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Velocity, Turbulent Intensity and Pressure Measurements in Turbulent Separated and Curved Flows

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Abstract**—*****Velocity, turbulent intensity and pressure measurements over various flow surfaces were carried out by a constant-temperature hot wire anemometer and a micro-manometer. The experiments performed over a flat plate, curved walls with a radius of 2.54 m either in concave or convex curvatures and a ribbed wall has a sequence of 7 ribs at the free stream velocity of 20 m/s encompassing turbulent flows. The results showed that the concave curvature destabilized the flow and increased turbulent intensity, contrary to the convex curvature. The presence of the ribs also caused bigger turbulent intensities and the flow separations and reattachments were determined before the first rib, between the ribs, on the first rib and behind the last rib.***

Index Terms**—*****Flow separation, turbulent intensity, curved flow, ribbed surface***

I. INTRODUCTION

The flow characteristics over the surfaces with surface curvature and ribs have in the past been the subject of numerous investigations because of its relevance in a multitude of engineering applications. Because the flow surfaces were investigated separately, the existing literature which shows an insight into the detailed flow behavior is still limited. Previous studies pertinent to this work are briefly summarized below.

Terekhov and Yarygina [1] analyzed the effect of free-stream turbulence on flows over obstacles and indicated that the effect of enhanced free-stream turbulence on the separated flow was much more pronounced than that of flat surface. The forced convective flow over two sequentially heated blocks was examined experimentally and numerically by Chen and Wang [2], who compared the experimental and numerical results and discussed the effect of the block spacing on heat transfer. Ryu, Choi and Patel [3] investigated the turbulent flow in channels roughened by two-dimensional ribs and three-dimensional blocks and they indicated that the different block arrangements exhibit distinct flow characteristics. Young and Vafai [4] performed a detailed investigation of the forced convection cooling process in a channel with an array of heated obstacle mounted on a horizontal wall. An experimental study was performed on the flows over grooved-walls by Wahidi, Chakrouni and Al-Fahed [5], who indicated that an increase in the drag over the smooth-wall was found in all cases.

Agelinchaab and Tachie [6] reported that the flow characteristics of the blocked surface were mainly dependent on block geometry. The turbulent flow in a channel with transverse rib roughness was investigated numerically by Cui, Patel and Lin [7] and they reported that the rib roughness elements imposed their own characteristic length scales on near-wall flow structures. Terekhov, Yarygina and Zhdanov [8] studied on the flows over a rib and a downward step in separation-flow regions and they stated that the rise of free stream turbulence suppressed flow separation. Miyake, Tsujimoto and Nakaji [9] carried out a numerical study on the turbulent flow in channels with rib-roughened wall, and offered that the major effect of the roughness element was to enhance the turbulent mixing and heat exchange. Boundary layer transition under high free-stream turbulence and strong acceleration conditions was investigated by Volino and Simon [10] who reported that high free stream turbulence shortens the transition length. Zhou and Wang [11] studied on combined effects of free-stream turbulence and streamwise acceleration on flow and thermal structures. Turbulent transport measurements in a heated boundary layer with combined effects of free stream turbulence and removal of concave curvature were carried out by Kestoras and Simon [12] and they determined that turbulence quantities immediately dropped at the bend exit. Turbulent boundary layer heat transfer on curved surfaces was studied by Mayle, Blair and Kopper [13]. Umur [14] carried out a study on the concave wall heat transfer characteristics with longitudinal pressure gradients and discrete wall jets and Zhang, Winoto and Chew [15] also studied on the measurement in laminar and transitional boundary-layer flows on concave surface, while Muck, Hoffman and Bradshaw [16] investigated the effect of convex surface curvature on turbulent boundary layers.

In the present study, the flow behavior over the concave, convex and ribbed surface is investigated experimentally at the free stream velocity of 20 m/s in turbulent flow and the measurements compared with each other and the flat plate values.

II. EXPERIMENTAL METHOD

Experiments were conducted in the blowing-type, low-speed wind tunnel in the Fluid Mechanics Laboratory of the Mechanical Engineering Department at Uludag University. The tunnel is run by a 5.7 kW axial fan and the flow rate is controlled by a butterfly valve. The free stream turbulence intensity in the wind tunnel is on average 0.7% at a free stream velocity of 30 m/s.

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Air passes through a metal duct, a honey comb with a cross-sectional area of 0.305mx0.305 m and thick of 0.15 mm, a nozzle which has 1.5:1 contraction ratio and 0.2mx0.305 m exit area and a straight duct with 400 mm length before the test section. The test section has 1.5 m. long and a cross section dimension of 0.2mx0.305 m. The sidewalls of the test section is made of clear acrylic (plexiglass) to provide full visibility of the flow area and the upper wall has a longitudinal channel to provide a clear access for the velocity probes.

The flow surfaces which have 0.24 m spanwise distance and 0.0008 m thick are shown in Fig. 1. The concave and convex surfaces with a radius of 2.54 m have the streamwise distance of 1.25 m, while those of the flat and ribbed surface are 0.75 m and 0.57 m, respectively. The ribbed surface with a sequence of 7 ribs has a rib height (h) of 0.02 m and width of 0.03 m, a distance between ribs of 0.03 m and a distance up to the first rib of 0.06 m. All measurements were performed at streamwise x-locations of 0.03, 0.075, 0.195, 0.315, 0.435, 0.555 and 0.675 m over the flat, concave and convex surfaces. The velocity, turbulent intensity and static pressures of the ribbed surface were measured at interval of 5 mm in the streamwise and 1 mm in the pitchwise directions.

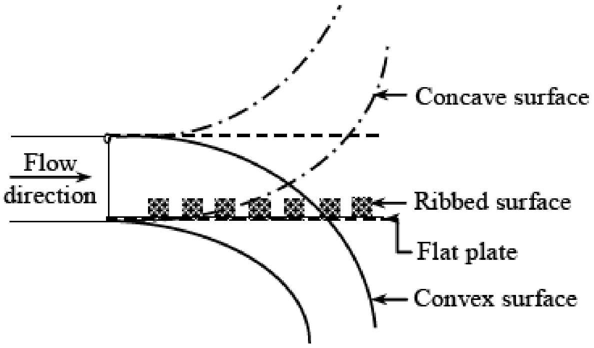

Fig. 1. Test section and heated surfaces assembly

A constant temperature hot wire anemometer (CTA) was used to obtain the mean velocity and turbulence intensity profiles of the all surface. A single wire probe (DANTEC 55P11) with probe support (DANTEC 55H20) and cable, a signal conditioner, an A/D converter (NI-PCIMIO-16 E-4) and a computer were also used in with the (CTA), as shown in Fig. 2. Furthermore, 3-D movements of the probe in the test section were provided with a traverse system, while the correct and rapid experiment results were obtained by a calibration device (DANTEC 90H020). The static pressures of the all surface were measured using pressure tappings with a diameter of 0.0008 m and were recorded by a micro-manometer.

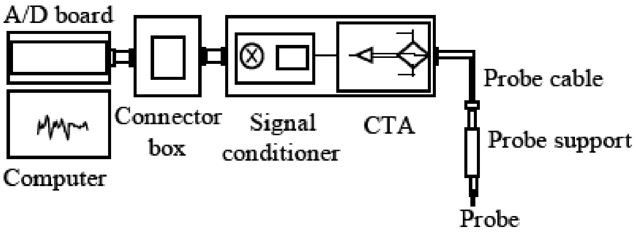

Fig. 2. Constant temperature anemometer and measuring equipment

The boundary layer parameters of boundary layer thickness (δ), streamwise distance Reynolds numbers ($Re_x = Ux/\nu$), momentum thickness Reynolds number ($Re_\theta = U\theta/\nu$) and shape factor ($H = \delta^*/\theta$) were used to identify the boundary layer over flat, concave and convex surface. The turbulent intensities and static pressure coefficients of all surfaces were calculated by $Tu=100xu_{rms}/U$ and $C_P=(P-P_0)/0.5\rho U^2$, respectively.

The maximum uncertainty of the velocity measurements considering the electronic noise, probe positioning, A/D resolution and environmental condition errors was obtained as 2.2%, while those of the pressure measurements caused by manometer slope, reading, surface stresses and random experimental error was found as ±4.5%. The overall uncertainty in the Reynolds number and pressure coefficient was estimated to be nearly ±2.3% and ±4.8% respectively, using the Kline and McClintock [17] uncertainty estimation method.

III. RESULTS AND DISCUSSION

The velocity and turbulent intensity profiles and static pressure coefficients were obtained at the inlet free stream velocity of 20 m/s over the flat, concave, convex and ribbed surface with near zero pressure gradients.

The dimensionless velocity profiles for the flat, concave and convex surface were presented at the first (x=0.03 m) and last (x=0.675 m) station in Fig. 3. The inlet boundary layer parameters of δ were obtained as 9, 12 and13, Re_x of $3.6x10^6$, $3.9x10^6$ and $5.7x10^6$, Re_θ of 1250, 1300 and 1600 and H of 1.15, 1.30 and 1.40 over the concave, flat and convex surface, respectively. These results showed that the inlet flow remained in turbulent region for all surfaces characteristics, which are in agreement with those of Kestoras and Simon [12] for the concave surface. The δ values of concave, flat and convex surface were varied as 11, 14 and 15, Re_x of $4.4x10^6$, $4.7x10^6$ and $6.6x10^6$, Re_θ of 1550, 2050 and 2300 and H of 1.2, 1.4 and 1.5 at the last measurement station respectively, which are similar to those of Volino and Simon [10]. The results indicated that the concave surface destabilized the flow and enhanced the onset of transition, contrary to the convex curvature.

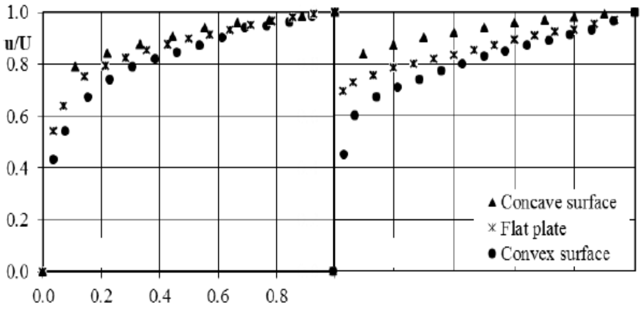

Fig. 3. Dimensionless velocity profiles over the concave, flat and convex surface

The location of separation and reattachment points over the ribbed surface were obtained by determination of mean zero velocity in experimental velocity profiles given in Fig. 4. The flow separated in front of the 1st rib at 0.5h and reattached on the rib at 1.1h, similar to Chen and Wang [2] results. The maximum local free stream velocity was obtained at the beginning corner of the 1st rib, due to the contraction and impact effects, as explained by Young and Vafai [4]. Recirculation regions also occurred in the cavities between the ribs and behind the last rib.

The length of the reattachment which formed due to the instant expansion and less momentum of behind the last rib was determined as 5.5h, in accord with the results of Ryu, Choi and Patel [3].

Streamwise variations of the turbulent intensities over the concave, flat and convex surface were shown in Fig. 5. The free stream turbulent intensities of the concave, flat and convex surface changed in the range of 2.2-1.72%, 1.3-0.56% and 1.0-0.45% in the streamwise distance, respectively. Because the effect of the surface curvature was to stabilize the boundary layer on the convex surface, the turbulent intensities decreased over the convex surface, contrary to the convex curvature and consistent with the Zhaoshun, Weidong and Hua [18] reports.

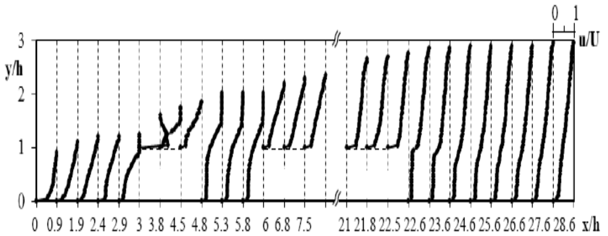

Fig. 4. Dimensionless velocity profiles over the ribbed surface

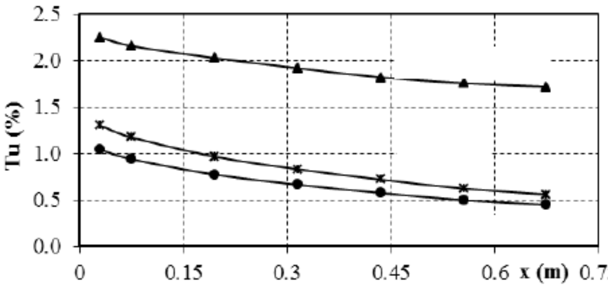

Fig. 5. Turbulent intensities with streamwise distance over the concave, flat and convex surface

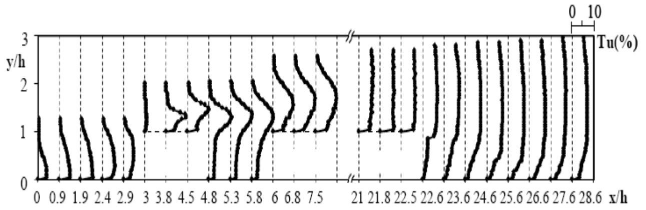

Fig. 6. Turbulent intensity profiles over the ribbed surface.

The turbulent intensities of the ribbed surface were measured in the range of 1.5-10.5% in streamwise direction, as presented in Fig. 6. The turbulence intensity value was found nearly 5.5%, 9% and 6% at the separation points before the first rib (y/h=0.25), over the 1st rib (y/h=0.4) and behind the last rib (y/h=1.4), respectively. The highest turbulent intensity was also determined between the ribs approximately 10.5% at y/h=1.25.

The pressure coefficients curves of the concave and convex surface were constant in the streamwise direction while that of the ribbed surface was variable, as seen in Fig. 7. The pressure coefficients took the positive values for the concave surface and the negative on the convex. The C_p values decreased initially, then increased up to the first rib and reached the minimum values at the front corner of the 1st rib where the maximum velocities occurred which is compatible to those of Nozawa and Tamura [19]. The values also increased over the first rib and then no remarkable change observed. The C_p increments pointed to the flow separations which were also verified with velocity and turbulent intensity measurements.

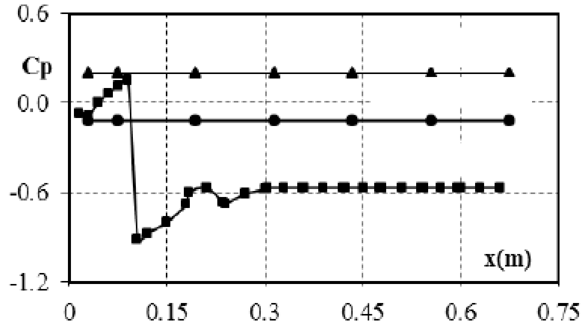

Fig.7. Pressure coefficients with streamwise direction over the concave, convex and ribbed surface

IV. CONCLUSION

The turbulent boundary layers over the flat, concave, convex and ribbed surfaces have been experimentally investigated in terms of the flow characteristics. It was found that the concave curvature destabilized the flow and caused thinner boundary layers, while the convex surface stabilized the flow and caused thicker boundary layers. The flow separations and reattachments were observed in front of the first rib, on the first rib, between the ribs and behind the last ribs. The presence of the concave curvature and ribs caused bigger turbulent intensities, while the smaller values were obtained on the convex surface, comparing to the flat plate. The great values of the turbulent intensity of the ribbed surface were also obtained at the corners of the ribs, separation regions and reattachment points. The pressure coefficient curves showed constant distribution in streamwise direction both on the convex and concave surface. The C_p values of the ribbed surface increased at the separation points, while the smallest value was obtained at the maximum velocity point.

Nomenclature

C_p pressure coefficient, [-]
h block height, [m]
H shape factor, [-]
P pressure, [Pa]
Re_x streamwise distance Reynolds number, [-]
Re_θ momentum thickness Reynolds number, [-]
Tu turbulence level, [%]
u streamwise velocity, [m/s]
u_{rms} root mean square velocity, [m/s]
U mean free stream velocity, [m/s]
x streamwise directions, [m]
y pitchwise directions, [m]
Greek symbols
δ boundary layer thickness, [m]
δ^* displacement thickness, [m]
θ momentum thickness, [m]
ν kinematic viscosity, [m^2/s]
ρ density, [kg/m^3]

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