Numerical and Experimental Analysis of an Electro-Thermal Coupled Problem for Transverse Flux Induction Heating Equipment

F. Dughiero, M. Forzan, S. Lupi and M. Tasca
Department of Electrical Engineering - University of Padua
via Gradenigo, 6/A - 35131, Padua, Italy

Abstract - **This paper describes a quasi 3D-FEM electromagnetic and thermal computation of transverse flux inductors used in the metal industry for the continuous heating of metal strips.**

The coupled steady-state eddy current and thermal problem is solved for the prediction of the temperature distribution in the workpiece, a fundamental step towards the optimum design of the inductors.

The computation has been used for the design of a heater for the continuous heat treatment of golden or silver metal strips. The suitability of the method here presented for the optimum design of transverse flux inductors has been confirmed by measurements on a laboratory prototype with thin silver strips workpieces.

Index terms- **Eddy current, finite elements method, induction heating.**

I. INTRODUCTION

In the last few years big research efforts have been done in different countries for the optimization of Transverse Flux Heaters (TFH) for heating plates, strips and thin slabs. In fact, this type of equipment has considerable advantages over the conventional Axial Flux Heaters, due to the need of lower frequencies, less reactive power and the inductor's geometry which, not encircling the workpiece, is particularly suitable for continuous processes. Moreover, the optimal design of the inductor, allows the designer to minimize the critical influence of the position of the inductor's edges relative to the workpiece width on the temperature uniformity in the strip cross-section at the inductor outlet, which is usually a stringent specification of the technological process [1,2]. In fact, the primary objective of the design is to obtain a uniform temperature distribution over the cross-section at the inductor's exit for different workpiece dimensions and materials. Many design parameters can influence the final result, e.g. the number of poles of the inductor, its geometric shape, the shape of the magnetic yoke, the frequency of the exciting currents. The solution of this problem is not easy because of the big number of parameters involved and the fact that both the electromagnetic and thermal patterns are coupled and fully three dimensional. The problem has been solved developing and testing a calculation procedure which couples a quasi 3D transient thermal solution with a 3D eddy current one.

Manuscript received November 3, 1997

II. SIMULATION PROCEDURE

The calculation procedure starts from the solution of the electromagnetic problem, which gives as result the induced power distribution in the workpiece. This power distribution is then used as the input of the thermal problem, whose solution gives the temperature distribution. The flow chart of the full procedure is shown in Fig.1.

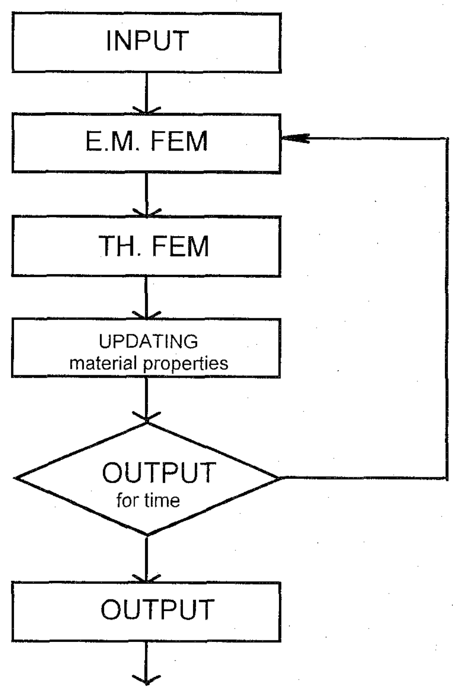

Fig. 1. Flow chart of the EM and thermal coupled procedure.

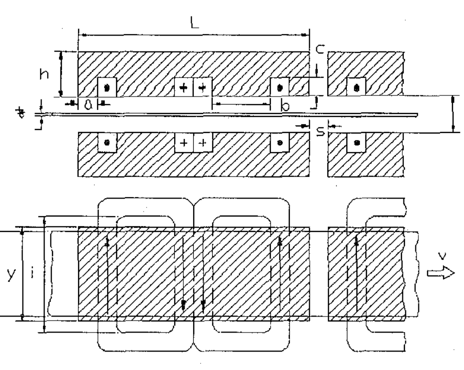

Fig. 2. Schematic of a transverse flux heater (TFH)

Starting from the general schematic of a transverse flux induction system shown in Fig. 2, three planes of symmetry can be defined. Thus, the numerical analysis can be limited to 1/8 of the total volume as shown in the model of Fig. 3. The computation of the electromagnetic field is performed on the basis of a finite element method. Meshes of 35.000-40.000 tetrahedral elements have been used, more dense in the workpiece in order to obtain a good resolution of the power density distribution in this region, which is characterized by one geometrical dimension much lower than the other two. The formulation is based on the H direct solution by the use of tangential elements, which are particularly suitable for 3D high-frequency eddy current problems. From the H solution it's easy to derive the power density distribution in the workpiece, which is the starting data for the thermal analysis. The workpiece is discretized into several subregions, as sketched in Fig. 3, chosen in such a way that for each of them, the power density distribution can be assumed practically uniform in the direction of the strip movement. Moreover, due to the relative low temperature differentials in the volume of each subregion element, electrical characteristics are supposed constant and corresponding to the average temperature of the element. All other main integral parameters can also be easily derived, e.g. inductor's equivalent impedance, electrical efficiency and power factor [3]. The solution of the thermal problem is obtained from the classical Fourier's equation:

$$\nabla \cdot \lambda \ \nabla T - c\,\lambda \ \frac{\partial T}{\partial t} = w \qquad (1)$$

(T is the temperature, t the time, λ the thermal conductivity, c the specific heat, w the induced power density) with non linear boundary conditions in order to take into account heat convection and radiation.

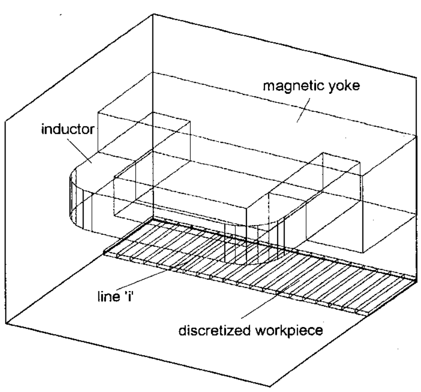

Fig. 3. Finite element model for electromagnetic calculation

The problem is solved considering the dependence of the thermal conductivity λ and specific heat c on temperature. The numerical solution is obtained also by finite element method using the Cranck-Nicholson scheme to solve the time dependent terms and the Newton-Raphson method to solve the non linear system. Since the workpiece is discretized in different elementary parallelepiped subregion elements orthogonal to the movement direction, the solution is obtained for the temperature distribution in the cross-section of one subregion at elementary intervals Δt. After one interval Δt this subregion has moved $\Delta s=[\Delta t \times v]$, where v is the strip velocity, then its new temperature distribution can be calculated starting from the final temperature values obtained at the previous interval Δt and the actual power distribution corresponding to the new position occupied by the element. The approximation introduced is that of neglecting the thermal heat transfer between adjacent elements in the movement direction.

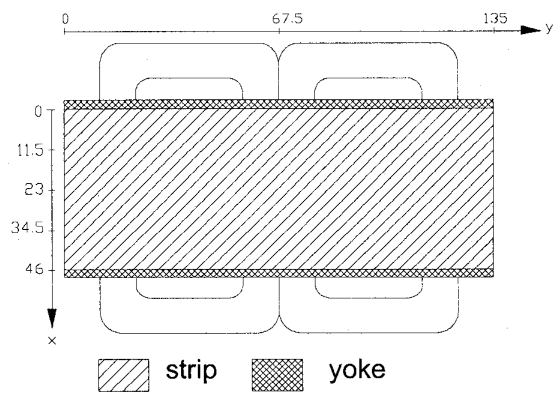

Fig.4. The simplified model.

As the real prototype of the inductor (Fig.5) built for the experimental tests is quite different from the ideal one shown in Fig. 4, a more complicated EM model was developed in order to perform a more accurate analysis. The solution of the new EM model, later in this paper called 'real model', requires a very long computation time.

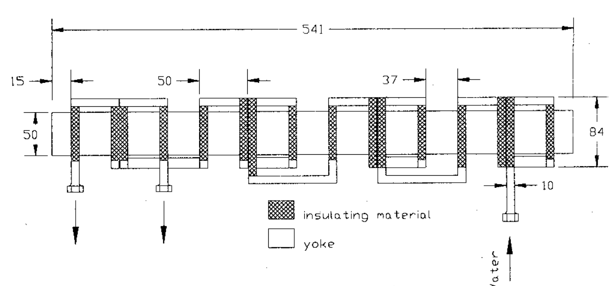

Fig. 5. The real inductor prototype.

The real model is shown in Fig. 6. The full analysis for the calculation of the thermal transient is constituted by the following iterative steps:

1. Solution of the EM problem for the first section of the inductor as in Fig. 4 or 6, respectively for the ideal and the real model.
2. Solution of the thermal problem, for the same section.
3. Updating of the EM characteristics of the materials.
4. Solution of the EM and thermal problem for the next section of the inductor.

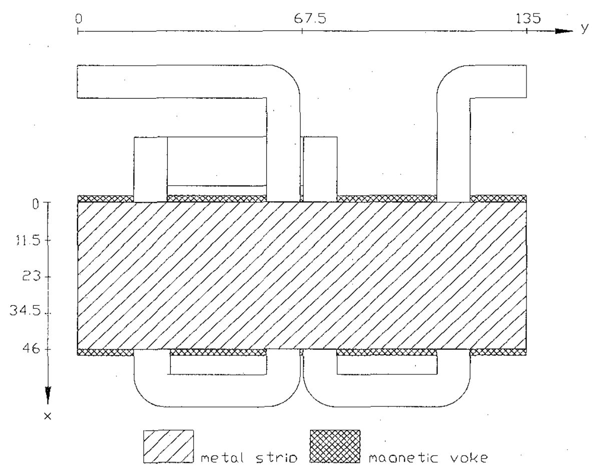

Fig. 6. The real model.

It should be pointed out that values of resistivity and temperature coefficient of the alloys used for the simulations have been derived from specific experimental tests.

An example of the results obtained by the simulation procedure previously described is shown in Fig. 7.

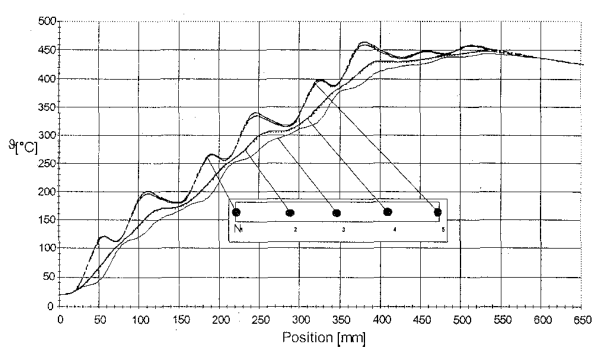

Fig. 7. Thermal transient for a silver strip obtained by the real model (f=1950 Hz, Strip Velocity 3.5 m/min, I=1130 A for the first three sections, I=565 A for the last section).

III. COMPARISON BETWEEN CALCULATION AND EXPERIMENTAL RESULTS

In order to validate the calculation procedure a series of experimental tests has been done.

In the experimental prototype the inductor consists of three sections (as in fig.6) conveniently spaced in the movement direction; the first three sections are connected in series and the fourth one is parallel connected so only ½ of the total current flows in it. The tests have been performed using thin silver strips. The temperature measurement have been done through sliding thermocouples placed at different points along the strip length.

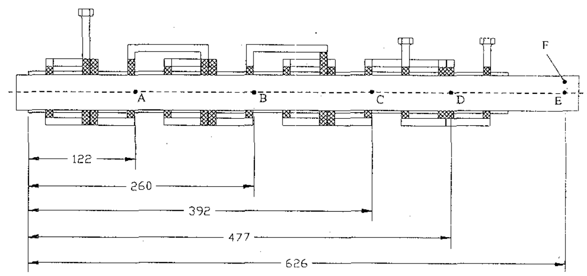

Fig. 8. Positions of thermocouples along the strip length.

The thermocouple error can be evaluated within ± 5 Celsius degrees for temperatures higher than 400 °C. Moreover, we have to add another error due to the position of the thermocouple; this error can be evaluated within ± 2 mm and this uncertainty of position influences the measured temperature. The strip velocity has also an uncertainty about ± 0.2 m/min.

Among a lot of tests performed, two different significant cases will be described in the following.

Table I
Data and results for the first experimental test.

PHYSICAL AND ELECTRICAL PARAMETERS	EXPERIMENTAL VALUES	NUMERICAL VALUES simplified model	NUMERICAL VALUES real model
Strip Velocity [m/min.]	3.5± 0.2	3.5	3.5
Frequency [Hz]	1950	1950	1950
I[A]	1130	1130	1130
V[V]	45.8	35.65	56.18
Re(Z) [mΩ]	5.8	5.2	5.4
Im(Z) [mΩ]	39.8	31.12	49.43
Z [mΩ]	40.2	31.55	49.72
cosφ	0.145	0.165	0.109
P_{strip} [kW]	—	3.8	4.3
P_{all} [kW]	7.6	6.8	6.89
η [%]	—	56	61.8

The first experimental test has given the results shown in Table I and the corresponding thermal transients of Fig.9.

The thermal transient calculated using the EM simplified model shows higher temperature values than the measurements while the real model gives better results. As can be seen, for the real model the maximum error is within 5%.

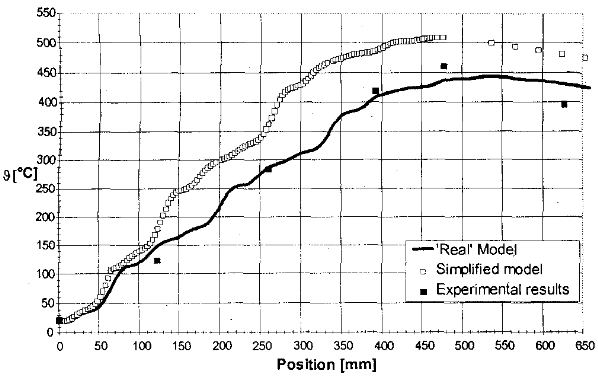

Fig. 9. Comparison among the results obtained by using the real model, the simplified model and the experimental values (First test).

Table II - Data and results for the second experimental test.

PHISICAL AND ELECTRICAL PARAMETERS	EXPERIMENTAL VALUES	NUMERICAL VALUES 'simplified model'	NUMERICAL VALUES 'real model'
Strip Velocity [m/min.]	2±0.3	2	2
Frequency [Hz]	1950	1950	1950
I[A]	1020	1020	1020
V[V]	42.1	32.18	50.7
Re(Z) [mΩ]	5.98	5.2	5.4
Im(Z) [mΩ]	40.46	31.12	49.43
Z [mΩ]	40.9	31.55	49.72
cosφ	0.146	0.165	0.109
P_{Slab} [kW]	—	3	3.46
P_{All} [kW]	6.34	5.4	5.6
η [%]	—	56	61.8

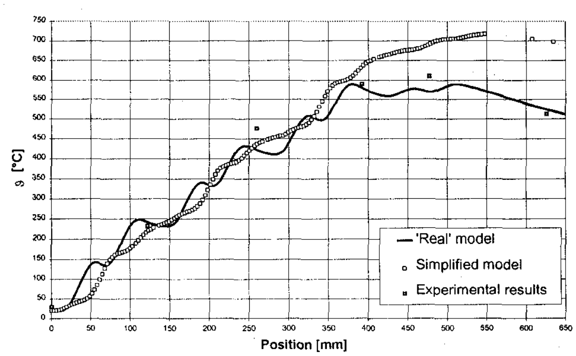

Fig. 10. Comparison among the results obtained by using the real model, the simplified model and the experimental values (Second Test).

The second example is relative to an experimental test performed at higher temperatures. Data and test results are shown in Table II and the corresponding thermal transients are shown in Fig. 10.

Also in this case, it should be pointed out that the simplified model gives errors within +20%, while the real model has errors within ± 3%.

IV. CONCLUSION

The simulation procedure described in the previous sections has demonstrated to be a good tool for the design of transverse flux heaters for thin metal strips.

The real model gives much better results and the differences between experimental and simulation results are within ± 3%. The simplified model gives higher errors but always in the same direction, i.e. it gives always higher temperatures in comparison with experimental data. The real model is much more complicated in comparison with the simplified one. In fact, for the EM solution it's not possible to take advantage of all the existing symmetries of the simplified model. For this reason, the calculation time is five times longer than the one required for the simplified model solution. Both models can be used for the design of transverse flux heaters. The first one for a preliminary analysis devoted to understand the behavior of the main parameters of the system, the second one can be used to guarantee the performance required by the specific process.

REFERENCES

[1] D. Schulze and Z. Wang, "3D Eddy Current Computation in the Transverse Flux Induction Heating Equipment." *IEEE Transactions on Magnetics,* vol. 30. no. 5, September 1994.

[2] D. Schulze and Z. Wang, "Developing an universal TFIH Equipment using 3D Eddy Current Field Computation." *IEEE Transactions on Magnetics,* vol. 32. no. 3, May 1996.

[3] F.Dughiero, M.Forzan, S.Lupi, "3D Solution of Electromagnetic and Thermal Coupled Field Problems in the Continuous Transverse Flux Heating of Metal Strips." IEEE Trans. On Mag. Vol. 33, N. 2, March 1997.

[4] V. Bukanin, V. Nemkov, F. Dughiero, M. Forzan, S. Lupi:"Induction Heating of Flat Metal Bodies", BNCE-UIE International Congress on Electricity Applications, Birmingham, UK, 16-20 June, 1996. M3-17.