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# NUMERICAL STUDY OF FLOW IRREGULARITY IN A NEW TYPE CONTROL SECTION OF STEAM TURBINE HIGH-PRESSURE MODULE

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*In order to improve the flow part of the control system and enhance energy performance, A. Podgorny Institute of Mechanical Engineering Problems NAS of Ukraine has developed a three-stage control system section of the K-325-23.5 steam turbine high-pressure module (HP), that has no equalization chamber. To determine the effectiveness of the control section's gas-dynamic improvement, the problem of the turbulent flow spatial structure studying was stated. For this, a numerical simulation of the steam flow was carried out in the rated mode, taking into account the partiality of the supply. The main task of the numerical simulation was to identify the magnitude of circumferential irregularity of gas-dynamic parameters in the first stages of the section and at the outlet. Spatial calculations of the steam flow in the studied flow parts were carried out using the* ***IPMFlow*** *software package for the spatial turbulent flow modeling in turbomachines developed at Institute of Mechanical Engineering Problems NAS of Ukraine. The study of the steam flow circular irregularity for modes with mass flow rates of 100%, 70% and 50% was carried out. The 70% and 50% modes are characterized by two closed control valves out of four, which corresponds to 37% of open blade channels. The results and analysis of the three modes calculations are presented in the form of distributions of mass flow rates and pressures in the stage gaps and at the section outlet. The graphs clearly show that the irregularity of the specific flow rate remains until the last stage, meanwhile the pressure irregularity is insignificant for all the considered modes. An analysis of the simulation results shows a rather slight irregularity of the steam parameters at the outlet of the control section in the partial modes and insignificant irregularity in the design mode. Based on the results of the analysis, a conclusion about the effectiveness of the new control section use for the steam turbine K-325-23.5 modernization was made. To implement the new control section, it is reasonable to study the level of unsteady loads on the HP blades further.*

***Keywords:*** *numerical simulation, spatial flow, steam turbine, nozzle control system, high-pressure module.*

## Introduction

Most steam turbines, including 200 and 300 MW units operating on alternating load schedules, must be designed to operate not only at full load but also at significantly (up to 50%) reduced load. Under these conditions, it is more efficient to use a nozzle steam distribution system [1]. In such turbines, all major changes in the flow structure associated with the operating mode occur in the control section that consists of the first (control) and second (first pressure stage) stages, as well as of the equalization chamber located between them. In [2] it is shown that the irregularity of the relative total pressure at the control system (CS) outlet can be more than 2% for the mode of a half mass flow rate. Pressure losses in the equalization chamber at the CS are about 2% of the total inlet pressure [3].

In order to improve the flow part of the CS section and to enhance the energy performance, a three-stage control section of the steam turbine K-325-23.5 HP module that has no equalization chamber was developed at the Institute of Mechanical Engineering Problems NAS of Ukraine. To determine the efficiency of gas-dynamic improvement of the CS section, it is necessary to study the spatial structure of the turbulent flow [2], [4], including the methods of mathematical modeling. In order to estimate the pressure and the mass flow rate irregularity at the CS outlet, the **IPMFlow** software package [5] was updated. The software package was developed by the Institute for numerical modeling of spatial turbulent flows in various power machines, in particular, steam turbines. A software module that allows to create a calculation area, which contains an arbitrary amount of blades, indicating the number and position of closed and open channels, has been added to the software package. This allowed the flow simulation in the CS with partial steam supply in all the turbine operating modes.

The results of the flow numerical studies in the steam turbine control section at partial and full supply are presented in this paper. The purpose of the study was to identify circumferential irregularity of pressure and steam mass flow at the control section outlet and the partiality effect on the irregularity.

**Object of research**

The Institute has developed a 3D flow part model of the three-stage control system of the steam turbine K-325-23.5 HP module. The turbine is equipped with a nozzle control system (Fig. 1), which means blocking of a certain number of channels for each operating mode. The flow part of the developed control system is devoid of the equalization chamber and consists of three stages (Fig. 1, c), unlike the original two-stage section (Fig. 1, b). The final version of the developed HP flow part efficiency, according to the results of the conducted calculations that don't include the steam takeoffs, was 94.7% at the rated operating mode.

The circumferential irregularity of steam flow for the operating modes of 100%, 70% and 50% of mass flow rate was studied. The 70% and 50% operating modes are characterized by two closed control valves out of four, which corresponds to 37% of the open blade channels. The studies were performed using methods and software developed by the Institute for simulation of 3D flows in power machines flow parts.

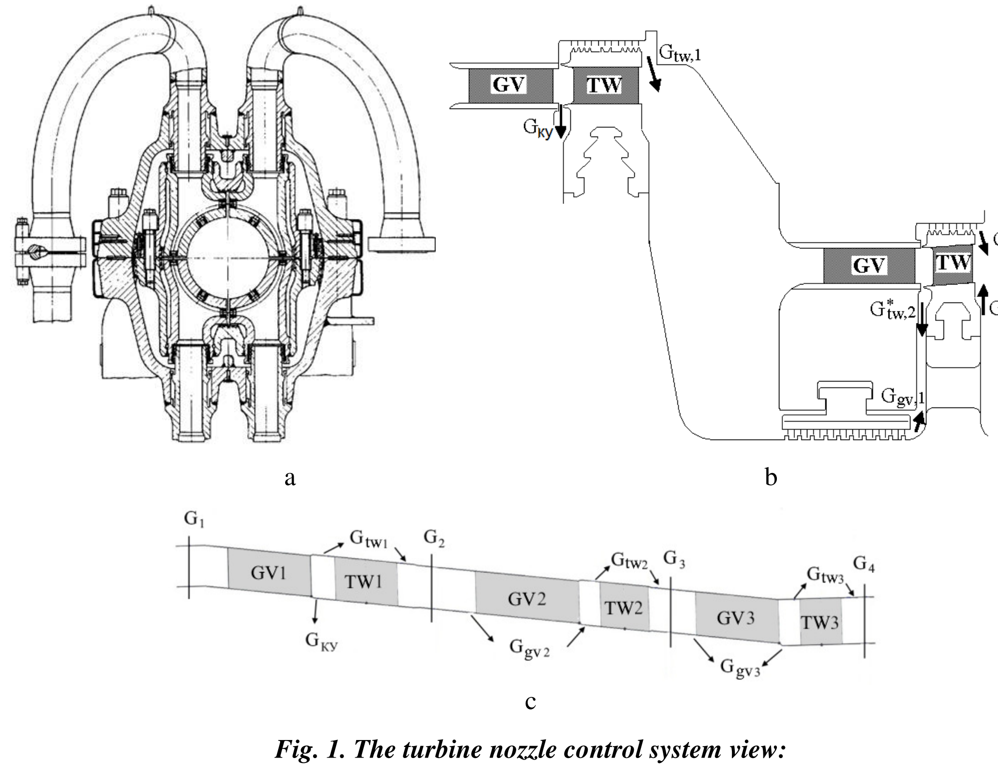



***Fig. 1. The turbine nozzle control system view:***
a – cross-section of the K-300 type turbine steam admission system; b – original structure of control section; c – new structure of control section

**Methods of research**

3D calculations of steam flow in the studied flow parts were carried out using the **IPMFlow** software package developed by the Institute [5]. The calculations of steam flow in the studied flow parts were performed on H-type computational mesh. The modeling of viscous turbulent flow was based on the Reynolds-averaged Navier-Stokes equations numerical integration. Turbulent phenomena were accounted by using the two-equation differential Menter's SST turbulence model [6]. For the description of thermodynamic dependences, the two-term Tamman's equation was used [7].

**Results and discussion**

The researched control section flow part consists of three stages, in contrast to the original structure with two stages. The pressure magnitude and mass flow rate irregularity at the outlet of control section in modes of 100%, 70% and 50% of mass flow rate was investigated. The developed software application was used to construct calculation areas corresponding to 100% mode (all valves open) and 50–70% (two valves open, two valves closed). Fig. 2 shows the view of the calculation area, which was used to calculate the flow in the control section for the mode of 100% power. The calculation area has a total number of elementary volumes (cells) of about 10 million.

Using the **IPMFlow** software, numerical simulation of the flow in the control section was performed in modes corresponding to 100%, 70% and 50% of the rated mass flow. For this purpose, the following boundary conditions were set: total inlet pressure – 22.73 MPa; 22.73 MPa; 16.1 MPa, total inlet temperature – 808.5 K, static outlet pressure – 16.578 MPa; 11.628 MPa; 8.306 MPa, respectively. Quasi-steady-state conditions were used to reduce flow steadying time at the computational grid inter-row boundaries, which ensure proper transfer of flow parameters between the rows without shifting rows in time relative to each other.

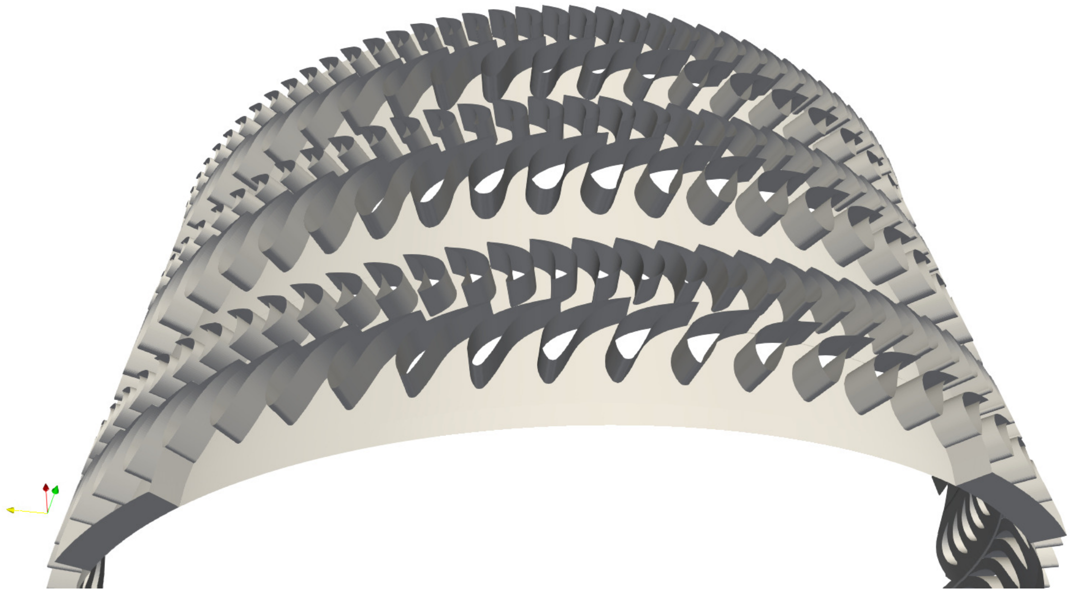


***Fig. 2. The calculation area view***

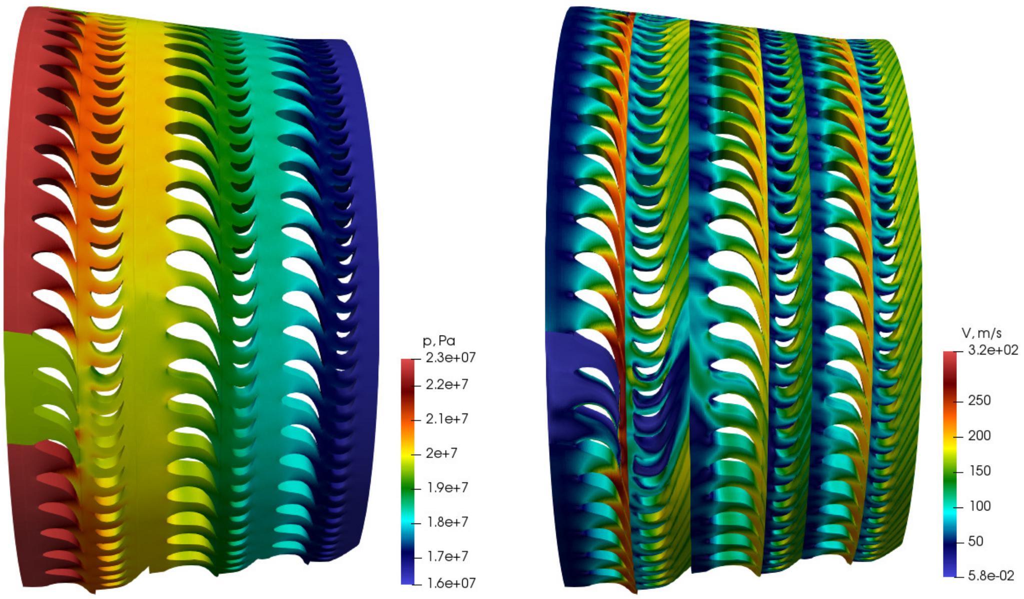
a b

***Fig. 3. First stage channel configuration:***
a – 100% mode; b – 70% and 50% modes

As a result of numerical simulation, the distribution of pressure and relative velocity fields for the 100% of mass flow mode was (Fig. 4). The figure clearly shows that the irregularity extends only to the first stage of the control section.

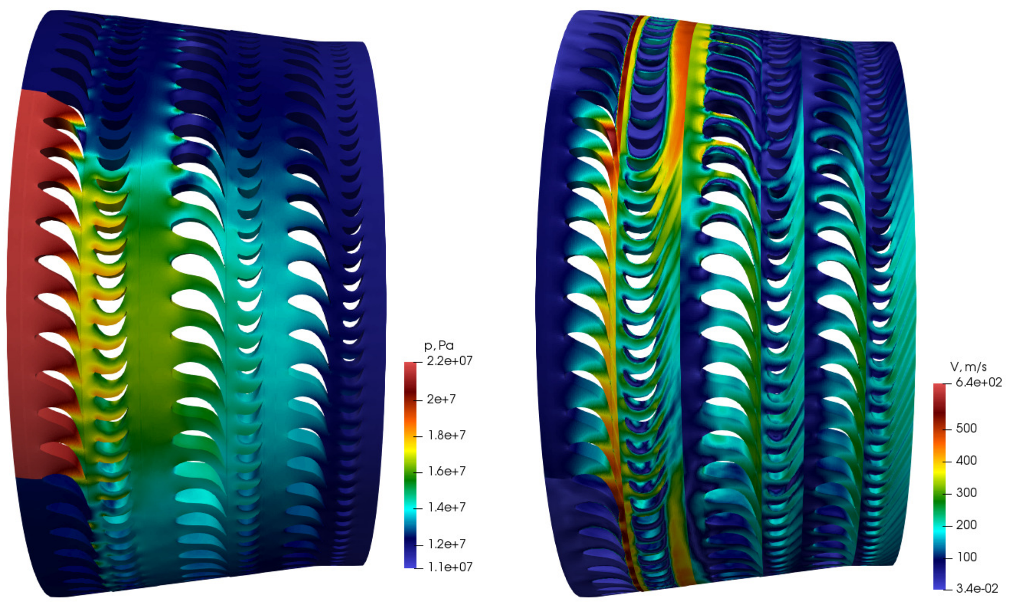
Also, as a result of numerical simulation, the distribution of pressure and relative velocity fields for the 70% of mass flow mode was obtained (Fig. 5). The figure clearly shows that the irregularity of pressure subsides at the last row, and the flow irregularity extends further beyond the control section. There are also significant ventilation flows in the inter-row gaps of the first stage turbine wheel.

Finally, as a result of numerical simulation, the distribution of pressure and relative velocity fields for the 50% of mass flow mode was obtained (Fig. 6). The figure shows a pattern similar to the 70% mode.



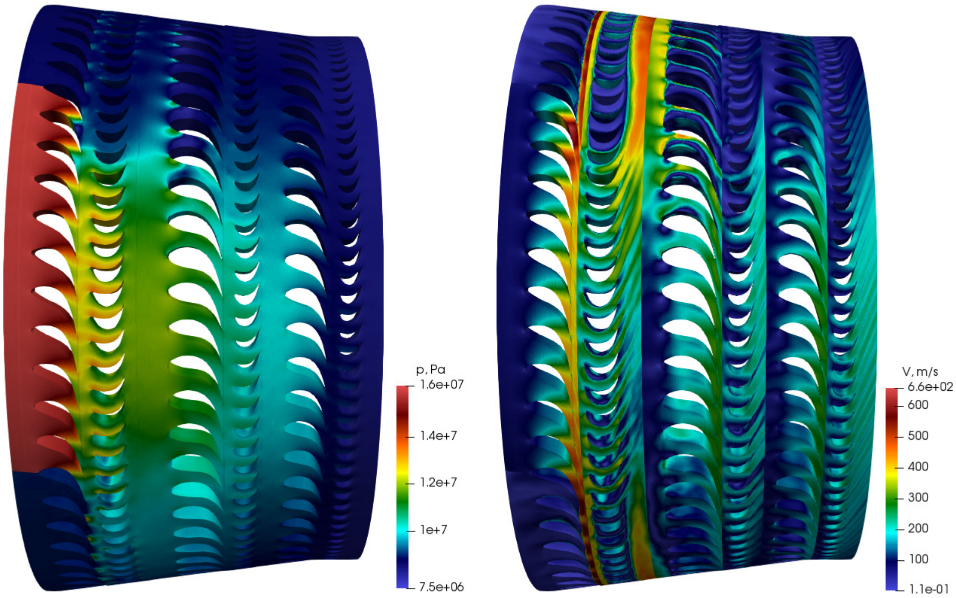

a b

***Fig. 4. Parameters distribution in the calculation area for the 100 % mode:***
a – pressure; b – relative speed




a b

***Fig. 5. Parameters distribution in the calculation area for the 70 % mode:***
a – pressure; b – relative speed




a b

***Fig. 6. Parameters distribution in the calculation area for the 50 % mode:***
a – pressure; b – relative speed

Fig. 7 presents graphs of pressure distribution along the semicircle in the middle cross-section along the rows of the control section for the mode of 100% power. Here θ denotes the relative position along the semicircle. The graphs clearly show that in the first stage the irregularity is quite significant, but in the last stage it is almost non-existent.

Fig. 8, 9, 10 show graphs of the specific mass flow rate distribution along the semicircle in the middle cross-section along the control section rows for the mode of 100% power. The graphs clearly show that the irregularity of channel-averaged specific flow rate remains to the last stage and reaches a minimum value of 9.2%.

Fig. 11 shows graphs of pressure distribution along the semicircle in the middle cross-section behind the control section rows for the mode of 70% flow rate. The graph clearly shows that as the flow passes rows, the pressure irregularity gradually decreases.

Fig. 12, 13, 14 show graphs of the specific flow rate distribution along the semicircle in the middle cross-section along the control section rows for the mode of 70% power. The graphs clearly show that the irregularity of channel-averaged specific flow rate remains to the last stage.

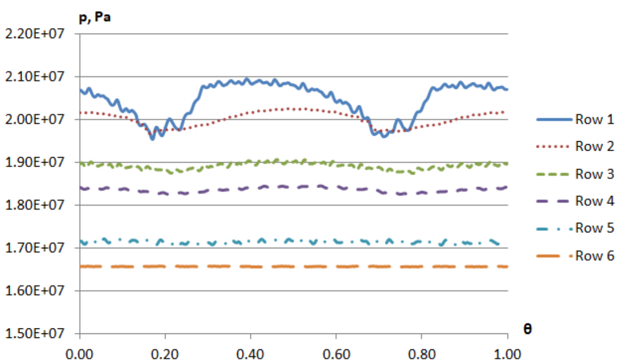



***Fig. 7. Circumferential pressure distribution on the control section rows, 100% mode***

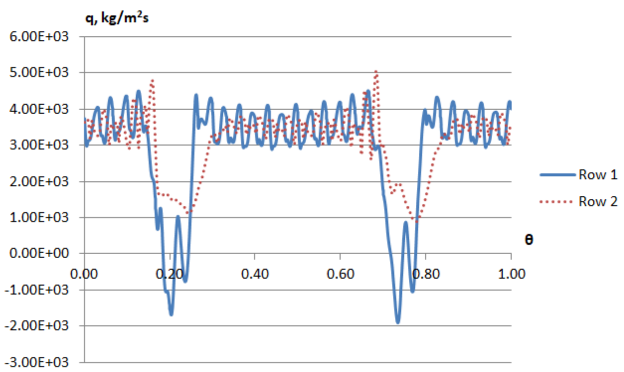



***Fig. 8. Circumferential distribution of the specific flow rate for the rows # 1, 2 of the control section, 100% mode***

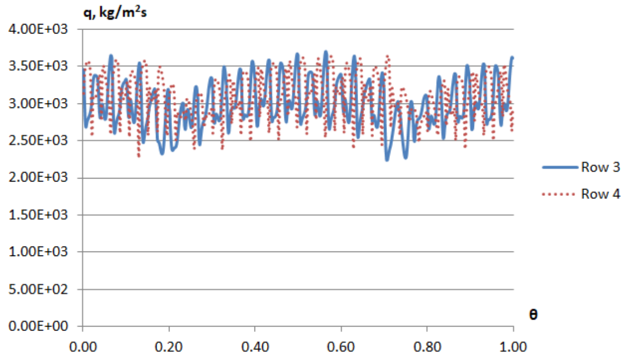



*Fig. 9. Circumferential distribution of the specific flow rate for the rows # 3, 4 of the control section, 100% mode*

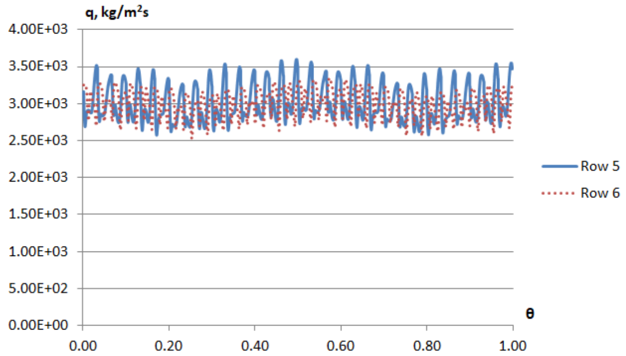



*Fig. 10. Circumferential distribution of the specific flow rate for the rows # 5, 6 of the control section, 100% mode*

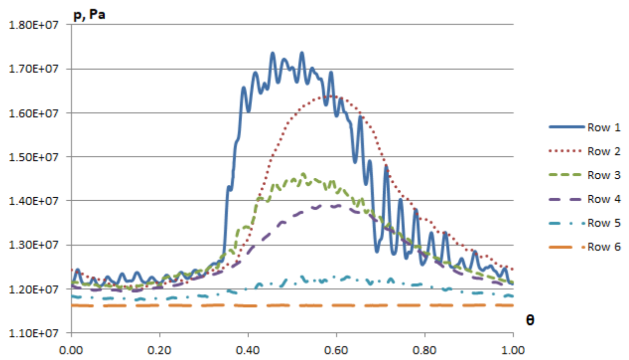



*Fig. 11. Circumferential pressure distribution on the control section rows, 70% mode*

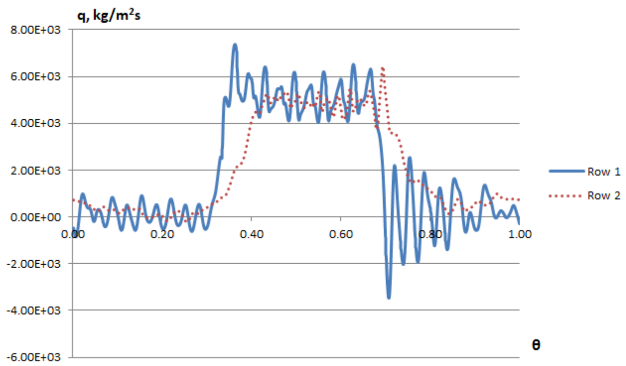



*Fig. 12. Circumferential distribution of the specific flow rate for the rows # 1, 2 of the control section, 70 % mode*

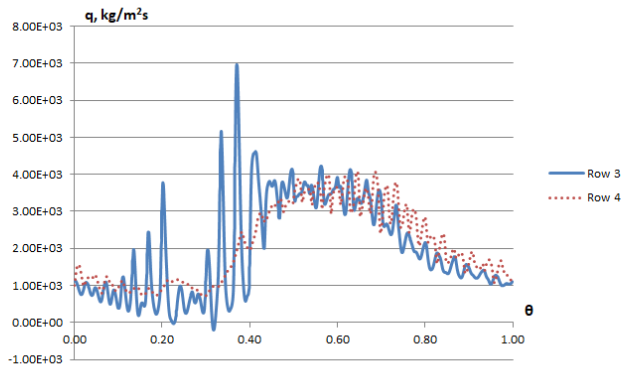



*Fig. 13. Circumferential distribution of the specific flow rate for the rows # 3, 4 of the control section, 70 % mode*

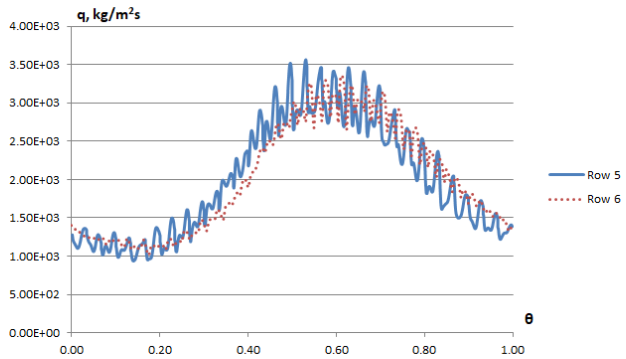



*Fig. 14. Circumferential distribution of the specific flow rate for the rows # 5, 6 of the control section, 70 % mode*

Fig. 15 presents graphs of pressure distribution along the semicircle in the middle cross-section along the control section rows for the mode of 50% power. The graph also clearly shows that in almost all stages there is a significant irregularity of pressure, except for the values at the section outlet, same as for the 70% mode.

Fig. 16, 17, 18 show graphs of the specific flow rate distribution along the semicircle in the middle cross-section along the control section rows for the mode of 50% power. The graphs clearly show that the irregularity of channel-averaged specific flow rate remains to the last stage.

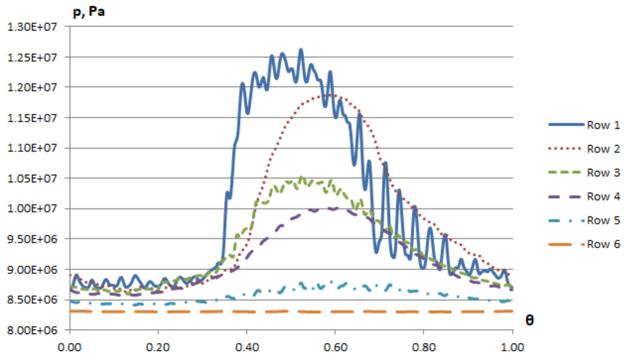



***Fig. 15. Circumferential pressure distribution on the control section rows, 50% mode***

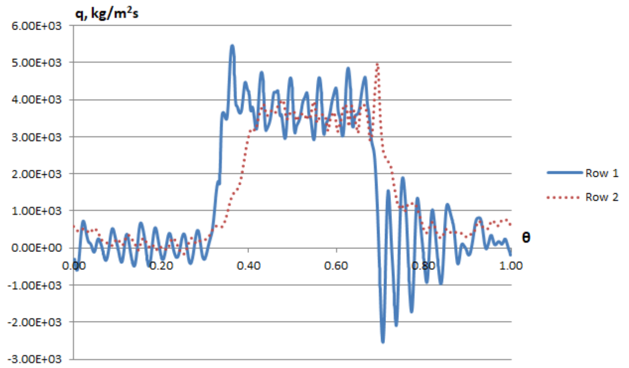



***Fig. 16. Circumferential distribution of the specific flow rate for the rows # 1, 2 of the control section, 50% mode***

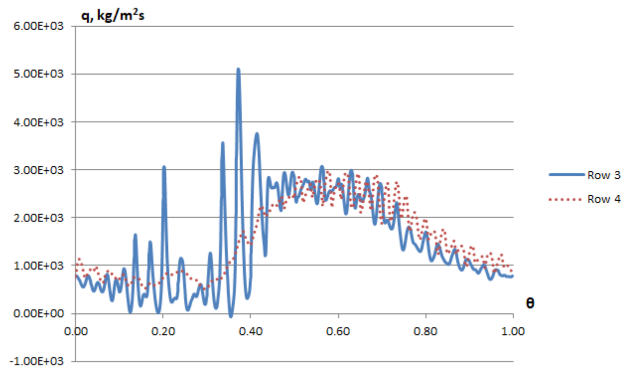



***Fig. 17. Circumferential distribution of the specific flow rate for the rows # 3, 4 of the control section, 50% mode***

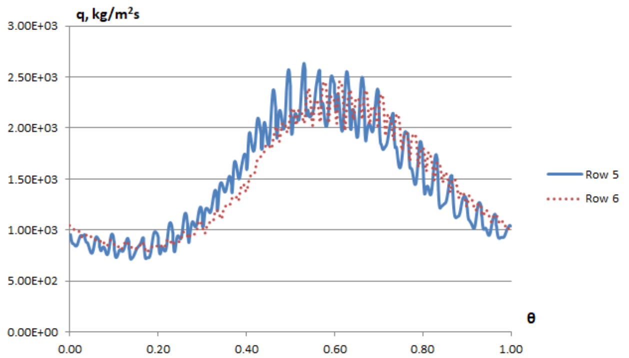



***Fig. 18. Circumferential distribution of the specific flow rate for the rows # 5, 6 of the control section, 50 % mode***

## Conclusions

The results and analysis of steam flow calculations in the K-325-23.5 steam turbine control section for three operating modes in the form of flow rate and pressure distributions in the inter-row gaps and at the section outlet are presented. The simulation results analysis shows a rather low irregularity of the steam flow parameters at the control section outlet in the partial supply modes and a slight irregularity in the rated mode. Based on the results of the analysis, a conclusion regarding the effectiveness of the developed control section of the HP module use for steam turbine K-325-23.5 modernization was made. However, to deploy the new design of the control section, it is reasonable to conduct additional studies of unsteady loads on the nozzle and turbine blades of the HP module, caused by circumferential irregularity of flow parameters at partial supply.

These results confirm the possibility of the updated software package **IPMFlow** usage for study more complicated features of the flow in the steam turbines stages, including effects caused by circular variations in the flow part geometry.

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## Числове дослідження нерівномірності потоку в регулюючому відсіку нового типу циліндра високого тиску парової турбіни

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*Для удосконалення проточної частини регулюючого відсіку та поліпшення енергетичних показників в ІПМаш НАН України розроблено триступеневий регулювальний відсік нового типу для циліндра високого тиску (ЦВТ) парової турбіни К-325-23,5, у якому відсутня камера вирівнювання тиску. Для визначення ефективності газодинамічного удосконалення регулювального відсіку постала задача вивчення просторової структури турбулентного потоку. Для цього було проведено числове моделювання течії пари у режимі з урахуванням парціальності підведення та у номінальному режимі. Основною задачею проведеного числового моделювання було виявлення рівня колової нерівномірності газодинамічних параметрів у перших ступенях відсіку та на виході з нього. Просторові розрахунки течії пари в досліджуваних проточних частинах проводилися за допомогою програмного комплексу* ***IPMFlow*** *моделювання просторової турбулентної течії в турбомашинах, розробленого в ІПМаш НАН України. Проведено дослідження нерівномірності потоку пари за колом для режимів 100, 70 і 50% масової витрати пари. Режими 70 і 50% характеризуються двома закритими регулювальними клапанами з чотирьох, що відповідає 37% відкритих міжлопатевих каналів. Наведені результати і аналіз розрахунків трьох режимів у вигляді розподілів масової витрати і тиску в міжвінцевих зазорах і на виході з відсіку. На графіках добре видно, що нерівномірність питомої масової витрати зберігається до останнього ступеня, водночас нерівномірність тиску виявляється незначною для усіх розглянутих режимів. Аналіз результатів моделювання демонструє досить низьку нерівномірність газодинамічних параметрів пари на виході з регулюючого відсіку в режимах з парціальністю та незначну нерівномірність у номінальному режимі. Виходячи з отриманих результатів аналізу зроблено висновок щодо ефективності застосування нового регулювального відсіку ЦВТ під час модернізації парової турбіни К-325-23,5. Для впровадження нової конструкції регулювального відсіку доцільно подальше дослідження рівня нестаціонарних навантажень на лопатки ЦВТ.*

***Ключові слова:*** *числове моделювання, просторова течія, парова турбіна, регулювальний відсік, циліндр високого тиску.*

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# MULTIPARAMETRIC IDENTIFICATION OF SEVERAL THERMOPHYSICAL CHARACTERISTICS BY SOLVING THE INTERNAL INVERSE HEAT CONDUCTION PROBLEM

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*Approaches to the identification of thermophysical characteristics, using methods for solving inverse heat conduction problems and A. N. Tikhonov's regularization method, are developed. According to the results of the experiment, temperature-dependent coefficients of heat conductivity, heat capacity, and internal heat sources are determined. In this case, the thermophysical characteristics are approximated by Schoenberg's cubic splines, as a result of which their identification reduces to determining unknown coefficients in the approximated dependencies. Therefore, the temperature in the body will depend on these coefficients, and it can be represented using two members of the Taylor series as a linear combination of its partial derivatives with respect to the unknown coefficients, multiplied by the increments of these coefficients. Substituting this expression into the Tikhonov functional and using the minimum property of the quadratic functional, we can reduce the solution of the problem to the solution of a system of linear equations with respect to the increments of unknown coefficients. By choosing a certain regularization parameter and some functions as an initial approximation, we can implement an iterative process in which the vector of unknown coefficients for the current iteration will be equal to the sum of the vector of the coefficients obtained in the previous iteration and the coefficient increment vector as a result of solving a system of linear equations. Such an iterative process of identifying the thermophysical characteristics for each regularization parameter makes it possible to determine the mean-square discrepancy between the resulting temperature and the temperature measured as a result of the experiment. It remains to choose the regularization parameter so that this discrepancy is within the root-mean-square measurement error. Such a search, for example, is identical to algorithms for searching roots of nonlinear equations. When checking the efficiency of using the proposed method, a number of test problems were solved for bodies with known thermophysical characteristics. An analysis of the influence of random measurement errors on the error of the identifiable thermophysical characteristics of the body being studied was carried out.*

***Keywords:*** *inverse heat conduction problem, Tikhonov's regularization method, stabilization functional, regularization parameter, identification, approximation, Schoenberg's cubic splines.*

## Introduction

Solution of inverse heat conduction problems (HCP) of identifying the parameters of mathematical models is of particular importance as an important step in ensuring the adequacy of these models in the presence of experimental information about the thermal process being studied. This article discusses the nonlinear internal inverse HCP of identifying thermophysical characteristics. These can be temperature-dependent coefficient of heat conductivity, heat capacity, internal heat sources, etc. The authors of [1–6] propose classifications