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Review of the doctoral dissertation
by Mr Mohammadsadegh Pahlavanzadeh, MSc Eng.
entitled "Assessment of the possibility of improving the momentum transfer in the flow between rotating discs"

I.
Basis for the review
The present review was prepared in response to a letter from Professor Krzysztof Labus, PhD, Chair of the Discipline Council for Environmental Engineering, Mining and Energy at the Silesian University of Technology, dated 3 October 2025. (letter no. RIE-BD.512.40.2025).

II. Overall assessment of the dissertation
The doctoral dissertation by Mohammadsadegha Pahlavanzadeh, MSc, prepared as a uniform series of six scientific publications, focuses on numerical analyses of the flow in a Tesla turbine. The doctoral dissertation includes an analysis of flows for various system configurations using several working fluids (air, water, organic refrigerant R1234yf and n-heptane), different turbulence models, i.e. RANS (Reynolds-averaged Navier-Stokes) and LES (Large Eddy Simulation), and with the use of smooth and rough disc surfaces. A key element of the research was to improve the efficiency of the Tesla turbine by applying appropriately selected rough structures to the surface of the rotating discs. The introduction of these elements resulted in an efficiency improvement of several per cent, which is a significant achievement for systems with low efficiency of several or more per cent. Numerical analyses using roughness elements (Aupoix model and porous layer model) to model flow in a Tesla turbine are not found in the literature, which makes this approach innovative in the context of increasing system efficiency. The use of rough structures, generating turbulent shear stresses, in systems where momentum exchange is achieved through adhesion and viscous shear stresses was a venture fraught with considerable uncertainty. It was necessary to conduct an in-depth study of the literature and perform numerous tests before it was possible to determine the configurations that improve turbine performance. The candidate demonstrated extensive knowledge and experience in this area. The rough surface models were calibrated based on the results of experimental studies available in the literature and obtained by the research team in which the doctoral student conducted his work.

An important element of Mr Mohammadsadegh Pahlavanzadeh's doctoral dissertation is also the validation of the RANS method used, based on his own LES results. This validation was necessary due to the lack of adequate quality data in the literature for flow through a Tesla turbine. The LES analyses required computationally demanding simulations of compressible and unsteady turbulent flows, ensuring adequate quality of discretisation in space and time. The obtained LES results allowed the selection of an appropriate RANS model (k- ω SST), which was crucial in the calculations of flows with roughness.

Issues related to the Aupoix roughness model, the determination of equivalent sand grain roughness, and the development of a porous structure model required the doctoral student to master advanced numerical programming procedures for such systems, which is a non-trivial task.

The results of numerical simulations of flow through a Tesla turbine, both without and with roughness, are unique and make a significant contribution to the development of the disciplines of environmental engineering, mining and energy, and mechanical engineering. The results of the work were developed in accordance with high research standards and published in scientific journals, which confirms the great scientific and practical significance of the obtained research results.

III. Structure of the dissertation and assessment of its scientific value
The present assessment concerns five monographic publications in scientific journals and one publication that was published at the time of submission of documents for the defence.

Publication No. 1 presents tests of selected roughness models using RANS methods on the example of flow simulations along flat plates and a simplified Tesla turbine configuration consisting of two rotating discs.

There is a typesetting error in the abstract, resulting from the fact that pages 86-87 were placed further on in the dissertation, although their content should follow page 78.

The scientific publication includes preliminary analyses performed using standard k-ε turbulence models with the assumption of modelling the flow in the viscous sublayer (approach for low Reynolds numbers), modelling the wall function (approach for high Reynolds numbers), and the k- ω SST model assuming the Aupoix roughness model. The analyses for simple flow configurations along flat plates were performed correctly. However, the reason for the discrepancy obtained for a smooth wall surface on a dense M1 mesh (Fig. 1) between the results of calculations performed using the k-ε SWF model (wall function) and the experiment is not entirely clear to me. For calculations performed on a dense mesh, the k-ε SWF model should modify the boundary conditions for the Navier-Stokes equations in the wall boundary layer for y^*< 11.225 and use an approximation based on a linear velocity profile. Perhaps the overestimation of the c_f coefficient results from the failure of the k-ε SWF model to adjust the boundary conditions for the transport equation for k (the standard condition is dk/dy=0). The doctoral student correctly undertakes to estimate the equivalent grain roughness, k_s^+, based on reliable literature sources (Knadikar et al., 2005). This parameter plays a key role in further flow simulations through a simplified Tesla turbine model, with the use of rough disc surfaces. The results obtained are logically consistent and confirm the correctness of the approach adopted. It is also important to demonstrate that the Aupoix model is a reliable approach for modelling roughness on dense computational meshes without the need for precise placement of the first mesh cell in the logarithmic profile zone, as is the case with the classic k-ε SWF model.

Publication No. 2 covers analyses of turbulent flows in microchannels using both smooth and rough surfaces, as well as simulations of flow through a simplified Tesla turbine gap using smooth and rough surfaces.

In the text, under equation 2, there is a slight inaccuracy regarding the definition of friction velocity, specified as $u_\tau = \surd \tau_w/\rho$ (the square root is missing in the paper). This inaccuracy also appears in publication no. 5.

The validation of the model used for rough surfaces was conducted on the basis of the available literature data, as well as using the results of experimental studies of flow through a mini-channel (assuming different Reynolds numbers), carried out at the Department of Power Engineering and Turbomachinery, Silesian University of Technology. The results of the experiments allowed to confirm the consistency of the numerical flow simulation results for rough surfaces using the Aupoix model, assuming a roughness height of 60µm. Good agreement was obtained between the numerical simulation results for smooth surfaces, both at low and high Reynolds numbers, in terms of the Fanning coefficient values. These results confirm the correctness of the adopted method of turbulent flow modelling for smooth and rough surfaces.

Papers numbered 3 and 4 include numerical analyses of more complex Tesla turbine systems. The tests took into account various configurations of intake systems. In publication no. 3, systems with six and forty nozzles were used, while in publication no. 4 a system with six nozzles supplying the working medium to the inter-disc space was employed. The flow in the inter-disc space was simulated in a rotating coordinate system, while the other elements of the turbine (inlet system) were defined in an inertial reference system. In order to reduce the cost of calculations, especially for the LES method, in publication no. 3, simulations were performed for a section of the inter-disc space covering 1/6 or 1/40 of the entire domain, depending on the use of six or forty nozzles, using periodic boundary conditions. This approach simplified the actual operation of the system, but the level of simplification adopted was fully justified. RANS and LES methods were used to describe fluid motion in publication no. 3, while publication no. 4 deals exclusively with LES analyses that use two different inlet nozzle configurations in which the medium (water) was fed into the inter-disc gap through a nozzle of the same size in the *z* the direction as the inter-disc channel depth (one-to-one) and a configuration involving a nozzle width larger in the *z* direction than the width of the inter-disc channels (one-to-many). The purpose of performing computationally expensive numerical analyses using the LES method, with smooth disc surfaces, was to obtain reference results for evaluating the accuracy of RANS methods. This approach was fully justified, given the relatively low Reynolds numbers (based on the gap width), ranging between 1000 and 7000. The choice of the LES method (with viscous sublayer modelling) was correct, as submesh viscosity damping was applied near the walls using the Piomelli et al. model. This damping was necessary to obtain the appropriate quality of the flow structure in the turbulent boundary layers developing near the high-speed rotating discs. The LES calculations were performed with appropriate computational mesh resolutions in space (LES IQ parameter and the ratio of the integral turbulence scale to the mesh size) and with a sufficiently fine time step. As expected, the results obtained using the LES method showed greater instabilities than those obtained using the RANS method, visible, among others, in the vorticity field in publication no. 3 (Fig. 9), but they allowed the usefulness of RANS tools (*k-ω SST* model) to be assessed in estimating half-velocities and pressures, shear stresses, and efficiency, power and torques for the Tesla turbine systems under investigation. LES analyses also made it possible to assess the quality and usefulness of the intake systems used and to conclude that the RANS model used is a reliable tool for simulating flow in a Tesla turbine. This was crucial for the implementation of further work related to the use of surface roughness elements in combination with the RANS method.

Article no. 5 concerned the numerical modelling of a Tesla turbine with an intake system reflecting the operation of six nozzles in a one-to-many system. Preliminary analyses were performed using LES and RANS methods, assuming smooth disc surfaces in the calculations. These analyses confirmed good agreement between the RANS results obtained with the k- ω SST model and the LES results. In the next part of the work, detailed analyses of the influence of disc surface roughness on turbine operating parameters were conducted, using both the Aupoix model and a new approach based on the porous layer model. The calibrations of the models for describing surface roughness were carried out based on the results of experimental studies (microchannel) obtained at the Department of Power Engineering and Turbomachinery. The doctoral student presents the research results in an accessible and interesting way in Figs. 6 and 7, analysing the impact of roughness *(*k=30, 60 and 120 μm) on changes in the circumferential velocity component and Mach numbers. Interesting test results were obtained, confirming the significant impact of surface roughness on turbine efficiency, power and torque. The porous layer model developed by the candidate allowed results similar to those obtained using the Aupoix model to be obtained without the need to determine the equivalent roughness of sand grains, which is a significant advantage of the porous layer model-based approach. Achieving good agreement between the numerical simulation results for two different approaches to roughness modelling constitutes a significant achievement of the doctoral student.

Publication no. 6 concerns the application of the developed porous layer model to simulate flow through a simplified Tesla turbine model (six nozzles, model with periodic boundary conditions) using the organic refrigerants R1234yf and n-heptane, assuming a real gas model (superheated steam). The aim of the work was to assess the impact of the modifications to the surface structure of the discs proposed by the doctoral student on the efficiency, power and torque of the turbine when using a working medium other than air, as well as to determine the nominal operating conditions of the system. The porous layer model was calibrated on the basis of the above-mentioned experimental data for flow through a mini-channel. The doctoral student obtained interesting test results, indicating significant differences in the obtained turbine operating parameters for the above-mentioned working fluids. For selected disc rotational speeds, the use of rough structures on their surfaces resulted in a 7-9% improvement in turbine efficiency compared to smooth surfaces, which translated into a relative increase in efficiency of 50-80%. The doctoral student demonstrated that the porous layer model he developed enables reliable and effective mapping of the impact of rough structures on the flow dynamics of working fluids with complex physical properties.

IV. Strengths and weaknesses of the dissertation

The strengths of the dissertation include obtaining reliable and consistent results of numerical flow analyses using rough disc surfaces, the use of which resulted in a significant (several percent) increase in the efficiency of the tested systems using various working fluids. Addressing the issue of improving turbine efficiency through the use of rough surfaces was not obvious at the beginning of the research, as their operation is based on the phenomenon of adhesion and the interaction of viscous shear stresses. This makes it all the more valuable to develop appropriately defined roughness models, prepare procedures for determining the equivalent roughness of sand grains, and to develop and calibrate a porous structure model (porosity parameter K) based on the results of experimental research obtained at the Department of Power Engineering and Turbomachinery. All these aspects confirm the great scientific and practical significance of the doctoral dissertation of Mr Mohammadsadegh Pahlavanzadeh, MSc. Eng.

The weaker aspects of the work include a somewhat simplified analysis of the LES results presented in publication no. 3, which did not fully explain the differences visible in the pressure fluctuation spectra in Fig. 10, obtained using different time steps. Some doubts are also raised by the not always unambiguous discussion of the so-called *resolved* velocity field fluctuations in the RANS approach. In the classical approach (steady-state RANS), RANS models completely model the fluctuating velocity field (more precisely, the turbulent stress tensor), which is why the conclusions regarding the excessive suppression of simulated velocity fluctuations (including the vorticity field) did not always seem clear. It also seems that publication no. 6 could have discussed in more detail the differences in the performance of the Tesla turbine for the organic refrigerants R1234yf and n-heptane. In my opinion, it would have been worthwhile to deepen the analysis of the impact of the different physical properties of the refrigerants (if they were the main cause of the observed differences) on the power and efficiency of the Tesla turbine at different rotational speeds.

V. Detailed questions for the author of the dissertation

This chapter contains detailed questions for the author of the dissertation:

1. Figure 14 in publication no. 2 shows the profiles of kinetic energy of turbulence and its dissipation for smooth and rough surfaces in the range ks^+ = 2-10% h. For smooth surfaces and small roughness, the dissipation profile shows the appearance of a local minimum on the wall and a peak value at a certain distance from the wall. The observed result differs from the results obtained in DNS analyses for a fully turbulent layer, where the maximum dissipation value is obtained at the wall itself. Is the underestimation of dissipation near the wall the result of an error in the RANS model (here the SST k- ω model), or is it a result that has some physical justification? Lardeau et al. (Modelling Bypass Transition with Low-Reynolds-Number Nonlinear Eddy-Viscosity Closure, Flow, Turbulence and Combustion 73: 49-76, 2004) indicate that in the laminar layer there is a significantly lower level of dissipation on the wall compared to that obtained in the turbulent layer. Please interpret the data presented in Fig. 14. Are the differences due to differences in the structure of the layer or are they the result of underestimation of dissipation by the RANS model?

2. Article 3 shows that the estimation of the mesh size Δ for LES analysis can be performed based on the criterion l_0/Δ =4.8, where l_0 is the total turbulence scale. Please indicate the source of literature on the basis of which the above estimate was adopted for the LES method. In Popa (2000), (p. 240, Table 6.2 and Fig. 6.19) it is indicated that for isotropic turbulence, there is a relationship between l_0/L=2.38 and l_0/L = 6.25 (for a Taylor number of 600), assuming that 80 and 90% of the energy is simulated (resolved), respectively. Assuming that the L scales are related to the smallest simulated scales and correspond to the mesh size Δ, this estimate can be used as a basis for selecting the computational mesh resolution, assuming a negligible contribution of turbulent kinetic energy production (isotropic turbulence). Please explain the meaning of this criterion. Were other criteria for estimating the computational mesh resolution also used in the study? If so, what were these criteria and what were the results of these analyses?

3. Article 3, page 13. The description of the vorticity shown in Figures 8 and 9 (cross-section) states that the k- ω SST model can simulate (resolve) vortex structures. Please explain how this statement should be understood, given that in RANS models and in some URANS simulations, most of the kinetic energy of turbulence is modelled. It is also unclear to me whether the vorticity contours presented for the LES and RANS methods are the result of averaging them over time or whether instantaneous values are shown. This is important in terms of better understanding the irregularities observed for the LES model in Fig. 9 (line 1). Was the contribution of submesh fluctuations also investigated in the LES method? If so, was it significant?

4. Article 3, page 13. Fig. 10 shows the amplitude spectra of pressure on the wall for the case without roughness obtained by the LES method, assuming time steps dt-le-6 and l.e-7 s, respectively. The amplitudes show qualitative differences in Fig. 10 a and b, in the sense that for dt-1e-7s (Fig. 10b) are characterised by a more "homogeneous" course, indicating greater diversity of turbulent scales in relation to the results shown in Fig. 10 a. What were the CFL numbers corresponding to these simulations and to what extent did they influence the result? How should the differences between these spectra be understood? Should frequencies associated with disc rotation be visible in the spectra, and if so, to what extent?

5. Publication 3, Conclusions (Chapter 5). The conclusions state that the k- ω SST model overestimates the torque by 4.25%. Please explain in relation to which results this overestimation is observed. It is further stated that the SST model suppresses fluctuations in certain quantities. The RANS model should, in principle, model velocity field fluctuations. What is the basis for this conclusion and how should it be understood?

6. Publication No. 4, Chapter 3.2. Figure 3 shows an indicator describing the quality of the computational mesh for LES analysis, where a high value of submesh viscosity results in low values of the LES_IG indicator. The conclusion (last sentence in this chapter) states that the contour plots of this quantity indicate that the dissipation obtained from the LES model accounts for at most 20% of the total dissipation. Please explain this statement.

7. Article 4, page 7. The description of the N60-M case states that the average velocity profile (radial component) depends on the inertial forces in circular motion, pressure forces and viscous forces. Further on in the article, it is stated that for case N60-M, the peak values of turbulent stresses (Reynolds) at points 1, 2 and 3 (Fig. 5 centre) are 1.67×10^4, 1.71×10^4 and 1.68×10^4 [Pa?] respectively. The forces resulting from Reynolds stresses seem to be quite significant, as they are comparable to the pressure forces shown in Fig. 6a (point 3). Was the contribution of viscous forces and inertial forces estimated in the study? If so, how large are these forces? Should not the forces resulting from the fluctuating motion of the fluid (turbulent stresses) also be considered quite significant in the analysed flow?

8. Article 4, page 8. Fig. 7 shows the distributions of turbulent stresses for cases N60-O and N60-M. The differences in the distributions of these quantities are significant. The profiles have been normalised to the maximum values of these quantities observed in these two cases. This makes it impossible to determine the contribution of these stresses in individual cases. Please supplement this result with information on the quantitative contributions of Reynolds stresses in the analysed cases (without normalisation) and explain how these quantities affect the operation of the turbine (if at all).

9. Article 5, page 37. Table IV presents the results of RANS analyses for different levels of surface roughness. The results for rough structures were obtained using the Aupoix model (change in boundary conditions for k and ω on the surface) and with the help of the PML model (porous structure model). Please evaluate the differences obtained with the use of the Aupoix and PML models. Can we say that one of these models gives more reliable results or better reflects the physics of the process that takes place in the actual Tesla turbine system? What is the advantage of the first or second approach (if any)?

10. The dissertation considered various rough surface models (Aupoix model, porous structure model), assuming a roughness height in the range of 30-120 µm, among others. Please advise whether adopting larger roughness layer sizes would lead to a deterioration in turbine performance. What factors influenced the choice of these particular roughness heights?

VI. Summary

The doctoral dissertation submitted for evaluation, comprising five scientific publications and one additional paper published in parallel with the submission of the dissertation for defence, demonstrates the Candidate's high competence in the modelling of compressible turbulent flows and the creation of numerical models of rough structures, as well as the Candidate's proficiency in conducting a comprehensive analysis of numerical calculation results and formulating coherent conclusions.

The peer-reviewed scientific publications clearly confirm the Candidate's significant contribution to the implementation of complex research and his preparation for conducting independent research in the field of broadly understood computational fluid dynamics, and in particular in the field of turbulent flow research in rotating systems.

I believe that the doctoral dissertation of Mr Mohammadsadegh Pahlavanzadeh, MSc, makes a significant contribution to the development of science, significantly expanding knowledge about the operation of the Tesla turbine and the possibilities for increasing its efficiency. The results obtained by the doctoral student also constitute a valuable contribution to the development of practical applications of this type of device, especially thanks to the analysis and implementation of rough disc surface models. The obtained research results are of great importance for the development of the disciplines of Environmental Engineering, Mining and Energy, and Mechanical Engineering.

In conclusion, I find that the doctoral dissertation of Mr Mohammadsadegh Pahlavanzadeh*,* MSc.Eng.*, entitled* ***Assessment of the possibility of improving the momentum transfer in the flow between rotating discs*" meets the requirements specified in the Act on Academic Degrees** and **Academic Titles** for doctoral dissertations, and I request that it be admitted to the next stages of the doctoral procedure.

[illegible signature]
Dr Sławomir Kubacki, Professor