RMIT UNIVERSITY

AERO2358 Computational and High-speed Aerodynamics

Laboratory Assignment: IR Thermography

Group 10

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Due on the 9$^{th\ of}$ April 2023 at 11:59PM

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CHAPTER 1: INTRODUCTION

Aerodynamics is extremely important in fluid-related instances such as in the field of aviation for example, flow over an air foil and flow through a turbine engine. As shown in ***Figure 1***, transition is the area where the fluid changes from laminar to turbulent flow. Clearly, laminar flow has a smooth and regular streamline, whereas turbulent flow has a random and uneven streamline. This emphasises the importance of predicting transition points because when transition happens, skin friction and heat transfer rate increase significantly, potentially increasing drag and aggravating aerodynamic heating [1].

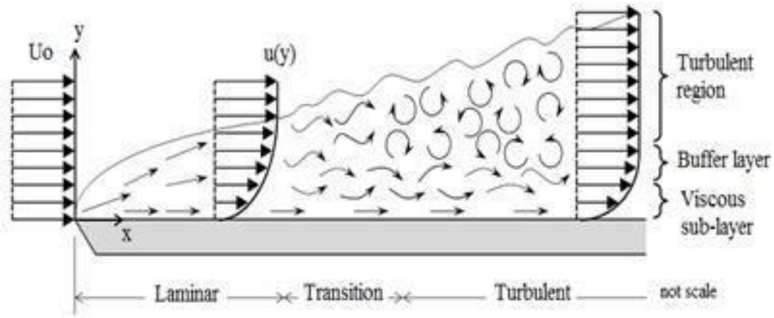

Figure 1: Flow behaviour over a flat plate [2]

The receptivity of external disruptions such as roughness and noise, as well as freestream turbulence levels, pressure gradients, Mach number, and Reynolds number, all influence transition layer [3]. Predicting when and where the transition will occur is difficult due to the complexity of the flow, which is still not completely understood till today.

Historically, hot wire anemometers were used to forecast the transition point. The most important characteristics of using a hot wire anemometer (see ***Figure 2***) in the decades are near constant sensitivity during test time and low noise outputs, to name a few [4]. The difference in temperature between laminar and turbulent flows identifies the transition point. In other terms, heat transmission from an electrically heated surface is proportional to the velocity of the fluid passing over the surface [5].

Figure 2: Hot wire anemometer [6]

There are two types of hot wire anemometers: constant current and constant temperature. With the constant current technique, a fixed current travel to the wire, heating the flow and changing its temperature. In the constant temperature method, however, the temperature of the wire must be maintained constant as flow passes over the device by increasing or reducing the current passing through the wire [7]. This approach, however, is intrusive.

Most fluid flow prediction is now done using Infrared (IR) thermography because it does not require contact with the equipment being monitored (i.e., a form of non-destructive testing) and has a fast turnaround. As shown in ***Figure 3***, this device measures the variation of heat (thermal radiation) passing through the component, which is directly linked to temperature and is analysed using an infrared camera [8]. Infrared camera is required because the wavelength is not visible to the naked eye as illustrated in ***Figure 4***. After capturing the required data, the temperature measurement will then be analysed on an infrared image such as the one in ***Figure 5***.

Figure 3: Infrared camera at RMIT wind tunnel lab

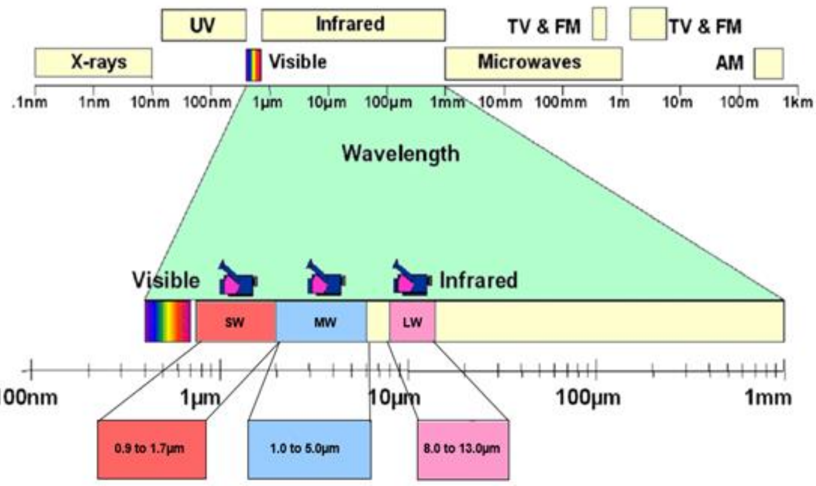

Figure 4: Infrared spectrum [9]

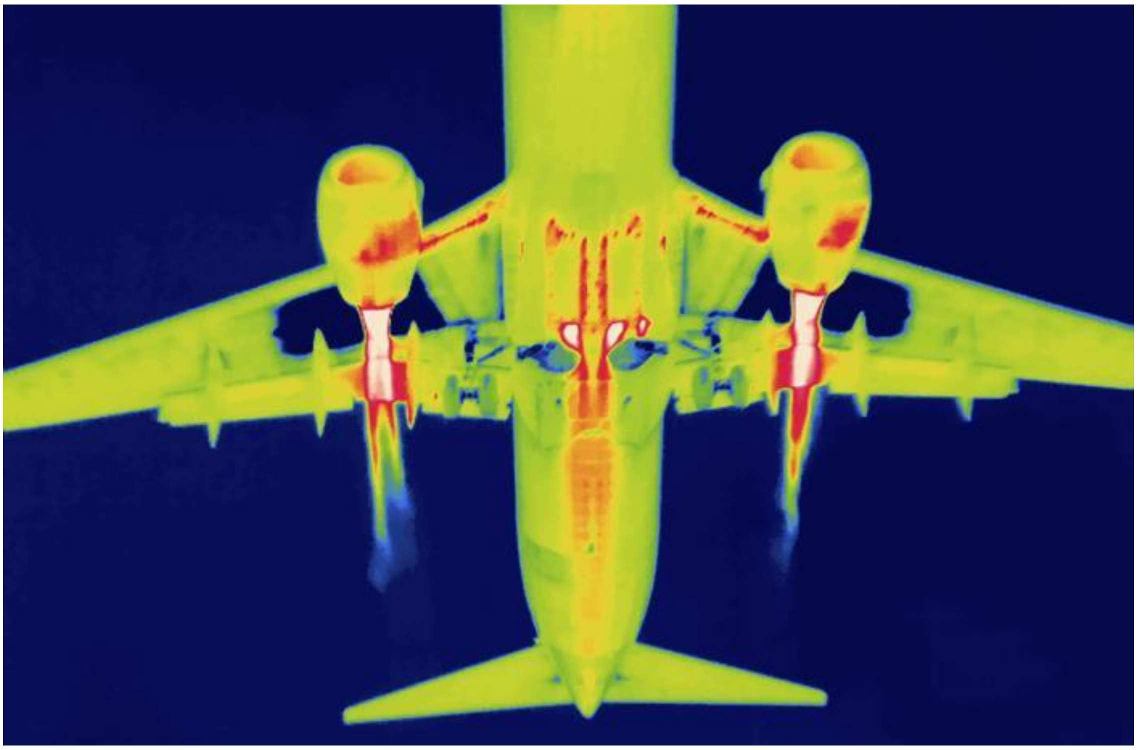

Figure 5: Example of thermal image showing heat dissipation on an aircraft [10]

In this laboratory report, a NACA0021 air foil is being tested in a wind tunnel located in Bundoora. The component is subjected to fluid flow at different Reynolds number, and an infrared camera is used to record the heat generated by the flow. Images can be manipulated in MATLAB to determine the transition point from laminar to turbulent, which is the objective of this lab. Following that, a computational analysis will be performed using XFoil to compare the findings. Finally, a summary of the findings, including the sources of errors, will be provided.

CHAPTER 2: APPARATUS

The IR thermography laboratory experiment was conducted at Bundoora East campus in front of the PC-9 aircraft building 252. The laboratory experiment was attended by all group members of Group 10. The laboratory technician gave us a brief introduction and safety precautions to be taken before proceeding towards the experiment. ***Figure 6*** shows the wind tunnel experiment configuration and Figure 7 shows the schematic diagram of the laboratory experiment.

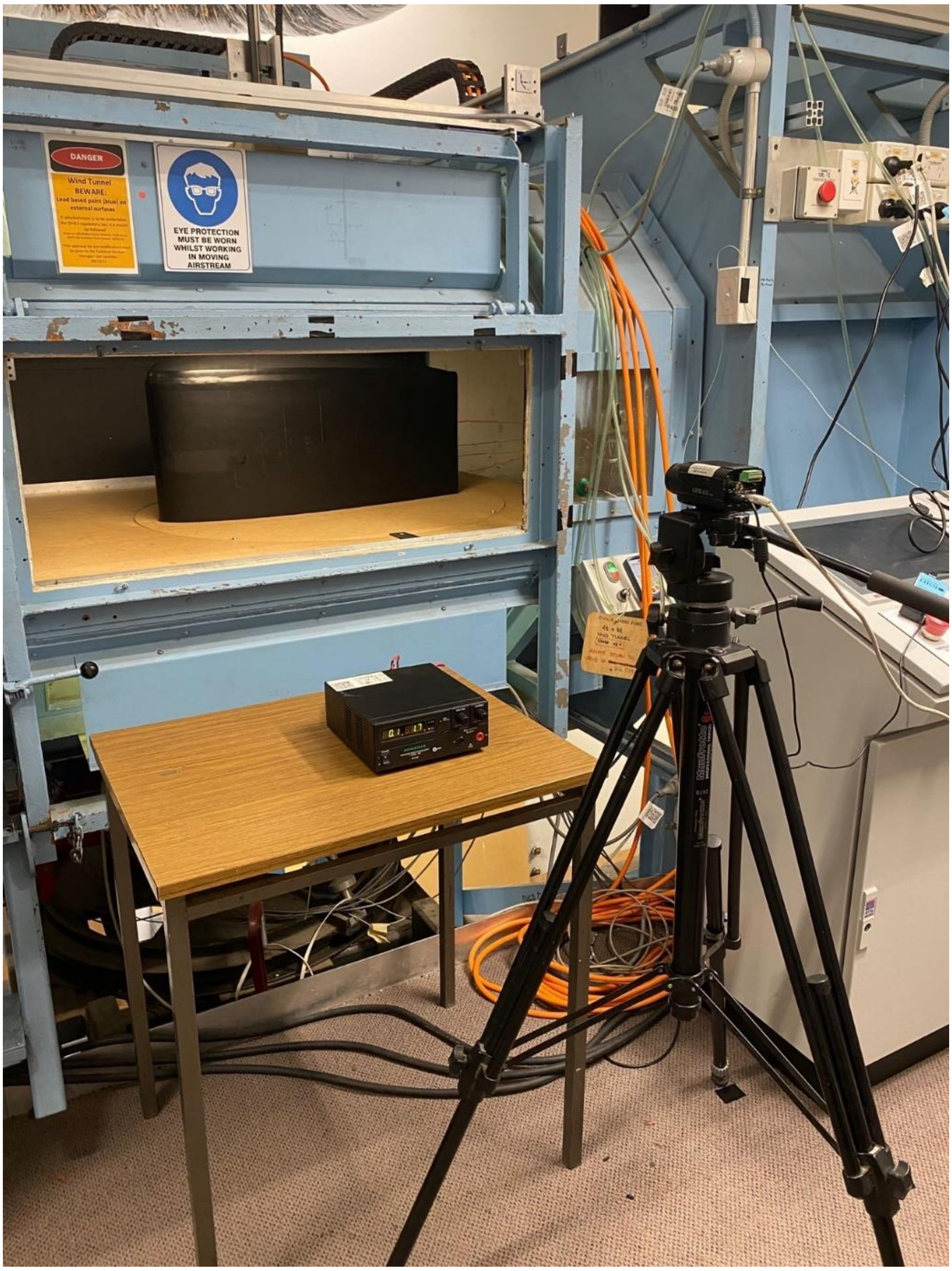

Figure 6: Wind tunnel experiment configuration

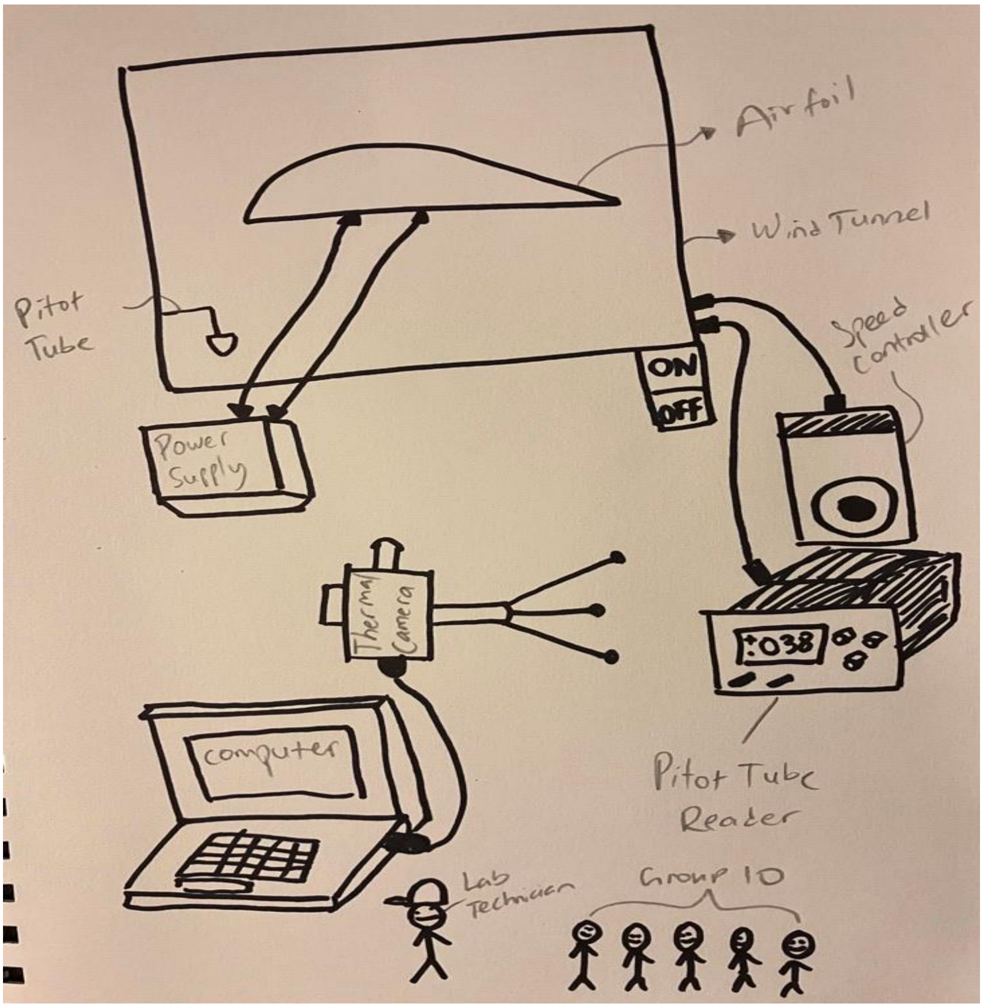

Figure 7: Schematic diagram of the laboratory experiment

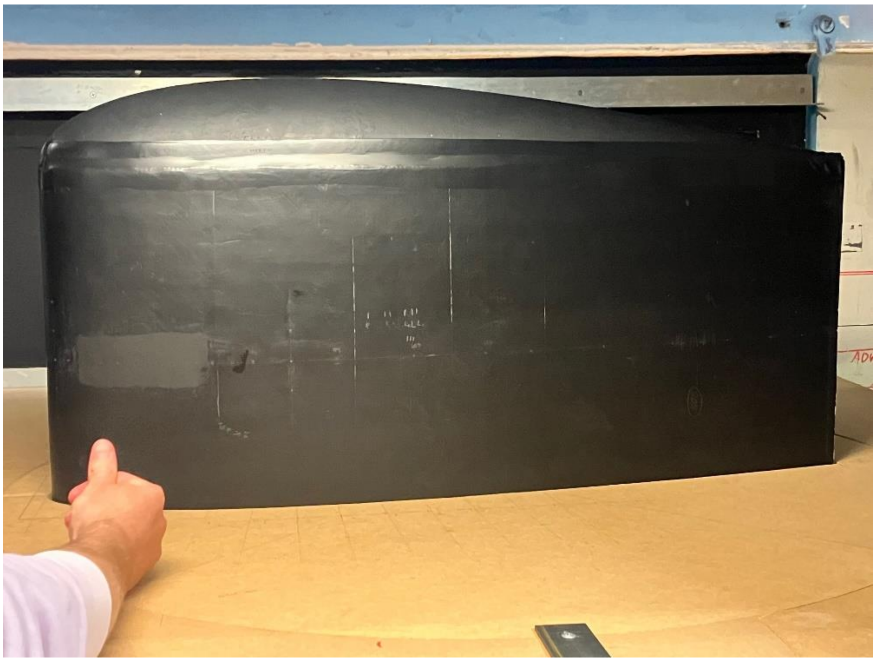

Figure 8: Air foil

Figure 9: Thermal camera with its read-out on the second display

Figure 10: Power supply

Figure 11: Pitot tube reader and speed controller

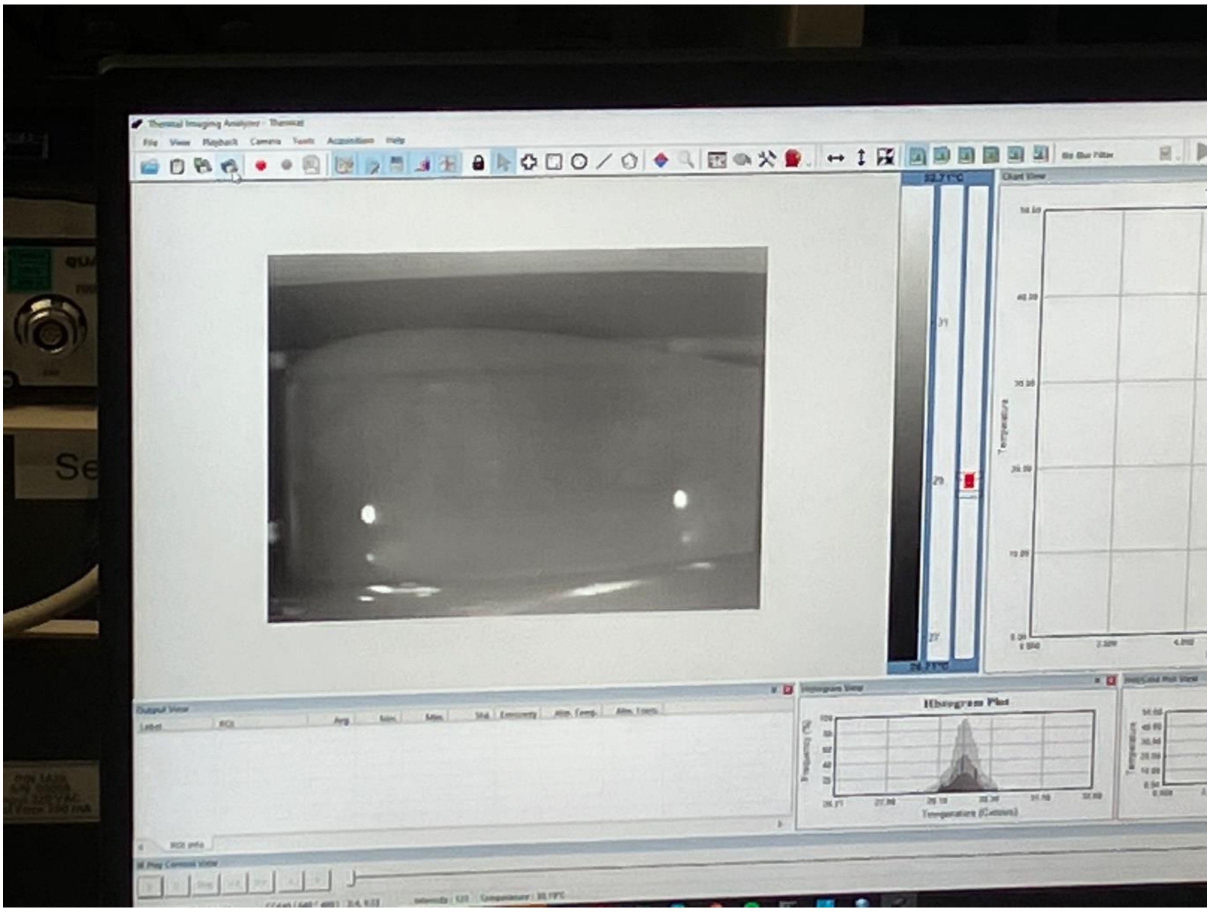

Figure 12: Read-out from the computer of the thermal imaging camera

The heating element is connected from the power supply as in ***Figure 10*** to the coils of the platform of the air foil as in Figure 8 to heat the surface uniformly with 30 Amps of current. The camera is stated as a COX CG-640 which is a long wave infrared (LWIR) camera as shown in ***Figure 9*** and Figure 13 with the following parameters:

- 640 x 480 pixels
- Spectral range of 8 – 14 micrometres
- Surface temperatures have an accuracy of plus or minus 2% of the reading.

Figure 13: COX CG thermal camera series [11]

The direction of the wind of the wind tunnel travels from left to right, and inside the wind tunnel is the air foil model which represents the sail of a submarine but is shaped like an air foil which is mounted vertically and is placed at zero angle of attack. The model of the air foil is a NACA0021 with its chord measuring at 0.865m and its span measuring at 0.4m. It is also vital that the model of the air foil is made of poor conductor of heat for the purposes of local heating and local cooling via the air in the wind tunnel. This is to prevent blurred temperature differences which results in poor images from the thermal camera. ***Figure 12*** shows the thermal imaging from the camera on the computer.

Inside the wind tunnel, a pitot tube is placed to measure the velocity of the wind tunnel. The read-out from the pitot tube as shown in ***Figure 11*** is dynamic pressure in pascals. The experiment is conducted with four different speeds or Reynold's number by changing the speed controller which is then the results are documented from the computer.

CHAPTER 3: RESULTS

3.1 Curves for Laminar and Turbulent Boundary Layer Temperature Profiles

To determine the critical Reynolds number for each of the experimental setups the data first had to be processed using MATLAB so that a clear boundary could be defined between Laminar, Transitional and Turbulent regions. As the experimental data was collected from a 3D Aerofoil post-processing was required to remove any deviations due to 3D effects. Notably, the effects from the edges of the aerofoil and where a pressure sensor had been patched. After completing this filtering an average could be taken across the span of the aerofoil and a temperature profile could be plotted. These profiles clearly show the various regions and allow for the calculation of the transition point. MATLAB code for these plots is attached in the appendix.

3.1.1 Temperature Profile 1

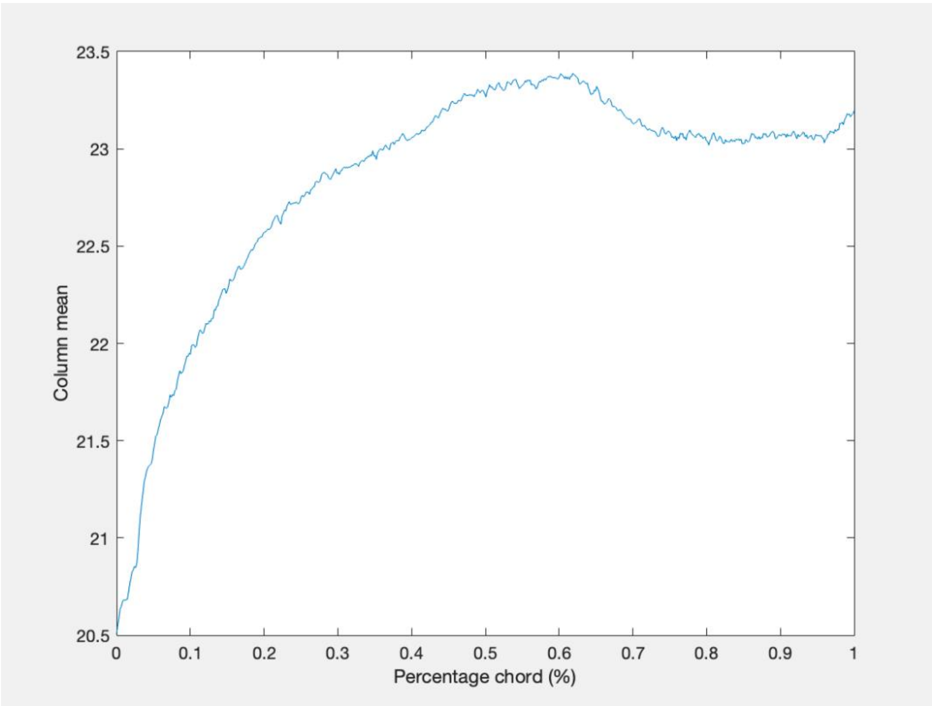

Figure 14: Temperature Profile for Aerofoil with Reynolds Number: 134237. Column Mean in units of Celsius.

3.1.2 Temperature Profile 2

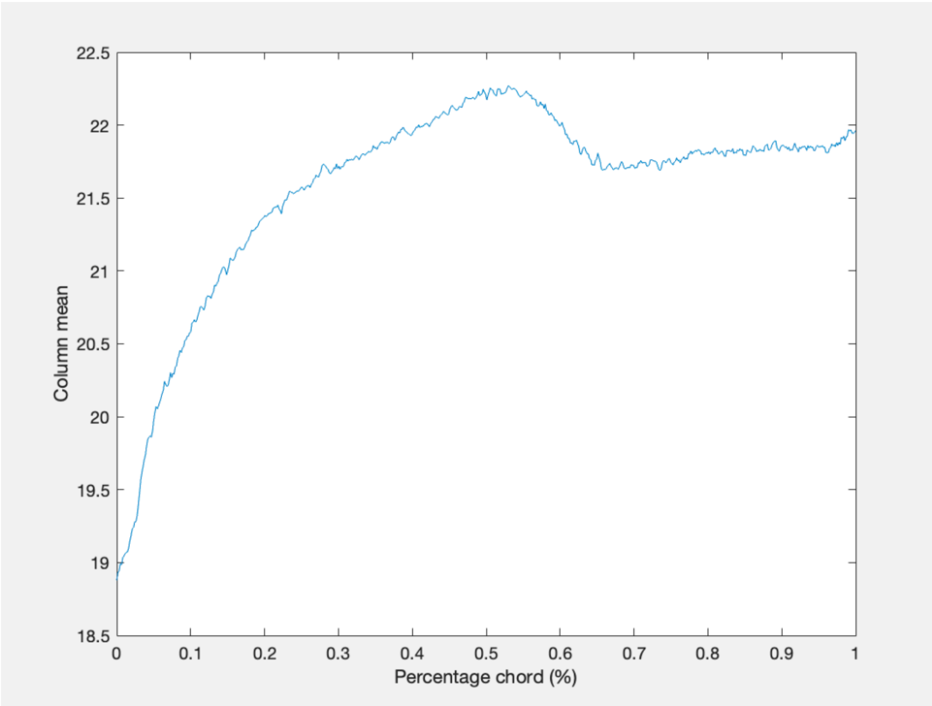

Figure 15: Temperature Profile for Aerofoil with Reynolds Number: 228497. Column Mean in units of Celsius.

3.1.3 Temperature Profile 3

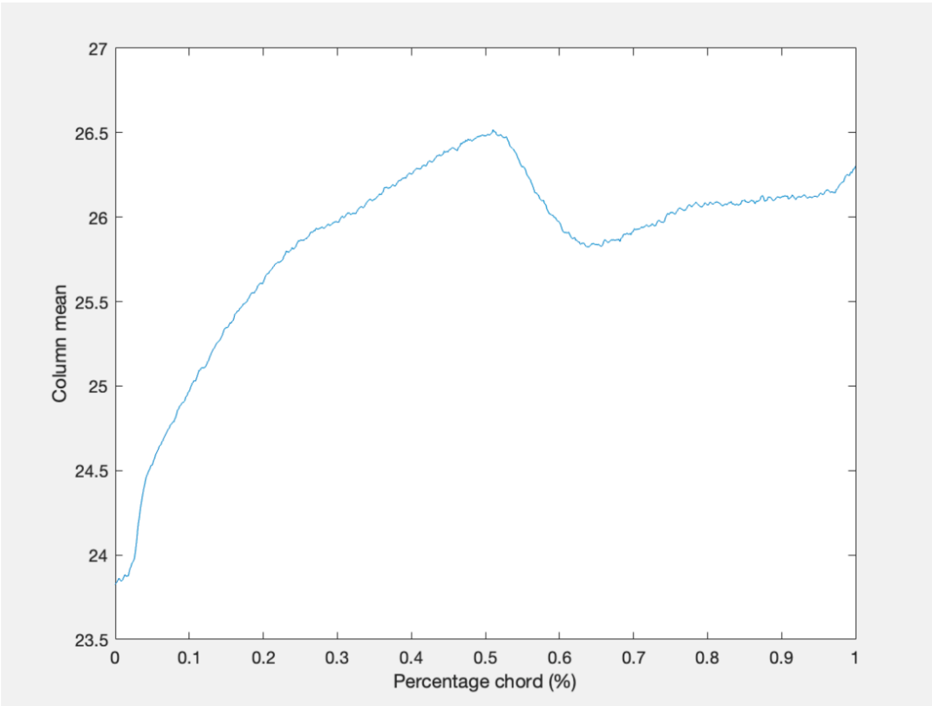

Figure 16: Temperature Profile for Aerofoil with Reynolds Number: 315731. Column Mean in units of Celsius.

3.1.4 Temperature Profile 4

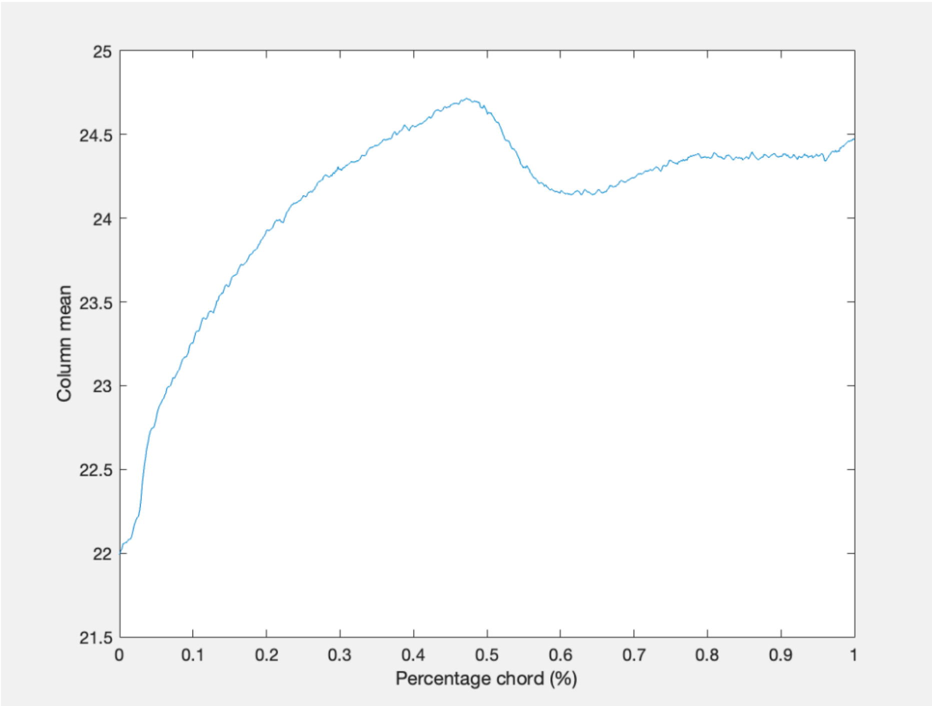

Figure 17: Temperature Profile for Aerofoil with Reynolds Number: 408267. Column Mean in units of Celsius.

3.2 Repeatability of Data

An Experiment was conducted to illustrate the aerodynamic performance of NACA0021 air foil in a wind tunnel, air thermography was used to measure the heat generated by the flow at Reynolds number of 134237, 228497, 315731 and 408267.

The following steps were taken to ensure repeatability of the data:

- Experimental Setup:

As explain on section 2. The wind tunnel used was closed circuit. However, the door was open which it may affect the results. The NACA0021 air foil with a chord of 0.865 meters and a span of 0.4 meters was mounted vertically at an angle of 0 degrees, and the test area was maintained at a constant temperature of 21.8°C.

- Instrumentation:

COX CG-640 long wave infrared (LWIR)

Camera was used to record the heat generated by the flow on the surface of the airfoil. The ca mera had a resolution of 640 × 480 pixels. Spectral range 8-14 µm. Surface temperatures.

Multiple runs: four runs were conducted under the same condition to collect sufficient data *Table 1*. The air foil was allowed to reach steady-state condition before and after each run. Furthermore, during the experiment, both velocity and Reynolds number were initially unknown.

To determine the velocity for each run, the velocity equation was applied. By using Equation 1. The velocity was successfully calculated for each run. Once the velocity was determinate, the Reynolds number for each run then found. The obtained results for the Reynolds number can be observed in Equation 2.

It should be noted that Reynolds number is an important parameter in fluid dynamics, as it is characterizing the type of flow, whether is laminar or turbulent. Therefore, the determination of Reynolds number in this lab exercise was crucial for the accurate analysis and understanding of the fluid behaviour.

$$V = \sqrt{\frac{2 * q}{\rho}}$$

Equation 1,Velocity Equation

$$R_e = \frac{\rho * V * l}{\mu}$$

Equation 2, Reynolds Number.

Table 1: Four Different runs of NACA0021 Airfoil at different Reynold Number

Times Run	Temperature	Reynolds Number	Dynamic Pressure	Velocity
1	21.8	134237.6738	15.6	5.105405
2	21.8	228497.4385	45.2	8.690347
3	21.8	315731.2118	86.3	12.00807
4	21.8	408267.9462	144.3	15.52748

Where temperature is in C° degrees, dynamic pressure is in Pa, and velocity is in m/s.

Statistical Analysis: The recorded temperatures were analyzed using statistical software, and the mean and standard deviation of the temperature values were calculated.

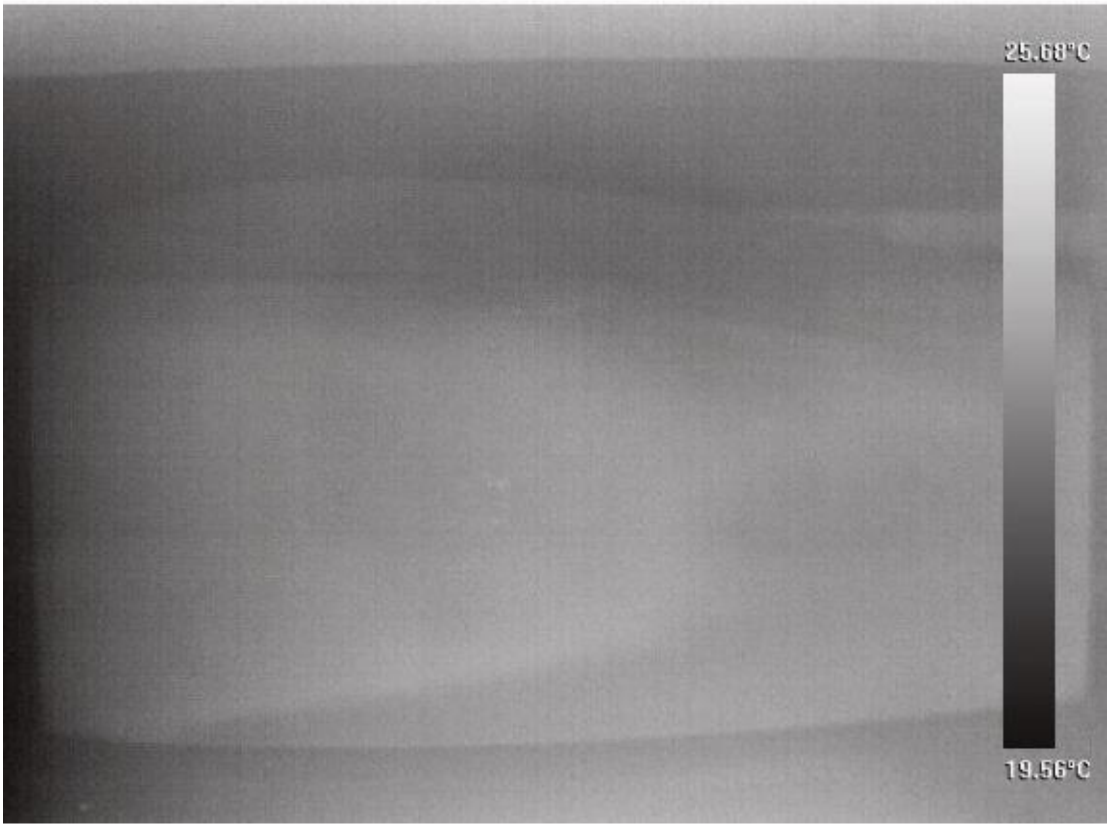

Figure 18: NACA0021 at pressure of 15.6Pa

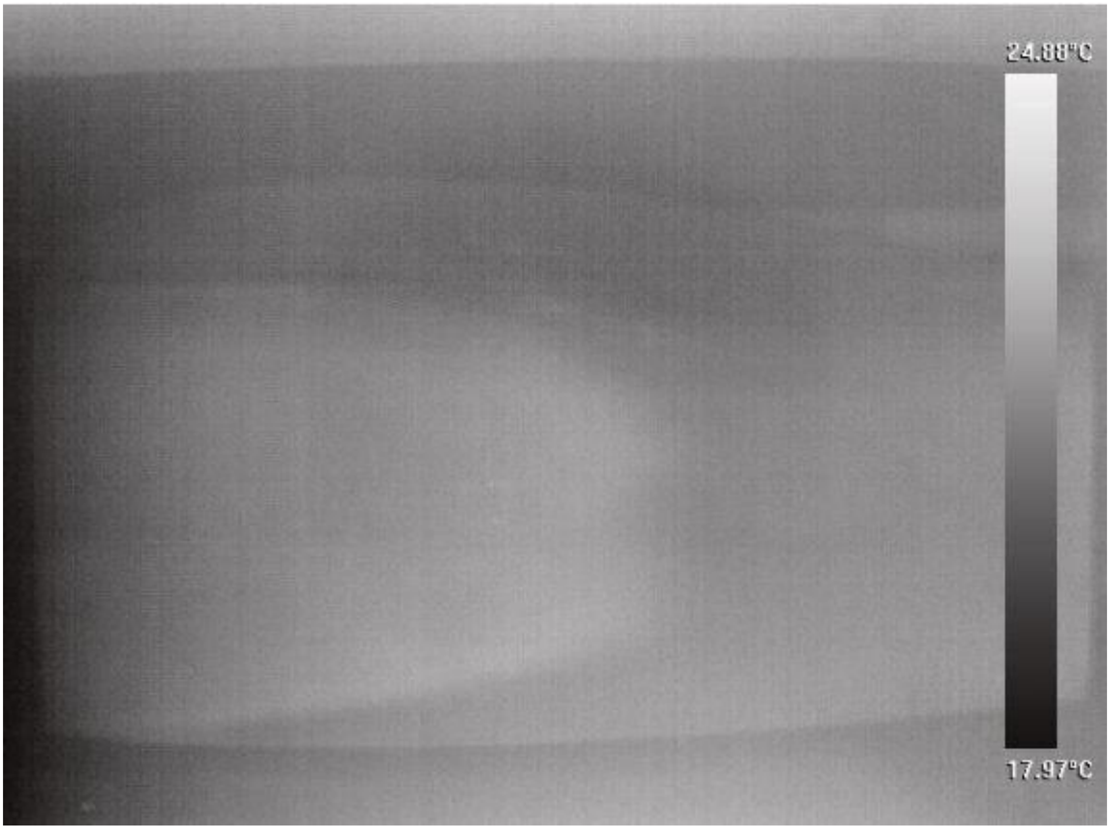

Figure 19: NACA0021 at pressure of 45.2Pa

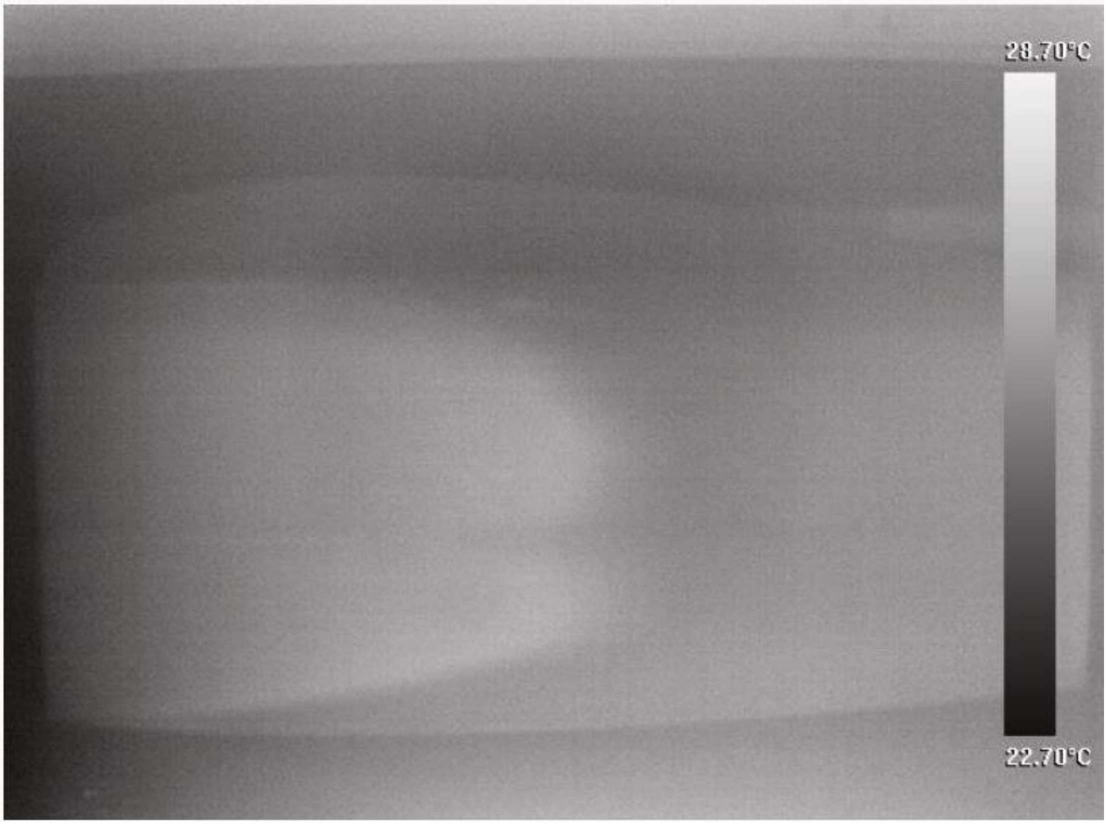

Figure 20: NACA0021 at pressure of 86.3Pa

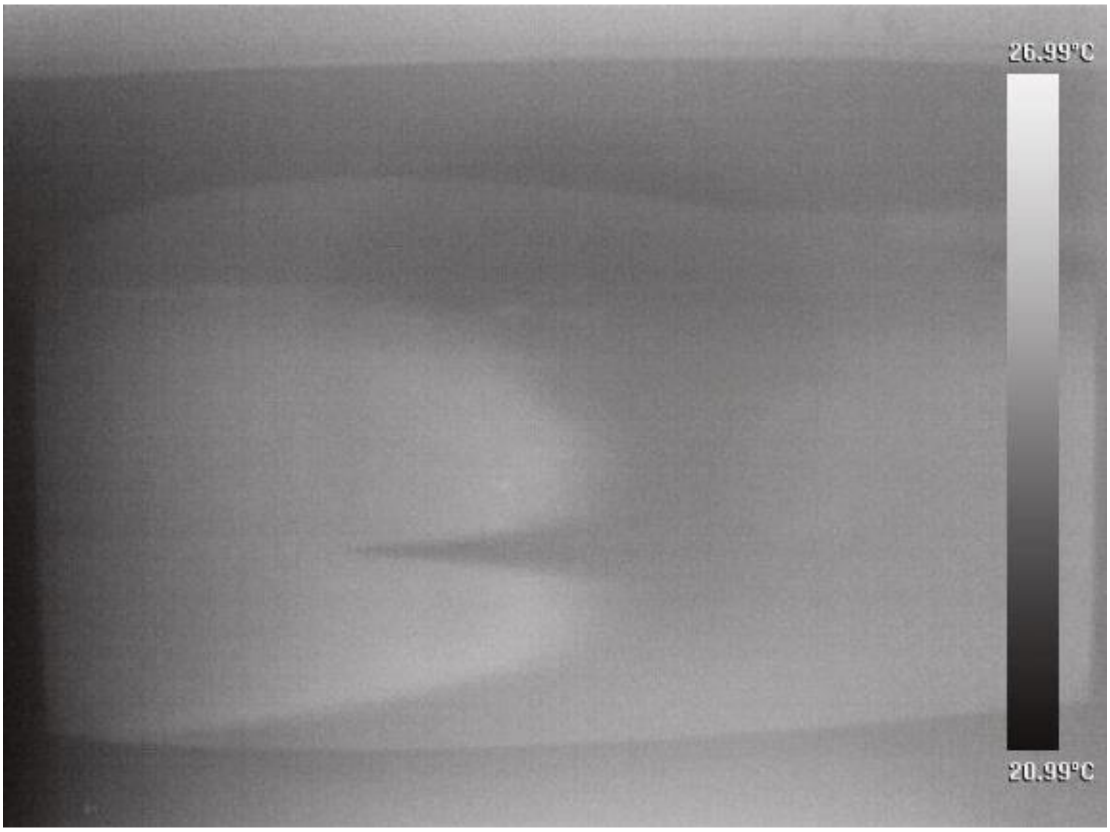

Figure 21: NACA0021 at pressure of 144.3 Pa

Table 2: Minimum and Maximum temperatures recorded for each run.

Dynamic Pressure	MIN °C	MAX °C
15.6 Pa	20.99	26.99
45.2 Pa	22.70	28.70
86.3 Pa	17.97	24.88
144.3 Pa	19.56	25.68

The temperature distribution over the airfoil surface was found to be not consistent across all runs, indicating different captures of temperatures at different velocity. The study demonstrated that effectiveness of air thermography in measuring flow patterns over the airfoil NACA0021. Future work could involve investigating the effect of different angles of attack or Reynolds numbers on the aerodynamic performance of the NACA0021 airfoil. In addition, the steps taken to ensure repeatability of the data are clearly described, and the presentation and analysis of the data are done in a rigorous and thorough manner, ensuring that the results are reliable and can be replicated by future researchers.

3.3 Critical Reynolds number

Based upon the temperature profiles in section 3.1 we can use MATLAB to find the peak temperature value. This point corresponds to the transition point or X Critical. Multiplying this value by the Reynolds number for the given setup yields the Critical Reynolds. These values are summarised in the table below. MATLAB code for these calculations is attached in ***Appendix A: MATLAB Scripts.***

Table 3: Table Summarising the Transition Points and Critical Reynolds Numbers for each Experimental Setup

Experimental Reynolds Number	Transition Point (% Chord)	Critical Reynolds Number
134237	0.6026	80889
228497	0.5299	121080
315731	0.5105	161180
408276	0.4717	192600

3.4 Comparison between Critical Reynolds Number and prediction by XFoil

The transition point is a critical parameter in aerodynamics, as it indicates the location where the boundary layer changes from laminar to turbulent flow. A precise estimation of the transition point is necessary for the accurate prediction of aerodynamic performance. Furthermore, XFOIL and MATLAB are two commonly used software programs for air foil analysis. XFOIL is a popular and widely used program that uses panel methods and iterative solutions to calculate aerodynamic properties of air foils, such as lift and drag coefficients.

MATLAB, on the other hand, is a programming language that can be used to develop custom codes and algorithms for air foil analysis. To estimate the transition point using XFOIL, the criterion was set to be n_cr = 6, which means that the program will predict the transition point when the local Reynolds number, based on the distance from the air foil's leading edge, reaches a value of 6. This is because is considered that the wind tunnel where it performed is characterized to be a dirty wind tunnel and to predict where the transition point will occur. To estimate the transition point using MATLAB, it was used a different approach, where finding the peak temperature value is the point that corresponds to the transition point or X critical.

As it can be seen from Table 4 there are significant differences in the estimated transition point locations between XFOIL and MATLAB. XFOIL consistently predicts a transition point that is closer to the air foil's leading edge than MATLAB. The difference between the two methods ranges from 0.0388c to 0.0954c, which is a significant variation for air foil design and optimization.

The reason for the difference in estimated transition points between the two software programs is due to the different numerical methods and algorithms used by XFOIL and MATLAB. XFOIL uses a panel method, which discretises the air foil into a series of panels and solves for the aerodynamic properties at each panel. This method is well-suited for predicting the transition point for smooth, attached flow. However, it may not accurately capture flow separation and other non-linear effects that can affect the transition point.

MATLAB, on the other hand, uses a custom algorithm that calculates the local Reynolds number at each point on the air foil surface and predicts the transition point based on the criterion temperature recorded. This method can be more accurate in predicting the transition point for complex flows and air foil shapes but may be more computationally intensive than XFOIL.

Based on these results, it is difficult to determine which software program is more accurate in predicting the transition point for the NACA 0021 air foil. Both methods have their strengths and weaknesses, and the choice of software program may depend on the specific design requirements and constraints. It is also important to note that the estimated transition point may vary based on.

Based on these results, it was compared the transition point results between XFOIL using N_{cr}=6 and MATLAB for the NACA 0021 air foil. Our results indicate that there were significant differences in the estimated transition points between the two software packages. While it is difficult to determine which software package is more accurate, the choice between the two will ultimately depend on the requirements and preferences. The estimated transition point locations for the NACA 0021 air foil, as calculated by XFOIL and MATLAB are summarized in the *Table* 4 below.

Table 4: Estimated transition poin from mathlab and Xfoil at 0 angle of attack

REYNOLDS NUMBER	MATLAB (% Chord)	XFOIL	Difference
134237	0.6026	0.5072	0.0954
228497	0.5299	0.4773	0.0521
315731	0.5105	0.4478	0.0627
408276	0.4717	0.4329	0.0388

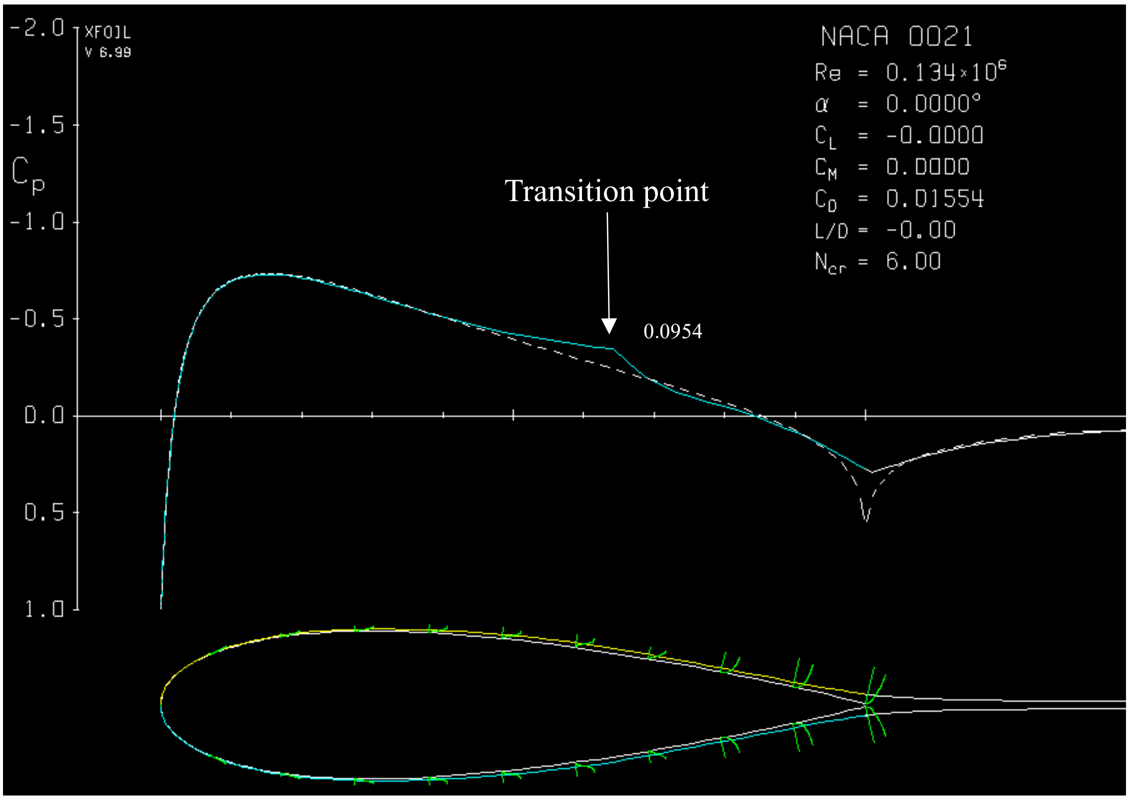

Figure 22: Xfoil Reynolds number of 0.134x10^6

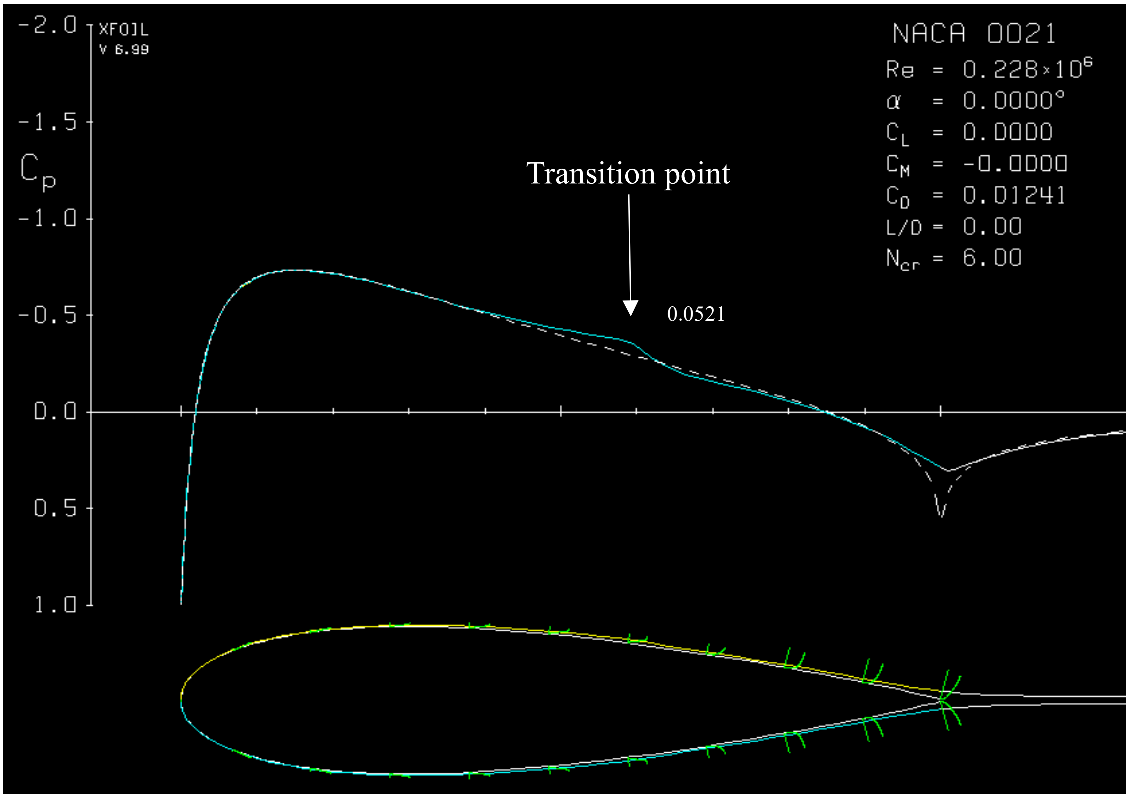

Figure 23: Xfoil Reynolds number of 0.228x10^6

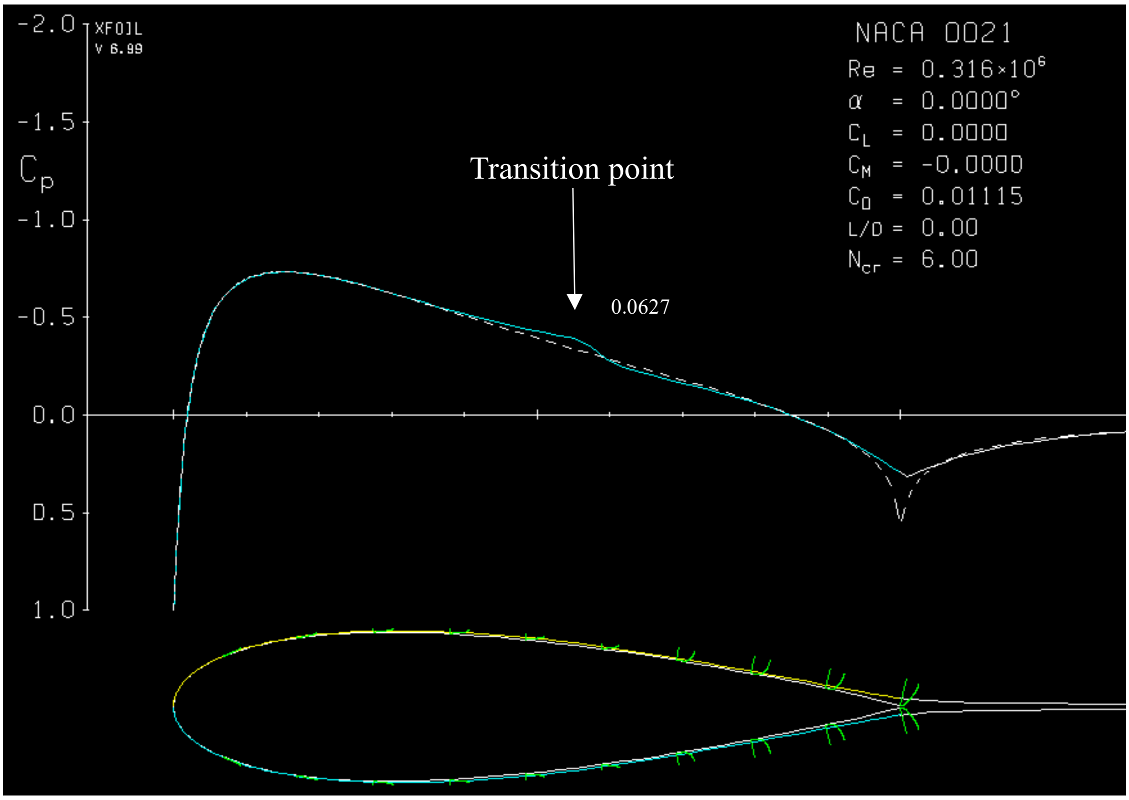

Figure 24: Xfoil Reynolds number of 0.316x10^6

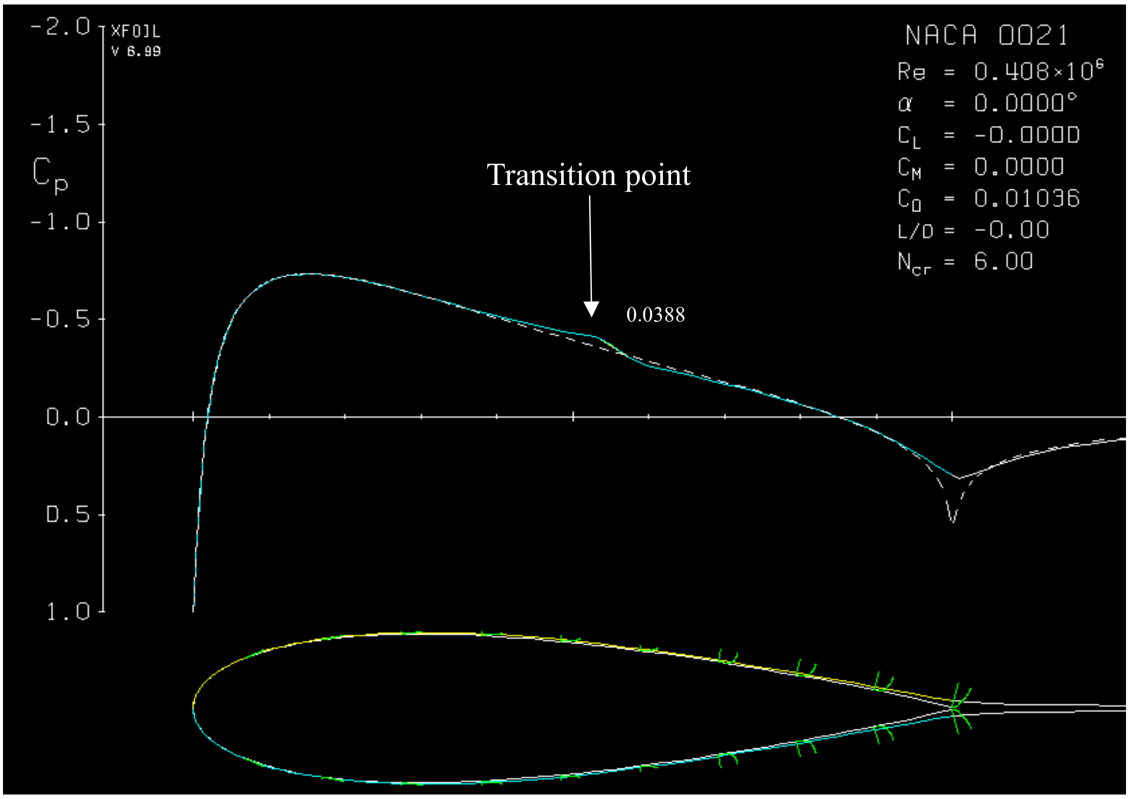

Figure 25: Xfoil Reynolds number of 0.408x10^6

CHAPTER 4: CONCLUSION

This report explores the transition from laminar to turbulent flow of a NACA0021 air foil using Infrared (IR) Thermography. An experimental setup consisting of a closed-circuit wind tunnel, infrared camera, and MATLAB program was used to complete the study. The air foil was analysed at a constant temperature of 21.8 °C, following this, four different dynamic pressures were then tested: 15.6Pa, 45.2Pa, 86.3Pa, and 144.3Pa. After obtaining the corresponding data for each dynamic pressure test, a temperature profile was generated on MATLAB based on the calculated experimental Reynolds number for the corresponding dynamic pressure tested.

These temperature profiles allow for the transition point between the laminar and turbulent flow to be identified. Furthermore, the repeatability of the data was also assessed, where the velocity was calculated to allow for a full understanding of the fluid dynamics. Furthermore, the peak temperature value was calculated by using MATLAB and the temperature profiles of each dynamic test, the peak temperature value is of great importance as it directly corresponds to an estimation of the transition point as a percentage of the chord length, as well as the critical Reynolds number. These values were then compared against those generated by XFOIL, to allow identification for possible sources of error.

It was discovered that the temperature distribution differed for each dynamic pressure that was applied, this is an indication that the infrared camera has captured the temperature varying as the velocity does. It was also found that based on the dynamic pressures tested, MATLAB yielded a transition point at chord percentage: 0.6026, 0.5299, 0.5105, and 0.4717 respectively. With XFOIL predicting: 0.5072, 0.4773, 0.4478, and 0.4329. The results from XFOIL also displayed the transition point to be closer to that of the air foil's leading edge, whereas MATLAB was further away. When compared, these results have a difference ranging from 0.0388 to 0.0954.

This variation is due to these two software's utilising different numerical methods to output results, with XFOIL using the panel method and MATLAB using a custom algorithm based on the local Reynolds number at a point of the surface of the air foil. However, it is also important to note that various sources of error may have produced inaccurate data during the experimental testing.

These sources of error may include:

- The wind tunnel may not have produced the constant temperature or dynamic pressure that was set, meaning the collected data may be inaccurate.
- Human errors in terms of calibrating the infrared camera correctly.
- The wind tunnel was open on one side, and closed on another which may cause the fluctuations in the temperature and dynamic pressure.
- Difference in roughness of the NACA0021 air foil

Overall, this study has allowed for an in-depth analysis and understanding of how transition points are identified on an air foil by using IR Thermography. By comparing the output from MATLAB and XFOIL, this has allowed for identification of possible sources of errors and inaccuracies within the data, as well as show the difference of results output from two different software's. To further explore the transition point between laminar and turbulent flow, future work on how the differing angles of attack and Reynolds number affects the transition point can be completed, as well as eliminating possible sources of error will allow for greater accuracy of results.

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APPENDICES

Appendix A: MATLAB Scripts

```
% READ CSV FILE
data = csvread('15.6.csv');

% Define RE
re = 134237;

%Filter Data
rows_to_keep = [230: 350];
columns_to_keep = [1:620];

%Redefine the matrix based on filters
selected_data = data(rows_to_keep, columns_to_keep);

%Find average of each column
column_means = mean(selected_data, 1);

%Convert to a matrix
means_matrix = reshape(column_means, 1, []);

% Calculate the chord length vector as a percentage of the maximum chord length
chord_length = linspace(0, 1, size(means_matrix, 2));


% Plot the data with percentage chord on the x-axis
figure;
plot(chord_length, means_matrix, 'Marker', 'none');
xlabel('Percentage chord (%)');
ylabel('Column mean');

% Find the maximum y-value of the plot
[y_max, index_max] = max(means_matrix);
x_max = chord_length(index_max);

% Output Data

x_crit = x_max

re_crit = re * x_crit


figure
mesh(data)
```

Figure 26: MATLAB Code for setup with Re of 134237

```
% READ CSV FILE
data = csvread('45.2.csv');

% Define RE
re = 228497;

%Filter Data
rows_to_keep = [220: 270, 320: 370];
columns_to_keep = [1:620];

%Redefine the matrix based on filters
selected_data = data(rows_to_keep, columns_to_keep);

%Find average of each column
column_means = mean(selected_data, 1);

%Convert to a matrix
means_matrix = reshape(column_means, 1, []);

% Calculate the chord length vector as a percentage of the maximum chord length
chord_length = linspace(0, 1, size(means_matrix, 2));


% Plot the data with percentage chord on the x-axis
figure;
plot(chord_length, means_matrix, 'Marker', 'none');
xlabel('Percentage chord (%)');
ylabel('Column mean');

% Find the maximum y-value of the plot
[y_max, index_max] = max(means_matrix);
x_max = chord_length(index_max);

% Output Data

x_crit = x_max

re_crit = re * x_crit


%figure
%mesh(data)
```

Figure 27: MATLAB Code for setup with Re of 228497

```
% READ CSV FILE
data = csvread('86.3.csv');

% Define RE
re = 315731;

%Filter Data
rows_to_keep = [245: 290, 335: 350];
columns_to_keep = [1:620];

%Redefine the matrix based on filters
selected_data = data(rows_to_keep, columns_to_keep);

%Find average of each column
column_means = mean(selected_data, 1);

%Convert to a matrix
means_matrix = reshape(column_means, 1, []);

% Calculate the chord length vector as a percentage of the maximum chord length
chord_length = linspace(0, 1, size(means_matrix, 2));


% Plot the data with percentage chord on the x-axis
figure;
plot(chord_length, means_matrix, 'Marker', 'none');
xlabel('Percentage chord (%)');
ylabel('Column mean');

% Find the maximum y-value of the plot
[y_max, index_max] = max(means_matrix);
x_max = chord_length(index_max);

% Output Data

x_crit = x_max

re_crit = re * x_crit


figure
mesh(data)
```

Figure 28: MATLAB Code for setup with Re of 315731

```matlab
% READ CSV FILE
data = csvread('144.3.csv');

% Define RE
re = 408276;

%Filter Data
rows_to_keep = [230: 290, 330:380];
columns_to_keep = [1:620];

%Redefine the matrix based on filters
selected_data = data(rows_to_keep, columns_to_keep);

%Find average of each column
column_means = mean(selected_data, 1);

%Convert to a matrix
means_matrix = reshape(column_means, 1, []);

% Calculate the chord length vector as a percentage of the maximum chord length
chord_length = linspace(0, 1, size(means_matrix, 2));


% Plot the data with percentage chord on the x-axis
figure;
plot(chord_length, means_matrix, 'Marker', 'none');
xlabel('Percentage chord (%)');
ylabel('Column mean');

% Find the maximum y-value of the plot
[y_max, index_max] = max(means_matrix);
x_max = chord_length(index_max);

% Output Data

x_crit = x_max

re_crit = re * x_crit


%%figure
%%mesh(data)
```

Figure 29: MATLAB Code for setup with Re of 408276