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CALCULATION OF ELECTRIC POWER AND TEMPERATURE DISTRIBUTION IN AN ELECTRIC HEAT ACCUMULATING CONVERTER

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This study presents the development and implementation of a three-dimensional mathematical model for calculating the distribution of active electric power and temperature within an Electric Heat-Storage Converter (EHSC). The model is based on the method of secondary sources, which enables precise simulation of electromagnetic processes in inhomogeneous media with complex geometry and variable material properties. The proposed approach is particularly relevant for autonomous hot-water-supply systems, where energy efficiency, reliability, and the integration of renewable energy sources are critical.

The electric heat-storage converter operates by accumulating thermal energy during off-peak hours when electricity tariffs are low, and releasing this energy during peak demand periods. This mode of operation significantly reduces energy costs, enhances energy autonomy, and reduces the load on electrical grids. The converter's design–compact, reliable, and compatible with standard three-phase grids–allows for easy integration into both new and existing systems, including solar thermal complexes, mini-boiler plants, and hybrid configurations.

A numerical method was applied using discretization of the converter volume into elementary geometric subdomains, with linear temperature distribution assumed within each. The Fredholm integral equations of the second kind, derived through the method of secondary sources, were solved numerically to simulate the electromagnetic field and calculate instantaneous power density. The results confirm the feasibility and accuracy of the proposed model for engineering applications.

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Ultimately, the findings support the effectiveness of electric heat-storage converters as energy-efficient components in decentralized heating infrastructures, and demonstrate the practical value of advanced computational methods–especially the method of secondary sources–for analyzing and optimizing such systems.

Keywords: electric heat-storage converter, energy efficiency, secondary sources method, hot-water supply systems, electromagnetic field modeling, thermal storage, numerical simulation

Formulation of the problem. Autonomous heating systems are rapidly gaining popularity in regions with limited access to centralized networks or where centralized heat supply is economically impractical. Typical solutions include mini-boiler plants, solar-thermal arrays, heat pumps, and other hybrid complexes that rely on renewable energy sources. Yet all of these installations share two persistent challenges: the pronounced daily unevenness of thermal loads and their dependence on external fluctuations such as insolation and ambient temperature [6].

Against this backdrop, the electric heat-storage converter (EHC) emerges as a pivotal component for intelligent thermal-flow regulation in autonomous hot-water-supply systems. More than a simple heat accumulator, the EHC provides operational flexibility and stability by storing thermal energy during periods of low electricity tariffs–typically at night–and releasing it during peak demand [6].

Analysis of recent research and publications. Recent advancements show that in mini-boiler plants, EHCs serve as buffer stores, shifting most electrical consumption to off-peak hours and markedly reducing energy costs for residential buildings, hotels, schools, and other facilities with stable daily demand curves. The same principle eases the burden on regional power grids during daytime peaks, thereby improving overall network reliability [6].

In solar-thermal systems, EHCs compensate for the diurnal variability of renewable heat production, guaranteeing uninterrupted hot-water supply at night or during overcast weather. In hybrid schemes, electric boosting is engaged only when solar output is insufficient, raising the system’s overall efficiency and environmental performance. Researchers note that the converter's versatility allows integration into both new and existing systems, thanks to its compact design, lack of complex moving parts, and compatibility with standard three-phase grids.

Moreover, studies highlight that by shifting consumption away from peak periods or utilizing surplus on-site generation (e.g., photovoltaics), EHCs reduce operational expenses and increase the share of renewables in the final energy balance [2,3]. This synergy leads to more sustainable operation without fossil-fuel dependency, marking EHCs as an important step toward intelligent, decentralized, and environmentally conscious energy infrastructure [1,4,5].

Formulating the purposes of the article. The aim of the present study is to develop and implement a mathematical model–based on the method of secondary sources–for accurately calculating the distribution of active electric power and temperature within an electric heat-storage converter, taking into account its geometric and thermophysical design parameters, and to subsequently evaluate the model's impact on the energy efficiency of hot-water supply systems operating on off-peak electricity.

Main part.

Mathematical Modeling and Structural Features of the Electric Heat-Storage Converter. To achieve this objective, it is essential to consider the physical configuration and operating principles of the electric heat-storage converter being analyzed. Structurally, the device consists of a sealed cylindrical tank filled with a heat-accumulating medium characterized by high specific heat capacity and low thermal conductivity. Inside the tank, three electrodes are symmetrically positioned along the central axis, corresponding to the three phases of the power supply (Fig. 1). The converter operates in a balanced sinusoidal mode, which ensures uniform heat distribution and minimizes localized thermal stresses within the storage medium.

It is proposed that the electric heat-storage converter will operate using electricity purchased at off-peak tariff rates, which enables a significant reduction in the cost of thermal energy production.

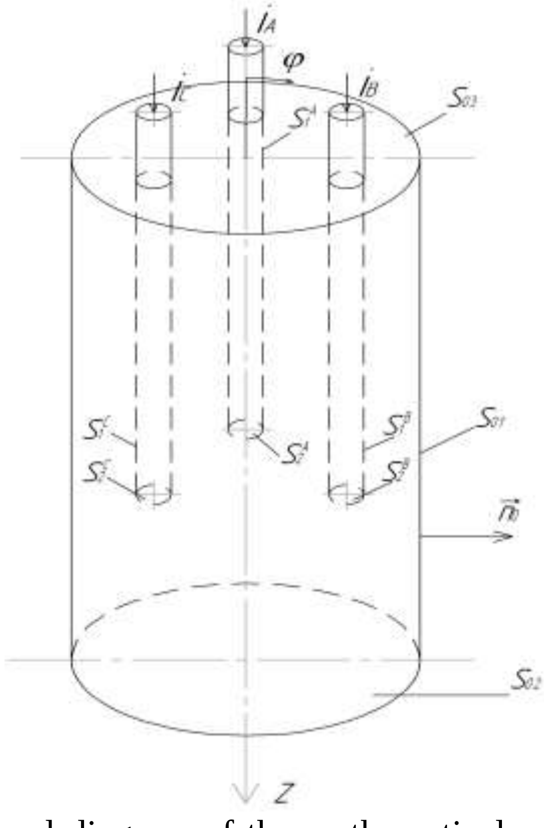

Fig. 1. Computational diagram of the mathematical model of the electric heat-storage converter: *S – surface area; 1 – lateral surface; 2 – bottom surface; 3 – top surface; A, B, C – phases; 0 – tank body.*

The key advantage of the proposed electric heat-storage converter (EHSC) lies in its ability to function without the need for a conventional water-based accumulator tank. Instead, thermal energy is stored directly in an intermediate heat-storage medium with high specific heat capacity. This medium is heated using electricity drawn from the grid during off-peak hours, when energy is available at significantly lower tariff rates. As a result, the overall cost of thermal energy production can be substantially reduced, while simultaneously alleviating the load on the electrical grid during peak demand periods. Moreover, in situations where the accumulated thermal energy proves insufficient–such as during seasonal consumption peaks or unexpected surges in demand–the converter can quickly switch to active heating mode, providing additional heat as a reliable backup source for the hot-water system.

To achieve the highest possible level of energy efficiency, it is essential to address a complex optimization problem that involves selecting the converter's design parameters and the most suitable type of heat-storage medium. The goal is to ensure the most favorable volumetric distribution of power within the device, as well as to optimize the dynamics of thermal accumulation and subsequent heat transfer to the water supply system. These processes are influenced by numerous interdependent factors, including the geometry of the tank, electrode placement, the thermophysical properties of the storage medium, heat loss through the insulation, and the timing and pattern of electrical power supply. Due to the multifactorial and nonlinear nature of these interactions, achieving a strictly optimal solution by analytical means is virtually impossible. Therefore, in practical engineering design, developers aim for quasi-optimal configurations using numerical simulation tools and iterative improvement algorithms. These approaches enable a gradual refinement of design parameters, ultimately yielding a cost-effective and reliable heat-storage solution.

The diversity and complexity of geometric forms and dimensions found in modern electrical and thermal equipment, combined with increasingly stringent requirements for calculation accuracy, significantly limit the applicability of traditional analytical methods. These classical approaches–based on simplifying assumptions and closed-form solutions to Maxwell's equations–are often inadequate for real-world configurations with irregular geometries and heterogeneous materials. At the same time, this limitation underscores the pressing need for the development and implementation of universal numerical algorithms capable of handling electromagnetic field calculations in complex, multidimensional environments. Such algorithms must be designed with computational efficiency in mind and must accommodate varying geometrical parameters, material properties, and boundary conditions. In this context, methods such as the Finite Element Method (FEM), Finite Volume Method (FVM), Boundary Element Method (BEM), and hybrid techniques like the Method of Secondary Sources offer the necessary versatility and computational robustness.

The availability of such advanced computational tools opens entirely new possibilities in engineering design. By systematically varying the geometry of electrodes, insulation thickness, and the thermophysical characteristics of the heat-accumulating medium, designers can perform extensive virtual prototyping. This replaces time-consuming and expensive physical experiments with fast, accurate simulations across dozens–or even hundreds–of design variants. As a result, research and development timelines can be significantly reduced, material costs minimized, and the likelihood of engineering errors greatly diminished.

Moreover, these numerical techniques lay the foundation for the automation and optimization of the design process. By integrating data-driven approaches–such as machine learning algorithms or evolutionary computation–engineers can perform automated parametric optimization under constraints related to mass, volume, cost, or thermal performance. This enables the generation of quasi-optimal configurations tailored to specific technical and economic requirements.

The advancement of universal numerical methods for modeling electromagnetic and coupled thermal processes is not only a scientific challenge but also a strategic necessity for the creation of the next generation of electric heat-storage converters. These tools ensure that such devices meet the high standards of energy efficiency, operational reliability, and design flexibility demanded by modern engineering practice.

For this purpose, an algorithm is proposed for constructing a three-dimensional mathematical model aimed at calculating the distribution of active power within the tank of the electric heat-storage converter. The model is formulated as a system of integral equations based on the method of secondary sources. The decisive advantage of this method over conventional techniques lies in its ability to construct universal and efficient numerical field calculation algorithms that are well-suited for implementation on digital computers and capable of handling inhomogeneous media and complex boundary geometries.

The method of secondary sources involves calculating magnetic and electric fields by introducing additional secondary sources into the system of integral equations being solved. It is well established that the influence of an inhomogeneous medium can be equivalently replaced by such sources embedded in a homogeneous medium–this is a fundamental property of electromagnetic fields [1]. This principle allows the transformation of Maxwell’s equations, which describe the field in an inhomogeneous medium, into a system that describes the field in a homogeneous medium by introducing secondary sources at every location where material properties change.

It is evident that the distribution of secondary sources cannot be arbitrary; rather, it must satisfy a well-defined system of integral equations that captures the coupling between material inhomogeneities and the resulting electromagnetic fields. These equations are formulated from the boundary conditions at interfaces where material properties change and from the fundamental laws governing electromagnetic behavior in heterogeneous media. Only by enforcing these conditions can one rigorously account for variations in conductivity, permittivity, and other parameters–an aspect that becomes crucial when modeling real-world devices composed of multiple materials and complex geometries.

Solving this integral system yields the spatial (volumetric or surface) distribution of secondary sources–that is, equivalent charges or currents that emulate the influence of the inhomogeneous regions. Once this distribution is known, the original problem simplifies dramatically: the field in the physical, non-uniform medium can now be treated as the field in a uniform medium augmented by these secondary sources. This transformation lets engineers employ the well-established, computationally efficient techniques developed for homogeneous domains, greatly improving numerical stability and reducing computational cost. In essence, the intricate behavior of the electromagnetic field in a real, layered structure is mirrored by a mathematically convenient model in which the complexities of material transitions are encapsulated entirely within the secondary sources located at the interfaces.

Accordingly, the calculation of electromagnetic fields in an inhomogeneous medium proceeds through a two-stage workflow. First, one sets up and numerically solves a system of Fredholm integral equations of the second kind, which incorporates medium parameters, interface geometries, and mutual interactions among all potential secondary sources. Solving this system (typically via iterative numerical methods) yields the precise distribution of secondary charges or currents on the relevant surfaces or within selected volumes. Second, with both primary and newly determined secondary sources now defined, one computes the equivalent field in an otherwise uniform medium. Standard numerical approaches–such as the superposition method, the finite-element or finite-volume method, or direct analytical integration–can then be applied without the need to model each material discontinuity explicitly, thereby accelerating simulations and lessening computational load.

By converting a physically and mathematically intricate inhomogeneous-field problem into a formally simpler homogeneous-field problem supplemented with virtual sources, the secondary-sources method offers a powerful and versatile framework. It is especially valuable in the design of modern electrotechnical devices, where both high accuracy and rapid computation are essential [2-4].

The calculation of electromagnetic processes using the method of secondary sources constitutes an efficient numerical approach that reduces the problem to solving Fredholm integral equations of the second kind. These equations are highly stable with respect to input perturbations and, in contrast to first-kind equations, exhibit more favorable convergence properties for iterative numerical techniques. Their mathematical structure allows one to formalize complex physical phenomena–such as the redistribution of currents and fields at the interfaces of dissimilar media–making the method widely applicable to heterogeneous and multilayer structures, including electrotechnical devices, waveguides, heating elements, and energy-saving components [5].

Solving Fredholm equations of the second kind within the secondary-source framework entails repeated evaluation of both volume and surface integrals, because one must account for the interactions between secondary sources and every observation point in space. Each surface or volume element carrying secondary charges or currents influences the field at all other points in the medium. To achieve the required accuracy, the integration domains–encompassing electrode surfaces, material boundaries, and the converter's interior–are subdivided into a large number of small discrete elements (triangles, rectangles, tetrahedra, or other simple shapes, depending on the implementation). This fine discretization localizes field singularities, captures material inhomogeneities, and yields numerically robust solutions even in the presence of steep gradients in potential or current density.

Enhancing the accuracy of the numerical solution on a digital computer depends not only on refining the mesh but also on embedding a priori information about the expected behavior of the solution. Symmetry conditions, field-continuity properties, boundary constraints, analytic behavior near edges, and empirical correlations from prior simulations or experiments can all be incorporated into the integral formulation. Such knowledge greatly improves accuracy while reducing computational cost, because it alleviates the need for excessively fine meshing throughout the entire domain. In addition, adaptive meshing–where element size varies according to local field gradients–can further optimize algorithm performance.

Consequently, secondary-source analysis is far more than a routine integration procedure: it demands careful orchestration of the entire computational workflow, from preliminary geometric discretization to specialized approximation and regularization schemes, particularly near field singularities. The end result is a numerically stable and physically rigorous model, well suited for the design and optimization of electro-thermal devices with a high degree of reliability.

According to the method of secondary sources, the distribution of the surface charge density σ of secondary charges satisfies a certain system of integral equations. The surface charge density σ(Q) at point Q, located on the interface between regions of uniform conductivity, is determined by the following formula:

$$\sigma(Q) = 2\gamma_0 \lambda_Q \vec{n}_Q^{\,0} \vec{E}(Q), \tag{1}$$

where γ_0 - is the electrical conductivity of a given homogeneous medium; $\vec{n}_Q^{\,0}$ is the unit normal vector to the interface at point Q; $\vec{E}(Q)$ - is the electric field intensity at point Q, created by all charges distributed along the boundaries of the regions, excluding the charge at point Q. Here, the parameter λ_Q depends on the conductivities of the adjoining regions:

$$\lambda_Q = \frac{\gamma^i - \gamma^e}{\gamma^i + \gamma^e}, \quad (2)$$

where γ^i - is the relative conductivity of the region from which the normal to the boundary is directed; γ^e - is the relative conductivity of the region into which the normal to the boundary is directed. λ_Q = -1÷1.

$$\vec{E}(Q) = -\frac{1}{4\pi\gamma_0}\int_S \sigma(M)\frac{\overrightarrow{r_{QM}}}{r_{QM}^3}dS_M, \quad (3)$$

where r_{QM} - is the distance between point Q (fixed), at which the electric field intensity is being determined, and point M (variable), where the charge $\sigma(M)dS_M$ is located; $\overrightarrow{r_{QM}}$ - is the distance vector between points Q and M, directed from the fixed point Q to the variable point M. Integration is carried out over all boundary surfaces of the regions, where the charges with density σ (secondary sources) are distributed; $S=S_0+S_A+S_B+S_C$ – are the surfaces of the conducting body (phases and the tank). By substituting the value of $\vec{E}(Q)$ from equation (3) into equation (1), we obtain a linear homogeneous Fredholm integral equation of the second kind for the unknown charge density σ on the boundary, with parameter λ:

$$\sigma(Q) + \lambda_Q \int_S \sigma(M)K(Q,M)dS_M = 0, \quad (4)$$

where

$$K(Q,M) = \frac{\overrightarrow{r_{QM}}\,\vec{n}_Q^{\,0}}{2\pi r_{QM}^3} \quad (5)$$

- kernel of the integral equation.

Knowing the components of the electric field intensity, we determine the instantaneous active power released in a unit volume V_q of the accumulator tank as follows:

$$p_q = \gamma E^2(q) = \gamma\left[E_\rho^2(q) + E_\phi^2(q) + E_z^2(q)\right](-\frac{1}{4\pi\gamma_0})^2 V_q. \quad (6)$$

The electric heat-storage converter has a height H_0 and a radius R_0 (see Fig. 2).

Let us divide the cylindrical volume of the electric heat-storage converter into a series of elementary geometric shapes, within each of which the temperature distribution law is assumed to be linear. This approach simplifies the numerical analysis and makes it possible to apply finite-element or finite-volume methods effectively. By segmenting the cylinder into small, well-defined sub-volumes–such as truncated cones, cylindrical rings, or rectangular prisms–we can locally approximate the thermal gradients with sufficient accuracy for engineering purposes.

Within each elementary volume, we assume that the temperature changes uniformly along the principal coordinate directions (radial, axial, and angular in cylindrical coordinates). This linearization allows the application of balance equations and constitutive relations in a simplified form, facilitating the computation of temperature fields and heat fluxes.

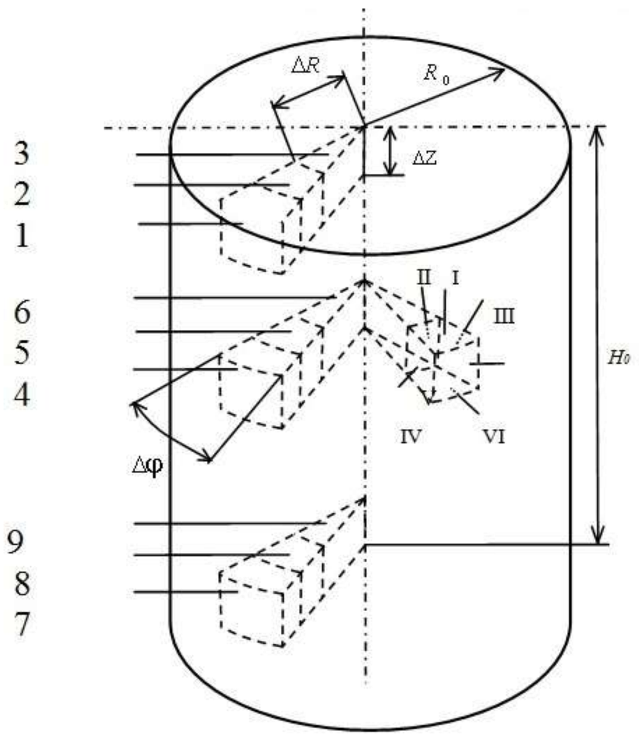

Fig. 2. Types of elementary volumes

Such a discretization method not only ensures a manageable computational load but also allows for adaptive meshing–refining the subdivision in regions with high thermal gradients or near heat sources such as electrodes. In doing so, we can more accurately capture the dynamic behavior of the thermal field while maintaining overall computational efficiency. This approach is particularly useful in modeling unsteady heating and cooling processes in complex thermal energy storage systems.

As the elementary geometric shape, we assume a sector with sides ΔR, Δz and angle Δφ. The calculation points are placed at the geometric center of each elementary sector. We introduce the following notations: N_φ – the number of subdivisions of the cylinder along the angular coordinate φ; N_z – the number of subdivisions of the cylinder along the *z*; *k* – the index of the elementary volume along the *R*. Depending on the location of the elementary volumes, nine types can be distinguished with boundary faces I, II, III, IV, V, VI. In order to ensure that the volume of each elementary sector ΔV, which contains the computational point, remains constant, we assign its value and, based on this, determine each increment ΔR_k along the *R*:

$$\Delta R_k = \sqrt{\frac{\Delta V N_\phi}{\pi \Delta z}} \left(\sqrt{k+1} - \sqrt{k} \right), \tag{7}$$

where $\Delta z = H_0/N_z$.

The general form of the heat balance equation for the considered elementary volume:

$$Q_I + Q_{II} + Q_{III} + Q_{IV} + Q_V + Q_{VI} + Q_W = \Delta J, \tag{8}$$

or

$$\sum_{i=1}^{n} Q_{ij} + Q_{Wj} = \Delta J_j, \tag{9}$$

where Q_I, Q_{II}, Q_{III}, Q_{IV}, Q_V, Q_{VI} - the amount of heat that has entered or exited the elementary volume during the time interval Δτ through the corresponding indexed faces; Q_{Wj} - the amount of heat released within the elementary volume during the time interval Δτ; ΔJ_j - the change in the internal energy (heat content) of the latter. Here, index *i* – denotes the face number of the elementary volume and *j* – denotes the number of the elementary volume itself.

Taking into account the introduced notations and after the corresponding transformations, we represent equation (9) in the following form:

$$t_{R,\phi,z}^{\tau+\Delta\tau} = t_{R,\phi,z}^{\tau} + \frac{1}{c_{vN} \rho \cdot \Delta V} \left(\sum_{i=1}^{n} Q_{ij} + Q_{Wj} \right). \tag{10}$$

The final equation makes it possible to calculate the temperature at the center of any elementary volume at the time $\tau + \Delta\tau$. As a result, knowing the flow rate of the heat transfer medium used for heat removal and its temperature before entering the converter, it becomes possible to determine the outlet temperature of the EHC at any given moment in time τ:

$$t_{out\ \tau}^{EHC} = t_{in\ \tau}^{EHC} + \frac{\dfrac{\sum_{j=1}^{m} Q_{j\tau}}{\Delta\tau} - Q_{m.n\tau}}{G_{m.н} C_{m.н}}, \tag{11}$$

где t_{in}^{EHC} – the temperature before the EHC, K; $G_{m.н}$ – the flow rate of the heat transfer fluid, m³/s; $C_{m.н}$ – its heat capacity, J/(m³·K); *m* – the number of elementary volumes washed by the heat transfer fluid; Q_j - the heat content of the j-th elementary volume, J; $Q_{m.n\tau}$ – heat losses associated with the type of insulation at the EHC installation site, W.

Conclusions. A three-dimensional mathematical model for calculating the distribution of active electric power and temperature within an electric heat-storage converter (EHC) has been developed and implemented. The model is based on the method of secondary sources, which enables an accurate description of electromagnetic-field behavior in an inhomogeneous medium while accounting for complex geometry and conductivity variations.

The analysis shows that the EHC can efficiently utilize off-peak (night-time) electricity, storing it in the form of thermal energy and subsequently releasing it during periods of peak demand. This capability markedly reduces operating costs, enhances the energy autonomy and stability of hot-water-supply systems, and lessens the load on electrical grids.

Temperature-distribution calculations inside the converter confirm the validity of the proposed numerical scheme and its suitability for engineering applications in the design and optimization of such devices. The calculation procedure–based on discretizing the volume into elementary sectors and numerically solving the heat-balance equations–allows flexible adaptation of the model to various converter configurations.

Overall, the results substantiate the practicality of electric heat-storage converters for autonomous heating systems and demonstrate the effectiveness of numerical techniques–particularly the method of secondary sources–for their analysis and design.

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РОЗРАХУНОК РОЗПОДІЛУ ЕЛЕКТРИЧНОЇ ПОТУЖНОСТІ ТА ТЕМПЕРАТУРИ В ЕЛЕКТРИЧНОМУ ТЕПЛОАКУМУЛЮВАЛЬНОМУ ПЕРЕТВОРЮВАЧІ

Коваленко В.Л., Коляденко О.А., Кокович Б.О., Тюнін О.О, Верьовкін О.В.

У дослідженні представлено розробку та впровадження тривимірної математичної моделі для розрахунку розподілу активної електричної потужності й температури в електричному теплоакумулювальному перетворювачі (ЕТП). Модель базується на методі вторинних джерел, що дає змогу точно моделювати електромагнітні процеси в неоднорідному середовищі зі складною геометрією та змінними матеріальними властивостями. Запропонований підхід особливо актуальний для автономних систем гарячого водопостачання, де критичним є підвищення енергоефективності, надійності та інтеграція відновлюваних джерел енергії.

Електричний теплоакумулювальний перетворювач накопичує теплову енергію у нічні (позапікові) години, коли тарифи на електроенергію є низькими, і віддає її у періоди пікового навантаження. Такий режим роботи суттєво знижує експлуатаційні витрати, підвищує енергетичну автономність і зменшує навантаження на електричні мережі. Компактна, надійна конструкція ЕТП, сумісна зі стандартними трифазними мережами, дозволяє легко інтегрувати його як у нові, так і в існуючі системи, зокрема сонячні теплові комплекси, міні-котельні та гібридні установки.

Чисельний метод реалізований шляхом дискретизації об'єму перетворювача на елементарні геометричні підобласті із припущенням лінійного розподілу температури в кожній з них. Інтегральні рівняння Фредгольма другого роду, отримані за допомогою методу вторинних джерел, розв'язано чисельно для моделювання електромагнітного поля та розрахунку миттєвої густини потужності. Результати підтвердили доцільність і точність запропонованої моделі для інженерних застосувань.

Отже, отримані висновки підтримують ефективність електричних теплоакумулювальних перетворювачів як енергоощадних компонентів децентралізованих систем теплопостачання та демонструють практичну цінність сучасних обчислювальних методів–особливо методу вторинних джерел–для аналізу й оптимізації таких систем.

Ключові слова: електричний теплоакумулювальний перетворювач, енергоефективність, метод вторинних джерел, системи гарячого водопостачання, моделювання електромагнітних полів, теплове акумулювання, чисельне моделювання.

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