DOI: https://doi.org/10.14311/TPFM.2025.029

# TURBULENT FLOW CONTROL BY A COMBINATION OF A DIMPLED SURFACE, BLOWING AND A SYNTHETIC JET INSIDE THE DIMPLES

**Ye. Shkvar[1,2], J. Kandume[1]**

**[1]Key Laboratory of Urban Rail Transit Intelligent Operation and Maintenance Technology & Equipment of Zhejiang Province, College of Engineering, Zhejiang Normal University, 688 Yingbin Road, Jinhua, 321005, China**

**[2]Institute of Hydromechanics of the National Academy of Sciences of Ukraine, Department of Hydrobionics and Flow Control, 8/4 Marii Kapnist St., Kyiv, 03057, Ukraine**

**Abstract**

The subject of the study is a scheme for the combined effect of two effectively interacting flow control methods, namely a dimpled surface and localized mass flux through a part of the surface inside the dimple to create an easy-to-use, cheap-to-manufacture streamlined surface of the desired design with a reliable and controlled effect of active influence on reducing aerodynamic drag. Special attention is paid to the periodic mode of the above-mentioned mass flux, well known as a synthetic jet, implemented in the back of shallow ellipsoidal dimples. In the latter case, it is possible to achieve an effect similar to intensive microblowing, but significantly reduce the cost of manufacturing a finely perforated surface, as well as its efficiency, since the dimple in this case works as a near-wall vortex generator, intensifying the spread of local blown flows over the surface. Special attention is paid to determining the most effective modes of mass flux through a streamlined surface with dimples, as well as the preferred location and geometry of the implementation of blown holes arrays.

**Keywords:** flow control; turbulence; drag reduction; dimple; penetrable surface; blowing; synthetic jet; Time-Resolved Particle Image Velocimetry; TR-PIV

## 1 Introduction

Flow control aimed to drag reduction is one of the topical areas in modern fluid dynamics, having both deep theoretical interest and a wide range of prospects for effective engineering application in order to improve the energy efficiency of modern and perspective vehicles as well as various hydraulic equipment. Due to the fact that physical processes near a streamlined surface are primarily responsible for the formation of turbulent exchange and friction, traditionally a significant number of technologies for drag reduction of well-streamlined bodies are localized near the wall and involve changing the geometric structure of its relief (riblets, dimples), or wall temperature change, or polymeric additives injection, or mass exchange organization through the surface (microblowing or suction), or the formation of desired near-wall disturbances through wall oscillations [1-5]. However, for an objective assessment of the efficiency and possibilities of practical implementation of turbulent friction drag reduction methods, it is necessary to take into account the accompanied factors, namely: the increase in pressure drag in the case of using active methods such as microblowing [6], as well as the need to maintain the cleanliness of a large area of artificial micro-ribbed surface during its regular operation, like, for example in case of AeroSHARK (so-called Sharkskin) Technology, developed and implemented by Lufthansa Technik in cooperation with BASF [7]. Despite the fact that this technology was supported and implemented by Austrian Airlines on the Boeing 777-200ER in early 2025 [8], the above-mentioned circumstances attract more attention to potentially more rational and universal approaches, one of which is the macro-profiling of the wall with small cavities like shallow dimples, which cause alternating spanwise excitations of near-wall flow, especially when arranged in a staggered pattern [9–12]. The flow control effect of deep dimples is usually connected with generating by their surface of the regularly arranged streamwise counter rotating vortex pairs (CRVPs) that intensify the transversal near-wall flow intensity [11]. It should also be noted that these CRVPs structures are well known and very effective, including for preventing flow separation due to modification of the wing leading edge with tubercles [13], but in this case their intensity varies widely depending on the angle of attack, significantly exceeding the generation of CRVPs by dimples, while using the same physical mechanism for increasing the spatiality of the three-dimensionality of the boundary layer near the wall. Nevertheless, as noted above, inside shallow dimples no intensive complex flow structures are observed, suggesting vorticity formation isn't the key drag reduction mechanism for this flow control technique [9–12]. Presumably, the alternating dimpled wall curvature initiates a transverse flow component resembling spanwise wall oscillations that reduce hairpin vortices intensity. Under certain conditions the dimpled surface demonstrates its ability to reduce drag, but it's still unclear if it's due to the dimples interaction with patterns of mean flow or near-wall boundary layer turbulence. Many studies were dedicated to the impact of geometric effects on vorticity transport and Reynolds stresses on a dimpled surface. The diamond design showed the highest drag reduction, while the symmetric circular design had the worst drag due to a 6.4% increase [12]. However, any modification of surface relief is a passive method of flow control, and therefore this method assumes workability in a fairly narrow range of operating conditions, for which it is adapted. Active control methods, which assume additional energy use for their implementation, are much more universal and have significantly greater potential. One of the promising active methods is various types of implementations of mass exchange through a streamlined surface (blowing or suction with a constant flow rate, or its alternating realization, well known as a synthetic jet). Blowing through the wall pushes the boundary layer away from it, modifying the mean flow by reducing, first of all, the near-wall velocity gradient in the normal to wall direction, which leads to a decrease in friction drag. Suction, on the contrary, affects the formation of near-wall instabilities (bursting) near the wall, effectively absorbing them into the wall, which leads to a delay in the transition to the turbulent mode (flow laminarization). Both technologies are efficient in certain areas of their application, but in practical implementation they require a finely perforated surface (the holes should not exceed 0.12-0.15 mm so that the surface retains hydraulic smoothness [14]), which increases the cost of the technology and worsens the prospects for its application in real operating conditions due to contamination and loss of permeability. In addition, another significant drawback is its dependence on an ongoing air supply, which can raise operating expenses and energy usage. On the other hand, synthetic jets, first introduced in 1998 [15], offer a more flexible method of flow control. In synthetic jets, a pulsating jet of air is guided into the flow field by vibrating a diaphragm or membrane [15–18]. Synthetic jets work by intermittently and usually periodically alternating sucking and expelling fluid, as opposed to blowing traditionally, which requires a steady supply of air. Because of this property, synthetic jets can generate secondary flow momentum that is not zero even when the net mass flux is zero. For applications needing dynamic flow modification without the hassle of an extra air supply, synthetic jets are especially attractive due to their adaptability and energy efficiency.

We propose to improve the efficiency of the above methods by combining blowing or synthetic jets with surface modifications such as dimples. Small surface indentations called dimples enhance lift characteristics and postpone flow separation. Combinations of blowing & dimples as well as synthetic jet & dimples can work together to produce a synergistic effect of creating the complex regular CRVPs flow structure that lowers drag and improves performance.

The purpose of this study is to experimentally demonstrate the advantages of combining the two above-mentioned approaches, namely the implementation of mass flux through an array of thin holes in the midplane, codirected with main flow direction, of curved dimple surface. The essence of the idea of the expediency of such a combination is that the vorticity inside the dimple will contribute to the intensification of the distribution of the working fluid supplied through the wall into the boundary layer, which reduces the strict technological requirements for the smallness of the hole diameter.

## 2 Experimental equipment and modeling approach

In order to investigate the impact of blowing and synthetic jets on dimpled surfaces, a controlled environment must be established. To see and measure flow patterns, a wind tunnel with Time-Resolved Particle Image Velocimetry (TR-PIV) measurement tool is used (Fig. 1). The closed loop wind tunnel DHS-600×600/1050×1050-V was manufactured by the Chongqing Lantian Co. Ltd. (2017) and certified by the National Institute of Metrology of China (2018). It has two octagonal test sections of 1.5 m long each with cross sections 1.05 ×1.05 $m^2$; (big) and 0.6 ×0.6 $m^2$ (small); air speed $U_\infty$ is ranged from 0.61 m/s to 60.59 m/s; spatial non-uniformity of the flow doesn't exceed 0.12%; undisturbed air flow turbulence intensity is less than 0.5%. The TR-PIV system, developed by LaVision Co. (2018), includes: dual cavity high-speed Nd:YAG laser with repetition rate 0.2-10 kHz; 2 cameras FASTCAM Mini AX200 with sensor resolution 1024×1024 pixels, pixel size 20×20 μm, frame rate 6400 fps, sensitivity ISO 40000-mono/16000-color, memory 16GB; lens Tokina 100 mm AT-X Pro Macro 100 F2.8D with focal length 70–300mm, aperture f/2.8–f/16; industrial aerosol generator based on evaporating an aqueous glycerin solution FOG-1000 with an average liquid particle size of 20 μm; synchronization unit PTU-X; computer with AMD Ryzen-9 9950x processor, 64GB DDR5-6000 RAM (dual channel), 1TB SSD, 20TB HDD; software Davis 10.2.1. This

TR-PIV system allows to get the maximum field of view of 180×180 mm and make the measurements for a flow velocity 0-200 m/s with a PIV data sampling rate of 3200 Hz in air with an accuracy of ~1%.

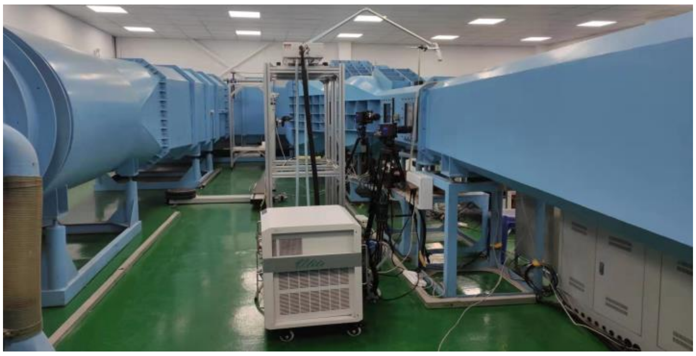

Figure 1: Wind-Tunnel and TR-PIV system, installed in the College of Engineering at the Zhejiang Normal University (Jinhua, China)

In this study of aerodynamic enhancements using dimpled surfaces, two distinct cases were proposed for the placement of hole arrays (Fig. 2): Case 1, which positioned the holes at the front inside the dimple, and Case 2, which placed them at the rear. The objective of these configurations was to optimize flow control and improve overall performance by complex manipulating the boundary layer characteristics using a superposition of two flow control approaches, namely dimples for wall vorticity generation (passive method) and mass flux through the wall (active method).

Case 1, with holes located at the front, aimed to inject fluid into the boundary layer early in the flow process. While this approach offered some benefits in terms of flow attachment, it proved less effective in overcoming the back flow inside the dimpled rear part.

Case 2, which utilized rear-placed holes, demonstrated significantly greater effectiveness. By rational positioning the holes in the rear of the dimple, this configuration allowed for the generation of thin flat local jet that actively controlled the boundary layer. This placement enhanced the ability to reduce drag more efficiently by accounting the back-flow inside the dimple at the position where the array of holes is located. As a result, Case 2 emerged as the preferred choice, showcasing superior performance in aerodynamic applications and highlighting the importance of hole placement in optimizing flow development within the dimple and in the boundary layer behind it.

The dimple geometry (Fig. 2) features are as follow: Length=60mm, Width=30mm and Depth=3mm with a space between two neighboring dimples of 10mm manufactured by stereo-lithography (SLA) to produce the dimpled plate with better surface smoothness. The diameter of internal holes is ~1.5 mm and the distance between the axes of any pair of neighbor holes, as well as the distance from the 1-st hole axis to the beginning and the distance from the last, 9-th hole axis to middle of the dimple, is ~3 mm. This dimpled test plate 1 (see the scheme on Fig. 3) had a thickness of 8 mm and dimensions of 350 mm in length and 200 mm in width, i.e. there were 5 dimples in the width direction and the distance from the beginning of the plate to the beginning of the dimples was 20 mm.

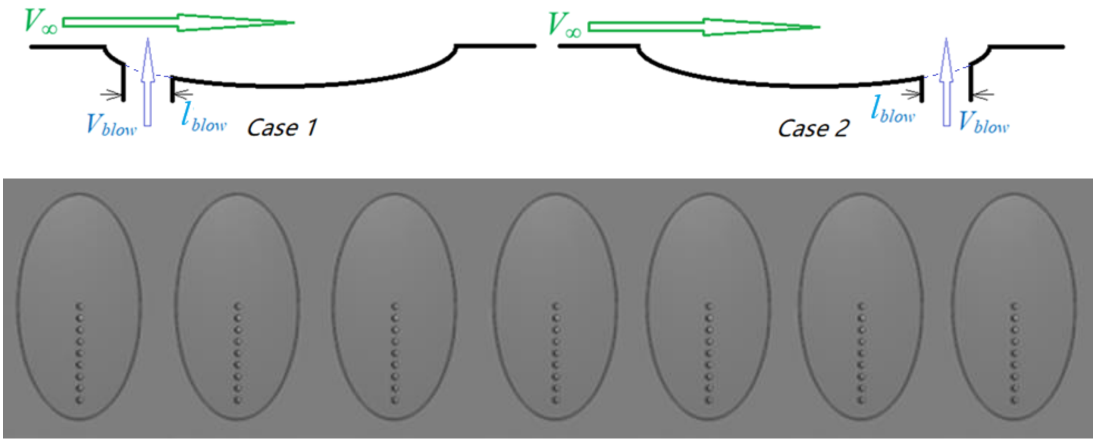


Figure 2: Schematics of two tested cases of the mass flux hole array

It should be noted here that in all the cases presented below, a flat plate 4, 1.5 m long, with a wire turbulator 5 (2 mm diameter, located at a distance of 150 mm from the leading edge), was tightly attached in front of the dimpled plate 1 (see Fig. 3, right, Fig. 4, right), over which the measurements were carried out, to thicken the boundary layer and achieve a fully developed turbulent flow mode in the measurement area 3 (~75×75 $mm^2$). As a result in the measurement place the turbulent boundary thickness was about 35-40 mm depending on the Reynolds number of the incoming flow $Re=10^6$. The longitudinal $x$-axis of the coordinate system was located 5 mm below the outer plane of the dimple test plate, and the normal $y$-axis was located 5 mm to the left of the beginning of the dimples to ensure that the inner region of the dimple in the longitudinal plane of its symmetry (the deepest region of the dimple in which the measurements were taken) was confidently included in the measurement field.

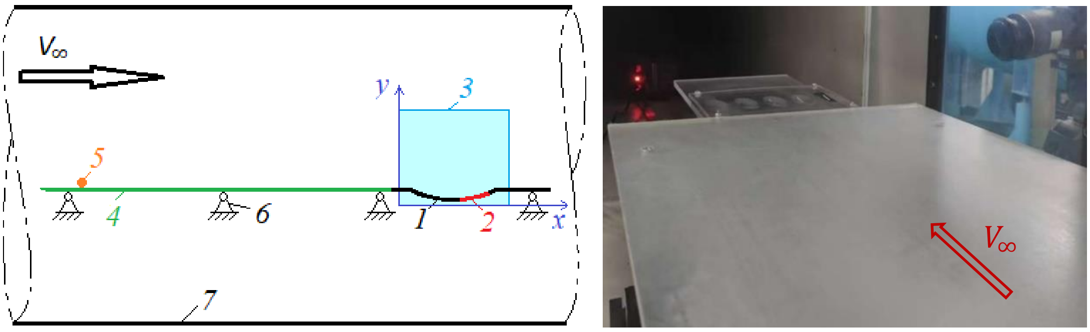


Figure 3: Test setup scheme (not to scale) – left and photo – right: 1 – dimpled testing plate; 2 – penetrable zone inside a dimple; 3 – measurement field; 4 – initial flat plate; 5 – wire turbulator; 6 – magnetic attachments; 7 – walls of small test section

In case of continuous blowing, a distribution chamber was organized under the surface of the test dimpled plate by means of another impermeable thick (10 mm) plexiglass panel and rubber seals along the perimeter between them. Secondary air was supplied from an oil-free compressor (nominal volume flow of 300 L/min, and a rated exhaust pressure of 0.7 MPa) through a flowmeter to a centralized connector in the lower impermeable panel (Fig. 4, left). In the case of generating a synthetic jet, a speaker was used instead of a compressor, the parameters of which (25 W, 4.5", 4 Ohm) were selected by ensuring visually comparable flow deformations at the moment of maximum flow disturbance in the mass exchange area and behind it with other external flow parameters remaining unchanged (Fig. 5). In this case, the maximum mode for constant blowing is determined by the maximum flow rate Q = 12 L/h through the total area of the array of 9 holes $A = 1.59 \cdot 10^{-5}$ $m^3$, which gives maximum averaged vertical velocity of secondary flow $V_y$=0.21 m/s and corresponds to 2.1% of the main flow velocity $V_\infty$=10 m/s for the measurement results presented here. Thus, it can be stated that continuous injection and a synthetic jet are close in terms of the maximum disturbing effect on the main flow.

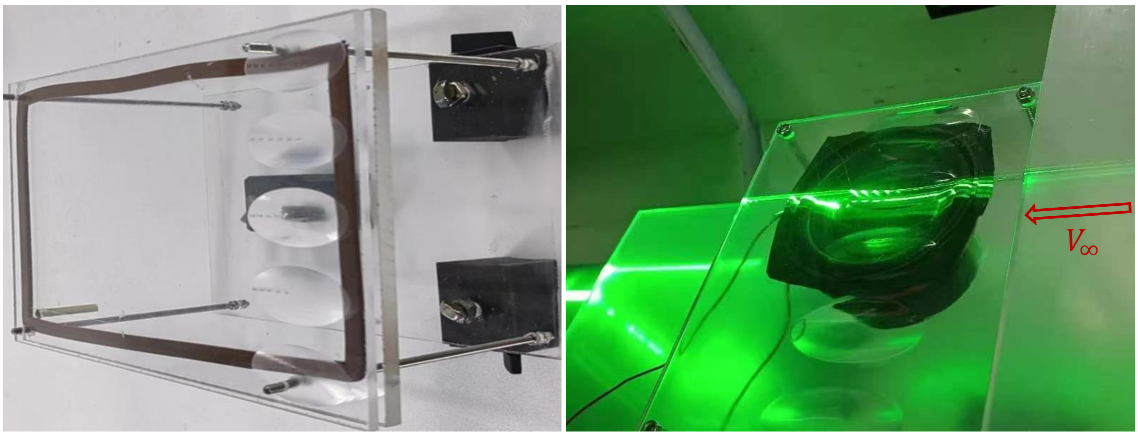


Figure 4: Test setup for study of mass flux through the dimpled wall:
continuous blowing – left; synthetic jet – right

The integration of blowing and synthetic jets through the rear part of a dimple presents a compelling approach to enhancing aerodynamic performance. Blowing, which involves the continuous introduction of fluid, can significantly energize and intensify spatial CRVPs structures in the boundary layer, reducing drag and potentially delaying flow separation. Therefore, this technology appears to be particularly effective in applications requiring high lift and improved flow stability characteristics. However, when evaluating the advantages of the achieved potentially promising configuration, it should be taken into account that its reliance on an external air supply can complicate system design and increase operational costs, especially in energy-constrained environments.

In this regard, periodic mass flux, implemented using a synthetic jet generation system, which consists of an oscillating diaphragm of a speaker located under a dimpled plate (Fig. 5), is an alternative that is relevant for further study.

It is important to note that the synthetic jet, in comparison with continuous blowing, appears to be more flexible in its mode control and effectively adjusting to the desired operating mode by simply changing the frequency of membrane oscillations in a wide range. In addition, changing the supply of electrical power also allows changing the amplitude of oscillations in a certain range.

## 3 Results of experimental modelling and comparative analysis of continuous blowing vs. periodic blowing-suction (synthetic jet)

The PIV method enables obtaining informative visualization of instantaneous measurements of flow development in the measurement area. Examples of the obtained visualizations are presented for both continuous blowing (Fig. 5, left) and a synthetic jet (Fig. 5, right). The results obtained for the mean velocity profiles and shear-stresses in a reduced measurement window of 70×50 mm$^2$ (length in flow development direction × height, normal to the wall) are presented in Fig. 6 for three values of secondary air flow rate (Q = 5, 12 L/h) including the reference case (Q = 0). It is easy to see the formation of a local region of strong disturbances over and behind the array of blowing holes, the intensity and size of which grow as the secondary flow rate increases. The blue dashed line shows the exact position of the dimple surface in its longitudinal midsection, and the green dotted line shows the reconstruction of this surface based on the velocimetry results and using the no-slip condition. The agreement between these two lines allows us to evaluate the quality of measurements in the wall region inside the dimple as quite satisfactory, taking into account the inevitable and harmful reflections of the laser beam from the streamlined surface.

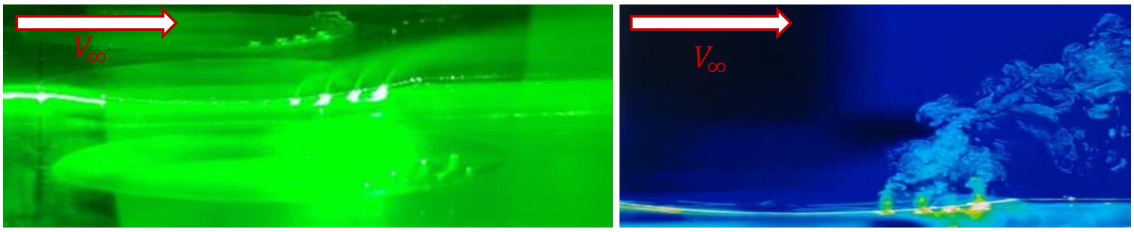


Figure 5: TR-PIV continuous blowing (left) and synthetic jet (right) visualization pictures: for better clarity, a case with a higher discreteness of holes (4 instead of 9) is shown

In the case of intense blowing, the mean velocity and shear stress profiles lose monotony in this local disturbed zone. Thus, the blowing intensity can be an effective factor in optimizing this control method for the expected operating conditions.

The results of experimental testing the alternative studied configuration – combination of dimpled surface and synthetic jet in the form of measured instantaneous and mean velocity fields in the same measurement window of 70×50 mm$^2$ are presented in Fig. 7 for two non-zero values of speaker membrane frequency (f = 50, 150 Hz) as well as for the reference case (f=0). Here we can also see intense deformation of the velocity field, localized in the region above and behind the place of the synthetic jet generation, but only for snapshots of the instantaneous flow field at the time close to the fluid injection phase into the boundary layer (left-side pictures), whereas on the mean velocity profiles (righ-side pictures) the changes are present, but they are much weaker in comparison with the case of continuous blowing (Fig. 6).

Thus, based on this comparison, it can be stated that continuous blowing is more effective as a strong influence on the mean velocity field, while the synthetic jet allows introducing intense, but short-term periodic disturbances, which, apparently, can have a stronger interaction with the structure of the disturbed motion caused by turbulence. That is, these two methods of flow control, having a largely similar technical implementation, have a significantly different physical mechanism of influence on various (mean and pulsating) components of motion in the turbulent boundary layer.

This difference, being fundamental, gives grounds for different application of blowing and synthetic jet. Considering that the flat synthetic jet of the considered in this study geometry, formed inside the dimple, will strongly disturb the spatial CRVPs system, and rather even generate its own longitudinal CRVPs structure of variable intensity, this mechanism of interaction with the turbulent boundary layer seems to be much more complex than in the case of continuous blowing, and requires further, more in-depth study.

In addition, another positive aspect of the synthetic jet is significantly lower energy costs compared to the implementation of blowing. However, in the case of their application inside the dimple, the advantage of the found position of the localization region in its rear part at this stage is already definite and preferable.

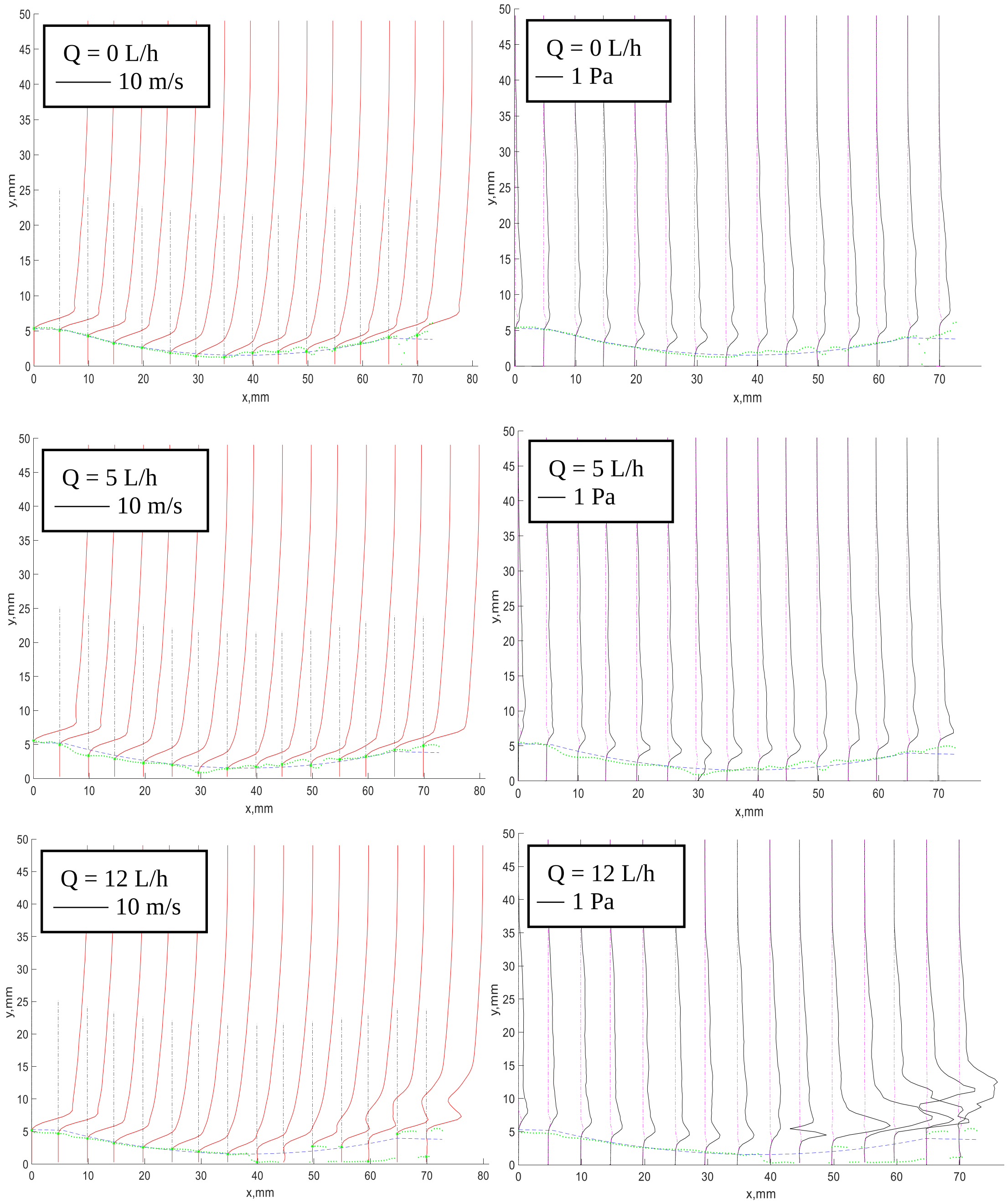


Figure 6: Velocity profiles (left) and turbulent shear stress profiles (right): measuring place – dimple midplane, output flow speed – V=10m/s and blowing intensity in range: Q=0–12 L/h (flow is directed from left to right)

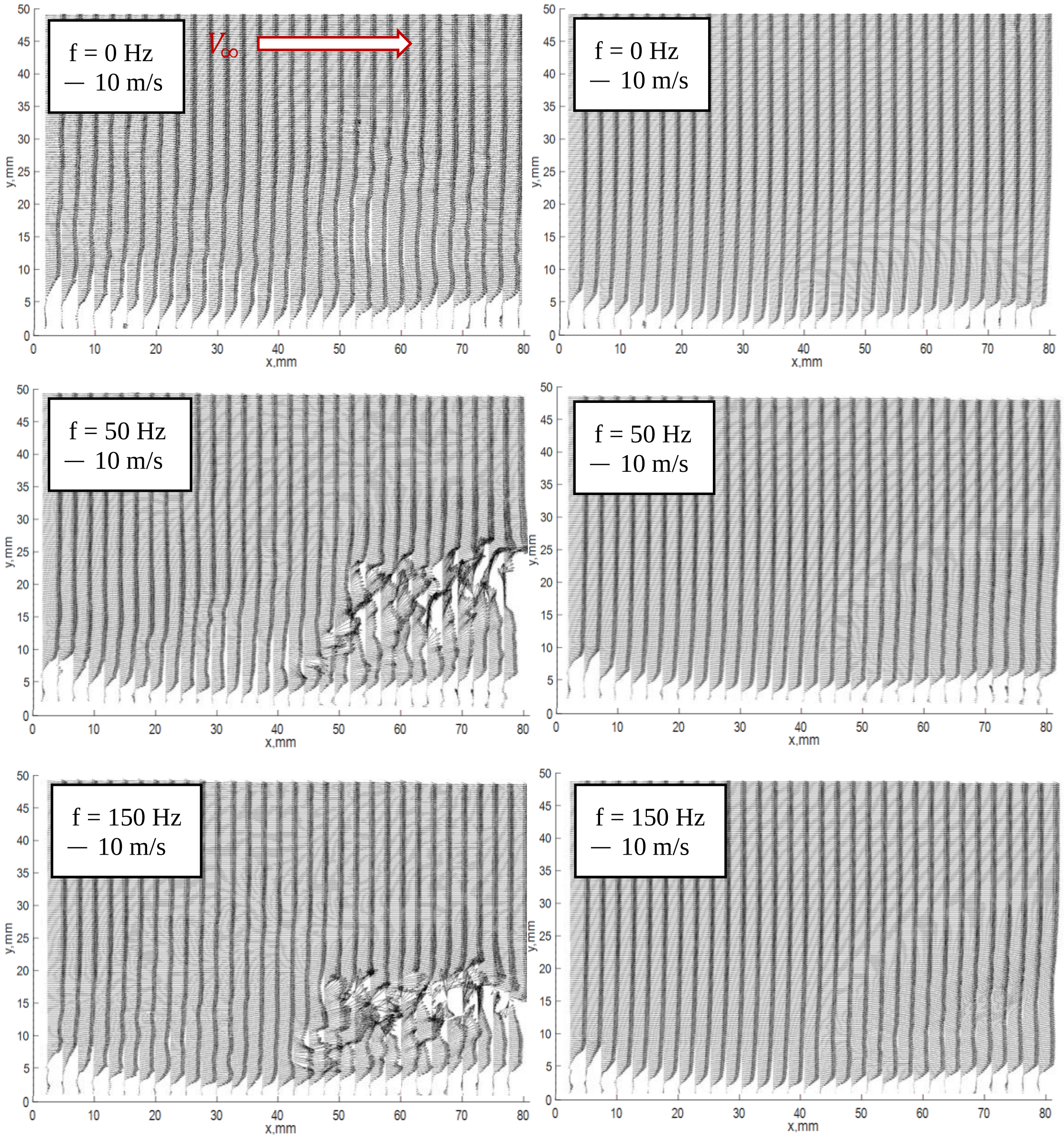


Figure 7: Typical instantaneous velocity field frames (left) and mean velocity field (right) in the midplane of the dimple with array of 9 holes d=1.5mm, V=10 m/s and frequency of the speaker f=0–150 Hz

# 4 Conclusions

1. A comparative experimental PIV-based study of continuous blowing and synthetic jet through a flat array of small holes in the rear part of the dimple was performed and, in both cases, showed the technical feasibility and rationality of such a configuration.
2. The comparative analysis performed showed that while continuous blowing achieved higher immediate performance metrics, synthetic jets offered greater versatility and adaptability. The non-zero secondary flow momentum generated by synthetic jets enhances their effectiveness in a wide range of applications, especially in environments where space and energy efficiency are critical. Ultimately, the choice between continuous blowing and synthetic jets depends on the specific requirements of the application. Continuous blowing may be preferable for high-performance scenarios, while synthetic jets provide a more sustainable and flexible solution for modern aerodynamic challenges.
3. The ability to rapidly adjust frequency and amplitude versus the more inertial ability to adjust continuous blowing secondary flow rate, increases the attractiveness of the synthetic jet and further enables optimization in a variety of aerodynamic conditions. Therefore, synthetic jets are a viable option

in flow control technologies because of their dynamic controllable flow characteristics, which enable flexibility in a range of aerodynamic situations.

4. Synthetic jets are a cost-effective alternative to conventional blowing methods in flow control technologies due to their efficient mechanism, which uses oscillating diaphragms, reducing operating expenses and the need for external air sources.
5. Synthetic jets' adaptability in changing flow patterns, combined with surface alterations like dimples, enhances aerodynamic performance. This synergy improves boundary layer control, lowers drag, and increases lift, making them attractive for aerodynamic applications.
6. Synthetic jets offer efficient flow management in automotive design and aerospace, using less energy. They are flexible, cost-effective, and promising for aerodynamic optimization and performance improvement when combined with dimples, paving the way for further advancements.
7. Further efforts will be made to more deeply study the interaction of the vortex structure formed by the considered flow control methods, not only in the main plane of its development, but also in planes parallel to the wall, as well as in transverse planes, in order to obtain information on the spatial distribution of vorticity of the modified turbulent boundary layer.

## References

[1] Gad-el-Hak, M.: *Flow Control: Passive, Active and Reactive Flow Management.* Cambridge University Press: (2000) 442 p.

[2] Truong, V.T.: *Drag Reduction Technologies.* DSTO Aeronautical and Maritime Research Laboratory 506 Lorimer St Fishermans Bend Vic 3207 Australia AR-011-925: (2001) 121 p.

[3] Kornilov, V.: Current state and prospects of research on the control of turbulent boundary layer by air blowing. *Prog. Aerosp. Sci.* 76: (2015) 23 p.

[4] Babenko, V.: *Experimental Hydrodynamics for Flow Around Bodies.* Academic Press: (2021) 653 p.

[5] Shkvar, Ye., E, Sh. & Kryzhanovsky, A.: Mathematical modeling of turbulent boundary layers, modified by wall-localized drag reduction techniques. *Aerospace Science and Technology*, Vol. 93, 105359: (2019) 7 p.

[6] Kornilov, V.I. & Shkvar, E.A.: Methodological aspects of airfoil flow control by means of distributed mass transfer. *Actual Problems of Continuum Mechanics: Experiment, Theory and Applications*, *AIP Conf. Proc.* 2504, 030027: (2023) 6 p.

[7] Nature as a Role Model: Lufthansa Group and BASF Roll Out Sharkskin Technology. Available online: www.basf.com/global/en/media/news-releases/2021/05/p-21-204.html

[8] Austrian Airlines takes off with sharkskin for the first time. Available online: www.austrianairlines.ag/en/2025/01/14/austrian-airlines-takes-off-with-sharkskin-for-the-first-time/

[9] van Campenhout, O., van Nesselrooij, M., Veldhuis, L., van Oudheusden, B. & Schrijer, F.: Flow visualization over drag reducing dimpled surfaces in turbulent boundary layers using Particle Image Velocimetry. In *Proc. of the 18th Int. Symposium on the Application of Laser and Imaging Techniques to Fluid Mechanics*: Lisbon, Portugal Springer: (2016) 21 p.

[10] van Nesselrooij, M., Veldhuis, L.L.M., van Oudheusden, B.W. et al.: Drag reduction by means of dimpled surfaces in turbulent boundary layers. *Exp Fluids* 57, 142: (2016) 14 p.

[11] Tay, C. M. J., Khoo, B. C., & Chew, Y. T.: Mechanics of drag reduction by shallow dimples in channel flow. *Physics of Fluids* 27, 035109: (2015) 22 p.

[12] Gattere, F., Chiarini, A., Quadrio, M.: Dimples for Skin-Friction Drag Reduction: Status and Perspectives. *Fluids* 7, 240: (2022)

[13] Shkvar, Ye., Kandume, J., E, Sh., Islam, M. & Kryzhanovskyi, A.: Particle Image Velocimetry in the Near-wake of a Wing with Leading Edge Tubercles, *Physics of Fluids* 36, 094103: (2024) 14 p.

[14] Hwang, D.P.: *A Proof of Concept Experiment for Reducing Skin Friction by Using a Micro-Blowing Technique.* NASA TM 107315: (1996) 13 p.

[15] Smith, B.L., Gezler, A.: The formation and evolution of synthetic jets, *Physics of Fluids* 31: (1998) pp. 2281-2297

[16] Smyk, E., Wilk, J. & Markowicz, M.: Synthetic Jet Actuators with the Same Cross-Sectional Area Orifices-Flow and Acoustic Aspects. *Appl. Sci.*, 11, 4600: (2021). 14 p.

[17] Smyk E.: Interference in axisymmetric synthetic jet actuator. *EPJ web of conf.* 143, 02111: (2017) 6 p.

[18] Al-Atabi, M.: Experimental Investigation of the Use of Synthetic Jets for Mixing in Vessels. *Journal of Fluids Engineering*, Vol. 133/094503: (2011) 4 p.