WIND TUNNEL TEST OF BLUNT-EDGE DELTA WING VFE-2 PROFILES AT HIGH ANGLES OF ATTACK

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ABSTRACT

The main objective of this project is to investigate the flow characteristics of the VFE-2 blunt edged delta wing profiles at high angle of attack. The vortex is developed on the upper surface of delta wing and this flow physics is very complicated. The vortex on the blunt-edged wing is not developed in the apex region but at a certain cord wise position based on angle of attack, Reynolds number and leading edge bluntness. The primary vortex moved upstream with increasing angle of attack. The problem is that this vortex will be formed up to the apex if the angle of attack is further increased. No data available at higher angle of attack of beyond $\alpha = 30°$ during the VFE-2 experiments due to the constraint of the experimental work. This paper present the surface pressure measurement data performed at 1×10^6 and 2×10^6 Reynolds number at higher angle of attack of α=31°. The experiments were conducted at Universiti Teknologi Malaysia Low Speed Tunnel (UTM-LST) with maximum speed of 83 m/s. The data were interpreted using pressure coefficient, C_p against distance of pressure tube that based on the delta wing chord. Apart from that, tuft method was also performed to visualize the flow characteristics above the surface of delta wing at high angle of attack. The results highlight interesting flow physics above blunt-edged wing at high angle of attack. The result shows that the primary moves upstream closed the apex at high angles of attack.

1. INTRODUCTION

The first Vortex Flow Experiment (VFE-1) for blunt-edged delta wing configuration was conducted in the early 1980's (between 1984 until 1986). The purpose of this experiment was to obtain a good experimental data to validate the Euler method codes (Hummel, 2008). However, there were some problems in the results of the VFE-1 experiments. It was found that even for the sharp leading edges the Euler codes were not able to calculate the pressure distribution on a slender wing properly. This is due that the secondary separation was not modeled at all in the coding (Hummel, 2008). Thus, some of the objectives of the VFE-1 experiments could not be achieved.

Few years later, a new research group is formed to further investigate the flow structure on the blunt-edged delta wing, the team called as Vortex Flow Experiment (VFE-2). The main objective of the VFE-2 test was to validate the results of Navier-Stokes calculations and to obtain a more detailed experimental data. The VFE-2 experiments were carried out for both sharp and blunt leading edge shape delta wing (Hummel, 2008; Luckring &Hummel, 2008; Mat, et al, 2016).

Many researchers had published data on blunt-edge VFE-2 profile in early 2010 (Mat, et al, 2016; Said, et al, 2015; Luckring, 2013; Konrath, 2013; Fritz, 2013). The results obtained from VFE-2 are summarized in Figure 1 below. The round-edged wing exhibits different flow physics compared with the sharp-edged wing especially in the region near the leading edge and the apex. The main difference is due to the attached or non-separated flow covering the wing apex region. The flow stays attached to the wing surface, starting from the apex to a certain chord-wise position which depends on Reynolds number, angle of attack, Mach number and the leading edge profile itself show this bluntness effect.

Mat, et al (2016) has performed a comprehensive flow visualization studies on blunt-edge delta wing. The examples of the results are shown in Figure 2. From the figure the flow attached to the surface of the wing at considerable low angle of attack. At higher angle of attack, the flow in the leading edge region is fully attached extending from the apex to the trailing edge. The primary vortex is developed at certain chordwise position and progress upstream with angle of attack; however there is no data in VFE-2 indicating that the vortex progressed up to the Apex region with angle of attack increases. Thus the main objective of this to perform the experiment of VFE-2 model that built in UTM at higher angle of attack (Said, et al, 2015).

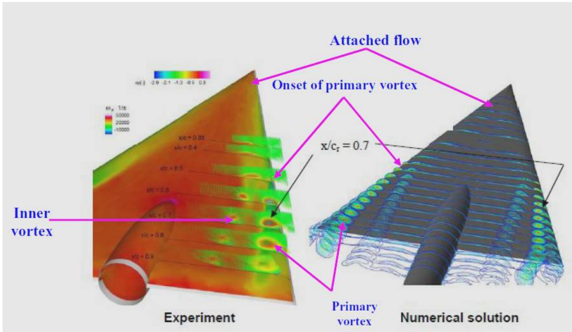


Figure 1: Comparison of experimental measurement and Numerical studies above VFE-2 configurations at α=13° (Luckring & Hummel, 2008)

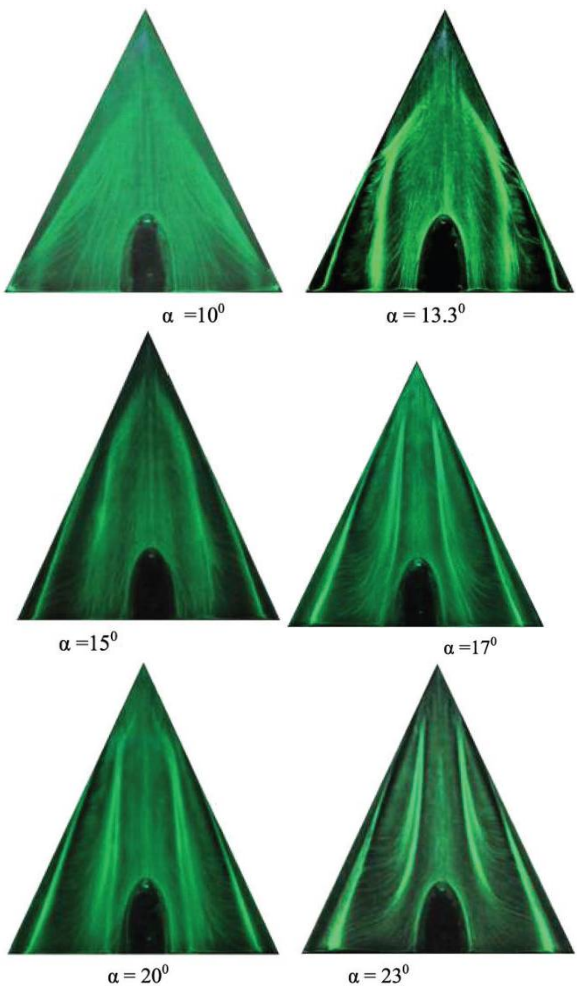
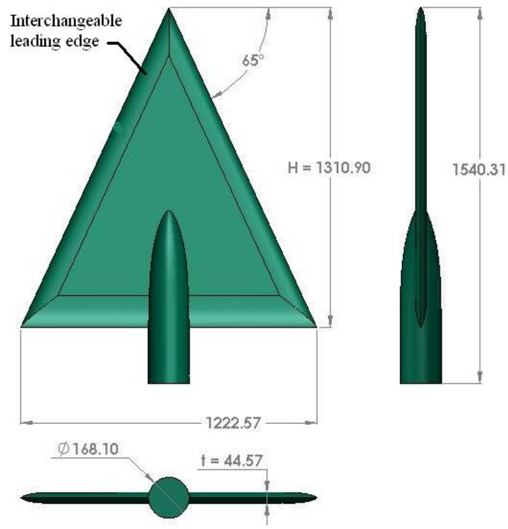


Figure 2: Flow topology above large-edged wing at Reynolds number of $1{\times}10^6$, α varies from 10° to 23° (Mat, et al, 2016).

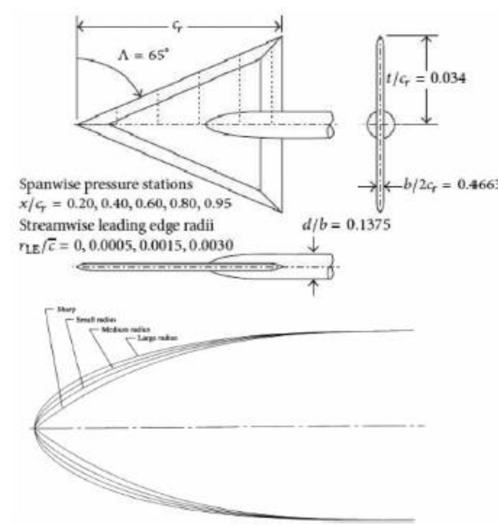
2. METHODOLOGY

A model of VFE-2 model was designed and fabricated in Universiti Teknologi Malaysia wind tunnel under Malaysian Ministry of Education grant, as shown in Figure 3(a) below (Said, et al, 2015). The designed was exactly based on the original profile of Chu & Lucking (1996) as Figure 3(b).

The installation of the UTM VFE-2 model in Universiti Teknologi Malaysia wind tunnel is shown in Figure 4 below. For this paper, two measurement techniques were employed; i.e. experimental surface pressure and flow visualization tuft techniques. The experiments were performed at angle of attack varies from α = 0° to α = 31°.



(a) Taken from Said, et al,(2015)



(b) Taken from Chu & Luckring (1996)

Figure 3: (a) UTM-LST delta wing VFE-2 profiles (b) Original Chu & Luckring profile.

Figure 4: The installation of UTM VFE-2 model at α=5°

The experiments were conducted at two different values of velocity corresponding to two different values of Reynolds number. In order to differentiate the effects of leading edge bluntness, the experiments were also performed at two different leading edge shapes namely the large and medium leading edge. The angles of attack varies from α = 0° to 31°. However, the focus for this experiment was on angle of attack between α = 23°, 25°, 27°, 29° and 31°. To differentiate the effects of Reynolds number, the experiments was also performed at two speeds of 18 m/s and 36 m/s that corresponding to 1×10^6 and 2×10^6 Reynolds number, calculated from Eqn. 1 and summarize in Table 1.

$$Re = \frac{\rho V x}{\mu} \quad (1)$$

where,

Dynamic viscosity, μ = 1.846×10^{-5} kg/ms
Density of air, ρ = 1.18 kg/m^3
Length, x = 0.874 m

The test configuration for this experiment is in Table 2. Nevertheless for the experiment at Reynolds number of 2×10^6, the angle of attack was limited to α = 23° only.

Table 1: The values of Reynolds number and velocity.

Reynolds number, Re	Velocity, V
1×10^6	18 m/s
2×10^6	36 m/s

2.1 Pressure Distribution Study

The pressure distribution around the surface of delta wing was measured using automated pressure scanner of Scanivalve that located underneath the model. The location of pressure locations is shown in Figure 5 below. From the Scanivalve, the Pressure data was transmitted into the Lab View. The data was recorded at several repeatability procedures.

Table 2: Testing configurations of delta wing.

Reynolds number, *Re*	1×10^6	2×10^6
Leading edge	(i) Large (ii) Medium	(i) Large (ii) Medium
Angles of attack, *α*	0°,2°,4°,6°,8°,10°,12°,13.3°, 16°, 18°, 20°, 23°,25°,27°,29°,31°	0°,2°,4°,6°,8°,10°,12°, 13.3°,16°,18°, 20° ,23°

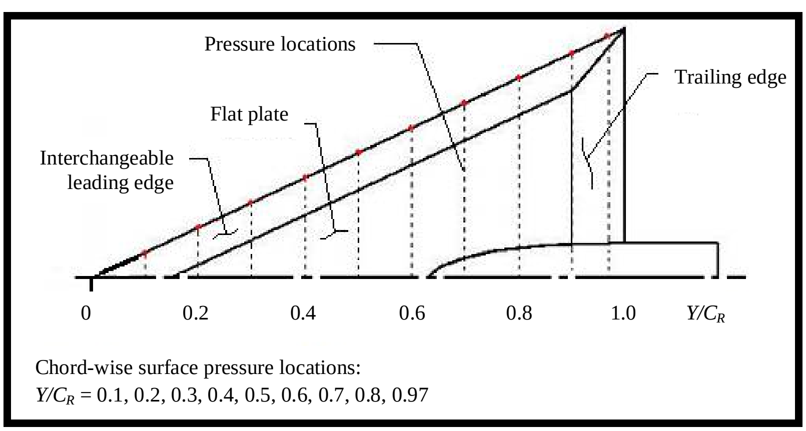


Figure 5: Location of pressure sensors of UTM-VFE-2 model.

2.2 Flow Visualization.

Tuft method was used for to visualize the development of the vortex above the wing. This method was achieved by using an array of threads tied to the net which was placed in front of the model as shown in Figure 6 below. The dimension of net was slightly bigger than wind tunnel test section of 1.7m × 2.1m. Each thread is 2m long and a total of 600 threads were used. The threads flows freely under the influence of the air flow over and below the surface of the model. This method provides a useful tracer for visualization of the air flow.

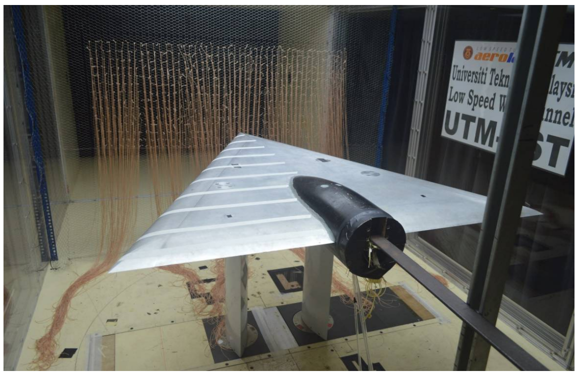


Figure 6: Complete setup of tuft method

3. RESULT

This section discusses the results obtained from the surface pressure measurement study. The effects of angle of attack, Reynolds number and leading edge bluntness are discussed in the next sub section.

3.1 Pressure Distribution

3.1.1The Effect of Angle of Attack

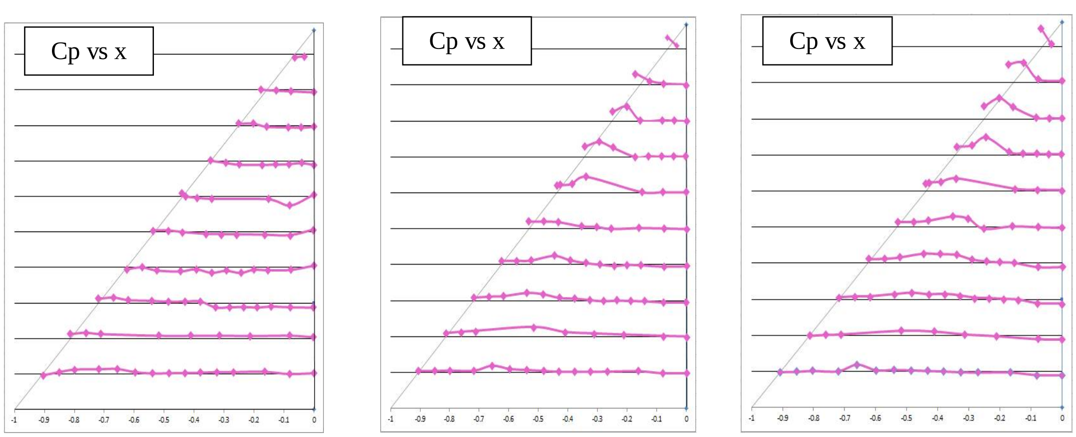
Figure 7 shows the pressure coefficient on the upper surface of the VFE-2 profiles at three different angles of attack varies from α = 6°, α = 18° and α = 31°. The results presented here is the one at Reynolds number of Re = 1×10^6 and large-radius wing. At highest angle of attacks, α = 31°, as shown in Figure 7(c), the result showed that the primary vortex is developed at about 20% of the wing compared to about at 30% of root chord for α = 18°. It should be noted here that the attached flow still exist at angle of attack of α = 31°. The results obtained here showed that the primary vortex progress upstream with the angle of attack. At lower angle of attack of α = 6°, the flow in the leading edge region is still attach to the wing surface.

The effects of angle of attack at higher angle Reynolds number of Re=$2\times10^6$is shown in Figure 8. Similar trend is observed at this conditions but the upstream progression of the primary vortex towards the apex has been delayed.

The results on the sharper wing of medium-edged wing at 1×10^6 Reynolds number is shown in Figure 9 below. At α = 6^o the flow relatively attached to the wing surface in the leading edge region. The primary vortex is developed at 30% and 30% from the wing chord if angle of attack is increased to α = 18^o and 31^o. Once again, the results obtained indicate that the attached flow is still exists even though the angle of attack has been increased.

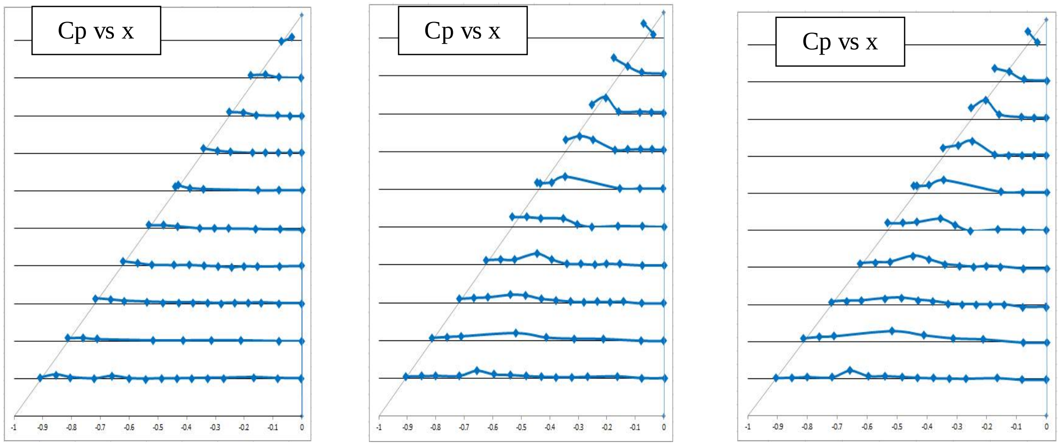
3.1.2 The Effect of Reynolds Number.

The Figure 10 show compares the effects of Reynolds number at different angle of attack of α = 6^o, α = 18^o and α = 23^o. The results here showed that the increase in the Reynolds number has slowed down the separation process. For high angle of attack it can be noted that the size of the vortex decreases when the Reynolds number is increased.



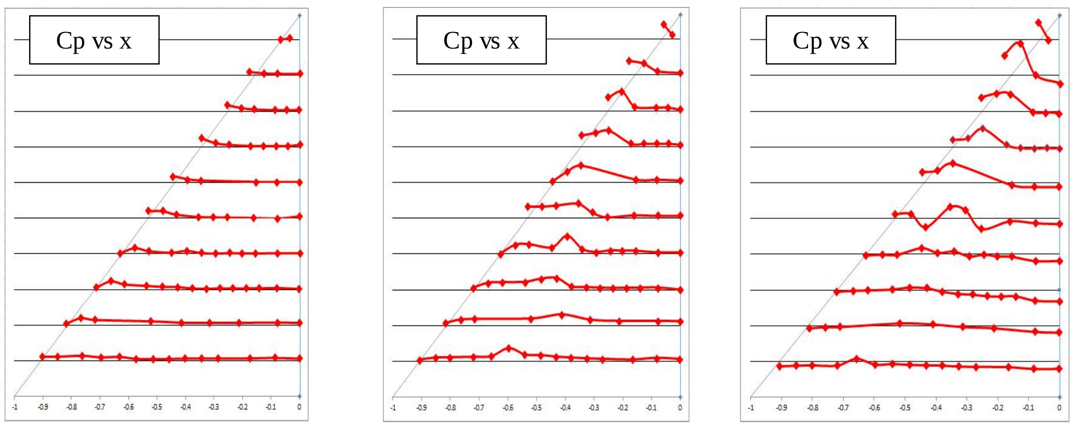
(a) α = 6° (b) α = 18° (c) α = 31°

Figure 7: Pressure distribution for large leading edge at Re = 1×10^6



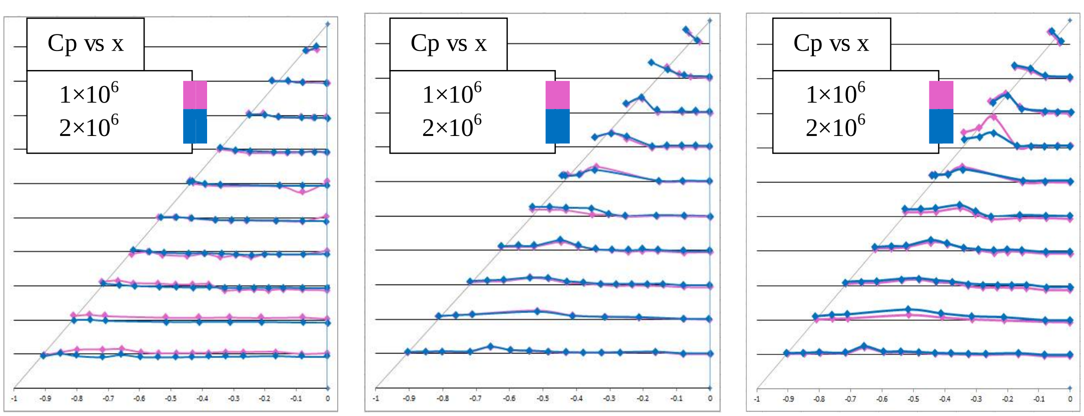
(a) α = 6° (b) α = 18° (c) α = 23°

Figure 8: Pressure distribution for large leading edge at Re = 2×10^6



(a) α = 6° (b) α = 18° (c) α = 31°

Figure 9: Pressure distribution for medium leading edge at Re = 1×10^6



(a) α = 6° (b) α = 18° (c) α = 23°

Figure 10: Pressure distribution for large leading edge.

3.1.3 The Effect of Leading Edge Bluntness.

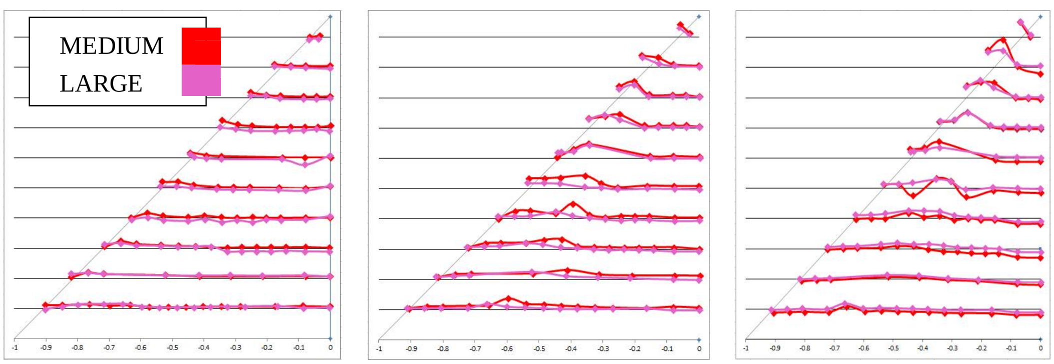
The effects of leading edge bluntness on the vortex properties in now discussed. As mentioned earlier, the experiments were performed at two different profiles of leading edge, namley the medium and the large-edged wings. From Figure 11 (a), the results show the attached flow developed on the entire wing for both cases. The effect of leading edge bluntness appears at higher angle of attack of $\alpha = 18^0$. The vortex is generated at about 20% of the wing chord for the medium case compared to about 30% of the wing for large-radius wing. Very important to note that the flow characteristics at higher angle of attack of $\alpha = 23^0$ on both wings are similar. This situation happens because the primary has progressed near the wing apex and diminishing the effects of leading edge bluntness. The results obtained here showed that the increase in leading edge bluntness has delay the progress of the primary vortex futher aft of the wing.

3.2 Flow visualization.

The sample images of the tuft experiments carried out at α = 23° are shown in Figures 12 (a), (b) and (c). These experiments were performed at the speed of 10, 15 and 20 m/s. These images showed the primary vortex developed in the leading edge of the wing while vortex breakdown is observed in the trailing edge region. This method cannot confirm whether the vortex is formed up to the Apex, more flow visualization techniques is needed in the future to visualize this complicated phenomenon.

4. CONCLUSIONS

The results obtained from this experiment showed that the attached flow is still developed in the apex region even at higher angle of attack. This means that there is still leading edge pressure that caused the attached flow in the Apex region. The results obtained here also shown that the primary vortex of blunt-eged wing will not behave as the one of sharp-edged wing even the angle of attack is increased until α=31°. More experiments are needed to verify this complicated flow topology.



(a) α = 6° (b) α = 18° (c) α = 23°

Figure 11: Pressure distribution at Re = 1×10^6.

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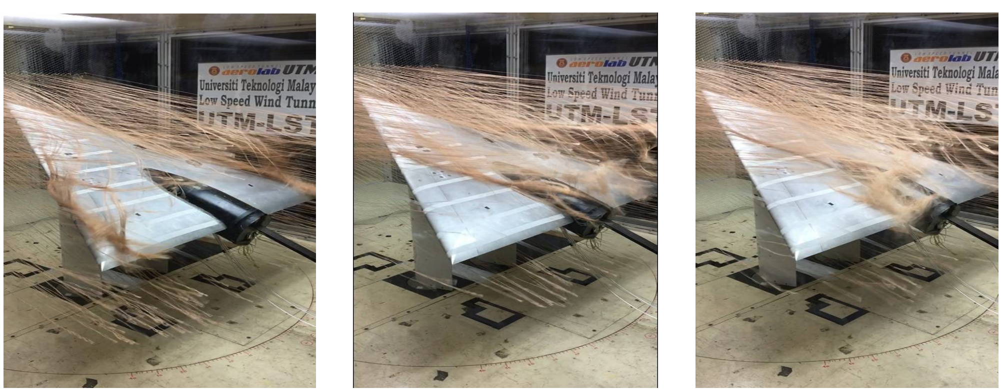

(a) V = 10m/s (b) V = 15m/s (c) V = 20m/s

Figure 12**:** Flow visualization at α = 23°

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PHOTOS AND INFORMATION

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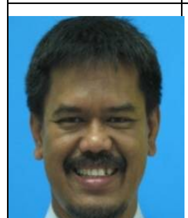
	**Kannan Perumal** is an airline captain currently on the B777 fleet with a major Asian Airline. He received his BEng and MEng in aeronautical engineering from Universiti Teknologi Malaysiia. He is also an Adjunct Profesor at UTM. His reseach interest is in aviation education, flight dynamics and simulation.
	**Tholudin Mat Lazim** is currently an Associate Professor in Department of Aeronautical, Automotive & Ocean Engineering at UniversitiTeknologi Malaysia. He is actively involved in several numbers of research projects in fields of Aerodynamics, CFD, Combustion and Heat Transfer.
	**Wan Zaidi Wan Omar**is currently a Senior Lecturer in Aeronautical Engineering at UniversitiTeknologi Malaysia. His areas of research interests include UAV, light aircraft design and aerodynamics, and smart structures. He also has interests in renewable energy systems.