

## **MULTIPHYSICS FINITE ELEMENT MODEL OF A CONTINUOUS THIN METALLIC SHEETS HEATER WITH ROTATING PERMANENT MAGNETS SYSTEM**

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*Articolul prezintă modelul numeric 2D multifizic în element finit al unui sistem cu magneți permanenți pentru încălzirea tolelor metalice în regim de defilare. Modelul consideră atât mișcarea de rotație a rotorului cu magneți permanenți (inductor) cât și mișcarea de translație a tolei (indus). Sistemul de încălzire poate fi utilizat în scopul uscării tolelor după vopsire, a încălzirii acestora în scopul călării termice sau a prelucrărilor mecanice ulterioare.*

*The paper presents the multiphysics 2D finite element numerical model of a continuous thin metal sheets heater by rotating permanent magnets system. The model takes into account the rotating motion of a rotor with permanent magnets (inductor) coupled with the translating motion of a thin metal sheet. The system can be used to dry painted metal sheets, to prepare the sheets for mechanical processing or for thermal hardening.*

**Keywords:** finite element model, permanent magnets, thin metal sheets heater

### **1. Introduction**

The direct conversion of energy represents a very actual subject of research for specialists all over the world. The heating through eddy currents has a very good efficiency and is a constantly developed and improved method. The usual heating systems [1] convert the electrical energy into heat through Joule effect. The direct conversion of the kinetic mechanical energy into heat represents a good alternative for the classic heating systems [2]...[6]. The originality of these systems is represented by the source of the magnetic field and the type of the energy converted into heat. The heating devices with permanent magnets driven by kinetic energy have a limited use. The continuous development of the permanent magnets contributes to develop this type of heating systems.

The conception of this new heating system is based on the idea of use of the permanent magnets and kinetic rotating energy. The induction heating supposes a time varying electromagnetic field applied to a metallic billet heated

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by Joule effect of the eddy currents. Such a system is usually composed by an inductor supplied by alternative current and a metal billet or by an inductor supplied by direct current and a rotating metal billet in an invariable magnetic field. This novel system, presented in figure 1, contains the inductor – 1 composed by a metallic cylinder named rotor, surrounded by an even number of permanent magnets – 2, the thin metal sheet – 3 to be heated and the magnetic field concentrator - 4.

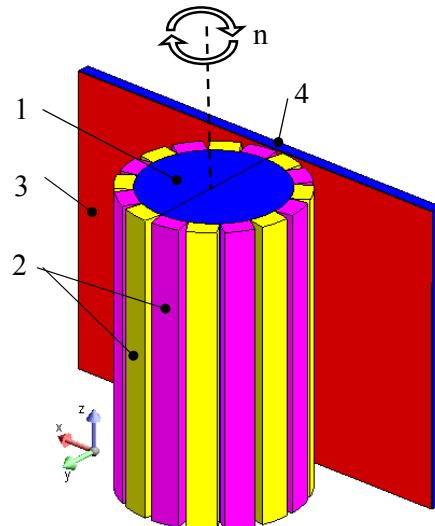


Fig. 1. System with permanent magnets for continuous heating of thin metallic sheets through eddy currents

The concentrator concentrates the magnetic field on the metal sheet area. The rotating motion of the inductor generates eddy currents in the metal sheet, currents that generate heat by Joule effect. The induction heating method of the metallic sheets has a good efficiency in comparison with other heating methods because the heat is generated directly in the billet or metallic sheet with reduced heat losses.

The study of the continuous heating of the thin metal sheets to the desired stabilized temperature starts with the 2D numerical model of heating thin aluminum sheets in a system with one inductor and a magnetic field concentrator and continues with an optimized model of the heating system for the same metal sheet with two inductors and no concentrator. The main objectives are the determination of the induced power, the heating time to the desired stabilized temperature and the speed of the continuous heating process.

## 2. The multiphysics 2D finite element model of continuous thin aluminum sheets heater with rotating permanent magnets system and magnetic field concentrator

The building of the numerical model supposes some stages such as the construction of the system computation domains, the mesh of each problem, the definition of the physical properties and finally the evaluation of the induced power and the corresponding temperature. The numerical model is composed by the computation domains corresponding to the studied electromagnetic and thermal phenomena. The eddy currents heating systems need a step by step in time domain computation type. The heating study supposes:

- a transient magnetic problem in which are studied the eddy currents, the induced power in the metallic sheet and the time variation of the specific variables;
- a transient thermal problem in which is studied the sheet temperature and the time variation of the temperature.

### A. The geometry, mesh and the physical properties of the two problems

The rapid and intense variation of the magnetic field (North-South polarity) in the aluminum sheet along a complete rotation of the rotor in order to increase the system efficiency requires a large number of magnetic poles  $2p = 16$  poles. The geometry of the transient magnetic computation domain and the mesh are presented in figure 2.

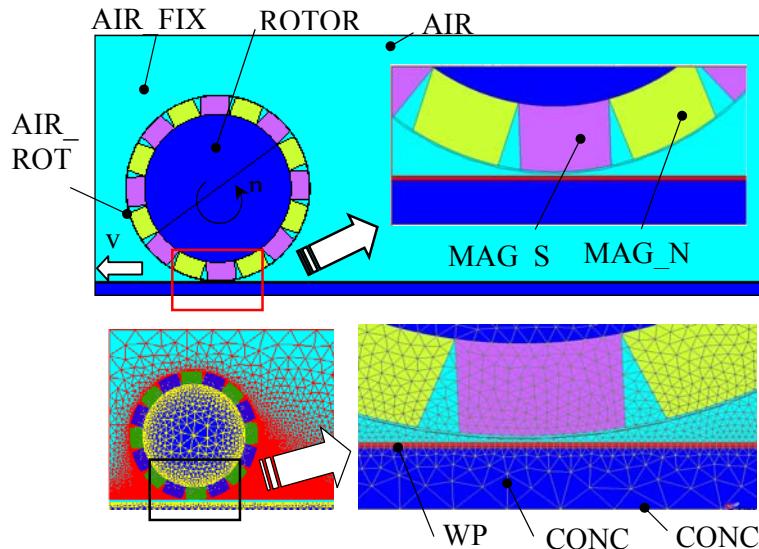


Fig. 2. Transient magnetic computation domain and the mesh

The inductor inner diameter is  $D_{in} = 120$  mm, the inductor outer diameter is  $D_{ex} = 150$  mm, the inductor rotating speed is  $n = 3000$  rpm, the aluminum sheet thickness and the minimum air gap between the inductor and the metal sheet is  $WP = AG = 2$  mm, the concentrator thickness is  $CONC = 20$  mm, the depth of the computation domain is  $d = 1000$  mm. Between the sheet and the concentrator is supposed to be a small air gap to avoid contact between them. The mesh of the magnetic problem has 29297 second order element nodes, and it is composed of triangles elements on the entire computation domain, except the WP region where it is mapped. The magnetic computation domain contains the following regions:

- ROTOR – steel magnetic nonlinear and nonconductive laminations, saturation  $B_s = 2$  T and initial relative permeability  $\mu_{ri} = 2000$ ;
- MAG\_S, MAG\_N – magnetic nonconductive regions – anisotropic linear permanent magnets,  $\mu_r = 1,1$  and  $B_r = 1$  T;
- WP – nonmagnetic conductor - aluminum made with  $\mu_r = 1$  and linear temperature depending resistivity  $\rho = 2,8 \cdot 10^{-8} \cdot [1 + 3,75 \cdot 10^{-3} \cdot (\theta - 20)] \Omega \cdot m$ ;
- CONC – same properties as ROTOR;
- AIR\_ROT – nonmagnetic nonconductor – the air surrounding the ROTOR region;
- AIR\_FIX – nonmagnetic nonconductor – the air surrounding the AIR\_MOB region;
- AIR and CONC boundary regions with Dirichlet conditions ( $A=0$ ).

The mechanical sets are as follows:

- ROTATING motion for ROTOR, MAG\_N, MAG\_S, AIR\_ROT regions;
- FIX for WP, CONC, AIR\_FIX regions.

The meshed thermal computation domain, presented in figure 3, contains only the WP region with the following properties:

$$\lambda = 243 \cdot [1 - 2,88 \cdot 10^{-4} \cdot (\theta - 20)] \text{ W/m}^{\circ}\text{C} \text{ and specific heat } \gamma c = 2700 \cdot 879 \cdot [1 + 6,71 \cdot 10^{-4} \cdot (\theta - 20)] \text{ J/m}^3 \text{ }^{\circ}\text{C}.$$

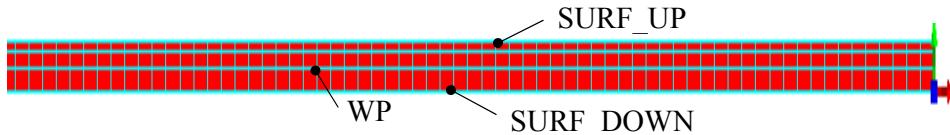


Fig. 3. Transient thermal computation domain

The thermal problem mesh has 1800 second order element nodes and is mapped. The convection thermal transfer coefficient to the surrounding air  $\alpha = 50 \text{ W/m}^2 \text{ }^{\circ}\text{C}$ ,  $\varepsilon = 0,8$  and to the concentrator region  $\alpha = 20 \text{ W/m}^2 \text{ }^{\circ}\text{C}$ ,  $\varepsilon = 0,8$  is modeled by the SURF\_UP and SURF\_DOWN regions.

### *B. The multiphysics coupling method*

In this paragraph is presented the multiphysics coupling solving method. The inductor rotating motion with imposed speed  $n = 3000$  rpm is simulated by successive positions of the inductor with respect to the metal sheet, defined by the angular step  $\Delta\alpha = (2\pi n/60) \cdot \Delta t_m = 5,6^\circ$ , where  $\Delta t_m = 5 \cdot 10^{-5}$  s is the magnetic time step and  $\Delta t_h = 0,11$  s is the thermal time step found after several simulations. The continuous heating of the metal sheet is equalized with the displacement of the inductor over the x coordinate of the metal sheet. Thus, in the continuous heating process to the desired temperature, the inductor will make several displacements  $\Delta x$ . This means that the heating study needs different geometries for the magnetic problem for each position of the inductor and a single geometry for the thermal problem.

Considering the ambient temperature of the sheet and the corresponding material properties, a first evaluation of the magnetic problem is made until the steady state is reached, and the mean of the induced power volume density in every node of the sheet over a period  $T = 1,25$  ms is computed, the mean value which represents the source of the thermal problem and with which is computed the first thermal time step  $\Delta t_h$ .

After the evaluation of the magnetic and thermal variables in the initial position of the inductor, a new magnetic geometry is build in which the inductor is displaced with  $\Delta x = 25$  mm from initial position, along the sheet x coordinate. The computation of the mean induced power volume density in the new position of the inductor is initiated from the temperature of the first thermal time step, and the mean of the induced power represents the computing source of the second thermal time step, initiated from the first time step temperature. Thus, the cycle is repeated until the sheet temperature is stabilized to the desired value. The  $\Delta x$  corresponds with  $\frac{1}{4}$  of inductor diameter and every displacement place the inductor in the “cold” area of the sheet, at  $T = 20^\circ\text{C}$ .

### *C. Results analysis*

The main objectives are the determination of the heating time to the desired temperature  $T = 350^\circ\text{C}$  and the continuous heating speed process. The chart of the magnetic flux density in the entire computation domain is presented in figure 4.

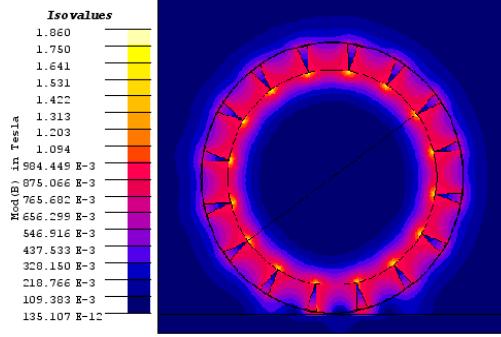


Fig. 4. The chart of the magnetic flux density in the entire computation domain

The chart of the eddy currents density is presented in figure 5.

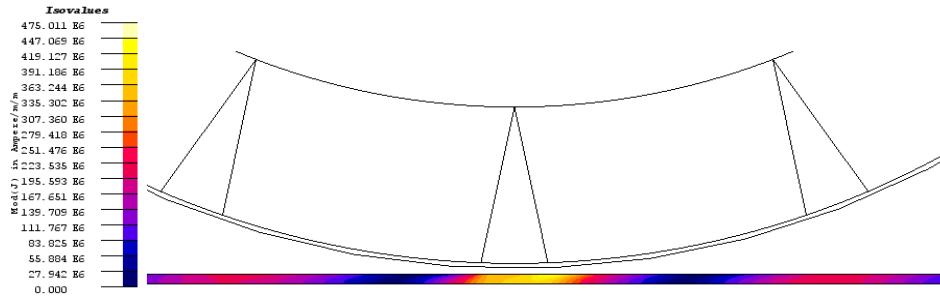


Fig. 5. The chart of the eddy currents density in the sheet

The induced power is  $P = 238,4$  kW. The mean density of the induced power in three positions of the inductor, at the initial position ( $1 \times \Delta x = 0,025$  m), after ten displacements ( $10 \times \Delta x = 0,25$  m) and in the last position ( $21 \times \Delta x = 0,525$  m) is presented in figure 6 and the temperature corresponding to these positions is presented in figure 7.

$\times 10^9$

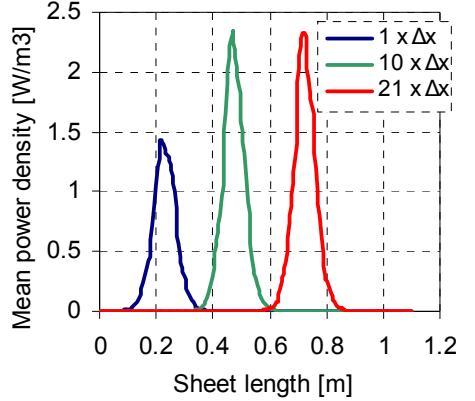


Fig. 6. The mean power density in the metal sheet for three positions  $\Delta x$

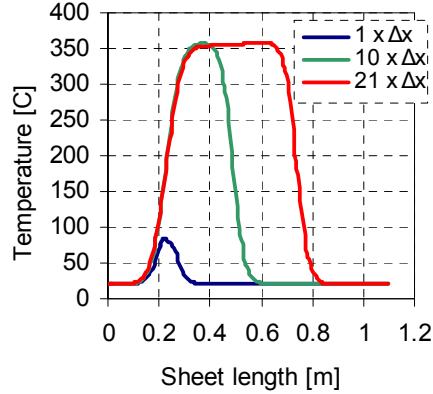


Fig. 7. The corresponding temperature of the metal sheet for three positions  $\Delta x$

The chart of the mean induced power density and the chart of temperature after the first thermal time step are presented in figure 8 and figure 9.

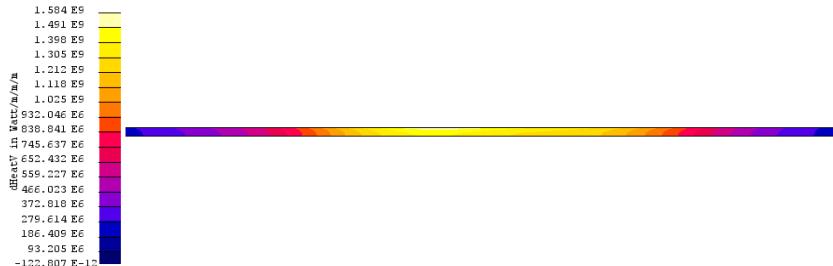


Fig. 8. The chart of the mean induced power density in the metal sheet

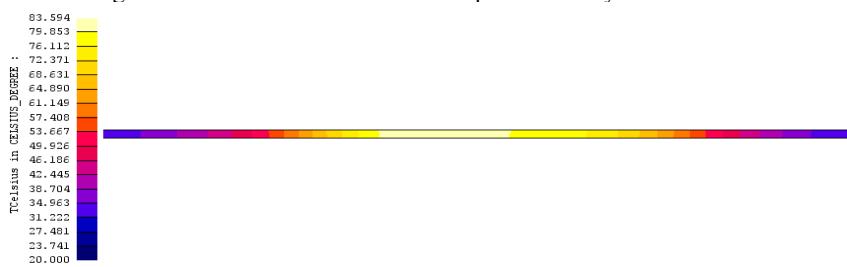


Fig. 9. The chart of the metal sheet temperature at first thermal time step

The stabilized temperature  $T = 350^\circ\text{C}$  is reached after 22 inductor displacements, after the time  $t_{\text{th}} = 22 \cdot \Delta t_{\text{th}} = 2,42$  s. The continuous heating process speed is given by  $v = \Delta x / \Delta t_{\text{th}} = 0,025 / 0,11 = 0,22$  m/s. The  $\Delta x$  is obtained after several simulations of the heating process and corresponds to the desired final

temperature and to chosen  $\Delta t$ . The chart and the variation of sheet temperature with respect to inductor positions are presented in figure 10.

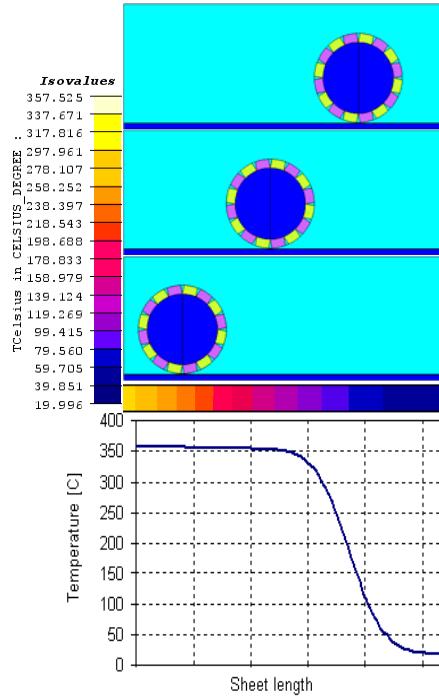


Fig. 10. The chart of the sheet temperature with respect to the inductor positions and the variation of sheet temperature at the last  $\Delta t$

The magnetic properties of the permanent magnets can be affected by the sheet heat. To monitor the possible negative effect, the magnets temperature must be computed in a future 3D model. Taking into account that the inductor is continuously rotating with high speed and the metallic sheet is also in continuous movement, it can be said that the temperature may not affect the magnets properties. The concentrator may cause mechanical problems in the system functioning time. Because of the 2D model limitations, to obtain results with a better match with the reality, the 3D model must be studied. Also the experimental model can help to obtain real results.

### 3. The multiphysics 2D finite element model of continuous thin aluminum sheets heater with rotating permanent magnets system with two inductors and no magnetic field concentrator

The system presented in figure 11 is optimized in order to obtain less heating time at the same desired temperature and increase the system efficiency. The system contains two inductors placed on both sides of the aluminum sheet and no concentrator. The system geometry permits to reduce the computation domain by defining a symmetry condition at the median plane of the sheet.

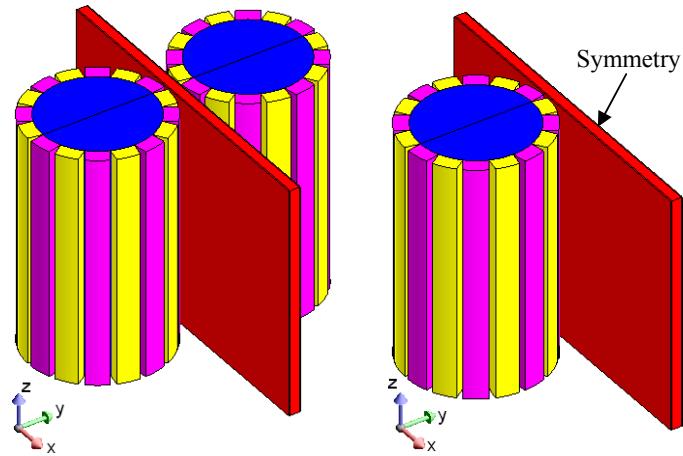


Fig. 11. System for heating metallic sheets with two inductors and no concentrator

#### *A. The geometry, mesh and the physical properties of the two problems*

The rotating motion of the inductors generates eddy currents on both sides of the sheet and the Joule effect of these currents generates heat. The number of poles, the geometrical dimensions, the thermal problem, the inductors rotation speed, the mesh, the physical properties of the both problems and the multiphysics solving method are the same as in previous case, except the lack of the concentrator region.

The transient magnetic computation domain is presented in figure 12.

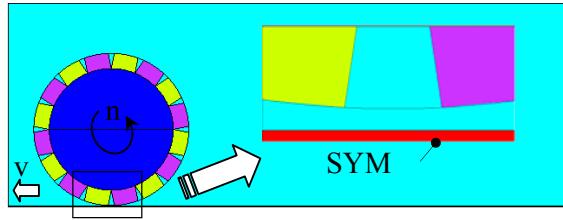


Fig. 12. Transient magnetic computation domain

### B. Results analysis

The objectives are the determination of the induced currents density, the computation of the mean of the induced power density and the stabilized temperature. In this case, the stabilized temperature for the same continuous heating speed or for the same heating time may be double than the previous case because the eddy currents are induced on the both sides of the sheet. The chart of the eddy currents density on the sheet is presented in the figure 13.

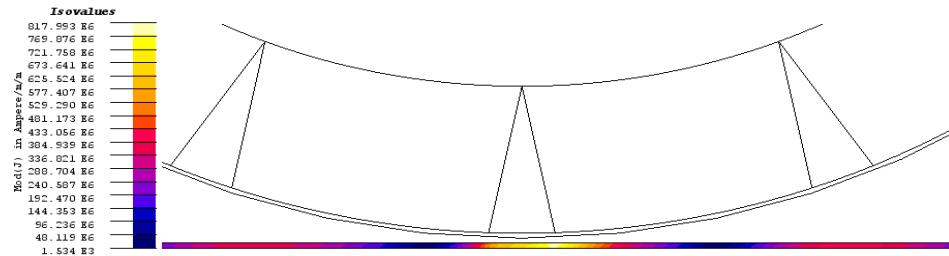


Fig. 13. Chart of the eddy currents density

The charts of the mean power density and the corresponding temperature at the first thermal time step are presented in figure 14 and 15.

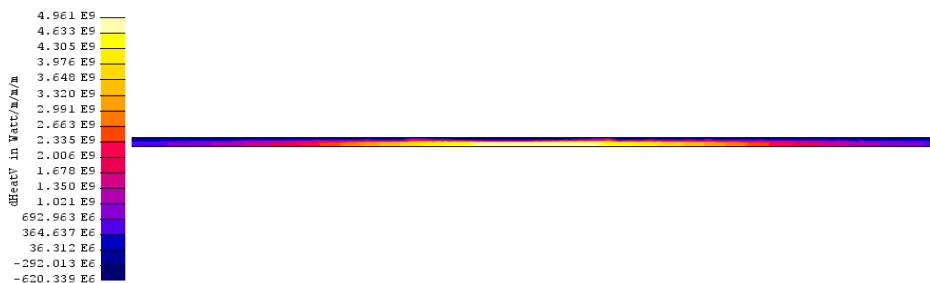


Fig. 14. Chart of the mean volume density of the induced power

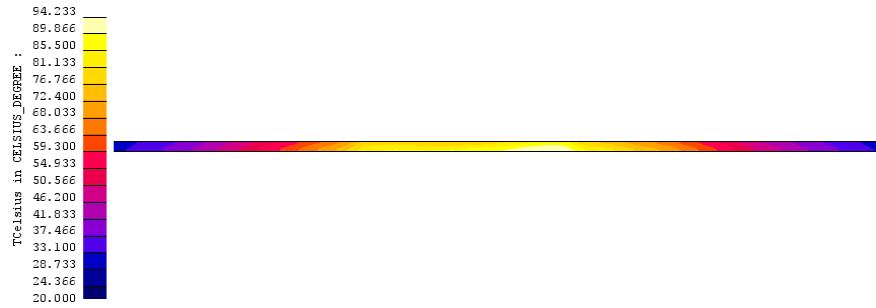


Fig. 15. Chart of temperature after at the first thermal time step

The mean volume density in the initial position of the inductor ( $1 \times \Delta x = 25 \text{ mm}$ ) and after six displacements ( $6 \times \Delta x = 150 \text{ mm}$ ) are presented in figure 16 and the corresponding temperature with comparison for both presented cases is presented in figure 17.

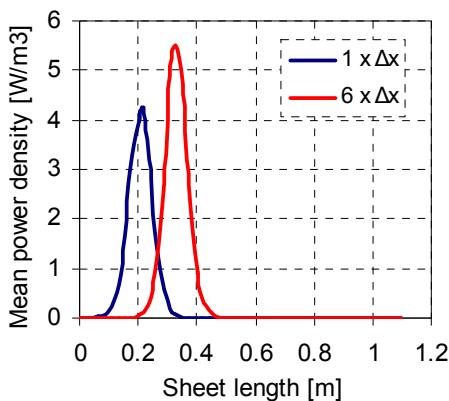


Fig. 16. The mean power density in the metal sheet for two positions  $\Delta x$

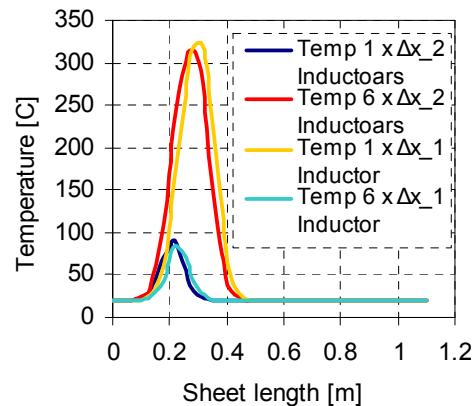


Fig. 17. The corresponding temperature of the metal sheet for two positions  $\Delta x$

The temperature in the initial position and after six movement of the inductor has the same value for both studied cases. The induced power in this case is  $P = 480,3 \text{ kW}$ , double in comparison with the previous case. This means that for the same desired temperature  $T = 350^\circ\text{C}$ , the heating time will be  $t_{\text{th}} = 1,21 \text{ s}$ , and the continuous heating process speed will be  $v = 0,11 \text{ m/s}$ .

#### 4. Conclusions

The paper presents the possibility and the efficiency of continuous thin metallic sheets heating with rotating permanent magnets system. The main objectives are the computation of the heating time and the continuous heating process speed for a desired stabilized temperature of the sheet. The system with two inductors and no concentrator increase the temperature and eliminate the mechanical problems caused by the concentrator.

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