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Review of thesis titled: “Numerical modeling of a turbulent boundary layer on wavy and irregular surfaces” by Piotr Kamiński

1. Introduction

Passive flow control modifies fluid motion without external energy input, offering simple and robust alternatives to active methods. In wall-bounded flows, surface-based strategies for turbulent boundary layer (TBL) manipulation are of particular interest due to their efficiency. Among these, streamwise surface waviness has emerged as a promising approach for delaying separation and modifying near-wall turbulence.

Experimental and numerical studies have shown that such geometries can increase wall shear stress and postpone turbulent separation under adverse pressure gradients (APG) [1, 2]. However, despite confirmed performance benefits, the underlying physical mechanisms - particularly the interaction between surface waviness, APG, and turbulent structures remain insufficiently understood [3, 4].

Key open questions include the relative roles of local and global APG, the evolution of flow structures over repeated waviness, and the dependence of near-wall dynamics on geometric parameters. Furthermore, it remains unclear whether these effects persist under realistic conditions such as curved surfaces and varying Reynolds numbers [5].

Piotr Kamiński thesis addresses some of knowledge gaps by investigating turbulent flow over wavy wall (WW) surfaces, linking flow physics mechanism to geometry and assessing performance under practical conditions. In addition, he explores the potential of surface waviness for heat-transfer enhancement through increased near-wall mixing, with attention to optimizing geometry for both performance and manufacturability.

In particular, the study focuses on:

(i) evaluating the respective roles of local and global APG in the development of the turbulent boundary layer;

(ii) analyzing the evolution of flow structures developing over WW;

(iii) exploring the relationship between near-wall flow characteristics, global flow statistics, and the defining geometric parameters of the waviness;

(iv) assessing the potential for performance enhancement through geometric refinement of the surface;

(v) examining the effectiveness of the waviness in more realistic conditions, specifically when applied to airfoil-like curved surfaces and pipes and channels (used in heat exchangers) subjected to variations in Re.

2. Analysis of Kamiński papers

Author of thesis provided a set of papers [K1-K6] as the main achievement. In this works he focused on the analysis of two issues related to aerodynamics and heat exchange: a) reduction or elimination of TBL separation by using a wavy wall (WW), i.e. a passive form of flow control (no need to supply energy); b) optimization of shapes of pipes and channels walls used in the heat exchanger to minimize their pressure drop and maximize the temperature uniformity.

Research presented in reviewed thesis is based mostly on computational fluid dynamics (CFD) simulation results. This modelling technique provide high-resolution, time-dependent, and spatially detailed flow field data which is particularly valuable in the near-wall region, where flow behavior is highly complex and difficult to capture experimentally. Also CFD enables use of different boundary conditions and geometric parameters, that's why it is well-suited for parametric investigations that would be prohibitively time-consuming and resource-intensive in an experimental setting. In performed numerical research Kamiński employed both LES (Large Eddy Simulation) and RANS (Reynolds-Averaged Navier-Stokes) turbulence modeling approaches.

As found during review process Kamiński published a preliminary paper [K0] that is not mentioned in the main achievement. In this work he compared popular CFD models RANS and LES for the configuration with WW adopted from Elsner et al. [6]. The main conclusions was that RANS models offered significantly lower computational cost (around 1/50 of LES) but yield inadequate key flow phenomena results. Direct Numerical Simulation (DNS), on the other hand was excluded due to its prohibitively high computational cost, around ten times greater than that of LES.

TBL detachment reduction is the subject of the first four reviewed papers:

In paper [K1], two cases are analyzed for each type of pressure gradient (ZPG and APG) for: a) flat wall, b) wavy wall. The novel experimental research needed to validation of numerical calculations, were obtained also in Częstochowa University of Technology by Dr Vasyl Sokolenko and Dr habil. Artur Dróżdż [K1]. In main experiments APG magnitude was controlled by deflection of the upper wall and a suction through a perforated section, while in the ZPG configuration, a constant pressure along the channel was achieved by implementing a slight, gradual rise of the top wall in the streamwise direction. Velocity fields were acquired using a single hotwire anemometry (HWA) in four positions WW. The flow upstream of the wavy section was set to be Re_τ = 2500 – this selection fill the gap between $Re\tau$ = 1350 and 4000 considered in earlier Częstochowa team works of Drozdz et al. [1] and Elsner et al. [6]. Kamiński reduced the size of the computational domain to include only the flow region essential for the analysis, then LES simulations computational time decreased from approximately 2 months of continuous CPU time to just 1 month for each analyzed test case. Simulations were carried out using the ANSYS Fluent program. Spatial discretization employed a bounded second-order central difference scheme for the convective terms, while a second-order central difference scheme was used for the continuity equation, pressure gradient, and viscous terms. Pressure–velocity coupling was handled using the SIMPLE algorithm and time integration was performed with a second-order implicit scheme. The flow field was initialized with zero velocity in all directions (steady initial state), then a transient phase, during which the flow evolved and reached a fully turbulent state, lasted approximately for three flow-through time units ($t_{FT} = L_x/U_{in}$). A constant time step $\Delta t = 10^{-4}$ s, resulting in CFL ≈ 0.82 was applied. At the inlet boundary a streamwise velocity profile was prescribed matching experimental measurements, while turbulent fluctuations were introduced via the Fourier-based synthetic turbulence generation (STG) technique. Flow dynamics near the crests and along the uphill and downhill sections of the waviness were examined. The received results of LES simulation for four positions: x/λ=0.25; 0.75; 4.25 and 4.75 showed a very good agreement (close match of shape and magnitude) between experimental data especially for mean velocity profiles , and some minor deviation of fluctuation profiles (for x/λ=0.25 and 4.75). Waviness significantly influences the flow field, as evidenced by a pronounced reduction in velocity along the downhill slopes, i.e., where local APG develops, while the opposite trend is observed on the uphill sides due to local FPG (local favorable pressure gradient). In this paper Kamiński also study shifts to the wall shear stress (time-averaged streamwise component). The results showed that the wall waviness results in an increase in wall shear stress in the downstream region only when the boundary layer is subjected to APG.

In Kamiński et al. paper [K2] PhD candidate use effective slope (ES) parameter (introduced by Napoli et al. [7]) that characterize the waviness geometry. The main objective was to identify combinations of amplitude A and number of waviness periods $N\lambda$, corresponding to specific values of ES, that result in the greatest increase in τ_w relative to the flat wall case - to achieve maximum delay of the separation point. In all simulations flow upstream of the wavy section was set as in first paper [K1] to be Re_τ = 2500 Fifteen cases was tested in range of effective slopes from ES = 0 (flat wall) to ES = 0.2455. The impact of the waviness parameters (A_0 = 0, 0.25,..., 2.0 and $N\lambda$ = 1, 2,..., 7) on τ_w in the region down-stream of the corrugation. Kamiński observed that increasing A_0 leads to a rise in $\Delta\tau_w$, reaching a maximum at $A_0 = 1.2$ and similarly $\Delta\tau_w$ increases with $N\lambda$, peaking at $N\lambda = 5$, after which a rapid decline follows. Analysis of the spatial distribution of τ_w confirmed that confirm that the increase in τw persists throughout the entire downstream area, which satisfies the necessary condition for delaying the onset of flow separation. It is also observed that increasing A_0 leads to a reduction in velocity within the outer region of TBL ($y/\delta > 10^{-1}$) and increase of values of streamwise velocity fluctuations (throughout the entire boundary layer). The examination of both time averaged and instantaneous flow quantities provided deeper insight into the underlying flow mechanisms, thereby extending the knowledge about passive flow separation control method which employs 2D streamwise waviness to control the turbulent separation.

A novel type of WW characterized by tilting of subsequent waves (Fig. 1) are object of the research in paper [K3].

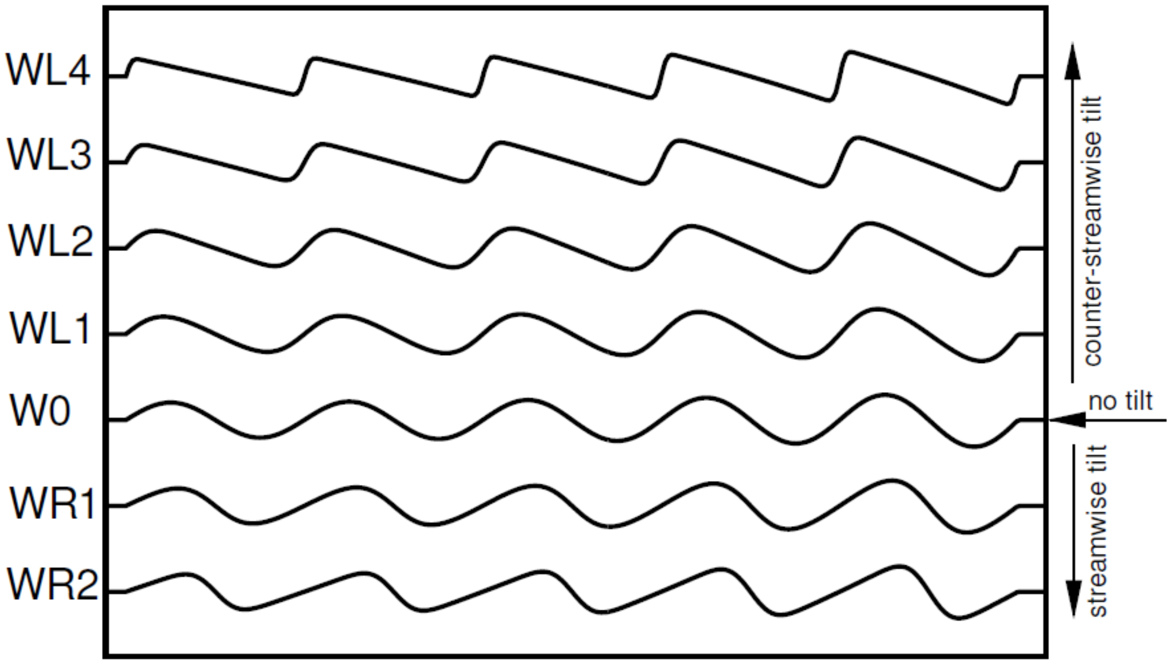

Fig. 1 Different analyzed wall waviness shapes [K3].

The main aim is to demonstrate that control of turbulent separation via the surface waviness can be improved by introducing a novel type WW characterized by tilting the subsequent waves. Performed simulation showed that leftward tilting (WL) increases $\Delta\langle\tau_{w,x}\rangle_{avg}$, whereas rightward tilting WR results in its reduction. These changes are accompanied by variations in C_d parameter, whose value either increases or decreases depending on the tilt direction and magnitude. Configuration WL2 achieve a minimum in C_d while yielding $\Delta\langle\tau_{w,x}\rangle_{avg} = 18.4$ %, representing a 72.4 % improvement in wall shear stress relative to the baseline case W0, constituting a significant enhancement. Shape

WL2 resembles that of a streamlined body, such as a teardrop, and are therefore expected to minimize flow separation along its surface. Analysis of contour maps shown that WL2 configuration fully eliminates separation on the downhill slope, thereby preserving near-wall momentum in the downstream region (in WR2 configuration, the opposite effect is found). Other very promising configuration WL3 yields an even higher $\Delta\langle\tau_{w,x}\rangle_{avg}$ = 20.1 % nearly doubling the improvement over W0 while maintaining the same C_d. From work [K3] it then follows that the control of turbulent separation via surface waviness can be significantly improved via tilting of WW. The optimal choice is a leftward tilt, as it increases wall shear stress and decreases Cd relative to a non-tilted surface so flow field, and in particular the turbulence, is strongly influenced by WW tilt.

In last related to TBL reduction paper [K4] Kamiński rightly notice that in real-world applications (in wind turbine blades) surfaces have curvature that are combined with a variable angle of attack. Object of research was selected to be NACA 4412 airfoil, in which WWs was embed into the suction side. Wider range of Re_τ = 1200 – 2500 was chosen to perform sensitivity analysis of WW impact. To establish a well-developed TBL and minimize the influence of synthetically generated turbulence at the inlet, a ZPG inlet section 7.5 m in length is placed upstream of the airfoil section. Curvature is responsible for inducing the APG reflects on the suction side of inclined NACA 4412 airfoil (5° angle of attack). Six numerical cases are analyzed W1 up to W6 (range of ES from 0.125 to 0.208). In comparison to earlier papers [K1-K3] in this paper [K4] the computational domain is significantly longer and therefore partially contains the separation region (not present in earlier works). Figure 3.17 shows that the separation point for analyzed curved WW is delayed only for some optimal values of ES (not for relatively small 0.125 and relatively high 0.208). The most pronounced reduction in $A_{sep.}$ (area of separation) occurs in configuration W4 (ES=0.17; λ=0.; N=5), where the waviness postpones separation to the largest extent. This W4 case is further in detail analyzed by the spectrograms (computed based on the streamwise, wall-normal and spanwise scaled velocity components) which are compared to smooth airfoil results. Streamwise spectra calculated for the smooth wall (S) case exhibit two distinct peaks in E/U_e^2, a characteristic feature of APG boundary layers, whereas for W4, a broad region of elevated E/U_e^2 is observed. The near wall large-scale energy amplification observed in the streamwise and spanwise directions for W4 suggests increased activity of quasi-streamwise vortices, indicating enhanced momentum transfer toward the wall and contributing to higher τw.

Analysis performed for different Re_τ: 1200, 1700, 2300, and 2500 [K4] indicate that W4 achieves the most pronounced separation delay (maximum $\Delta x_{sep.}$) at Re_τ = 2500, accompanied by the largest $\Delta\langle\tau_w\rangle$ (effect of increase in TBL thickness at lower Re_τ). This highlight the importance of properly tailoring the WW geometry to the expected inflow conditions in order to ensure desired separation control performance.

Findings from work [K3] inspired Kamiński to further extend the WW application scope to control the heat exchange process, whose efficiency largely depends on the mixing intensity. In paper [K5] Kamiński et al. used machine learning (Bayesian optimization - BO) to optimize the WW shape in an axisymmetric circular pipe. The aim is to improve temperature uniformity while minimizing pressure losses. Research for pipe flow is performed for Re=4000 (v_m=6 m/s) and the inlet temperature T_{in} = 300 K. Upstream of the WW, the wall temperature is also set constant at T_w = 300 K. In heated WW segment, a constant heat flux is applied, defined as $\phi_w = P_w/A_w$ (P_w = 10 W is the supplied heating power and Aw the surface area of WW) while beyond this section, the wall is treated as adiabatic with zero heat flux ϕ_w = 0 W/m^2. During simulations local wall temperature adapts to the flow and geometric conditions at each point. In a reference case of a smooth-walled pipe, the wall temperature in the heated section is $T_{w,ave}$ = 395 K, while the average fluid temperature at the outlet of the heated region is $T_{f,ave}$ = 317.5 K. Kamiński points that enhanced mixing, shows typically as a consequence of greater pressure drop along the pipe with respect to the uncorrugated configuration. The goal of this research [K5] was to find the wall shape (using BO) ensuring the maximum temperature uniformity without a significant increase of pressure drop. Kamiński et al. introduce a cost function *J* calculated as a multiplication of two ratios of WW to flat wall configurations (standard deviations of temperature uniformity and pressure drops). The interesting scatter plot from performed results were showed – see Fig. 2.

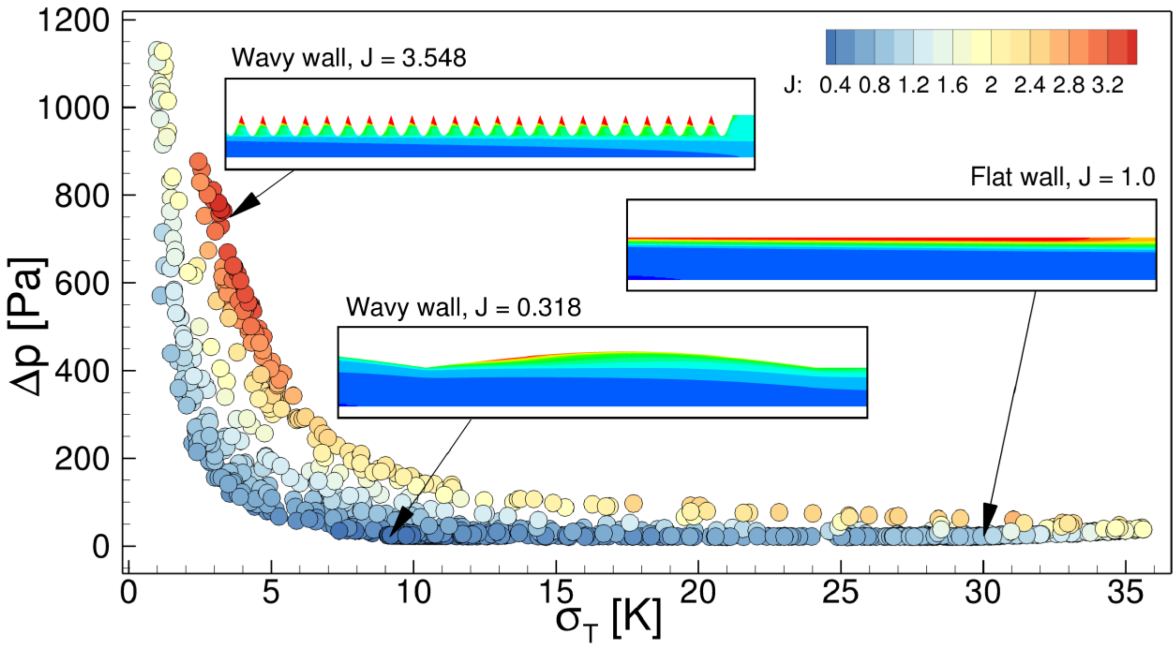

Fig. 2 Scatter plot of $\Delta p = f(\sigma_T)$ for different WW [K5].

As seen from the Fig. 2 the combined BO–RANS process successfully identified an optimal configuration (see WW with *J* = 0.318), characterized by two outward-facing waviness cavities. This shape enhances TKE production while minimizing obstruction in the pipe, thereby avoiding the large pressure losses seen in less favorable designs. The worst performing configuration (also showed on Fig 2 - WW with J = 3.548) have all of the waviness peaks oriented inward, therefore exhibits a pressure drop that heavily penalizes its performance. Additional analysis of temperature contours for worst case shown that the flow undergoes strong recirculation. Two recirculation regions were detected: a primary (large) driven by the core flow, and a secondary (small) where the recirculation is induced by the primary recirculation zone. Secondary recirculation region restricts heat transfer from the sharp corners of the cavity, where temperatures can reach nearly 600 K. This configuration is then unsuitable for practical applications due to the severe thermal gradients and resulting thermal stresses posing a high risk of material degradation and surface failure over a relatively short operational period.

Unreviewed paper published in preprints library [K6] is a continuation of idea proposed in conference paper [K5] to enhance heat transfer keeping very small pressure drop in pipes. This time Kamiński et al. extend analysis to thin channel, which represents a critical component of compact heat exchangers. The objective was again to minimize the pressure drop Δp and maximize the temperature uniformity. The simulation was performed for case with laminar flow Re = 2000 [-] (v_m = 0.112 m/s) and inlet temperature set to be T_{in} = 300 K. A constant heating power of P_w = 10000 W is imposed to WW section, for a non-wavy channel (analyzed for comparison) the heated wall reaches an average temperature of $T_{w,mean}$ = 379.2 K, while the mean fluid temperature downstream of the heated section is independent of wall shape and equals $T_{f,mean}$ = 307.9 K.

Two approaches were employed to alter the wall shape: a) modification of a sinusoidal wave by adjusting the number of periods, amplitudes, and tilt (iterative procedure, starting from a sinusoidal profile and deforming it according to 4 control parameters); b) employing a spline-type interpolation function PCHIP (piecewise cubic Hermite interpolation polynomial – defined by 21 control points located on WW). Initial test analysis was conducted using different turbulence model. Test cases for optimal and worst cases were performed in 3D while for other 2D approach that significantly reduced computation time was used. The comparison to experimental research of Zontul et al [8] showed that among different turbulence models k-epsilon model was closest in different regions to the experimental result – this model was adopted for following numerical research. Near walls the mesh is unstructured based on triangulars elements while in preceding and downstream of the waviness mesh is structured and composed of quadrilateral cells. Performed simulation showed that for sinusoidal wall type the BO procedure after 150 iteration was able to give a shape represented with very small J=0.066. With PCHIP method the best result was received after many more iteration and was twice that large J=0.1256 as for sinusoidal wall type `

A similar scatter plot (as in paper [K5]) was prepared showing the best and worst scenarios (Fig. 3).

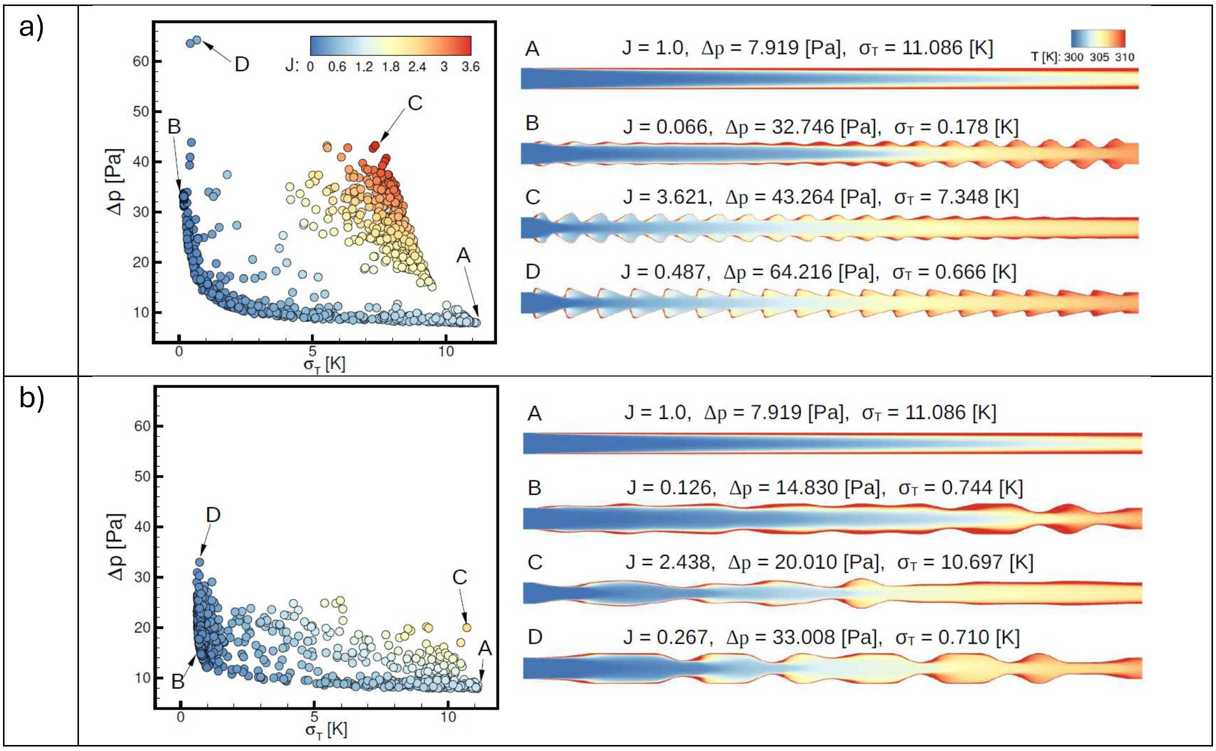

Fig. 3 Scatter plot of $\Delta p - \sigma_T$ colored by J results for the: a) sinusoidal wall type, b) spline-shaped wall [K6]

Later in this paper, Kamiński et al. discusses selected results: a) profiles of the temperature; b) contour maps of temperature; c) axial profiles of the temperature, streamwise velocity, pressure, and turbulent kinetic energy (for the wavy wall created with sinusoidal and spline function); d) contour maps of TKE; e) profiles of temperature at the wall; f) contour map of U_x showing a close-up of the waviness cavity, with regions where $U_x < 0$, indicating separated flow, shaded in grey; g) profiles of σ_T , Δp, and J as a function of the removed periods.

In one of the last sections Kamiński et al. [K6] improved the best WW scenario by improving its geometry by hand (authors call it HAO – human assisted optimization) – this helped authors to reduce *J* a little bit *J* = 0.0546.

3. Questions

The thesis is written in great detail, but its thorough analysis carried out for the purposes of this review revealed certain details about which I would like to ask PhD candidate during the defense of the doctoral thesis:

1) why the WW section in experimental research [K1] not begins for $x_{s,w}$ = 0 m but instead in position given with $x_{s,w}$ = 0.01 m?

2) What would be the differences if the flow would be assumed to be compressible in LES simulation, have the author of thesis tested the modelling differences? How much

would the simulation time extend? Could the simulation results using compressible LES model be closer to experimental ones?

3) In eq. (2.6) on page 22 we do not have ϕ^n, I understand it should be just ϕ describing the phase angle?

4) “The mesh was uniform in both the streamwise and spanwise directions, with grid spacings equal to: 0.3125 < Δx+ < 2.5, 0.3 < Δy+ < 0.92, and 0.3125 < Δz+ < 2.5.” – From Fig. 2.4 it appears that in y direction the ratio of M1 and M4 layers grid size are larger than suggested 0.3 < Δy+ < 0.92?

5) From Fig. 2.5 (page 23) it follows that research related to heat transfer in pipelines and channels with corrugated wall geometry are related to a hypothetical case in which the pipe wall thickness was not assumed. In reality the pipe wall thickness play an important role (in both elastic pipes and channels as in viscoelastic). Why the real pipe wall was not simulated and its effect? We do also see that from Fig. 2.5 a) it follows that author have two different amplitudes A1 and A2 – are they related to the initially defined amplitude function A which only have the positive values (higher and higher with x grow).

6) Given the limitations of the RANS framework reported in papers [K1–K4], why was it employed in papers [K5] and [K6] instead of LES, as described in Section 2.2.3? Why different block-structured grid consisting of quadrilateral cells is used (near wavy section, the mesh is unstructured and composed of triangular elements) – not the same as in papers [K1-K4]?

7) We do not know which case (of four analyzed in paper [K1]) is presented in Fig. 3.1 (page 28).

8) In Fig. 3.4 the intersection points with grey zero wall shear stress line indicate the positions of boundary layer separation and reattachment. In my opinion the change of system from ZPG to APG did not changed a lot – the fall of this results below 0 is on similar points and with similar magnitude. Can author of thesis explain why such results was received? Also we do see the damping of shear stress amplitudes of W-APG (except last for abscissa 5) while for W-ZPG we see peaks shear stress values to rise – could the author also discuss this differences? Can they be somehow physically explained?

9) “Based on the conclusion from Paper 1 that WW enhances τ_w only under APG conditions...” - what is the purpose of wall shear stress enhance? How can it be explained with use of Fig. 3.4 (presented on page 31)?

10) What means $L_{x,w}$ in eq. 3.1 is it the same L_w as in Fig. 2.5?

11) In paper [K2] what means a line in Fig. 3?

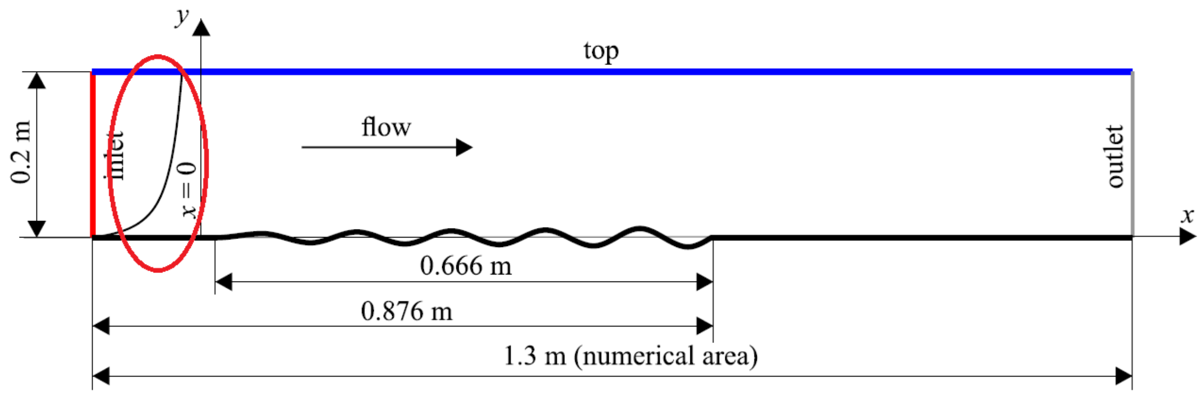

Fig. 3. Computational domain for LES study.

12) Should Equation (3.4) not be expressed in summation form?

13) The reviewed thesis shows that no attempt was made to analyze the influence of unsteady pressure gradient effects. In a new interesting paper [9], we read that:

“In many engineering scenarios, however, pressure gradients vary in time as well as in space. For example, manoeuvring aircraft experience time-varying pressure fields due to changes in angle of attack or vehicle acceleration/deceleration. Vehicles operating in gusty weather conditions encounter sudden temporal changes in pressure gradients due to fluctuations in atmospheric turbulence. In rotating machinery, such as turbines and compressors, blades experience dynamically changing spatial pressure gradients. These factors further complicate the physics, and the governing parametric space expands to additionally include the type (periodic pulsating/non-periodic transient), magnitude and time scale of unsteadiness.”

I am asking the author of the dissertation to justify (explain me and the audience, during the defense) what problems would arise related to the numerical analysis assuming unsteadiness of the pressure gradient (a real transient modelling scenario).

14) Why the coefficients of ES parameter under equation (3.6) is different than mentioned earlier in eq. (3.1) of reviewed thesis?

15) In paper [K5] authors assumed a pipe of heat exchanger to have a radius of R = 0.005 m and a total length of L = 0.25 m. Is such dimensions used in practice, can PhD candidate give some reference proving that dimensions?

16) Is really width W(0.15 m) so much larger than this channel height H (0.018 m) in research performed in paper [K6] ? Or is it some typo?

17) Kamiński writes that : “To eliminate the influence of side boundaries on the flow in the central region, periodic boundary conditions are applied”. Did You mean corners of the channel? What kind of periodic boundary was used – how it help to minimize tailored computational meshes in corners? Can it be explained in more details?

18) In Fig. 11 in paper [K6] it's hard to see any difference between 2D and 3D results for x=0.95 m. If they overlap it's good to use a different color of 3D line – then maybe the overlap will be confirmed.

19) Why the flow analyzed in paper [K6] where Re = 2000 is treated as a turbulent flow. While the critical Reynolds number is under 2300 the flow is in analyzed geometries treated standardly as laminar. Could the Phd candidate show a comparison of laminar flow results for this case and discuss the differences?

4. Conclusion

The submitted doctoral thesis presents a coherent, methodologically rigorous, and highly relevant contribution to the field of fluid mechanics, particularly in the area of turbulent flow control and heat transfer enhancement. The work is well-structured, consisting of a logically organized series of publications that collectively address both fundamental and applied aspects of surface waviness as a passive control strategy.

A major strength of the dissertation lies in its clear two-part structure, which reflects both scientific depth and practical orientation. The first part demonstrates a systematic and well-justified investigation of turbulent flow separation control using wavy-wall geometries. The progression from simplified channel-flow configurations to realistic airfoil simulations is particularly commendable, as it ensures both methodological validation and applicability of the results. The use of Large Eddy Simulation (LES) is appropriate and convincingly validated, providing high-fidelity insight into the underlying physical mechanisms.

The candidate shows a strong ability to interpret complex flow phenomena. The identification of the role of adverse pressure gradients, the careful parametric optimization of waviness geometry, and the innovative introduction of tilted configurations all demonstrate originality and scientific maturity. Especially noteworthy is the finding that properly designed tilted waviness can simultaneously increase wall shear stress and reduce drag, this is an outcome of clear practical importance. The spectral analysis further strengthens the work by linking observed macroscopic effects to coherent turbulent structures, indicating a deep understanding of turbulence physics.

The second part of the thesis extends the concept of surface waviness into the domain of heat transfer, introducing a well-formulated optimization framework that combines RANS modeling with Bayesian Optimization (BO). This part of the work stands out for its interdisciplinary character and engineering relevance. The formulation of a cost function balancing thermal performance and pressure losses is both practical and elegant. The results demonstrate substantial improvements over baseline configurations, and the introduction of human-assisted optimization (HAO) adds an innovative and pragmatic dimension, addressing manufacturability alongside performance.

The results are not only scientifically sound but also carry clear application potential, particularly in aerodynamics and thermal systems such as heat exchangers or energy devices. The thesis demonstrates consistency across different Reynolds numbers and configurations, while also critically acknowledging limitations, such as the reduced effectiveness at lower Reynolds numbers.

In my opinion, the main weakness of the thesis is the limited investigation of Reynolds-number sensitivity. In the case of turbulent boundary layer (TBL) separation investigated in the wind tunnel, the phenomena of WW effect in the range $2500 < Re_\tau \leq 4000$ were not analyzed. Furthermore, in the heat-exchanger studies, the analysis was limited to only a single Reynolds number ($Re = 4000$ for the pipe geometry [K5] and $Re = 2000$ for the channel geometry [K6]).

From a formal perspective, the dissertation meets the standards expected of doctoral thesis in Poland. The candidate demonstrates independence in research, the ability to formulate and solve complex scientific problems, and a significant contribution to the discipline. The publication-based format further confirms the high quality of the work, as the results have undergone peer review. The journals *Energy*, *Aerospace Science and Technology*, *Journal of Wind Engineering and Industrial Aerodynamics*, and *Physics of Fluids*, in which the PhD candidate published his results, are well-recognized leading journals in the field and have maintained Q1 rankings for many years.

In conclusion, the thesis represents an original and valuable contribution to the mechanical engineering field. The thesis meets the requirements for doctoral theses specified in the polish Act published July 20, 2018 titled: Law on Higher Education and Science. From a formal perspective, I wish to admit the candidate to the next stages of the doctoral process, and strongly recommend the dissertation for acceptance and consider the candidate fully deserving of the PhD title.

The scope of the work and the quality of the obtained results (analyses performed) significantly exceed the average level of doctoral theses. The results contribute to a significant advancement of knowledge in the field of reducing separation associated with TBL and the development of passive methods for increasing the efficiency of practical heat exchangers. Considering the above, I propose that Mr. Piotr Kamiński's doctoral dissertation be distinguished.

Associate Professor Kamil Urbanowicz

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