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Energy-efficient flow control around blunt bodies

Nina F. Yurchenko*

Department of Thermal & Fluid Dynamic Modeling, Institute of Hydromechanics,
National Academy of Sciences of Ukraine, 8/4 Zheliabov St, Kiev 03680, Ukraine

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Abstract. The developed concept of smart flow control based on turbulence scale modification was applied to control a flow around a circular cylinder. The concept was realized using arrays of vortex-generators regularly spaced along a cylinder generatrix with a given step. Mechanical and thermal vortex-generators were tested, the latter having been based on the localized surface heating or plasma discharges initiated with microwave radiation near the surface. Thus depending on a particular engineering solution, flow transport properties could be modified in passive or active ways. Matched numerical and experimental investigations showed a possibility to delay flow separation and, accordingly, to improve the aerodynamic performance of blunt bodies.

Keywords: scaled vortices; thermal riblets; aerodynamic performance; multidisciplinary investigations

1. Introduction

Biological evolution-made systems are often found to be ahead of man-made products. Firstly, systems of living creatures are in a process of dynamical balance that helps them adjusting to varying conditions while engineering systems are static. Secondly, after a long period of science disintegration, only now a need has become clear to combine different disciplines on basis of common principles and goals. Well known drag reducing riblet surfaces were designed having taken the shark skin structure as a prototype (Fig. 1(a), (b)). However polymer riblet films provide only passive control of flow characteristics and, in addition, are not justified economically because of their short life time.

The next engineering solution exploiting the same idea (Yurchenko and Babenko 1980, Yurchenko *et al.* 1990, Yurchenko 2000) was developed on basis of an array of heated elements embedded in a model surface layer (Yurchenko and Delfs 1999). These “thermal riblets” maintain the surface smooth and control the flow in an active mode due to a varying $\Delta T(z)$ temperature boundary condition (Fig. 1(c)) (Yurchenko 2008, Yurchenko *et al.* 2008, Yurchenko 2010, Yurchenko and Esakov 2011). Matched numerical and experimental investigations showed that this approach enabled to manage a sustainable vortical structure near a surface to raise lift-to-drag values (Yurchenko *et al.* 2008, Yurchenko 2010, Yurchenko and Esakov 2011).

Active thermal riblets were demonstrated to have the same impact on the flow and to be no less efficient than passive mechanical riblets in terms of the aerodynamic performance improvement.

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*Corresponding author, Ph. D., E-mail: nina.yurchenko@gmail.com

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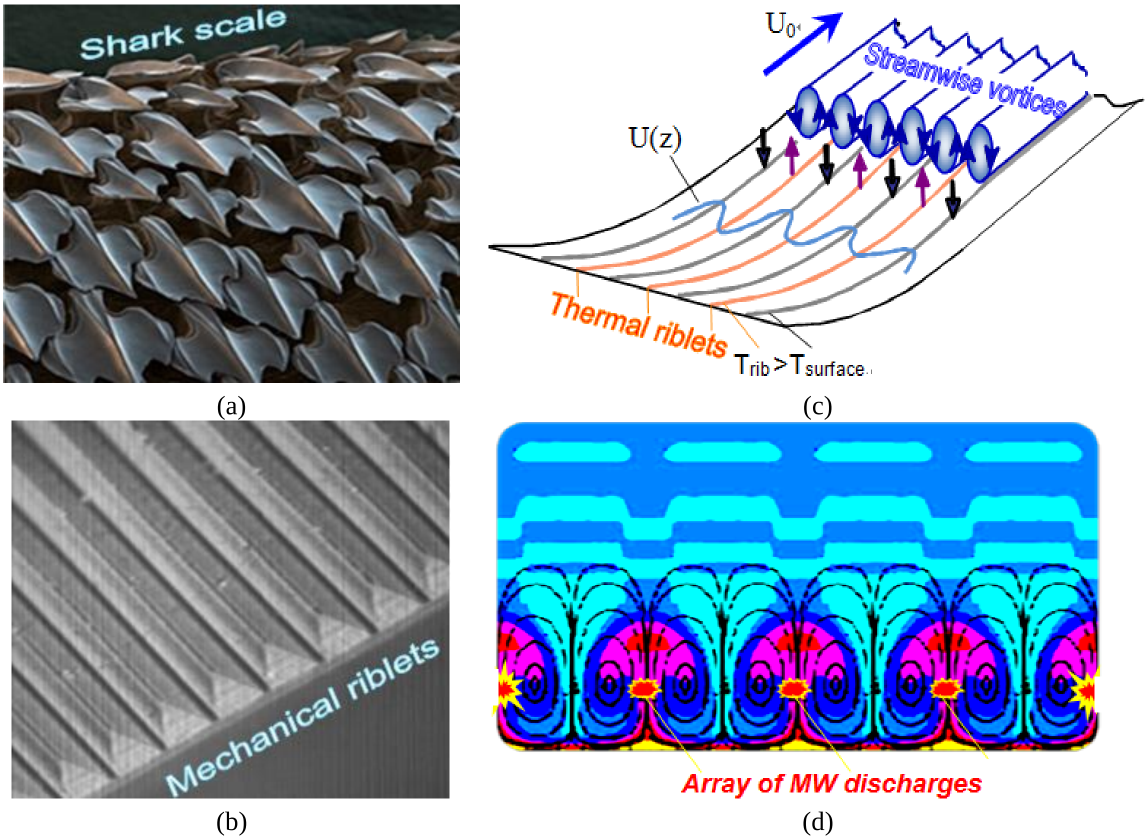
Fig. 1(d) illustrates generation of regular vortices using a spanwise array of plasma discharges initiated with microwave radiation. This multidisciplinary engineering solution realized an active and remote management of flow characteristics (Yurchenko 2010, Yurchenko and Esakov 2011).

1.1 Problem formulation: a circular cylinder in a crossflow



(a) (c)

(b) (d)

Fig. 1 Evolution of riblet coatings for flow control: (a) Orderly scale structure of high-speed sharks, (b) Mechanical riblets: passive flow control, (c) Thermal riblets – array of embedded heated strips: active flow control and (d) Thermal riblets – array of plasma discharges: active and remote flow control

Development of optimal flow-control strategies based on deep understanding of flow and vortex formation mechanisms results in the expected outcome like drag reduction, lift enhancement, noise and vibration control or improvement of aerodynamic performance.

To get an insight into flows over blunt bodies, a circular cylinder in a viscous crossflow was extensively studied. During the last two decades, various passive and active techniques of flow control around a cylinder have been successfully employed. Passive techniques are usually based on geometry and surface modifications of various kinds. Active techniques are based on energy deposition into the basic flow, e.g. in a form of blowing-suction, generated oscillations, etc. Among a variety of approaches, there is one based on introduction of a disturbance varying in the spanwise direction (see e.g. Tang and Aubry 2000, Kim and Choi 2005, Jukes and Choi 2009).

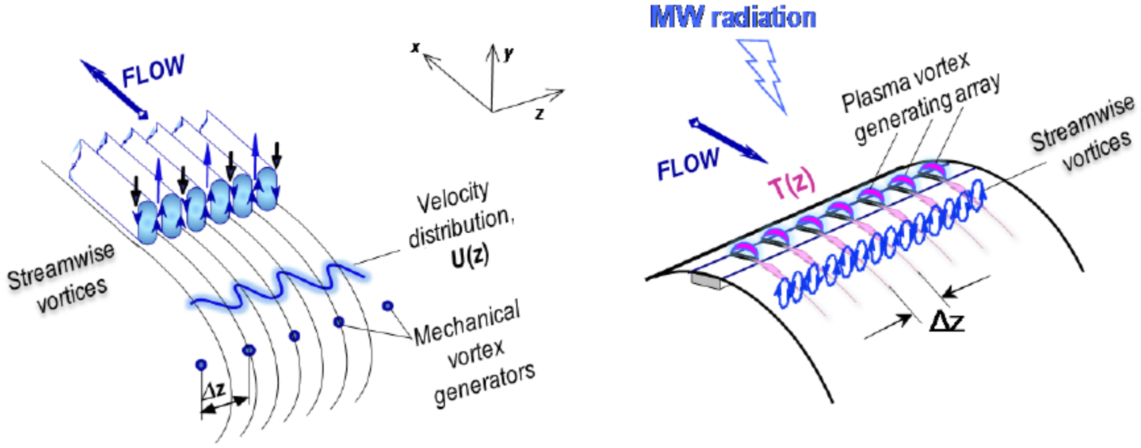


Fig. 2 Streamwise vortices initiated and maintained in a boundary layer with a given z scale using arrays of mechanical or thermal (plasma) vortex-generators

As mentioned above and illustrated in Fig. 1, an optimal step between the disturbers in a spanwise dirction (pitch interval, Δz) is an important characteristics of the controlled system not depending on passive or active methods of flow control and on their particular engineering realization. It is a key issue of the developed energy saving flow-control concept based on the forced scaling of turbulent motion (Yurchenko and Delfs 1999, Yurchenko 2008, Yurchenko *et al.* 2008, Yurchenko 2010, Yurchenko and Esakov 2011). In practice, it is realized through the aiming energy deposition to support streamwise vortices inherent to boundary-layer flows as it is shown schematically in Figs. 2 and 3(c).

The present work is the parametric investigation focused on the Δz pitch interval of the vortex-generating array (a scale of generated vortices) in correlation with basic flow parameters that is to improve the aerodynamic performance.

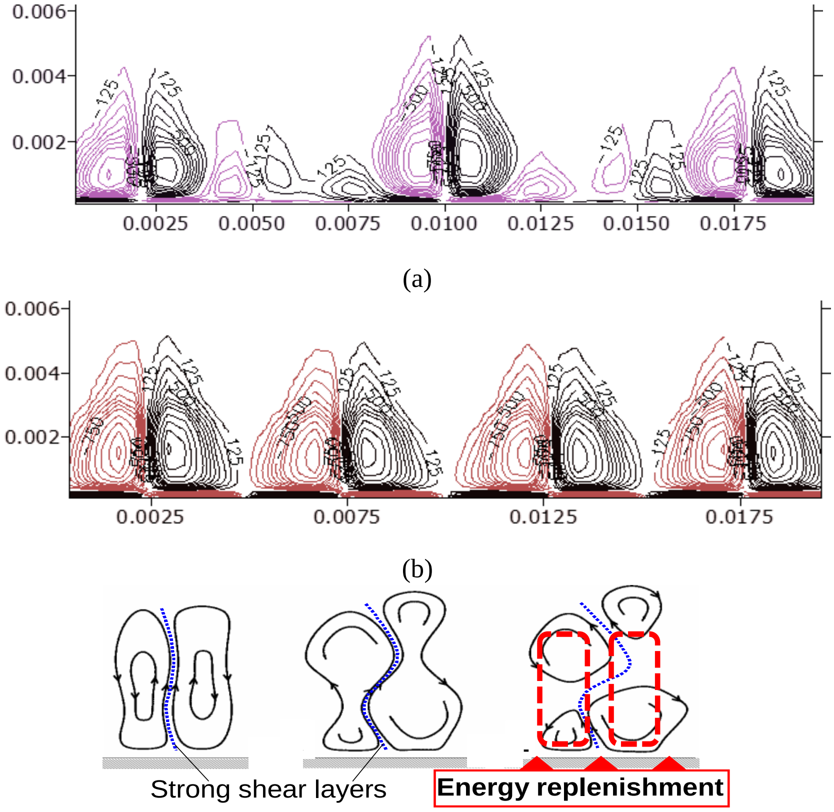
2. Results and discussion

2.1 Numerical simulation of the flow field

A canonical case of a circular cylinder in a crossflow is used to study possibilities to control separated flows on basis of the developed concept. Since an impact of initiated streamwise vortices on the flow development (Fig. 2) is of the primary importance, the relevant analysis is carried out in the framework of the 3D formulation for near-critical Reynolds numbers Re ~ $1.3\text{x}10^5$. Such a flow is characterized with the form drag dropped from C_D ~1.2 to ~0.3 and the separation point shifted downstream to 120˚ from its ~80˚ position at lower Reynolds numbers.

Numerical simulation of the flow field structure was based on the 3D Reynolds stress transport model. Secondary flows over curved surfaces of a constant radius were investigated for a 3D nonisothermal viscous compressible flow with an imposed spanwise-regular temberature boundary condition. Values of basic flow parameters were chosen to coincide with wind-tunnel conditions.

Further, fluid dynamic modeling tools were built basically on the ANSYS software. The computational domains and meshes were built using the Design Modeler and ICEM CFD (later the



(a)

(b)

(c)

Fig. 3 Iso-vorticity lines in turbulent boundary layers with thermally initiated streamwise vortices with a given scale: (a) Δz=2.5 mm and (b) Δz=5 mm, $Re=5\cdot 10^5$ and (c) schematic view of the vortical system maintenance

Pointwise). The mesh was imported into ANSYS CFX, where the required flow physics, boundary and initial conditions were applied; a solution was obtained and results were post-processed. Obtained numerical values of drag coefficients C_D ~0.33÷0.36, distribution of pressure coefficients C_p, and the Strouhal number St~0.25 for a reference case were in a good agreement with known data. Thus it was concluded that the numerical simulation could guide much more laborious and costly experimental investigations.

First of all, an impact of the “thermal riblets” on the boundary-layer flow structure was studied. Figs. 3(a) and (b) demonstrate the boundary layer receptivity to spanwise-regular disturbances introduced with the temperature gradient $\Delta T(z)=35^0$ varying along a surface span. It was found to be low for introduced small space scales Δz=2.5 mm (Fig. 3(a)) and much higher for the twice greater scale Δz=5.0 mm (Fig. 3(b)).

A mechanism of the sustainable vortical structure maintenance is illustrated in Fig. 3,c. Naturally arising streamwise vortices in a boundary layer undergo a number of development stages from their growth normally to the wall to the breakdown aggravated with strong shear layers. However the aiming energy release can significantly slow down the process. An amount of required energy is not high since it goes for the “proper” scaling of the predisposed vortical

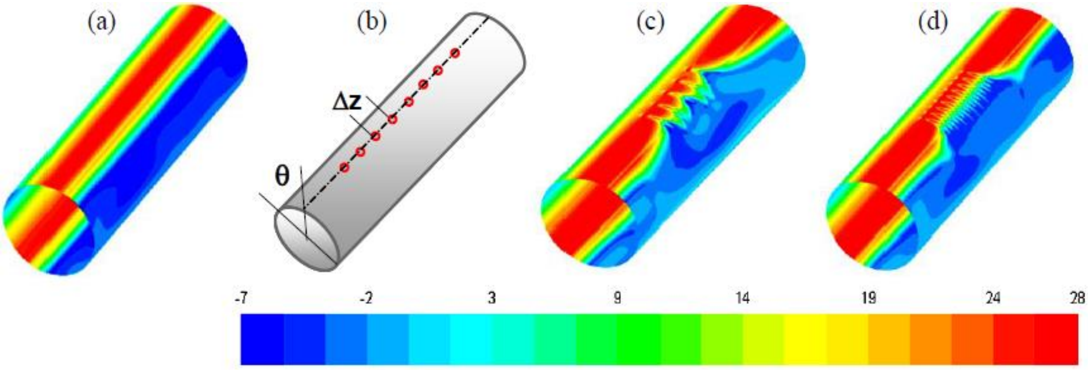


Fig. 4 Streamwise components of shear stress on the cylinder surface, U_0=60 m/s: (a) reference case, (b) sketch of a plasma-controlled case, (c) Δz=2 cm, (d) Δz=1 cm

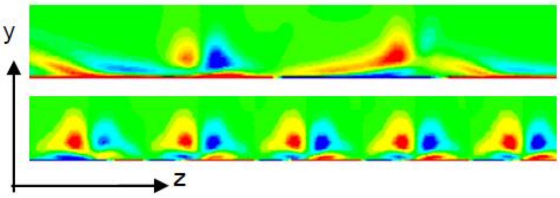


Fig. 5 Streamwise vorticity along the cylinder generatrix, U_0=60m/s: (a) Δz=2cm, (b) Δz=1cm

structure rather than for the total flow restructuring. Thus changing transport properties near the wall, one can expect to get an integral impact on the flow, e.g. in a form of the separation delay.

For that, spanwise-regular disturbances were introduced into the flow over a circular cylinder. To match the experiment conditions and models, the numerical parameters were chosen as follows: the cylinder diameter, D = 90 mm; span, L= 180 mm; free-stream velocity, U_0=10-60 m/s corresponding to the Reynolds number based on the cylinder diameter, $Re_D \sim 2.2 \times 10^5 \div 3.4 \times 10^5$. The spanwise-regular temperature gradient of ΔT(z)=1000° simulating microwave-initiated plasma discharges was applied to the ambient temperature of 300°K. To model numerically the thermal flow-control system, an array of 2-mm diameter high-temperature spheres was placed along the cylinder generatrix at the angular position of θ=60°. The arrays spanned within z=11–19 cm with Δz =10 mm or Δz =20 mm spacing between thermal sources. This step was a consequence of electrodynamic requirements to the design of the plasma array and its stable operation in given modes. Fig. 4 shows a flow response to the introduced disturbances.

Since the separation at such flow velocities is located behind the cylinder middle (θ=90°), thermal wakes behind plasma sources and generated longitudinal vortices reside in the attached flow over the cylinder surface up to the separation point. For the Δz=1cm spacing (d), the vortical pairs almost completely covered the controlled span, they were regular with almost circular cross-section and maintained the initially given spanwise scale (Fig. 5, bottom). Surface shear stress in the wakes of thermal sources decreased that would lead in a total drag reduction of the cylinder. The twice wider spacing between thermal vortex-generators (c) appeared to be improper to generate a regular vortical system (Fig. 5, top). Instead, it tended to instability with a larger space scale developing downstream.

For lower flow velocities, similar flow response and vortical patterns were obtained though with lower intensities.

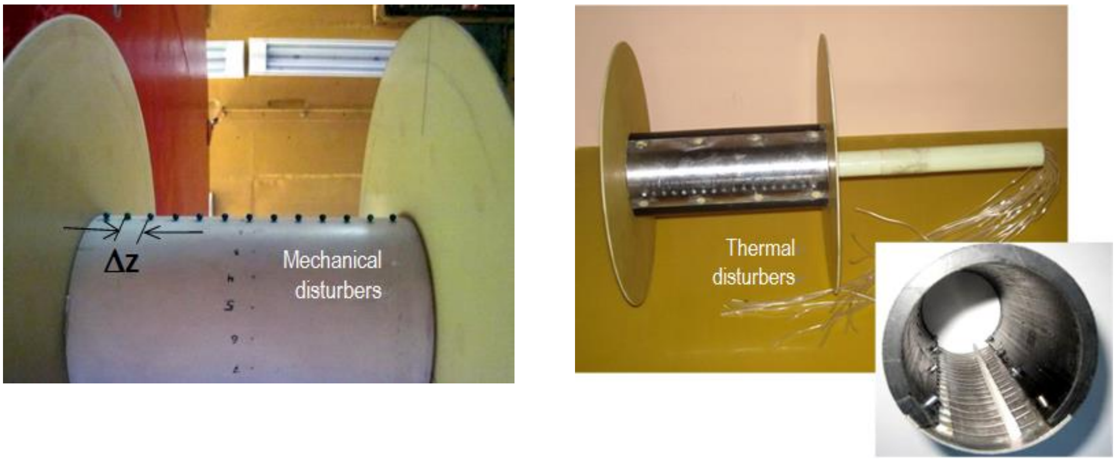
Thus for the considered flow conditions, the spanwise spacing of about 1 cm between the high-temperature sources at ΔT(z)=1000° is optimal for initiation and maintenance of regular pairs of streamwise vortices. A closer spacing led to the overlapping of neighboring vortices and a loss of their intensity; a wider step left too much space between the vortical pairs and allowed them travelling in a spanwise direction that was another manifestation of flow instability.

2.2 Experimental investigations

Measurements of drag and lift coefficients together with pressure distributions for reference and controlled models were carried out for the same values of basic flow and control parameters. It enabled to analyze jointly the numerical flow field results and measured integral flow characteristics. In addition to the models described above, 200 mm long cylinders were fabricated with diameters, D = 128 mm and 106.6 mm. All the models had side plates to provide the flow two-dimensionality (Fig. 6).

Two engineering solutions were tested in the framework of the developed flow-control concept. The first one realized passive control (Fig. 6(a)) having been based on application of mechanical vortex generators (spheres with a diameter of 3 mm). The second one based on localized plasma discharges was used for active flow control (Fig. 6(b)). Mounted along a cylinder generatrix, these arrays of disturbers caused asymmetry of the flow around the a-priori symmetrical body. A spanwise step Δz between the vortex-generators was a variable parameter in a course of experiments carried out within free-stream velocities, $U_0 \approx 15 - 60$ m/s.

The microwave (MW) generated plasma required a special wind-tunnel facility equipped with MW radiation and protection systems. In addition to active flow control, such an approach enables remote operation with obvious prospective applications, that required the creation of a new facility, Aerodynamic Complex for Interdisciplinary research (ACIR). It is designed so that to provide a wide range of both classical aerodynamic experiments (single models and cascades) and those with MW radiation and plasma generation (Fig. 7).



(a) (b)

Fig. 6 Circular cylinder models: (a) with spherical vortex-generators for passive flow control and (b) with arrays of plasma initiators for active flow control

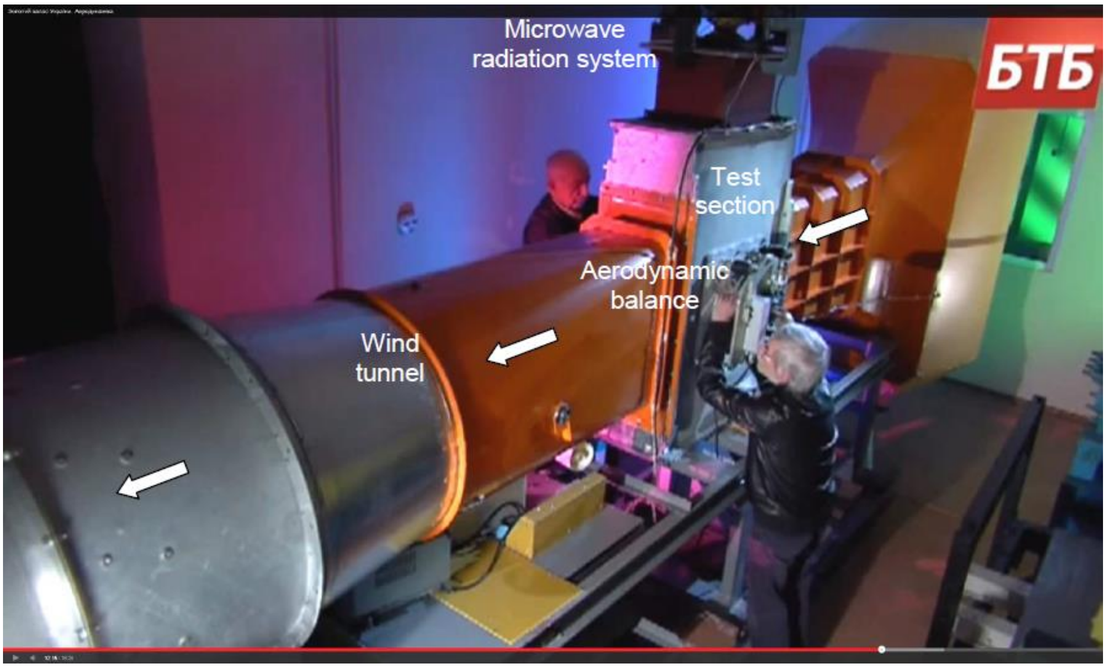
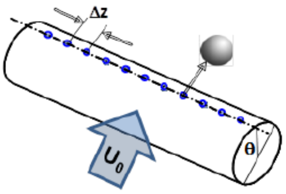


Fig. 7 Aerodynamic complex for interdisciplinary research (ACIR)

Application of mechanical vortex-generators showed both reduced drag and appeared lift that took place for all tested Reynolds numbers (Fig. 8). Drag coefficient was found to be reduced by ~ 25% using the vortex-generator array with **Δ**z = 5 mm at its angular position of θ=30°. For further growing θ, drag rapidly recovered to its reference value at θ = 70°, while lift coefficients dropped here to negative values having recovered to zero at θ > 100°. Two and three times greater Reynolds numbers showed a similar impact on aerodynamic coefficients depending on θ. A lift gain could reach a value of 0.64.

For Δz = 10 mm and 20 mm, aerodynamic coefficients showed a similar behavior although with a lesser drag drop at θ = 30° (Fig. 9). However unlike for the Δz =5 mm case, a range of angles of attack with reduced drag values was considerably wider. The same effect of a wider θ range was obtained for lift coefficient increments which, in addition, were higher for larger Δz values. Thus the spanwise scale of Δz=10 mm can be recommended as an optimal value for the given flow parameters.

The illustrated passive flow control using mechanical vortex generators was studied as a prototype problem of the active plasma-controlled case based on the same concept of the spanwise-regular flow disturbances. The physical phenomena involved into the developed flow-control strategy using MW-initiated plasma arrays are rather complex because of their multidisciplinary nature. However unlike the DBD and other types of plasmas, MW discharges offer the control factor in a form of temperature as their characteristic feature. Thus the earlier investigations (Yurchenko and Delfs 1999, Yurchenko 2000) together with the results shown in Figs. 4 and 5 related to the vortical system formation make the “prototype results” applicable to plasma based experiments in terms of a choice of optimal vortex scales and azimuthal locations of the vortex generators. They are two basic control parameters under consideration, i.e. an optimal



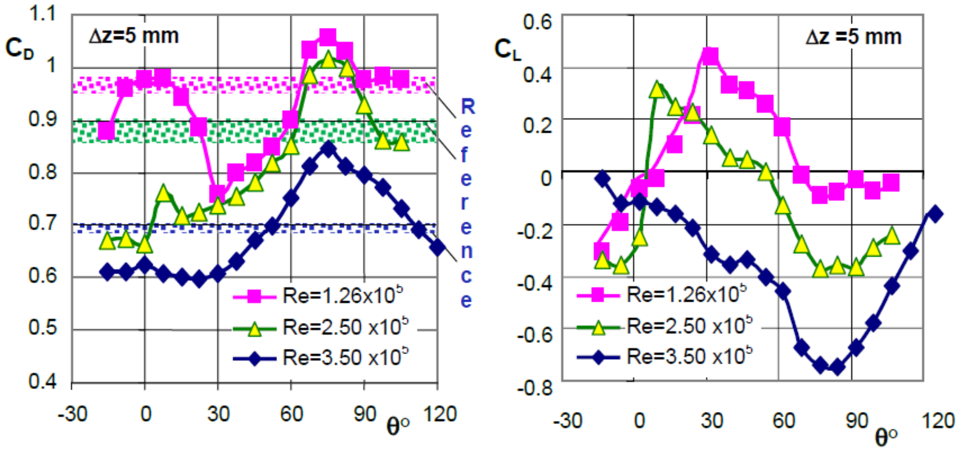


Fig. 8 Drag C_D and lift C_L coefficients depending on azimuthal θ locations of the mechanical vortex-generator array with Δz=5 mm for different Re_D around the drag crisis

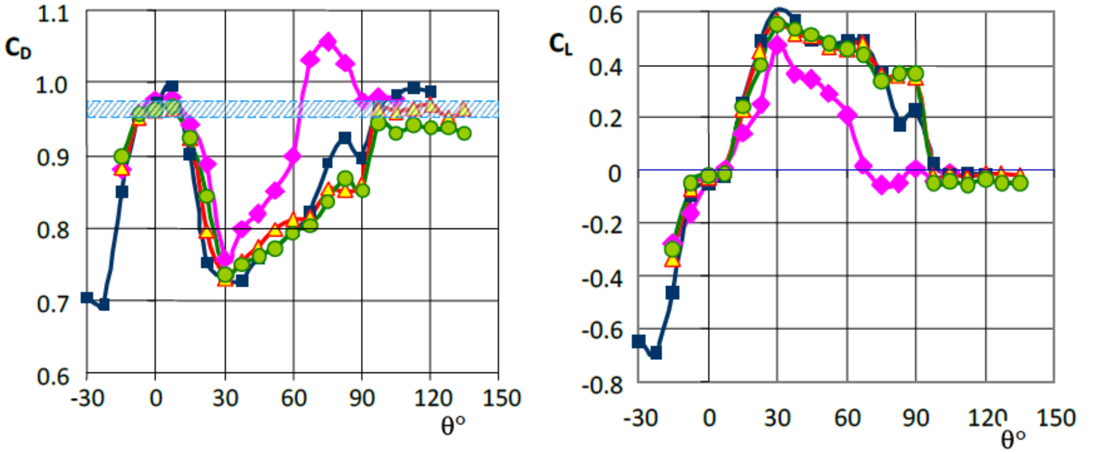


Fig. 9 Drag and lift coefficients depending on azimuthal θ locations of the mechanical vortex-generator array with various scales of Δz=5 ◆, 10 ■, 15 ▲ and 20 ● mm; ▨ Reference C_D ; Re_D ~ 1.25×10^5

value of a spanwise distance, Δz, between the vortex-generators and an azimuthal location, θ°, or an angle of attack between the array and flow velocity vector, as it is shown in Figs. 4, 6 and 8). These aerodynamically optimal values must be matched with those required electrodynamically from a viewpoint of reliable ignition of the discharges along the whole array and their stable operation. Usually, a number of compromises between aero- and electrodynamic requirements is

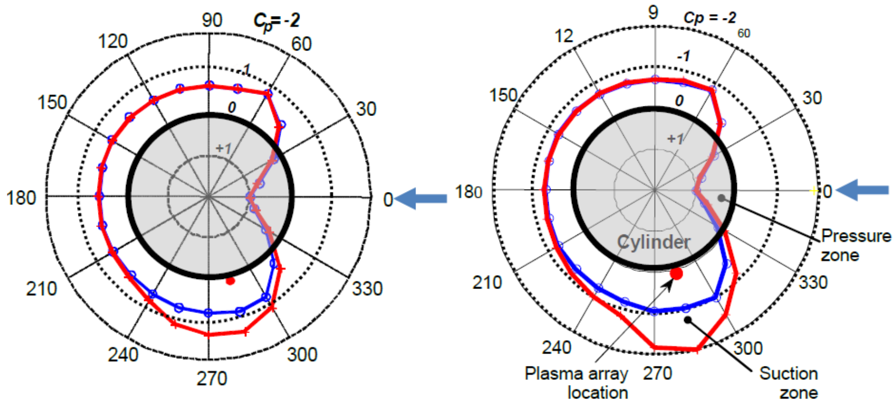


Fig. 10 Pressure distribution over the circular cylinder with an array of plasma discharges: Re = 1.23x105, Δz=10 mm, θ = 315°; t= 60 μs; F =500 Hz; θ =75°, Δz=10 mm (left), t= 500 μs; F= 50 Hz (right)

necessary to provide reliable operation in the environment of wind-tunnel experiments. As a result, the value of Δz =10 mm having shown drag drop and lift rise for θ = 20° – 80° for the tested circular cylinder model in the prototype experiments was recommended as an optimal one for the plasma-based experiments.

This Δz happened to be in a good agreement both with the numerical prediction and with electrodynamic requirements to generation of multiple localized plasma discharges. Closer spacing of plasma actuators Δz <10 mm resulted in unstable generation of point plasma discharges in the array and thus in the irregular T(z) temperature boundary condition

To minimize energy consumption, a low-power MW generator was used which operated in a pulse mode. It provided additional control parameters like intensity of MW radiation, MW pulse duration π and repetition rate F. The pulse mode justification and values of parameters were evaluated in aerodynamic numerical modeling for the given basic flow parameters. Thermal wakes downstream of plasma discharges were found to merge, e.g. for the combination of basic flow and control parameters shown in Fig. 10. These merging high temperature lines formed an array of thermal riblets at the outer edge of a boundary layers similar to that of the spanwise-regular surface heating. Fig. 10 shows pressure distributions around the circular plasma-controlled cylinder with various modes of pulsed MW radiation.

In particular, it was found that for the shown Reynolds number, the MW pulse duration had a primary importance under conditions of all other equal parameters including the duty cycle.

3. Conclusions

Flow control around blunt bodies is studied by example of a canonic case of circular cylinders in a crossflow. An array of vortex generators is placed along the cylinder generatrix with a fixed distance between the neighboring generators. There were investigated cases of asymmetric flow excitation with spherical disturbers (passive flow control) and with arrays of localized plasma discharges initiated with microwave radiation (active flow control).

Mimicking the plasma array configuration, flow control with mechanical vortex-generators was intended to get general recommendations for optimal parameters and an arrangement of the control system. Two basic control parameters under consideration were an optimal value of a spanwise distance, Δz, between the vortex-generators in the array and its angular location, θ°, on the cylinder relative to the flow velocity vector.

The numerical simulation problem was formulated in the framework of the developed concept of flow control using spanwise-regular disturbances and its match to the experiment (test model size and geometry, basic flow parameters). Modeling for a reference case of an uncontrolled smooth cylinder for high Reynolds numbers showed a good agreement with known results. Arrays of thermal sources in a form of localized plasma discharges were modeled by a set of fluid spheres 2 mm in diameter with temperature T=1300°K which were spaced at Δz =10 or 20 mm from each other and located at an angular position of θ= 80°. The spanwise spacing, Δz ≈ 10 mm was found to be optimal for sustainable vortex generation and was recommended for the experiment arrangement.

Application of spherical vortex-generators showed optimal drag drop and lift rise for Δz =10 mm spacing and the array location within θ=20°–80° in the range of $Re_D = (1.25\text{-}3.5) \cdot 10^5$.

These aerodynamically optimal values were matched with the electrodynamic requirements to reliable ignition and stable operation of plasma discharges along the whole array monted on a test model. The electrodynamic modeling of multiple localized plasma discharges justified the Δz =10 mm value for the wind-tunnel environment with inevitable reflections of MW field and for aerodynamic measurements.

The Aerodynamic Complex for Interdisciplinary Researches was designed and manufactured for experimental studies of advanced plasma-based approaches to flow control aimed at the improvement of the aerodynamic performance. It is equipped with the stationary systems of microwave radiation and protection for efficient and safe plasma generation over test models. Measured drag and lift forces, as well as pressure distributions around plasma-controlled cylinders showed an impact similar to that found for mechanical vortex-generators. However MW-based methods providing active and remote control of flow characteristics proved to be more flexible and efficient.

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