DESIGN AND DEVELOPMENT OF A ROLLER WITH EMBEDDED HEATING FOR UNIFORM TEMPERATURE GENERATION

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Abstract: This paper provides design experience based on 2D FE electromagnetic and heat transfer analysis that are used to support product development. An induction in-roll heater is analyzed, tested and verified. The scientific challenge is to develop fast and fair models to provide design guidelines for layout specification, material selection and performance estimation. The transferred energy capability and efficiency are the essential performance figures focused on the first hand in prior to temperature distribution and profiles.

Keywords: Induction heating, Design, numerical field computation, Finite element method.

1. INTRODUCTION

This article presents the design process for a product development based on internal induction heating of roll units. An elegant solution is to embed the inductor inside of the roller, closed by end plates and supplied with current and cooling water through the shaft to which the roller is connected with bearing. The goal for the design process is not just solve a specific engineering task rather than present the design sequence from the rough dimensioning towards an cost efficient design specification and product realization. The power capability and energy conversion efficiency are the explicit value for dimensioning of the induction heating unit. The main focus is directed towards the electromagnetic design of a 10-40 kHz excitation unit. Therefore the selection and this dimensioning of the excitation coil and the supporting magnetic core have the key issue for the electromagnetic design and optimization (Bianchi, 1992) and the heat transfer analysis remains a resulting interest after the power loss generation and distribution is solved. Ultimately the design and analysis should contribute to the manufacturing and facilitating the selection of heater coils for uniform heat and temperature generation. Due to high computation cost of 3D finite element analysis (FEA) a whole sequence of 2D FEA is developed in order to support product development and practical realization. The work is carried out in several steps. The first one is to analyze the principles for a rough dimensioning of a cross-sectional layout of the primary coil in relation to power transfer capability and efficiency, and to compare the suitability of a longitudinal and transversal coil arrangement (Fig. 1). The second part of the work focuses on an analysis of the manufacturing options for a transversal flux inductor layout for an in-roll induction heating system. The third stage of this work is the practical experimentation and model evaluation, where transferred power density and efficiency supports the choices of material models and properties.

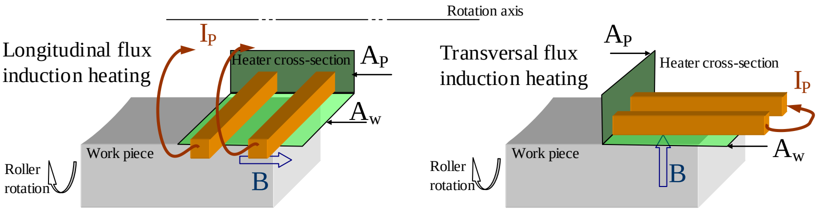

Fig. 1. Principal sketch of a fraction of in-roll unit with longitudinal and transversal flux induction heating. Two areas of interest: A_p – cross-section of heater and A_w – heating area.

The primary goal for an electromagnetic design is to relate a heater construction with a geometric layout and material selection to a transformed power capability and efficiency. Generally, a specific heating power, which is the transferred power per unit of magnetizing surface (A_w – heating area in Fig. 1), is the convenient figure to specify the size and power for the induction heating. Therefore 2D FEA is used to specify the materials and the layout (A_p – heater cross-section in Fig. 1). The specific interest of this work is to study how a soft magnetic moldable composite (SM^2C) material meets the performance and the production requirements compared to other type of high frequency magnetic material. This material has low permeability and magnetic saturation and, as an advantage, power losses and allows easy manufacturing processes due to injection or rotocast molding (Svensson, 2012).

2. GENERIC MODEL FOR INDUCTION HEATER

The size/performance specification of an induction heater is influenced by 1) material selection, 2) design and production and 3) energy conversion capability and efficiency. Therefore a generic model – 2D FE cross-section of an induction heater is provided in order to identify the rough size of the device and also specify coarse design guidelines for further optimization and prototyping of the entire piece of equipment. This generic model is suitable both for a longitudinal as well as transversal flux type of heater. The geometric layout of the induction heater with a magnetizer and a work piece is shown in Fig. 2 left and the calculation flowchart in the right.

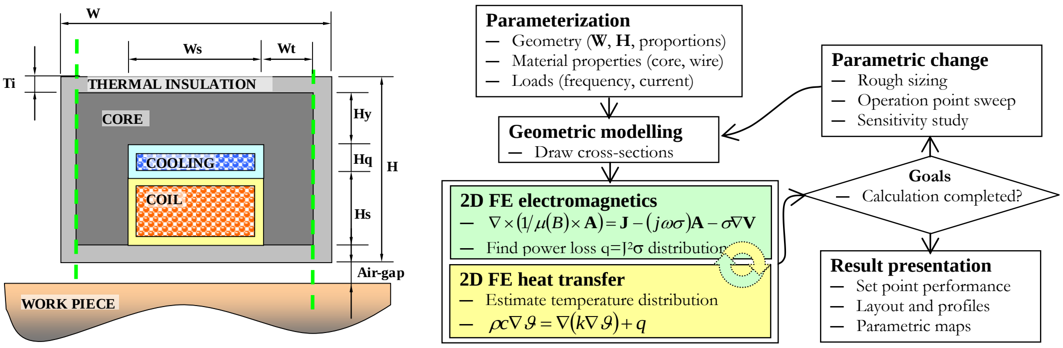

Fig. 2. Generic geometric cross-section of the induction heater (left) and the calculation flowchart (right).

The model cross-section (W·H) of the induction heater consists of a coil with a main electric insulation ($W_s \cdot H_s$) and without return path, an integrated cooling circuit ($W_s \cdot H_q$) behind the coil, a semi-closed magnetic core around the coil and the thermal insulation (T_i) around the induction heater. The geometric layout of the device is rather primitive and it can present either the cross-section of the longitudinal or transversal type of excitation coils. By far the other units can be adjacent to the one presented in Fig. 2. Green lines (Fig. 2) symbolize the symmetric boundaries to the adjoining unit if it is present. This model is used to obtain rough dimensions, material specifications and performance of the device. The challenging part of this FE model is adequately considering the material response to high temperature and high frequency. Therefore, for the sake of computation time it is desirable to carry out the electromagnetic analysis of the device at the nominal operation point and use the thermal model just for validating the thermal (cooling) conditions for the operation point. A overview on the different domains is given (Fig. 2) where the main concern is the practical choice of materials with adequate models for the electromagnetic and thermal analysis.

2.1. Excitation coils

From an efficient energy conversion point of view it is desirable that the power losses and the temperature are low on the heater (primary side) and the power losses and the temperature is high on the work piece (secondary side). It is assumed in priory that the winding operates at 120°C. The excitation coils carry a high frequency current that establishes time varying induction and power losses in the work object. Due to self induction the additional load appears in the excitation coil itself that because of high frequency and current displacement. In order to prevent these power losses the winding diameter of the conducting strands, the wire insulation and the spacing between the conductors are selected so that eddy current and proximity effects are both reduced. This can be controlled by using a proper Litz wire (Sullivan, 1999) and is defined with equivalent models in FEMM software (Meeker). The selected Litz wire has strand diameter 0.2 mm and fill-factor slightly below 50%. It is considered that this specification suits fine into the presumed range of operation frequencies from 10 to 40 kHz.

2.2. Integrated cooling system

A number of flexible plastic pipes are used to provide cooling straight behind the excitation coils. The water-cooling is defined by the average temperature of coolant that have expectedly the inlet temperature of 20°C and the outlet temperature about 80°C. The average coolant temperature, which is 50°C, is used as a fixed temperature in the thermal model.

2.3. Soft Magnetic Core

The magnetic core should not only shield the magnetic field and guide the magnetic flux into the air-gap, but should contribute to the heat dissipation of the excitation coils and support with the mechanical strength. There are a few examples of a wide variety of soft magnetic materials: 1) isotropic SM^2C with maximum magnetic permeability $\mu_{max}=15$ and magnetic saturation $B_{sat}=1.2$ T, 2) Ferrite $\mu_{max}=1500$, $B_{sat}=0.3$ T and 3) Vitroperm 500V (from Vacuumschmelze GmbH) $\mu_{max}=150000$, $B_{sat}=1.2$ T. These materials are given for comparison and rough electromagnetic dimensioning. The specific interest here is to investigate the importance of soft magnetic material to the performance of the induction heater as initially the devices have a large magnetic air-gap. As a matter of fact the SM^2C material provides the attractive production technique where the magnetic core is established by a material injection and low pressure compaction (Svensson, 2012). This material is initially chosen for the design and as the flux density of the induction heater is relatively low it is fair to use linear materials.

2.4. Thermal insulation

A thin layer of mineral insulation or wool is selected around the induction heater in order to separate the high temperature of the work piece from the low temperature of the heater. The values of the heat conductivities used in the model are the following: thermal insulation k=0.04 W/mK, electric insulation and cooling tubes: k=0.12 W/mK Litz wire conservatively k=0.3 W/mK and SM^2C about k=3 W/mK.

2.5. Work piece

The operation over a wide temperature range challenges the modeling of for the work piece. It is selected that at nominal operation point the electric conductivity of the work-piece is 0.73 MS/m. The work piece is austenitic stainless steel with a low relative magnetic permeability about 2.5. In the modeling it is first hand assumed that the relative magnetic permeability is 1 as for the saturated core and the worst case for magnetic coupling.

3. ROUGH SIZING OF INDUCTION HEATER

The cross-sectional area of W=50 mm times H=50 mm is selected as an initial size for the induction heater ($0.5A_p$ in Fig. 1). The objective of the analysis is to specify roughly the layout (Fig. 2), define the energy transfer capability as a function of inductor size and proportions, material selection, supply frequency and current. The active length is selected to be 1 meter long and there is no end-turns considered in this calculation. There are no other losses included in the calculation than the power losses in the excitation coil and in the work piece at the supply frequency.

3.1. Model initialization

Magnetic calculations resolve magnetic induction and induced power losses. These power losses are used as heat sources for the heat transfer model. Heat transfer steady state is used to determine not only the temperature distribution but also the cooling condition for the induction heater so that the coil temperature should not exceed 120°C. The screen shot of the flux density, current density and temperature distribution is shown in Fig. 3.

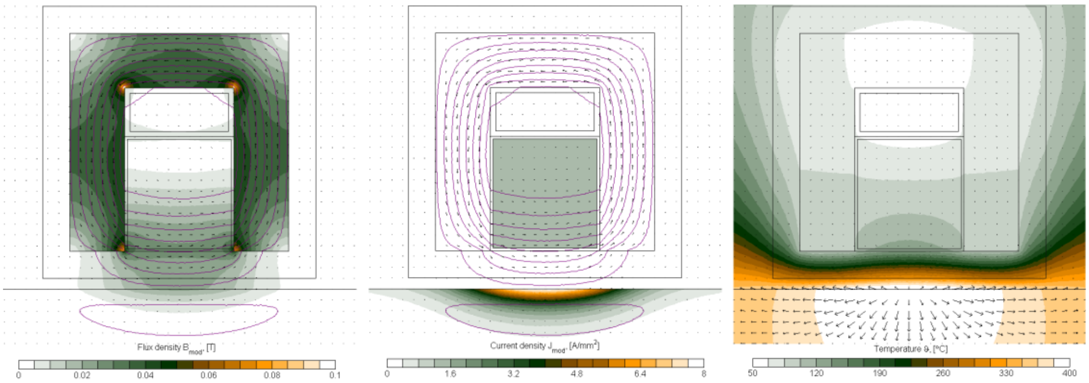

Fig. 3. Model outcomes at the initial calculation point where the width (W) and height (H) of the heater are equal. Flux density distribution at J_{1m}=4 A/ mm^2 (left), current density (middle) and temperature (right).

Apart from the energy transfer capability the transfer quality is also investigated. The qualitative aspects here are the heating profiles and power distribution over the magnetizing area (Fig. 4). It is considered that the cooling profiles are relatively homogeneous while the heating takes place where most of the eddy currents are induced.

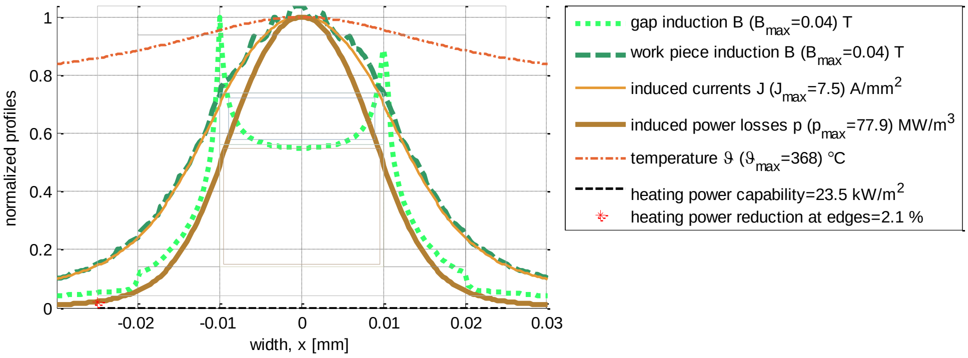

Fig. 4. Flux density distribution on the magnetising edge of the induction heater and flux density, induced current density and power loss density near to the surface of work piece.

3.2. Sensitivity study

The purpose of the sensitivity study is to provide design guidelines such as size, material and supply selection for the induction heater. The supply conditions present the influence of the frequency and current density to the transferred power capability, efficiency and power factor (Fig. 5). In this study it is shown that the power losses in the Litz wire is increasing faster with frequency than the transferred power in the work piece. Even though the increase of supply frequency and current density both add to the increase of the heating power the efficiency and the power factor are reduced with frequency according to this example.

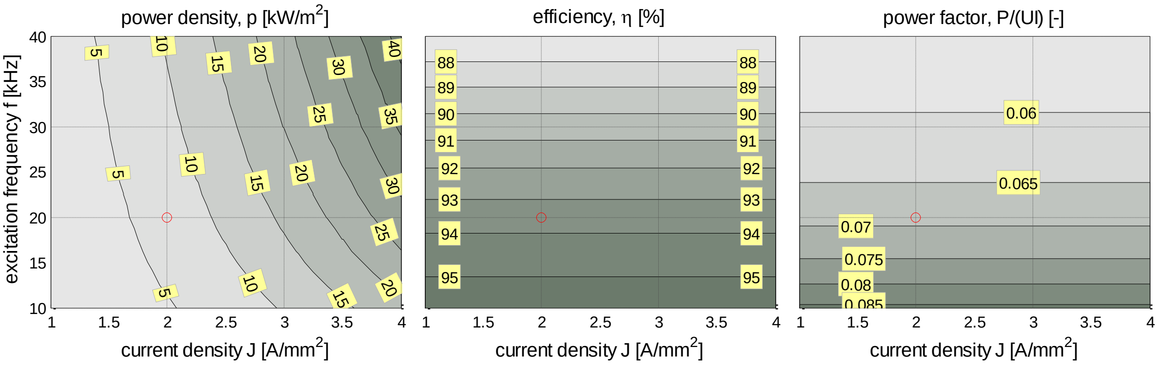

Fig. 5. Heater performance as a function of magnetizing frequency and maximum current density in the strands. Transferred power over the heater magnetizing surface (left), heater efficiency is defined as transferred power over the total active power (middle) and power factor: active power over the total apparent power (right).

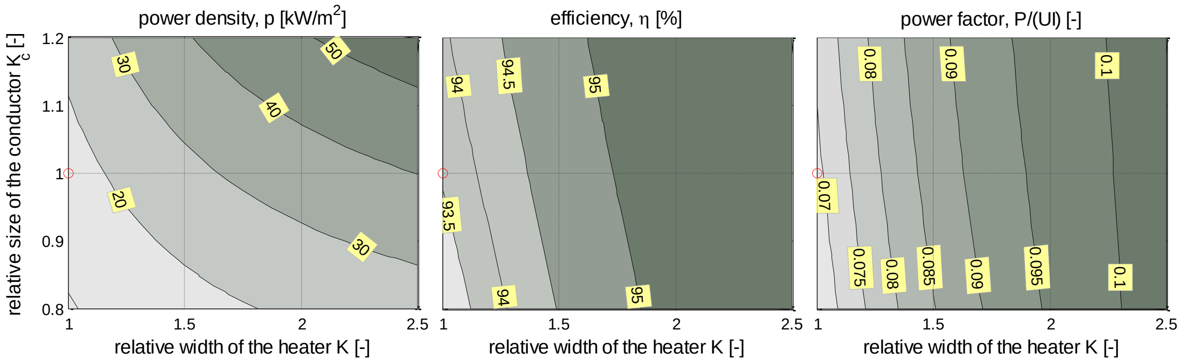

Fig. 6. Heater performance as a function of relative width and relative coil size of the heater.

The geometric arrangement of the induction heater ($K=(W-2T_i)/(H-2T_i)$) and the relative size of the magnetic core to the coils are shown in Fig. 6. In this analysis the supply frequency is selected 20 kHz and the peak value of the current density in the coils is chosen 2 A/mm^2. Along the horizontal axis the proportions of the induction heater is changed so that the heater becomes 2.5 times wider and also as many times lower. Inside this cross section the proportions between the magnetic core and the excitation coil is changed. This change is presented in vertical axis (Fig. 6), where the coil is changed 0.8 to 1.2 times of the original size where the coil width is half of the total pole magnetizer width ($K_c=W_s/2W_t=H_s/2W_t$). The analysis shows that the performance of the magnetizer is improved when it becomes wider and the size of the coil is dominating. This study is limited to a single core material SM^{2}C. The continuation of the analysis focuses on the selection criteria for the magnetic core and the influence upon the wide magnetic air-gap (Fig. 6).

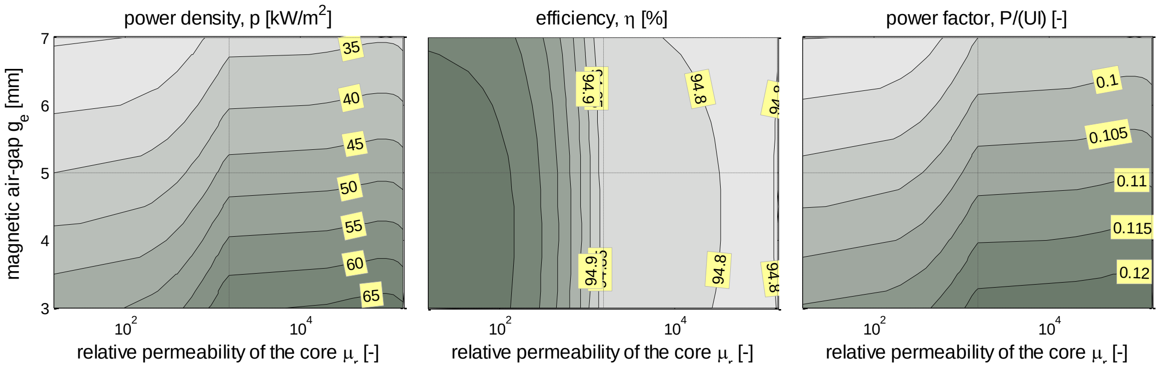

Fig. 7. Heater performance as a function of thickness of thermal insulation (magnetic air-gap) and core material.

The variation of the magnetic air-gap, which consists of the mechanical air-gap and the thickness of the thermal insulation, is relatively small, a few millimeters (Fig. 7), while the selection range of the core material is selected in three steps where the relative magnetic permeability is 15, 1500 and 150000. The low magnetic permeability means the material itself has an apparent air-gap and the development of the material properties improves the performance of the device. The improvement of the magnetic core properties have drawback of increased cost and manufacturing complexity.

4. IN-ROLL INDUCTION HEATER

The goal of the second step of this work is to specify, design and build an induction heater inside a roller. As the heater is located inside the roller it is called in-roll induction heater. Apart from the application requirements, which are the size of the roller and the simple realization process for prototyping, the specific aim of this part is to further develop a geometric modeler and FE analysis tool (Fig. 2) for the in-roll heater.

4.1. Coil topology selection

When comparing the excitation coil arrangements of a longitudinal induction heating to the transversal induction heating then it is obvious that transversal field heater can be designed for a sector heating while longitudinal field heater should have heating coil all around the inner roller periphery. It is vital that the longitudinal coils can provide rather equal heating along the longitudinal axis, while the coil design for the transversal flux heater should more be focused on the energy exchange over the end turn region. Fig. 8 shows the geometric layout of the end-turn region inside a cylinder that can be seen as a sector of longitudinal and transversal flux coil. Practically, it is not rational to require the sharp turn from xy-plane to rz-plane so that the conductors follow closely the surface of the work piece and the magnetic impedance remains the same along the conductor path. One perfect coil layout with a number of smaller Litz wires and practical arrangements are shown in Fig. 8.

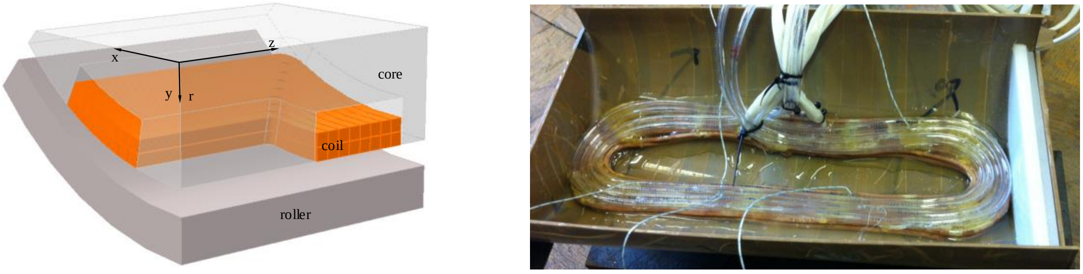

Fig. 8. Section of an excitation coil placed against the cylindrical work piece (left), and practical realization of inductor for in-roll heater (right).

4.2. Design for manufacturability

A number of test induction heaters have been built in order to study the practical arrangement of the excitation coils (Fig. 8 right). 2D FEA is preferred as it is considerably faster than 3D FEA and from manufacturing point of view only the 2D FE model can provide useful support of defining the size, selecting the materials and estimating performance. Therefore the scientific challenge is to provide fast computation tools for rational manufacturing guidance and realistic power estimation of the device.

5. MODELLING OF IN-ROLL HEATER

The design target is a transversal field induction in-roll heater where the specification of geometry and materials are shown in Table 1. The inner space of the cylinder determines the size of the in-roll induction heater.

Table 1. Layout and material specification for in-roll heater.

Part specification	Specific dimensions	Material type
Work piece, cylinder	D_o=217mm, D_i=194 mm, H=366 mm	Stainless steel, υ=0.73MS
Magnetic core	Relative magnetic permeability 15	Soft magnetic moldable composite
Litz- wire	Quadratic wire 3.5, 7.5, 11.5 mm	Copper, 0.2 mm strands
Electric insulation	0.5 mm thick	Polymer like or kapton
Thermal insulation	5 mm thick	Mineral wool, 0.04 W/mK

The first target of 2D model in multiphysics compromises rapid design to incomplete analysis results. The incompleteness is mainly related to the power loss modeling – only conductor losses are modeled and the limited thermal model that considers natural cooling of the stand-still roller. An overview of various coil arrangements for D_o/D_i 200/180 mm roller is shown in Fig. 9 and the outcomes in Table 2. Here the results are presented for 1 meter long roll. The excitation coils are excited with the same current density but they are showing rather different power density due to different field intensity and the ampere area.

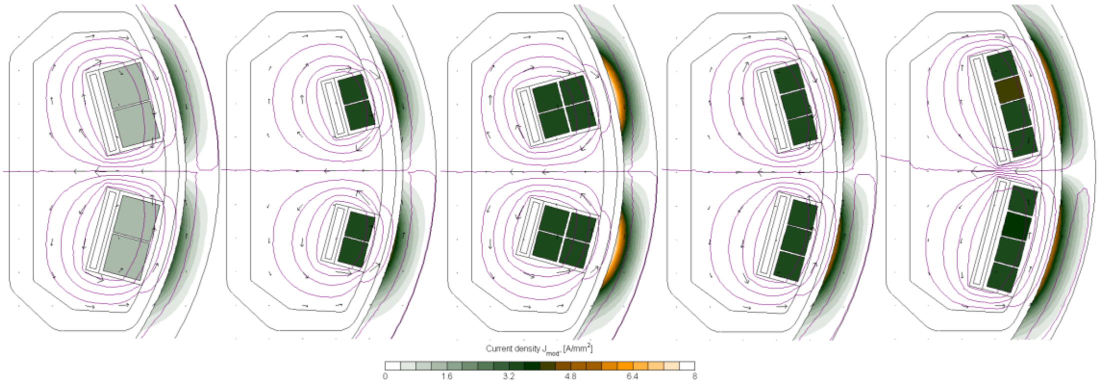

Fig. 9. Cross-section of a few proposed coil configurations.

Table 2. Comparison between the proposed coil arrangements (Ø200/180 mm, active length 1 m).

Coil arrangement	Voltage phasor [V] @19.1kHz	Transferred power [W]	Primary power losses [W]	Apparent power [kVA]	Power capability [kW/m^2]	Efficiency [%]
2x1 11.5x11.5 mm	$91e^{j83.4}$	849	67	9.1	9.1	92.6
2x1 7.5x7.5 mm	$114e^{j82.9}$	1124	102	11.4	12.1	91.7
2x2 7.5x7.5 mm	$516e^{j84.1}$	3752	373	51.6	40.4	90.9
3x1 7.5x7.5 mm	$192e^{j82.5}$	2088	158	19.2	22.5	92.9
4x1 7.5x7.5 mm	$264e^{j82.8}$	2845	210	26.4	30.6	93.1

The models of the built prototypes for D_o/D_i 217/194 mm roller are shown in Fig. 10 and the results are included in Table 3. These results are presented over the active length of the prototype and all the winding turns in series. Practically the parallel coil connections reduce the need for a high supply voltage and it is realizable as long the parallel inductances are nearly the same.

Table 3. Comparison between the prototyped devices (Ø217/194 mm, active length 0.34 m).

Coil arrangement	Voltage phasor [V] @19.1kHz	Transferred power [W]	Primary power losses [W]	Apparent power [kVA]	Power capability [kW/m^2]	Efficiency [%]
Prototype 1 (left)	$98.8e^{j79.4}$	2339.2	56.7	26.1	39.3	98.8
Prototype 2 (right)	$229e^{j78.7}$	698.5	18.6	7.4	11.8	97.4

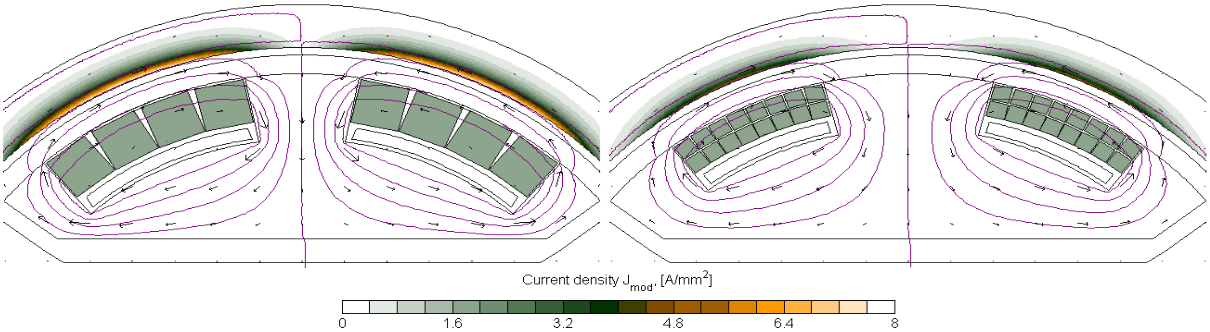

Fig. 10. Model of the prototyped heater units excited with 264 A (left) and 32 A (right) that gives 4 A/mm^2.

6. EXPERIMENTAL EVALUATION OF ROLL HEATER

The aim of the experimental evaluation is to focus on the power transfer capability and the efficiency. The induced power can be derived from the temperature response and more complex measurement of the temperature development due to the heating and cooling. More simple way to study the energy transfer capability of the device is to analyse the transformer parameters of the induction heater (Spagnolo, 2010).

6.1. Experimental setup and measurements

A transversal flux inductor with a curved geometry to follow the roller is designed according to the simulation model and manufactured based on 6 mm^2 Litz wire with 0.2 mm strand diameter. The coil is made of 2 parallel circuits, each with 8 turns, equipped with temperature sensors and cooling channels on the back side before being molded into SM^{2}C. The unit is then embedded in thermal insulation material in terms of 4 mm super wool. The impedance of the inductor coils is measured of the magnetically uncoupled set-up – coils in air and magnetically coupled when the heater coil is mounted inside the in-roll work-piece (Fig. 11).

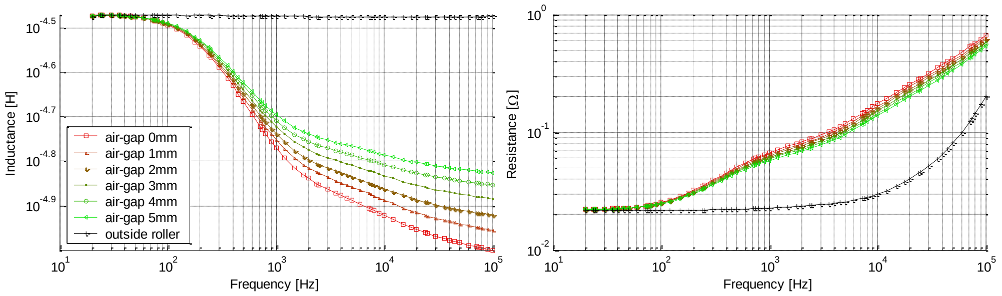

Fig. 11. Frequency characteristics of inductive heater as a function of inductor placement.

The length of the heater is 25 mm shorter than the austenitic stainless steel roller in order to be able to adjust the heater to find the optimal position in relation to the edge of the roller. The position of the inductor is critical to heat the roller uniformly, too far out results in overheating, while too far from the edge results in under heated ends. The best location seems to be where the inductor and roller start at the same point. Also the distance between inductor and the roller is critical, significantly affecting the system efficiency. The rotation distributes the heat evenly around the roller, which limits the task to heat the work piece uniformly along one dimension. Pictures of the setup are presented in Fig. 12.

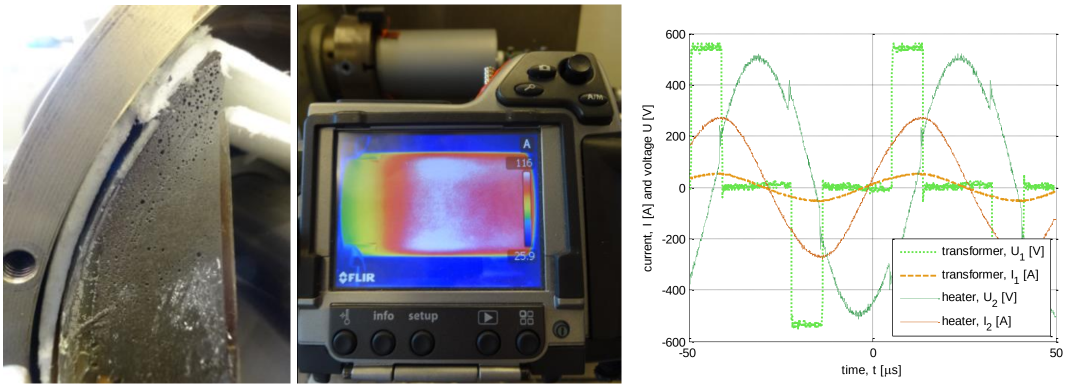

Fig. 12. Section view of the prototype induction heater inside the roll (left) and IR image of the induction heater system in operation (middle) and supply conditions close to resonance at 19.1 kHz (left).

6.2. *Heating power and temperature profiles*

The analysis of the heating pattern is performed using thermography. By integrating the thermal energy in the roller and measuring the electrical power, given the elapsed time it is running is known, the efficiency can be estimated. A number of experiments are done where the heating profiles are investigated. In Fig. 13 the temperature profiles are studied over the heating area (Fig. 12 middle) from the outer edge of the roller. The edge of the heater 1) is moved inwards, 2) is aligned, and 3) is moved outwards. The heating power is in range of 2.5 to 3.5 kW and the heating time less than 2 minutes before the outer surface temperature of the rotating roller reaches to the reference temperature of 80°C.

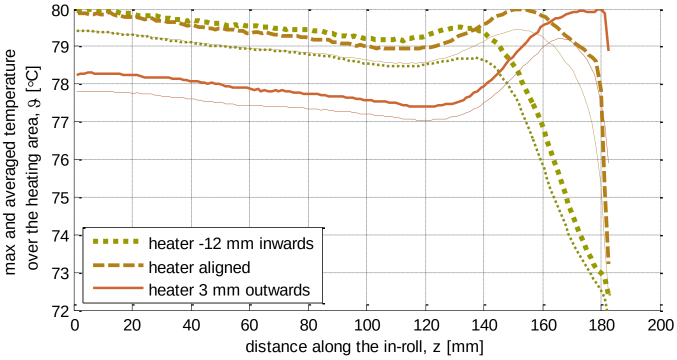

Fig. 13. Temperature profiles from the middle of roller towards the edge. Bold line presents the maximum temperature and thin line presents average temperature.

7. CONCLUSIONS

The aim of this paper is to provide practical design strategy: 1) rough sizing with power capability and efficiency in focus, and 2) layout specification for realization that is used for the development and production of an induction in-roll heater with transversal flux coils. Theoretically the continuous specific heating power can be as high as 40 kW/m^2 and it depends on the arrangement of the coil area and the average magnetizing flux path. The efficiency is more than 92% and higher for larger inductors according to theoretical estimation that includes the power losses only in the inductor coil and the roll. The experimental estimation of the efficiency that is based on the frequency response indicates that the efficiency is around 90%. The 2D FE electromagnetic and heat transfer models are incorporated to the product development so that the computation tool helps to define the circuit parameters and frequency response also the supply system, rough dimension the layout of the device and include the materials according to their availability. The practical arrangement and packaging of the end-turns so that they contribute to the uniform power loss distribution and heat generation is the remaining challenge and 2D FE fast design tool becomes clearly limited. Eventually a 3D FE fully coupled model is the best option to analyze induction heater as it can count the 3D and edge effects. At the same time the 3D FE becomes impractical when FE models are used for design and optimization. The usefulness of 3D is relevant in the stage of design refinement or analysis. Nevertheless, the scientific challenge is to develop models that are able to specify the device performance quickly and with reasonably high accuracy.

ACKNOWLEDGEMENTS

The work was carried out with the support of the Mistra, within the Mistra Innovation project In-Roll and Vinnova's Sustainable Production Initiative (SPI). This support is gratefully acknowledged.

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