Batch heating of tube

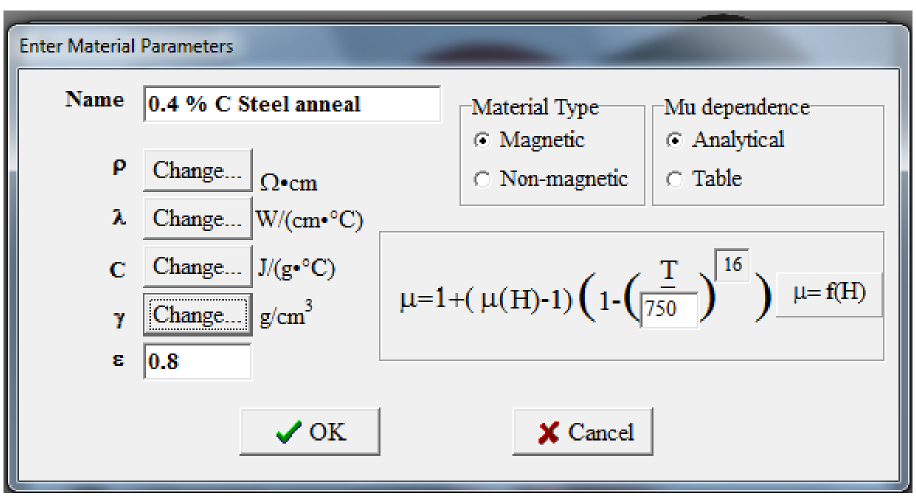
Magnetic permeability is the most complicated physical property for simulation. In general, it is necessary to describe dependence of relative permeability upon temperature T and magnetic field strength H for each magnetic material. Accurate account for magnetic permeability is difficult due to three factors: magnetic hysteresis, non-linear dependence of Mu vs. field strength H and strong dependence of Mu from temperature when it approaches to Curie point.

In almost all induction heating applications losses for hysteresis are much lower than for eddy-currents and may be neglected.

Non-linear dependence Mu vs. H results in non-sinusoidal curves of the coil current or voltage or both and accurate calculation requires simulation in time domain, i.e. for many points during each cycle of electromagnetic field. This approach leads to very big calculation time and it is almost never used in simulation of induction heating. However in sense of power transfer and therefore temperature dynamics it is possible to use a method developed initially by Prof. L. R. Neumann [1] and later modified by Prof. A.E. Slukhotsky [2, 3]. ELTA makes simulation using this method. Instead of real non-sinusoidal values of current, voltage and magnetic field it is using the effective values (root mean square aka rms) of the first (basic) harmonic of these quantities (I, U, B, H). These rms values of H and B are being used for determination of permeability from the standard curve Bm = f(Hm) or Mu = f(Hm). This approach gives good results for practical calculations, especially for surface hardening and mass heating for forging, when the surface layer is non-magnetic during significant part of the heating time.

Account for permeability variation with temperature is considered below.

Superposition of two dependences of $\mu = f(H)$ and $\mu = f(T)$ is used in ELTA. Dependence of $\mu = f(H)$ for different materials is described in a table format. There are two options for description of $\mu = f(T)$: **Analytical** and **Table**.

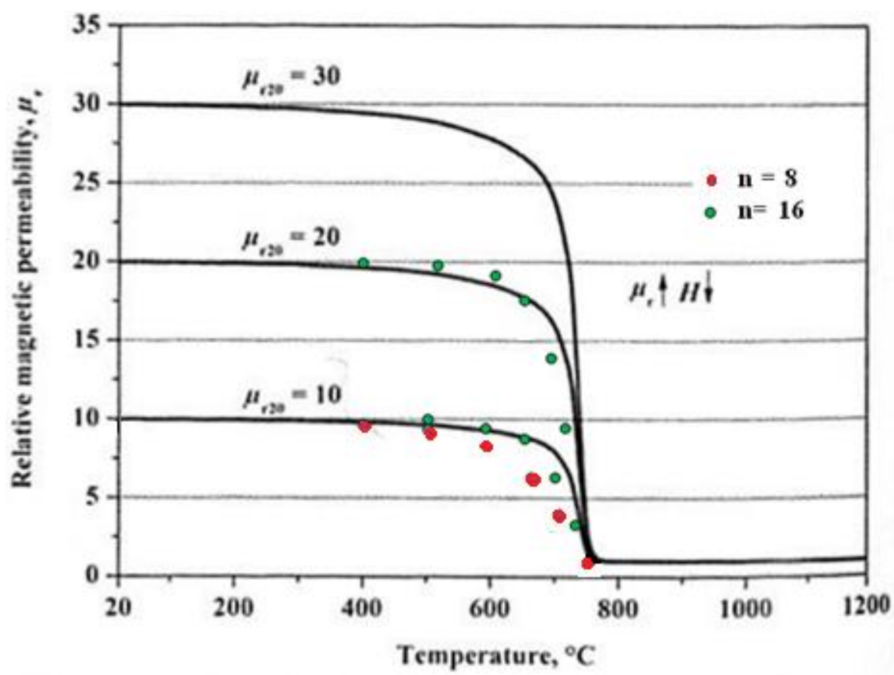


In analytical method, the temperature dependence is described by parabolic type curve, which ends at Curie temperature with value equal to 1. Above Curie point permeability is set automatically as 1. This approximation is good enough for practical calculations. Table format may be used for more accurate description of temperature dependence for a particular material. You can use the installed table or insert your own data.

In order to use analytical method for a new material, the user must insert a table $\mu = f(H)$

at room temperature and Curie temperature T_C. For iron-carbon alloys (carbon steels) Tc varies from 720 °C for pearlite (app. 0.76 % of carbon by weight) to 770 °C for pure iron. For typically used in induction hardening steels with carbon content of 0.4…0.5 %, the Curie temperature is app. 740…750 °C.

Another parameter describing permeability dependence from temperature is a number **n** in a member $(T/Tc)^{\mathbf{n}}$ of the above formula. This number describes how fast permeability drops when temperature approaches to T_C. The default value of **n**=2 was used in calculations of surface hardening inductors at low frequencies when field strength was very high and the surface permeability at room temperature was 5…8. The latest studies showed that **n** should be much higher in order to describe more sharp permeability drop near Tc. Figure below shows temperature dependence of the carbon steel permeability [4]. Marks on the chart show dependences for different values of **n**. It follows from this chart that **n** must be in the range of 12…16. Higher **n** should be used for weaker fields. For pure iron and weak field the permeability can grow with temperature and after reaching maximum at app. 650 °C quickly drops to one.



It is important to note that for forge heating and surface hardening, influence of **n** on final temperature distribution isn't big because a significant part of the heating cycle occurs at temperatures above Tc. For low temperature processing (tempering, stress relieving) correct value of **n** may be more important.

<u>Example of study</u>
<u>Load:</u> Tube OD = 9 cm, length 26 cm, wall thickness 0.5 cm, material Steel 1040.
<u>Coil:</u> internal diameter 11 cm, length 24 cm, turn number 16, tubing 1×1×0.2 cm.
<u>Circuitry</u>: parallel, resonance conditions, fixed frequency 10 kHz, coil voltage 420 V.

<u>Comparison:</u> ELTA 6.0 vs. FLUX 2D program.
<u>Results of comparison are shown below:</u>

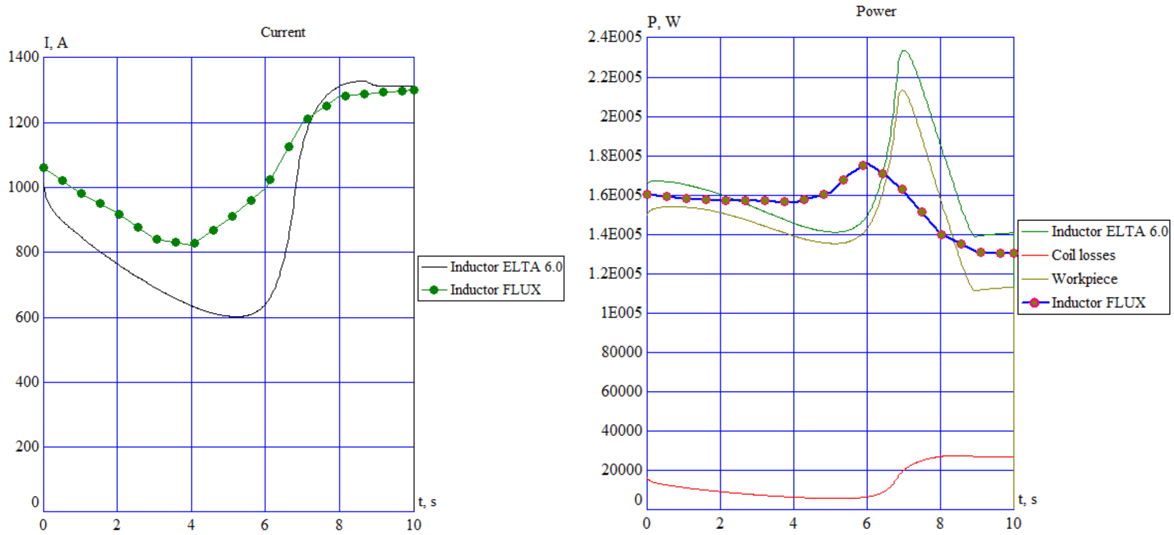


Figure 1. Current and Power variation in the process of heating (ELTA n=16)

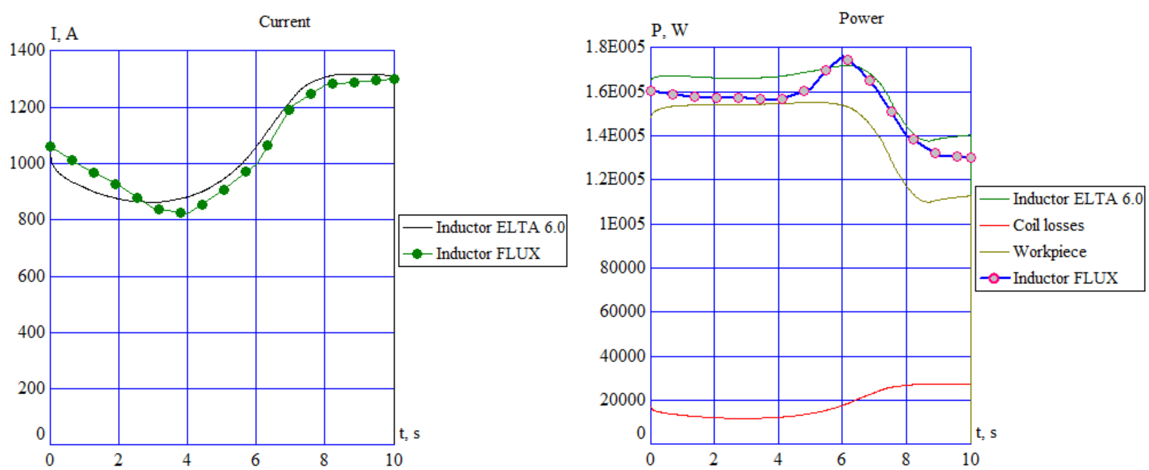


Figure 2. Current and Power variation in the process of heating (ELTA n=2)

Final surface temperature: FLUX 2D – 900 °C at the center and 800 °C at the tube ends; mean surface temperature along the tube surface under the coil – 850 °C.

Final surface temperature: ELTA – 843 °C (n=16) and 821 °C (n=2)

1. L. R. Neumann. Skin-effect in ferromagnetic bodies, Moscow-Leningrad, Energoizdat, 1949 (in Russian).
2. V. S. Nemkov, V. B. Demidovich. Theory and Calculation of Induction Heating Devices. Leningrad, Energoatomizdat, 1988, 280 p. (in Russian).
3. A. E. Slukhotsky, S. E. Ryskin. Inductors for Induction Heating, Leningrad, Energoizdat, 1974 (in Russian).
4. T. Zedler, A. Nikanorov, B. Nacke. Investigation of relative magnetic permeability as input data for numerical simulation of induction surface hardening. Int. Scientific Colloquium "Modelling for EM Processing", Hannover, Oct. 2008.