Aerodynamic Characteristics of Flow over Circular Cylinders with Patterned Surface

U. Butt and C. Egbers

***Abstract*—Flow over circular cylinders with patterned surfaces is investigated and discussed taking into consideration the well known characteristics of flows over rough and dimpled cylinders in this paper. Investigations were performed in a subsonic wind tunnel to observe the effect of hexagonal patterns on the flow of air at Reynolds numbers ranging from 3.14E+04 to 2.77E+05. The investigations revealed that a patterned cylinder with patterns pressed outwards (can be referred as hexagonal bumps) has a drag coefficient equal to 65% of the smooth one. Various flow visualization techniques including measurement of velocity profiles in the wake region and smoke flow visualization were employed to elucidate the effect and hence comprehend the reason of drag reduction. Besides that the investigation of vortex shedding frequencies determined by using hot wire anemometry suggested that they do not change significantly with the decrease in drag coefficient in contrast to the dimpled cylinders.**

***Index Terms*—Drag reduction, flow control, vortex-shedding.**

I. Introduction

The flow over circular cylinder had been subjected to intensive research for a long time. A circular cylinder produces large drag due to pressure difference between upstream and downstream direction of the flow. The difference in pressure is caused by the periodic separation of flow over surface of the cylinder. Periodic separation induces fluctuations in the flow and makes the cylinder vibrate. To reduce the amount of drag or the drag coefficient of a cylinder various active and passive flow control methods have been employed and tested successfully. These methods include roughened surfaces [1], [2], dimpled surfaces [3]−[6], trip wires [7] and active blowing and suction of air [8]. A comparison of drag coefficients for above mentioned methods is illustrated in Fig. 1.

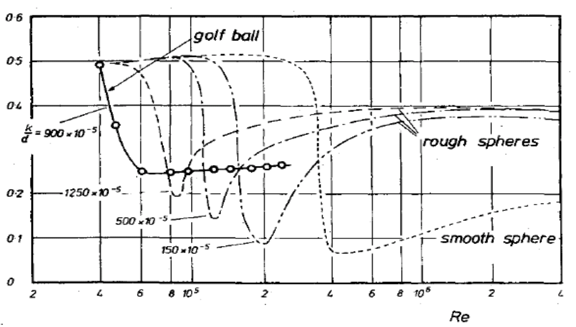

Fig. 1. Variation of drag coefficient with (Re) numbers for smooth and sand roughened spheres

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A 48% drag reduction of cylinder by installing a much smaller cylinder in the upstream direction of flow has been reported by Triogi, Suprayogi and Spirda [9]. The shear layer coming from the smaller cylinder changes the pressure distribution around the larger cylinder in such a way that the drag coefficient is dramatically altered. Takayama and Aoki [10] show a clear reduction in drag of a cylinder with circular grooves having a depth to diameter ratio of $3.75*10^{-3}$. Various qualitative flow visualization techniques such as smoke flow visualization and surface oil film technique as well as quantitative techniques such as PIV have been employed to locate the position of transition and separation of boundary layers. Smoke flow visualization has been used by Bakic and Peric [11] to visualize the delayed separation of the flow over a smooth sphere at Reynolds number of 4**E*5. Numerical investigations have also been very helpful in visualization of these complex flows over such structures. Yamagishi and Oki [12] performed numerical investigations on the flow over grooved cylinders and have been able to locate exactly the position of boundary layer separation.

No studies have yet been made on the flow over cylinders with hexagonal patterns. Patterns investigated in this paper can also be referred as hexagonal dimples or bumps of $k/d = 1.98 \times 10^{-2}$, here k is the depth of pattern. The behavior of the patterned cylinders for a particular range of Reynolds numbers is investigated in this paper by measuring their drag, flow visualization, velocity profiles and Vortex-shedding in the wake of cylinders.

II. Experimental Setup

In this paper flow over cylinders with hexagonal patterns has been investigated. It is essential to mention here that these patterns were pressed on steel sheets having a smoothed surface to avoid any effects of surface roughness on the flow. The motivation behind these investigations was to study the effects of above mentioned hexagonal structures on the flow of air and their contribution in affecting the drag of the body. The cylinders to be investigated were made by bending and welding patterned steel sheets firstly with facing the patters outwards and secondly the patterns facing inwards. The orientation of these patterns towards the free stream of air was also changed during the Investigations and hence the investigations could be performed over five different configurations.

Fig. 2. Investigated cylinders with patterns

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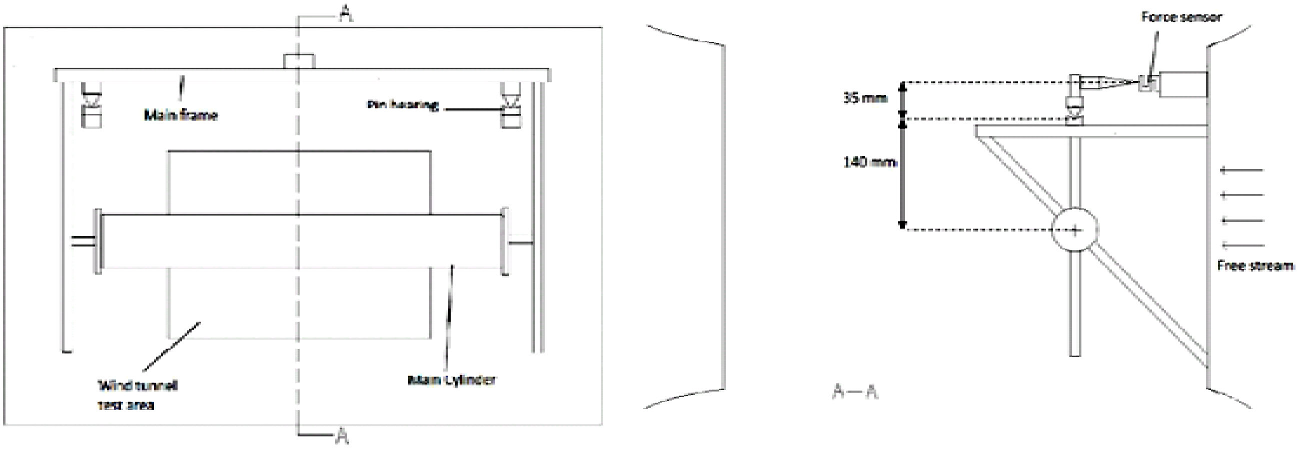


Fig. 3. Experimental setup, front view (left), side view (right)

The velocity profiles in the wake region of all the cylinder configurations were measured using hot wire anemometry. A single measurement was recorded for 15 seconds at a sampling rate of 10,000 */sec*. Flow visualization was carried out by injecting Fog exactly at the centre of the Test chamber of the Wind Tunnel into the free stream of air with the help of 3 mm diameter tube. A 1200 Watt Fog machine was the source of the Fog. A light sheet above the cylinder illuminated the smoke flow over the cylinder which was captured by a high performance Digital Camera having a Resolution of 8 Mega Pixels at a rate of 4 *frames/sec*.

The experiments were performed in a subsonic closed wind tunnel. The dimensions of the test chamber are 585 × 585 ×1300 *mm*. The free stream turbulence intensity, defined as the ratio of root mean square of the velocity fluctuations to the mean velocity is less than 0.5% for all experiments. The investigations were carried out for Reynolds numbers ranging from 3.14*E*+04 to 2.77*E*+05 based on cylinder diameter. The length of the cylindrical holder on which the test cylinder was mounted was intentionally made a little larger than the length of the test chamber to avoid the effects of finite cylinder length. Hence the body can be considered as an infinitely long cylinder. The whole setup containing test cylinder and the stand on which it is mounted acts like a pair of beam balances supported on point edges on a mutually perpendicular axis perpendicular to the axial centerline of the cylinder (Fig. 3).

The total drag coefficient of the cylinder configuration was measured using a piezoelectric force gauge having an uncertainty of ±0.1 % of the full scale value which is 980 *N*. The least count of the sensor is 0.2 *N*. Data were recorded at a rate of 4 values */sec* for a time period of 10 seconds. An average of all these measured values was taken.

Hot wire anemometry was used to determine the vortex-shedding frequencies for each configuration of circular cylinders. A 10 *sec* long hot wire signal was obtained at a sampling frequency of 5 *kHz* and processed in Matlab to determine the vortex-shedding frequency. The measurements were performed at a distance of 450 *mm* form the axis of the cylinder in the downstream direction of flow. It corresponds to about 3 times the diameter of the investigated cylinder. However the vertical position of the hot wire is dependent on the velocity of incoming flow. It is chosen where the fluctuating velocity (*r m s* velocity) of the flow has its maximum value.

TABLE I: PROPERTIES OF THE CONFIGURATIONS

	Configuration	Diameter	Direction/shape	*k/d*	Orientation/size
A1	Smooth		-	-	-
A2	Outwards 90 °		Outwards/hexagonal		90 °/33 *mm*
A3	Outwards 0 °	156 mm		$1.98 * 10^{-2}$	0 °/33 *mm*
A4	Inwards 0 °		Inwards/hexagonal		90 °/33 *mm*
A5	Inwards 90 °				0 °/33 *mm*

III. Results and Discussion

A. Variation of Drag Coefficient

Fig. 4 shows the measured relative drag coefficients against Reynolds numbers for all the investigated configurations.

A clear reduction in drag coefficient can be seen for nearly all the configurations at higher Reynolds numbers with a largest drop for A2. The most interesting fact to know about the hexagonal patterns is that the highest reduction in drag coefficient is observed for the configurations pressed outward (can be referred as hexagonal bumps) (Fig. 4) rather than the configuration pressed inwards (can be referred as hexagonal dimples) as one would expect because of their resemblance to the dimples in shape and structure.

It is also confirmed that these hexagonal patterns behave in a totally different way than the roughened surfaces whose drag coefficient rises dramatically at higher Reynolds numbers and hence cannot be characterized as a roughness structure.

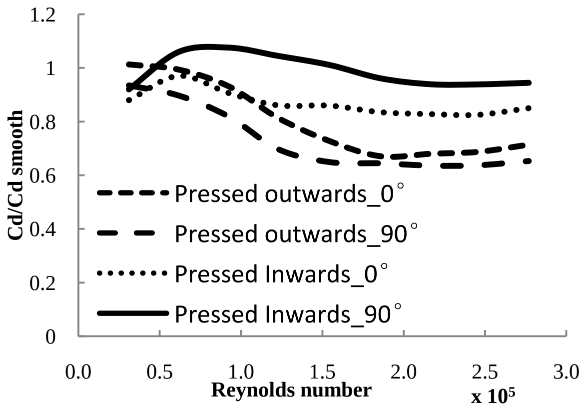


Fig. 4. Relative drag coefficients vs Reynolds Numbers: hexagonal patterns (k/d=1.98 $\times 10^{-2}$), here k is the depth of hexagonal pattern

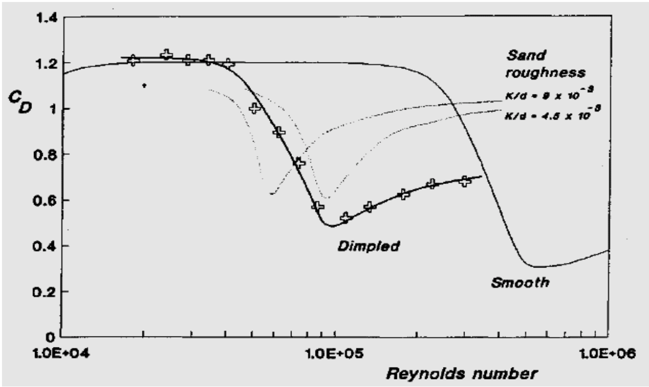


Fig. 5.Variation of drag coefficient with Re numbers for smooth, sand roughened and dimpled cylinders [3]

A common feature among hexagonal bumps (Fig. 4) and dimples (Fig. 5) is that the change in drag coefficient at higher Reynolds numbers after reaching its minimum at critical Reynolds number is minute which suggests that the mechanism of drag reduction for hexagonal bumps can be similar to that of dimples. On the other hand, significant reduction in drag coefficient has been observed for hexagonal bumps instead of hexagonal dimples which may be caused by a totally different mechanism. A nearly unchanged drag coefficient even at higher Reynolds numbers is probably due to the fixed separation angle in contrast to a roughened cylinder whose separation angle shifts upwards at higher Reynolds numbers.

B. Velocity Profiles in Wake Region

To validate this effect velocity measurement in the wake region were performed using hot wire anemometry at a Reynolds number of 2.3E+05. The profiles are obtained by placing the hot wire probe at 45 cm at the rear of the axis of the cylinder which corresponds to a ratio of x/D=3. As expected the configuration A2 and A3 have the smallest wake region compared to the others confirming the evidence of their lowest drag coefficients. Symmetry of these wake regions indicates the absence of any forces other than the drag force. The patterns on the surface disturb the pressure distribution around the cylinder in such a way that the separation process is altered proving them a suitable passive control.

These velocity profiles do not provide any information about the nature of flow above the surface of cylinders and hence the mechanism of drag reduction. A smaller wake region definitely suggests that the separation process has been altered. Whether the separation is a result of a delayed laminar separation or caused by a transition from laminar to turbulent boundary layer is yet unanswered. It is essential to investigate the separation process to comprehend the mechanism of drag reduction. In following two different techniques were used to shed light on the separations process.

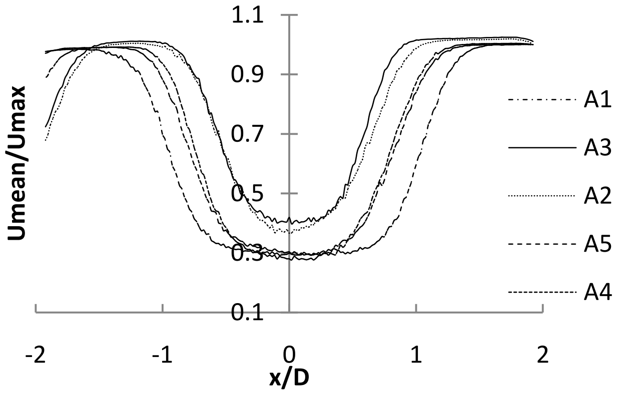
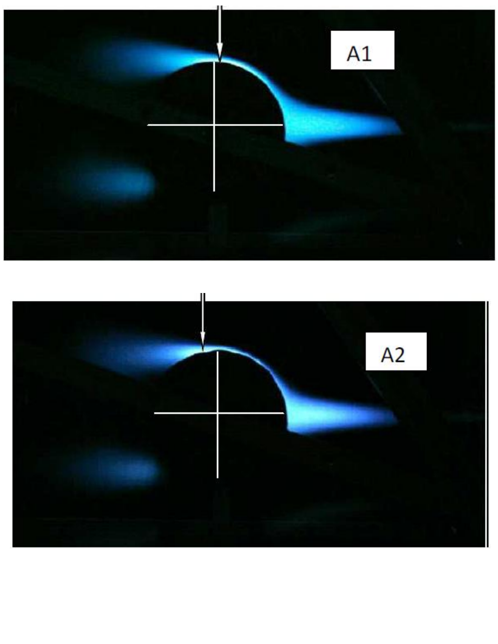


Fig. 6. Variation of Mean velocity profile behind the cylinders for Re=2.3E5

C. Smoke Flow Visualization

Smoke flow visualization was carried out at a Reynolds number of 2.3E+05 respectively. The smoke follows the air and traces its path when enlightened via light sheet. A noticeable delay in separation was observed for the configurations A2 and A3 having the smallest drag coefficient among all. An estimated position of the flow separation has been marked with the help of an arrow (Fig. 7). The positions of the separation arrows in the configurations A4 and A5 are very much near to the one on smooth cylinder indicating the fact that their drag coefficients do not differ significantly from the drag coefficient of A1. The smoke flow visualization results clearly validate the drag coefficient measurements and give an explanation for the observed phenomenon i.e. the delay in separation process occurring on the surface of the cylinder at a lower Reynolds number than the critical Reynolds number of a smooth cylinder is mainly responsible for the reduction in drag coefficient of the cylinders.



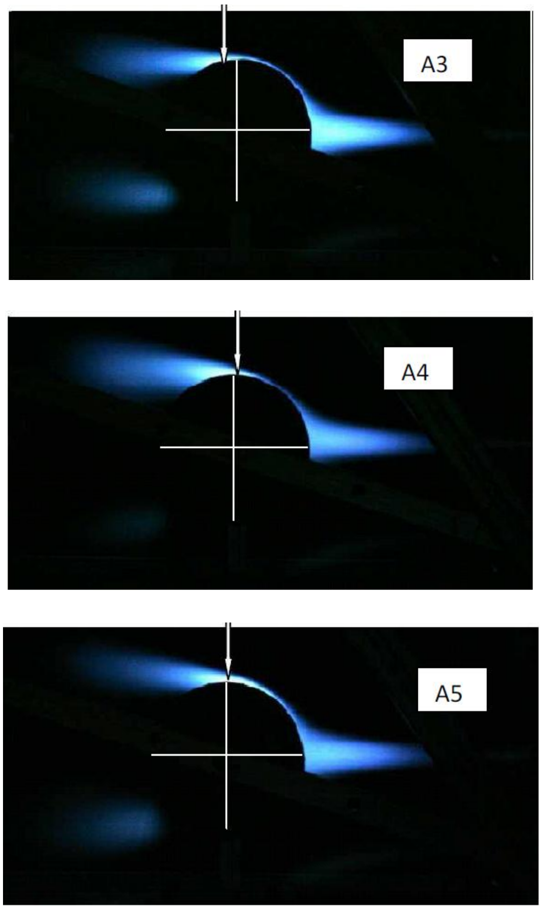


Fig. 7. Smoke flow visualization over A1, A2, A3, A4, A5

D. *Vortex Shedding*

An unsteady oscillating flow takes place resulting in Vortex-Shedding when a fluid flows over a bluff body at certain velocities depending on the Reynolds number. In this flow vortices are created at the back of the body and detach periodically from either side of the body. The fluid flow past the object creates alternating low pressure vortices on the downstream of the object. The object will tend to move towards the low pressure zone. If the cylindrical structure is not mounted rigidly and the vortex-shedding frequency matches the resonance frequency of the structure it can begin to resonate, vibrating with harmonic oscillations driven by the energy of the flow. The Vortex-shedding frequencies in the wake region of investigated circular cylinders caused by the periodic separation of flow from the surface were also investigated. The investigations were performed for four different Reynolds numbers. A peak in each figure identifies the shedding frequency present in the wake region of cylinder (Fig. 8). Vortex shedding frequency increases with increasing Reynolds number for all the configurations illustrated in Fig. 8. The interesting fact to know here is that the vortex-shedding frequency at a particular Reynolds number for different configurations does not change significantly. It seems that the shear layer coming from the surface of the patterned cylinder does not get irregular or stronger as in case of transition from laminar to turbulent boundary layer on the surface of a smooth cylinder. The vortex generation by the patterned cylinder remains steady even at critical Reynolds number or higher. In contrast, the vortex-shedding frequency of a dimpled cylinder [3] increases at critical Reynolds number which indicates that the dimples affect the shear layer coming from the surface of the cylinder dramatically besides reducing their drag coefficient.

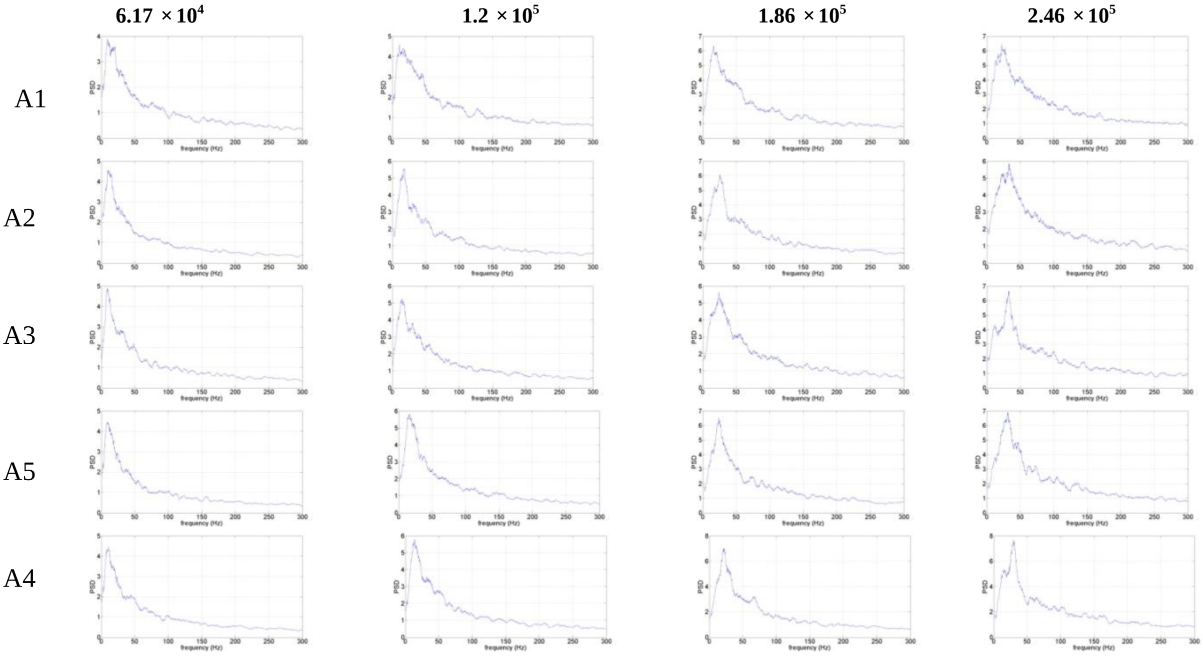


Fig. 8. Power spectrum of flows over all the investigated configurations at four different Reynolds numbers

IV. Conclusion

The flow over cylinders with patterned surface of k/d = 1.98×10^{-2} were investigated in a subsonic wind tunnel by measuring drag, velocity profiles in the wake region and smoke flow visualization for a range of Reynolds numbers from 3.14E+04 to 2.77E+05. Drag measurement results show that the drag coefficient of the configuration pressed outwards at 90° possesses the lowest drag coefficient which remains nearly constant even at higher Reynolds numbers unlike roughened cylinders. On the other hand patterned cylinder A3 behaves quiet similar to the dimpled cylinder at higher Reynolds numbers. Velocity profiles in the wake region of cylinders suggested that the wake of patterned cylinders is smaller than the wake of smooth cylinder accounting for reduction in drag coefficient. Smoke flow visualization confirmed that a delayed separation of flow is responsible for a smaller wake region and hence a smaller drag coefficient. Investigation of vortex-shedding frequencies using hot wire anemometry revealed that vortex shedding does not get stronger or irregular with the decrease in drag reduction.

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