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V.Yu. Grytsiuk, M.A.M. Yassin

Numerical modeling of coupled electromagnetic and thermal processes in the zone induction heating system for metal billets

Introduction. *For many modern manufacturing processes, induction heating provides an attractive combination of speed, consistency and control. Multi-inductor (zone) systems with continuous billets feed are the most promising, which keep the billet cross sectional average temperature equal. It allows to avoid overheating at low throughputs and reduces the number of rejected billets.* ***Problem.*** *With zone induction heating systems for metal billets developing it is necessary, at the design stage, to perform a quantitative analysis of the main characteristics of the electrothermal process and provide recommendations for optimal parameters and heating modes selections. Accurate calculations for induction heating systems involve considering the distribution of the magnetic field, current density, and changes of material properties throughout volume of the heated billet.* ***The goal*** *of the work is to develop the numerical model and analyze the coupled electromagnetic and thermal processes in zone induction heating system for metal billets to determine the optimal power ratio of the inductors and choose rational heating modes for the billets.* ***Methodology.*** *The spatiotemporal distribution of the electromagnetic field and temperature throughout the volume of the billet during the induction heating process is described by the system of Maxwell and Fourier equations. For numerical calculations by the finite element method, the COMSOL Multiphysics 6.1 software package was used. All three methods of heat transfer are taken into account – conduction, convection, and radiation. Multiphysics couplings use electromagnetic power dissipation as a heat sources, and the billet material properties are specified by temperature functions. The operation of the inductors' coils is modeled using the «Multi-Turn Coil» function, which uses a homogenized model. The translational motion of the billet is modeled by using the «Translational Motion» function.* ***Results.*** *The numerical 3D-model of coupled electromagnetic and thermal processes in the zone induction heating system for metal billets has been developed. Modeling was carried out for the design of a four-inductor system with the nominal capacity of 5000 kg/h. Data on the spatial distribution of the electromagnetic and temperature fields in the moving heated steel billet were obtained.* ***Originality.*** *Three-dimensional graphs of electrical conductivity and relative magnetic permeability change inside the moving heated steel billet are presented. Results of the temperature distribution calculations along the length of the steel billet for different inductors power ratios are provided. It is shown how the change in the power distribution of the inductors affects the billet heating parameters.* ***Practical value.*** *Analysis of the obtained data allows to determinate the necessary inductors powers to ensure the required heating mode. The results make it possible to reduce the time and resources required for the development, optimization of the design and improvement of the technological process of zone induction heating for metal billets.* References 20, table 1, figures 13.

Key words: **zone heating, numerical model, inductor, temperature field, finite element method, metal billet, electrical conductivity.**

Вступ. *Для багатьох сучасних виробничих процесів індукційний нагрів забезпечує привабливе поєднання швидкості, узгодженості та контролю. Найбільш перспективними є багатоіндукторні (зонні) установки з безперервною подачею заготовок, що підтримують середню температуру поперечного перетину заготовки рівною. Це дозволяє уникнути перегріву за низької продуктивності та зменшити кількість бракованих заготовок.* ***Постановка проблеми.*** *При розробці установок індукційного зонного нагріву металевих заготовок необхідно, на етапі проєктування, виконати кількісний аналіз основних характеристик електротеплового процесу та виробити рекомендації щодо вибору раціональних параметрів та режимів нагріву. Уточнений розрахунок індукційних нагрівальних установок передбачає врахування розподілу магнітного поля, густини струму та зміни властивостей матеріалу по всьому об'єму заготовки, що нагрівається.* ***Метою*** *роботи є розробка чисельної моделі та аналіз взаємопов'язаних електромагнітних і теплових процесів в установці індукційного зонного нагріву металевих заготовок для подальшого визначення оптимального співвідношення потужностей індукторів та вибору раціональних режимів нагріву заготовок.* ***Методика.*** *Просторово-часовий розподіл електромагнітного поля та температури по об'єму заготовки в процесі індукційного нагріву описується системою рівнянь Максвелла і Фур'є. Для проведення чисельних розрахунків методом скінченних елементів використано програмний комплекс COMSOL Multiphysics 6.1. Відтворюються всі три способи теплопередачі – теплопровідністю, конвекцією і випромінюванням. Мультифізичні зв'язки використовують розсіювання електромагнітної потужності як джерела тепла, а властивості матеріалу заготовки задані функціями температури. Робота котушок індукторів моделюється із застосуванням функції «Multi-Turn Coil», яка використовує гомогенізовану модель. Поступальний рух заготовки моделюється за допомогою функції «Translational Motion».* ***Результати.*** *Розроблено чисельну 3D-модель взаємопов'язаних електромагнітних і теплових процесів в установці індукційного зонного нагріву металевих заготовок. Розрахунок проведено для конструкції чотириіндукторної установки номінальною продуктивністю 5000 кг/год. Отримано дані просторового розподілу електромагнітного та температурного поля в рухомій сталевій заготовці, яка нагрівається.* ***Наукова новизна.*** *Представлено тривимірні картини зміни електропровідності та відносної магнітної проникності всередині рухомої сталевої заготовки, що нагрівається. Наведено розрахунки розподілу температури по довжині сталевої заготовки для різних співвідношень потужностей індукторів установки зонного нагріву. Показано, як зміна розподілу потужностей індукторів впливає на показники нагріву заготовки.* ***Практична значимість.*** *Аналіз отриманих даних дозволяє встановити необхідні потужності індукторів, за яких забезпечується необхідний режим нагрівання. Результати дозволяють зменшити час і ресурси, необхідні для розробки, оптимізації конструкції та вдосконалення технологічного процесу індукційного зонного нагріву металевих заготовок.* Бібл. 20, табл. 1, рис. 13.

Ключові слова: **зонний нагрів, чисельна модель, індуктор, температурне поле, метод скінченних елементів, металева заготовка, електропровідність.**

Introduction. A number of technological processes, including high-temperature processing of solid materials, liquid and granular substances, are based on the induction heating use [1–5]. The application area of induction heaters is quite wide: from hot water supply to process heating, including smelting and thermal processing of metals, thermal processing of bulk materials or liquid substances (for example, liquid fuel) placed in a metal container for its recycling. For many modern manufacturing processes, induction heating provides an attractive combination of speed, consistency and process control. In addition, induction heating is an environmentally friendly form of heating.

Modern induction heating installations are complex set of devices. Their main components are: an inductor with a billet, a control system, power supply, a billet supply system, etc. [1, 2]. The alternating magnetic field of the inductor excites eddy currents of the same frequency inside the billet, which create internal heat sources in the billet. In industry, the following main methods of implementing through induction heating processes are used: periodic, methodical and continuous, as well as periodic heating with reciprocating movement of the billet (Fig. 1).

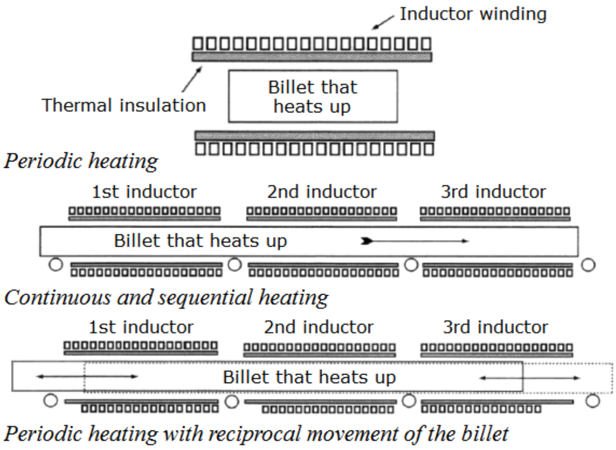

Fig. 1. Main methods of implementing through induction heating processes

In periodic heating systems, the billet is placed in the inductor for the time required to reach the desired temperature conditions, after which it is unloaded and transferred to the next technological operations, and a new billet is loaded in its place. The process is repeated with the periodic release of heated billets from the inductor. Methodical heating systems are designed for the sequential heating of two or more billets in a single- or multi-section inductor during their discrete movement (pushing) with a certain step in time and distance, with the step equal to the length of one billet from the entrance to the inductor to its exit.

Continuous heating systems provide heating of billets in an inductor of single- or multi-section design during their continuous movement at a constant speed inside the heater.

In systems with periodic heating and reciprocating movement of the billet, the depth of the billet inside the inductor periodically changes during heating. This compensates for undesirable longitudinal edge effects and helps to reduce temperature variations along the length of the billet. Such systems are used for heating long billets.

In mass production conditions, where it is necessary to ensure high productivity and heating quality, as well as the possibility of implementing different heating modes by changing the parameters of the heated billets, multi-inductor (zone) systems with continuous billets feed are the most promising [6–9]. In contrast to conventional billet heaters, zone heaters keep the billet cross sectional average temperature equal and independent of the throughput and billet dimensions. Due to that uniformity this technique avoids overheating at low throughputs and reduces the number of rejected billets. With the aid of a suitable control program the temperature profile can be modified in order to find the best compromise between low billet sticking and scaling rate, uniform temperature distribution within the billets and low energy consumption [6].

The accuracy of heating is ensured by the power supply system through the power distribution between the inductors and appropriate control of power in each inductor. The inductors can be either identical or differ from each other. The power supply system must include semiconductor power sources corresponding to the number of inductors. The most efficient power sources for induction heating devices before further plastic deformation are thyristor and transistor frequency converters [2, 4, 10].

Transistor inverters are predominantly used because they allow the transistor to be turned off not at the «zero» current point but when it is necessary. The use of resonant inverters with transistors and freewheeling diodes eliminates no-load pauses, significantly improving the harmonic composition of the output current. Additionally, the presence of freewheeling diodes eliminates the possibility of voltage overloads.

A generalized circuit of frequency converters is shown in Fig. 2. It includes an input rectifier that provides the required constant output voltage, a filter for coordination, a resonant inverter, and a load.

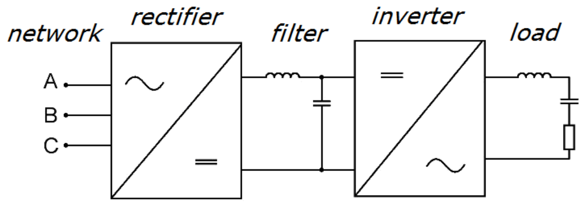

Fig. 2. Frequency converter circuit for induction heating

When developing automated complexes for zone induction heating for metal billets, it is necessary, at the design stage, to perform a quantitative analysis of the main characteristics of the electrothermal process and provide recommendations for selecting optimal parameters and heating modes. This will allow choosing the most efficient heating mode, and the obtained power values will serve as guidelines during the subsequent tuning of the technological cycle. The primary goal of achieving the specified temperature evenly throughout the volume of the billet must be attained with the highest possible performance indicators, which include process productivity, metal loss due to scaling, energy consumption, and the cost of the heating system.

Accurate calculations for induction heating systems involve considering the distribution of the magnetic field, current density, and changes of material properties throughout volume of the billet being heated [11, 12]. High precision in calculating thermal characteristics, which are necessary at the design stage of such systems, must be ensured.

Analysis of approaches to calculating electromagnetic and thermal processes in induction heating systems. Determining the distribution of the electromagnetic field and the temperature of the heated billet is generally performed by using numerical methods, such as the finite element method, considering skin effect, proximity effect, and ring effect [13]. This approach can be fully implemented with a small number of inductor turns (w = 1–5 turns). From the thermal calculation perspective, it is essential that the main part of the energy is released within the depth of the magnetic field penetration into the conductor. For a large number of turns, the electromagnetic field of round massive conductors with current, representing a multi-turn coil model, has been studied by various authors. Is considered the high-frequency mode characterized by a pronounced skin effect and analyzed the case of using both massive conductors and multi-stranded litz wire. A method is proposed for calculating the resistance of the litz wire inductor winding for induction heating. The resistance is determined taking into account eddy current losses and winding temperature. The calculation of eddy currents and losses in the turns of high-frequency device inductors is carried out based on the experimental data analysis.

Solving the field electromagnetic problem for an induction heating system with a large number of massive inductor turns ($w \geq 10$) generally requires applying a fine computational mesh to cover the cross-section of all conductors and considering the aforementioned effects. Discretization the inductor turns in this case is associated with significant computational difficulties, and typically, each individual turn in the model ends up being too small to correctly account for the non-uniform current density distribution in its cross-section when calculating the entire system.

One approach to simplifying the task solution is to preliminarily calculate the frequency-dependent equivalent parameters of a separate inductor (assuming the heated billet is absent) and then use the found parameters in the overall system calculation [14]. However, in the case of a strong skin effect, using this approach may be ineffective since the inductor parameters significantly depend on the value of the resulting field created by the currents in the inductor turns and the billet.

We will consider a multi-scale modeling technique for calculating electrothermal processes in induction heating systems [13]. The traditional understanding of this approach involves sequentially considering hierarchical levels with information transfer both top-down and bottom-up, with refinement performed iteratively based on the system's main parameter – the equivalent resistance of the inductor. Two spatial levels are distinguished for the induction system. At the macro level, the electromagnetic process in the entire system volume is considered. At the micro level, the problem of the volume of a single inductor turn is solved. As a result of solving the electromagnetic task at the micro level, the equivalent resistance of the inductor is determined, which is then used as a set parameter for calculating the current value in the inductor at the macro level. Tasks that consider the electromagnetic process at two spatial levels are solved jointly using successive approximations, with the solution of the micro-level task refining the solution of the macro-level task.

Using multi-scale modeling, a numerical calculation of coupled electrothermal processes in the heated metal billet is performed [13, 15]. The dependence of the magnetic properties of its material on temperature is considered. An analysis of the processes occurring in the electrical circuit of the induction system's power supply is conducted.

The task of developing models for calculating electromagnetic and thermal processes in induction systems is relevant and allows determining their optimal parameters and efficient modes of electromagnetic controlled processing of conductive materials at the design stage of such systems [14].

Mathematical models for calculating such processes can be created based on both the theory of electromagnetic and thermal fields and the theory of equivalent thermal circuits. Models based on the theory of thermal circuits are widely used, for example, for analyzing thermal processes in electric machines. When constructing a thermal model of an induction system for heating a moving billet, the processes of convective heat transfer play an important role [14].

Field Theory Method: this method is characterized by high accuracy in calculating the temperature distribution within the billet volume, but it requires significant computational power and does not allow modeling electrical processes in a complex-structured power source, such as one with a rectifier and inverter.

Thermal Circuit Method: this method is simpler to implement, does not require significant computational power, and allows quickly obtaining the billet temperature values online as input parameters (billet movement speed, inductor current, etc.) change. By adding an electrical circuit of the power source to the model, this approach allows accurately modeling the processes in the inverter as part of the power source and in the compensating capacitor, as well as modeling the entire system, for example, the automatic control system of the billet temperature both at the inductor exit and along the billet length. The disadvantage of this method is its lower calculation accuracy compared to the field theory method.

The non-uniform current distribution in the inductor and the heated billet leads to the emergence of several specific effects that determine the main physical laws of induction heating [11, 12]. For typical induction heating systems of cylindrical billets placed inside the inductor, the ring effect, together with the skin effect and proximity effect, leads to current concentration on the inner surface of the inductor winding at the minimum distance from the heated billet. This increases the electrical efficiency coefficient in the electromagnetic system «inductor-billet» [8].

The highest accuracy in analyzing electromagnetic and thermal processes is ensured when solving a three-dimensional problem. This becomes possible when considering the influence of the aforementioned physical effects, which manifest more deeply under conditions reproducing the finite length and detailed geometry of the inductors and the billet. Such three-dimensional problems are of practical interest.

The goal of the work is to develop a numerical model and analyze the coupled electromagnetic and thermal processes in zone induction heating system for metal billets to determine the optimal power ratio of the inductors and choose rational heating modes for the billets.

Mathematical description of coupled electromagnetic and thermal processes. In general, the spatiotemporal distribution of the electromagnetic field and temperature throughout the volume of the billet during the induction heating process is described by the system of Maxwell and Fourier equations for electromagnetic and thermal fields [16, 17]:

$$\mathrm{rot}\,\boldsymbol{H} = \boldsymbol{J} + \frac{\partial \boldsymbol{D}}{\partial \tau};\qquad(1)$$

$$\mathrm{rot}\,\boldsymbol{E} = \boldsymbol{J} + \frac{\partial \boldsymbol{B}}{\partial \tau};\qquad(2)$$

$$\mathrm{div}\boldsymbol{B} = 0;\qquad(3)$$

$$\mathrm{div}\boldsymbol{D} = \rho;\qquad(4)$$

$$c(T)\gamma(T)\frac{\partial T}{\partial \tau}\mathrm{div}(\lambda(T)\mathrm{grad}T) + c(T)\gamma(T)\boldsymbol{V}\mathrm{grad}T = F,\qquad(5)$$

where $\boldsymbol{H}$ is the magnetic field strength vector; $\boldsymbol{E}$ is the electric field strength vector; $\boldsymbol{J}$ is the conduction current density; $\boldsymbol{B}$ is the magnetic flux density vector; $\boldsymbol{D}$ is the electric flux density vector; T is the temperature of the billet; τ is the time; $c(T)$, $\gamma(T)$, $\lambda(T)$ are the specific heat capacity, density, and thermal conductivity of the metal, respectively; $\boldsymbol{V}$ is the velocity vector of the billet's movement; F is the internal heat sources.

In the considered task, the source of heat is resistive losses in the billet due to the flow of eddy currents, as well as hysteresis losses. The power of heat generation per unit volume of the heated body can be found by calculating the transferred energy of the electromagnetic field:

$$F = \mathrm{div}[\boldsymbol{E}\cdot\boldsymbol{H}].\qquad(6)$$

Obtaining a unique solution to the system (1) – (4) for all unknowns, whose number exceeds the number of equations, is possible if this system is supplemented with the following basic relationships [16, 17]:

$$\boldsymbol{D} = \varepsilon\varepsilon_0\boldsymbol{E};\qquad(7)$$

$$\boldsymbol{B} = \mu\mu_0\boldsymbol{H};\qquad(8)$$

$$\boldsymbol{J} = \sigma\boldsymbol{E},\qquad(9)$$

where ε is the relative permittivity of the billet material; ε_0 is the permittivity of vacuum; μ is the relative magnetic permeability of the billet material; μ_0 is the permeability of vacuum; σ is the electrical conductivity of the billet material.

Taking into account (7) and (9), equation (1) becomes:

$$\mathrm{rot}\,\boldsymbol{H} = \sigma\boldsymbol{E} + \frac{\partial(\varepsilon\varepsilon_0\boldsymbol{E})}{\partial \tau}.\qquad(10)$$

In the case of induction heating of metals at frequencies below 100 MHz, the density of the induced conduction current is much higher than the displacement current density. Therefore, the second term on the right side of (10) can be neglected. Thus, we get:

$$\mathrm{rot}\,\boldsymbol{H} = \sigma\boldsymbol{E}.\qquad(11)$$

The electrical conductivity σ and relative magnetic permeability μ of the billet material are functions of temperature, defined analytically and tabularly during numerical implementation. For induction heating, these dependencies are significant since the thermal power generated in the billet is related to σ and μ of the material. Their decrease when heating the billet leads to a reduction in heating power, a change in skin depth, and the efficiency of the heating process.

During induction heating, all three methods of heat transfer take place – conduction, convection, and radiation. Heat transfer within the heated billet from its more heated layers to less heated ones occurs due to the conduction process, described by the fundamental Fourier's law.

The convective heat exchange process between the heated billet and the surrounding environment is carried out according to Newton's law, which states that the heat transfer rate is directly proportional to the temperature difference between the billet surface T_1 and the surrounding environment T_0. Heat loss from the billet surface to the surrounding environment by radiation is described by the Stefan–Boltzmann law, which states that the heat transfer rate is proportional to the difference of the fourth powers of the absolute temperatures $T_1^4 - T_0^4$. Such a description of radiative heat losses is satisfactory when constructing mathematical models in most real tasks of studying induction heating processes.

The thermophysical parameters λ and c in (5) are nonlinear functions of temperature. In practice, the assumption of a constant thermal conductivity coefficient λ = const does not usually lead to significant errors when modeling temperature fields during induction heating. Similar approximation of the temperature dependence of specific heat capacity can lead to substantial errors in calculating the required power and thermal profile of the billet. Together with the corresponding boundary and initial conditions, equation (5) describes the three-dimensional temperature distribution at any time for any point throughout the volume of the heated billet. The solution to the system of equations (1) – (5) can only be realized by numerical methods. These methods are widely used in modern multiphysics simulation software packages such as Cedrat FLUX, COMSOL Multiphysics, ANSYS, and others.

Equations (1)–(6), (11) provide a general description of the coupled three-dimensional electromagnetic and thermal fields, allowing for the determination of all necessary structural characteristics of the induction system. In this case, equations (1), (2), (10) are rewritten in frequency domain [16]. This approach enables solving the tasks of optimal control of multidimensional temperature fields both in the process of continuous induction heating and in the optimal design of induction heating systems.

Numerical implementation of coupled electromagnetic and thermal processes calculation. For numerical calculations, the COMSOL Multiphysics 6.1 software package was used. The preparation of the calculation process can be divided into several stages. The first stage is the synthesis of the model, which begins with the selection of the model's dimensionality and physical modules. In this software package, there is an option to choose a module that is already highly adapted for calculations in induction heating devices – «Induction Heating». This can be selected through the «Electromagnetic Heating» branch. The multiphysics module (interface) «Induction Heating» is used for calculations of induction and eddy current heating and includes a magnetic fields interface and a heat transfer in solids interface. Multiphysics couplings add electromagnetic power dissipation as a heat source, and the electromagnetic properties of the material can depend on the temperature. Moreover, combinations of frequency domain modeling for the «Magnetic Fields» interface and stationary modeling for the «Heat Transfer in Solids» interface are supported, known as frequency-stationary and frequency-transient modeling.

The «Heat Transfer in Solids» interface allows modeling of heat transfer by conduction, convection, and radiation. The solid model is active by default in all domains. The temperature equation defined in solid regions corresponds to the differential form of Fourier's law, which may include additional heat sources.

Model geometry synthesis. Each inductor heats a part of the billet in a specific area of space. Optimal heating programs and the required final temperature can be achieved by ensuring that each inductor individually transfers the corresponding power to the billet. This approach requires solving the task of forming the necessary power by the inductors, which determines the design of the inductors and the circuit design of the power part of the converter that powers them.

Modeling was carried out for the design of a multi-inductor system for zonal heating of steel billets with the nominal capacity of 5000 kg/h. The geometric dimensions and technical parameters of the zone induction heating system are presented in Table 1. The model consists of four cylindrical inductors and a cylindrical billet. Each inductor is 1,5 m long, and the billet has a length of 6,5 m and a radius of 0,05 m. The power distribution is such that all inductors have the same operating frequency and number of turns but different current values. For the initial modeling, the power ratios of the inductors were chosen as 1 : 0,8 : 0,8 : 0,6. The inductors are numbered according to the direction of the billet's movement.

Table 1

Geometric dimensions and technical parameters of the zone induction heating system

Parameters	Value
Length of one inductor l_1, m	1,5
Distance between inductors l_2, m	0,1
Inner radius of the inductor r_1, m	0,07
Outer radius of the inductor r_2, m	0,1
Length of the steel billet L_1, m	6,5
Radius of the steel billet R_1, m	0,05
Initial temperature of the billet T_1, °C	20
Ambient temperature T_0, °C	20
Required heating temperature T_2, °C	950
Velocity of the billet V, m/s	0,022
Frequency of the inductor current f, Hz	1000
Current density in the conductors of individual inductors J, A/m^2	
1st	$8{,}9\cdot10^6$
2nd	$7{,}12\cdot10^6$
3rd	$7{,}12\cdot10^6$
4th	$5{,}45\cdot10^6$
Electrical conductivity σ of the billet material at 20 °C, S/m	$5{,}56\cdot10^6$
Relative magnetic permeability μ of the billet material at 20 °C	16

The model geometry can be constructed using COMSOL Multiphysics tools or in AutoCAD, with subsequent importation.

Setting physical constants and properties. After creating the model's geometry, constants are defined. In our case, it is recommended to introduce several constants: $J_1 - J_4$ – the current density values for each inductor. These values equal the product of the current and the number of turns of the inductor divided by the cross-sectional area of the corresponding inductor. Also, f – the frequency of the current in the inductors. Using constants simplifies the subsequent reconfiguration of the model.

The calculation of the electromagnetic field is solved first in the frequency domain modeling step, and the calculation of the temperature field is solved in the subsequent stationary step.

The billet's movement speed is sufficiently low, so the induced current density due to the movement of the conductor is considered negligible compared to the current density induced by the alternating field. The operation of the inductors' coils is modeled using the «Multi-Turn Coil» function, which employs a homogenized coil model consisting of a large number of thin conductors [18, 19].

The boundary conditions applied to the radiating surface of the billet (the surfaces in contact with air) are a combination of thermal flux considering natural thermal convection in the air and a diffuse surface modeling radiative heat transfer to the environment. The translational motion of the billet at a constant speed is modeled using the «Translational Motion» function in the «Heat Transfer in Solids» module.

Finite element mesh construction. The minimum size of the finite elements (given the order of the approximating function polynomial) and the minimum calculation time should be chosen based on the required accuracy of the electromagnetic field calculation. The discretization requirements are applied to the conductive elements of the structure where eddy currents are calculated. Mesh step in these elements should be less than 1/4 of the field penetration depth. Reducing the size of the finite elements increases the calculation time, and the solution becomes more accurate.

Figure 3 shows a fragment of the finite element mesh, representing one of the four inductors and part of the steel billet (inside the inductor, shown in blue).

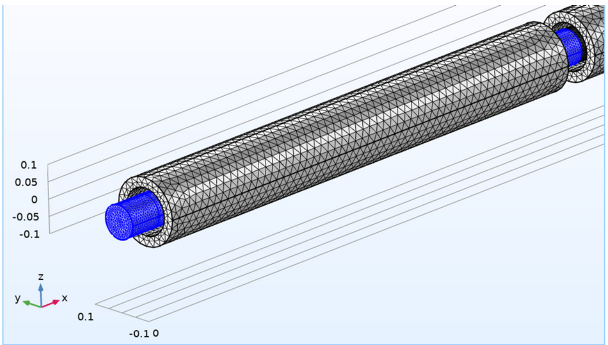

Fig. 3. Fragment of the finite element mesh representing one of the four inductors and part of the steel billet

Results of modeling and discussion. The results of determining the spatial distribution of eddy current density within the steel billet in the form of longitudinal and several transverse sections are presented in Fig. 4. According to the obtained results, the highest heat generation occurs in the layers of the steel billet adjacent to the inner surface of the inductor. In the operating zone of the first inductor, which initiates heating, the maximum current density on the surface of the billet reaches approximately $105\cdot10^6$ A/m². This value rapidly decreases along the axis of the billet and at a distance of 2 mm from the surface, it is around $45\cdot10^6$ A/m².

For comparison, these values in the billet at the edge of the fourth inductor are approximately $65\cdot10^6$ A/m² and $28\cdot10^6$ A/m², respectively. Presumably, this difference is solely due to the varying powers of the first and fourth inductors (approximately 1,65 times difference). The influence of changes in σ and μ of the billet material on the redistribution of heat sources within it is minor, as this change primarily occurs within the operating zone of the first inductor. Figure 5 shows the change in temperature T and electrical conductivity σ along the length of the heated steel billet.

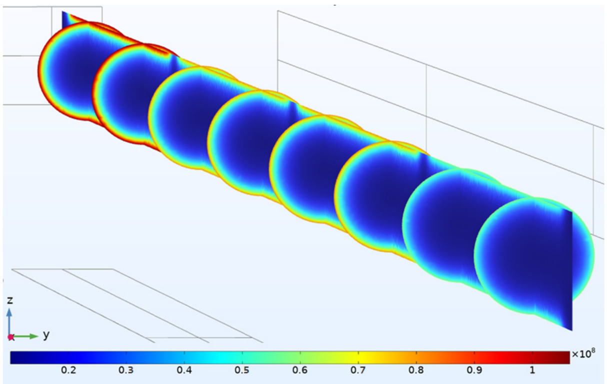

Fig. 4. Spatial distribution of eddy current density inside the billet in the form of longitudinal and several transverse sections

As observed, under such a power ratio between the inductors, the surface temperature of the billet at the end of the first inductor's working zone exceeds 660 °C, while it is 375 °C along the central axis. The electrical conductivity of the billet material in this section decreases by a factor of 5.5 on the surface and 3.1 along the axis compared to its initial values. However, until the completion of heating, the electrical conductivity of the billet decreases by only 25 % and 55 %, respectively.

Figures 6, 7 present the spatial change of σ and μ inside the billet in the form of longitudinal and several transverse sections. Due to skin effect, the surface of the billet transitions through the Curie point earlier than its center. This transition occurs gradually; however, Fig. 7 clearly shows a paramagnetic layer over the ferromagnetic layer within the heating zone of the second inductor, indicating a significant transition. From the perspective of magnetic properties, the billet material becomes two-layered over a length of approximately 1,25 m. Thus, these findings are crucial from a design standpoint. Specifically, the magnetic field strength and distribution of eddy currents, as well as changes in material properties, directly affect temperature control, heating rate, and the formation of localized heat treatment zones in billet.

Figure 8 shows typical curves of equivalent parameters changes of the inductor replacement circuit with the billet during heating for magnetic and non-magnetic metals.

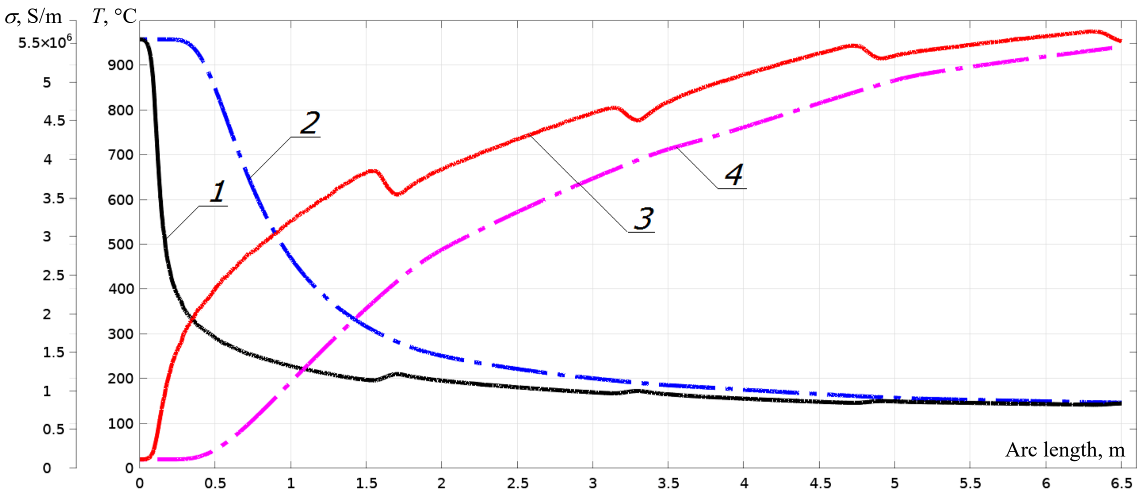

Fig. 5. Change in electrical conductivity and temperature along the heated steel billet length: *1* – value on the surface of billet $\sigma(L_1)$; *2* – value along of billet central axis $\sigma(L_1)$; *3* – value on the surface of billet $T(L_1)$; *4* – value along of billet central axis $T(L_1)$

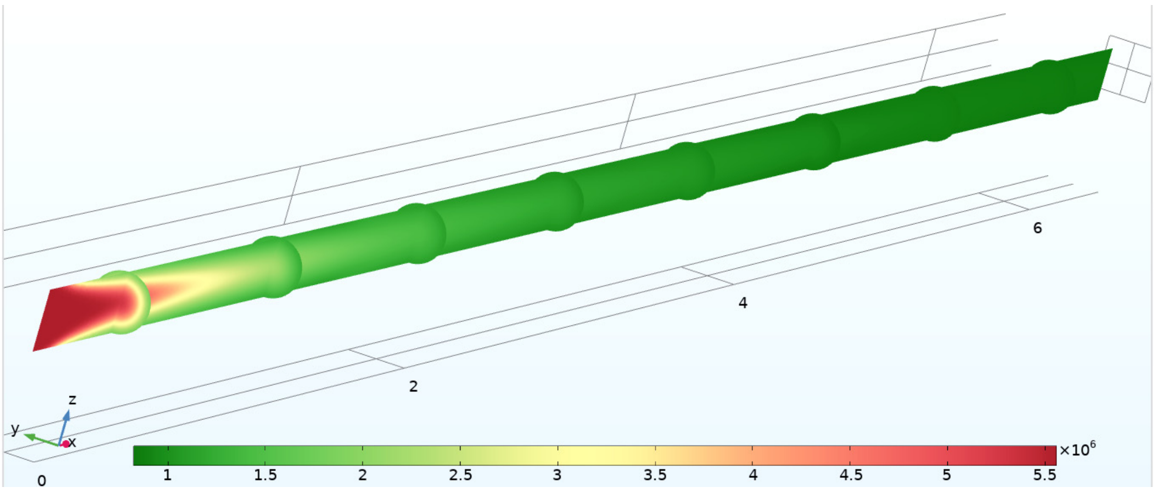

Fig. 6. Change in electrical conductivity σ inside the heated steel billet

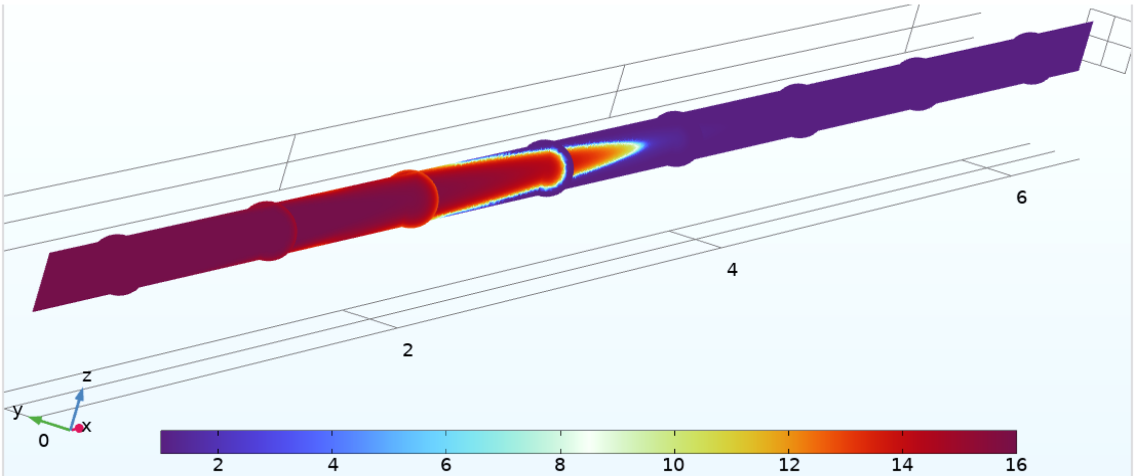

Fig. 7. Change in relative magnetic permeability μ inside the heated steel billet

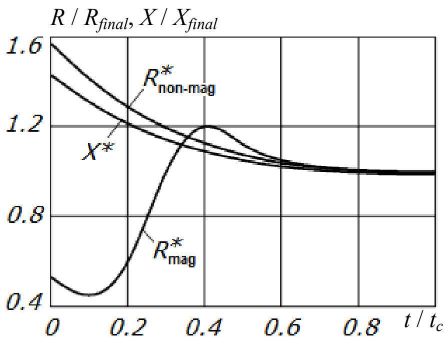

Fig. 8. Change of heating parameters for magnetic and non-magnetic billets (relative to final values) as a function of relative time t/t_C, where t_C – duration of the heating cycle

The curves of changes in R and X are provided for the parallel replacement circuit [10]. The parameters correspond to the complete filling of the inductor with fully heated metal. The ratio of the maximum R value to the minimum ranges from 1,5 to 2,5. The X value decreases during heating by 1,3 to 1,6 times. Accordingly, the quality factor can vary by 2 to 3 times.

The conclusion of the modeling involves obtaining comprehensive data on the spatial distribution of temperature inside the billet. Figure 9 presents temperature field maps of the billet at a time moment of 290,91 s (end of heating). The billet moves from left to right. Current density values in the inductors were chosen so that the exit temperature of the billet from the system would be approximately 950 °C.

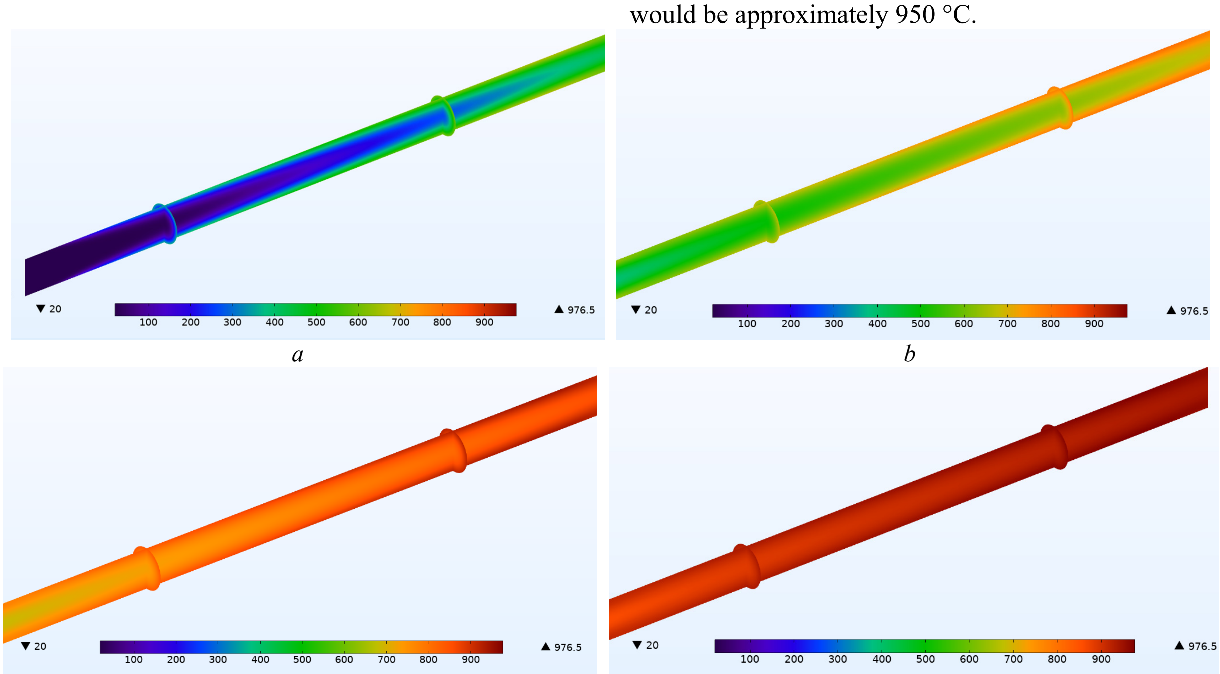

Fig. 9. Temperature spatial distribution in longitudinal and transverse sections of the steel billet for individual heating zones:
a – heating zone of the first inductor; *b* – heating zone of the second inductor;
c – heating zone of the third inductor (*c*); *d* – heating zone of the fourth inductor

Temperature spatial distribution in longitudinal and transverse sections of the steel billet for the four heating zones allows a visual assessment of the heating intensity as the billet moves into the zones influenced by individual inductors. For instance, the maximum temperature is found at the end of the heating zone of the fourth inductor (on the surface of the billet), reaching 976,6 °C. Due to skin effect, the center of the billet heats up slower than its surface, resulting in a temperature gradient between them during heating. Depending on the heat source power, this gradient may exceed the allowable temperature uniformity specified for subsequent rolling or stamping processes, where permissible temperature gradients between the surface and center of a steel billet typically range from ±50 °C to ±25 °C, given the required heating temperature of 1000–1250 °C.

This temperature gradient is somewhat reduced due to heat losses from the billet surface through convective and/or radiative heat exchange with the surrounding environment. Analysis indicates that convective losses predominate in low-temperature heating setups, whereas in high-temperature heaters (for steel, titanium, cobalt, and nickel billets), heat loss predominates through radiation. In our case, the nature of the temperature gradient between the center and surface of the billet can be visually assessed using the temperature distribution across the radius of the billet at the output of each inductor (Fig. 10).

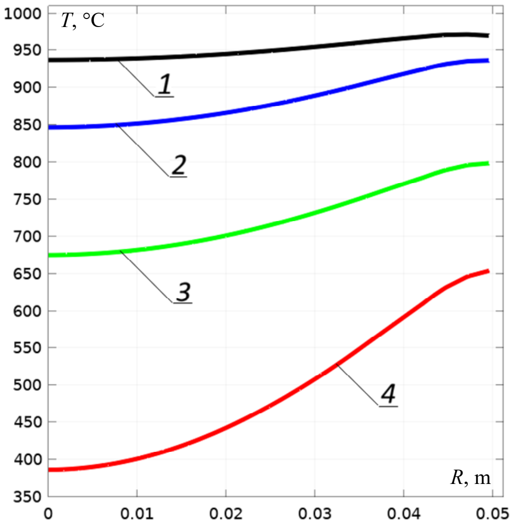

Fig. 10. The temperature distribution across the radius of the billet at the output of each inductor: *1* – the output of the 4th inductor; *2* – the output of the 3rd inductor; *3* – the output of the 2nd inductor; *4* – the output of the 1st inductor

The obtained temperature distribution closely resembles the distribution of eddy current density across the radius of the billet. The temperature difference between the center and the surface of the billet (under the edge of the fourth inductor) is 32 °C. However, this difference decreases rapidly, reaching about 11 °C within 4,5 s, explained by the rapid cooling of the billet surface. Figure 11 shows the temperature distribution across the end section of the billet as contours and surface plots at the exit of the zone heating system.

As we can see, after the billet exits the working zone of the last inductor, the temperature maximum of 960 °C is maintained at a distance of 5 mm from its surface.

Additionally, a series of numerical calculations were carried out to determine the optimal power distribution of the inductors when heating the steel billet. The conditions for comparing all calculations were as follows: the total power of all inductors (only the distribution changes), constant current frequency, productivity (speed), geometry (see Table 1), and cooling conditions. The required surface temperature of the billet at the output is 950 °C (within ±20 °C). Heating indicators such as the amount of heat loss in the billet (including the areas between inductors), overheating, and the temperature gradient along the length and cross-section of the billet are taken into account.

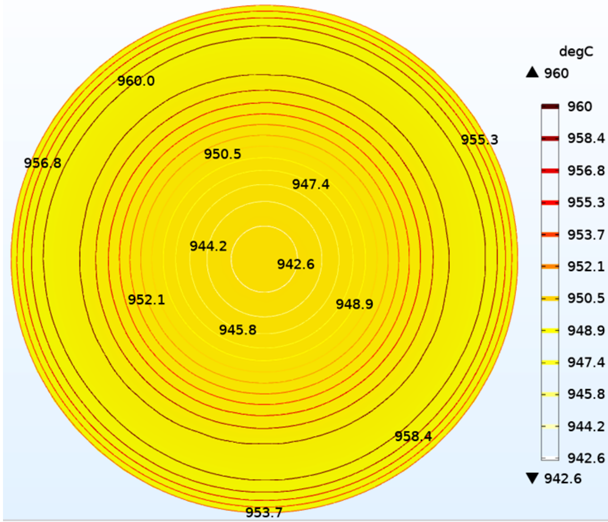

Fig. 11. Temperature distribution on the billet end part at the exit from the zone heating system

As previously established [20], to ensure an effective thermal process for heating billets, the power ratio of the inductors should be 1 : 0,5 : 0,25 : 0,125. The result of modeling such a power distribution for the inductors is overheating of the billet surface within the first inductor zone to 1150 °C (Fig. 12). However, subsequently, the billet begins to cool rapidly due to the lack of power from the other inductors, and the center (1009 °C) of the billet has a higher temperature than its surface (968 °C) at the output of the fourth inductor. In the forging industry is advantageous to achieve a homogeneous billet temperature at the outlet of the heater with the shortest possible coil line installation length while at the same time minimizing the scaling rate and energy consumption. These objectives should be obtained not only for the nominal billet diameter and throughput but also for smaller billets and throughputs. Since these requirements are partly in conflict the solution generally involves reaching a compromise [6].

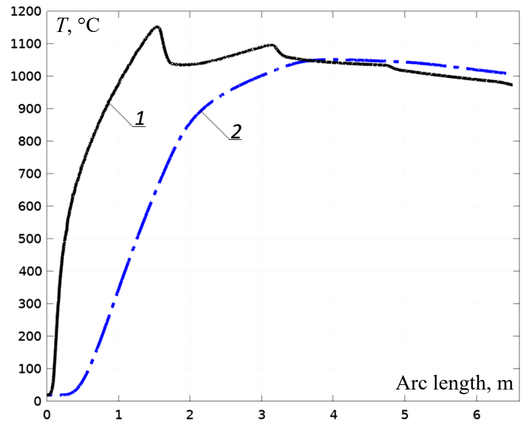

Fig. 12. Temperature along the billet length for the inductors power ratio 1 : 0,5 : 0,25 : 0,125: *1* – temperature on the surface of the billet; *2* – temperature along the central axis of the billet

From the standpoint of minimizing the temperature gradient across the cross-section of the billet, an acceptable power distribution for the inductors was found to be when the power of each subsequent inductor decreases by 33 % compared to the power of the previous one. That is, the ratio is 1 : 0,67 : 0,45 : 0,3. In this case, the first inductor provides a rapid heating of the billet to 880 °C, and the temperature inside and on the surface of the billet equalizes at the beginning of the movement into the heating zone of the last inductor (Fig. 13). However, this design as a whole is characterized by thermal losses between the zones of individual inductors, which requires further improvement of the device.

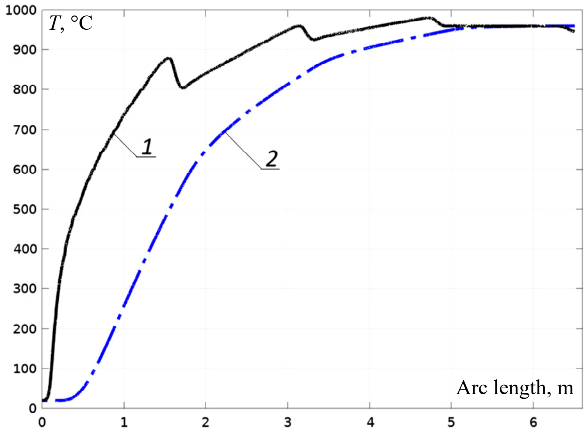

Fig. 13. Temperature along the billet length for the inductors power ratio 1 : 0,67 : 0,45 : 0,3: temperature on the surface of the billet (1); temperature along the central axis of the billet (2)

The task of defining the heating program for a multi-inductor heating complex generally involves subtasks to determine the power variation processes for each inductor. Determination of the inductors power ratio and heating programs for a multi-inductor complex presented in detail in works [6, 20].

The setup and resolution of the problem can be significantly simplified by predefining the function of power variation for each inductor over time. If the power of each inductor is assumed to be constant over time (taking into account data on changes in σ and μ throughout the billet volume), then the task of determining the inductor powers (power distribution among the inductors) can be solved using an iterative approach. This requires further modeling under various inductor power conditions to meet the heating requirements, gradually approaching the final result – power values. This approach significantly reduces resources when determining the optimal heating modes for a metal billet. The model can be represented as an m-file, describing geometric parameters, constants, global variables, nonlinear properties of the media, solver settings, and more.

Conclusions. This work presents the numerical 3D-model of coupled electromagnetic and thermal processes in zone induction heating system for metal billets. The model considers various effects that determine the fundamental physical principles of induction heating.

Using the finite element method and the COMSOL Multiphysics 6.1 software package, data on the spatial distribution of the electromagnetic and temperature fields in the moving heated steel billet were obtained. Three-dimensional graphs of electrical conductivity and relative magnetic permeability change inside the moving heated steel billet are presented.

Analysis of data on the distribution of the electromagnetic field, the temperature of the billet, and the changes in material properties allows for determining the necessary inductors powers to ensure the required heating mode. The established power distribution can serve as a reference for preliminary setup at the beginning of the zone heating system's operation.

Results of the temperature distribution calculations along the length of the steel billet for different inductors power ratios are provided. It is shown how the change in the power distribution of the inductors affects the billet heating parameters.

The thermal losses observed between the zones of individual inductors are a challenge that needs addressing. These losses can lead to inefficiencies and potential quality issues of the billet. Future work should focus on reducing these thermal losses, possibly through design modifications or improvement of thermal insulation and the heating process control system.

The presented 3D-model of coupled electromagnetic and thermal processes can be used for quickly readjusting initial parameters (frequency, power and number of inductors, billet dimensions and material, etc.) to obtain variations in numerical calculations. This allows for predicting the efficiency and performance indicators of zone heating, such as efficiency, speed, heating depth, temperature, and gradient.

The obtained results have practical application and make it possible to reduce the time and resources required for the development, optimization of the design and improvement of the technological process of zone induction heating for metal billets. Experimental validation of the developed technique and obtained numerical results is a prospect of further research.

Conflict of interest. The authors of the article declare that there is no conflict of interest.

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V.Yu. Grytsiuk[1], *PhD,*
M.A.M. Yassin[1], *Senior Engineer,*
[1] University of South-Eastern Norway,
56, Kjølnes ring, Porsgrunn, 3918, Norway,
e-mail: Volodymyr.Grytsiuk@usn.no (Corresponding Author);
Mohammed.Yassin@usn.no

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