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Simulation and Mathematical Modeling of a Steam Turbine Installation for a Nuclear Power Unit

S. N. Kamarova¹⁾, K. H. Hristov²⁾, G. G. Zhabalova¹⁾, O. N. Onichshenko¹⁾,
Y. N. Bolatov³⁾

¹⁾Karaganda Industrial University (Temirtau, Republic of Kazakhstan),

²⁾Technical University of Sofia (Sofia, Republic of Bulgaria),

³⁾Nazarbayev University (Astana, Republic of Kazakhstan)

Abstract. The steam turbine installations in nuclear power units are of the condensation type. The main parameters affecting the performance of condensation-type steam turbine installations are the steam flow rate at the turbine inlet, the temperature variation, and the flow rate of cooling water entering the condenser. Any change in these parameters directly influences the amount of electrical energy produced by the steam turbine. To study their influence, it is necessary to collect a large amount of data and synthesize a mathematical model. Data collection through measuring and recording equipment is a complex, time-consuming process associated with both the technological time required for gathering and subsequent processing. Simulation modeling is a modern research tool that allows studying energy systems without disrupting the technological process. This modeling involves developing an analogue of an existing object in a graphical software environment where geometric and physical parameters characterizing the object's properties are defined. The results obtained from solving the simulation model must be compared with data from characteristic operating modes of the examined object. The present paper aims to develop a simulation model for assessing the performance of a condensation-type steam turbine installation of a nuclear power unit model K-1000-60/1500-2. This steam turbine installation is typical for nuclear power units of the VVER-1000 type. The data obtained from the simulation model will be used to construct a mathematical model determining the parameters characterizing the operation of the condensation steam turbine installation.

Key words: mathematical model, steam turbine installation, simulation calculations, nuclear power unit, condensation type, electrical power output, efficiency

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Имитационное и математическое моделирование паротурбинной установки атомной электростанции

С. Н. Камарова¹⁾, К. Х. Христов²⁾, Г. Г. Жабалова¹⁾, О. Н. Онищенко¹⁾,
Е. Н. Болатов³⁾

¹⁾Карагандинский индустриальный университет (Темиртау, Республика Казахстан),

²⁾Технический университет Софии (София, Республика Болгария),

³⁾Назарбаев университет (Астана, Республика Казахстан)

Реферат. Паротурбинные установки на ядерных энергетических блоках относятся к конденсационному типу. Основными параметрами, влияющими на эффективность работы

Адрес для переписки

Христов Калоян Х.
Технический университет Софии,
бульвар «Климент Охридски», 8
1000, г. София, Республика Болгария
Тел.: +359 2 965 2359
k.hristov@tu-sofia.bg

Address for correspondence

Hristov K. H.
Technical University of Sofia
8, Blvd«Kliment Ohridski»
1000, Sofia, Bulgaria
Tel.: +359 2 965 2359
k.hristov@tu-sofia.bg

таких установок, являются расход пара на входе в турбину, изменение температуры и расход охлаждающей воды, поступающей в конденсатор. Любое изменение этих параметров непосредственно отражается на количестве электрической энергии, вырабатываемой паровой турбиной. Для изучения их влияния необходимо собрать большой объем данных и построить математическую модель. Сбор данных с помощью измерительного и регистрирующего оборудования является сложным и трудоемким процессом, связанным как с технологическим временем, необходимым для их получения, так и с последующей обработкой. Имитационное моделирование представляет собой современный исследовательский инструмент, который позволяет изучать энергетические системы без нарушения технологического процесса. Этот вид моделирования предусматривает создание аналога существующего объекта в графической программной среде, где задаются его геометрические и физические параметры, характеризующие свойства объекта. Результаты, полученные при решении имитационной модели, должны быть сопоставлены с данными, полученными в характерных режимах работы исследуемого объекта. Настоящая работа направлена на разработку имитационной модели для оценки характеристик конденсационной паротурбинной установки ядерного энергетического блока модели К-1000-60/1500-2. Такой тип установки является типичным для энергоблоков с реакторами ВВЭР-1000. Полученные в результате моделирования данные будут использованы для построения математической модели, определяющей параметры, характеризующие работу конденсационной паротурбинной установки.

Ключевые слова: математическая модель, паротурбинная установка, имитационные расчеты, ядерный энергетический блок конденсационного типа, электрическая мощность, КПД

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Introduction

Condensation-type steam turbine installations account for the largest share among the facilities used for electrical energy production. One of the primary tasks of the operational personnel is the forecasting of the electric load as a result of the various factors influencing the operational process. A modern tool for studying the impact of different parameters on the performance of technological systems is simulation modeling [1–10]. Unlike direct testing of physical facilities, simulation modeling does not require the use of expensive equipment, human resources, or technological downtime for conducting experiments [11–15].

Simulation modeling is performed through specialized software, which enables the creation of a virtual analogue of the studied technological system. Geometric parameters and physical quantities are introduced to accurately describe the investigated object. Conducting modeling in a virtual environment makes it possible to implement and analyze operating modes that, under real operating conditions, would be difficult to achieve or would approach the operational limits of the equipment [16–27].

The present study aims to develop a simulation model of a condensation steam turbine installation for a nuclear power plant. By synthesizing the turbine model within the software environment, multiple computational scenarios will

be performed to support the development of a mathematical model describing specific energy characteristics of the analyzed steam turbine installation.

Modeling of Technological Systems

Fig. 1 presents a block diagram of the stages involved in developing a mathematical model based on simulation modeling. According to the block diagram, the modeling process consists of the following stages:

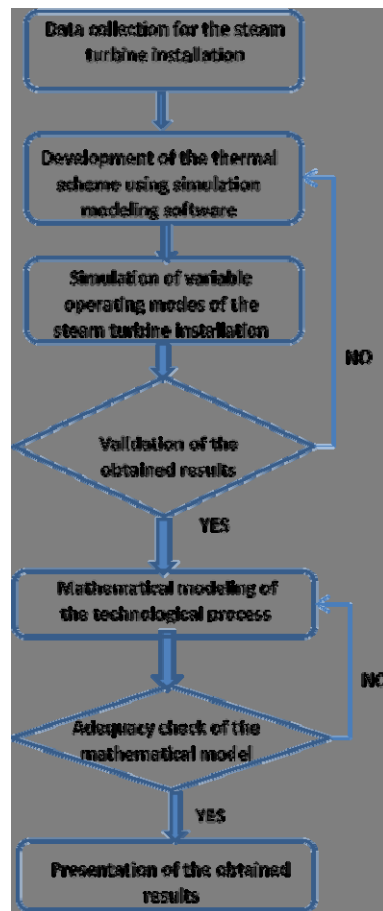


Fig. 1. Block diagram for developing a mathematical model of a steam turbine installation based on simulation modeling

Collection of information about the combined heat and power installation. This initial stage aims to clarify the operational mechanism of the investigated system. The collected information is derived from the technical documentation of the steam turbine installation and includes: the heat flow diagram with connections between individual components, as well as the geometric and physical parameters of the installation elements.

Synthesis of the heat flow diagram using simulation software. With the help of simulation software, an analog of the technological system under study is developed. The software tools provide the capability to define parameters that characterize the individual components forming the heat flow diagram of the system.

Simulation of characteristic operating modes of the combined heat and power installation. At this stage, modeling of characteristic operating regimes of the steam turbine installation is performed. The operating modes to be simulated are usually specified in the technical documentation of the examined power system.

Validation of the obtained results. In this step, the results from the model are compared with those provided in the technical documentation.

If the deviations remain within acceptable limits, the model can be used for further studies of the system. If the simulation results show excessive discrepancies relative to the technical documentation, the simulation model must be adjusted. A new simulation is then performed until the results accurately reproduce the reference data.

Mathematical modeling of the technological process. The structure of the mathematical model is selected. To develop the mathematical model, an extensive data set is required. In this study, a simulation model is applied to obtain the necessary data through multivariable calculations.

Adequacy check of the mathematical model. It is verified whether the results of the mathematical model adequately describe the behavior of the studied system. For this purpose, statistical criteria are applied. If the model does not sufficiently represent the real system, modifications to the model structure are undertaken.

Visualization of the obtained results. This is the final stage. Graphs of the main dependencies are plotted and analyses are carried out. The impact of individual factors on the output parameter is assessed.

Simulation Modeling of the K-1000-60/1500-2 Steam Turbine Installation

The investigated object is the K-1000-60/1500-2 steam turbine installation, which is operated in 17 power units across three countries. The design is single-shaft, comprising a high-pressure cylinder and three low-pressure cylinders. The regenerative system of the steam turbine installation consists of a condenser, four low-pressure feedwater heaters, a deaerator, and two high-pressure feedwater heaters. The system includes seven uncontrolled steam extractions.

In the scheme of the steam turbine installation, before entering the low-pressure cylinders, the steam passes through a separator–reheater, where it is superheated prior to admission into the low-pressure cylinders. The purpose of this process is to reduce the moisture content under which the low-pressure cylinders of the turbine operate.

Using the Thermoflow software product, the thermal scheme of the K-1000-60/1500-2 installation was synthesized. In order to simulate the uncontrolled steam extractions of the steam turbine installation, it was necessary to represent the turbine within the software environment as consisting of eight cylinders. Fig. 2 illustrates the thermal scheme of the steam turbine installation.

Using the developed simulation model, a calculation was carried out for the nominal operating mode in accordance with the technical documentation. The monitored parameters include fresh steam flow rate (D_o , t/h), fresh steam pressure (p_o , MPa), fresh steam temperature (t_o , °C), condenser steam inlet pressure (p_c , kPa), and the electrical output of the steam turbine (N , kW). Table 1 presents the results of the simulation for the nominal operating mode, comparing the model outputs with the data from the technical documentation.

From the data obtained by solving the simulation model for the nominal operating mode of the K-1000-60/1500-2 steam turbine installation (Table 1), it can be observed that the model reproduces the data from the technical documentation with sufficient accuracy. This provides a basis for employing the mathematical model to determine the properties of the examined system under operating conditions different from the nominal ones.

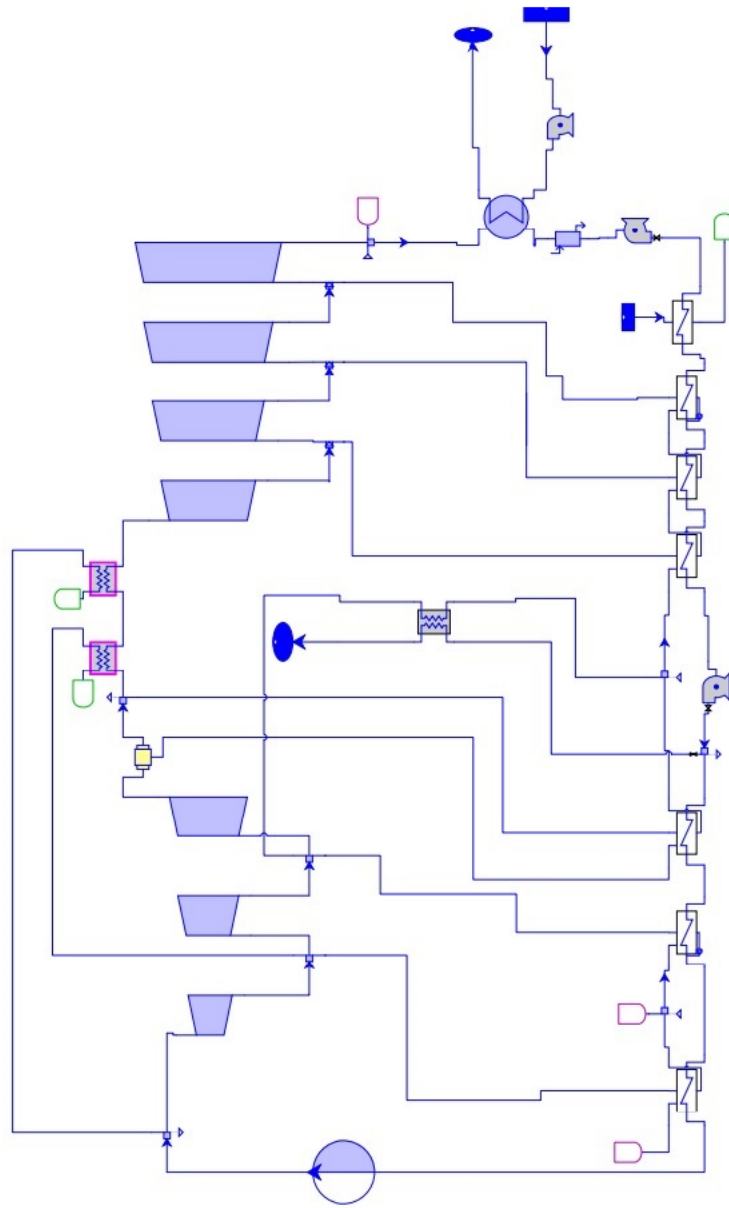


Fig. 2. Visualization of the thermal scheme of the K-1000-60/1500-2 steam turbine installation in the Thermoflow software environment

Comparative analysis of the model

Table 1

Parameters	Technical data	Model result	Deviation, %
D_0 , t/h	6430,00	6443,00	0,2
p_0 , MPa	6,00	6,20	3,3
t_0 , °C	274,30	275,60	0,5
P_c , kPa	4,00	4,15	3,8
N , MW	1014,00	1012,20	-0,2

Simulation Calculations

Using the software, multivariable calculations were carried out. The simulation was performed depending on the variation of the fresh steam flow rate at the turbine inlet (D_0 , t/h), the temperature of the cooling water supplied to the condenser (t_1 , °C), and the cooling water flow rate G (G_{cool-w} , t/h).

- Range of variation of steam flow rate in the steam generator: $3866 \text{ t/h} \leq D_0 \leq 6443 \text{ t/h}$;
- Range of variation of cooling water temperature in the condenser: $10 \text{ °C} \leq t_1 \leq 25 \text{ °C}$;
- Range of variation of cooling water flow rate: $107,000 \text{ t/h} \leq G_{cool-w} \leq 178,055 \text{ t/h}$.

When solving the software model within the specified parameter ranges, 280 simulation calculations were carried out. The quantities determined from the simulations are as follows:

- Thermal power generated by the steam generator – Q_0 , kW;
- Electric power of the steam turbine installation – N , kW;
- Efficiency of the installation – η , %;
- Specific fuel consumption for electricity generation – b_{el} , kg/kWh.

The results of the performed multivariable calculations are presented in Table 2.

Table 2

Simulation results

No	D_0 , t/h	t_1 , °C	G_{cool-w} , t/h	N , MW	Q_0 , MW	η , %	b_{el} , kg/kWh
1	6443	15	178055	1012.159	3239.612	31.2432	0.392857
2	6443	15	170160	1012.074	3239.612	31.2406	0.39289
3	6443	15	162265	1011.973	3239.612	31.2375	0.392929
...							
280	3866	25	107000	561.386	2026.137	27.7072%	0.442994

For the determination of the specific consumption of conventional fuel, a lower heating value of 29,330 kJ/kg is used. Based on the results obtained from the simulation calculations, a mathematical model will be developed for predicting the electrical power output of the steam turbine installation. Fig. 3 presents the steam turbine installation as a control object [25–26].

In Fig. 3, the schematic of the installation for condensation-based electricity generation is presented as a controlled object. The control parameters (factors) are the steam flow rate (D_0 , t/h, – X_3), the cooling water flow rate ($G_{cooling w}$, t/h, – X_1), and the temperature at which the cooling water enters the condenser (t_1 , °C, – X_2). The factors that can be subjected to regulatory influence are the steam flow rate and the cooling water flow rate. The non-controllable parameter is the temperature of the cooling water entering the condenser, which depends on climatic conditions.

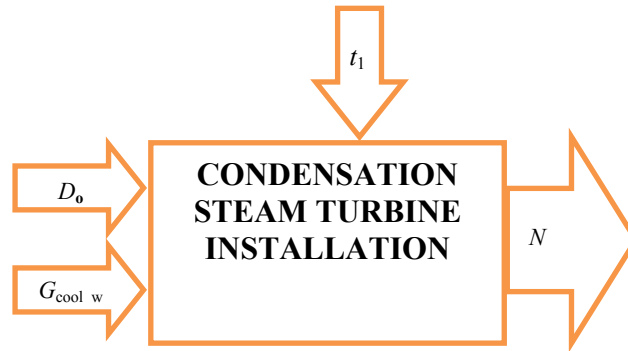


Fig. 3. Visualization of the steam turbine installation as a control object

The output variable of the regression model is the electrical power of the steam turbine installation (N , kW, $-\hat{y}$). The mathematical model of the analyzed steam turbine installation is sought in the following form:

$$\hat{y} = a_0 + a_1 X_1 + a_2 X_2 + a_3 X_3, \quad (1)$$

where a_0, a_1, a_2, a_3 are the coefficients of the mathematical model.

For the mathematical model to be applicable, the coefficient of multiple correlation must be verified according to Fisher's criterion [1, 14].

Mathematical Model for Determining the Electrical Power

After statistical processing of the data obtained from the simulation model, the coefficients of the regression mathematical model were determined, and equation (1) takes the following form:

$$\hat{y} = -94832,9375 + 172,4261 X_1 - 474,2372 X_2 + 0,03179 X_3. \quad (2)$$

The multiple correlation coefficient of the regression equation is $R = 0,9999$ (indicating a very strong correlation). In order to use the regression mathematical model, it is necessary to evaluate whether the multiple correlation coefficient is statistically significant. This procedure is carried out because no parallel observations are available, and Fisher's criterion is applied [28–29].

The critical value $F(\alpha, \nu_1, \nu_2)$ was determined as $as = 0.117$. This value was calculated for a significance level $\alpha=0.05$, with numerator degrees of freedom $\nu_1 = 3$ and denominator degrees of freedom $\nu_2 = 262$. The calculated value of the Fisher criterion is $F = 9108$, which is considerably greater than the critical value. Therefore, the multiple correlation coefficient is statistically significant, and the obtained regression model can be applied for studying the system

Results Visualization and Discussion

The mathematical model (2) was solved, and the results are presented graphically. Fig. 4 and 5 illustrate the variation of the electrical power output of the

steam turbine installation as a function of the steam flow rate (D_o , t/h), the cooling water inlet temperature to the condenser (t_1 , °C), and the cooling water flow rate ($G_{cool. w}$, t/h).

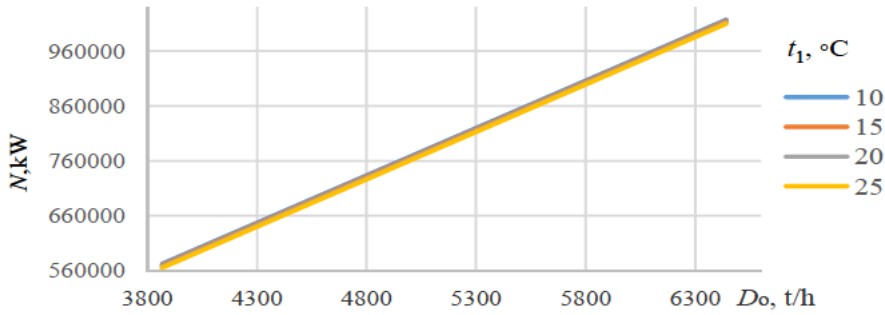


Fig. 4. Variation of the electrical power output as a function of the steam flow rate at the turbine inlet, the cooling water temperature, and the cooling water flow rate $G_{cool. w} = 178,000$ t/h

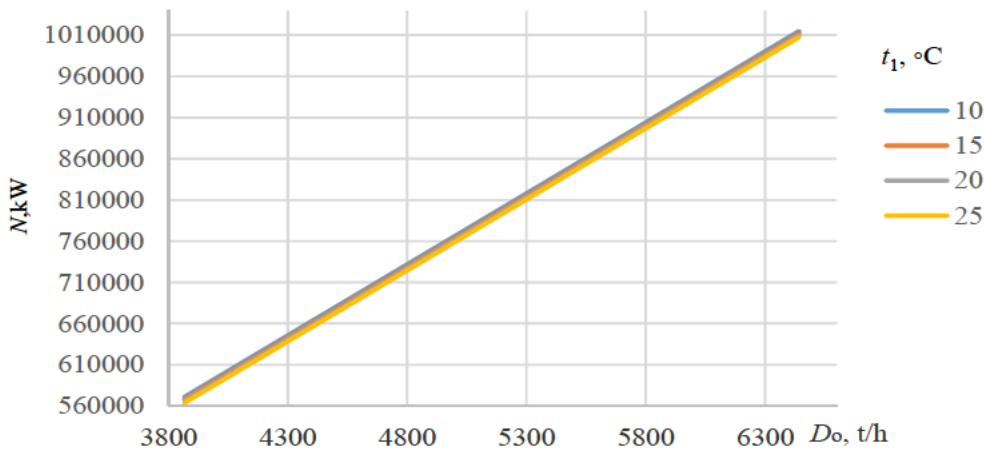


Fig. 5. Variation of the electrical power output as a function of the steam flow rate at the turbine inlet, the cooling water temperature, and the cooling water flow rate $G_{cool. w} = 107000$ t/h

The graphical results obtained from solving the mathematical model show that a decrease of the cooling water temperature at the condenser inlet by 1 °C leads to an increase in the electrical power output of approximately 470 kWh, assuming constant steam flow at the turbine inlet and constant cooling water flow through the condenser.

The specific steam consumption $\left(d_o = \frac{D_o}{N}, \text{ t/MWh} \right)$ for the installation varies within the range of 6.34–6.86 t/MWh. The lower value corresponds to the nominal steam flow at the turbine inlet, nominal cooling water flow, and a cooling water inlet temperature of 10 °C at the condenser.

The higher values of the specific steam consumption correspond to the operating regime in which the steam flow and the cooling water flow are reduced

to 60 % of their nominal values, combined with a cooling water inlet temperature of 25 °C. The higher values of the specific steam consumption correspond to an operating regime in which the steam flow and the cooling water flow are at 60 % of their nominal values, with a cooling water inlet temperature of 25 °C.

CONCLUSION

In the fulfilled study, a simulation model of the K-1000-60/1500-2 steam turbine installation was created using ThermoFlow software. The simulation model accurately reproduces the data from the technical documentation of the steam turbine installation. Using the simulation model, a multivariate analysis was conducted under variable operating conditions of the installation. Data were obtained for the specific fuel consumption, the efficiency of the steam turbine installation, and the electrical power output as functions of the steam flow rate at the turbine inlet, the temperature, and the cooling water flow rate at the condenser inlet.

The data obtained from the simulation model were subsequently used to synthesize a regression-based mathematical model. This model allows the determination of the electrical power output of the steam turbine installation depending on the steam flow rate at the turbine inlet, the temperature, and the cooling water flow rate at the condenser inlet. The mathematical model can be employed for forecasting the electrical power output of the steam turbine installation under variable operating modes of the power unit. Additionally, it can serve as a tool for predicting hourly load during start-up regimes of a nuclear power plant. The proposed approach for constructing mathematical models based on simulation modeling can also be extended to other parameters characterizing the operation of the power installation.

The developed mathematical model can also be used in the preparation of performance maps during the commissioning of the steam turbine installation, as well as throughout its operation.

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