3D-FEM Simulation of Transverse-Flux Induction Heaters

Bukanin V.**, Dughiero F.*, Lupi S.*, Nemkov V.**, Siega P.*
*Department of Electrical Engineering University of Padua, Via Gradenigo 6/a 35131 Padua (Italy)
** Electrotechnical University, ul. Prof. Popova 5, St. Petersburg (Russia)

Abstract **- In the present paper 2D and 3D FEM simulations of transverse-flux induction heating systems (TFH) have been performed and the calculated results have been compared with experimental ones. Several configurations of such systems have been studied in order to give useful advices about the choice of the main design parameters.**

I. INTRODUCTION

The induction heating of metal strips by transverse-flux inductors was firstly proposed in the fifties [1,2,3].

This induction heating process allows to overcome the problems which arise in heating thin metal strips by longitudinal flux systems.

In fact longitudinal flux heating can be used with relatively good efficiency only if the ratio of the thickness (d) of the strip and the penetration depth (δ) is greater than 2-2.5.

For this reason the main frequency may be used only for thick workpieces , while for thin strips there is the need to use medium or high radio-frequencies. The consequence is the increase of the cost of the heating installation, of particular importance when considering high power plants.

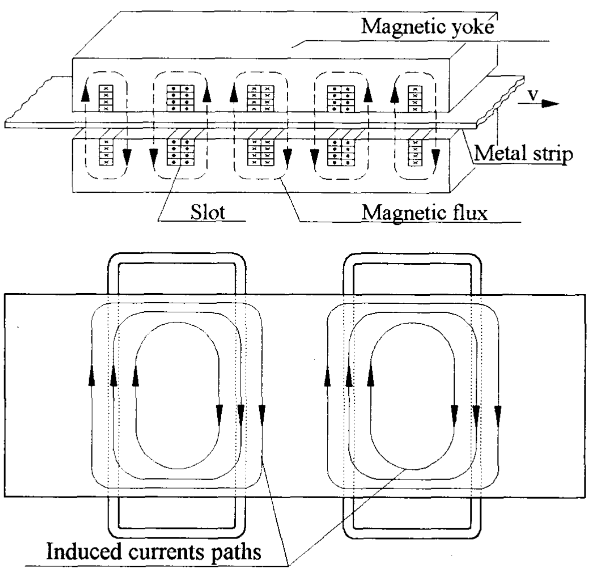

Figure 1 - Schematic of a transverse flux induction heater (TFH).

In the transverse-flux heating the exciting magnetic flux is directed perpendicular to the surface and through the metal strip. In this case the efficiency of the heating process depends on the pole pitch, slot and gap dimensions and workpiece characteristics, and a good efficiency can be achieved at frequencies lower than in the longitudinal flux heating.

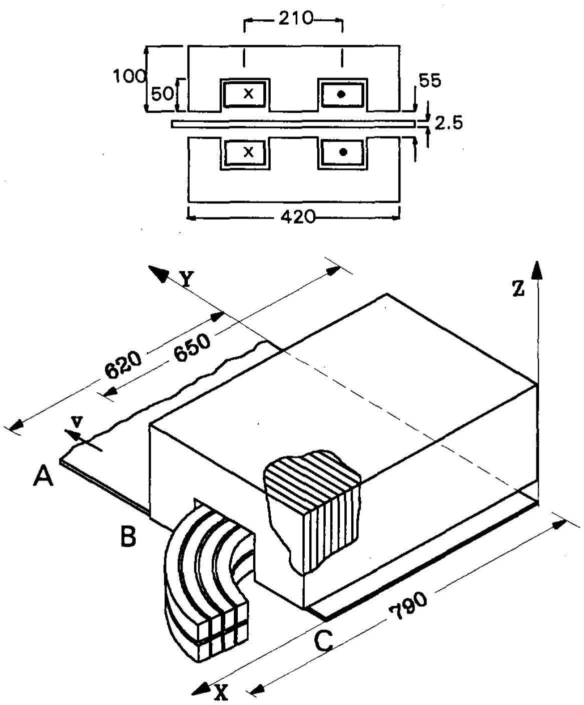

Figure 2 - Experimental Transverse-Flux heater TFH-I [Inductor: 8 turns water cooled copper tube 15x20x4 mm; Magnetic yoke : relative magnetic permeability :μ=1000, no losses ; Load : aluminium metal strip :σ=1.43e7 S/m]

A schematic of a transverse-flux system is shown on figure 1. This kind of systems are increasingly used in the industry for heating thin metal strips before metal working. In order to achieve the uniformity of temperature distribution required by the process it is particularly important to analyze the effect of the main parameters on the power density distribution at the surface of the body. This analysis can be performed using 2D or 3D calculation methods. The 2D procedure doesn't allow to take into account the transversal edge effects of the strip. The 3D calculation,on the contrary, is able to perform a complete analysis of the system, but it is time consuming and requires hardware and software not always avaible in the factories.

In the paper the results obtained by 2D and 3D FEM codes for an experimental system have been compared

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in order to understand the limits of the 2D analysis in comparison with the 3D one. Moreover a simple Tranverse-Flux test installation has been studied and a 2D and 3D parametrical analyses have been carried out.The calculations have been performed both for voltage and current supply conditions.

II. CALCULATION PROCEDURE

2D and 3D FEM codes were used for studying the TFH systems. The electromagnetic problem was solved with a combined scalar-vector potential technique using tangential vector elements with second-order basis functions [4,5]. Only materials with linear properties have been considered. Generally, the TFH systems include several exciting coils differently connected and energized by impressed currents or, more often, by applied voltages (e.g. in the case of multi-phase supply).

In order to perform the calculation for voltage supply conditions the impedance matrix of the system must be calculated. The impedance matrix computation is performed with a procedure in which only one conductor at time is excited with one Ampere current and the flux linkages with all conductors are calculated . This means that the procedure requires a complete field calculation for each inductor turn. The ohmic resistance of each current loop is calculated. Finally these terms are put together to form the impedance matrix.

By this way, taking into account that the above matrix is the same for a given geometrical configuration, it is possible to supply the inductors with different values of voltage solving the linear system [Z] [I]=[V] for the determination of the currents, and then, assigning these values of currents to the inductors, make the global field calculation.

Some problems arise when building the mesh. In the adopted code the finite-element mesh is automatically generated using the Delaunay algorithm and the accuracy of the solution is checked using an element by element error estimate. If the accuracy level is less than specified, the code adaptively refines the mesh on the basis of its assessment of global and local accuracy and solves again the problem. This process is iterated until the specified level of accuracy is reached. However, for the TFH system geometries it is very difficult to reach good results with the adaptive procedure. In fact there are too big differences in the dimensions of inductor and metal strip. For this reason the automatic procedure brings to a very large mesh which requires a lot of memory and high calculation times , solving the problem with a big number of elements also in the regions which are unessential for the analysis of the field distribution in the workpiece.

For this reason a manual mesh refinement has been adopted in the metal strip. By this way it has been possible to achieve good solution with a number of mesh elements much lower in comparison with that given by the adaptive procedure.

TABLE I
COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS FOR TFH-I

	V	I	P_{tot}	Q_{tot}	P_{strip}	$\cos\varphi$	η
	V	A	kW	kVAR	kW	-	-
Exp.	138	720	48.64	86.60	42.70	0.48	0.88
2D	138	804	61.20	90.80	52.90	0.56	0.86
3D	138	698	44.83	84.77	38.94	0.47	0.87

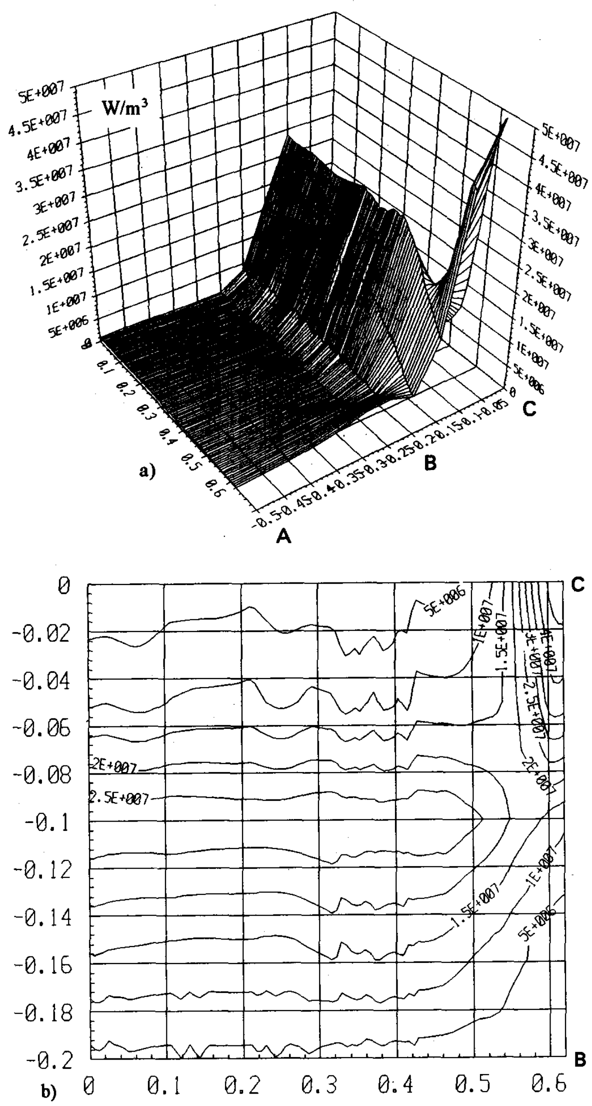

Figure 3 - Induced power density distributions in the strip for TFH-I [A,B,C and system geometry as in figure 2].

III. NUMERICAL AND EXPERIMENTAL RESULTS

For the comparison of numerical and experimental results the system of figure 2 has been considered. The procedure described in the previous paragraph was used both for 2D and 3D FEM calculations. In Table I the calculated results obtained for the integral parameters are given together with the experimental ones. It can be seen that there is a good agreement between experiments and 3D calculations.

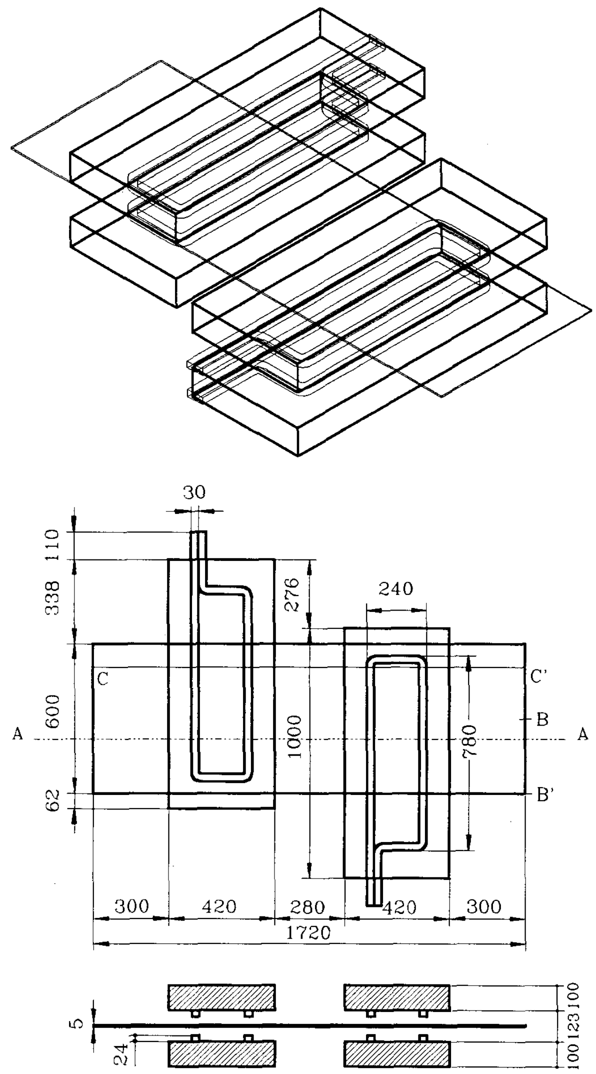

Figure 4 - *Experimental Transverse-Flux heater TFH-II[Inductor: 4 coils copper 30x24 mm; Magnetic yoke : relative magnetic permeability :μ=1000, no losses ; Load : non-magnetic steel metal strip :σ=1.2e6 S/m;Current supply I = 3080 A]*

On the contrary the 2D results are quite different from the experimental ones. This can be explained considering that the 2D code gives a satisfactory representation of the field only in the central part of the system, while in the edge zones of inductor and strip, where the field is intrinsically three dimensional, only 3D codes can assure a good accuracy in the calculation both for integral and distributed parameters. A complete 3D analysis of the induced power density distributions on the surface of the metal strip has been therefore developed. These results, given in figure 3, were obtained with a mesh of about 20000 elements. They show in figure 3-a the 3D power density distribution characterized by a pronounced peak in the region of the strip around the point C (see fig. 2), and in figure 3-b the corresponding equivalue lines.

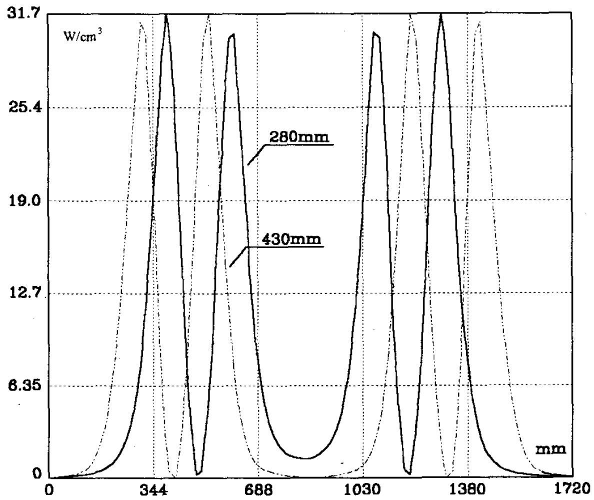

Figure 5 - *Induced power density distribution (W / cm³) in the strip along line A-A' for the TFH-II and two different axial distances of inductor coils [A,A' and system geometry as in figure 4].*

In order to understand how the supply frequency and the width of the strip influence the induced power density distributions, a 3D parametrical analysis for these quantities has been performed with reference to the test installation of figure 4 [6]. For each simulation a mesh of about 32000 elements has been used and the CPU time on HP735 was about 3 hours.

The diagrams of figure 5 show the power density distribution along the central line A-A', for two different axial distances of the inductor coils in the direction of the movement.

The curves of figure 6 and 7 give the distributions from B to B' of the values obtained integrating the volume power density curves along lines C-C' for different exciting frequencies and various strip widths.

The curves are again characterized by a power density increase at the edges of the metal strip and, therefore, a consequent local overheating could generally take place.

However this phenomenon may positively be used, by a suitable choice of frequency and relative inductor/strip position, when a uniform temperature distribution is required, since the edges of the strip generally undergo a faster cooling than the central part of it.

These curves represent the energy absorbed in the strip and, therefore, give useful elements to the designer for predicting the temperature profile at the exit of the TFH system.

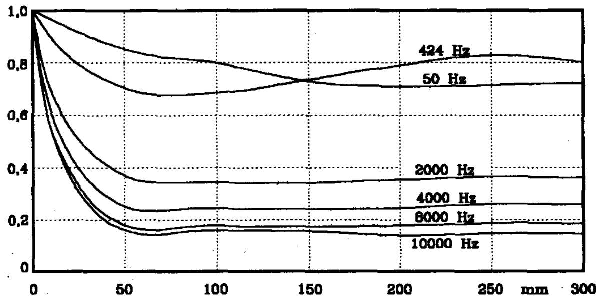

Figure 6 *- Relative distributions from B' to B of the power density values integrated along lines C-C' for the TFH-II, at different exciting frequencies [B,B',C,C' and system geometry as in figure 4]*

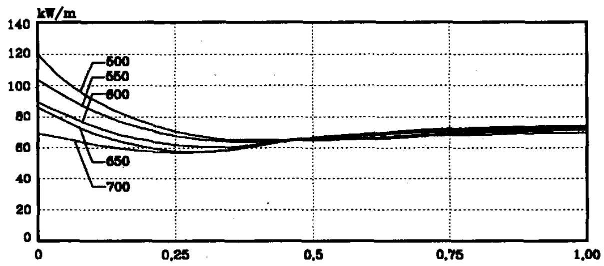

Figure 7 *- Distributions from B' to B of the power density values integrated along lines C-C' for the TFH-II, and different strip widths [B,B',C,C' and system geometry as in figure 4]*

IV. CONCLUSIONS

FEM codes are powerful tools for calculation of 3D fields of induction systems but they require big CPU times even for relatively simple configurations with 2D eddy current distributions.

Manual mesh correction is desiderable to take into account the particular features of the system and reduce the number of mesh elements.

The numerical and analytical analysis is advisable for the choice of main parameters on the preliminary stage of the inductor design, while 3D calculations are necessary for final conceptions.

Good theoretical knowledge of the induction system behaviour is very important for the effective use of 3D codes and results interpretation.

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