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Rzeszów, 9 September 2025

Review of a doctoral dissertation

entitled:

Analysis of the blade geometries for a highly efficient wet steam turbine stage

1. SUBJECT OF THE REVIEW AND BASIS FOR THE STUDY

1.1. Title of the dissertation and basis for its preparation

The subject of the review is the doctoral dissertation by Sima Shabani, MSc, entitled: Analysis of the blade geometries for a highly efficient wet steam turbine stage. The work was carried out in the Department of Power Engineering and Turbomachinery (KMiUE) at the Faculty of Energy and Environmental Engineering of the Silesian University of Technology (SUT) in Gliwice.

The review was prepared on the basis of contract No. UMC/2614/2025 of 22 July 2025, concluded between the Silesian University of Technology in Gliwice, represented by Prof. Mariusz Dudziak, PhD, Eng., and the undersigned contractor.

1.2. **Assessment of the dissertation layout**

The doctoral dissertation of Ms Simi Shabani, MSc, written in English, comprises a total of six chapters and 151 pages. The beginning of the dissertation includes the affiliation, table of contents and a list of symbols and abbreviations. The dissertation concludes with a summary and conclusions, a list of references, a list of figures and tables, and an abstract in Polish and English. Its structure is essentially logical and correct, with a separate section on field research and a computational section justifying the choice of the two-phase medium model and testing the tools used to analyse the chosen cases.

Chapter 1 provides an introduction to the subject matter of the dissertation. In addition to a review of the literature on the state of research and numerical modelling of wet steam flows (WSF) in steam turbines, the main problems and directions of their development are described. As indicated on the basis of the current state of knowledge and the results of research conducted by many centres and the author herself (including in cooperation with SUT), the issues addressed in this dissertation are very topical and important.

In Chapter 2, the doctoral student described the tests and techniques used in experimental measurements of a flow with water vapour condensation, in particular the optical methods based on light scattering (LEM) used by her to identify the concentration, size and generation rate of condensate droplets. Data acquisition and calibration of the measurement system is an important issue there. The aim was to implement the appropriate relationships introduced into the transport equations in 2D and 3D flow calculations in the internal channels of steam turbine components. The modelling of two-phase steam flows in steam turbine components has been a subject of interest to the industry and many research centres around the world for many years.

The paper validates the previously proposed models of turbulence and steam condensation dynamics, including the generation and growth of water droplets in the steam flow. The results obtained show good agreement with currently available data in this respect. Models of water droplet growth in the flow for continuous, kinetic and mixed models were also considered. Limited information from research conducted in this area does not always lead to clear indications allowing an assessment of which model should be used in relation to the specifics of the aerodynamics of flow machines under consideration.

This work is part of the mainstream of that research, and the main and original part of the work is contained in Chapters 2 - 5. Laboratory experiments (Chapters 2.2-2.3) concerned measurements of a transonic water vapour flow in an IWSEP nozzle. Similar bench tests involved a model of a 5-blade flat stator palisade and a rotor of an LPT class ~200 MW steam turbine stage. The quantitative measurements and their visualisation were further used as a basis for verifying the methods and models used in numerical techniques for modelling WSF flows in the further part of the dissertation. This part does not raise any significant comments or doubts.

The numerical calculations performed by the doctoral student (Chapters 3.2-3.4 and Chapters 4.3-4.5 and Chapters 5.1-5.3) were based on both reference examples from her own research and the cited literature (papers including [1], [3], [9], [19], [31], [46]). Chapter 3 discusses the problems arising from the complexity of describing WSF processes and modifying transport equations and their use in 3D steam flow modelling. This applies to the description of fluid properties (IAPWS-97, Young, NIST-Refprop 9.0 equations of state) and the assumptions for RANS and DNS techniques in Ansys CFX and Fluent suites (Section 3.2). They are presented in a clear manner and justify further detailed analyses and the presented simulation cases. More attention could have been paid here to the discussion of the graphical results of the WSF flow analysis through the IAPWS nozzle and flat palisades (pp. 59–71).

The techniques of flow analysis in an expansion stage presented in Chapter 4 of the dissertation include both a simple 1.5D model based on averaged flow field parameters as well as velocity kinematics, and introduce the CFD models used later in the description. The results of the analysis of water droplet nucleation processes and their impact on the flow field imaging in the rotor and stator palisades of the last stage of the LPT ~200 MW turbine show significant differences and changes in the parameters along the span of the blades. However, it would have been worthwhile to add a few comments on the differences between the adiabatic and diabatic flow models, the distribution of losses, and the impact of steam condensation on irreversible thermodynamic and flow phenomena (Figs. 4.5–4.28).

An interesting proposal is included in the final part of the dissertation (Chapter 5). It concerns preliminary analyses related to the optimal selection and modification of the geometry of the stator and rotor blades of the final stages of LPT steam turbines. The number of 2D/3D blade outline modification variants accepted for CFD computational analysis is very large here (profiles 1-8, 4-8, change in the number of rotor and stator blades, and others). The original results of the simulations are given in Chapters 5.2 and 5.3 (see cases given in Tables 5.1 and 5.2). They were referenced and compared with reference examples from the works of Bakhtar [8] and White [9].

Chapter 6 provides a brief summary of the results obtained in this dissertation. The conclusions presented here involve the assessment of the correctness of modelling condensation processes and the determination of losses in the flow through the internal channels of nozzles, as well as moving and stationary end stages of steam turbines. The influence of non-equilibrium condensation and wave phenomena on the location and intensity of disturbance zones on efficiency were estimated. The results presented here are new and, in several cases, completely original.

1.3. Selection of literature

The bibliography at the end of the dissertation includes 72 items (including 71 in English). The selected source materials are relevant and substantively related to the subject matter and research programme of the doctoral student (two-phase internal flows with condensation). They thus justify the presentation of her own results against the background of current global achievements of other research authors (including the period before and after 2000). The doctoral student has familiarised herself with the results of fundamental work on models for the description and study of two-phase flows with phase change (including A. Kantrovitz [26], G. Gayarmathy [33], W.G. Courtney [24] and J. Young [51]), and skilfully utilised their practical results.
Well-documented studies described, among others, in the works of Y. Bakhtar ([1], [3], [8], [27]) and A. White ([9], [13]), as well as J. Young [31], and national teams from the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences ([55], [751) and the Silesian University of Technology ([53], [54], [70]). The selection and scope of the literature sources was therefore appropriate and correct. A number of source papers were skilfully used, among others, in the course of our own research and experimental tests, as well as in the selection and verification of the engineering models of effective computational tools used.

1.4. Indication of the purpose and scope of the dissertation

The work presented for review concerns laboratory research and CFD modelling of internal flows of compressible media in the near-sonic velocity range, taking into account the dispersion effects resulting from water vapour condensation. The issues discussed here are topical and of significant importance from the point of view of cognitive science and engineering practice. The motivation for the doctoral student to undertake this difficult and complex issue is indicated in Chapter 1.2, which, among other things, results from a review of the literature on the state of research and the application of its results in engineering practice. The main objectives and scope of the work are directly presented in Chapter 1.3 (pp. 21 and 22).

The main objectives of this work focused on:

- the selection of test examples and the performance of a series of measurements in the IMiUE research laboratory in order to verify the correctness of models of droplet generation and growth in a steam flow with condensation,

- the selection of the suitability of real gas equations of state (EOS) to describe the thermodynamic properties of water vapour near the saturation line and the Wilson line,
- implementation of models and flow measurement results into CFD numerical schemes for 3D flow modelling in the LPT stage of a 200 MW turbine
- determination of local structures and steam condensation zones in a 2D/3D flow on the surface of blades, as well as in inter-blade and Laval nozzle channels,
- identification of areas with the highest entropy generation and energy losses in the rotor and stator of the LPT steam turbine stage,
- comparison of indicators that characterise the operation of the LPT steam turbine stage under adiabatic and diathermic flow conditions (with the presence of condensate),
- selection of blade geometry and their modification (optimisation of the geometry of the turbine rotor and stator profiles) and assessment of the practical effects on reducing losses and improving the efficiency and performance of the LPT turbine stage.

1.5 Evaluation of the research methods used

The research methods and tools used were carefully and correctly selected and skilfully applied by the doctoral student. This refers to the laboratory testing of turbine blade palisades and flow nozzles under condensation flow conditions, as well as their computer simulation in states of limited thermodynamic equilibrium stability. In addition, the usefulness of typical CFD packages was tested using equations and descriptions of wet steam mixture parameters and flow loss assessments for the test cases (IWSEP nozzle, SUT flat turbine palisade, 200 MW turbine LPT stage blades). The significant impact of the choice of phenomenon model and moisture droplet formation mechanism on the generated entropy losses and efficiency drop in the LPT turbine blade system was confirmed. Current CFD calculation techniques, including ANSYS Fluent and CFX suites, were correctly applied. Tried and tested models for describing the parameters of the working medium were selected, including effective calculation codes that ensure reliable computer simulation results. A preliminary analysis of the possibilities for modifying the stator ring vanes and rotor ring blades of the steam turbine indicates new opportunities for improving their flow characteristics.

1.6 Discussion of the results

The results of the doctoral dissertation are summarised in Chapter 6. They focus on the selection of the most effective tools in CFD computational analysis for internal steam flows in Laval nozzles and in the rings and blade systems of the final stages of condensing turbines.

To this end, the doctoral student performed a series of experiments and measurements at the KMiUE laboratory, which provided a reliable database for further simulations and testing of computational models in the Ansys CFX and FLUENT CFD techniques.

Out of several models used to analyse quasi-equilibrium processes of mass exchange and transport, momentum and energy in a steam flow with condensation, two were selected, namely Fuchs-Satugin and Gyarmathy.

The adopted concept of adapting the density of computational grids to the flow channel zone and the computational area, as well as the appropriate turbulence model (*k-ε and k-ω*), were well confirmed during computer simulations. Only the hardware requirements (PC, hardware) and the time of iterative calculations for selected cases were not provided here.

Their consistency with the experimental data is confirmed in particular by 3, 4 and 6 for test calculations for both the IWSEP nozzle flow and flat turbine palisades. Here (Chapter 3.4), it was possible to attempt a more in-depth interpretation of the reason for the ineffectiveness of the Yo-Yo model (Case 2) for the analysis of a flow with condensation in the IWSEP nozzle, as well as in the rotor blade palisade (Yo-IAPWS, Cases 1, 2 and 7). This mainly concerns the location of the condensation zones and the wave effects.

The conclusions regarding the role of the condensation phenomena in the flow in the last stages of steam turbines, contained on pages 138-139, and the level of losses they generate are correct. It is worth noting here that in this engineering practice, Baumann's correction (1912) is used to estimate efficiency losses.

The potential for improving the design of blade rings in 2D and 3D has been demonstrated. The significant impact of the configuration, outline and changes in the blade pitch relative to the track in the circumferential and axial directions (including CLI CL2 and ASCL) has been confirmed, which significantly improves performance and reduces losses in the turbine stage. These measures also have a beneficial effect on efficiency and reduce the effects of condensate droplet deposition on the blades in the LPT turbine stage. These preliminary analyses may be considered in further research and more complex 3D numerical analyses using CFD and multi-criteria optimisation methods and AI (artificial intelligence) tools.

1.7. Possibilities for practical application of research results

In scientific research and engineering applications, both steam and wet gases are important working media. Steam in low-pressure steam turbines (LPT) which operate in thermal power plants is usually expanded to a vacuum, and its outlet section operates under wet steam conditions. In geothermal and nuclear power plants, almost all turbine stages operate in wet steam, as the temperature of the fresh steam at the inlet is lower than in thermal power plants. The presence of a two-phase medium in the flow path leads to a number of negative processes caused by the mechanical and thermodynamic interaction of liquid particles with the steam flow and the surfaces of the inter-blade channels. These processes result in blade erosion, which directly affects the operation and reliability of the turbine.

The research results presented in the dissertation, in addition to their cognitive value, also have potential practical applications. This applies in particular to:

- the selection of the equation of the state for water vapour in the Wilson region in CFD suites,
- the selection of the computational grid density for CFD in the two-phase steam flow,
- the development of better correlations for the assessment of moisture losses in the LPT stage
- the optimisation of the 2D/3D blade geometry to reduce thermodynamic and flow losses, including the improvement of the performance of the last stages of LPT steam turbines.

1.8. Irregularities and errors identified in the work

The dissertation also contains several shortcomings related to the editing of the text of the dissertation and others. In particular, several issues are mentioned here, such as:

- Important indicators of simplified flow, such as stage reactivity (the rotor contribution to the gas expansion), dimensionless flow coefficient and load coefficient, were not included in the description of turbine stage operation (section 4.1.2). Their changes in operating conditions and stage kinematics significantly determine the gradients of, among other things, pressure and enthalpy along the blade span. Radial equilibrium analysis allows for the conscious reduction of flow losses associated with energy dissipation, also in a flow with condensation, and their compensation through the modification of the 2D/3D geometry and velocity kinematics in the flow channels of the stage.
- The symbols used to describe the flow in the axial turbine stage are not always consistent throughout the dissertation. This applies to the use of different symbols for the same velocity components in the cylindrical coordinate system $\{r, \vartheta, z\}$ in several chapters of the dissertation. It can be assumed that this is related to the presentation of some of the results of the dissertation in several earlier publications.
- The basics of wet steam flow physics in LPT axial turbines and the need for their improvement, presented in the Introduction (Chapter 1.1), could have been more focused on its practical engineering objectives (see, among others, A. Weiss: *Aerodynamic design of advanced LP steam turbines.* ABB Review, 5/1998), which is directly related to the utilitarian objectives of the dissertation.
- On pp. 36-47, there is no comment on the comparison of the results of pressure distribution measurements in the IWSEP nozzle and on the surface of the stator and rotor blades of the turbine with Schlieren imaging for each case. This applies in particular to the wave phenomena in the flow (Case 2) in Figs. 2.16 and 2.18, Figs. 2.21 and 2.22, and Figs. 2.25 and 2.26. However, it is valuable that the doctoral student independently performed many tests in the KMiUE laboratory and confirmed their usefulness in the further computational part of the research.
- The pressure distribution around the blade profiles obtained as a result of measurements in the SUT laboratory (pp. 41–46), shown in Fig. 2.21 and Fig. 2.25 for Case 1 and Case 2, is incomplete (points 1 -20 and 1-15 should form a closed contour).
- In the reviewer's opinion, the simplified description of the aerothermodynamics of flow in the turbine stage, points 4.1.1 - 4.1.3 (pp. 72 - 81), would be better combined in point 1.1.2 (pp. 9 - 11) to maintain its thematic compactness.
- The kinematics of velocity in Fig. 4.1 (p. 74) refers exclusively to the condition of constant rotor circumferential velocity at a selected radius r_m, where $u = \omega x r_m$. Long blades of the last stages of LPT turbines in the inlet-outlet system from the rotor often do not meet this condition (meridional conical flow, Fig. 5.27).
- In Chapter 4.2 of the dissertation (pp. 82-85), the meridional *r-z* cross-section and the basic dimensions (blade height) of the stationary ring and the rotor ring of the modelled 13K215 turbine stage are not shown (see item [2] in the doctoral student's CV).
- The full condition for maintaining rothalpy (backpressure enthalpy in the relative rotor system, see formula (4.7), p. 76) has not been correctly defined. In the case of a large span of the final blades of the turbine stages, the increase in circumferential velocity u (D >< r) significantly affects the distribution of parameters and the load on the stage.
- There is no assessment of the choice of computational mesh density and the assumed convergence conditions of the iterative solution for the simulation in ANSYS CFX (Section 4.4).

- There is no indication of how to average the absolute velocity *c* and the relative velocity *w* for the flow in the stage (Figs. 5.4, 5.9, 5.15 and Fig. 5.20), i.e. after the cross-section or after the expenditure.
- In Figures 5.4, 5.9 and 5.15, which illustrate changes in *c* and *w* velocities along the span of the blades, it would be useful to provide the corresponding average Mach numbers.

Other minor editorial comments:

- The list of symbols and abbreviations (pp. 6-8) is missing several designations (including: *E* — total specific internal energy, *e* — specific internal energy, *H* — specific total enthalpy, *g* — gravity acceleration, *g* — extinction coefficient, *w* — specific work, *Q* — heat, *q* — heat flux, Γ — mass generation rate; and abbreviations: NNLS INNLS, MUSCL, SST, TEOR, SUT).
- On page 49, formula (3.2) has not been supplemented with the mixing condition $p = p_l\, p_v$.
- The bibliography (pp. 140-145) is not in alphabetical order, nor are the citations in the text, which usually makes it easier to read.
- There is a lack of consistency in the notation of journal title abbreviations (e.g. [10, [32], [36], [40]).
- The quantity α is not defined in formula (3.2) on p. 49 for averaging the density of the mixture ρ_m (compare formulas (4.26) and (4.27)).
- The doctoral student's CV could have been included in the text of the dissertation, as is usually done in this type of work.
- The formulas (4.12) – (4.14) do not include any comments on the rules for transitioning from backpressure parameters to static parameters in calculating the efficiency of the blade system of the turbine stage.

1.9. Originality of the work and its merits

The reviewed doctoral dissertation of Mrs Simi Shabani's is an important and original contribution to research aimed at better understanding the complex mechanisms and phenomena accompanying thermodynamic and flow processes in stages and components of rotary machines. New research tools and measurement techniques now enable a more detailed assessment of these complex processes and the optimisation of solutions to minimise losses associated with steam flow and condensation. This research focuses on the best possible estimation of the generation, size and concentration of condensate droplets. At the same time, models of phenomena related to condensation are included to supplement the description of Navier-Stokes equations in the CFD techniques.

An interesting proposal is included in the final part of the work (Chapter 5). It concerns preliminary analyses related to the optimal selection and modification of the geometry of the stator vanes and rotor blades of the final stages of LPT steam turbines. The number of 2D/3D blade outline modification variants accepted for CFD computational analysis is very large here (profiles 1-8, 4-8, change in the number of rotor and stator blades, and others). The original results of own simulations are given in Chapters 5.2 and 5.3 (see cases given in Tables 5.1 and 5.2). They were referenced and compared with reference examples from the works of Bakhtar

[8] and White [9]. The potential for further improvement of the design solutions in 2D and 3D was demonstrated.

The significant impact of the configuration, outline and change in blade inclination relative to the track in the circumferential and axial directions (including CLI CL2 and ASCL) has been confirmed, improving performance and reducing losses in the stage.

These measures also have a beneficial effect on efficiency and reduce the effects of condensate droplet deposition on the blades in the LPT turbine stage. These preliminary analyses may be considered in further research and more complex 3D numerical analyses using CFD and multi-criteria optimisation methods and AI (artificial intelligence).

1.10 Assessment of the doctoral student's skills and level of knowledge

New research tools and measurement techniques now enable a more detailed assessment of these complex processes and the optimisation of solutions to minimise losses associated with steam flow and condensation. This research focuses on the best possible estimation of the generation, size and concentration of condensate droplets. At the same time, models of condensation-related phenomena are included to supplement the description of Navier-Stokes equations in CFD techniques.

During several internships and doctoral studies, Mrs Sima Shabani, MSc, has acquired extensive knowledge and confirmed her skills in conducting independent research and numerical modelling of complex internal flow issues in steam turbine nozzles and channels. This is documented, among other things, by important publications co-authored by the doctoral student (11 in international journals and 10 in conference proceedings) included in her CV.

In summary, it should be noted that both the doctoral student's knowledge and skill level guarantee her ability to independently conduct research and development work in her field and bode well for further scientific progress.

2. Final conclusion

Taking into account the above arguments, I conclude that the dissertation of Mrs Sima Sabani, MSc, meets the requirements set out in the provisions of the Act on Higher Education and Academic Degrees and Titles (Journal of Laws of 30 August 2018, item 1668) and I request that it be admitted for public defence.

Rzeszów, 9 September 2025 [illegible signature]