

This study explores heat and mass transfer processes in the structural elements of an umbrella-type hydrogenerator, as well as the ventilation and cooling system in the active components of the hydrogenerator. A vertical synchronous air-cooled hydrogenerator with a rated capacity of 60 MW has been investigated.

The task addressed relates to the cooling efficiency of generator components. Conventional analytical calculation methods do not make it possible to identify local overheating zones and pressure distribution in complex ventilation channels. Therefore, it becomes necessary to use numerical methods and algorithms to calculate and analyze the cooling efficiency of the generator's active parts.

The main result of this study is the designed structure of the guide channels (blades) of the rotor, which provides the required air flow rate of 45 m³/s. At the same time, the maximum values of the winding temperature do not exceed the permissible values for class F insulation.

The CFD calculation detailed the action of the superchargers and showed the real pressure in the channels and the volume of air passing through each section of the generator. The error between the results from CFD modeling and analytical calculations is less than 3%.

The results are attributed to the detailed reproduction of the geometry of the ventilation channels in the 3D model, which made it possible to determine the real aerodynamic resistance and cooling medium consumption.

The proposed method uses the boundary conditions of the third kind for a comprehensive calculation of the conjugate heat and mass transfer.

The proposed structure could be implemented in the design and modernization of air-cooled hydrogenerators

Keywords: hydrogenerator ventilation system, CFD simulation, rotor channels, fan operating characteristic

DEVISING A METHOD FOR ASSESSING EFFICIENCY OF THE COOLING SYSTEM AND DETERMINING THE THERMAL STATE OF VERTICAL SYNCHRONOUS HYDROGENERATORS USING THREE-DIMENSIONAL CFD SIMULATION

Andrii Yehorov

PhD, Associate Professor*

ORCID: <https://orcid.org/0000-0001-6643-4256>

Stanislav Kravchenko

Corresponding author

Doctor of Philosophy (PhD)**

E-mail: ksatfer@gmail.com

ORCID: <https://orcid.org/0009-0009-6409-4767>

Oleksii Duniev

PhD, Associate Professor*

ORCID: <https://orcid.org/0000-0001-8196-7077>

Oleksandr Vasyliiev

PhD Student**

ORCID: <https://orcid.org/0009-0001-9251-8768>

Denys Hromenko

PhD Student**

ORCID: <https://orcid.org/0009-0000-3073-3713>

Serhii Lukashevych

PhD, Professor

Department of Law***

ORCID: <https://orcid.org/0000-0001-8386-6237>

Oleh Buhaiiov

PhD Student****

ORCID: <https://orcid.org/0009-0002-1233-3569>

Kostiantyn Liakhov

PhD Student****

ORCID: <https://orcid.org/0009-0009-0417-4028>

Anton Kovryga

Doctor of Philosophy (PhD)

JSC "Ukrainian Energy Machines"

Heroiv Kharkova ave., 199, Kharkiv, Ukraine, 61037

ORCID: <https://orcid.org/0009-0006-5843-8349>

Dmytro Obidin

Doctor of Technical Sciences, Professor, Chief Flight Instructor

Flight Training School "Condor"

Bratv Zerovykh str., 14, Kyiv, Ukraine, 03037

ORCID: <https://orcid.org/0000-0002-9923-9024>

*Department of Electrical Machines

National Technical University "Kharkiv Polytechnic Institute"

Kyrpychova str., 2, Kharkiv, Ukraine, 61002

Department of Aero-Hydrodynamics*

***National Aerospace University "Kharkiv Aviation Institute"

Vadim Manko str., 17, Kharkiv, Ukraine, 61070

****Limited Liability Company "Kharkov Electric Machine-Building Plant"

Heroiv Kharkova ave., 199, Kharkiv, Ukraine, 61037

Received 06.11.2025

Received in revised form 18.12.2025

Accepted 19.01.2026

Published 27.02.2026

How to Cite: Yehorov, A., Kravchenko, S., Duniev, O., Vasyliiev, O., Hromenko, D., Lukashevych, S., Buhaiiov, O., Liakhov, K.,

Kovryga, A., Obidin, D. (2026). Devising a method for assessing efficiency of the cooling system and determining the thermal

state of vertical synchronous hydrogenerators using three-dimensional CFD simulation. *Eastern-European Journal of Enter-*

prise Technologies, 1 (8 (139)), 49–58. <https://doi.org/10.15587/1729-4061.2026.350505>

1. Introduction

Globally, there is a steady trend to invest in the modernization of existing hydroelectric power plants instead of building

new ones. This is due to lower costs and less environmental impact [1]. The world hydropower market continues to grow, especially in countries in Asia and Africa where hydropower is actively evolving [2].

Increasing energy independence in developed countries is always of strategic importance [3]. One of these areas is the modernization of existing power plants. It makes it possible to reduce dependence on imported fuel resources and ensure the stability of the energy system under conditions of an increasing share of renewable energy sources. For example, hydropower generators used at stations with renewable energy sources are able to effectively perform the functions of not only electricity generation but also emergency reserve functions.

The issue of modernization of powerful hydropower generators is becoming particularly relevant both in Ukraine and around the world. This is due to the global transition to renewable energy sources and the need to ensure the stability of energy systems. Hydropower remains one of the most reliable and efficient types of green energy and hydro generators play a key role in covering peak loads and maintaining the frequency in the network [4].

In the world, a significant part of the hydropower fleet consists of hydro generators that were put into operation several decades ago and, sometimes, as early as the middle of the last century [5].

For example, hydro generators are installed at hydroelectric power plants (HPPs) such as the Sredneodneprovska HPP or the Kremenchug HPP. These facilities require technical upgrades [6]. Modernization of such machines makes it possible not only to extend their operational life but also improve the efficiency, increase capacity, and enhance operational characteristics. Modern technologies make it possible to replace outdated insulation with class F materials, introduce more efficient cooling systems and modern control and management systems.

Therefore, it is a relevant task to carry out studies on improving the structure of a ventilation system in large-capacity hydrogenerators, which could simultaneously allow for reliable operation and high efficiency through reduced heat losses.

The introduction of current technologies in the hydropower industry of Ukraine opens up new opportunities for integration into the European energy system and ensuring the country's energy security. The design of such large machines is a multidisciplinary optimization task, covering electromagnetic, mechanical calculations, as well as cooling issues, which often leads to conflicting requirements. The calculation of magnetic and temperature fields of large hydrogenerators is a very complex process due to the complexity of their structure, different material properties, and the nonlinearity of the magnetization curve of electrical steel.

2. Literature review and problem statement

A combined design method for powerful salient-pole hydrogenerators is described in [7]; it integrates analytical calculations with numerical methods. The advantage of the proposed approach is the high accuracy of results with a calculation error of less than 4%, confirmed on the example of the modernization of a real 110 MVA unit, which makes it effective for multivariate optimization. However, the issues of using the boundary element model to calculate the field in the air gap, which did not directly take into account the saturation of the magnetic core, requiring additional analytical adjustments, remained unresolved. The work also did not disclose details regarding the calculation of power losses and mechanical stability of rotor nodes.

In [8], a comprehensive calculation method for large air-cooled hydrogenerators is outlined, which iteratively com-

bins analytical modeling of losses, an air flow network, and thermal networks to determine temperatures in all active parts of the machine. It is shown that the use of this approach makes it possible to obtain a complete overview of the temperature gradient in the machine, including the stator core, the stator winding protrusions and the rotor pole coil. However, the issues related to neglecting the influence of the local air temperature on its density and volumetric flow rate remained unresolved, which could lead to a decrease in the accuracy of the calculations. An option for overcoming the difficulties is to conduct thermal state modeling on a three-dimensional model of the hydrogenerator, taking into account all structural elements. This could allow for more accurate and visual identification of local overheating locations on the generator temperature map.

In work [9], capsule horizontal generators with a capacity of 50 MW were considered, in which, due to limited dimensions, the technology of evaporative cooling directly of the stator core was used to cool the winding. The advantage of the study is the comparative analysis of four schemes for the location of cooling tubes, which proved the possibility of significantly improving heat dissipation without a critical increase in magnetic losses in steel. However, the work does not fully address the technological difficulties of manufacturing a composite core with integrated tubes and the issue of maintaining the mechanical integrity of such a structure during vibration loads. An option to overcome these difficulties is to abandon the use of tubes and switch to air cooling. This approach could increase the mechanical strength of the composite core, and the use of three-dimensional modeling methods would help in verifying the thermal calculation.

In [10], a complex pattern of temperatures in the elements of a powerful hydrogenerator was constructed using a physically informed neural network to determine the permissible overload limits in the forcing and emergency operation modes. However, for training and using the neural network, a model of the object of study, in this case a powerful hydrogenerator, must be previously built, calculated, and verified. In [11], the gradient of temperature changes in the structure of the hydrogenerator stator in different pressure ranges was considered. The use of three-dimensional modeling methods made it possible to obtain patterns of the thermal state of the generator and analyze its sensitivity to voltage drops in the network, changes in water temperature and cooling air pressure. However, issues related to the establishment of fixed temperature limits of 120°C and 155°C remained unresolved, which does not take into account the cumulative degradation of insulation according to the Arrhenius law. An option for overcoming the difficulties is to analyze local overheating, which makes it possible to identify critical zones where a point breakdown of insulation can occur.

In work [12], the results of studies on the operation of a generator with a capacity of 125 MW under the mode of sudden short circuit are reported. Operation in such a transient process causes significant thermal and mechanical loads. Three-dimensional transient heat conduction equations are used to analyze thermal processes. It is shown that in the generator model, the solution area of the stator temperature field is defined as the range of the cross-section of half the tooth, half the groove and half the axial core. This approach makes it possible to significantly simplify the model, reduce the modeling time, while maintaining the required accuracy of the calculation result. The authors of the work considered the application of the finite element method for the analysis

of the transient stator temperature field during a sudden short circuit of the SF125-96/15600 generator in [13]. That paper reports the results of the calculation of the short-circuit current with a description of the derived heat conduction equations. It is shown that the reliability of the parameters of heat conduction, convection and losses is confirmed by comparing the calculations with full-scale measurements in the stationary mode. Such a verified model was used to analyze the transient process of a short circuit. However, the questions of how the rotation of the rotor and its heating affect the thermal state of the stator remained unresolved. The reason for this may be the difficulties associated with the significant complication of the three-dimensional model and the addition of calculation regions with small element sizes to it. An option for overcoming related difficulties may be some simplification of the calculation model or the combination of small structural parts into a composite unit, while preserving its properties and purpose.

In [14], the results of the study on the thermal state of an electric machine with a transverse magnetic flux are reported. In the course of the work, the influence of the design features of the machine on the heating of the stator coil and permanent magnets, which are the most temperature-sensitive elements in the system, was investigated. It was shown that the experiments conducted correlate with the results of 3D modeling. An important conclusion in [14] is that the stator coil in a machine with a transverse magnetic flux is heated unevenly, with temperature fluctuations in areas where there is no air circulation. The method proposed in the work reduces the temperature of the stator coil and permanent magnets by 10%, which is important for the temperature stability of the magnet. However, issues related to the replacement of permanent magnets with electromagnets remain unresolved. The reason for this may be the desire to simplify the design of the machine by preventing the addition of a contact node. However, electromagnetic excitation allows one to improve the characteristics of the engine, its temperature stability of operation, and minimizes the use of expensive rare-earth materials. All this gives grounds to argue that it is advisable to conduct research on improving highly efficient cooling systems using controlled electromagnetic excitation instead of machines with an unregulated magnetic field.

In work [15], the problem of operation of turbogenerators in maneuvering modes is considered: covering peaks and dips of the load. The use of the SolidWorks (USA) software package is shown for modeling the distribution of mechanical stresses in the tie prisms. However, the study focuses mainly on one critical unit of the machine – the fastening of the core and tie prisms. It is shown that constant load fluctuations provoke critical fatigue of the stator core fastenings in the turbogenerator, which leads to accelerated thermocyclic degradation of the casing insulation materials. An option for overcoming the relevant difficulties may be the use of hydrogenerators as they are much more adaptable to maneuvering modes.

A significant limitation of the reviewed literature [7–15] is the lack of sufficient experimental data. This is explained by the fact that the production of powerful hydrogenerators is carried out according to individual projects or is small-scale. This factor leads to a limited number of reports with the results of field tests for hydrogenerators with different design solutions. In this context, the priority tools are software systems that use numerical modeling methods, the validity and high accuracy of which are generally recognized today. In particular, the computational fluid dynamics (CFD) method described in [16, 17] has become widely used. The disadvan-

tage of the method is its high sensitivity to the accuracy of setting the boundary conditions, which directly determines the adequacy of the results obtained.

All this gives grounds to argue that it is advisable to conduct a study aimed at assessing the efficiency of the cooling system and specifying the thermal state of medium and high-power hydrogenerators. Such machines have significant potential for transition to more efficient air cooling systems by modernizing the structure of the discharge elements, in particular, profiled blades on the rotor rim.

3. The aim and objectives of the study

The purpose of our study is to devise a method for assessing the efficiency of the cooling system and determining the thermal state of the active parts and structural elements of vertical synchronous hydrogenerators of the umbrella type after reconstruction using three-dimensional CFD modeling. This will make it possible to determine with increased accuracy the parameters of the head and flow rate of the cooling medium, which are necessary to maintain the temperature of the active components of the hydrogenerator at an acceptable level for class F insulation. In addition, this will make it possible to scientifically substantiate the feasibility of introducing special guide channels in the form of profiled blades into the hydrogenerator cooling system.

To achieve the goal, the following tasks are set:

- to build a detailed three-dimensional model of the hydrogenerator ventilation system in the SolidWorks environment, which takes into account the geometry of the stator, rotor, frontal parts of the windings, as well as air coolers channels;
- to determine by using CFD analysis the distribution of velocity fields and pressure drops of cooling air in the ventilation channels, as well as define the required flow rate of the cooling medium;
- to substantiate the geometry and efficiency of the proposed guide channels (blades) on the rotor rim to ensure the required air flow at nominal load.

4. Materials and methods

4.1. The object and hypothesis of the study

The object of our study is the processes of heat and mass transfer in the structural elements of the hydrogenerator, as well as the ventilation and cooling system in the active components of the hydrogenerator.

The principal hypothesis assumes the uniformity of the distribution of additional heat losses over the external structural surfaces. In this case, it is assumed that heat generation occurs in the conductive components, and additional air friction losses are set separately over the surfaces they flow around. The work accepts that heat exchange does not occur between the foundation structures, and all losses are removed from the gas cooler heat exchanger.

After the reconstruction of a high-power vertical synchronous hydrogenerator, a stable thermal regime of its active parts must be ensured under all operating modes, which are provided for by the relevant regulatory documents and operating instructions. The use of new insulating materials, changing the geometry of individual components, modernization of the excitation system and installation of modern control devices lead to changes in heat flows and distribution of ven-

tilation air. Conventional analytical methods for calculating ventilation systems provide only averaged characteristics and do not make it possible to determine local pressure drops and the velocity field of the refrigerant. First of all, this is due to the complex geometric shape of the ventilation channels of the stator and rotor cores, as well as the cooling paths of auxiliary elements. This complicates the assessment of possible overheating zones, the influence of the geometric features of the channels and the efficiency of the ventilation elements. Therefore, there is a need to apply detailed 3D CFD simulation, which makes it possible to reproduce the operation of the entire cooling system under real conditions, compare it with analytical models, and determine the optimal parameters for safe and reliable operation of the hydrogenerator.

4. 2. Basic technical parameters of the hydrogenerator

The study considered the synchronous vertical hydrogenerator SVKr 1347/150-96 manufactured by PAT "Ukrainian Energy Machines", designed to operate as part of a hydroelectric unit at the Kremenchuk HPP. As a key element of the power system, it is designed to generate peak power, as well as perform the functions of a high-speed emergency and frequency reserve. The unit operates under the nominal mode S1 in accordance with the international standard IEC 60034-1-2004.

Its rated power is 75 MW · A (active power – 60 MW) at a rated voltage of 13800 V and a frequency of 50 Hz. The rated power factor of the machine is 0.8 (inductive).

The generator has a vertical design, protected type, with a thrust bearing on the turbine cover. The design includes one guide bearing in the oil bath of the upper crosspiece. The rotor is connected directly to the shaft of the rotary-blade vertical hydroturbine. The rated speed is 62.5 rpm, but the generator is designed for coasting speeds up to 175 rpm.

The overall and design parameters of the generator are as follows: the stator bore diameter reaches 12970 mm, and the length of the active stator steel is 1500 mm. The stator housing is welded from six sectors, which are attached to 12 foundation plates through special transition plates with radial pins, which makes it possible to compensate for thermal expansion.

The stator core is a magnetic core assembled from stamped segments of cold-rolled electrical steel sheet 0.5 mm thick, coated with insulating varnish. The stacking is performed "in a ring" directly at the assembly site. The core is divided into packages in height with ventilation channels between them for effective cooling. The stator boring surface and grooves have a semiconducting coating to prevent surface discharges.

Electrical parameters include a rated stator current of 3138 A and a rated excitation current of 995 A. The machine is characterized by a short-circuit ratio of 0.95 v.o. and a statistical overload of 2.4 v.o., which indicates its high electromagnetic stability. The rotor flywheel moment is 49700 t · m², which provides sufficient mechanical inertia.

The excitation system is made according to a static thyristor self-excitation scheme without the use of series transformers. The contact rings and brush traverse are located inside the stand installed on the upper crosspiece, which provides their protection from external influences.

The ventilation system is implemented in a closed loop with air cooling in 18 water coolers located on the outer casing of the stator housing. The necessary head for air circulation is generated by ventilation struts on the rotor rim. The cooling water flow rate through the air coolers is 500 m³/h, through the thrust bearing oil coolers – 60 m³/h, and through the bearing oil coolers – 20 m³/h. The maximum operating

temperature of the cooling water is 28°C, and the maximum temperature of the cooling air is 40°C.

Three-dimensional modeling using the CFD simulation was chosen as the research method. As a simplification, a separate calculation of the superchargers was performed: the pressure characteristics of the fan and the characteristics of the pressure loss in the hydrogenerator ventilation system were specified, which were obtained from analytical calculations.

To ensure the operation of the ventilation system, guide channels (blades) were designed on the rotor rim, making it possible to provide the required air flow at the rated power of the hydrogenerator.

The operability of the designed structure was confirmed using CFD analysis and comparison of its results with the analytical calculation from the hydrogenerator manufacturer.

4. 3. Study of the design efficiency

A study of the thermal state of the hydrogenerator SVKr 1347/150-96 of the Kremenchuk hydroelectric power station, which belongs to the umbrella type and has a capacity of 60 MW, was conducted.

To perform this study, it is necessary to preliminarily determine the permissible ratios of the pressure capabilities of the injection elements and the aerodynamic resistance of the ventilation tract of the hydrogenerator. Additionally, it is necessary to calculate the gas consumption through the active and structural elements of the generator to determine their thermal state. In addition, power losses for ventilation and friction of rotating parts against the air will be obtained with the possibility of choosing boundary conditions in thermoelasticity problems.

The ventilation system of the entire structure of the hydrogenerator with a capacity of 60 MW of the umbrella type occupies a large volume (over 50 m³) with the presence of small (up to 5 mm) and large-sized (up to 5 m) parts in it. The combination of the specified factors leads to the need to simplify the solution of the problem.

The required power of the ventilation system's pressure element is determined using the following formula

$$P = \frac{H \cdot Q}{1000 \cdot \eta}, \quad (1)$$

where η is the efficiency of the fan; H is the head; Q is the volumetric flow rate.

The criterion for the convergence of the calculation is the minimum ventilation losses while ensuring the cooling medium flow rate required for cooling the machine and the degree of uniformity of the temperature fields of the "active parts" of the generator.

Based on the analytical calculation of the ventilation system, in order to maintain the operating temperatures of the active parts at an acceptable level (according to DSTU EN 60034-1 for the insulation heat resistance class F), it is necessary to ensure a gas flow rate (pumping) of 45 m³/s. For this purpose, it is necessary to design and calculate the power of the centrifugal blower located on the rotor, which provides an air flow rate of 45 m³/s, and analyze the resulting pressure in the ventilation ducts for "pushing" the system and the acting pressure on the structural elements.

The main features of the operation of this hydrogenerator include the fact that the cyclic elements of the rotor are simultaneously a supercharger, for which temperatures must also be determined. A significant advantage is the possibility

of applying symmetry conditions for 1/4 of the design. In this case, the arrangement of all elements, including air coolers, is cyclic.

In the problem under consideration, the hydrogenerator cooling system is a forced, air-water one, with a closed air circulation cycle through the "active" and structural parts of the machine. The forced air is supplied by a rotor, in the rim of which radial ventilation channels are made.

The air enters the rotor star windows and the upper fan from above from the upper air duct, from the lower air duct air is supplied to the star windows and the lower fan. From the rotor star, under the action of the excess pressure created by the rotor, the air passes through the channels in the rotor rim, in the interpole space, in the air gap, through the ventilation channels in the stator core and is collected in the chambers of the stator housing. After the fans, the air is directed through the chambers of the frontal joints and the channels of the pressure combs, through the gap between the "active" stator steel and the housing, as well as through the holes in the internal shelves of the housing. Air enters the chambers of the stator housing, where it is combined with the air that has passed through the "active" stator steel and is directed to 12 air coolers. In the air coolers located along the perimeter of the hydrogenerator housing, heat is extracted from electromagnetic and mechanical energy losses. After the air coolers, air is supplied through the upper and lower air ducts to the inlet to the rotor star and fans. In order to avoid significant air flows through the gaps between the stationary and rotating parts of the hydrogenerator, it is allowed to install air separation shields.

The cooling medium of the hydrogenerator is air at normal atmospheric pressure and a temperature of $T_{air} = 40^\circ\text{C}$.

In order to ensure the effective functioning of the ventilation system and achieve the required volumes of cooling air circulation during the operation of the hydrogenerator at rated power, special guide channels in the form of profiled blades were designed and implemented on the rotor rim. Fig. 1 shows a sketch of the designed blade.

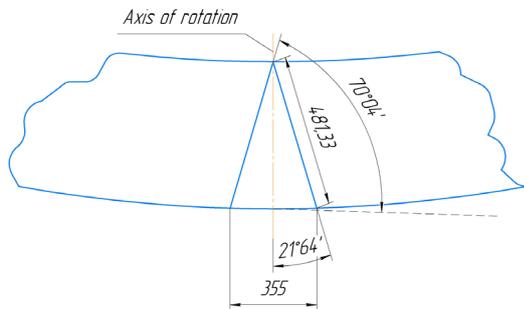


Fig. 1. Sketch of the blade profile

Analytical calculation of the superchargers was performed using the classical method applying classical equations of gas mechanics [18], which exploits the basic equations from gas mechanics.

4. 4. Investigation of velocity fields and pressure drops of cooling air using the CFD method

The Navier-Stokes equations were used as the basic mathematical model, which described a three-dimensional unsteady flow of a heat-conducting viscous gas under pressure. The effects of flow turbulence on the flow parameters at the statistical level were taken into account. For their prediction,

the Reynolds-Favre averaged equations were used. The resulting system of equations takes the following form [19]:

$$\begin{cases} \frac{\partial \rho}{\partial t} + \frac{\partial(\rho V_j)}{\partial x_j} = 0; \\ \frac{\partial(\rho V_j)}{\partial t} + \frac{\partial(\rho V_i V_j + p \delta_{ij})}{\partial x_j} = \frac{\partial(\sigma_{ij} + \tau_{ij})}{\partial x_j}; \\ \frac{\partial E}{\partial t} + \frac{\partial[(E+p)V_j]}{\partial x_j} = \frac{\partial[V_i(\sigma_{ij} + \tau_{ij}) + q_j + q_j^T]}{\partial x_j}, \end{cases} \quad (2)$$

where ρ is the density; V is the velocity; p is the pressure; E is the total energy per unit volume; σ_{ij} is the viscous stress tensor; τ_{ij} is the turbulent stress tensor; q_j is the heat flux vector component; q_j^T is the turbulent heat flux vector component.

The result of the above-described averaging in the equations is the appearance of additional terms – Reynolds stresses. In SolidWorks Flow Simulation (USA), the transport equation for turbulent kinetic energy and its dissipation rate – the k - ε model is used to close this system of equations. It should be noted that the use of the standard turbulence model k - ε KES is possible only in high-Reynolds calculations (on a relatively coarse grid with wall functions).

The calculation of flows in models with moving walls is performed by setting the appropriate boundary conditions. In order to reduce the dimensionality of the calculations, the calculation of flows in models with rotating parts is performed in the coordinate systems associated with the rotating parts of the model. In this case, the condition must be met that the fixed parts of the model must be axisymmetric with respect to the axis of rotation (axisymmetric simplified model).

The conservation equations of mass, angular momentum, and energy in a Cartesian coordinate system rotating with angular velocity Ω around an axis passing through the origin take the following form:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u_i)}{\partial x_i} = S_M^p, \quad (3)$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} + \frac{\partial p}{\partial x_i} = \frac{\partial(\tau_{ij} + \tau_{ij}^R)}{\partial x_j} + S_i + S_{ii}^p, \quad (4)$$

$$i = 1, 2, 3; \quad j = 1, 2, 3;$$

$$\begin{aligned} \frac{\partial \rho H}{\partial t} + \frac{\partial \rho u_i H}{\partial x_i} &= \frac{\partial}{\partial x_i} u_j (\tau_{ij} + \tau_{ij}^R) + q_i + \\ &+ \frac{\partial p}{\partial t} - \tau_{ij}^R \frac{\partial u_i}{\partial x_j} + \rho \varepsilon + S_i u_i + S_H^p + Q_H, \end{aligned} \quad (5)$$

$$H = h + \frac{u^2}{2} + \frac{5}{3}k - \frac{\Omega^2 r^2}{2} - \sum_m h_m^0 y_m, \quad (6)$$

where u is the fluid velocity; ρ is the fluid density; S_i is the mass-distributed external force per unit mass; h is the thermal enthalpy; S_M^p , S_{ii}^p , S_H^p are the additional interfacial exchange terms due to the interaction of Euler-Lagrange particles; Q_H is the heat source or flow per unit volume; τ_{ij} is the viscous shear stress tensor; q_i is the diffusion heat flow; Ω is the angular velocity of the rotating coordinate system; r is the distance from the point to the axis of rotation in the rotating reference frame; k is the kinetic energy of turbulence; h_m^0 is the individual thermal enthalpy of the m -th component of the mixture; y_m is the concentration of the m -th component of the mixture.

The subscripts denote the summation over the three coordinate directions.

The mass-distributed external force per unit mass is determined from the following formula

$$S_i = S_i^{porous} + S_i^{gravity} + S_i^{rotation}, \tag{7}$$

where S_i^{porous} – resistance of the porous medium; $S_i^{gravity}$ – gravitational force, defined as $S_i^{gravity} = \rho g_i$ (g_i – component of gravitational acceleration along the i -th coordinate direction); $S_i^{rotation}$ – rotation of the coordinate system.

5. Results of research on the hydrogenerator cooling system

5.1. Three-dimensional physical model and defined basic parameters for three-dimensional calculation

The results of calculating the dependence of losses on the volume of pumped air are shown in Fig. 2. It demonstrates the dependences of head characteristics of the system and the head characteristics of the fan. The intersection point of these plots corresponds to the operating point. It can be seen that when pumping 45 m³/s, the required head should be 235 Pa.

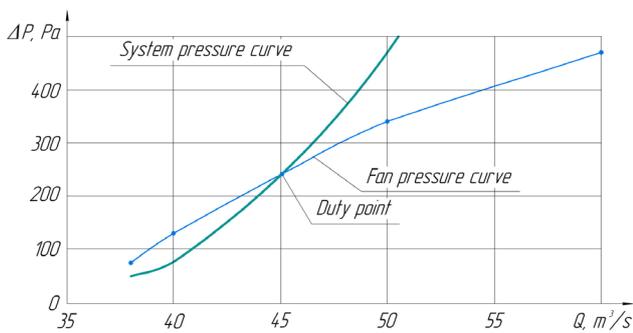


Fig. 2. Dependence of losses on the volume of pumped air

The operating characteristics of the fan depending on the flow rate of pumped air, Q (m³/s), are given in Table 1.

Table 1

Fan performance characteristics

Parameter ID	Value				
$Q, m^3/s$	38	40	45	50	60
P, Pa	75	130	235	340	470
$\eta, r. u.$	0.5	0.54	0.65	0.7	0.75
N, kW	63.2	65.6	73.6	81.6	96.8

A detailed three-dimensional model of the hydrogenerator ventilation system was constructed in the SolidWorks environment, which takes into account the geometry of the stator and rotor channels, the frontal parts of the windings, and the air coolers (Fig. 3).

The initial data for the calculation are as follows: geometric parameters of the structure; rated speed – $n = 62.5$ rpm; temperature – $T_{gas} = 40^\circ C$; initial pressure in the system – $P_{atm} = 101325$ Pa; hydraulic resistance of air coolers – 250 Pa.

Fig. 4 shows the cross-section, for which the results of the calculation of the operating pressures are given below.

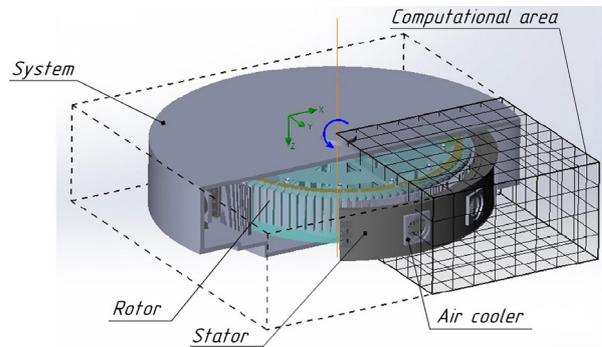


Fig. 3. Calculated three-dimensional model of a hydrogenerator

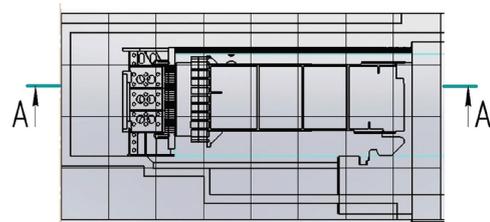


Fig. 4. Calculation cross-section along section A-A

For further comprehensive research of the hydrogenerator SVKr 1347/150-96 at the Kremenchuk HPP, a three-dimensional model of the hydrogenerator ventilation system was built using CFD methods. According to the results of analytical calculations, the parameters of this model are set according to the parameters of the head characteristic obtained during the research (Fig. 2) and the operating characteristics of the fan (Table 1). This is confirmed by the plot of the dependence of losses on the volume of pumped air (Fig. 2): the head characteristic of the fan intersects with the resistance curve of the cooling system at the operating point. The operating point has the following parameters: $P = 235$ Pa, $Q = 45$ m³/s.

5.2. Results of investigating the distribution of velocity fields and pressure drops of cooling air using the CFD method

The results of ventilation calculations in the form of distributions of pressures and speeds of cooling air along the rotor and stator channels, performed in SolidWorks Flow Simulation, are shown in Fig. 5–8.

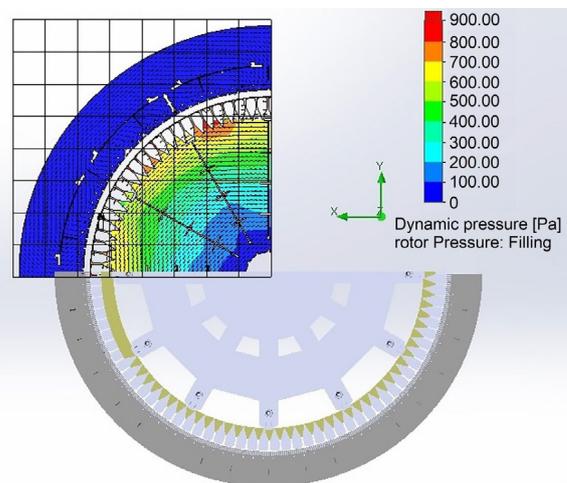


Fig. 5. Rotor dynamic pressure distribution

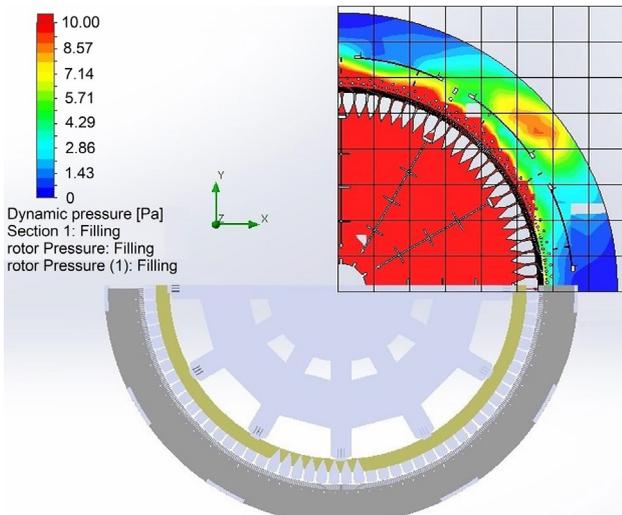


Fig. 6. Distribution of dynamic pressure through the stator channels

The results of the calculation of dynamic pressures for the rotor and stator are illustrated in Fig. 5, 6, respectively.

The gas flow rates through the rotor and stator channels are shown in Fig. 7, 8, respectively.

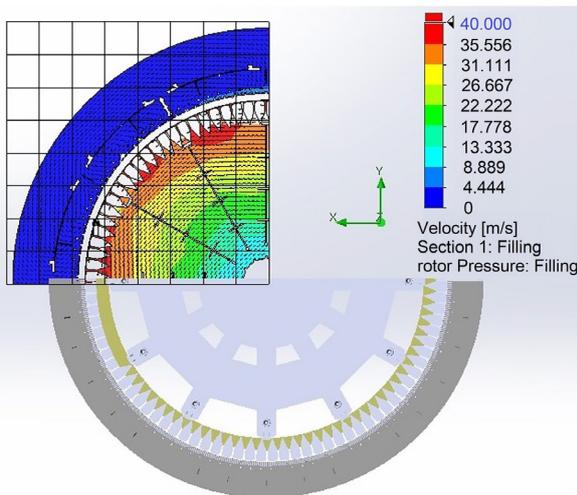


Fig. 7. Speed distribution through rotor channels

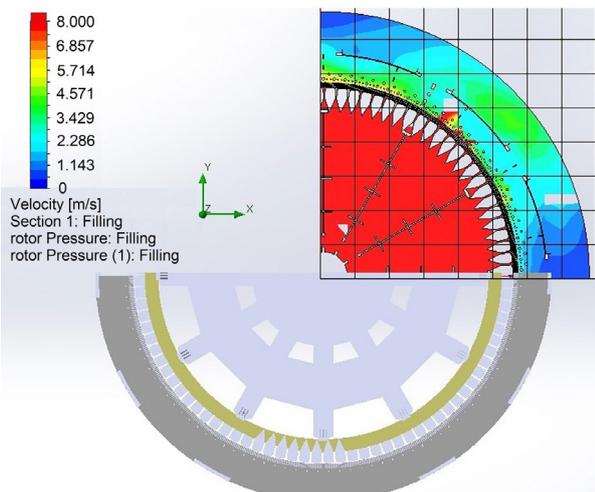


Fig. 8. Speed distribution through stator channels

During the three-dimensional calculation according to the proposed CFD method, the speed and pressure of the cooling medium were determined. In the working elements of the rotor, the speeds of the cooling air are in the range of 6–8 m/s (Fig. 7). In the stator ventilation channels, these speeds are in the range of 5–6 m/s (Fig. 8). In the locations of the frontal parts of the stator winding rods, the speeds are in the range of 6.6–7 m/s (Fig. 7, 8). At the same time, at the inlet to the gas cooler, the speeds of the cooling air are from 4.5 to 5 m/s. The calculated cooling air head is 235 Pa. The temperature of the cooling medium (without adding mechanical and electromagnetic losses to the calculation conditions) almost does not increase (the excess is no more than 1°C, which is within the measurement error zone). This is explained by the low degree of pressure increase and significant air consumption. Later, these parameters were used to determine the cooling quality of the hydrogenerator design, namely the total refrigerant flow rate, which was 45 m³/s. In turn, this allowed us to take these above-mentioned data as the starting point when determining the optimal parameters of the discharge unit for guaranteed removal of heat losses with a value of 73 kW.

5. 3. Substantiation of the geometry and efficiency of the proposed guide channels (blades)

A comparison of the results of calculations performed analytically and using SolidWorks Flow Simulation is given in Table 2. The calculations performed showed that the air flow rate when using the designed channels (blades) on the rotor rim is 45 m³/s at a static pressure of 235 Pa, and additional losses caused by air friction on the rotor elements are 75 kW. This provides the necessary air circulation inside all ventilation channels of the hydrogenerator. The necessary pressure drop of the refrigerant for its normal passage through the gas cooler is also provided.

The temperature of the "active parts" of the hydrogenerator did not exceed the limits of permissible values in accordance with the requirements of DSTU EN 60034-1 for the insulation heat resistance of class F, according to electromagnetic calculation, at an air temperature of $T_{air} = 40^{\circ}\text{C}$. Table 3 gives the results of calculating the temperatures of the hydrogenerator components.

Table 2
Comparison of analytical and three-dimensional calculation results

Calculation	P, Pa	Q, m ³ /s	N, kW
Analytical	235	45	73
3D (SolidWorks Flow Simulation)	235	45	75

Table 3
Temperature of generator components under a rated mode

Parameter ID	Temperature, T, °C
Maximum rotor pole temperature	70
Maximum rotor winding temperature	96
Maximum stator winding temperature (front part of the lower rod)	74
Maximum stator winding temperature (slotted part)	77
Maximum stator winding temperature (front part of the upper rod)	80
Average stator winding temperature	76
Maximum stator steel temperature (tooth)	80
Maximum stator steel temperature (back)	72
Maximum pressure comb temperature (top)	95
Maximum pressure comb temperature (bottom)	100

Based on the results given in Table 3, one can see that the maximum temperature is reached in the comb of the pressure flanges, which are not conductive elements and have no restrictions on the insulation class. The temperature values obtained for the conductive components of the hydrogenerator are at a lower level. There is no significant temperature difference within one node (for example, a difference in the active steel of the stator core). Accordingly, the constructed cooling system is effective and balanced in terms of temperature distribution and allows the temperature of the active components of the hydrogenerator to be within the permissible limits according to the technical requirements for this class of machines.

6. Discussion of the results of research of the ventilation system and thermal state of an umbrella-type hydrogenerator

As a result of our review of the related literature, it was determined that the key problem is the difficulty of accurately determining aerodynamic resistance and local overheating zones by analytical methods. However, in this work, an algorithm combining theoretical calculations with detailed three-dimensional CFD simulation has been developed and successfully tested.

The calculation method proposed in the study combines an analytical component for the injection components, based on classical equations of hydro-gas dynamics, and a general calculation method for the cooling system. A feature of the general calculation method is the problem of the compressor and gas cooler in the form of areas with increased and decreased pressure. The boundary conditions are set along the contour of the entire machine in the form of the first and third kind.

The constructed three-dimensional model (Fig. 3) fully corresponds to the design documentation for the SVKr 1347/150-96 hydrogenerator for the Kremenchuk HPP. Owing to close cooperation with the manufacturer, it was possible to avoid unnecessary simplifications that reduce the accuracy of the calculations. Unlike the approach considered in [7], in which significant abstractions were used due to the complexity of the design, the result of our study was obtained on a model with detailed geometry. This allows us to take into account the influence of each part of the hydrogenerator on aerodynamics, which was previously practically impossible within the framework of classical models.

The work used numerical methods for three-dimensional modeling and analysis of the cooling efficiency of the active parts of the hydrogenerator. Unlike the method given in [8], in which the determination of power losses and temperatures is carried out using an iterative process, the approach we proposed allowed us to immediately obtain a solution to the problem. This became possible due to the correct combination of classical gas mechanics equations with the modern CFD analysis method in the SolidWorks Flow Simulation environment. The calculation of the distribution of dynamic pressures (Fig. 5, 6) and gas velocities (Fig. 7, 8) confirmed the correctness of the selected configuration of the flow part. This combination of methods allowed us to achieve high accuracy of calculations. The difference between the data (Table 2) obtained by analytical method and numerical modeling was 2.67%.

Modeling of hydraulic processes in the cooling system is the main aspect of this study. Unlike works [10, 11], in which physically informed neural networks are used, our 3D mod-

eling makes it possible to detect zones of local overheating. The use of neural networks gives only an averaged predicted picture of the thermal state. The method used in this study makes it possible to detect places of critical overheating, in which insulation breakdown is possible. In addition, unlike studies [12, 13], in which the analysis was limited only to the stator, this work implements a comprehensive approach. The result of our study makes it possible to assess the thermal state not only of the stator but also of the rotor with its poles and the damper system. The study revealed that local overheating zones occur in places with maximum heat release, such as the inner parts of the rods and local places of the stator core, which are surrounded by air with a speed approaching zero. This allows for a more accurate assessment of the insulation heat resistance margin for the entire unit, and not only in its individual units.

In addition, the results of this study complement the strategic directions of energy modernization. Unlike work [14], which considers only excitation from permanent magnets, the result of our study is based on the use of electromagnetic excitation for the rotating part of the hydrogenerator. The results of studies in [15] are related to the mechanical strength of hydrogenerator elements in maneuvering operating modes, while our study offers a specific modernization of ventilation units, adapted to the needs of hydrogenerators.

The results reported in the study allow us to determine the heat flows in complex ventilation ducts. This becomes possible due to the use of third-kind boundary conditions for nodes on the model boundaries when calculating using the finite element method. This study allows us to scientifically substantiate the permissible ratios of the pressure capabilities of the discharge elements and the aerodynamic resistance of the ventilation tract of the umbrella-type hydrogenerator. Thus, it has been proven that the modernized ventilation system enables the normal operation of the hydrogenerator in long-term operation. The determined aerodynamic discharge parameters and the verified CFD analysis method can be successfully used to calculate the thermal state and reduce ventilation losses in the hydrogenerator.

The practical value of the above research results relates to the possibility of their direct implementation when designing new series of medium and high-power hydrogenerators and when modernizing existing rotors.

However, it is worth considering certain limitations of this study. The proposed results and modeling conditions primarily relate to umbrella-type hydrogenerators with air cooling. When trying to apply these data to machines with hydrogen or direct water cooling, significant adjustments will be required both in the three-dimensional model and in the heat transfer coefficients. The results of our study were obtained for the stationary operating mode S1. When analyzing non-stationary or starting modes, as well as during sudden changes in load, the obtained data could be used as a base point for dynamic calculations. It is important to understand these application limits for further implementation of the methodology in the design of new series of similar hydrogenerators.

As a priority area for further research, an in-depth three-dimensional analysis of the cooling system's injection complex has been identified. This would allow for a detailed picture of the pressure distribution in the most complex zones of the ventilation tract. This approach could make it possible to optimize the geometry of the injection elements to minimize aerodynamic losses and ensure the necessary air flow under all generator operating modes.

7. Conclusions

1. A complete three-dimensional model of the hydro-generator ventilation system has been built, including the geometry of the stator and rotor ventilation channels, frontal areas, coolers, and air ducts. CFD analysis in SolidWorks Flow Simulation has made it possible to obtain detailed velocity and pressure fields that cannot be determined by analytical methods. That has made it possible to accurately identify the nature of the air movement and potential overheating zones, as well as determine the required cooling medium flow rate.

2. It was established that the designed guide channels (blades) on the rotor rim provide the required air flow of 45 m³/s at a static pressure of about 235 Pa. This confirms the sufficient pumping capacity of the ventilation system to maintain the standard temperatures of the active parts at rated power. CFD calculation detailed the action of the superchargers and showed the real pressure in the channels and the volume of air passing through each section of the machine.

3. Temperature analysis has confirmed that all hydrogenerator components operate within the permissible limits for class F insulation. The maximum temperatures of the windings, stator steel, rotor poles, and pressure combs do not exceed the limit values, even at an inlet air temperature of 40°C. This means that the modernized ventilation system is able to provide long-term S1 operating mode without the risk of local overheating and insulation degradation. Comparison of CFD results with analytical calculations demonstrated a high level of convergence – the error did not exceed 3%. This confirms the correctness of the proposed modeling methodology and the possibility of its application for verification and refinement of analytical models.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted without financial support.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors used artificial intelligence technologies of the Gemini model within permissible limits for structuring, concise presentation of the material, and improving the language in the sections of analysis of literary data and discussion of the research results.

Artificial intelligence was not used to generate the text, but only structured the material previously written by the authors from the above sections. All research was conducted exclusively by the authors of the paper and has been verified.

Authors' contributions

Andrii Yehorov: Conceptualization, Methodology, Data Curation, Project administration, Writing – original draft, Formal analysis; **Stanislav Kravchenko:** Conceptualization, Methodology, Validation Data Curation, Investigation, Writing – original draft, Writing – review & editing; **Oleksii Duniev:** Methodology, Data Curation, Writing – original draft, Writing – review & editing, Formal analysis, Software; **Oleksandr Vasyliiev:** Methodology, Investigation, Visualization, Writing – original draft; **Denys Hromenko:** Investigation, Formal analysis; **Serhii Lukashevych:** Supervision, Project administration; **Oleh Buhaiov:** Investigation, Visualization; **Kostiantyn Liakhov:** Investigation, Visualization; **Anton Kovryga:** Investigation, Resources, Validation; **Dmytro Obidin:** Validation, Data Curation.

References

- Hydropower Special Market Report (2021). International Energy Agency. Available at: <https://www.iea.org/reports/hydropower-special-market-report>
- Siciliano, G., Urban, F. (Eds.) (2017). Chinese Hydropower Development in Africa and Asia. Routledge. <https://doi.org/10.4324/9781315440040>
- Rutschmann, P., Kampa, E., Wolter, C., Albayrak, I., David, L., Stoltz, U., Schletterer, M. (Eds.) (2022). Novel Developments for Sustainable Hydropower. Springer International Publishing. <https://doi.org/10.1007/978-3-030-99138-8>
- Renewable Power Generation Costs in 2022 (2023). IRENA. Available at: <https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022>
- 2023 World Hydropower Outlook (2023). International Hydropower Association. Available at: <https://www.hydropower.org/publications/2023-world-hydropower-outlook>
- Quaranta, E., Aggidis, G., Boes, R. M., Comoglio, C., De Michele, C., Ritesh Patro, E. et al. (2021). Assessing the energy potential of modernizing the European hydropower fleet. *Energy Conversion and Management*, 246, 114655. <https://doi.org/10.1016/j.enconman.2021.114655>
- Traxler-Samek, G., Binder, A., Bartosch, M. (2020). Combination of Numerical and Analytical Methods for Hydrogenerator Calculation. 2020 International Conference on Electrical Machines (ICEM), 2589–2595. <https://doi.org/10.1109/icem49940.2020.9270973>
- Traxler-Samek, G., Zickermann, R., Schwery, A. (2010). Cooling Airflow, Losses, and Temperatures in Large Air-Cooled Synchronous Machines. *IEEE Transactions on Industrial Electronics*, 57 (1), 172–180. <https://doi.org/10.1109/tie.2009.2031191>
- Yu, W., Fangmian, D., Jiankangy, W., Ziran, C., Lin, R. (2022). Effect of evaporative cooling of stator core on electromagnetic field of large horizontal generator. 2022 25th International Conference on Electrical Machines and Systems (ICEMS), 1–4. <https://doi.org/10.1109/icems56177.2022.9982834>

10. Tome-Robles, D. J., Nøland, J. K., Maurer, F., Øyvang, T. (2023). Thermal Mapping of the Hydrogenerator's Reactive Power Boosting Ability at Various Time Windows. 2023 IEEE Power & Energy Society General Meeting (PESGM), 1–5. <https://doi.org/10.1109/pesgm52003.2023.10252548>
11. Shan, R., Duan, J., Zeng, Y., Qian, J., Dong, G., Zhu, M., Zhao, J. (2024). Study on the Thermal Field of a Hydro-Generator under the Effect of a Plateau Climate. *Energies*, 17 (4), 932. <https://doi.org/10.3390/en17040932>
12. Fan, Y., Wen, X., Xu S., Deng, W. (2006). 3D Analysis and Calculation of Stator Temperature Field of Hydro-generator in the Case of Sudden Short Circuit. Conference Record of the 2006 IEEE International Symposium on Electrical Insulation, 155–158. <https://doi.org/10.1109/elinsl.2006.1665280>
13. Fan, Y., Wen, X., Jafri, S. A. K. S. (2012). 3D transient temperature field analysis of the stator of a hydro-generator under the sudden short-circuit condition. *IET Electric Power Applications*, 6 (3), 143–148. <https://doi.org/10.1049/iet-epa.2011.0039>
14. Yehorov, A., Duniev, O., Masliennikov, A., Gouws, R., Dobzhanskyi, O., Stamann, M. (2025). Study on the Thermal State of a Transverse-Flux Motor. *IEEE Access*, 13, 20893–20902. <https://doi.org/10.1109/access.2025.3534284>
15. Shevchenko, V. V., Shylkova, L. V., Strokous, A. V. (2022). Determination of the Permissible Range of Turbogenerators Non-Nominal Operating Modes at Thermal Power Plants. 2022 IEEE 4th International Conference on Modern Electrical and Energy System (MEES), 01–05. <https://doi.org/10.1109/mees58014.2022.10005663>
16. SanAndres, U., Almandoz, G., Poza, J., Ugalde, G. (2014). Design of Cooling Systems Using Computational Fluid Dynamics and Analytical Thermal Models. *IEEE Transactions on Industrial Electronics*, 61 (8), 4383–4391. <https://doi.org/10.1109/tie.2013.2286081>
17. Dang, D.-D., Pham, X.-T., Labbe, P., Torriano, F., Morissette, J.-F., Hudon, C. (2018). CFD analysis of turbulent convective heat transfer in a hydro-generator rotor-stator system. *Applied Thermal Engineering*, 130, 17–28. <https://doi.org/10.1016/j.applthermaleng.2017.11.034>
18. Vasylenko, S. M., Kulinchenko, V. R., Shevchenko, O. Yu., Piddubnyi, V. A. (2024). *Hidrohadodynamika*. Kyiv: Vydavnychiy dim "Kon-dor", 676. Available at: <https://condor-books.com.ua/monografiyi/gidrogazodinamika-monografiya>
19. Howard, G. J. (2017). Finite Element Modelling of Creep for an Industrial Application. University of Pretoria. Available at: <http://hdl.handle.net/2263/60133>