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# The Effect of Hemispherical Discrete Roughness Elements on the Flat Plate Boundary Layer Transition

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***Abstract:*** *Transition delay of the laminar flow to turbulent, is one of the most important subject in fluid mechanics. Over the years, some passive mechanisms investigated to delay the transition process. Among these methods, the Discrete Roughness Elements (DRE) are efficient enough. In the present paper, we show the result of the wind tunnel experiments in which the transition can be delayed by using the hemispherical roughness elements on the flat plate. The height of these elements are chosen in such a way to delay the transition process. Experiments were carried out at a speed of 4.5 m/s in the wind tunnel of Shiraz University of Technology. The data measurings were done once without elements and then repeated by placing the elements in three different arrangements on the flat plate. Based on the results, with the presence of elements, the rate of velocity change in the normal direction to the flow is reduced, that shows the delay of the boundary layer transition.*

***Keywords:*** *Boundary Layer Transition, Hemispherical Discrete Roughness Elements, Laminar Flow Control, Skin friction coefficient reduction, Transition Delay.*

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## I. Introduction

The importance of the boundary layer is remarkable when the well-ordered laminar flow becomes turbulent. Generally the transitional region is a boundary between these two regions. The Flow characteristics of laminar and turbulent boundary layers are different. As an example, in the turbulent flow, the skin friction [1] and heat transfer are too high, so it is not suitable for the surfaces like the wings. In fact delaying the onset of transition is necessary in many of the fluid dynamic and heat transfer problems.

The topic of first researches was about the reasons that made the flow change from laminar to turbulent [2]. It is near half of the century that scientists have investigated the methods of Laminar Flow Control and transition delay [3-4]. Some of these studies, are about the use of Discrete Roughness Elements [5-6-7]. In 2006 for the first time the experiments proved the transition delay by using circular roughness elements [5-6-7]. Until then, there was a belief that roughness elements usually act as disturbance source accelerating the transition process to turbulence [8-9]. "Fransson" showed that a specially design roughness elements, which are pasted in the normal direction to the flow, have turned out to be so effective in attenuating disturbance growth. Here, vortex interaction mechanism, is responsible of the transition postponement. Next a numerical method confirmed these results[10].

The efficiency of DRE, depends on their geometry shape including height, span [11]. In fact the flow behavior downstream, depends strongly, on the particular roughness height and shape [11-12-13-14-15]. Actually, the critical height is determinant and described as half of the boundary layer thickness at the roughness location. The elements of the height less than the critical value, leads to the stability of the boundary layer, and postpone the transition; while those of the height more than the critical value, promotes the transition to turbulence [16- 17-18].

The influence of the elements geometry on both the flow behavior and the transition process, can not be ignored. This paper investigate experimentally the impression of the new geometry of DRE (hemispherical elements) on the transition delay for the first time.

## II. Experimental Setup and DataAcquisition

The experiments were conducted in the subsonic Wind Tunnel of Shiraz University of Technology. Five screens, a honey comb in the inlet section and a proper contraction ratio are used to obtain longitudinal turbulence level of $Tu_x = 0.6$. Fig.1 shows an image of this windTunnel.

**Figure 1:** Wind tunnel of Shiraz University of Technology

This tunnel is of the type of open circuit with a blower fan. The maximum frequency of its motor is 30Hz. The test section has a cross section of 0.6*0.6 $m^2$ and a length of 3 m. The experiments were performed on a flat plate made of aluminum with a specially designed elliptical leading edge to avoid the flow separation. Fig.2 is a photo of the leadingedge.

**Figure 2:** Leading edge of the flat plate

The flat plate, mounted horizontally in the test sections at an angle of attack at zero degrees. During the experiments, the free stream velocity of $U_\infty$ = 4.5 m/s was kept constant. Data have been obtained by Hot-Wire Anemometer measurements of the streamwise velocity component of u in both longitudinal and normal direction to the flat plate. The Hot Wire Anemometer is of the type of Constant Temperature Anemometer (CTA). CTA is generally used in the velocity measurements. The Hot Wire sensor is a wire of Tungsten with a diameter of 0.005 mm and a length of 1.25 mm. The sensor is one dimensional of the kind of Single Normal (SN). Fig.3 shows thesensor.

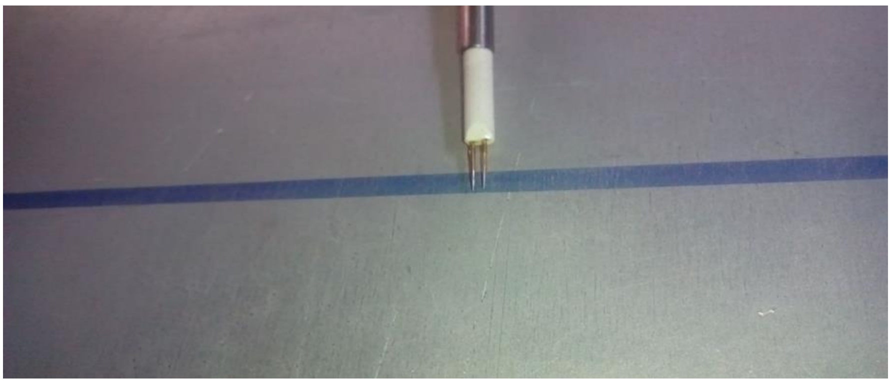

**Figure 3:** Sensor of the Hot Wire

Fig.4 shows the Hot-Wire probe while measuring $u_\infty$ on the flat plate in the test section of the tunnel.

**Figure 4:** Hot-Wire probe while measuring the streamwise velocity on the flat plate in the test section

Getting the data is computerized via the Labview software program. The software carries out functions like: the calibration of the Thermometer, setting the Pressure Transducer, Overheat setting and velocity calibration. It controls Pitot-Tube and one channel Barometer and finally processes the data which is acquired by the Hot Wire probe. The resolution of the derived velocity is 0.00001 m/s.

The probe displacement was done by the Traverse System Mechanism. This system has 3 degrees of freedom with computerized control working in connection with Labview software. The Precision of the probe movement is 0.01 mm. In Fig.5 the Probe Traverse System is seen

**Figure 5:** Probe Traverse System

For measuring the velocity changes, the traverse mechanism moved the Hot Wire probe in both longitudinal and vertical orientations in the test section.

The Labview program also performs the setting of the Hot Wire frequency response. The cut- off frequency of this experiment is f=10000 Hz, so Hot Wire can measure only the velocity disturbances with the maximum frequency of 10000 Hz. The Hot Wire probe of this experiments belong to "Fara Sanjesh Saba" Company (F.S.S) which assembled parts of the wind tunnel and exerted the setting of Labviewsoftware.

In the present experiments, the pressure gradient is close to zero in the measurement domain resulting in an almost constant boundary layer shape factor of H = 2.59. The boundary layer thickness at the roughness elements location (δ), is 5 mm and obtained by the Eq.(1):

$$\boldsymbol{\delta (x) = 5 \sqrt{(\nu x / U_{99})}} \quad (1)$$

Where, $U_{99}$ is the flow velocity in the exit of the boundary layer, ν is the air kinematic viscosity and x is the distance from the leading edge.
Hence the hemispherical roughness elements of the height less than the critical value (diameter=3.8 mm and height=1.9 mm) were chosen to achieve the goal of the present work. The elements periodically spaced in the spanwise direction. The distance between the elements is 6 mm, so they are considered discrete.

## III. Experiment Details

The experiments were done in four sets. First, the data were measured inside the boundary layer along the flat plate without DRE. Then, the experiments were repeated with one row of elements at the distance of 300 mm from the leading edge. Next, second row of elements was added parallel to the first row at the distance of 310 mm from the leading edge and the two rows made an inline form. Finally the arrangement of the second row was changed and this time two rows had a stagger form. By measuring the velocity inside the boundary layer along the air flow direction the velocity profile and skin friction coefficient are computed. Fig.6, Fig.7 and Fig.8 show this three arrangements of the elements on the flatplate.

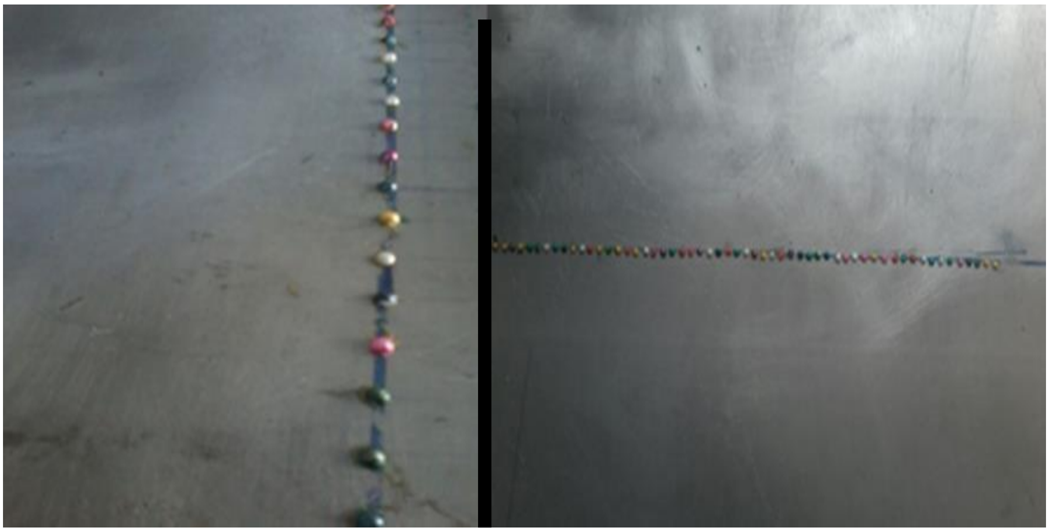

**Figure 6:** One row of the elements on the flat plate

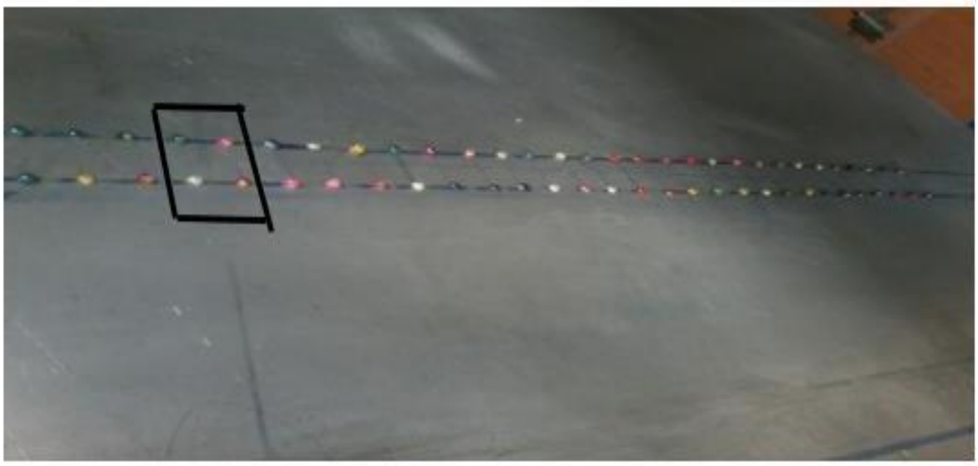

**Figure 7:** Two rows of the elements in the inline form

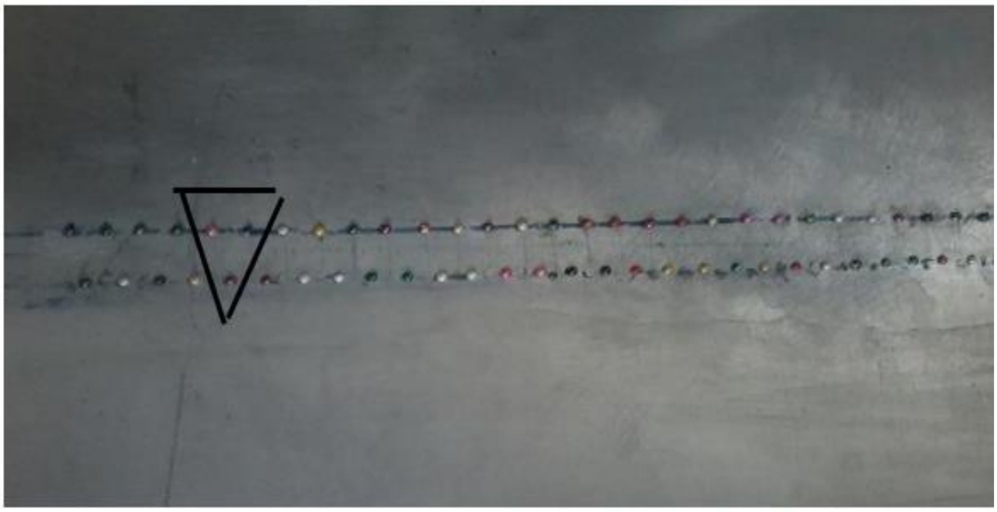

**Figure 8:** Two rows of the elements in the stagger form

## IV. Results andDiscussion

**Data Validity:** To ensure the correctness of the data measurements, the achieved velocity profile on the flat plate are normalized and compared with Blasius′ velocity profile. The Blasius′ velocity profile is the standard velocity profile of the laminar boundary layer which has been obtained from similarity solution by "Blasius". Fig.9 shows the results[19].

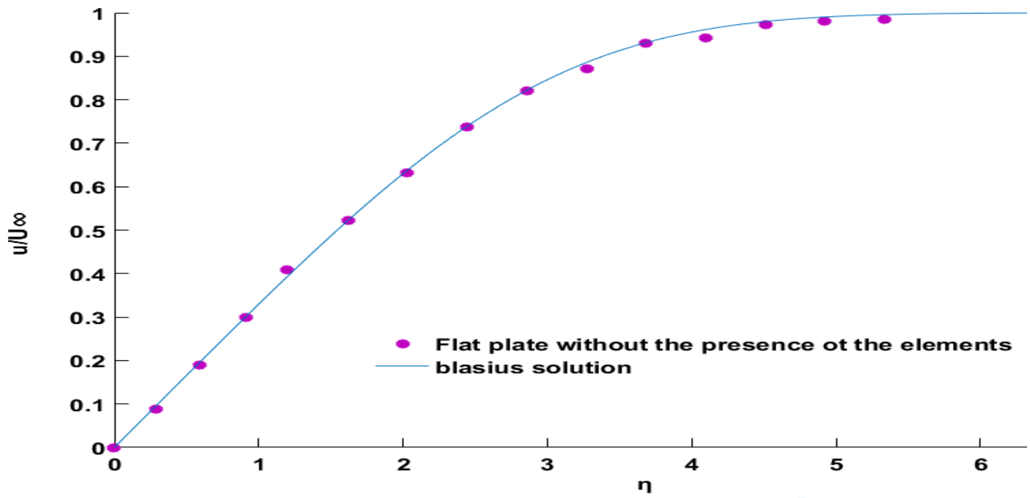


**Figure 9:** Comparison of normalized velocity profile with Blasius′ solution

Where $u/U_\infty$ is the nondimensional velocity profile and η is the nondimensional coordinate normal to the plate which is given by Eq. (2):

$$\eta = y/\delta \quad (2)$$

Here, δ is the boundary layer thickness. In Fig.9, the obtained velocity profiles is in accordance with the Blasius′solution. It shows the accuracy of measuring the velocity distribution within the boundary layer by Hot Wire Anemometer.

**Critical Reynolds Number:** Linear Stability Theory states that, the Reynolds Number at which transition start, is Critical Reynolds Number [20] and estimated at approximately 500,000.

Based on the empirical "Mayle" equation (Eq. (3)), the critical Reynolds Number depends on the turbulence intensity of the free stream [21]:

$$\mathbf{Re_{\theta t} = 400Tu^{(-5/8)}} \quad (3)$$

Where $Re_{\theta t}$, is the critical Reynolds Number by momentum thickness and is related to Reynolds Number by longitudinal distance ($Re_x$) in Eq. (4):

$$\mathbf{Re_{\theta} = 0.664\sqrt{(Re_x)}} \quad (4)$$

In the present work the free stream turbulence intensity is $Tu_x = 0.6$, hence from Eq. (3) & Eq. (4) the longitudinal Critical Reynolds Number by the "Myle" equation is 687218 which is more than the theoretical value of 500000. The Critical Reynolds Numbers of this experiments are given in Table no 1:

**Table no 1:** The Critical Reynolds Numbers of different arrangements of experiments.

| | Critical Reynolds Number |
|---|---|
| Flat plate without elements | 676700 |
| One row of elements | 699260 |
| Two rows of elements in inline form | 704810 |
| Two rows of elements in stagger form | 774700 |
| Myle equation | 687218 |

As seen in Table no 1, without DRE, the Critical Reynolds Number is less than Myle′ equation while, DRE increase the Critical Reynolds Number (Fig.12). In the stagger form of the elements, the Critical Reynolds Number is the most which means the transition starts at the longest distance from the leading edge.

**Velocity profile:** The effect of using hemispherical roughness elements on the velocity profile for four states is shown at two distances from the leading edge in the Fig.10 andFig.11.

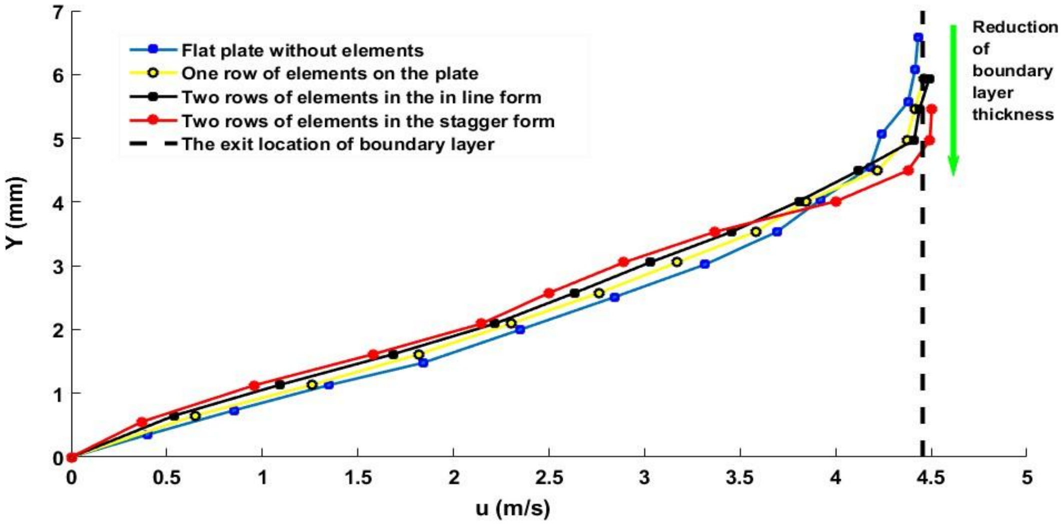


**Figure 10:** Comparison of velocity profile for four states at the distance 458 mm from leading edge

Fig.10 and Fig.11 show that the hemispherical DRE presence on the flat plate, lead to the less growth of the disturbances and the flow modulation [19], which means the rate of velocity change within the boundary layer, isdecreased.Inotherwords,byusingDRE,theboundarylayerthicknessisreduced(Fig.10&Fig.11),sothetransition to turbulence, is delayed. Adding the second row of elements, decreases the rate of the velocity changes more, and in the stagger form of the elements, the change reduction is the most. Hence the transition delay in the stagger form of the two elements rows, is the most among the arrangements of this research.

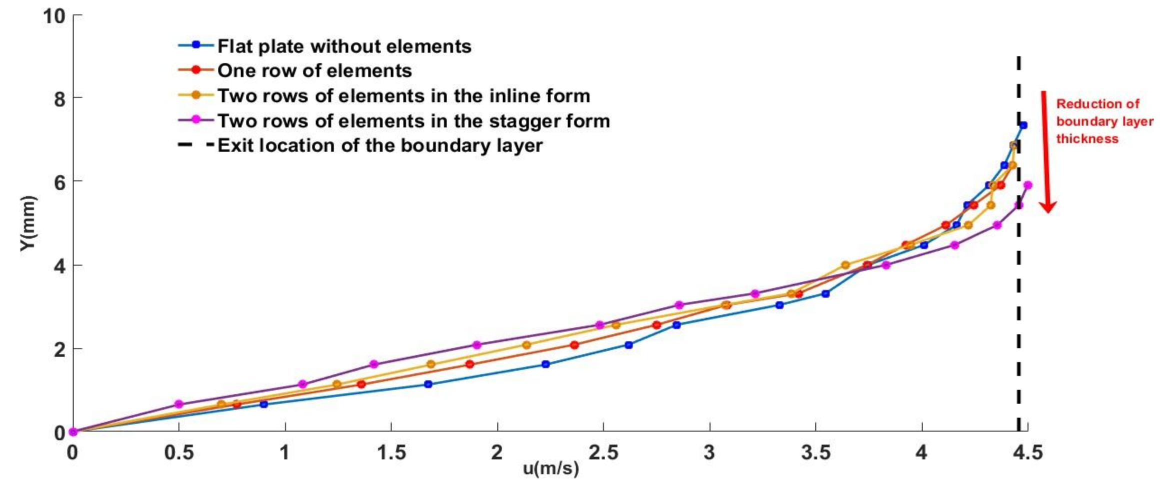


**Figure 11:** Comparison of velocity profile for four states at the distance 585 mm from leading edge

**Skin friction coefficient:** The boundary layer parameter like the skin friction coefficient ($C_f$) is calculated from measuring velocity profiles along the flat plate. Since the skin friction coefficient of the laminar flow is much less than the turbulent flow, the DRE reduce the skin friction drag of the flow by keeping it, laminar. The results of the skin friction coefficient measurements are shown inFig.12.

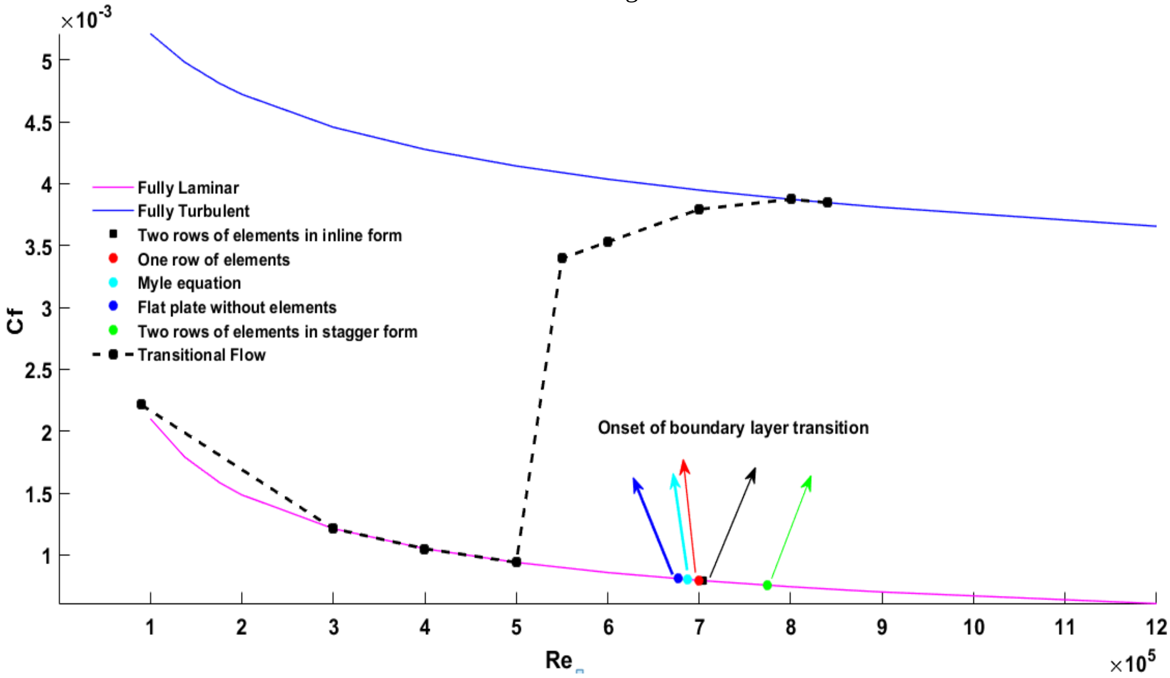


**Figure 12:** Comparison of measured skin friction drag coefficient of the different states in experiments with theory results

In Fig.12, the changes of skin friction coefficient versus longitudinal Reynolds Number is seen for both laminar and turbulent flow. Also the skin friction coefficient of the transition start is signed and compared with the transition onset of the "Myle" equation for four cases of this research. Results show that, by pasting the first row of elements on the flat plate, the point of transition onset, moves downstream and keep the flow laminar formore distance along the flat plate. So the net skin friction drag coefficient of the flow is dropped. It relates to the fact that, the skin friction coefficient of the laminar flow is much less than the turbulent flow. $C_f$ reduction is more by adding the second row of the DREs on the plate. As mentioned before, in the stagger form, the transition onset occurs at the most distance from the leading edge hence $C_f$ reduction of the flow is thelargest.

## V. Conclusion

The present work provides a passive method to delay the transition to turbulence using the hemispherical discrete roughness elements. The transition process delay on surfaces like wings, can lead to efficient fuel consumption. The project goal was to show the influence of different geometry shape of DRE (hemispherical) and three arrangements of pasting them on the surface. Until now there has been few experimental works to validate the physical model in this field. The decrease of velocity change in the normal direction to the flow and the reduction of the flow skin friction coefficient, are the results of this experiment; which indicate the transition process delay.

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