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Simplified simulation technique of rotating, induction heated, calender rolls for study of temperature field control

Abstract: Predictive computer simulation of the temperature field control system of an induction heated object encounters difficulties associated with the nonlinearityof systemon the one hand,and the time of calculation on the other hand, during numerical analysis of the magneto-thermal field of the object, especially in 3D. The paper presents a methodology for the fast simulation of temperature field for a completed induction heating system of calender rolls. The method of 3D calculations of rotating calender rolls with a moving web of wet paper can be connected easily with a simulation of the temperature field controller, for simulation of complex control systems.

Keywords: induction heating, temperature distribution control, calender rolls

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1 Introduction

One of the final stages of the production of paper and paperboard is the process of its honing, so-called calendering. This consists of passing the paper web through a set of rollers which give it the proper thickness, shine and smoothness. This process is implemented in the final stage of drying the paper, the most energy intensive manufacturing cycle. In the drying section the paper web is usually drained by using rollers heated by steam. The calender rolls can alternatively be heated by induction [1], which is especially useful in recently developed high temperature calandaring [2–4] technology. The induction heating method gives the possibility of local heating to chosen areas of the roll to reduce non-uniform temperature distri-

bution caused by for example differences of moistening of the paper. The temperature stability of the rollers helps to maintain their constant diameter, and thus helps to maintain a constant thickness of the paper web. The induction heating method can be used as local overheating of the calender cylinders already heated by the steam or can be used separately. The systems of inductors (see Figure 1) can be used to dynamically correct for the temperature distribution along the rolls, to eliminate the adverse effects of various types of noise (e.g. different humidity of the moving paper web). In this case we can distinguish two different research tasks: design the induction heating setup and design the control system of temperature field distribution, which will be able to maintain quickly and steadily the desired temperature distribution along the calender roll. The design and test of such a complex nonlinear control system with several moving inductors, should base on computer simulation process combining the simulation of control systems and simulation of inductors, i.e. the calendering roll system (control object). A similar situation occurs in a control system supported on-line by computational prediction.
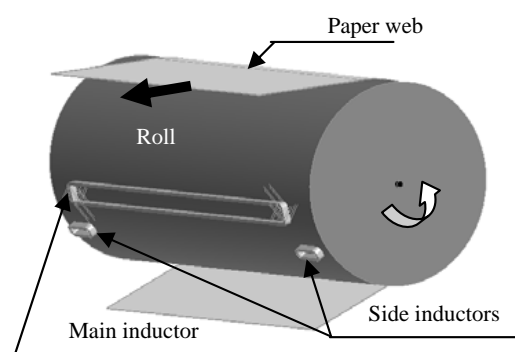

Figure 1: Induction heated calender roll

Unfortunately the simulation model of the induction heated calender roll (3D, nonlinear, including rotation motion and linear motion of an infinite web of paper, Figure 1)

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seems to be very complicated, and the time of its numerical analysis is usually unacceptable for such an application.

This paper presents a methodology of constructing a simplified model of the induction heated calender roll, which can be used to simulate complex temperature distribution control systems.

2 Numerical simulation of the induction heating of the rotating cylinder

The uniform induction heating of rotating cylinders can be realized in practice by different types of inductor systems, for example a relatively simple solution is one main inductor and two additional side inductors, Figure 1. Regardless of design, the ability to simulate the electromagnetic and thermal fields associated with the rotating cylinder is helpful. It is best if coupling of the inductor-charge system with the energy source is taken into account [5, 6] too. Additionally, the heat exchange existing between inductively heated rolls and a dried wet web of paper (or cloth) is difficult to analyze.

The mathematical analysis of such a system, as briefly shown in Figure 1, is carried out by solving Maxwell equations describing the magnetic part and Fourier-Kirchhoff equations describing the thermal part.

To show the difficulties of simulating the system leading to long time of calculation, the simplified system, Figure 1, without the web of paper, has been calculated first. It was done for a rotating steel cylinder with diameter D = 600 mm, length L = 1250 mm and wall thickness g = 7 mm.

The problem was considered by FEM, solving a coupled electromagnetictime harmonic field with transient thermal field, using the commercial Flux program.Taking into account the size of the considered model and power supply frequency f = 20 kHz, the surface impedance method for solving electromagnetic field was used.

For an assumed rotating speed θ = 40 rpm the time of one full rotation cycle is t_r = 1.5 s, which for the time step Δt = 0.03 s gives 50 steps of cylinder motion during its one cycle of rotation. As an example, for the current I = 500 A and I = 300 A in main and side inductors respectively, the distribution of the eddy current (Figure 2a) and the temperature in the load (Figure 2b) after time t = 12 s are presented. The total power dissipated in the load was about 13.5 kW. As it can be noticed after eight cycles of rotation (t = 12 s), the cylinder temperature increased only about

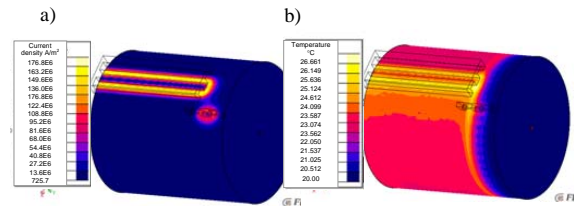(3÷6)°C, but it required 400 expensive, coupled calculations.

Figure 2: The distribution of eddy current (a) and temperature (b) of an induction heated rotating roll, after t = 12 s of its heating

This example confirmed that for the considered inductor-load system, the typical FEM approach of solving coupled electromagnetic, thermal and motion (even without linear motion of the paper web) physics, is not appropriate for the control system simulation. Taking this into consideration, and additionally that the temperature of calendering rolls typically changes only a few degrees, another approach based on the one hand on partial decoupling and on the other hand on simplified modeling of the moving paper web, has been suggested.

3 Simulation of induction heating of rotating cylinder with wet paper web

In the work [7] the simplified method of simulation of heat transfer between calendering roll and paper is presented. By combining thermal conduction and existing thermal conditions with energy balance, the movement of the paper web can be neglected, as it is shown (for 2D model)in Figure 3. As can be seen, two types of cylindrical surfaces (in 3D volumes) have been created: rotating (steel roll) and non-rotating (generally representing heat sources and sinks). There is no thermal resistance between these two types of region. The fixed regions may represent this part of roll surface where power is dissipated (regions under inductors), as well as areas of intensive heat removal (in contact with the wet web of paper). This approach may solve the problem of connecting the rotation motion of the roll with linear motion of the endless paper web. The material parameters of the area which represents the paper web can be treated as a function of the observation time. This makes it possible to analyze the dynamic effects of changing these parameters (e.g. moisture and temperature) on

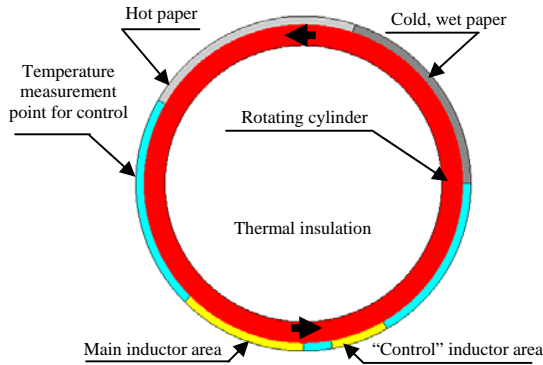the temperature of the rotating roller smoothing the paper.

Figure 3: The 2D model of heat transfer between the rotating cylinder and the moving paper web

In general, two main problems can be highlighted in the considered issue. Firstly, how to present and simulate the induction heating (power generation), and secondly how to simulate the heat transfer to wet web, its drying and heating.

It was assumed that the large roll diameter in comparison to the circumferential size of inductors, as well as the skin effect and high speed of rotation, means the integral of volumetric power density dissipated in the roll (along the circumference and thickness of the cylinder wall)can be used in thermal calculations, instead of the actual distribution of volumetric power density. This leads (in 3D) to the usage of the linear power density distribution along the length of the cylinder in thermal calculations.

Taking into account that the temperature of calendering rolls changes during the work only about a few degrees, the linear power density along the length of cylinder can be calculated (for roll working temperature) by electromagnetic calculation not coupled with the thermal calculations. This allows a significant reduction in considered area and the omission of motion, as is shown in Figure 4. For example, in Figure 4a the volumetric power distribution on the surface roll under the inductor and calculated linear power density along a generatrix of the cylinder, for two values x of position of the side inductor (for the same inductor parameters and power supply as assumed above), is shown in Figure 4b.

The calculated linear power distribution for 3D analysis or power for 2D can be used as the power source in "Main inductor area" or "Control inductor area", Figure 3, in considered simplified thermal model of rotating cylin-

der and moving paper web. It can be [7] used for simulating both the process of induction heating of a calender roll without paper web, and when the roll (on part of its circuit) has contact with wet paper web, as shown in Figure 1.
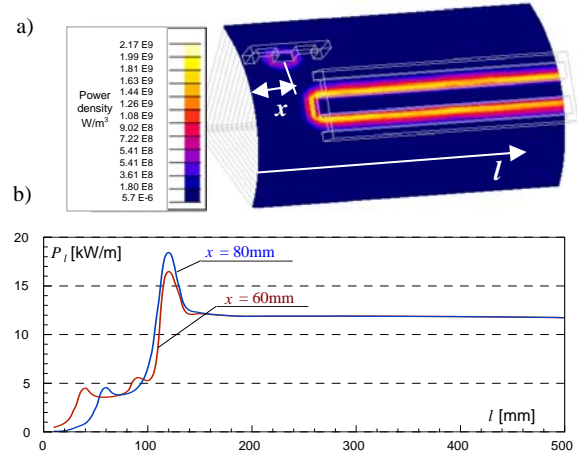

Figure 4: The volumetric (a) and linear (b) power density distribution, in the considered part of stationary cylinder

During the time Δt_c of contact, the paper web is warming up from temperature ϑ_{in} to ϑ_{out} close to the temperature of cylinder ϑ_{cyl}. The average ϑ_{av} temperature of the paper cross section achieves $\vartheta_{av} > 0.95 \cdot \vartheta_{cyl}$ usually in a time Δt less than the time Δt_c. Taking this into account the area of the cylinder-paper contact can be divided into two areas, referred to as "cold paper" and "hot paper". In a such situations it can be assumed that in a "hot paper" area there is no energy accumulation in the web paper but the area (Figure 3) "cold paper" should consume the power ($\vartheta_{av} > 100°C > \vartheta_{in}$) with volumetric density [7]:

$$p_v = -\frac{[c_{pap} \cdot (\vartheta_{av} - \vartheta_{in}) + w \cdot c_{vap}] \cdot \rho_{pap}}{\Delta t} \cdot \frac{g}{g_m} \quad (1)$$

where: ρ_{pap}– paper density, c_{pap} – specific heat of the paper, c_{vap} - water vaporization heat, w – paper moisture, g – real thickness of paper web, g_m– thickness of paper web in the simulation model.

The value Δt of time should be chosen in such a way that for a cylinder rotating at speed θ, described by (2) the angular part $\Delta\psi$ of the cylinder which adjoins the "cold paper" would be less than angular part $\Delta\psi_w$ of the cylinder that adjoins the whole web of paper,

$$\Delta\psi = \frac{\theta}{60} \cdot 2\pi \cdot \Delta t \quad (2)$$

where: θ- rotating speed in rpm.

Using the above method, the calendering process with induction heated roll was simulated. As an example it is

presented in the case of paper web width $2 \cdot w_p = 1$ m, with $\vartheta_{in} = 120°$C and $\theta = 40$ rpm (so in expression (1) $w \cdot c_{vap} = 0$). It is assumed that the roll has already been heated to a temperature of approximately 200°C and the longitudinal distribution of linear power density is as in Figure 4b, for $x = 80$ mm. In Figure 5 the temperature distribution which occurs along the cylinder, in the half of its angular part adjoining the paper web, was presented.

The example of longitudinal temperature distribution, Figure 5, presents the very important problem of calendering.

Non-uniform temperature distribution leads to differences in roll diameter, which leads to differences in thicknesses of the treaded web of paper. As shown this nonuniformity depends on the web of paper and its parameters (temperature, moisture, etc.)
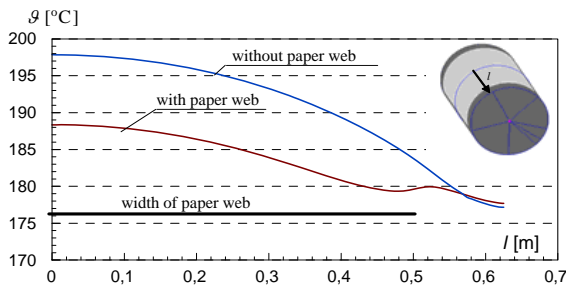

Figure 5: The temperature distribution along the length of the rotating cylinder with and without paper web

This requires correction which is possible when the induction heating method is used. This can be realized by the set of additional inductors, ("control" inductors) which can be similar, Figure 6, to the side inductors mentioned above or a mobile inductor [8]. The work of such a mobile inductor should be controlled (position and dissipated power) in order to stabilize the uniform temperature distribution regardless of disturbance by the paper web. The exact shape of such an inductor and the associated special control system can be determined by using the presented method to simulate the calendering system.

The distribution of the linear power density in the roll for an additional "control" inductor can be calculated, as done above for a main inductor, by separately solving the electromagnetic numerical model of the inductor, Figure 6.

For magnetic parameters of a steel cylinder described by saturation $J_s = 1.9$ T and initial magnetic relative permeability $\mu_r = 1000$, the distribution of linear power density $P_{l,con}$ dissipated in the cylinder along direction s (Fig-
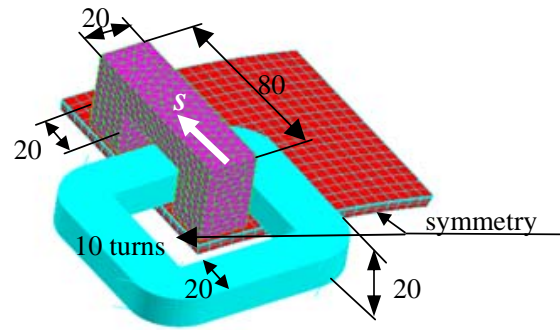

Figure 6: The simulation model of "control" inductor-steel cylinder system

ure 6), for two different values of current in a 10 turns inductor ($f = 20$ kHz), is shown in Figure 7a. The average value of the linear power density for each of the eight highlighted sections (10 mm width) of the "control" inductor was calculated.

During simulation of the temperature control process, the distribution of power in the roll (induced by the "control" inductor) is controlled to obtain the required temperature distribution. The distribution of the linear power density $P_{l,con}$ generated by the "control" inductor is calculated in another numerical model and only then the results are transmitted to the thermal model, which is used for simulation of the control system. Additionally, we must remember that the steel roll is a magnetic nonlinear material, so there is also a nonlinear relationship between current in the inductor and generated power. Taking this into account, for the "control" inductor not only distribution of linear power density $P_{l,con}$ but also the linear resistance $R_{l,con}(I_{ind},n)$ as a function of inductor current I_{ind} (has influence on magnetic field strange) for each n section of cylinder, Figure 7b, under the "control" inductor must be calculated:

$$R_{l,con,n} = \frac{P_{l,con,n}}{I_{ind}^2} \tag{3}$$

The magnetic non-linearity has direct influence not only on the resistance, but on the inductance $L_{total,con}$ of the system too (Figure 7b),which in turn has an impact on the resonant frequency of the power supply inverter and in this way (penetration depth) again on resistance. This should be taken into account when in the thermal calculations the distribution of the linear power density $P_{l,con}$ is calculated, based on the above linear resistances (3).

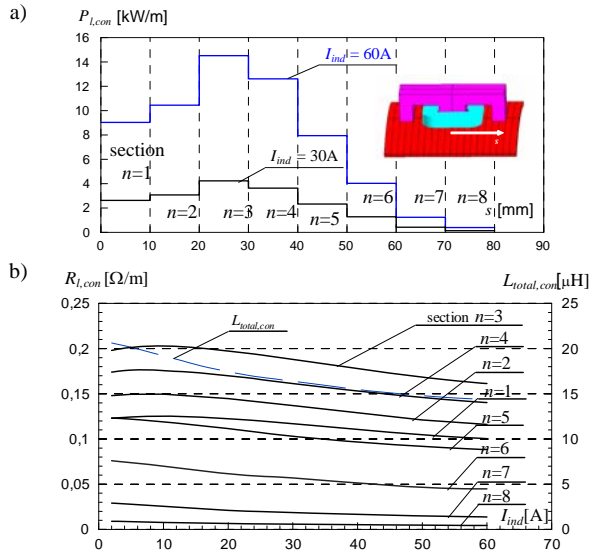The initial electromagnetic calculations are realized as time harmonic for constant frequency values (in that

a)

b)

Figure 7: The distribution of the average linear density $P_{l,con}$ of power in each n section on cylinder (a), the linear resistance $R_{l,con}$ of sections and inductance of the system $L_{total,con}$ as function of effective value of inductor current (b)

example for $f = 20$ kHz). Assuming, that the imposed frequency occurs, in real setup, for inductor current close to the zero values $I_{ind} \rightarrow 0$, the calculated linear resistance $R_{l,con}(I_{ind}, n)$, Figure 7b, should be corrected (in thermal calculations) in accordance with:

$$R_{l,con}^{corr}(I_{ind}, n) = R_{l,con}(I_{ind}, n) \cdot 4\sqrt{\frac{L_{total,con}(0)}{L_{total,con}(I_{ind})}} \quad (4)$$

where: $L_{total,con}(0)$- inductance of the system for $I_{ind} \rightarrow 0$.

Equation (4) gives an approximate account of the effect of the current value (by the value of inductance $L_{total,con}$) on the resonant frequency and then (by varying the penetration depth) on the linear resistance of the charge.

The presented methodology was tested in the case of simulation of the temperature distribution control system (see Figure 8) by joining the work of two commercial programs, Flux and Portunus. In the FEM program (Flux) the temperature ϑ 3D distributions were calculated. Additionally, for paper web the average (on the thickness) temperature ϑ_{ave} along the width $2w_p$ of paper web and average temperature ϑ_{contr} on the "control" inductor width $2w_{contr}$ (used for control) were calculated. In the presented example the "control" inductor was used to correct temperature distribution around the edge of the paper web. It was placed in such a way that its axis of symmetry was located at a distance of 30 mm from the edge of the paper web (location of the minimum temperature), Figure 5.
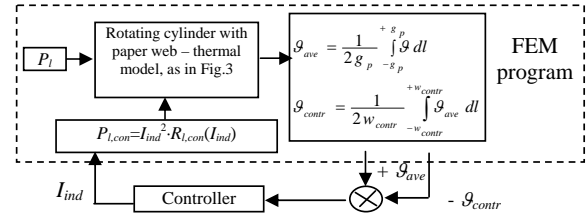

Figure 8: A block diagram of the simulation model for the control of temperature distribution for induction heating of rotating cylinder with paper web

For a simple P controller with gain 10, Figure 9a shows the surface temperature distribution around the perimeter of the cylinder on its symmetry surface (no "control" inductor influence) and on symmetry surface of "control" inductor (after two and three rotations, 3 s and 4.5 s). Figure 9b shows the longitudinal temperature distribution under the paper web, for 3 sand 4.5 s after switching on the temperature control system.
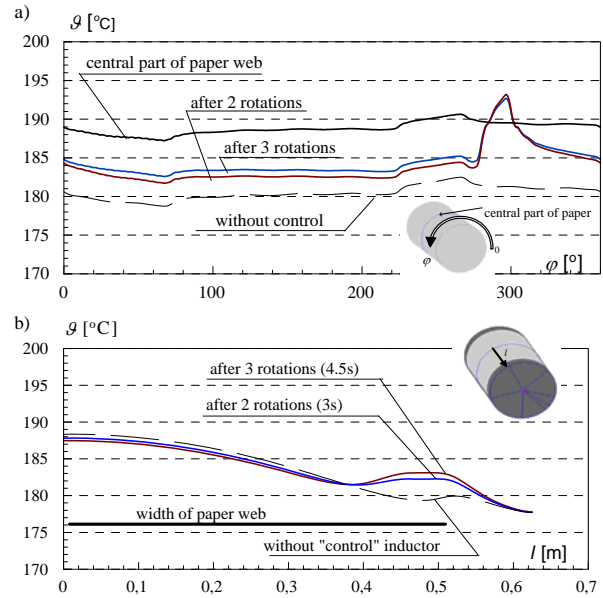
a)

b)

Figure 9: The temperature distribution along the circumference (a) and the length (b) of the rotating cylinder with temperature control system

4 Conclusions

The temperature distributions in Figure 9 show that the method presented above may be used to simulate a 3D temperature field control system for the induction heating of the rotating steel roll with a linear motion of paper web taken into account. The resulting temperature distribution along the cylinder length, seen in Figure 9, is obviously not satisfactory, but the aim of the present study was not to optimize the inductors but to present the simulation methodology. The presented method is suitable for the fast simulation of the whole control system including the process of calendaring, with 3D FEM calculation of induction heating, considering the rotation (roll) and the linear movement (paper). The methodology can take into account the magnetic and the thermal nonlinearities of the system, on the one hand, and allows simulation of the problem within a reasonable time, on the other hand.

References

[1] Urbanek P., Skorek A., Zaremba M.B., Magnetic-Flux and Temperature Analysis in Induction Heated Steel Cylinder, IEEE Trans. Magn., 1994, 30, 5, 3328-3330.

[2] Matsumoto Y., Induction Heated Jacket Roll-High Temperature Calender Roll for Paper Finishing, Japan TAPPI J., 1998, 52, 4, 520-524.

[3] Nakano S., Induction Heated Jacket Roll for High Temperature Calender, Japan TAPPI J., 1999, 53, 8, 1031-1033.

[4] Fujimoto K., The Instance of Soft Calender and Hard Nip Calender with Induction Heated Heat Pipe Calender Roll, Proc. of 55th Appita Annual Conf., Australia, 2001, 377-388.

[5] Zgraja J., Computer simulation of induction hardening of moving flat charge, IEEE Transaction on Magnetics, Vol. 39 (2003), no 3, pp. 1523-1526

[6] Zgraja J., Simulation of Induction Hardening of Flat Surfaces of Moving Massive Elements, Int. Journal of Materials & Product Technology, 2007, 29, 1/2/3/4, 103-123.

[7] Zgraja J., Simplified model for simulation the heat transfer between induction heated calender rolls and wet paper, Przeglad Elektrotechniczny, 2011, 11, 85-88, (in Polish).

[8] Fraczyk A., Kucharski J., Surface temperature control of a rotating cylinder heated by moving inductors, App. Therm. Eng., 2017, 125, 767-779.