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Experimentelle Untersuchung Turbulenter Strukturen und deren Beeinflussung in der Grenzschichtströmung

Experimental Investigation of Turbulent Structures and their Control in Boundary Layer Flow

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Abstract

One of the successful method to control near-wall turbulence and skin friction drag is Micro-Blowing Technique (MBT). Overall objective of this study was to investigate turbulent boundary layer within the range of $1788 \leq Re_\theta \leq 3800$, using Micro-Blowing at different blowing ratio. It was established that due to interaction between the main flow and the applied blowing from the surface in wall normal direction, an overlap layer was being formed, which blocks the energy exchange between the external flow and the surface of the permeable wall. In addition to surface friction quantification, mean properties of the boundary layer was studied. As a consequence of increasing blowing air amplitude, three distinct phenomena are observed in the flow: reduced friction drag, increasing stream-wise fluctuation and boundary layer thickness. The relationship between blowing velocity to these phenomena is discussed using statistical data.

Introduction

For subsonic and supersonic aviation industry, skin friction drag contribute to the maximum fuel consumption. Estimations show that, nearly 50% of the total drag of an aircraft and 30% of automobiles are constituted from skin friction drag (Kornilov et al. 2004). On the contrary, all the transportation system including automobiles in USA consumes 25 % to 27% of their total energy to overcome their aerodynamic drag (Wood et al. 2004). Experimental and numerical approaches has been extensively used to quantify different drag reduction method in aerodynamic and hydrodynamics flows such as vibrators, actuators, polymer additives, gas micro-bubbles, surfactants, riblets, large eddy break-up devices (LEBU), micro-electro mechanical systems (MEMS) and Micro-Blowing technique (MBT) (Hwang et al. 2004, Kametani et al. 2015). According to Hwang 2004, classified as an active drag reduction method, MBT is very promising to reduce skin friction drag reaching upto 50 % depending on the aspect ratio and geometry of the surface. However, several researches have been published to outline the statistical nature of the MBT application in turbulent flow and has established its proof of concept. Besides engineering application of MBT in drag reduction and controlling wall temperature, large interest has been observed to explain the influence of blowing phenomena over turbulent structures present in wall bounded flow. Recent DNS from Kametani et al. 2011 has shown that uniform blowing reduces the skin friction drag and simultaneously enhances turbulence, most significantly in the outer region of the boundary layer. In engineering applications and in nature, boundary layer flow is beyond the ranges that can be studied using wind tunnel experiments or numerical simulations. Despite providing with high quality data, numerical methods are limited to low Reynolds number regime due to its limitation imposed by the present day computational capacity. In 2015, Large Eddy Simulation (LES) from Kametani et al. had presented stochastic data of the flow upto $Re_\theta \approx 2500$ using 0.1 % as their blowing ratio compared to free stream velocity of the flow. This external flow input resulted in more than 10% of drag reduction over the blowing surface. Beside statistical data from measurements, in laboratory experiments, high Reynolds number flow is investigated with a focus towards coherent structures and most importantly their interactions in terms of frequency, energy content and wave length. Much of the efforts being utilized for the classical boundary layer flow, spacious scope is there to study the same when external flow is applied. Large organized vortex clusters forming superstructures, that dominate the turbulent air flow in nature and technology, can cause high velocity fluctuation. They affect the global transport of mass, heat and momentum. The control of wall bounded turbulent flow can be achieved through the control of large-scale structures and very large-scale structures which are vividly termed as LSM and VLSM. For instance, Smits et al. 2011 argued that with regard to the coherent motions, VLSMs or superstructures exist at all Reynolds number, but they become increasingly important in terms of their energy content and their interaction with the smaller scales near the wall with increasing Reynolds number. Besides flow over unperturbed zero pressure gradient (ZPG) boundary layers investigated in the former reference, synergistic phenomena between LSM and VLSM are still unexplained when the flow is actively influenced by low magnitude uniform blowing. With the help of stochastic study of the mean parameters within the range of moderate Reynolds number regime, this experiment aims at analysis of MBT application in ZPG boundary layer. Present results exhibit progressive evidence of changing mean flow properties using stochastic and instantaneous data. Accurate skin friction measurement is highly important as a part of boundary layer flow investigation and becomes increasingly difficult with increasing Reynolds number. Moreover, complex flow interaction between blowing and mean flow has restricted the applicable measurement technique for skin friction measurement. In this paper changes in salient boundary layer properties due to MBT will be presented in comparison to their flow over smooth surface.

Experimental Setup

The experiment was realized using a closed-return subsonic wind tunnel at Brandenburg University of Technology, Cottbus, Germany at $1788 \leq Re_\theta \leq 3800$, where Re_θ is the Reynolds number obtained using momentum thickness (θ), free stream velocity and fluid kinematic viscosity (ν). The wind tunnel has a test section of $0.6 \times 0.5\, m^2$. Test section has an optical access made from glass with minimum refractive index deviation (Fig.1 (a)). Details of the wind tunnel parameters can be found in Zanoun et al. 2014. A total of 24 measurements were performed in different wall normal heights at a constant stream-wise position using Laser Doppler Velocimetry (LDV). Mean and statistical measurement was extended further to identify the instantaneous state of the turbulent structures using Particle Image Velocimetry (PIV). However, in this paper, experiment using LDA technique will be highlighted and initial results from PIV will be reported. Data acquisition was performed at x = 58 % in z = 33 % which represent the stream-wise and span-wise position respectively over the plate (Fig.1 (b)). Accurate measurement of wall shear is paramount to determine the viscous scaling of the flow. On the other hand, emphasis was given to precise measurement of the wall normal distance (y). However, there are several method to measure the wall shear and friction coefficient (τ_w and C_f), according to Smits et al. 1983, 2D measurement of the velocity component near the wall where $yu_\tau/v < 10$ is suitable for flow within moderate Reynolds number. A label printed tape letter X ($0.7 \times 5\, mm^2$, height × width) in a row at stream-wise position of x = 5 % was used as the tripping device for early transition to the turbulent regime. Two smaller sections of smooth flat plates ($250 \times 125 \times 14\, mm^3$, length × width × height) were prepared to install in the main frame of the main flat plate ($1055 \times 595 \times 14\, mm^3$, length × width × height). First measurement was taken installing smooth anodized aluminum plate to obtain a non shiny black surface to avoid LDA light reflection. To apply constant blowing, a second plate was manufactured with the same exterior dimension with electron beam drilled holes, uniformly distributed over the entire surface. Fig.1 (c) represents the microscopic view of the perforated region. Each hole in the surface having a diameter of 0.18 mm and equidistant to each other by 0.4 mm. Porosity of the perforated plate is 18 % and aspect ratio (Thickness/hole diameter) is 5.55. Porous surface is attached to a pressurized chamber where air is supplied from cylinder through a digital flow meter, DFM-47 (Aalborg 47), with an accuracy of ± 1 % via hermetically sealed pneumatic system. Using the flow rate and porosity of the surface, blowing velocity is applied and verified using LDA data taken at a wall normal distance of 0.013 mm. For subsequent presentation of the result, smooth solid plate and perforated plate will be indicated as plate-1 and plate-2 respectively. A constant blowing velocity in the range of 0, 0.075 and 0.15 m/s was applied. When blowing velocity is expressed as a fraction of free stream velocity, U_∞ in percentile, thus we obtain the blowing ratio, F. Blowing ratio can also be expressed in terms of Reynolds number based on hole diameter and the local velocity at individual hole outlet, which in this case is $0 < Re_D < 1.72$.

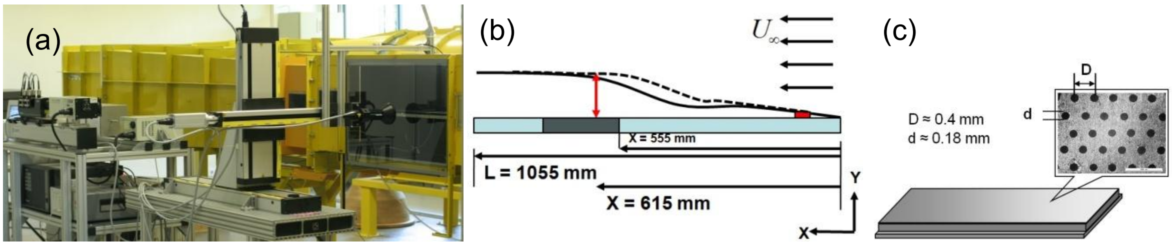

Fig.1: (a) Photograph of LDA setup, (b) Schematic of the flat plate in XY plane, measurement location indicated with red arrow and (c) Schematic of the perforated plate, inset figure indicate microscopic view. (Motuz. 2014)

Result and Discussion

Mean stream-wise velocity profiles at, $Re_\theta = 1788$, is presented in Fig.3:(a). Kornilov and Boiko, 2012, proposed a new technique for the scaling of the outer region of the boundary layer, where the empirical data is normalized with, $(U_\infty/\delta^*)/\delta_{99}$ (Here, U∞ is the corresponding free stream velocity, δ^* is the displacement thickness and δ_{99} is the boundary layer thickness obtained from the condition, $u/U_\infty = 0.99$). From Fig.2 (a), a distinct change of the mean flow is visible for different blowing ratio. As the blowing ratio increases, mean stream-wise component reduces within the wall normal distance at about 0.1 to 0.6.

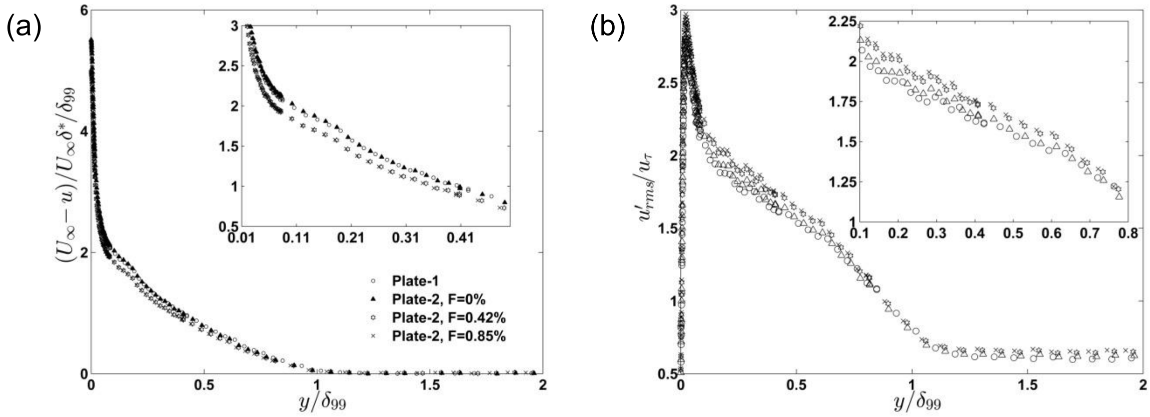

Fig.2: (a) Stream-wise mean velocity profiles normalized using outer scaling variables for Re_θ=1788, 0 < *F* < 3 %, (b) Level of velocity fluctuation (Root mean square) profiles normalized with friction velocity, designations are the same as in (a).

The inset figure shows the precise difference of velocity reduction. Fig.2 (b) exhibit RMS fluctuation of the stream-wise velocity component and presented with local viscous scaling, u_τ (Here, Friction velocity, $u_\tau = \sqrt{\tau_w/\rho}$, where τ_w is the wall shear and ρ stands for air density) for the same flow condition. From this figure an opposite trend of increasing turbulence is observed in the outer region. It is also interesting to see the changes in boundary layer profile for changing blowing ratio. Fig.3 (a) is another presentation of the measurement over plate-2, using local inner viscous length scale as a scaling parameter. Here, mean flow in the viscous sub-layer is qualitatively indifferent to blowing application. At the same Reynolds number, applying blowing at $= 0.4$ %, 13 % of friction reduction is achieved compared to no blowing application. This in terms, contribute to the scaling of RMS fluctuation of mean stream-wise velocity component. Most interesting phenomena that is observed here is that, the emergence of the second peak in the logarithmic layer stretching up to wake region. Wall normal distance is presented here as a product of Friction velocity and kinematic viscosity. Mean profiles obtained from non-blowing cases follow the logarithmic profile where, $U^+ = 1/C \ \ln y^+ + B$ using constants, $C = 0.41$ and $B = 5.5$. As Kametani and Fukagata 2011, showed that uniform blowing induces turbulence in the outer region of the boundary layer flow even at momentum thickness Reynolds number as low as 700, similar phenomena within the bound of all Reynolds number range in this experiment has been observed. It is also reported from Kametani et al. 2015 that uniform blowing has a steady impact with the progressive Reynolds number. LES performed from the mentioned literature was limited to $Re_\theta = 2500$. Fig.4 shows the spatial growth of the boundary layer momentum thickness Reynolds number for blowing at different ratio over plate-2 as a function of plate-1 (smooth surface). Linear dependence of the increasing boundary layer thickness is determined using least square fit of the linear regression using the empirical values. However, due to limited scope within the bound of this paper, preliminary PIV results are shown in Fig.5. where (a) presents the instantaneous vortices over plate-1 and (b) shows the changes of vortices over perforated plate at $F = 0.4\%$. Stream-wise and wall normal distance is scaled with the viscous length scale obtained from LDA measurements. Color scheme indicate local stream-wise velocity component and vectors indicate 2D components of the local velocity after subtracting from the mean values. Primary analysis of these images indicates a distinct spatial shift of the vortices in wall normal positions. The vortex packet, however, shows qualitative change in their spatial growth.

Conclusion

Despite the difficulty to measure data in viscous sub-layer, friction co-efficient over plate-1 is in good agreement to the data from Zanoun et al. 2014. Mean profiles of the flow is well fitted to the linear and logarithmic profiling. However, different outer scaling is being investigated for MBT application. Even at minimum blowing ratio, deviation from the traditional concept of logarithmic profiling is no longer satisfactory. Though, significant changes are present in the mean profiles at different ranges of blowing ratio, constants of the log-law requires further investigation for exact quantification. Standard deviation from turbulent fluctuation demonstrate a second peak in outer region for all ranges of Reynolds number investigated. It will be inquisitive to investigate the spectral ranges of the boundary layer, thus further measurements are required to study and quantify the turbulent parameters in the modified flow.

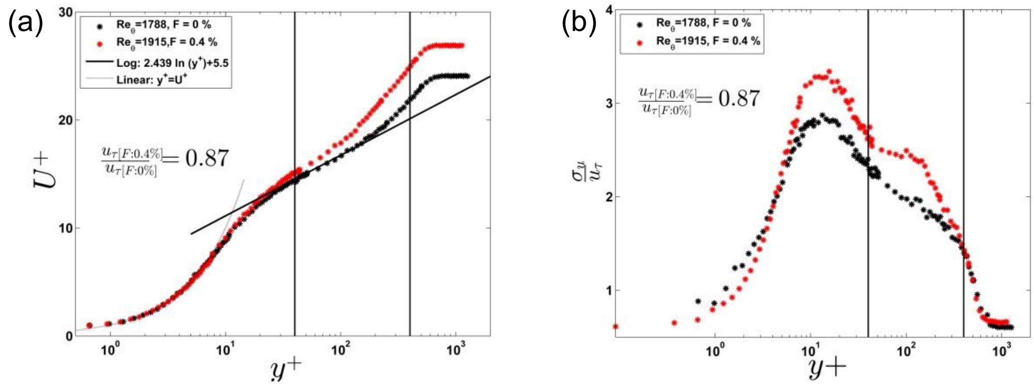

Fig.3: Time averaged LDA measurements at, $Re_\theta = 1788$ and 1915 scaled and plotted with inner variable; (a) Profiles of the mean stream-wise velocity in different wall-normal locations and (b) RMS stream-wise velocity fluctuation.

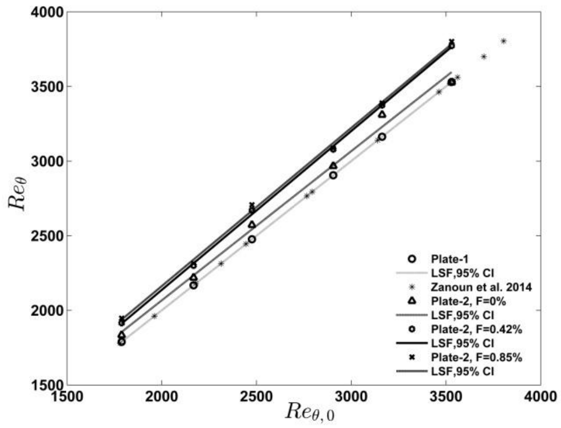

Fig.4: Reynolds number relation Re_θ for each blowing ratio over plate-2 as a function of the Reynolds number over plate-1 (smooth surface) $Re_{\theta,0}$. x represent the measurement from Zanoun et al. 2014

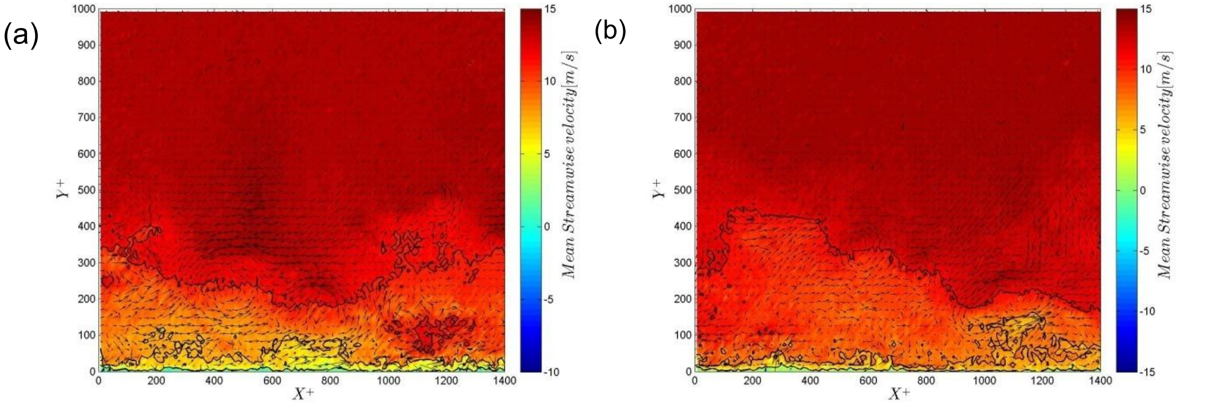

Fig.5: Instantaneous contour maps of stream-wise velocity with vector fields after subtracting from convection velocity, stream-wise and wall-normal plane scaled and plotted with the same inner variables, obtained using PIV measurement at Re_θ =1788 and 1915 (a) Flow over solid surface and (b) Flow over perforated surface at F = 0.4%.

Literature

Kornilov, V.I., 2005: "Reduction Of Turbulent Friction by Active and Passive Methods", Thermophysics and Aeromechanics, 2005, Vol. 12, No. 2, P. 175–196.

Wood, R., 2004: "Impact of Advanced Aerodynamic Technology on Transportation Energy Consumption". SAE International, Technical Paper 2004-01-1306

Smits, A. J., McKeon, B.J., Marusic I., 2011: "High–Reynolds Number Wall Turbulence", Annual. Rev. Fluid Mech, Vol-43, pp.353–75.

Motuz, V., 2014: "Gleichmäßiges Mikro-Ausblasen zur Beeinflussung einer Turbulenten Grenzschicht", Ph.D. Thesis, URL: http://nbn-resolving.de/urn:nbn:de:kobv:co1-opus4-31242 (28.04.2016).

Kametani, Y. & Fukagata, K. 2011: "Direct Numerical Simulation of Spatially Developing Turbulent Boundary Layers with Uniform Blowing and Suction". J. Fluid Mech. vol-681,pp.154–172.

Kametani, Y., Örlü, R., Schlatter, P. and Fukagata, K. 2014: "Drag Reduction in Turbulent Boundary Layers: Effect of Uniform Blowing and Suction", In Proceedings of 10th International ERCOFTAC Symposium on Engineering Turbulence Modelling and Measurement. Marbella, Spain.

Kametani, Y., Örlü, Schlatter, P. and Fukagata, K. 2015: "Drag Reduction in Spatially Developing Turbulent Boundary Layers by Blowing at Constant Mass Flux", In proceedings of 9th International Symposium on Turbulence and Shear Flow Phenomena, Melbourne, Australia.

Kametani, Y., Fukagata, K., Örlü, R., and Schlatter, P. 2015: "Effect of Uniform Blowing/Suction in a Turbulent Boundary Layer at Moderate Reynolds Number", International Journal of Heat and Fluid Flow, Vol-55, pp.132-142

Smits, A., J., Matheson, N., and Joubert, P., N. 1983: "Low-Reynolds-Number Turbulent Boundary Layers in Zero and Favourable Pressure Gradients", Journal of Ship Research, Vol-27, No-3, pp. 147-157

Kornilov, V., I., and Boiko, A.,V. 2012: "Efficiency of Air Microblowing Through Microperforated Wall for Flat plate Drag Reduction", AIAA, Vol-50, No-3, pp.724-732