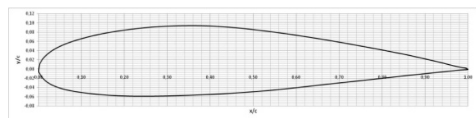


Fig. 3. NACA 2415 Airfoil 2415

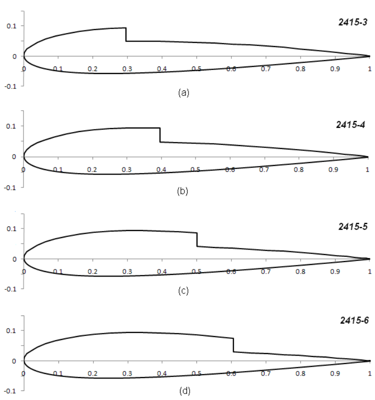
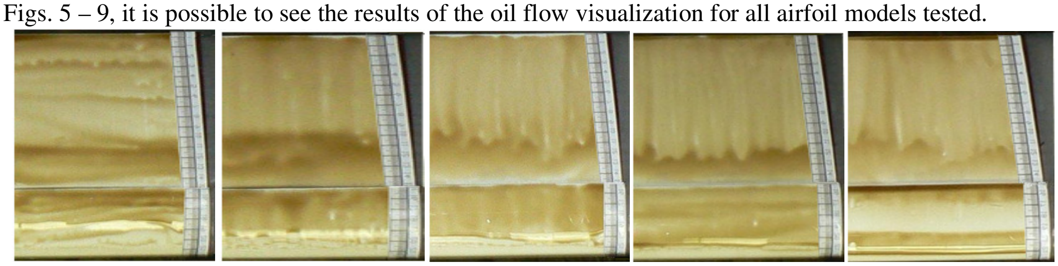


Fig. 4. Airfoils developed for testing (a) 2415-3, (b) 2415-4, (c) 2415-5, (c) 2415-6.

RESULTS AND DISCUSSION

In Figs. 5 – 9, it is possible to see the results of the oil flow visualization for all airfoil models tested.



0° 4° 8° 12° 16°

Fig. 5. Oil visualization results for the 2415-3 airfoil from 0 to 16 deg. of AOA.

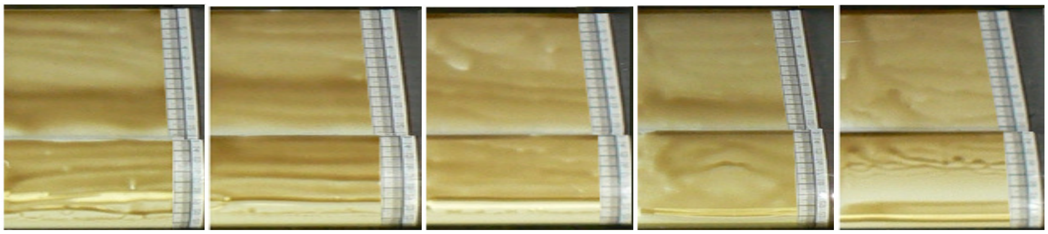


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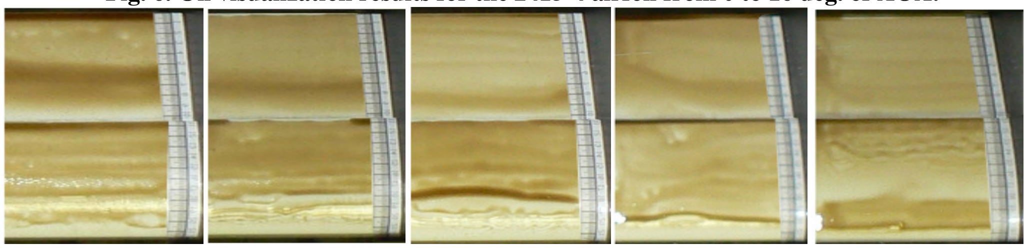
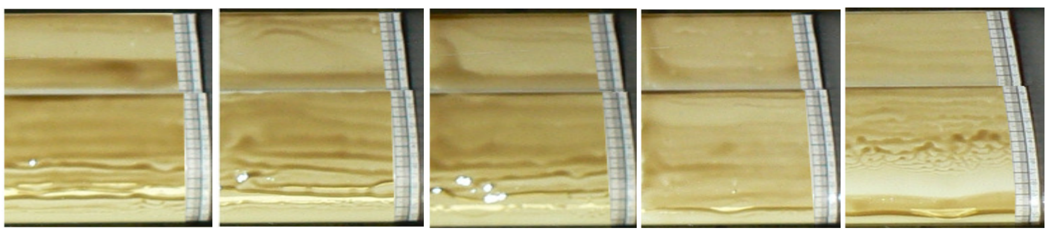
Fig. 6. Oil visualization results for the 2415-4 airfoil from 0 to 16 deg. of AOA.



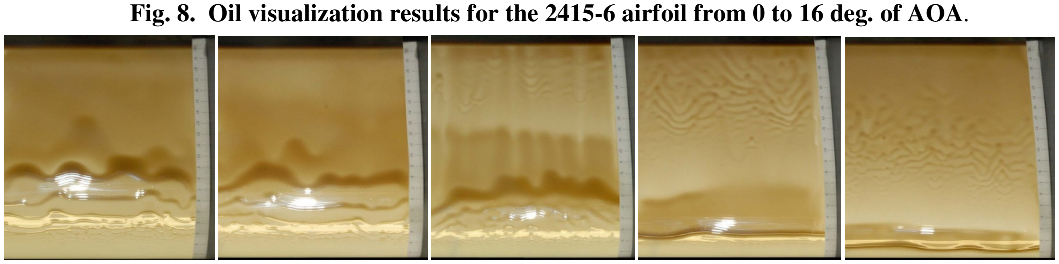
0° 4° 8° 12° 16°

Fig. 7. Oil visualization results for the 2415-5 airfoil from 0 to 16 deg. of AOA.



0° 4° 8° 12° 16°

Fig. 8. Oil visualization results for the 2415-6 airfoil from 0 to 16 deg. of AOA.



0° 4° 8° 12° 16°

Fig. 9. Oil visualization results for the NACA 2415 airfoil from 0 to 16 deg. of AOA.

It is possible to see, for instance in Fig. 8, for 0 degrees of AOA how the flow smoothly streaks the oil from the leading edge until the step where the separation starts. Beyond this point and inside the bubble, there is very little flow and the oil does not change. At reattachment, located approximately at 79% of the chord length which is quite unsteady and vigorous, the flow impinges on the surface and creates high shear stress that scours away the oil. It moves some oil upstream and some oil downstream as the downflow splashes onto the surface effectively defined by a very fine dividing line. The oil going downstream moves towards the trailing edge.

When increasing the AOA, two different behaviors can be distinguished. For airfoils 2415-3 and 2415-4, the rise of the AOA moved the reattachment point closer to the trailing edge. It is possible to observe this in Fig. 5 for 0 and 4 degrees of AOA, the reattachment is effective at around 50% for an AOA of 0 deg. then 58% for 4 deg. of AOA. A similar behavior is shown in Fig. 6 for 0 and 4 degrees of AOA

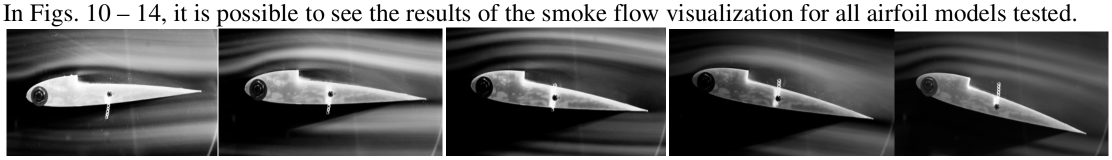
Whereas, in the case of 2415-5 and 2415-6 airfoils for 0 and 4 degrees of AOA, the reattachment occurred closer to the step (Figs. 7 and 8). The location of these reattachment points was at 76% and 70% of the chord length respectively.

Then for higher AOA (8 to 16 degrees), the determination of reattachment is not possible. It seems that the flow does not stick back to the airfoil for these values of AOA. For instance, Fig. 5 for 8 degrees of AOA shows a confusing result, since the separation starts at the step, there is very little flow which cannot streak the oil, however in this case, the oil downflows by the action of the gravity.

Finally for the last value of AOA (16 degrees), we noticed separation bubble phenomena on all airfoils tested which can be shown for instance in Fig. 6. The location and length of the separation bubble is approximately the same for all airfoil tested.

To sum up, for all airfoils, up to 12 degrees of AOA separation of flow occurs at the step. Reattachment can be seen up to 4 degrees of AOA and two different behaviors regarding the movement of its position along the chord exists. Then from 8 to 12 degrees photographs show that the flow does not reattach. Finally, for 16 degrees of AOA, separation bubble phenomenon appears and separation of flow occurs before the step.

In Figs. 10 – 14, it is possible to see the results of the smoke flow visualization for all airfoil models tested.



0° 4° 8° 12° 16°

Fig. 10. Smoke visualization results for the 2415-3 airfoil from 0 to 16 deg. of AOA.

0° 4° 8° 12° 16°

Fig. 11. Smoke visualization results for the 2415-4 airfoil from 0 to 16 deg. of AOA.

0° 4° 8° 12° 16°

Fig. 12. Smoke visualization results for the 2415-5 airfoil from 0 to 16 deg. of AOA.

0° 4° 8° 12° 16°

Fig. 13. Smoke visualization results for the 2415-6 airfoil from 0 to 16 deg. of AOA.

0° 4° 8° 12° 16°

Fig. 14. Smoke visualization results for the NACA 2415 airfoil from 0 to 16 deg. of AOA.

It is possible to see, for instance in Fig. 10 for 0 degrees of AOA the separation of the flow at the step because the smoke streamlines continue parallel to the shape of the airfoil before the step, detaching from the airfoil surface and giving place to a bubble which can be seen as a dark zone in the picture, however afterwards the smoke streamlines decline until they begin to be in contact with the surface of the airfoil, this is the reattachment point. On the other hand, at 16 degrees of AOA the flow never reattaches to the surface of the airfoil.

With smoke visualization method was possible to confirm the two different behaviors distinguished in the oil visualization experiment. For airfoils 2415-3 and 2415-4, the rise of the AOA moved the reattachment point closer to the trailing edge. It is possible to observe this in Figs. 10 and 11 for 0 and 4 degrees of AOA. For airfoils 2415-5 and 2415-6 for 0 and 4 degrees of AOA, the reattachment occurred closer to the step (Figs. 7 and 8).

It is also possible to observe the separation point just before the step which is presented in all airfoils tested for an AOA of 16 degrees, for instance in Fig. 11 it is possible to observe in the 2415-4 airfoil that at approximately 35% of the chord, the smoke tracks are not anymore parallel to the airfoil.
Then, for AOA of 8 deg. and 12 deg., it is difficult to determine with certainty whether the flow reattaches or not. The streamlines seem quite parallel to the airfoil, but reattachment cannot be clearly noticed.
Based on the previously observed, smoke visualization demonstrated to be a very good method to observe the streamlines of the flow past airfoils. It confirmed the results of oil visualization. However, the certainty about the estimation of the reattachment point at the testing velocity (7.7 m/s) was not very high.
The following table summarizes the obtained results combining both visualization methods (all the values are in percentages of the chord)*:

Table 1. Flow visualization results summary.

AOA (deg.) / Airfoil	0		4		8		12		16	
	SP	RP	SP	RP	SP	RP	SP	RP	SP	RP
2415-3	step	50	step	58	step	no	step	no	step	no
2415-4	step	63	step	68	step	no	step	no	34	no
2415-5	step	76	step	70	step	no	step	no	38	no
2415-6	step	79	step	71	step	no	step	no	39	no
NACA2415	95	no	93	no	81	no	60	no	35	no

****SP*:** Separation Point, ***RP*:** Reattachment Point.

CONCLUSION

The main scope in this investigation was the visualization of the flow field past the airfoils, which was achieved after an exhaustive study of experimental procedures in order to adapt them to the particular case. It is possible to say that the visualization of flow was possible thanks to the complementation of oil and smoke visualization techniques which made possible to obtain the flow field along the airfoil by means of streamlines and also the points of separation and reattachment for all airfoils tested at different angles of attack, all of these results, which are in good agreement with numerical ones from references allowed to observe and comprehend the phenomena of separation of flow and its influence on the performance of the models tested.

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