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***Ryndyuk D.V.***
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

***Bednarska I.S.***
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"

# MODELING OF STEAM GAS DYNAMICS IN MAIN PIPELINES OF NUCLEAR POWER PLANTS

*The article considers the process of wet steam flow through the main steam pipelines of nuclear power plants. The system of main steam pipelines, which is designed to transport steam from the steam generator to the high pressure cylinder of the turbine, is considered. The gas-dynamic properties of the medium moving by these steam pipelines are investigated. The simulation of the process of wet steam flow from one of the steam generators is performed. The task is presented in a 3-dimensional, stationary setting, using a model of fully compressible fluid. The article presents the results of the first stage of a set of numerical experiments. A good agreement was obtained with the data of control and measuring devices located on the steam pipelines of Unit №2 of the Nuclear Power Plant. The result is a 3-D gas-dynamic structure of the flow, the distribution of velocities in the flow, temperature fields, pressure distributions. Analysis of the results of numerical simulations made it possible to study in detail the gas-dynamic characteristics of the flow of wet steam through steam pipelines. Based on numerical simulations, the influence of steam pipe geometry on gas flow dynamics can be estimated. Based on the obtained results, graphs of pressure drop on each of the four steam pipelines at characteristic points in the calculation schemes are constructed. As a result of the simulation of the process of wet steam flow from the steam generator №2 through steam pipelines to the check valve on the power unit №2 of NPP, data on the distribution of pressures, temperatures and velocities of the environment by steam volume. The adequacy of the numerical model and the correctness of the modeling were verified by comparing the calculated results with the NPP data. Comparison of research results and real data gave a satisfactory match. The average relative error of the model is about 5%. The developed simulation model is adequate and can be used to calculate the parameters of steam flow in steam pipelines.*

***Key words:*** *nuclear power plant, steam pipelines, gas dynamics, mathematical modeling.*

Formulation of the problem. Nuclear energy is the main alternative to fossil fuels – coal, oil and gas in the field of electricity generation, as well as reducing the emission of carbon dioxide and thus reducing the greenhouse effect [1].

According to various sources, the share of nuclear power plants in electricity generation has been gradually increasing recently [1]. However, some NPP units are close to exceeding their design life – 40 years [2].

Due to the approaching expiration of the installed life of the NPP power unit, the problem of assessing the technical condition of the equipment, forecasting the residual life and extending the term of its further operation becomes urgent. This means that it is necessary to develop tools and methods for uninterrupted long-term operation of the station elements in accordance with the requirements of the energy system, to begin assessing the life of equipment and make recommendations for its further work [3].

All this inevitably requires a set of measures to analyze the condition of the main equipment (turbine rotors and housings, valves, base metal of steam pipelines), address the issue ofpossible further operation, as well as develop measures to extend service life.

It should be noted that extending the life of existing nuclear power plants is one of the most effective ways to ensure the return on investment in the energy sector in the world [3].

One of the important elements of equipment at nuclear power plants is the steam distribution system. The system of "fresh" steam pipelines is designed to transport saturated steam from the steam generator to the high pressure cylinder (HPC) of the turbine and superheater (SP) [11]. The first step in determining the state of steam pipelines is to study the gas-dynamic properties of the medium moving through these steam pipelines.

**Analysis of recent research and publications.** Modern development of science and computer technology makes it possible to study objects that are too complex for analytical research with the help of mathematical models created in automatic design systems. It is known that the method of testing a computer model is one of the important problems that must be solved if the goal is to correctly predict the variable temperature field. In [4] the possibility of using measurements of vapor temperature and temperature of selected points of the studied elements to determine the boundary conditions of the heat transfer problem, as well as verify the operational correctness of the developed computer models.

Also in [5] developed his own method of analysis of mechanical behavior of the power plant component, which includes analysis of temperature fields taking into account the boundary conditions based on the operating parameters and the model of thermoplastic material.

Important in the study of gas-dynamic properties of the medium is the effect of time-varying heat transfer coefficient on the course of temperature, which was studied in [6]. The object of the test was a steam valve. The standards provide for a constant value of this factor in the design of such a component. However, given that in the devices used in energy, the physical state of the environment and its consumption often change, it was concluded that the value of the coefficient should be considered as variable. Its value depends on temperature and pressure. It is shown that changes in the heat transfer coefficient over time have a strong effect on the temperature distribution in the component.

The normative documents [7, 8], which are officially recognized in the industry, describe the limiting conditions of heat transfer in the elements of turbines and methods of their calculation. The authors of [9, 10] were guided by these methods and instructions when estimating the residual life and prolongation of operation of steam turbine housings and rotors, valves and other parts of power units.

In [9], the limiting heat transfer conditions for the rotor during cold, uncooked and hot starts are calculated, which change over time during the entire start-up period. Limit heat transfer conditions were calculated according to [7]. Also, when calculating them, the authors take into account changes in parameters on variable modes of operation.

In works [9, 10] the estimation of a resource of details of turbine installations, by means of the described technique of calculation of a thermal condition of these details at characteristic operating modes was offered. The limit conditions of heat exchange at the control points were calculated, which are shown in the calculated geometric models, in which the voltage intensity ranges for all periods of starts from different thermal states were determined. However, this approach to determining the resource of parts of turbines involves the human factor and, therefore, requires a lot of time to calculate the boundary conditions of I-IV kind. Note that it is not possible to determine with sufficient accuracy the boundary conditions of the I-IV kind for objects that have a complex geometric shape. It is also worth noting the design changes in the details of turbines, which occurred during the entire service life, which can not be taken into account with sufficient accuracy using the method described in [7-10].

**Task statement.** After a detailed analysis of recent research and publications, it was concluded that the above methods and approaches to determining the life of turbine elements and valves are time consuming in calculating boundary conditions and are not accurate for objects of complex geometric shapes.

The aim of this work is to develop an alternative method for determining the resource indicators of high-temperature elements of turbines, based on the replacement of time-consuming process of calculating the boundary conditions of heat transfer by modeling the dynamics of wet steam flow on the example of main steam power plants An approach to determining the distributions of pressures, temperatures and velocities of the environment by the volume of the studied object, which is necessary for further calculation of the stress-strain state and resource indicators.

**Outline of the main material of the study.** The system of "fresh" steam pipelines consists of four parallel main steam pipelines.

Each of the main steam pipelines connects the steam generator (SG) with its shut-off and control valve of the turbine [11]. The tracing of fresh steam pipelines is shown in Figure 1.

The numbering of steam mains corresponds to the numbers of steam generators. Nominal parameters of steam in the system of steam pipes of "fresh" steam during operation of the power unit with nominal load [12] are presented in table 1.

The list of controlled parameters of the system is given in table 2 [12]. The list of parameters will be used to verify the data obtained.

Table 1

**Nominal parameters of “fresh” steam**

| Parameter Name | Value |
|---|---|
| Vapor pressure after steam generator, MPa | 6,3 |
| Vapor pressure before shut-off and control valve, MPa | 5,88 |
| Steam temperature before shut-off and control valve, °C (K) | 274 (547) |
| Humidity of steam in front of the turbine, % | 0,5 |
| Steam consumption from steam generator, t / h | 5870 |
| Steam consumption from steam generator to superheater, t / h | 510 |

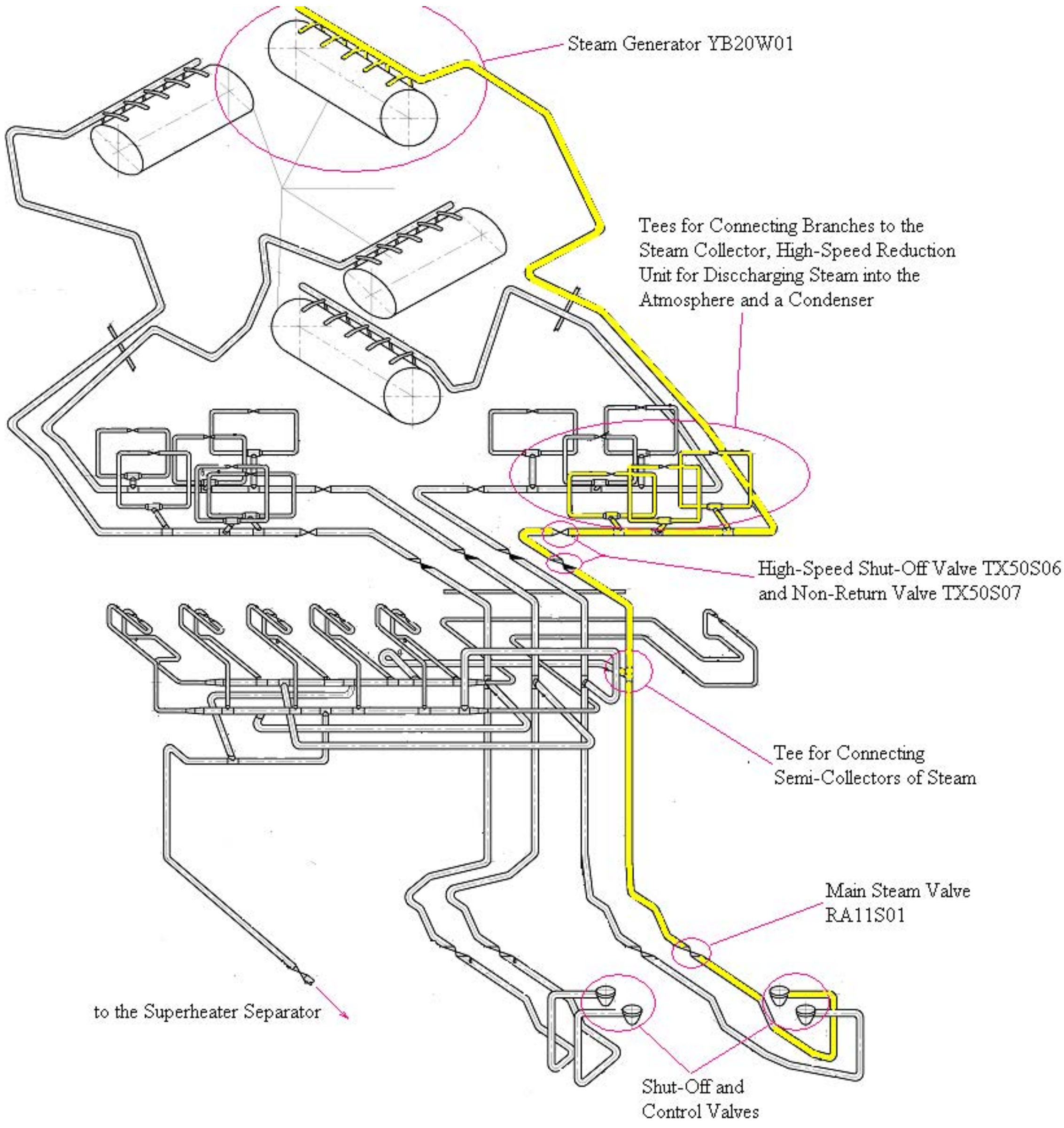


**Fig. 1. Tracing of "fresh" steam pipelines [13]**

Table 2

**Nominal parameters of "fresh" steam**

| Parameter Name | Nominal value | Place of output of information |
|---|---|---|
| Vapor pressure after steam generator, MPa | 6,3 | Block control panel |
| Steam pressure in front of the main steam valve, MPa | 6,27 | On the spot |
| Steam pressure after the main steam valve, MPa | 6,27 | On the spot |

When equipping the system of fresh steam pipelines with control and measuring equipment, a minimum number of devices is installed on site.

As can be seen from the above list of controlled parameters (Table 2), control of gas dynamics of steam in steam pipelines is carried out only at three points, which is clearly not enough to understand the "full picture" of the processes occurring in them. Since the non-design equipment of the NPP steam pipeline system with control and measuring devices is controlled by the relevant normative documents, interference at the physical level in the design of the steam pipeline is impossible. Therefore, it is advisable to further determine the state of the metal of steam pipelines and fittings to conduct a set of numerical experiments based on modeling the flow of wet steam in the steam distribution system of a nuclear power plant with turbine K-1000-60 / 3000.

FlowVision 3.12.01 software package was used to study gas dynamics in steam pipelines. The geometric model was created in the 3D modeling system SolidWorks (Figure 2).

The mathematical model includes the laws of conservation of energy, mass, momentum, equations of state of liquid or gas, various closing relations, boundary and initial conditions [14].

The solution of the above equations is based on the finite volume method, which involves their integration by the volume of the cells of the calculation grid. By Gauss's theorem for an arbitrary vector or tensor quantity:

$$\int(\nabla \cdot F)\, d\Omega = \sum (F_i \cdot n_i) \cdot \Delta S_i, \qquad (1)$$

where Ω – cell volume,
$\Delta S_i$ – the area of the i-th face of the cell.

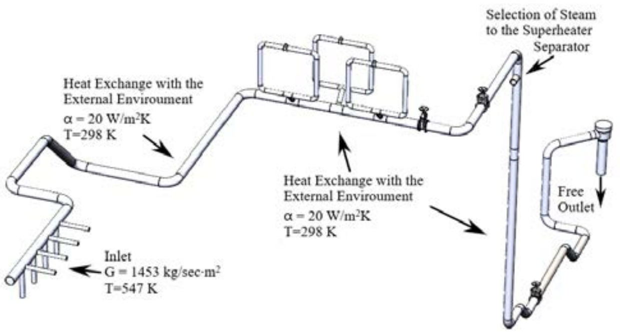


**Fig. 2. Estimated scheme of the steam pipeline YB20W01 from the steam generator № 2**

Thus, when integrating the solvable equations in the cells, the summation of the flows of mass, momentum, energy and turbulent quantities calculated on the faces of the cells is performed.

The parameters obtained at Unit № 2 of Khmelnitsky NPP were taken as initial and limit conditions: humid steam temperature t = 274.3°C; vapor pressure after steam generator P = 6.3 MPa; the degree of dryness of the vapor x = 0.995; steam consumption from all steam generators G = 5870 t / h; roughness for the studied pipes $10^{-4}$ m.

In this problem we need to determine the distribution of velocities, temperatures and pressures. The task was solved in a 3-dimensional, stationary setting, using a model of fully compressible fluid. During the trial calculations, the parameters of the calculation model (time step, conditions of adaptation of the calculation grid) were specified, which allowed to optimize the calculation and get a good match with the experimental data obtained directly at the station.

Data on the 3-D gas-dynamic structure of the flow, the distribution of velocities in the flow, temperature fields, pressure distributions were obtained. Analysis of the results of numerical simulations made it possible to study in detail the gas-dynamic characteristics of the flow of wet steam through steam pipelines. Numerical modeling allowed to estimate the influence of steam pipe geometry on gas flow dynamics.

Given the high requirements for computer power and the considerable duration of calculations, it was decided to investigate only certain sections of one steam pipeline, which are equally present in each of the four. The adopted measure has made it possible not only to reduce the time and resources spent on research of the full task, but also is a very reliable method of predicting changes in pressure in similar sections of steam pipelines. The linear change of steam parameters on straight sections of steam pipelines was also taken into account.

As a result, of the conducted numerical experiments the distributions of temperatures, pressures and speeds of steam at movement on the investigated sites of steam pipelines are received.

Based on the conducted numerical experiments, graphs of pressure drop on each of the four steam pipelines were constructed. Figure 3 shows the curve of the pressure drop of steam for the steam pipe YB20W01 from the steam generator №2.

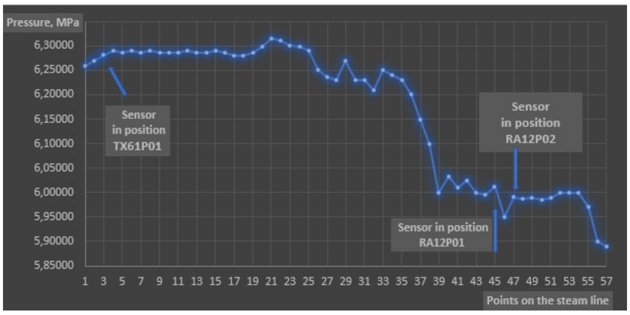


**Fig. 3. Pressure drop in the steam line YB20W01 from the steam generator № 2**

As can be seen from Figure 3, the indicators of the sensors coincide with the obtained data of numerical experiments performed on the basis of the developed mathematical model. Thus, the developed mathematical model of wet steam gas dynamics on the volume of the studied steam pipeline with sufficient adequacy reflects the real characteristics of the coolant and can be used in further calculations to determine the stress-strain state of high-temperature elements of the turbine steam distribution system and determine long-term strength and metal life.

**Conclusions.** As a result of the simulation of the process of wet steam flow from the steam generator №2 through steam pipelines to the check valve on the power unit №2 of Khmelnitsky NPP, data on the distribution of pressures, temperatures and velocities of the environment by steam volume. The adequacy of the numerical model and the correctness of the modeling were verified by comparing the calculated results with the KhNPP data. Comparison of research results and real data gave a satisfactory match. The average relative error of the model is about 5%. The developed simulation model is adequate and can be used to calculate the parameters of steam flow in steam pipelines. In the future, the obtained data will be used to determine the residual life of the main NPP steam pipelines.

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**Риндюк Д.В., Беднарська І.С. МОДЕЛЮВАННЯ ГАЗОДИНАМІКИ ПАРИ В МАГІСТРАЛЬНИХ ТРУБОПРОВОДАХ АЕС**


*У статті розглянуто процес руху вологої пари магістральними паропроводами атомних електростанцій. Розглянуто систему магістральних паропроводів, яка призначена для транспортування пари від парогенератора до циліндра високого тиску турбіни. Досліджено газодинамічні властивості середовища, що рухається цими паропроводами. Проведено моделювання процесу потоку вологої пари від одного з парогенераторів. Завдання представлено в тривимірному стаціонарному положенні з використанням моделі повністю стисливої рідини. У статті наведено результати першого етапу комплексу чисельних експериментів. Отримано хороше узгодження з даними контрольно-вимірювальних приладів, розташованих на паропроводах енергоблоку №2 атомної електричної станції України. Результатом є тривимірна газодинамічна структура потоку, розподіл швидкостей у потоці, температурні поля, розподіл тиску. Аналіз результатів чисельного моделювання дає змогу детально вивчити газодинамічні характеристики течії вологої пари паропроводами. На основі чисельного моделювання можна оцінити вплив геометрії паропроводу на динаміку газового потоку. За отриманими результатами побудовано графіки падіння тиску на кожному з чотирьох паропроводів у характерних точках розрахункових схем. В результаті моделювання процесу надходження вологої пари від парогенератора №2 по паропроводах до зворотного клапана на енергоблоці №2 АЕС отримані дані про розподіл тиску, температури і швидкості середовища. Адекватність чисельної моделі та правильність моделювання перевірено шляхом порівняння результатів розрахунків з даними АЕС. Порівняння результатів досліджень і реальних даних показало задовільний збіг. Розроблена імітаційна модель є адекватною і може бути використана для розрахунку параметрів потоку пари в паропроводах.*



***Ключові слова:*** *атомна електростанція, паропроводи, газодинаміка, математичне моделювання.*