Distribution of Dynamic Pressure in Micro-Scale of Subsonic Airflow around Symmetric Objects at Zero Angle of Attack

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***Abstract*—The turbulent flow pattern behind the objects induced by shape of solids and its skin-friction occurring, e.g., on the surface of an aircraft, automobiles or the carriage of a high-speed train, is responsible for excess fuel consumption and increased carbon emissions. The environmental, political, and economic pressure to improve fuel efficiency and reduce carbon emissions, and another factors associated with human activities, means that investigating fluid flow in micro scale to reduce skin-friction drag is a pressing engineering problem. This paper is presenting the results of laboratory experiments, studying appearance and magnitude of dynamic pressure in micro scale of subsonic air flow around right cylinder and symmetrical airfoil.**

***Index Terms*—Airflow, dynamic pressure, micro scale, symmetric object**

I. Introduction

Recent advances in science and technology are dedicate to make some devices smaller, however, the behavior and control of Fluid Flow at micro scale are not well understood. As a result, many researches and studies are developing in this field.

First of all, it is necessary and important to define concepts of boundary layer. The boundary layer defined as “a very thin layer of air flowing over the surface of an aircraft wing, or airfoil” [1]. The molecules directly touching the surface of the wing are virtually motionless. Each layer of molecules within the boundary layer moves faster than the layer that is closer to the surface of the wing. At the top of the boundary layer, the molecules move at the same speed as the molecules outside the boundary layer. The actual speed at which the molecules move depends upon the shape of the solid, the viscosity of the fluid flow, and its compressibility. As the boundary layer moves toward the center of the wing, it begins to lose speed due to skin friction drag. Next, at some point on the back side, the boundary layer separates from the obstacle's surface to form a vortex-filled wake, which transverse dimensions are similar to those of the obstacle itself and this phenomena is called boundary layer separation or separation point [2]. Author in [3] mentioned that in a fluid regime as dimensions decreases body forces become less important and surface forces become prominent. In the same way, the dimensions of a fluid regime are critical in order to the analysis of micro-scale.

According to “New Trends in Fluid Mechanics Research” [2] advances and applications in fluid dynamics are occurring at a rapid pace, and importance of understanding a fluid flow dynamics in micro scale is increasing. Consequently of this, it is resulting technology called micro-fluidics when the typical sizes of the fluid carrying channels are smaller than 1 millimeter, and the ability to control fluids in channels of such small dimensions is leading to advances in basic research and technological innovations in biology, chemistry, engineering, and physics. Likewise, in [4] author mentioned that smaller systems allow flow and reactions to be analyzed more rapidly, facilitate manipulation of medically relevant blood cells, and can be mass produced. Future developments in micro- fluidic science and engineering will have a wide impact on the world-wide economies. Understanding fluid dynamics in micro scale will be crucial to advances in science and engineering.

Authors in [4] consider that there are contradictory data in the researches that difficult the understanding the “micro-effects”. They investigated the problems of micro-hydrodynamics in different contexts. Therefore, they development the studies performed in these directions to encompass a vast class of problems related to flow of incompressible and compressible fluids in regular and irregular micro channels under adiabatic conditions, heat transfer, as well as phase change. This research is a big step in the field of fluid flow in micro scale. In the same way, a series of experiments are presented to demonstrate significant drag reduction for the laminar flow of water through micro- channels using hydrophobic surfaces with well-defined micron-sized surface roughness. Authors demonstrated in a set of experiments the existence of laminar drag reduction in micro channels having walls fabricated from hydrophobic surfaces with well-defined micron-sized roughness.

The fluid flow characteristics are determined by both inertia and viscosity of the fluid, but in micro scale the fluid flow can have different behaviors. In [5], [6] authors mentioned, that in micro scales the importance of surface forces increase dramatically when compared to body

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(volume) forces, which typically dominate on macro scales.

Good known, if right cylinder is not rotating the pattern of subsonic flow around the cylinder is symmetrical and there is no pressure difference to provide lift or curve.

So, according to traditional understanding in macro scale, for subsonic fluid flow around symmetrical objects at zero angle of attack, the pressure near opposite symmetrical points of object supposed to be the same. We decided to check experimentally this assumption in micro scale of subsonic fluid flow pattern. The results of experiments presented below on Fig. 1.

Apperance and magnitude of pressure around right cylinder on the graphs (Fig. 1) show, that Ideal fluid flow pattern remains attached all around the cylinder. In Real fluid flow, viscosity causes the flow to separate from the surface of the cylinder, and also we noticed, that locations of the points of flow separation on the upper and lower surfaces of cylinder are not cymethrical, as it was in macro scale.

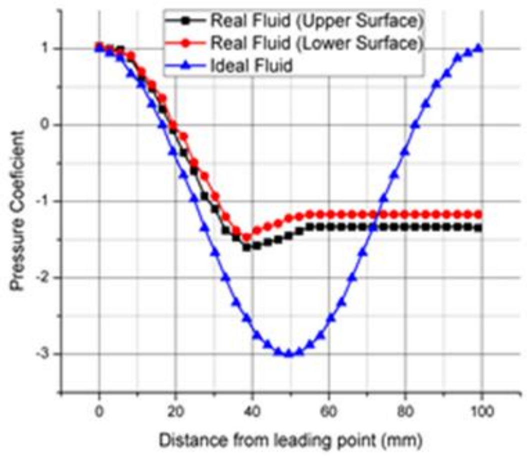

Figure 1. Appearance and magnitude of pressure of real and ideal fluids around right cylinder at flow velocity V = 30 m/sec, ambient temperature T = 18^{0}C, atmospheric pressure P = 1035 mbar and wall static pressure -71 mm H_2O.

We assumed, that in micro scale the appearance of dynamic pressure around the symmetrical object at zero angle of attack is not the same as in macro scale, because in micro scale is possible some influences of differences in ambient static pressure on the upper and lower surfaces of the cylinder, because good known that:

$$\frac{\partial P}{\partial Z} = -\rho g \quad (1)$$

$$\frac{\partial P}{\partial X} = 0 \quad (2)$$

$$\frac{\partial P}{\partial Y} = 0 \quad (3)$$

where: $\partial P/\partial Z$ -variations of pressure (∂P) in vertical (∂Z) scale; $\partial P/\partial X$ - variations of pressure (∂P) in horizontal (∂X) scale; $\partial P/\partial Y$ - variations of pressure (∂P) in horizontal (∂Y) scale.

To check our hypothesis we completed experiments in aerodynamic tunnel with right cylinder and symmetrical airfoil, positioned in testing area horizontally (first set of experiments), and vertically (second set of experiments).

II. Experimental Equipment and Procedures

The laboratory experiments were performed to obtain information (results) and investigate how the dynamic pressure appears and changes in macro and micro (in boundary layer) scales of subsonic flow pattern around right cylinder and symmetrical airfoil at zero angle of attack, but for horizontal and vertical positions.

A. Experimental Equipment

AF100 subsonic wind tunnel Compact, practical open-circuit suction subsonic wind tunnel used for the experiments. Air enters the tunnel through an aerodynamically designed diffuser (cone) that accelerates the air linearly. It then enters the working section and passes through a grill before moving through a diffuser and then to a variable-speed axial fan. The grill protects the fan from damage by loose objects. The air leaves the fan, passes through a silencer unit and then back out to atmosphere. A separate control and instrumentation unit controls the speed of the axial fan (and the air velocity in the working section). The control and instrumentation unit also includes manometers and electrical outlets to supply electrical power to other optional instruments. The working section of the tunnel is a square section with a clear roof, sides and floor. The sides are removable. The floor and each side panel has a special position to support the optional wind tunnel models. Supplied with the wind tunnel are a protractor and a model holder to support and accurately adjust the angle of any models fitted. A Pitot-static tube and a traversing Pitot tube fit on the working section, upstream and downstream of any models. They connect to the manometers of the instrumentation unit (or other optional instruments) to show pressure.

The Airfoil Model is symmetrical NACA0012 sectional airfoil of 300 mm span and 150mm chord. Airfoil has 20 pressure tapings that located symmetrical on the upper and lower surfaces of the airfoil.They are routed to set of small diameter tubes that emerge from the end of the aerofoil and connect to small labelled flexible pipes with adaptors (tappings) for connection to a larger diameter pipe. When the aerofoil is fitted in the wind tunnel, the pressure tappings may be connected to monometers for pressure measurement.

The Cylinder Model of 63.5 mm diameter and 300 mm length is made from a tube with one end sealed and the other end fixed to a hollow model support shaft with a pressure connection. When fitted inside the working section of the wind tunnel, and connected to a suitable pressure measurement device, the cylinder can be rotated to measure the pressure at any point and give the pressure distribution around the cylinder.

Pressure Measurement The two manometers (Kimo liquid column manometers) connect to the two Pitot Static tube assemblies on the working section of the Wind Tunnel, they both mount on the top of working section. Both units have a traverse mechanism, so that they may measure the air pressures across the working section from top to bottom. The Pitot static tube has two connections with monometer: one for the total pressure and another for static pressure (difference between total and static pressure shows the dynamic pressure in mmH_2O).

B. Experimental Procedures

To determine the pressure distribution around the right cylinder we fitted Cylinder Model in Horizontal position (first set of experiments) in testing area of Wind Tunnel. The Cylinder faced into the airflow (toward the inlet of the wind tunnel), and the pressure measurement hole of cylinder is at the same height as the centerline of the model and testing area (Fig. 2).

We took measurement of pressure at the interval of the each of 2.75 mm points (total of 48 points) of upper and lower surfaces of Cylinder Model by changing (rotating) the location of pressure measurement hole.

Next, for the second set of experiments with Cylinder Model we fitted the model in testing area vertically (see Fig. 2) and took measurement of pressure parameters at the same 48 points of surface. All experiments with Cylinder Model were completed at air flow speed in wind tunnel V=33 $m.s^{-1}$, wall static pressure -39 mmH_2O, atmospheric pressure 1035 mbar, ambient Temperature 17^0C and calculated air density 1.244 kg/m^3.

Figure 2. Cylinder model (63.5 mm diameter and 300 mm length) fitted in wind tunnel in horizontal (left) and vertical (right) positions to take measurements of pressure appearance and magnitude in micro scale of fluid flow around surface of model.

To investigate the pressure distribution (appearance and magnitude) around the symmetric airfoil we fitted *NACA0012 sectional airfoil (300 mm span and 150mm chord)* in Horizontal position (first set of experiments with symmetrical airfoil) in testing area of Wind Tunnel.

We positioned the airfoil at zero angle of attack and took measurement of pressure at 21 points of upper and lower surfaces of Symmetric Model (Table I).

TABLE I. TAPPING POSITIONS ON THE SYMMETRIC NACA 0012 AIRFOIL

Upper	Distance from Leading Edge.	Lower
0	0.0	0
1	0.76	2
3	3.81	4
5	11.43	6
7	19.05	8
9	38.00	10
11	62.00	12
13	80.77	14
15	101.35	16
17	121.92	18
19	137.16	20

Then, for the second set of experiments with Symmetric Airfoil Model, we fitted the model in testing area vertically and took measurement of pressure parameters at the same 21 points of surface. All experiments with Symmetric Airfoil Model were completed at Zero angle of attack and air flow speed in wind tunnel V=33 $m.s^{-1}$, wall static pressure -39 mmH_2O, atmospheric pressure 1035 mbar, ambient Temperature 17^0C and calculated air density 1.244 kg/m^3.

III. RESULTS AND DISCUSSION

To investigate how the dynamic pressure appears and changes in micro scales of subsonic flow around right cylinder and symmetrical airfoil at zero angle of attack, the laboratory experiments were performed for horizontal and vertical positions of models. The results of experiments for Right Cylinder Model fitted in Work Section in Horizontal and Vertical positions presented below on Fig. 3 and Fig. 4.

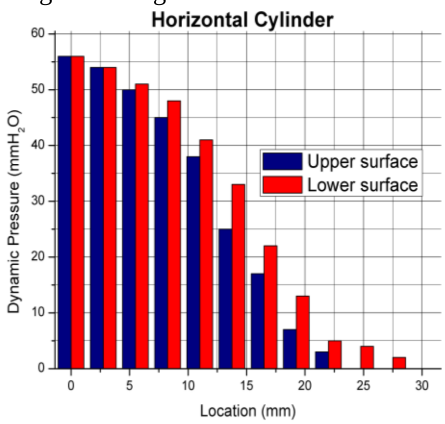

Figure 3. Dynamic pressure magnitude and appearance at the different points of upper and lower surfaces of horizontal located cylinder at flow velocity V = 30 m/sec, Ambient temperature T = 180C, Atmospheric Pressure P = 1035 mbar and Wall Static Pressure -71 mm H_2O.

We can see that for horizontal position of the Cylinder the pressure magnitude for the upper and lower surfaces at the front part of object (about 15 - 20 % of total surface) is equal, symmetrical and balanced.

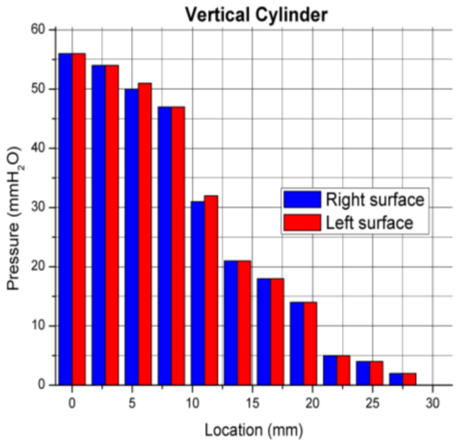

Figure 4. Dynamic pressure magnitude and appearance at the different points of right and left surfaces of Vertical located Cylinder at Flow Velocity V = 30 m/sec, Ambient temperature T = 18^0C, Atmospheric Pressure P = 1035 mbar and Wall Static Pressure -71 mm H_2O.

Then appears some difference of pressure magnitude at symmetrically located points on upper and lower surfaces, and this difference increases with the distance from centerline. The difference varies from 3% at the front part of solid, to almost 45% at the rear part of model (Fig. 3). Dynamic pressure appearance and magnitude at the different, but symmetrically located points of the surfaces of Vertical located Cylinder shown on Fig. 4. We can see that for vertical position of the Cylinder the pressure magnitude for the upper (left) and lower (right) surfaces is equal, symmetrical and balanced and doesn't have any variations. Analysis show that for horizontal position of Right Cylinder the appearance of dynamic pressure at symmetrical points of upper and lower surface is not the same - non symmetrical! But for vertical position of the object the dynamic pressure at symmetrical opposite points is equal, symmetrical and balanced.

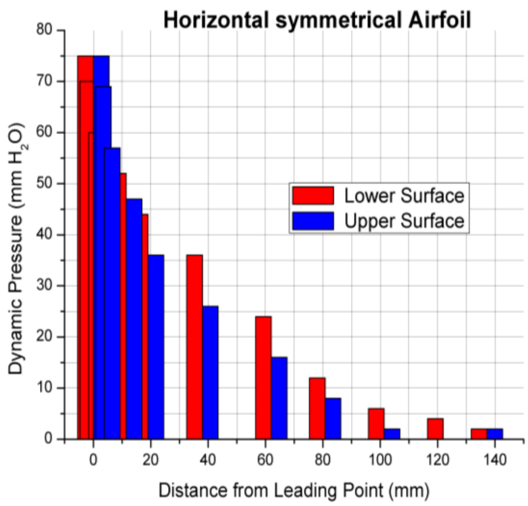

Figure 5. Dynamic pressure magnitude and appearance at the different points of upper and lower surfaces of Horizontal located cylinder at flow velocity V = 30 m/sec, ambient temperature T = 180C, atmospheric pressure P = 1035 mbar.

The appearance and changes of dynamic pressure in micro scales of subsonic flow around symmetrical airfoil in horizontal (at zero angle of attack) and vertical positions presented below on Fig. 5 and Fig. 6. The graph on Fig. 5 shows that in front part of airfoil located horizontally, close to leading edge, the magnitude of the pressure is the same in micro scale of fluid flow around upper and lower surfaces. With increasing distance from leading edge, the pressure at lower surface becoming greater, than at upper surface. The pressure difference increases at the points located closer to trailing edge, and maximum difference reaches up to 25% greater than at symmetrical point on upper surface. The dynamics of pressure distribution in airflow around symmetric airfoil (at zero angle of attack) is similar to pressure changes around Right Cylinder in horizontal position.

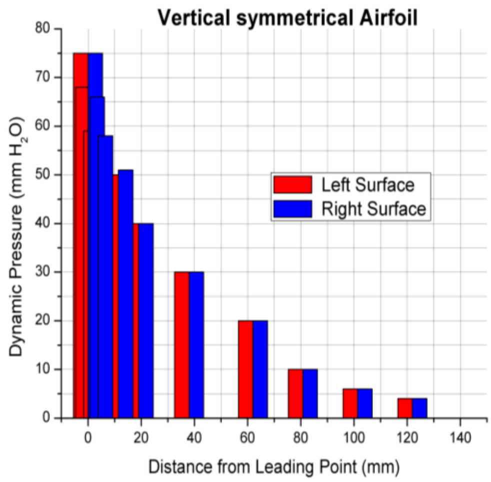

Figure 6. Dynamic pressure magnitude and appearance at the different points of upper and lower surfaces of Horizontal located Cylinder at Flow Velocity V = 30 m/sec, Ambient temperature T = 180C, Atmospheric Pressure P = 1035 mbar.

Pressure appearance and magnitude in fluid flow around upper (right) and lower (left) surfaces of Symmetric Airfoil, fitted vertical to work section of Wind Tunnel, presented on Fig. 6, where we can see, that variations of pressure at the points of the opposite surfaces are symmetrical and balanced.

Analysis show that for subsonic airflow and horizontal position of symmetrical object, at zero angle of attack, the appearance of dynamic pressure in micro scale at symmetrical points of upper and lower surface is not the same - non symmetrical! But for vertical position of the object the dynamic pressure at symmetrical opposite points is the same.

Next, we decided to investigate in macro scale the Wake of a cylinder using measurements of the dynamic pressure downstream from the model. Integrating the profile of the dynamic pressure across the wake perpendicular to the flow gives us understanding of the locations (symmetrical or non-symmetrical) of flow separation points and flow patterns behind the cylinder.

Whenever an object is moving in a fluid (or whenever a fluid is moving relative to an object) at a large enough speed (Re > 1), there is always a wake trailing behind. Fig. 7 gives a picture of the Dynamic pressure profiles for the cylinder at Fluid Flow Velocity V = 30 m/sec, Ambient temperature T = 19^0C, Atmospheric Pressure P = 1035 mbar and R=8500.

Three Dynamic Pressure profiles were measures for positions at P_1, P_2, and P_3 (25 mm, 45 mm, and 65 mm from the trailing edge of model). The 2D parameters of Dynamic pressure in the wakes were measured using the Pitot tube by moving it in “Y” scale.

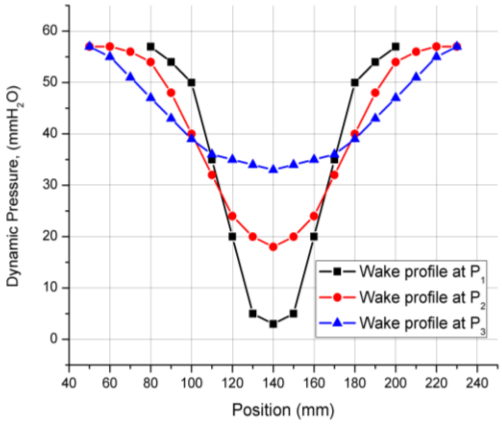

Figure 7. Wake Profile of Right Cylinder at various downstream locations (P1 = 25 mm, P2 = 45 mm and P3 = 65 mm) from the Trailing edge of model

Closer to the cylinder (P_1) the profile is thin and the deficit is large (Fig. 7). As the wake travels downstream it broadens while as the same time keeping the same geometry and the same Dynamic pressure. This confirms the theoretical picture of a cylinder wake spreading downstream. Also from Fig. 7 it is noted that since the curves are all centered about the same location, the wake travels symmetrical and straight downstream.

A majority of our Dynamic pressure measurements for both the cylinder and airfoil were in agreement with good known theoretical results given the precision of the experiment. Even thought that distribution of Dynamic pressure in micro scale of Subsonic airflow around horizontal symmetrical objects is not symmetrical at opposite points of upper and lower surfaces, the appearance and magnitude of dynamic pressure in macro scale of the Wake behind model is symmetrical and balanced.

IV. Conclusion

The laboratory experiments were performed to obtain information (results) and investigate how the dynamic pressure appears and changes in micro (in boundary layer) scales of subsonic flow pattern around horizontally and vertically positioned right cylinder and symmetrical airfoil at zero angle of attack. A majority of our Dynamic pressure measurements for both the cylinder and airfoil were in agreement with good known theoretical results given the precision of the experiment.

In micro scale of subsonic fluid flow the ambient static pressure influences on appearance of dynamic pressure around symmetrical objects. Magnitudes of dynamic pressure at opposite surfaces of object depend on good known factors and also on position of object in 3-D space. At horizontal position of object the dynamic pressure appearance at opposite surfaces in micro scale is not symmetrical, and it becomes symmetrical at vertical position of the object.

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// September-December, 2015 pp 107-115 and E. Martinez, "Critical Success Factors of Six Sigma" in Proceedings of the 2nd Annual World Conference of the Society for Industrial And Systems Engineering, Las Vegas, NV, USA November 5-7, 2013 pp 94-100.
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