Evaluating airfoil behaviour such as laminar separation bubbles with visualization and IR thermography methods

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Abstract. A study of airfoil behaviour is undertaken using two independent non-intrusive measurement techniques, surface oil flow visualization (SOFV) and infrared thermography (IT) to quantitatively determine flow parameters such as separation and reattachment points on the airfoil. Several airfoil heating methods are described and several airfoil materials are evaluated. Results are presented here for constant Re = 4.7 × 10^4, with the angle of attack varied from 0° to 13°. Innovative post processing methods are used for the IR temperature data to reveal important details of the flow. All methods provide comparable results and allow further understanding of these characteristics and the extension to large scale, dynamic and unsteady flow situations.

1. Introduction
Predictable high performance is important for wind turbine blades and it depends on the blade design, particularly for small wind turbines that normally operate without control features and are frequently installed in poor wind resource locations. Further improvement in blade design would be achievable if there was data to investigate flow behaviour with different airfoils and flow conditions, especially in dynamic flows that are not fully understood. Here flow behaviour over an SD7037 airfoil at low Reynolds number (Re) is investigated using surface oil flow visualization (SOFV) and infrared thermography (IT). In low Re flows under some conditions, transition occurs in the presence of a laminar separation bubble (LSB) where the flow separates from the surface and if the energy of flow in the transition phase is high enough, the flow reattaches to the surface creating the shape of a bubble on the surface (LSB).

In the past, many experimental methods and visualization techniques have been used to facilitate the investigation of the boundary layer flow such as pressure tabs, hot films, pressure sensitive paints, particle image velocimetry, SOFV and IT [1–6]. Most of these methods are more challenging when dealing with small or complex model sizes, and low Re flows [7]. For example, placing pressure tabs in complex or small geometries would not be practical. With advancing technology in infrared cameras, IT provides high resolution visualized data. Heat flux between the surface and flow is different for laminar and turbulent flows. As mentioned, in low Re flows, LSB forms due to the laminar flow separation and turbulent flow reattachment therefore detecting these areas utilizing IT allows the opportunity of detecting LSB characteristics on the surface of the airfoil [8]. A useful study related to separation detection using IT was reported...
where the flow about a cylinder was studied and also investigated the separated flow area in deep stall condition over an airfoil using thermographic imaging, and temperature fluctuation to detect the separated flow. Simon et al. [10] studied the laminar-turbulent transition on a flat plate using several heating methods and stated that overall internal heating was more suitable than others. As expected, the heating method and post-processing techniques are more crucial in unsteady cases where the temperature changes due to irregular unsteady structures. In this regard, in this study different heating methods and post-processing techniques were investigated in the steady case to evaluate the possibility and accuracy of using them for unsteady cases of complex flow about wind turbines in subsequent experiments.

2. Experimental setup
All experiments have been performed in a closed circuit subsonic wind tunnel belonging to the wind energy group at the University of Waterloo with turbulence intensity less than 1%. The test section dimension is 152.4mm × 152.4mm. The airfoil model is an SD7037 airfoil with 25.7mm chord spanning the entire tunnel width. For these tests, three airfoil models were used, one precision machined from aluminum and the other two 3D printed from polycarbonate material with enhanced resolution. Although using a small model is a very challenging task when working in the vicinity of the surface using thermography it does allow a high resolution of the local flow. In the presented results, tests were completed for constant Re = 4.7 × 10^4, with the angle of attack changed from 0° to 13°. In following subsections, details of the experiments are presented.

2.1. Surface Oil Flow Visualization (SOFV)
In surface oil flow visualization, the suction surface of the aluminum airfoil was coated with a pigmented oil mixture. Many different mixtures were evaluated during the development of this study. The final oil mixture used in this study contained mineral oil, titanium dioxide and a very small amount of linseed oil and was painted on the airfoil. In this study after 5 to 10 minutes of running the wind tunnel, the oil mixture had dried and the model was taken out for photographs with a high resolution digital camera [3].

2.2. Infrared Thermography
The IR camera used in the infrared thermography experiments is a T650sc FLIR camera with an array of 640 × 480 pixels while the thermal sensitivity is < 20mK@ +30°C. Minimum focus distance is 0.15m, and the image acquisition frequency is 30Hz at the full array. The detector type is Focal Plane Array (FPA), uncooled micro bolometer with a spectral range between 7.5 and 14µm. Figure 1 shows the experimental setup with the acrylic test section although in final results clear acrylic walls were replaced by less reflective walls to prevent inappropriate reflections.

In these experiments, airfoil heating was accomplished by using three different methods including two active and one passive approach. First, Joule heating was implemented with a resistive heating wire mesh on the pressure side of the aluminum airfoil. For the mesh, the heating wire is bent in a zig-zag formation to heat the airfoil evenly along its span and chord and to have the least amount of effect of the flow around the airfoil, a thin heating wire with a diameter of 0.25 mm is chosen. A thin layer of Kapton tape is placed between the airfoil and the heating wire due to the conductivity of the airfoil. Another layer of Kapton tape is placed on top of the heating wire mesh to prevent direct thermal contact with airflow while keeping it attached to the airfoil’s surface. Although using regular heating pads are more common and available, size constraints prevented their use. Therefore, design and custom fabrication of the tools to heat the airfoil uniformly was necessary.
Second, the suction side of the 3D printed airfoil was uniformly coated with electrically conductive paint. This method could eliminate the errors caused by the non-uniformity of heating distribution on the surface. Also, there are no considerable temperature changes in flow in the vicinity of the airfoil surface because there is no need to heat up the entire airfoil, just the suction side. Figure 2 shows prepared airfoils for the first and second methods.

In the third method an air heater was used to heat the airfoil surface (both aluminum and 3D printed models) to the desired temperature then the wind tunnel was turned on, and temperature changes were recorded. After a few seconds, constant behaviour was seen for awhile before the airfoil cooled down completely. The printed airfoil was a better option than aluminum because of its heat transfer characteristics. However, post-processing of data from passive methods is more challenging than active methods and data should be observed precisely to find the desired time and extract the proper data.

Figure 1: Schematic of wind tunnel and IT thermal camera experimental setup.

Figure 2: Resistive heating wire mesh on the pressure side of the aluminium airfoil (top) the suction side of the 3D printed airfoil coated with electrically conductive black paint (bottom)

Reflection effects and small temperature ranges are a significant matter in low Re flows with the existence of LSB, because of a slight temperature difference after the turbulent reattachment point that can be due to the irregular movement of existing small vortices or possibly a reflection error. Therefore solving reflection problems is one of the priorities in thermography experiments.

3. Results
In this section, the results of thermography are presented in comparison with SOFV. Figures 3 and 4 present a set of results of the third heating method, utilizing the air heater, a passive heating technique on the 3D printed airfoil for a range of angles of attack (AOA) from 4° to 11°. For these results averages and fluctuations of temperature were calculated with 10 individual images in sequence while the standard deviation determined from a spanwise average of 100 pixels from each of the individual images. In figure 3, two AOA a) 4°, b) 7° and in figure 4, two AOA a) 10°, and b) 11° are presented. For all figures, the flow is from left to right (from LE to TE of the airfoil) as indicated at the base of each plot. For each AOA presented the top colour figure shows an IR image indicating the surface temperature variation from leading edge (LE) on the left side to the trailing edge (TE) on the right side that is scaled by chord length. The temperature legend presented above those figures indicate a sufficient range of temperature difference in using this method that is about 2°C. The lower plot for each AOA shows the standard deviation of the temperature along the chord from the LE to the TE with
the image of surface oil flow visualization (SOFV) results in the background of the plot obtained at the same AOA and Re. Text labels indicate where the flow separates and reattaches on the airfoil if appropriate. There is a significant amount of information revealed in the combined figure that will now be discussed. Firstly, it is evident that there is a close correspondence between the SOFV and the IR images regarding the separation and reattachment regions for all cases shown increasing confidence in the IR methodology. As can be seen, at separation and reattachment of the flow the temperature fluctuation as shown by the standard deviation increases considerably and that may be used to determine these points. After reattachment, the temperature fluctuations are much lower and may also be used to locate the reattachment point. Within the laminar separation bubble that forms there is a decrease in fluctuation in the core of the bubble. Another noticeable point on these plots is the change of the slope of the temperature standard deviation at the reattachment points which is correctly matched with the SOFV results. Although the results presented in these figures are for Re of 47,000 there is no reason that the techniques and results would not be applicable to a much larger surface or larger Re values such as full scale turbines. This is especially true in the passive heating technique presented here in that a small temperature difference could occur in a natural outdoor setting.

Figure 3: Thermographic flow visualization with air heater (top image of each angle), and Surface oil flow visualization in the background of temperature fluctuation graph (bottom image of each angle) for two AOA: a) $4^\circ$, b) $7^\circ$ at $Re=47,000$ horizontal axis $x/c$. 

(a) $4^\circ$  
(b) $7^\circ$
Figure 4: Thermographic flow visualization with air heater (top image of each angle), and Surface oil flow visualization in the background of temperature fluctuation graph (bottom image of each angle) for two AOA: a) $10^\circ$, and b) $11^\circ$ at $Re=47,000$ horizontal axis $x/c$.

Figure 5 presents plots of the temperature gradient along the non-dimensional chord of the airfoil with surface oil flow visualization SOFV results in the background for AOA: a) $4^\circ$, b) $7^\circ$, c) $10^\circ$, and d) $11^\circ$. In all the AOA, no matter if the LSB is long or short in length (the difference between separation and reattachment locations), there is a peak in separation and reattachment points and the temperature gradient decreases along the bubble. Looking at this figure it indicates the difference between the laminar (pre-LSB) and turbulent flow (post-LSB). The temperature gradient changes linearly in the laminar flow region before the separation points, but after reattachment, the temperature gradient is almost constant. This is clearer at higher angles where the turbulent flow after the LSB has higher fluctuation than lower angles. Therefore, either using standard deviation or gradient of temperature as a post-processing technique, the type of flow on the surface of the airfoil would be determinable through thermography results utilizing an air heater.
The data post-processing technique of using temperature fluctuation (standard deviation of temperature in time) has also been used to extract data from raw images of thermographic flow visualization from the second heating method, electrically conductive paint on the 3D printed airfoil. Sample results can be seen on the left side of Figure 6. These results are calculated from 100 individual sequential images. Although separation and reattachment lines are visible in the raw data, keeping uniformity of the paint on the airfoil surface is a challenging task and small non-uniformity causes a large difference especially at lower AOA. Also, it should be mentioned that this technique requires a constant heating source during the experiment, to keep the surface temperature in a reasonable range to provide usable results and not influence the flow. Since this heating method provides uniform data along the span, another post-processing technique was used so that in each chord position, temperature data are multiplied along the span (for the length of 100 pixels). This technique amplifies the temperature changes along the chord and the graph makes the separation and reattachment points reasonably clear. Sample results are presented on the right side of Figure 6.

Figure 7 presents the data using the resistive heating wire attached to the pressure side of the aluminum airfoil, the first heating method, for two AOA: a) 1°, b) 7°. In collecting the data for these results, the source of heating was turned off during the experiment to avoid excessive
Figure 6: Surface oil flow visualization and normalized multiplied temperature data along the span of the airfoil for three AOA (left side) a) 4°, c) 10°, and e) 13°) and surface oil flow visualization and standard deviation of temperature for three AOA (right side) b) 4°, d) 10°, and f) 13°) at Re = 47,000 (results of Thermographic flow visualization with electrically conductive paint, second method)
temperature. These data are the result of averaging the data over time for about 50 frames and 100 pixels span-wise correspondingly. In both sample angles that are presented in this figure, a sudden jump in temperature shows the separation and reattachment points. At $7^\circ$ the flow structures are clear from both graphs of the average of temperature and surface oil flow visualization image. As can be seen at $1^\circ$, the separation point is a bit uncertain. In this method, the wire did not cover the whole pressure side of the airfoil and part of LE and TE of the airfoil was left with less heating coverage that may have caused less accurate data regarding the change of the angle of attack compared to the two other methods. Also from thermographic flow visualization graphs in this figure, it is clear that the range of temperature difference in using this method is less than $1^\circ$C which may increase the error.

![Figure 7: Thermographic flow visualization of first heating method (resistant heating wire method), surface oil flow visualization and the average of temperature over spanwise direction, a) $1^\circ$, b) $7^\circ$ at Re= 47,000](image)

Figures 8 and 9 show the measured location of the separation point ($x/c$) and reattachment point for both the SOFV and IT (resistive heating wire method) for varying AOA. Each data point represents 600 chordwise measurements for every one of the 200 IR images analysed. The linear relation found for both separation and reattachment is expected and has also been found using different techniques. The measured differences between separation and reattachment for different AOA predict that the bubble size decreases and moves toward the leading edge as AOA increases. In general, both methods show close agreement although the slope of the separation measured with IT is different than the SOFV. It could be due to the following reasons; first, the results for this graphs are obtained from preliminary IT tests that acquired while transparent wind tunnel section walls were used. Using transparent walls increase the errors due to the
reflection effects on the airfoil surface. Second, effects of the oil visualization materials on the airfoil surface.

Figure 8: Measured separation location for SOFV and IT methods.

Figure 9: Measured reattachment location for SOFV and IT methods.

4. Conclusion
The goal of this research was a study of low Re flow behavior over a SD7037 airfoil in steady conditions using SOFV and IT. Both approaches provided a clear picture of the surface structures present on the airfoil. Numerous approaches were utilized to create a temperature difference on the airfoil and obtain IR images for this study. Techniques for post-processing the IR temperature data both temporally and spatially revealed several innovative approaches that reveal important details of the flow. Airfoil performance depends not only on the LSB characteristics (height and length) but also flow characteristics at transition and reattachment points. Because in unsteady motion the flow behavior changes dynamically therefore evaluating the entire airfoil allows the opportunity to obtain a complete understanding of the LSB effects on airfoil performance. While results among the techniques vary somewhat the only technique that has potential application to larger scale wind turbine blades would be the air heating approach where a small temperature difference as could be obtained through solar radiation may be enough to determine the performance of the airfoil under dynamic conditions. This will be a focus of a future study.

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