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Dynamics of Fluid Flow around Aerofoil, and Submarine: Effect of Winglets

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Abstract

The continued increase in the hydrodynamic interactions between the layers of a flowing fluid leads to the formation of complex flow patterns. The shape and location of these patterns determine the stability of underwater vehicular systems. In order to understand the dynamics of flow around an aerofoil, and a submarine this investigation was undertaken. The aerofoil and the submarine were investigated in water tunnel at water speed up to 16kmph.

The results suggest that the fluid flow around the aerofoil produces rotational flow and above a critical flow speed, "shed vortex" is formed. The airplane and submarine suffer from drag that is produced as a result of the vortex formed behind them. The center of the vortex formed behind the submarine corresponds to the mid-plane of the submarine. In order to shift the plane of the center of the vortex, the submarine models were augmented with winglets to the aerofoil shapes located at the rear section of the submarine model. The results suggested that the winglets have shifted the plane of the vortex away from the mid plane of the submarine. A simple calculation of the viscous drag on the submarine with winglets at 30^o angle suggests that the winglets will reduce the drag by about 3.4%.

Key words: Model Submarine, winglets, drag reduction

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I. Introduction

The hydrodynamic interactions within a fluid often influence the stability of the system [1]. For example, at slow air or water speeds, the flow is typically a laminar flow. In laminar flow the fluid moves in layers and the layers slide over one another without fluid being exchanged between layers. At higher speeds, secondary random motions are superimposed on the simple streamline flow and the fluid flow from adjacent layers is changed. This produces turbulence [2]. The final outcome of severe turbulence is the formation of vortex. If a smooth surface such as a circular disc is introduced into the path of a laminar flow no significant changes of the flow patterns occur. Under those conditions, there will be no drag. However, if the fluid is viscous, the viscous effects introduce rotational flow characteristics and eventually the laminar flow becomes turbulent. In addition, an internal friction will be developed within the fluid and the friction extends to the surface of the body. Such extension of the friction attributes a drag on the free flow [3].

Similarly, when an object with smooth surfaces (such as a submarine shape or a missile) is moving at very slow speeds in water, the fluid from the adjacent layers will exchange between layers. This may create some topological changes in the moving wave front. However, the laminar flow will not undergo any turbulent effects. This is because at these low speeds, the fluid flow is associated with only weak hydrodynamic interactions. If a simple shape is augmented with wings, the resulting shape will be similar to that of airplane. The flow pattern around airplane will be different at different locations. For example, the fluid that surrounds the main body or the fuselage of an airplane will exhibit certain flow behavior, while the flow characteristics near the wings will be different. The net effect will be the formation of a vortex. The vortex will offer significant resistance to the free flow of fluid. Such resistance will have considerable effect on both the stability and the motion. Therefore, the shape and location of the vortices determines the stability of aerospace and underwater vehicles. It was reported that the winglets attached to wings lower the drag and improve the aerodynamic efficiency by controlling the cross flow in the tip region of the wings [4]. The winglets attached to Boeing 737 aircraft, have reduced the drag by nearly 5 – 7% [5]. In practice an airplane flying, or a submarine diving encounters different opposing forces such as the viscous drag, friction drag etc., from its surrounding environment. The goal of this investigation is (1) to understand how a free flowing fluid behavior changes with the introduction of objects of different shapes and (2) to understand the effect of winglets on the drag characteristics of submarine.

II. Experimental

During the present study, series of preliminary experiments were carried out to understand the dynamics of flow in presence of objects such as a cylinder, a cube, an ellipsoid and a cone. These shapes were placed in a water tunnel and the changes in the flow patterns were obtained. Once the simple flow patterns were analyzed, the detailed and more focused study was carried out on aerofoil shapes using a water tunnel. During this study for small sample testing a 110 cm long X 25 cm wide X 15 cm deep-water tunnel was used while for model submarine testing large 600 cm long X 100 cm wide X 100 cm deep water tunnel was used. and for was built at home. The aerofoil shape, airplane and submarine samples were designed using CAD program and they were fabricated out of commercial polymeric epoxy resin “Accura 40” using single layer lithography technique. The submarine model has winglets attached at 0^o (i.e. no winglets) and 30^o.at the rear of the submarine. Figure 1 shows submarine models used for this investigation.

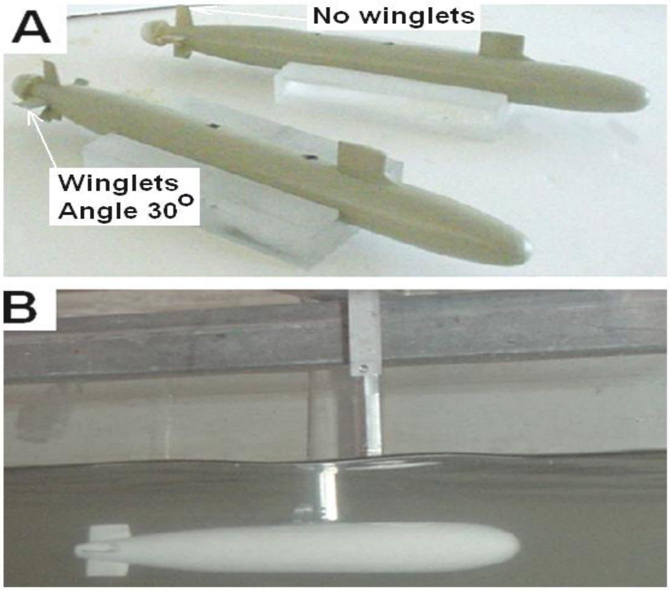

Figure 1. The submarine models used for testing. (A) Submarine models with and without winglets and (B) the submarine positioned inside the water tunnel for testing.

III. Results and Discussion

Figure 2 shows typical flow patterns observed in presence of cylindrical object present in flow path of a fluid. The results suggest that the flow of fluid in presence of different shapes at low speeds is laminar and higher fluid flow rates, the behavior changed from laminar flow to rotational flow. Similar behavior is observed for flow in the presence of different shapes. Some of flow patterns for shapes investigated here are shown in Figures I- VII in Appendix-1. Figure 3 shows typical fluid flow patterns formed around the aerofoil shape during testing in a water tunnel and at maximum flow speed of water of about 16 kmph. The results suggest that at the fluid speed investigated here the presence of aerofoil shape introduces rotational flow and also creates a ‘Shed Vortex”.

In general, the mechanism of the drag reduction due to winglets in airplanes has been postulated as follows: The air currents along the normal wings produce vortex [6]. The center of the vortex falls on the same mid plane of the airplane. The winglets shift the center of vortex away from the mid -plane of the airplane. This reduced the drag on the airplane.

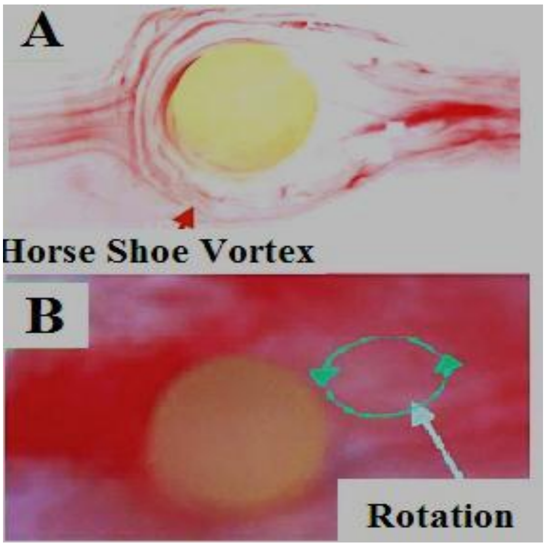

Figure 2. Flow patterns around circular object. Water flow speed and **Reynolds Number** (RE) are (A) 2 k mph, **10**, (B) 16 k mph, **100**.

If winglets shift the plane of the vortex, it is possible that model submarines augmented with winglets will also shift the plane of vortex from the plane of the submarine. As a result the viscous drag suffered by a submarine will be reduced. Figure 3 shows a schematic diagram of submarine with and without winglets at the rear. The plane of the submarine and the plane of submarine with winglets are also shown in the figure. The schematic representation of the plane of the vortex formed due fluid flow with and without winglets at the rear and the plane of the winglets is also shown in Figure 4.

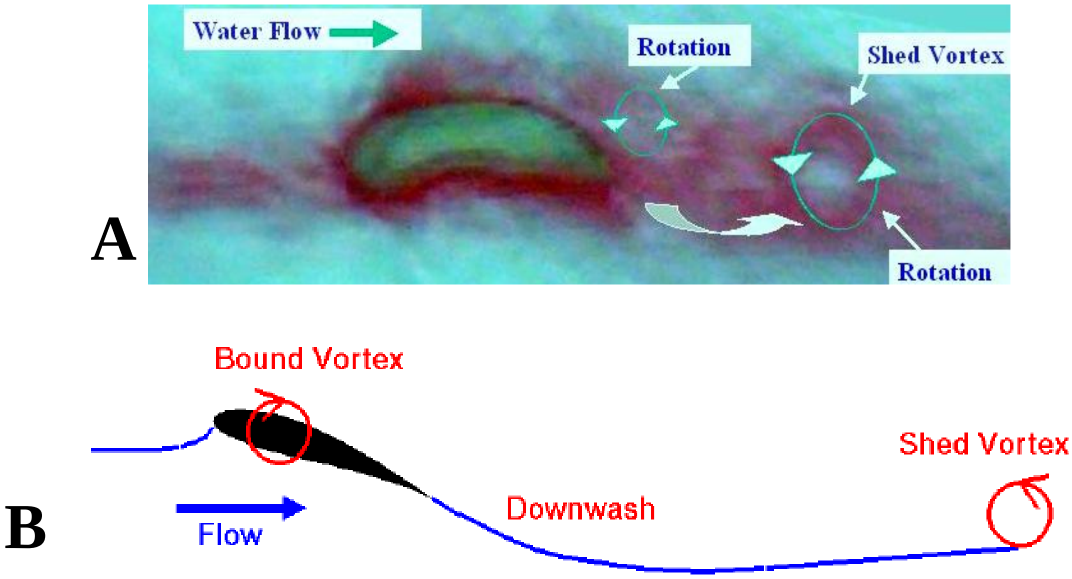

Figure 3.(A) Typical flow patterns observed due to the presence of an aerofoil. water speed in the water tunnel was 16 kmph. (B) Schematic diagram of "shed Vortex"(Ref: 1- NASA Glen Research Center).

In order to verify this hypothesis and also determine the extent of drag reduction, two submarine models (with and without winglets attached to the aerofoil at the rear of the submarine) were tested in water tunnel. Figures 5 (A) and (B) show the water flow patterns along the front and side of submarine model, Figure 5 (C) shows the flow pattern at the rear of a submarine model. The flow patterns near the rear section of a model submarine with winglets are shown in figure 6. It is clear from the figures 5 and 6 that the vortex formed behind the model submarine with winglets has moved away from the plane of the submarine.

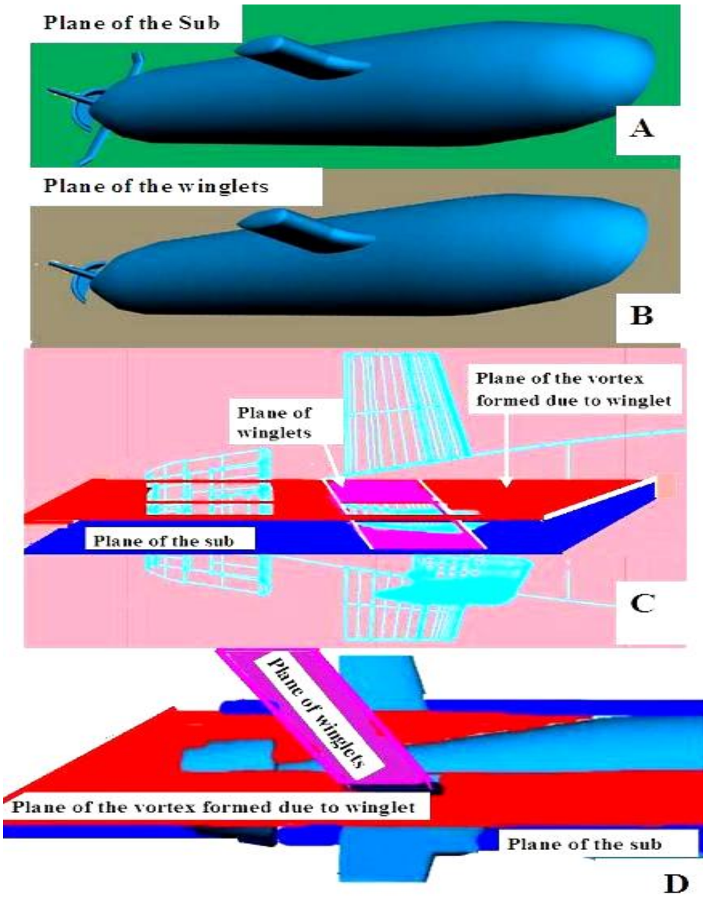

Figure 4. Schematic diagram showing (A) mid - plane of the sub, (B) the plane of winglets for the sub with winglets (C) and (D) enlarged view of different planes at the rear of the submarine.

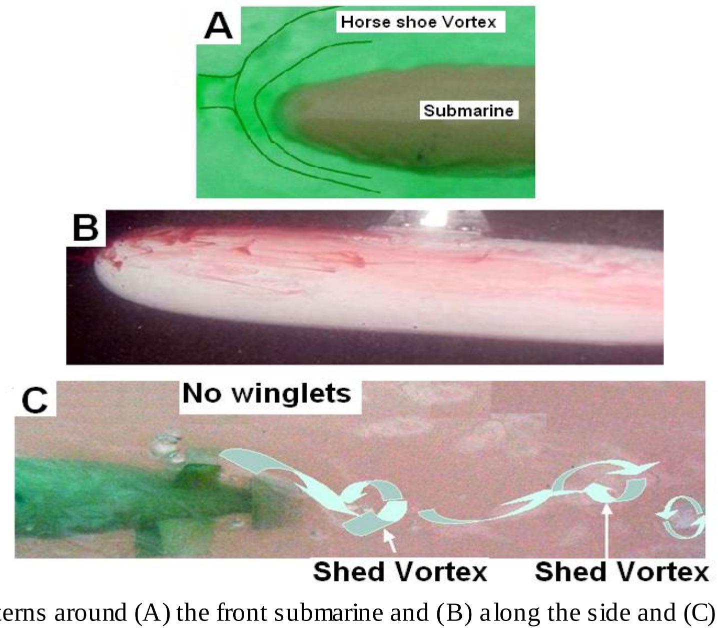

Figure 5. Flow patterns around (A) the front submarine and (B) along the side and (C) at the rear of the model submarine where four airfoils are attached. The water flow speed is 16 kmph.

Assuming that the vortex formation is primarily due to the shape of the submarine, one can estimate the reduction in the viscous drag by considering only the resolved force vector. If the submarine has winglets attached at 30^o angle, the vortex produced by the aero foils will be off centered to the mid plane of the submarine [Figure 4 (D)]]. Simple analytical calculation suggested that the flow was off centered to the mid plane of the sub by about half the winglet angle (i.e. in this case about 15^o. Therefore, it is possible that the viscous drag that is exerted on the mid-plane of the sub will be cosine (15^o) times the drag exerted on the same plane as the winglet tips.

The drag force on the submarine with winglets ≈

(Total the drag force) X (the cosineof the half of the winglet angle) …….. (1)

and the reduction in the drag on the submarine with winglets ≈

Drag on the submarine without winglets – the drag on the submarine with winglets …. (2)

For submarine with 30^o winglets, the reduction in the drag is about 3.4%. It has to be emphasized that this conclusion is based on very simplified calculation and a thorough analysis is being developed and the results will reported at a later date.

V. Conclusion

The conclusions of the present investigation can be summarized as follows:

1. The normal flow behavior is affected as a result of the introduction of objects. The shed vortex introduces significant drag.

2. The flow around the submarine's hull is primarily the "laminar Flow" while at the rear turbulent flow.

3. For the fluid flow speeds investigated here, horse shoe type of fluid flow patterns develop at the front of the submarine model, and along the side of the submarine, rotational flow patterns tend to develop at 16 kmph. At the rear of the submarine, significant rotational flow patterns develop even for speeds of 2 kmph.

4. Simple calculations suggest that the winglets (at an angle of 30o) at the rear of the submarine appear to reduce the drag by ~ 3.4% tendsto shift the drag on the submarine

5. The winglets reduced the drag by shifting the plane of the vortex formed due to fluid flow from the direct plane of the submarine.

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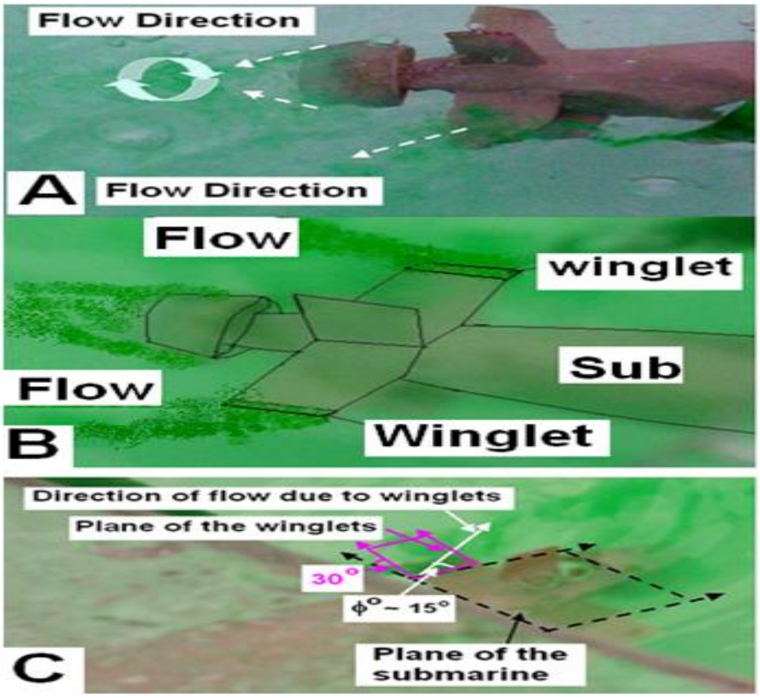

Figure 6. (A) Flow patterns at the rear of the model submarine with winglets attached to four airfoils. (B) The flow patterns were highlighted for ease of understanding and (C) details different planes and the direction of flow due to winglets. The water flow speed is 16 kmph.

APPENDIX - 1

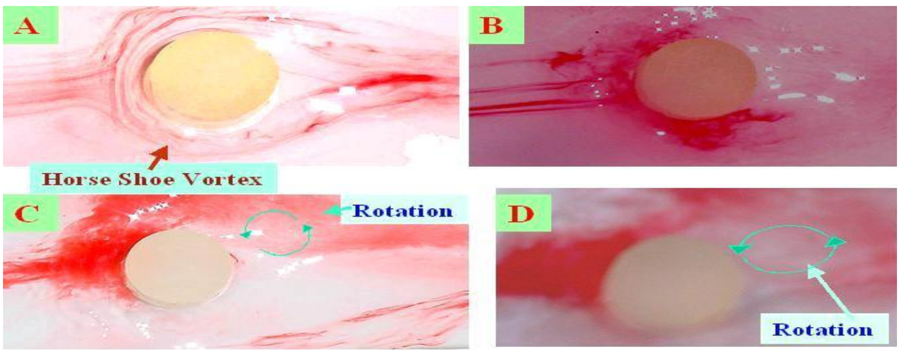

Figure I. Flow patterns around circular object. Water flow speed and **Reynolds Number** (RE) are (A) 2 kmph, **10**, (B) 3.2 kmph, **20**, (C) 8 kmph, **50** and (D) 16 k mph, **100** respectively.

The circular object on the path of free flowing fluid introduces horse shoe type vortex. At low speed (2kmph), the flow past the object remains steady and no rotational flow is produced. At higher speeds (above 8kmph), some rotational flow patterns are developed on the wake. At highest speed (16 mph), in addition to rotational flow , some turbulent flow behavior, will also develop. For comparison, typical flow character generated by computer modeling is shown in below

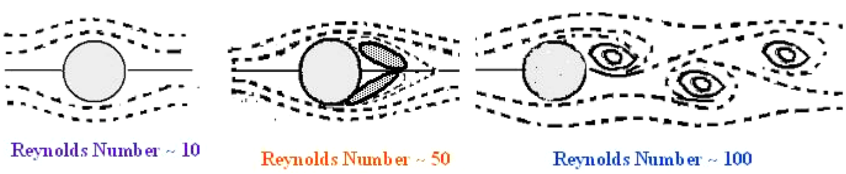

Figure II. The fluid flow patterns around a circular object as were predicted using the computational fluid dynamics (CFD) (Ref. 5).

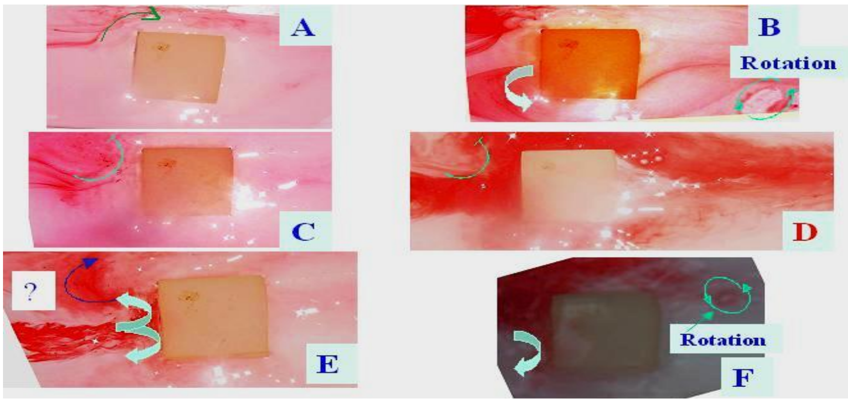

Figure III. Flow patterns around square object. Water flow speed and **Reynolds Number (RE)** are (A) 1.2 kmph, **5**, (B) 2kmph, **10**, (C) 3.2 kmph, **20**, (D) 4.8 kmph, **30**, (E) 8kmph, **50** and (F) 16kmph, **100** respectively. The introduction of a square into the flow not only developed some rotational character, but the flow tends to reverse its direction (?). Although such behavior is not expected it is possible that edge constraint on the flow may result such anomaly.

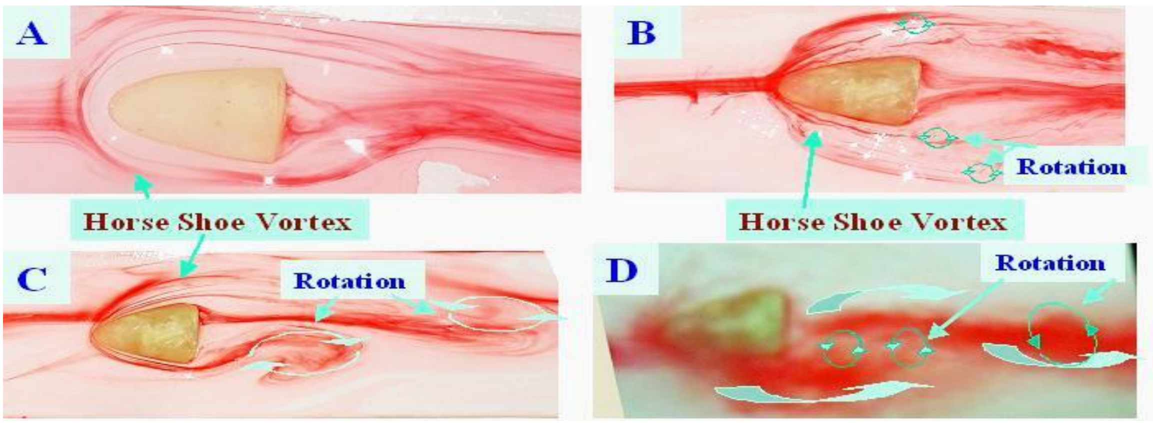

Figure IV. Flow patterns around (wide faced) elliptical shape. Water flow speed and **Reynolds Number (RE)** are (A) 2 kmph, **10**, (B) 3.2 kmph, **20**, (C) 8kmph, **50** and (D) 16kmph, **100** respectively.

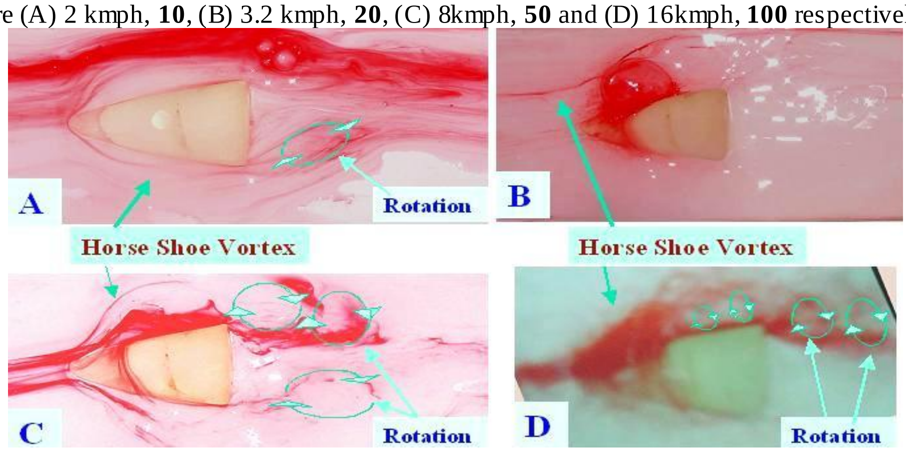

Figure V. Flow patterns around a (narrow faced) elliptical shape. Water flow speed and **Reynolds Number (RE)** are (A) 2 kmph, **10**, (B) 3.2kmph, **20**, (C) 8kmph, **50** and (D) 16 kmph, **100** respectively.

The results on the flow patterns of elliptical object produces horse shoe type vortex in the flow. At low speed (2kmph), the flow past the object remains steady and no rotational flow is produced. At higher speeds (above 8kmph), some rotational flow patterns are developed on the wake. At highest speed investigated (16kmph), in addition to rotational flow, some turbulent flow behavior, will also develop. The elliptical shape with its surface narrow at the end alters the flow character more than the surface with wider end.

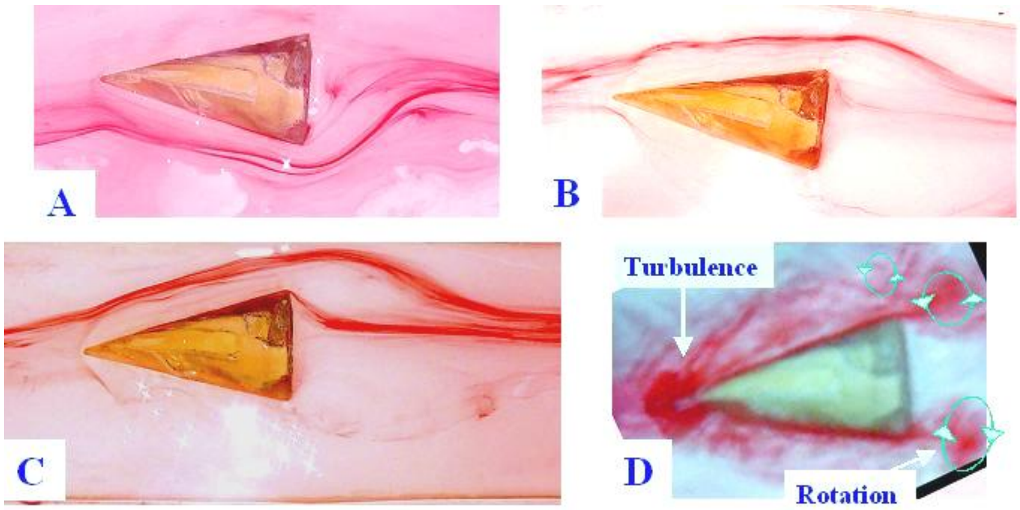

Figure VI. Flow patterns around a cone shape. Water flow speed and **Reynolds Number (RE)** are (A) 2 k mph, **10**, (B) 3.2 kmph, **20**, (C) 8 kmph, **50** and (D) 16kmph, **100** respectively.

The introduction of conical surface introduce horse shoe type vortex to the flow, however, it does not impart any turbulence to the flow for speeds up to 8 kmph. At higher speeds (above 16 kmph), some rotational flow patterns with turbulence is noticeable.

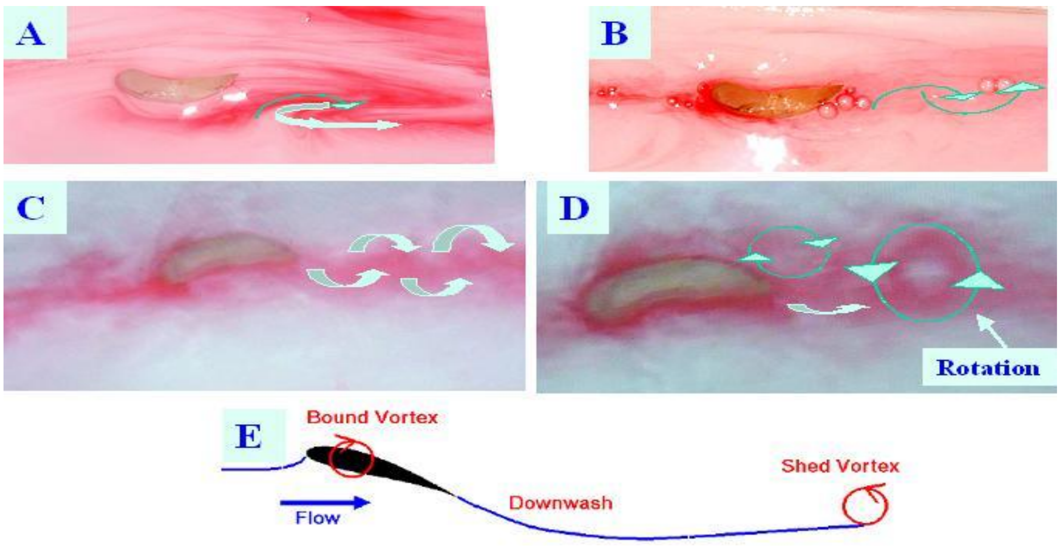

Figure VII. Flow patterns around an Airfoil. Water flow speed and **Reynolds Number** are (A) 2kmph, **10**, (B) 3.2kmph, **20**, (C) 8kmph, **50** and (D) 16kmph, **100**and (E) schematics of the shed vortex formation (Ref. for (E): NASA Glenn Res. Center).

The introduction of aerofoil shape into the flow introduces rotational and shed vortex formation.