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Characteristics of Installations for Direct Resistance Heating of Ferromagnetic Bars of Square Cross-section

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Abstract

In the paper the influence of the circuit reactance on the heating parameters of installations for the Direct Resistance Heating of ferromagnetic bars of square cross-section is examined. Diagrams for the evaluation of the heating times and the final temperature difference in the bar cross-section are given for a wide range of bar dimensions.

Introduction

The design of Direct Resistance Heating (DRH) installations for heating ferromagnetic steel bars of square cross-section over a wide range of bar dimensions and throughput rates requires a sound analysis of the influence of the installation's total impedance on the current flow in the bars.

In fact, in order to meet the production specifications, the transformer secondary voltage must drive sufficient current through the total impedance of the secondary circuit, which comprises the impedance of the bar, which strongly varies with temperature, the fixed bus-bars, the flexible jumper leads and the contact assemblies.

Moreover, the corresponding heating transient must comply with the final temperature distribution requirements dictated by the technological process.

In the paper the analysis of the DRH installation characteristics is developed by a numerical FEM programme and the trustworthiness of the calculated results is validated by experimental data.

1. The installation's equivalent circuit

As known, a DRH installation basically consists of a single-phase power transformer fed at constant voltage, of fixed bus-bars and flexible jumper leads and of the contact assemblies whereby the current is carried into and out of the bar, as shown schematically in fig.1. The equivalent circuit of the installation can be represented by the simplified series circuit sketched in fig.2. In this circuit the resistances of the transformer, the high current secondary circuit and the contacts are neglected, while the external reactance X_e takes into account the series reactance of the supply transformer (referred to the secondary terminals) and the external reactance of the high current circuit [1,2]. In this circuit X_i and R_a represent respectively the internal reactance and the a.c. resistance of the bar to be heated, which both undergo strong variations during the heating transient.

Detailed data for the evaluation of the equivalent circuit parameters are given in [2]. Here we will give only some elements useful for a rough estimate of the value of X_e, which constitutes a constant ballast limiting – to an extent depending on the bar dimensions - the variations of the current during the heating cycle. In fact, for given bar dimensions and heating time, the value of X_e has a strong influence on the VA rating of the supply transformer, the maximum value of the current I flowing in the bar (from which in turn depends the life of contacts), the skin effect (which define the power density distribution in the bar cross-section) and the circuit power factor.

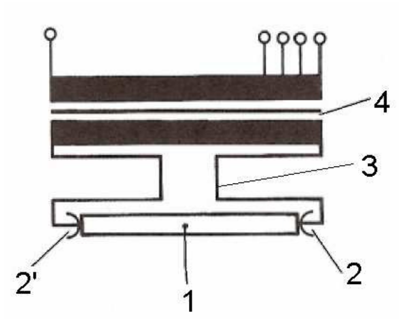


Fig. 1 – *Schematic of a DRH installation [1- bar to be heated; 2, 2'- contacts; 3 - high current secondary circuit; 4 – supply transformer]*

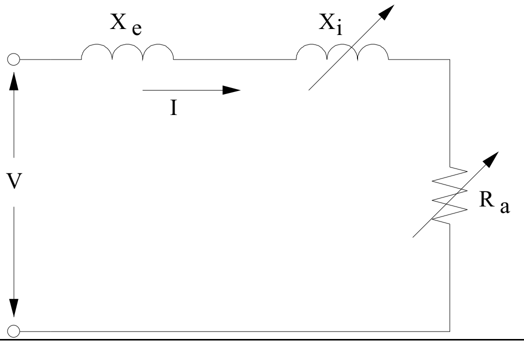


Fig.2 – *Simplified equivalent circuit of the DRH installation [V – transformer secondary voltage; X_e – total equivalent external reactance; X_i – bar internal reactance; R_a – bar a.c. resistance]*

The reactance X_e is mainly constituted by the "external" reactance of the high-current secondary circuit and therefore depends on its construction and geometry [2].

A series of theoretical formulae exists in the bibliography for the calculation of X_e with different geometrical layout of conductors, with conductors of different cross-sections, valid either for uniform current density in the conductor's, or taking into account the phenomena of proximity and skin effects. To these formulae must address the reader for the calculation of X_e of a specific installation starting from the characteristics of the design.

However, a first rough estimate can be obtained using the curve of figure 3 which gives the values of X_e per unit length calculated with a FEM numerical programme for a system of two rectangular conductors (Cu or Al 20x120 mm cross-section, arranged as sketched in the figure) in which currents flow in opposite directions, as a function of the distance *D* between them.

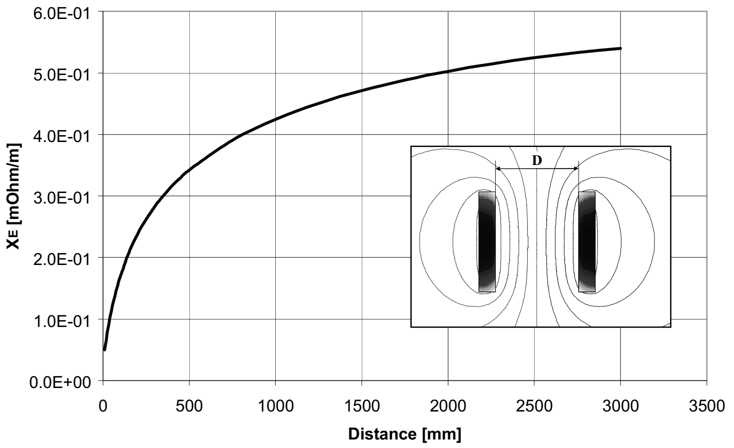


Fig. 3 – *Reactance X_e per unit length of the system of two conductors of rectangular cross-section (20x120 mm) arranged as sketched in the figure, in which currents flow in opposite directions, as a function of the distance D between them*

Since the value of the reactance is directly proportional to the circuit length, the diagram shows that for bar lengths of some meters – which are usual in these installations – external reactance values ranging from 1 mohm up to few mohms can be expected.

This conclusion has been confirmed by the comparison between calculated and experimental results, performed to the end of validating the numerical procedure used.

The comparison refers to the experimental data of an industrial installation, available in the bibliography [1], for the heating of magnetic steel bars, 100x100 cross-section - 4,4 m length in heating times of about 100 and 200 s.

As shown by the diagrams of figure 4, the temperature transient distributions measured at points 2-3-6 of the cross section (fig. 4-a) can be reproduced within engineering accuracy (fig. 4-b) applying the calculation procedure to the equivalent circuit of fig.2 with X_e=1 mohm and supply voltage of 95 and 130 V respectively.

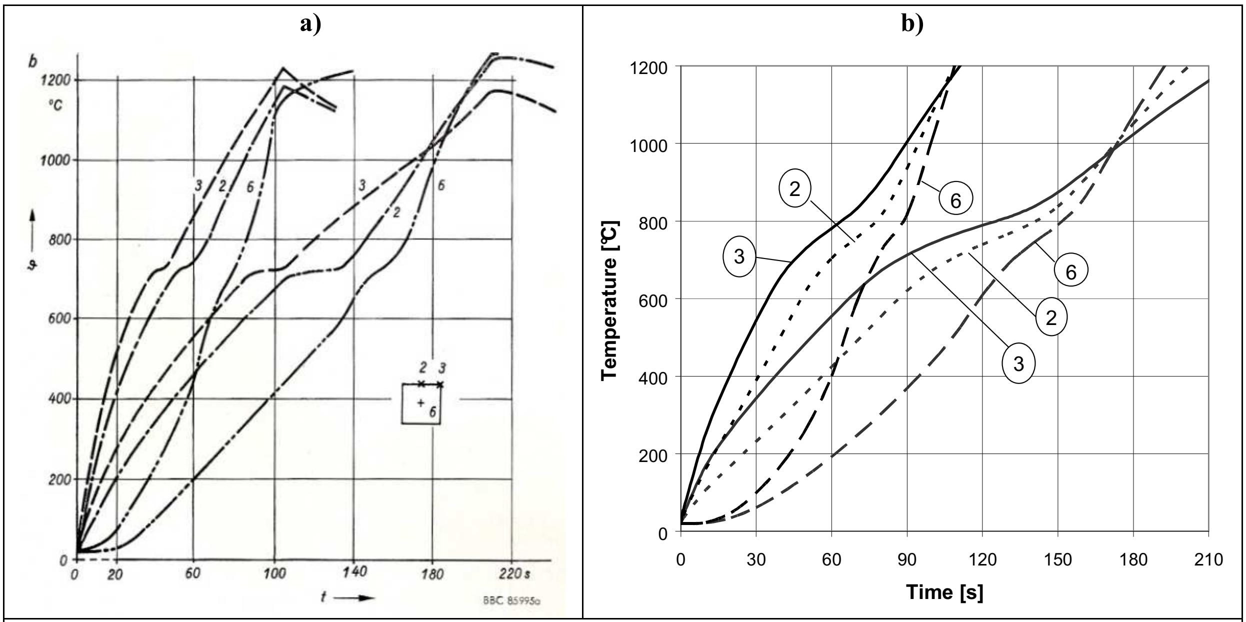


Fig. 4 - *Surface and core transient temperature in a magnetic steel bar of square cross section for different heating times [bar dimensions: 100x100 mm; ℓ=4,4 m; a) experimental values from [1]; b) calculated values with X_e=1 mohm, V=95 and 130 V]*

Also the comparison of the maximum temperature difference in the bar cross-sections during the heating transients shown in figure 5, confirms the reliability of the calculation procedure.

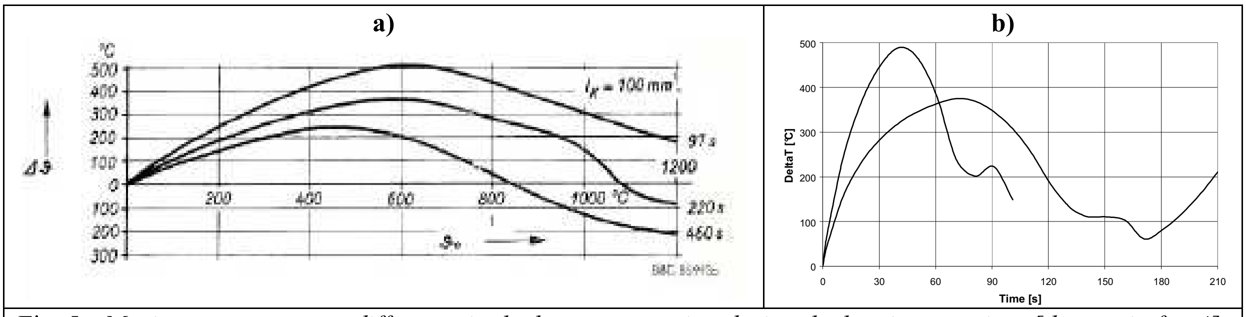


Fig. 5 - *Maximum temperature difference in the bar cross-section during the heating transient [data as in fig. 4]*

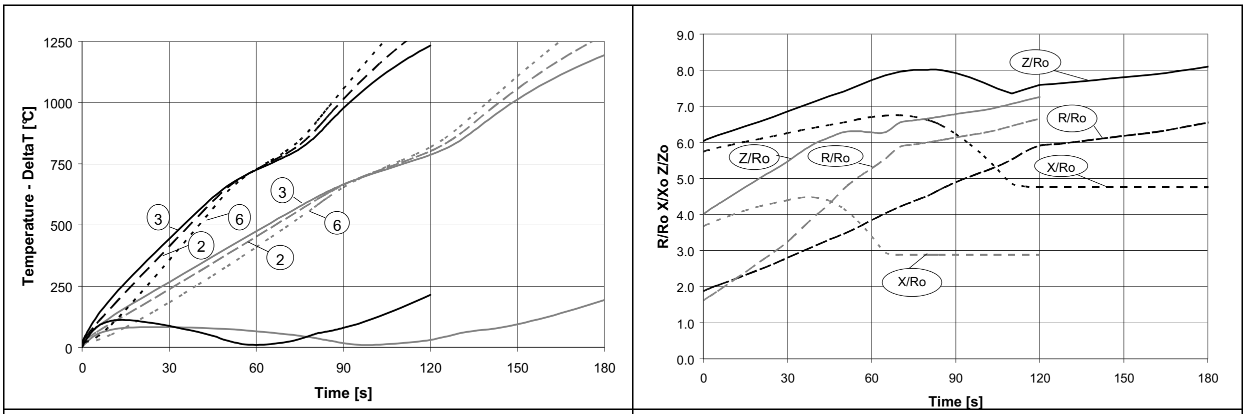
The small differences between experimental and calculated data can be attributed to the uncertainty on the value of X_e of the industrial installation (not given in [1]) and, as regards fig. 5, to the fact that the curves of fig. 5-a are deduced from the experimental data of fig. 4-a (i.e. at points 2-3-6), without taking into account that in some instants of the heating cycle the maximum temperature is experienced in a different point of the cross-section.

2. Analysis of the installation characteristics

As known, the values and distributions in the cross-section of the bar of the current density and power per unit volume are strongly dependent on the dimensions of the cross-section, the current intensity and the temperature. The current in turn is a complex function of the voltage V, of the reactance X_e and the dynamic values of the internal impedance of the billet, which are current and temperature dependent.

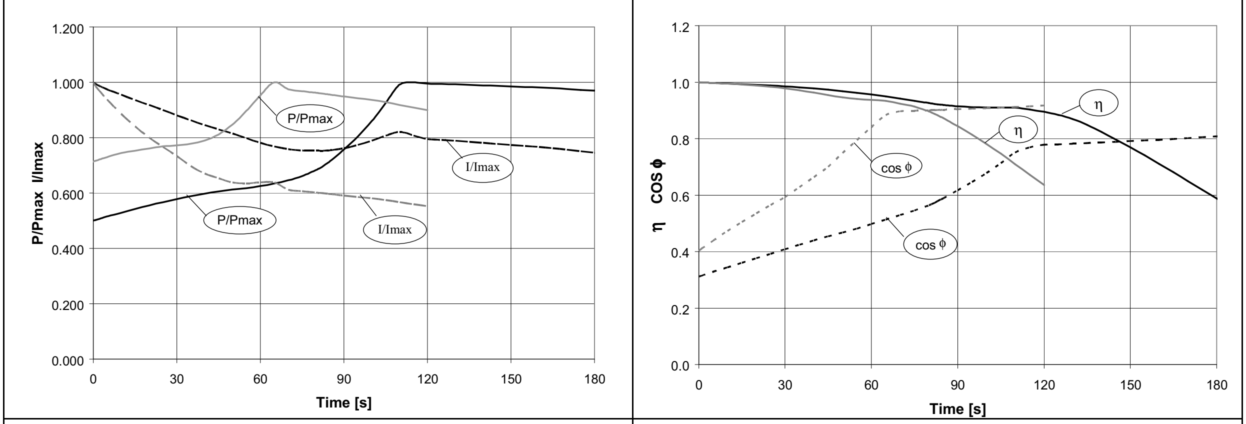
The numerical analysis allows to obtain a deep knowledge of all these dependencies at each instant of the heating transient, taking into account the variations of the electrical and thermal material's physical characteristics with temperature and – as regards magnetic permeability – also with the local magnetic field intensity.

A typical example of the results that can be obtained is shown in figure 6, which refers to the heating of a magnetic steel bar – 10 m length, 50x50 mm cross section – with supply voltage of 100 V and X_e equal to 1,0 and 2,5 mohm respectively.



a) *Transient temperature distributions at points 2-3-6 of fig.4 and maximum temperature difference in the cross-section*

b) *Resistance, reactance and impedance variations during heating (referred to the d.c. resistance R_0 of the bar in "cold" conditions)*



c) *Variations of absorbed current and active power referred to the maximum values during heating*

d) *Variations of cosφ and thermal efficiency η during heating*

Fig.6 – *Heating characteristics of a magnetic steel bar 50x50 mm; ℓ=10 m; V=100 V; R_0=0,8 mohm; [X_e=1 mohm: I_{max}=31194 A_{rms}; P_{max}=1,758 MW; X_e=2,5 mohm: I_{max}=20708 A_{rms}; P_{max}=1,288 MW]*

The analysis shows that for the smaller bar dimensions (e.g. from 20x20 to 50x50 mm) the temperature transient distribution is characterised by relatively small temperature differences in the cross-section below Curie point, while the high final temperature difference is always due to the radiation and convection losses from the bar surface above 750 °C.

The diagrams of figure 7 show a summary of the results for magnetic steel bars of 10 m length, 20x20 mm and 50x50 mm respectively. Figure 7-a) gives the heating times for reaching the maximum temperature of 1200 °C as a function of the reactance X_e for different values of the supply voltage V; figure 7-b) gives the corresponding final temperature difference in the bar cross-section. The curves show that for the 20x20 mm bars the influence of the reactance X_e is practically negligible.

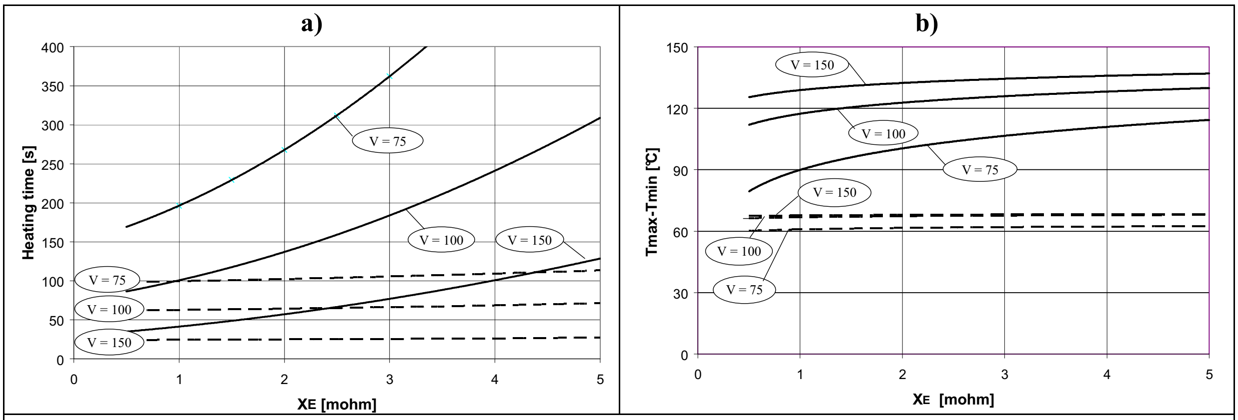


Fig.7 – *Heating characteristics of magnetic steel bars (length:10 m - cross-section: 20x20 mm – dashed lines; 50x50 mm – solid lines) heated to 1200 °C maximum temperature as a function of the reactance X_e for different supply voltage values [a) heating times; b) maximum final temperature difference in the cross-section]*

A different situation can be observed for greater cross-section dimensions. As illustrated in figure 8 by the heating transients of bars 70x70 and 100x100 mm, 10 m length, and by the examples already shown in the figures 4 and 5, in these cases final temperature differences consistent with the requirements of the subsequent hot working can be obtained only if the heating conditions are chosen such to achieve the crossing of the surface and core temperature curves close to the end of the heating cycle.

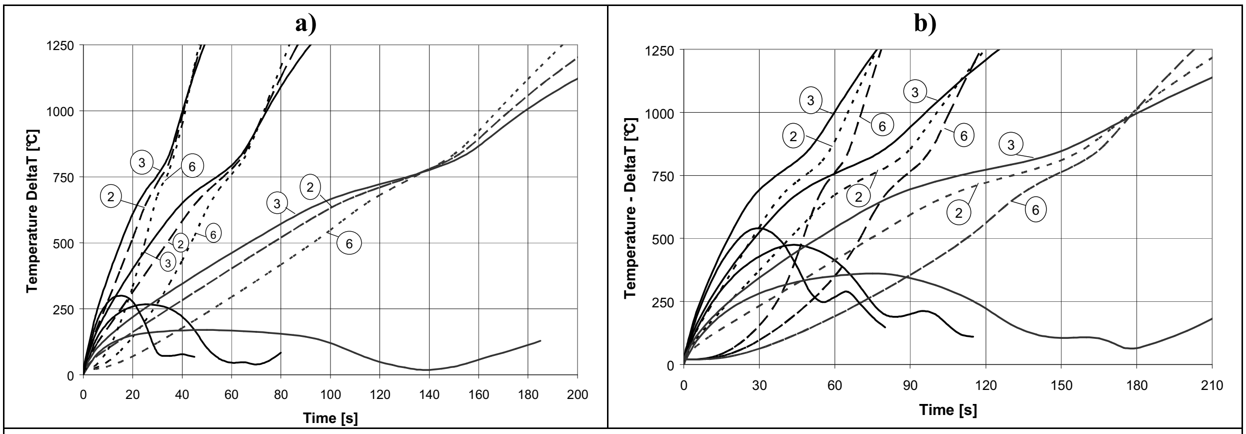
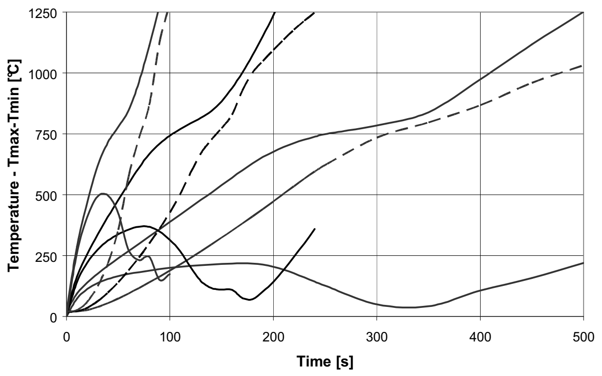


Fig. 8 - *Transient temperature distributions at points 2-3-6 of fig.4 and maximum temperature difference in the bar cross-section [Xe=1 mohm; V=100-150-200 V; ℓ=10 m; a) 70x70 mm, b) 100x100 mm]*

Table I – *Heating parameters of transients of figure 8 [$\cos\varphi_m$ – average value during heating up to 1200 ºC]*

	70x70 mm			100x100 mm		
Supply voltage [V]	I_{max} [A_{rms}]	P_{max} [MW]	$\cos\varphi_m$	I_{max} [A_{rms}]	P_{max} [MW]	$\cos\varphi_m$
V = 100	33938	2,161	0,564	35588	1,817	0,420
V = 150	53684	4,862	0,538	57724	4,100	0,395
V = 200	73719	8,642	0,522	77668	7,272	0,373

However, it must be pointed out that at the instant of intersection of the surface and core curves of points 2, 3 and 6 (see figure 4), the temperature difference in the bar cross-section is not necessarily zero, since the maximum temperature value can be experienced in a different point of the cross-section. This is confirmed also by the curves of figure 9, which show the maximum and minimum temperature variations and their difference, during heating of the bar 100x100 mm cross section, 10 m length for the same supply voltage and different values of the external reactance Xe.



X_e [mΩ]	I_{max} [A_{rms}]	P_{max} [MW]	cosφ_m
1,0	88170	9,171	0,394
2,5	56327	3,968	0,263
5,0	35028	1,534	0,182

Fig. 9 – *Temperatures T_{max}(solid lines), T_{min}(dashed lines) and (T_{max}- T_{min}) in the cross-section during heating and heating parameters [bar: 100x100 mm, 10 m length; supply voltage: 225 V; X_e=1 - 2,5 -5 mohm]*

Finally, the diagrams of figure 10 give a summary of the main heating parameters for magnetic steel bars of 10 m length, 70x70 mm and 100x100 mm respectively.

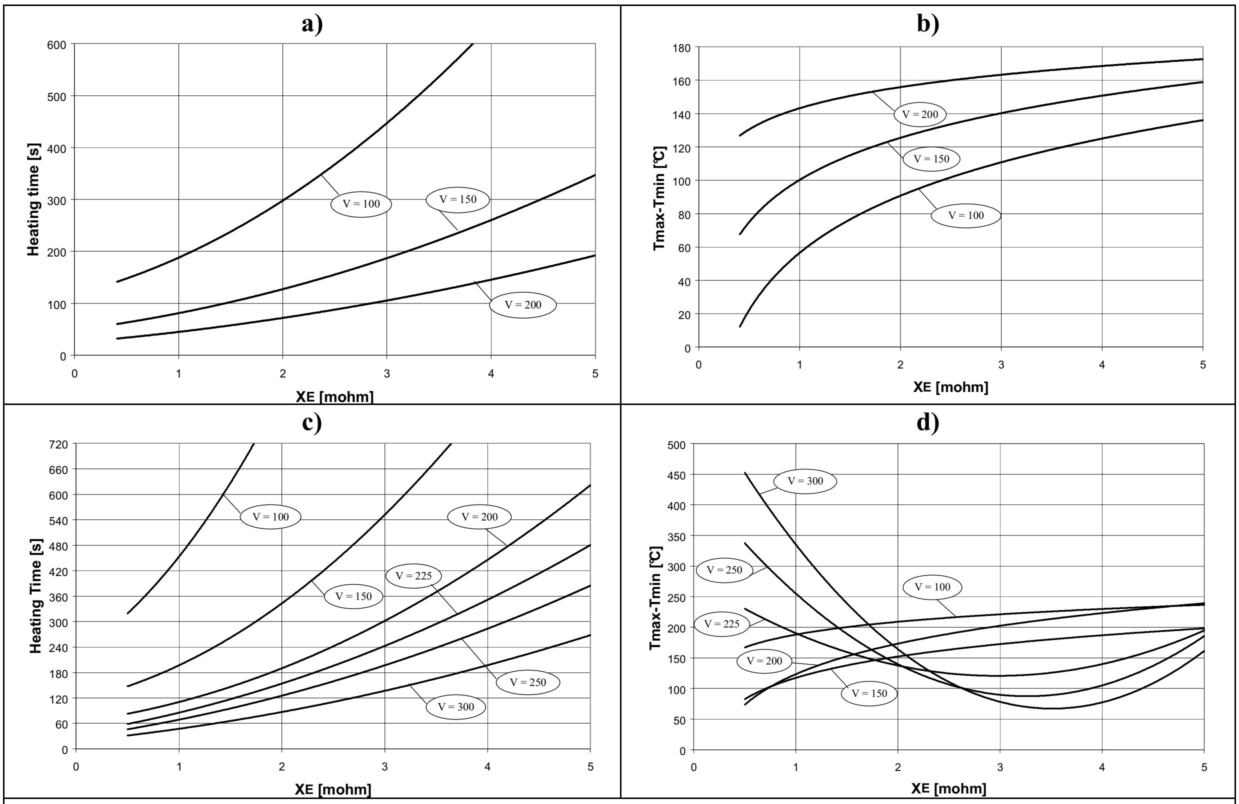


Fig. 10 - *Heating characteristics of magnetic steel bars [length:10 m - cross-section: 70x70 – diagrams a) and b); 100x100 mm – diagrams c) and d)] heated to 1200 °C maximum temperature as a function of the reactance X_e for different supply voltage values [a) and c) heating times; b) and d) maximum final temperature difference in the cross-section]*

The diagrams of figures 10-a) and –c) give the heating times for reaching the maximum surface temperature of 1200 °C as a function of the reactance X_e for different values of the supply voltage V; figures 10-b) and -d) give the corresponding final temperature difference in the bar cross-section.

Conclusions

In the paper the analysis of the characteristics of the installations for the direct resistance heating of ferromagnetic steel bars of square cross-section has been developed by a FEM numerical model. [5]

The comparison with experimental results available in the literature has shown that the model gives a very accurate representation of the variations of all electrical and thermal parameters during the heating transients.

The analysis shows the possibility of obtaining final temperature distributions in the cross-section of the bar suitable for subsequent hot working, by a convenient choice of the heating parameters.

Diagrams for the evaluation of the heating times and the maximum final temperature differences in the bar cross-section are given as a function of the installation's external reactance X_e, for a wide range of bar dimensions.

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