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# Effectiveness of Triangular Depressions and Asymmetric Circular Dimples for Drag Reduction

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## Abstract

The effectiveness of shallow triangular depressions and circular asymmetric dimples for turbulent drag reduction are investigated experimentally in a turbulent channel flow facility at Reynolds numbers between 12,000 and 65,000. The triangular depressions have a depth of $0.05L$, where $L$ is the streamwise length of the depression, and the deepest point within the depression is located at the triangle apex and the bottom surface slopes upwards towards the base of the triangle. The triangular depressions may be installed with their apex pointed upstream or downstream in the experimental channel flow set-up. The circular dimples have a rounded edge and a similar depth of $0.05D$ where $D$ is the dimple diameter, and have their deepest point shifted by $0.1D$ in the streamwise direction from the dimple center and may be installed with their deepest point located upstream or downstream of the dimple center. The results show that the triangular depressions cause a drag increase instead of a drag reduction regardless of whether the apex is pointed upstream or downstream, most likely due to significant flow separation within the depression. The drag increase is greater with the apex pointed upstream than pointed downstream. The circular asymmetric dimples also show a drag increase at low Reynolds numbers, but produce a drag reduction at higher Reynolds numbers. The dimples with the deepest point shifted downstream of the dimple center shows a consistently lower drag than the dimples with the deepest point shifted upstream, showing a drag reduction of almost 4% at a Reynolds number of 65,000. The reason for this difference is most likely due to reduced flow separation with the more gradual entry into the dimple when the deepest point is shifted downstream from the center.

## Introduction

Much energy is expended overcoming fluid resistance, or drag when moving objects through fluid such as air or water. This drag comprises of two components, form drag and skin friction drag. Form drag is dominant in bluff or non-streamlined objects and it can be reduced substantially by streamlining. For streamlined objects, skin friction drag becomes significant and can account for as much as 48% of the total drag for an aircraft [1]. Because of this, much effort has been made to reduce turbulent skin friction drag since many engineering applications are in the turbulent flow regime.

It is well known that smooth surfaces have generally lower skin friction drag than rough surfaces [2]. Thus, one way to reduce skin friction drag is simply to reduce the surface roughness and make the surface exposed to the air smoother. However, there is a limit to how much surface smoothness can contribute to reducing skin friction drag. Below a certain critical surface roughness, the surface becomes “hydraulically smooth” and further reduction in surface roughness is no longer able to reduce the skin friction drag further. Other means have also been attempted in the past to reduce the skin friction drag further.

One possible way is through surface contouring. Riblets, or small longitudinal grooves on the surface aligned in the streamwise direction have been successfully used to reduce skin friction drag below its hydraulically smooth level [3, 4], showing drag reductions of up to 10%. Both experiments and numerical studies have shown that they stabilize the flow which results in reduced frictional drag. However, due to their small size, they suffer from the effects of surface contamination by dirt and various small debris. These tend to clog the surface grooves and change their resulting surface geometry, making the riblets no longer effective. Also, the surface skin friction may increase above that of the hydraulically smooth level if the flow direction changes and the riblets are no longer aligned with the mean flow [5].

Circular dimples have recently been shown to have the potential to reduce skin friction drag below that of the hydraulically smooth level [6, 7]. Compared to riblets which have to be aligned to the mean flow to be effective, the use of axisymmetric circular dimples may make changes in flow direction unimportant. While the drag reduction properties of riblets have been extensively studied, the use of dimples for drag reduction is not well understood. Tay et al. [8] proposed that drag reduction with dimples arises due to the dimples creating streamwise vortices that result in spanwise flow near the solid surface. This has the effect of inhibiting the natural skin friction creation mechanism and thus reduce the skin friction drag. The use of three dimensional dimples however also introduces form drag, which becomes significant when flow separation over the dimples is present. This may sometimes overwhelm the skin friction reduction and result in a drag increase, particularly at low Reynolds number. This hypothesis, supported by both experimental and numerical results [8] opens up two areas of optimization related to drag reduction with dimples, these being the creation of stronger streamwise vortices to reduce skin friction and the minimization of flow separation to reduce form drag.

It is well known that delta wings are able to operate at high angles of attack due to the creation of strong streamwise vortices over it. Triangular shaped vortex generators are also known to have a similar effect in producing streamwise vortices. These results led us to believe that triangular depressions may also produce similar strong streamwise vortices, and have motivated the present study using an array of triangular depressions for the purpose of turbulent drag reduction. Being depressions with no protrusions into the flow may reduce the added form drag that triangular protrusions or half delta wing might otherwise create. To further reduce form drag, a slope within the triangular depression is introduced to minimize abrupt changes in flow direction within the depression.

Although drag reduction is observed in rounded edge shallow dimples at relatively high Reynolds numbers, at low Reynolds numbers, drag increase is observed due to flow separation [8]. This flow separation can be minimized by careful contouring of the dimple. The present investigation also includes a preliminary study of an array of asymmetric dimples where the deepest point within the dimple is shifted in the streamwise direction for both upstream and downstream from the dimple center. This changes the gradient of the surface geometry upstream and downstream of the dimple center and can be used to control flow separation, and hence the form drag that results from it.

## Methodology

Experiments were conducted in a long turbulent channel flow facility that is sufficiently sensitive to measure small changes in drag for various wall geometries. The tests were carried out at low subsonic speeds at Reynolds numbers based on the centerline velocity and channel height of between 12,000 and 65,000. The turbulent channel flow environment was chosen because it offered greater control of the flow, which is required because of the accuracy needed to measure the expected small changes in drag. Two sets of experiments were carried out in this turbulent channel flow environment. The first set involves studying the effectiveness of triangular depressions for drag reduction, and the second was to study the effectiveness of asymmetric dimples for drag reduction. The surface geometry of interest was installed in the 2.4 m long test-section of the channel facility, and its hydraulic resistance or drag of the test pieces in the test-section was determined from the static pressure drop along the length of the channel according to Tay [7]. The relatively long length of 8 m for the entire channel flow facility allows very small changes in the drag to be measured accurately. The experimental error obtained using this method is about ±0.3%. The channel measures 400 mm wide by 20 mm high, giving a relatively high channel aspect ratio of 20 and ensures that the flow near the channel centreline is reasonably 2-dimensional. The Reynolds number range of about 12,000 to 65,000 (based on the channel height and centerline velocity) corresponds to flow speeds of about 10 m/s to 50 m/s along the channel centerline.

To study the effectiveness of triangular depressions for drag reduction, an array of triangular depressions was machined onto an aluminum plate and installed as part of the wall of the channel test section. The dimple array fully covers the 2.4 m section of the test section in the channel flow facility. The bottom surface within the depressions slope up from its deepest point at the triangular vertex towards the base of the triangular depression to meet the flat channel surface outside the depression. Details of the triangular depression geometry is shown in Figure 1. The experimental set-up was designed to allow the test plate to be mounted with the vertex of the triangle pointed upstream or downstream to study its effect on drag. Static pressure measurements were then carried out to determine the drag of the triangular depressions and compare to the baseline plane channel case, according to the method proposed by Tay [7]. This was done for both configurations, with the triangular dimples pointed upstream or downstream separately.

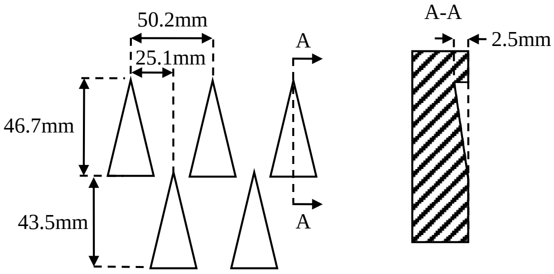


Figure 1. Schematic for triangular dimple array.

The second set of experiments involved measurements with an array of rounded edge circular asymmetric dimples carried out in the same channel flow facility. These dimples have a circular cross section, but have their deepest point within the dimple depression shifted from the center downstream by $0.1D$, where $D$ is the dimple diameter and is 50 mm in the present study. A schematic of the dimple array used is shown in Figure 2. The depth $d$ of the dimples is 2.5 mm, giving a depth to diameter ratio $d/D$ = 5%. The dimples are machined onto aluminium plates which form part of the channel wall as before. The set-up allows the test plates to be reinstalled after a 180 degree rotation, thus allowing the dimples to be installed with their deepest point shifted upstream or downstream of the dimple center. A similar range of Reynolds number (Re = 13,000 to 65,000) was used when running the experiments with these asymmetric dimples to determine their drag compared to the baseline plane channel case.

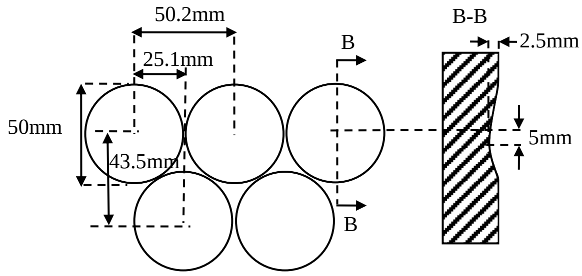


Figure 2. Schematic for asymmetric circular dimple array.

## Results

The experiments with the triangular depressions showed significant drag increase compared to the plane channel flow, particularly when the apex of the triangular depressions are pointed upstream. Figure 3 shows the drag variations for the array of triangular depressions with the apex pointed both upstream and downstream. The drag difference for the depressions with the apex pointed upstream compared to a plane channel increases as the Reynolds number increases, though at a decreasing rate. The drag increase varies from about 4% at a Re = 12,000 to about 16% at Re = 50,000. Above the Reynolds number of 50,000, the drag increase appears to remain at about 16% with no further increase. It is likely that flow separation due to the sudden change in wall geometry at the upstream triangular apex is responsible for the significant drag increase. For the case where the triangular apex is pointed downstream, a more modest drag increase was observed. Figure 3 shows that the this drag increase is about 3% more than the plane channel case and is relatively independent of the Reynolds number for the Reynolds number range investigated. In this configuration, the triangular base is oriented upstream. Flow separation for this case is likely to be significantly less than the previous case since the surface slopes down gently from the triangular base towards its deepest position at the triangular apex located downstream in this configuration.

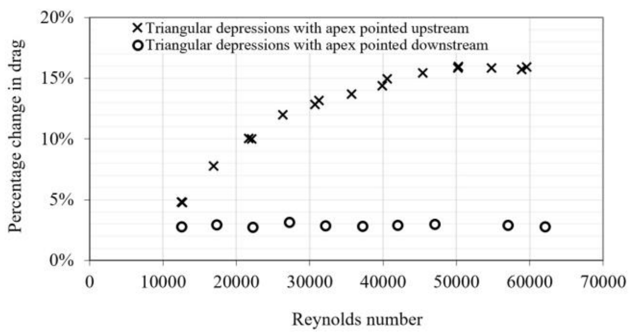


Figure 3. Percentage change in drag for array of triangular depressions.

The significant drag increase for these triangular dimples suggest that the drag increase due to likely flow separation is more significant than any drag reduction that may occur due to any streamwise vortex formation over the triangular dimples.

Unlike the triangular depressions, the array of asymmetric circular dimples show drag reduction at sufficiently high Reynolds numbers. Figure 4 shows the drag variation for both the asymmetric dimple configurations; one with the deepest point shifted upstream and the other with it shifted downstream. Also included for comparison is the results for the axisymmetric dimples with its deepest point located at the dimple center from Tay et al. [8]. For both asymmetric dimple geometries, the observed drag reduction generally increases with Reynolds number. At low Reynolds numbers however, a drag increase is observed. With the deepest point shifted upstream, this drag increase is almost 6% at a Reynolds number of 13,000. With the deepest point shifted downstream, this drag increase is much less with a modest value of 0.5% at the same low Reynolds number. As the Reynolds number increases, this drag increase moderates when compared to the plane channel case, so that at the highest Reynolds number investigated, both the circular dimple geometries show a drag reduction. Maximum drag reduction measured for the dimple with the deepest point shifted upstream is about 2%, and it is almost 4% for the one with the deepest point shifted downstream at a Reynolds number of 65,000.

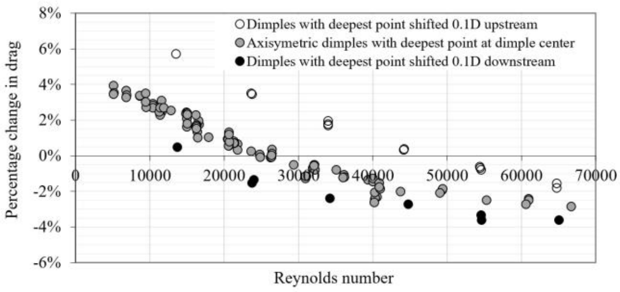


Figure 4. Percentage change in drag for array of asymmetric circular dimples compared with symmetric circular dimples.

Moreover, the results in Figure 4 show that at any Reynolds number, dimples with the deepest point shifted upstream produce higher drag than the ones with the deepest point shifted downstream. Again, this is most likely due to greater flow separation occurring when the deepest point is shifted upstream. This is because with the deepest point within the dimple shifted upstream, the surface gradient at the upstream portion of the dimple becomes steeper, resulting in greater flow separation. The reverse is true with the deepest point shifted downstream, hence reducing any flow separation that may occur. Previous work with arrays of symmetric circular dimples show that such flow separation regions within the dimple can decrease with increasing Reynolds number. As a result, drag reduction increase with the Reynolds number.

## Conclusions

The effects of triangular and asymmetric circular dimples (with their deepest point shifted in the streamwise direction) on turbulent skin friction drag have been determined using a channel flow facility. The triangular dimples produced drag increases regardless of whether the triangular apex was pointing upstream or downstream. With the apex directed downstream, the surface gradient within the triangular dimple was gentler and this resulted in significantly less drag increase than the ones with the apex pointed upstream.

Drag reduction was observed with the circular asymmetric dimple at sufficiently high Reynolds numbers. At low Reynolds numbers, the circular asymmetric dimples produce drag increase, regardless of whether the deepest point was shifted upstream or downstream of the dimple center. As the Reynolds number increases, the drag decreases and eventually falls below the baseline case of a plane channel flow, resulting in a drag reduction. When the deepest point is shifted forward, the dimples produce a higher drag compared to the ones with the deepest point shifted downstream. Maximum drag reduction measured for the asymmetric circular dimples is almost 4% at a Reynolds number of 65,000, i.e. with the deepest point downstream of the dimple center.

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