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Drag reduction in turbulent boundary layers by means of dimpled surfaces

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Contents

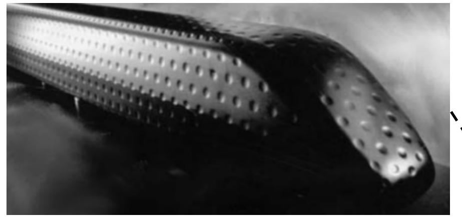
Various experimental studies have indicated a potential drag reduction by means of dimpled surfaces in turbulent boundary layers

- Linked to the Inventors Network GmbH
- Delft University of Technology
- National University of Singapore

1977 — 2015

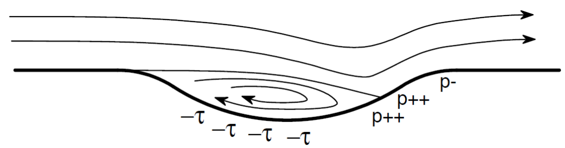
First discovery in USSR.

First publication by Kiknadze et al (1984).



Founding of the Inventors Network GmbH in 1998

Tornado Like Technology by Kiknadze et al.



5-10% drag reduction by Vervoort (2007).

2% drag reduction by Tay (2011).

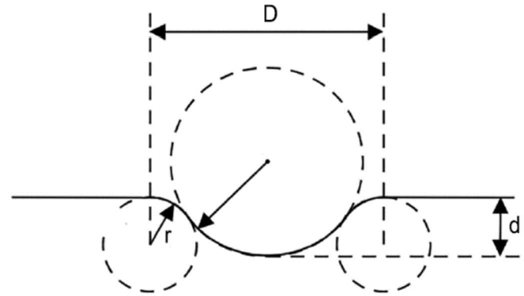
Sources: G. I. Kiknadze, Y. K. Krasnov, and Y. V. Chushkin, Investigation of the Enhancement of Heat Transfer due to Self-Organization of Ordered Dynamic Twisted Heat-Carrier Structures on a Heat-Transfer Surface, Report (Kurchatov Institute of Atomic Energy, 1984). L. L. M. Veldhuis and E. Vervoort, Drag effect of a dented surface in a turbulent flow, in Proceedings of the 27th AIAA Applied Aerodynamics Conference (2009). C. M. Tay, Determining the effect of dimples on drag in a turbulent channel flow, in Proceedings of the 49th AIAA Aerospace Sciences Meeting (2011). C. M. J. Tay, B. C. Khoo, and Y. T. Chew, Mechanics of drag reduction by shallow dimples in channel flow, Physics of Fluids 27, 035109 (2015). van Nesselrooij, M., Veldhuis, L. L. M., van Oudheusden, B. W., and Schrijer, F. F. J., Drag reduction by means of dimpled surfaces in turbulent boundary layers," Experiments in Fluids, Vol. 57, No. 9, 2016, 142 (2016)

Contents

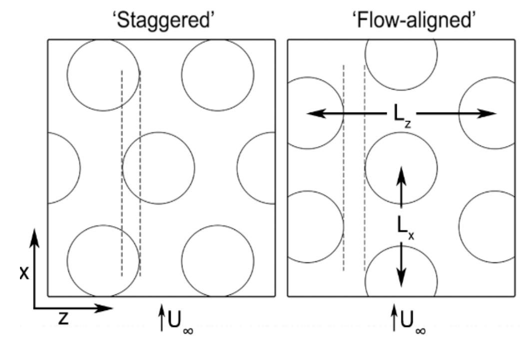
Direct force measurements were performed on 7 different test plates

The test plates are based on designs in literature and investigate parametric sensitivity

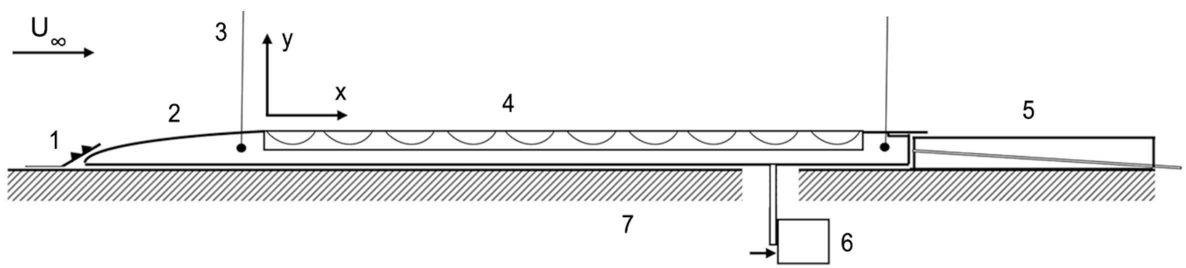
- Spherical dimples, key parameters:
  - Diameter (D)
  - Depth (d)
  - Edge curvature radius (r)
  - Streamwise dimple spacing (L_x)
  - Spanwise dimple spacing (L_z)
- All dimples were measured for two different turbulent boundary layers:
  - $\delta \approx 15$ mm
  - $\delta \approx 30$ mm
- Both staggered and aligned patterns were investigated



Cross-sectional geometry of a rounded spherical dimple. Depth is exaggerated for clarity



Definition of the difference between a staggered and flow-aligned pattern

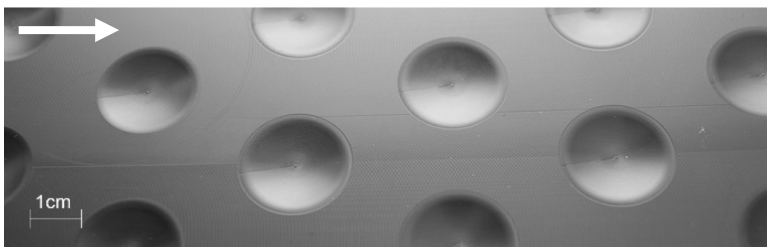


Side view of the setup. 1) deflector with carborundum roughness elements, 2) suspended test frame, 3) pendulum cable, 4) test plate, 5) rear flow guide, 6) force sensor, 7) wind tunnel floor

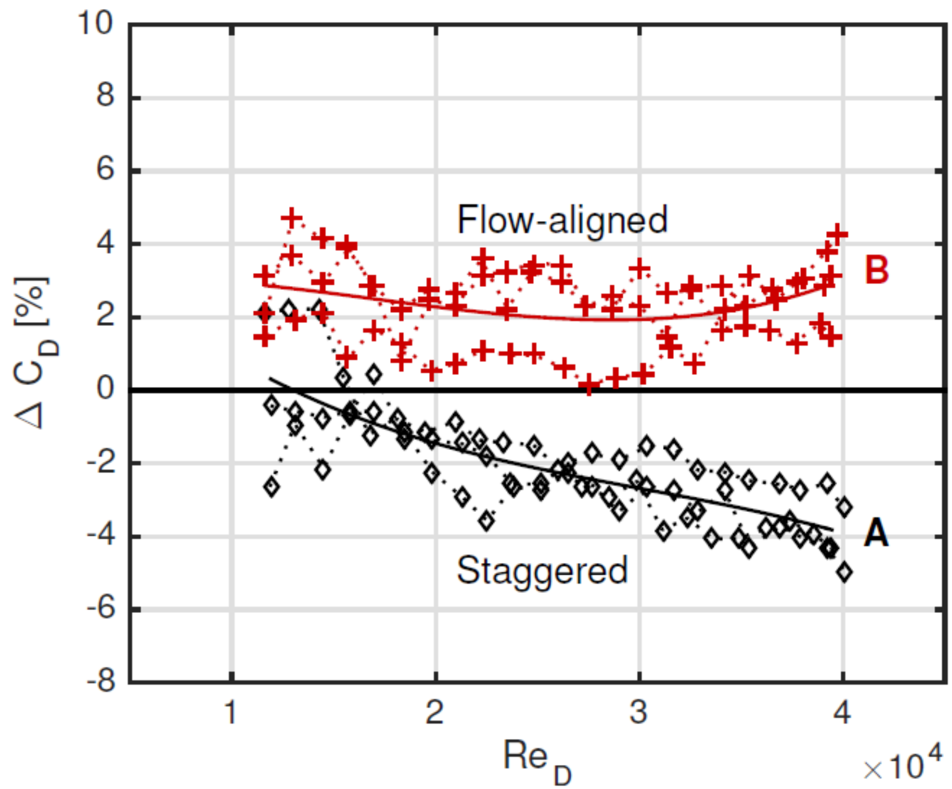
…which showed low single-digit drag reductions for one configuration

Repeatable drag reductions of ≈ 4% were achieved at a Re_D of 40,000

- Drag reducing plate (A-configuration):
  - Dimple depth = 0.5 mm and diameter = 20 mm
  - Staggered configuration
- Decreasing drag with increasing Re_D
- When rotating the drag reducing dimples (configuration A), by 90 degrees such that it becomes flow-aligned (configuration B), no drag reduction is observed



Photograph of A-configuration test plate which reduces turbulent skin friction drag



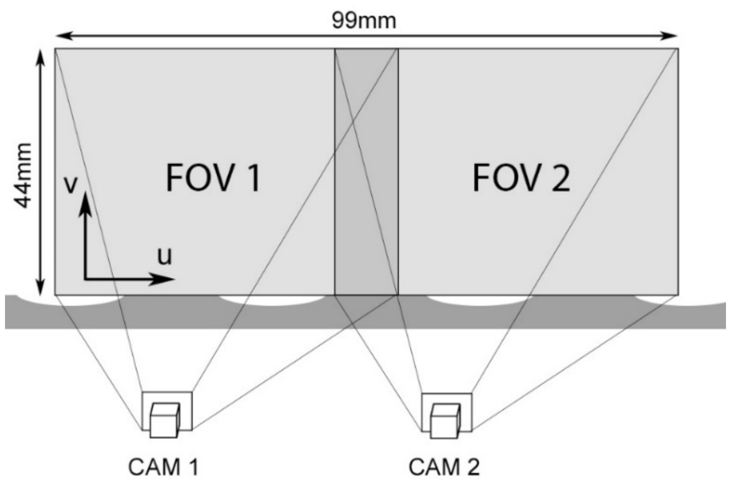
Drag performance of the A- and B-configuration plate relative to a flat plate for the thin boundary layer with $Re_D = U_\infty D/\nu$

Contents

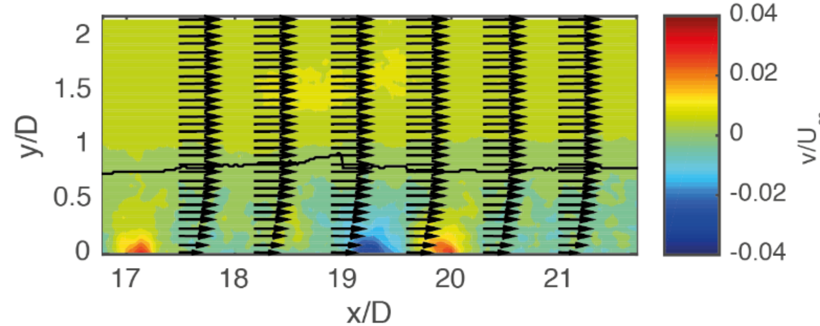
PIV measurement campaigns

2C-2D PIV in a vertical plane was performed to investigate the effect on the boundary layer

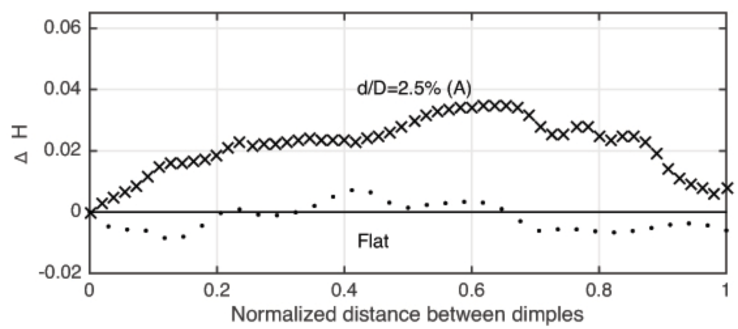
- Settings: FOV = 99x44 mm, px/mm = 24, pitch = 0.34 mm, Δt = 13 μs and acquisition frequency = 30 Hz
- δ, δ^*, Θ and H were not significantly affected by the dimpled surface



PIV configuration showing the locations of the field of view (FOV) w.r.t. the dimpled surfaces



Contours of v, local δ (solid black line) of plate A at $Re_D \approx 40{,}000$ (thin boundary layer)

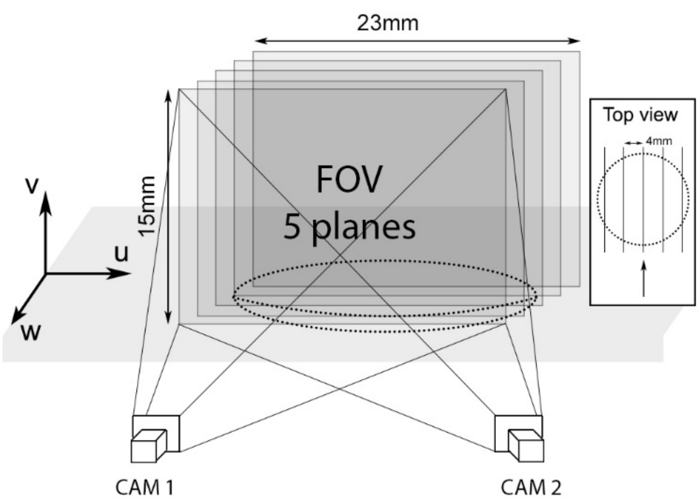


Development of the shape factor over the flat region between two dimples at $Re_D \approx 40{,}000$ (thin boundary layer)

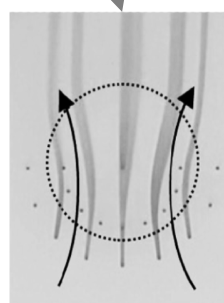
PIV measurement campaigns (cont'd)

Stereoscopic PIV in multiple vertical planes to recreate the 3D mean flow in a single dimple

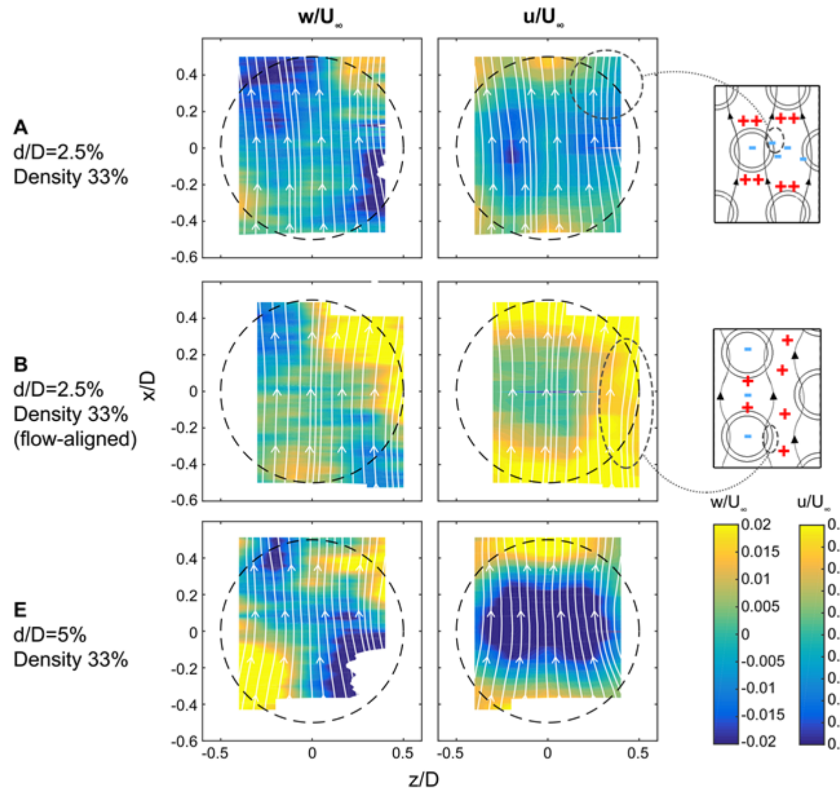
- Settings: FOV = 23x15 mm, px/mm = 65, pitch = 0.13 mm, Δt = 6 μs and acquisition frequency = 30 Hz
- No flow reversal and a *converger-diverger* flow topology is observed, agreement with the prediction by Tay (2014)



PIV configuration showing the locations of the field of view (FOV) w.r.t. the dimpled surface



Stage 1 flow by Tay (2014)

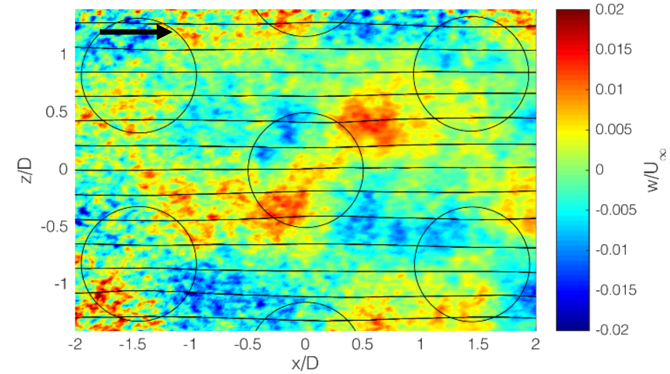


Top view of the flow structures reconstructed at 1 mm above the surface. Thin boundary layer case at $Re_D \approx 40{,}000$. The w-component in the streaklines is amplified 5 times for clarity

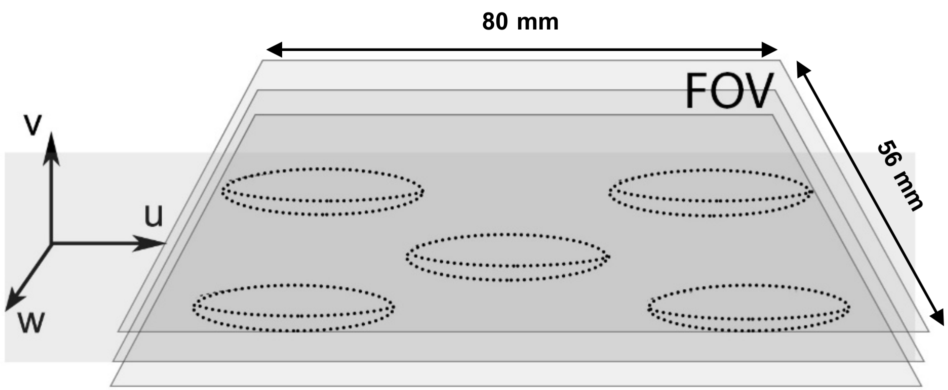
PIV measurement campaigns (cont'd)

2C-2D PIV in horizontal near-wall planes to investigate interaction of the dimple flow topology

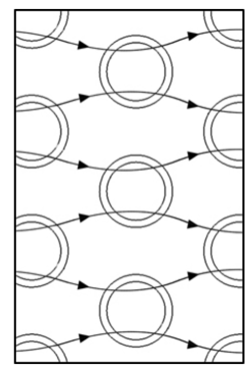
- Settings: FOV = 56x80 mm, px/mm = 20, pitch = 0.28 mm, Δt = 13 μs and acquisition frequency = 0.5 Hz
- An oscillation of spanwise velocity components is indeed captured in the PIV results above the drag-reducing dimple geometry
- The spanwise oscillation is observed in the flow at y/δ = 20% with dimensionless variables in the order of T^+ = 135 and w_m^+ = 0.3



Spanwise velocity at 3 mm above the drag reducing surface for U_∞ = 30 m/s. Flat plate data subtracted



PIV configuration showing the locations of the field of view (FOV) w.r.t. the dimpled surface

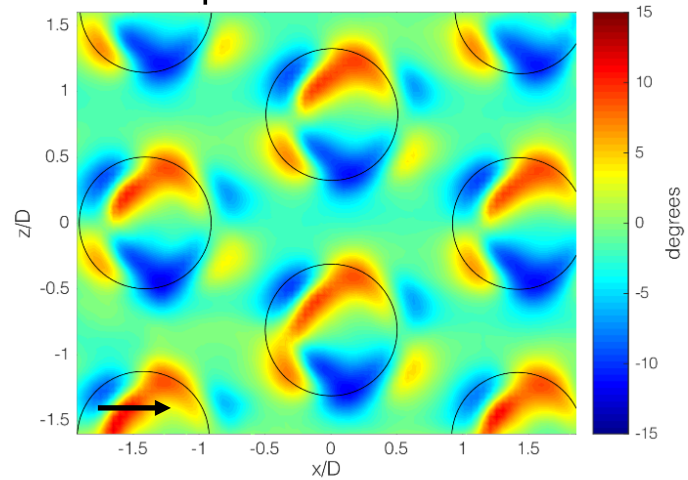


Oscillation due to an array of dimples.

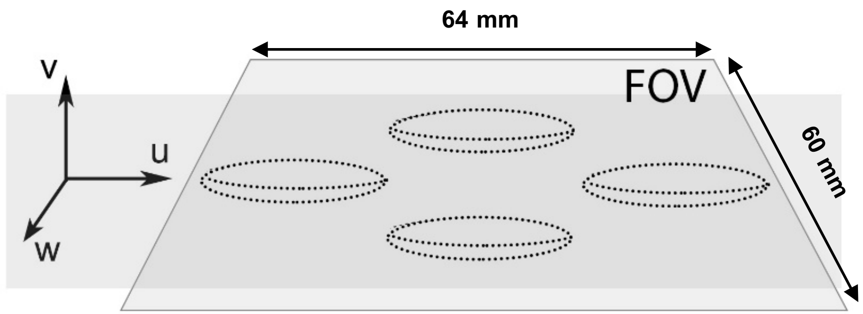
Particle Image Surface Flow Visualization (PISFV)

PISFV was used to investigate the surface shear streamlines over the dimples

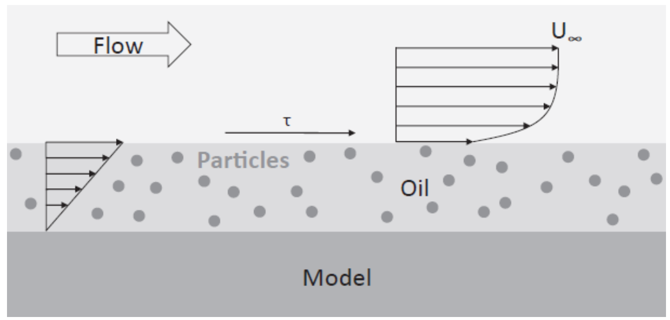
- Surface oil is pigmented with contrasting particles. In reaction to the shear force exerted by the flow on the oil film, the oil will be transported and carry the embedded particles along
- The particle motion, hence the shear flow, can be calculated by correlation of image pairs similar as with PIV
- *Converger-diverger* flow topology confirmed. The local shear vector angle varies between 0 and +/- 10° w.r.t. U_∞. No reversed shear is observed in any of the instantaneous vector fields



Local vector angle (anti-clockwise positive) w.r.t. U_∞ which is 30 m/s



PISFV configuration showing the location of the field of view (FOV) w.r.t. the dimpled surface



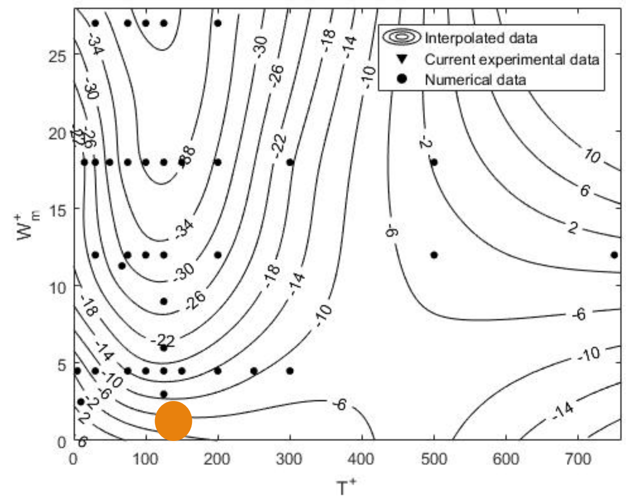
Schematic overview of oil film and particles, adapted after Mosharov (2005).

A novel explanation on a drag reduction by means of dimples is proposed

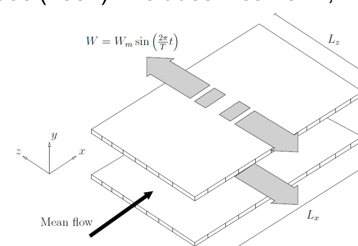
This theory is in contrast to what has often been proposed in literature

- It is proposed that the interaction between dimples creates a pattern of alternating spanwise velocity close to the surface
- This pattern could interact with the coherent structures in the boundary layer in analogy with drag reduction by spanwise wall oscillations
- Choi & Clayton (2001) showed a 45% reduction in turbulent drag from DNS study on spanwise wall oscillations
- The drag reduction is in the order of what can be expected when considering numerical research regarding wall oscillations (approx. 3%)

Flow behavior analogy must be studied further to establish solid groundwork for this analogy



Bi-linear interpolation of drag reduction versus T^+ and W_m^+. DNS data for a channel flow by Quadrio and Ricco (2004). Includes mean of A, B and C region.

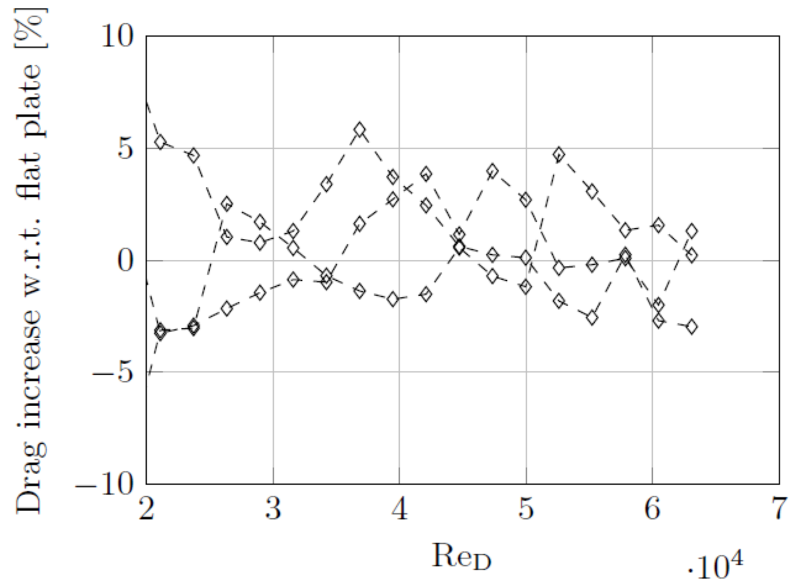


Active wall oscillation schematic of physical domain by Ricco and Quadrio (2008).

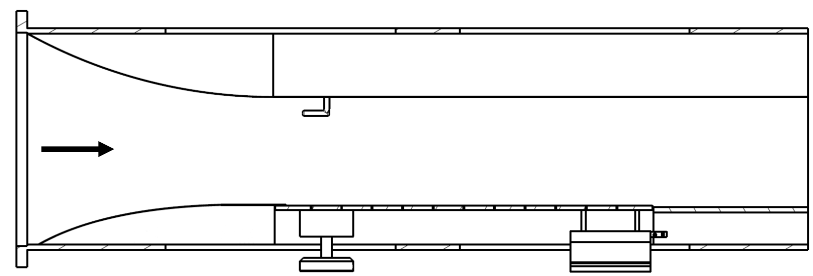
Contents

The Reynolds regime was extended by increased tunnel contraction

- The setup was improved with an air bearing system and tunnel contraction to reach Re_D of over 60,000
- An active system of 242 vacuum-driven actuators was built to create a variety of dimple patterns on-demand
- Previous drag reduction was not repeated, and random errors increased due to the new setup architecture
- The favorable pressure gradient suppresses near-wall turbulence generation. Thus, elimination of the drag reduction effect may ***support the oscillating wall analogy***



Drag results in the active dimple setup for the drag-reducing dimple topology

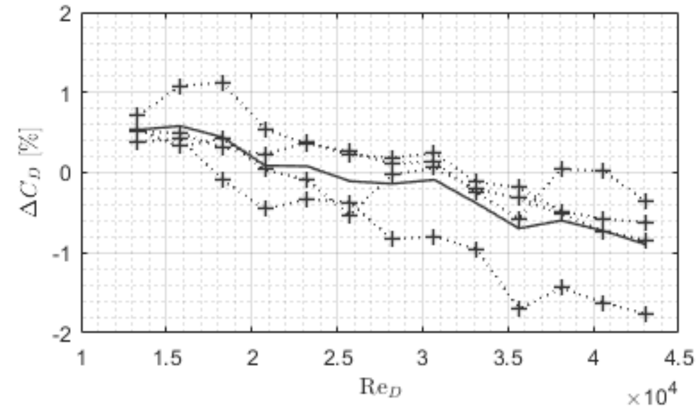


Side view of the increased velocity direct force measurement setup

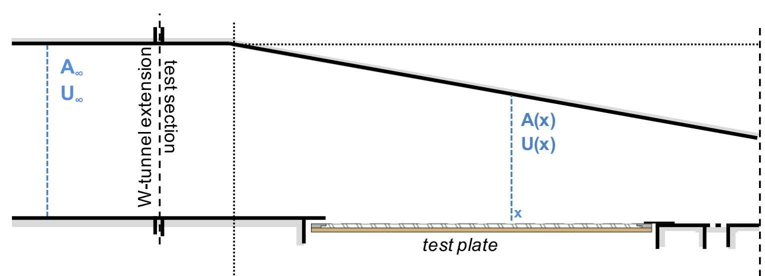
Pressure gradient effects were studied further with an adjustable tunnel

A wind tunnel extension with an adjustable top wall was created to control the pressure gradient

- In pursuit of repeatability, setup robustness and ease of operation, a force balance utilizing flexures was developed
- Good repeatability was found for the zero pressure gradient. A drag reduction, increasing with Re, was again observed
- The tested favorable or adverse pressure gradients behaved significantly different and the results were dominated by random errors
- Anomalies in setup need addressing (e.g. thermal expansion of flexures, vibration of the adjustable wall system)



Drag measurements results obtained from the flexure setup for a zero pressure gradient condition



Schematic of the flexure setup used in the variable pressure gradient direct force measurement campaign

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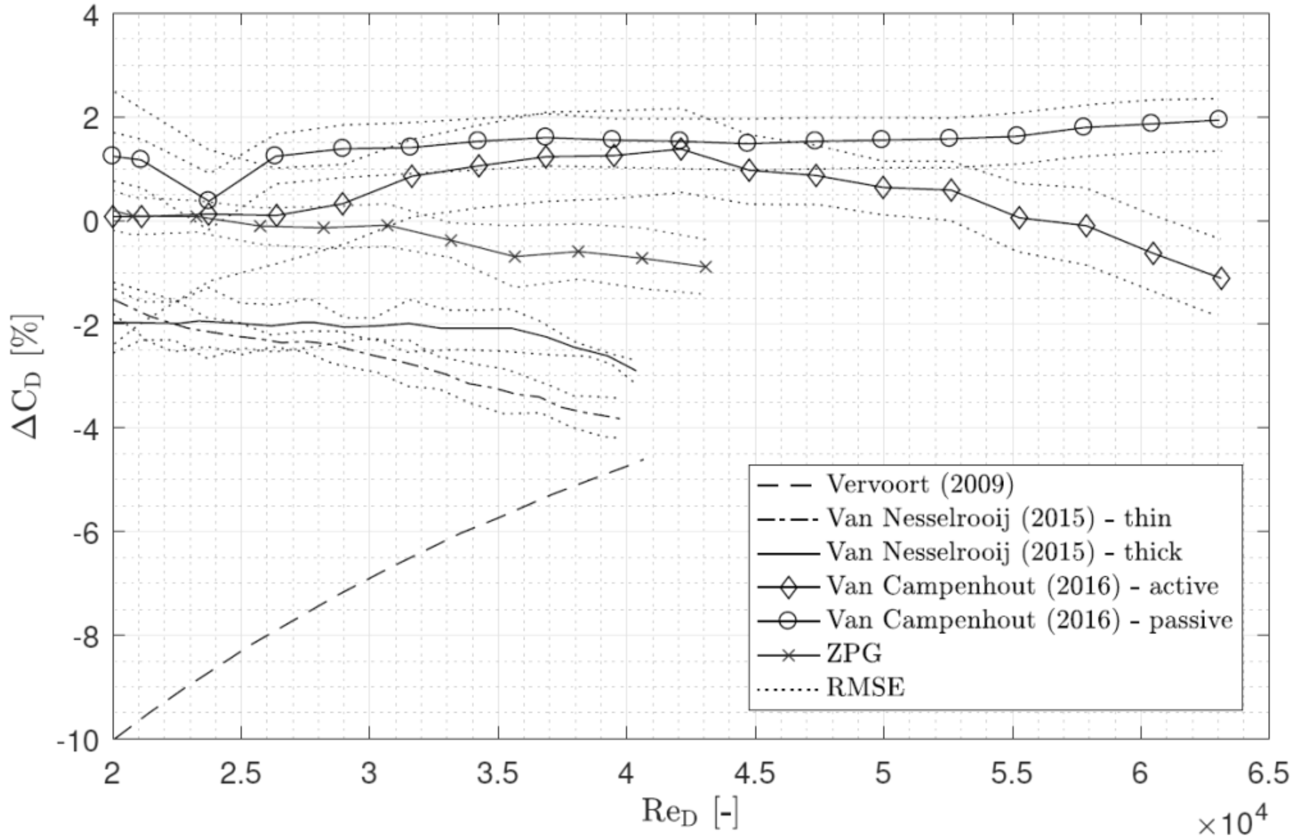
Direct force measurements do not yet provide a consistent overview

However, significant flow control potential is identified



Drag results obtained at DUT during all measurement campaigns

Final conclusions and recommendation

Significant flow control potential is identified. Fundamental research is ongoing

- The range of direct force measurements and flow visualization studies performed at Delft University of Technology have laid the groundwork for a new proposal for the drag-reducing mechanism of dimples in turbulent boundary layers

- Initial drag results are promising, showing up to 4% drag reduction and a favourable trend with Reynolds number. Repeatability between setups and flow conditions is inconclusive

- Notable advantages of dimples as a flow control technology:
  - They are very shallow and do not require special cleaning or maintenance
  - They are not prone to wear or soiling, in contrast to e.g. riblets
  - They can easily be (retro)fitted on skin panels and are not expected to pose substantial design implications

- Further research is planned to understand the flow sensitivities, to investigate the drag-reducing mechanism further, and to exploit its potential in real-world applications

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