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Development of flow structures over dimples

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ABSTRACT

Dye flow visualization conducted for dimples with depth to diameter ratios ranging from 5% to 50% show six different flow stages as the Reynolds number varies from 1000 to 28000. The flow in stage I is fully attached with streamlines that curve towards and then away from the dimple centerline. In stage II, a separated flow region appears in the upstream half of the dimple. In stage III, a pair of counter-rotating vortices connected by a vortex line forms within the dimple. One of these vortices grows and dominates the flow in stage IV. Its rotational direction is fixed and its axis remains tilted from the vertical. In stage V, the axis of this vortex becomes vertical and its rotational direction switches randomly. The flow pattern in stage VI depends on the dimple depth to diameter ratio, though the mean flow is always symmetric about the dimple centerline. This flow development can be achieved either by changing the Reynolds number or dimple depth to diameter ratio. Not all six of these development stages occur for all dimples. Dimples with low depth to diameter ratios show fewer development stages than deeper ones. Sharp and round edged dimples both show similar behavior.

1. Introduction

Dimple geometries have found various heat transfer applications due to their significant heat transfer enhancement for a relatively small penalty in pressure drop in channel flows [1,2]. There has also been interest in the possible drag reducing properties of such geometries [3,4]. Various efforts have been made to study the complex flow structures that form over the dimple cavities in such flows [5–7].

Unlike the well-studied flow past a two-dimensional circular cylinder, the flow past a three-dimensional dimple cavity is much more complex. Many studies have been devoted to identifying the different flow regimes and structures that result from the flow past a circular cylinder [8,9]. Different two-dimensional invicid flow patterns as well as steady and unsteady vortex structures have been identified and carefully studied. Relationships between the vortex shedding frequencies and the flow Reynolds numbers have also been carefully catalogued [10]. Even though circular cylinders are two dimensional in shape, three dimensional vortical structures in the wake of such cylinders have also been identified at sufficiently high Reynolds numbers [11].

In contrast with the comprehensive work done with two-dimensional circular cylinders, studies on flow past three dimensional circular dimples are so far relatively scattered. The many parameters that seem to affect the flow past such dimples make effective comparisons between studies extremely difficult. Like the flow past circular cylinders, instabilities in flows over dimples give rise to different vortex structures under different flow conditions. Strong three dimensional effects add further complexities to the flow. Studies have shown that the flow Reynolds number and dimple depth affect the resulting flow structure and these in turn affect the hydraulic resistance [12] and heat transfer of the dimpled surface [13]. Despite the lack of comprehensiveness in the scattered studies of flow over dimples, some coherent trends can still be observed.

At low speeds and for dimples with shallow dimple depths, Kovalenko et al. [13] observes that the streamlines flowing over the dimples become curved and tend to move towards the center of the dimple before curving outwards again when leaving the dimple. At slightly higher speeds, a separation zone appears at the leading edge of the dimple. Typically, dimples with depth to diameter ratios of less than 10% are observed to show only such flow behavior regardless of the flow speed. Kovalenko et al. [13] calls this flow regime the diffuser–confuser flow.

Gathering from the results of experiments from about 30 different authors, Kovalenko et al. [13] proposed two more flow regimes that occur as the flow speed or dimple depth is further increased. As the flow speed or dimple depth increases, a second flow regime defined by the formation of a symmetrical horseshoe vortex structure appears where both ends of this vortex lie within the dimple itself. At the same time, the boundary layer above the dimple periodically rolls up and becomes separated. Kovalenko et al. [13] terms this second flow regime the horseshoe vortex regime. A similar

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symmetric vortical structure with periodic shedding events is also observed in the air channel experiments of Mahmood et al. [1].

With the further increase in the flow speed or dimple depth, Kovalenko et al. [13] noted that one of the ends of the horseshoe vortex rises above and exits the dimple depression so that only one end of the horseshoe vortex remains within the dimple. This defines the third flow regime suggested by Kovalenko et al. [13]. The position of the single vortex end inside the dimple may be unstable and moves within the dimple. In the case of Snedeker and Donaldson [14], a bi-stable flow is observed, where the single vortex may rotate clockwise or counterclockwise randomly upon starting the wind tunnel flow, but maintains the same rotational direction once the vortex is formed. However, by introducing a small vane at the bottom of the dimple, they were able to change the flow rotation from one direction to the other by using this vane to direct the flow at its location. Such sensitivity to initial conditions has also been demonstrated in the numerical simulations of Isaev et al. [15], where a spherical dimple can give rise to both symmetric and asymmetric flow patterns depending on the kind of perturbation introduced into the flow. The formation of this single-ended tornado-like vortex generally results in a significant increase in heat transfer, together with the hydraulic resistance of the flow [12].

Kovalenko et al. [13] further proposed that since the dimple is a three dimensional geometry, the length scale in the Reynolds number should take into account both the dimple diameter and depth, and that a hybrid length scale based on these two variables should then be used in the Reynolds number to define the three different flow regimes they observed in dimple flows. In their proposal, the transitioning to the next flow regime can be obtained by either increasing the flow speed, or by increasing the dimple depth. This is in agreement with the numerical results of Isaev et al. [16], where these same three flow regimes observed by Kovalenko et al. [13] can be clearly distinguished by increasing the dimple depth while maintaining the same flow velocity.

Using dye flow visualization, the present study intends to systematically characterize the observed flow regimes for dimples of various depths. It is interesting and important to note that as the flow velocity is further increased after observing the above mentioned three flow regimes, the flow over the dimple is observed to develop further. As such, besides characterizing the different flow regimes, this paper also aims to examine and study the dynamic change in flow structures over a single dimple as the dimple depth and the Reynolds number are varied. Both the variation in dimple depth, from 0.05D to 0.5D, where D is the dimple diameter, and the Reynolds number, from 1000 to 28000 is relatively much wider than previously published experimental studies. The use of a single test rig over these ranges of dimple depth and Reynolds number eliminates uncertainties due to differences in the test set-ups and serves as a useful consolidated reference for flow structure observations using dye flow visualization.

2. Experimental details

The experiments were conducted in a re-circulating water tunnel with a 6:1 contraction followed by a test section measuring 750 mm $\times$ 1000 mm $\times$ 2250 mm. The velocity in the test section can be varied between 0.01 m/s to 0.7 m/s, and hot film measurements show that the turbulence intensity in the test section is about 1% for velocities below 0.3 m/s and about 0.5% for velocities close to 0.7 m/s. A test plate consisting of a 10 mm thick aluminum plate measuring 330 mm in width and 1000 mm long was mounted in the test section. This plate has an elliptical leading edge with a major to minor axis ratio of 10:1. End plates of 250 mm in height are fixed along both sides of the aluminum plate to minimize three dimensional effects over the plate. A schematic of the set-up is shown in Fig. 1.

A total of three such test plates are made with two dimples machined on each test plate. The two dimples are positioned side by side of each other, at a streamwise location of 550 mm down-

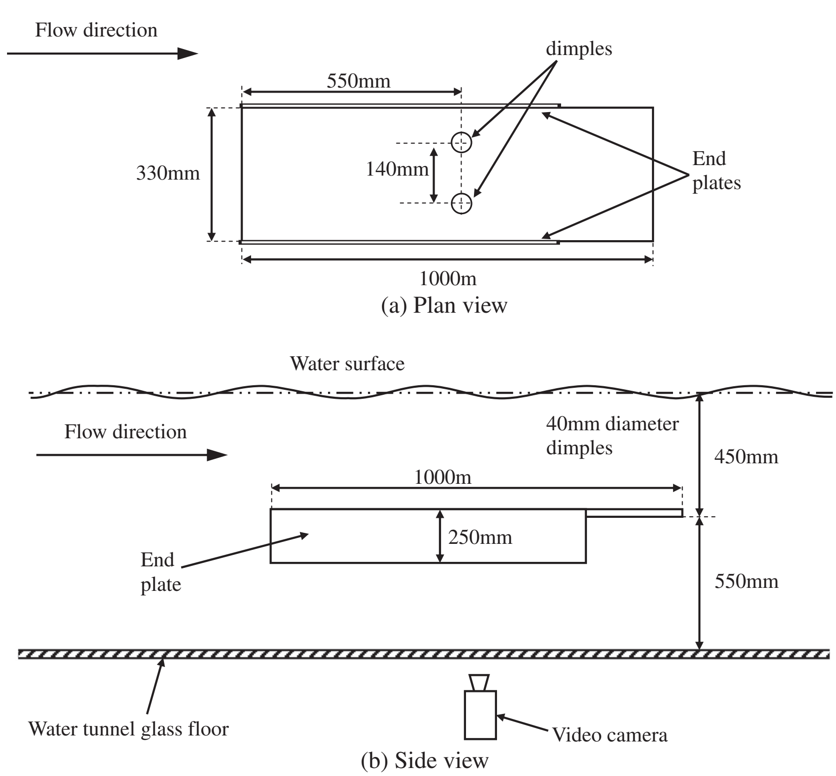

Fig. 1. Schematic of experimental set-up, not to scale.