When and why 2DELTA may be used

Many induction heaters have cylindrical form (Figure 1).

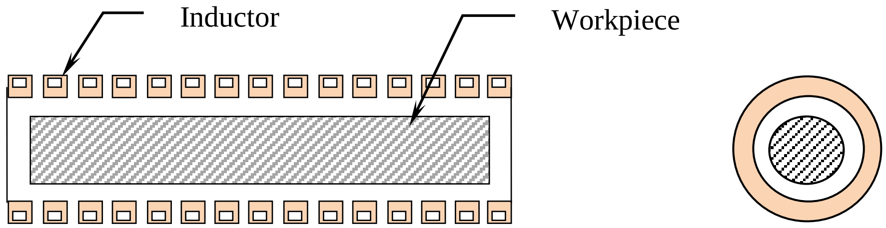


Figure 1. The main type of external cylindrical inductors

1D program ELTA can calculate such systems but cannot give distribution of heat sources and temperature in the volume of workpieces.

2DELTA (Two Dimensional ELectro-Thermal Analysis) is a subject oriented program developed to design of induction heating processes and equipment for a cylindrical system [1]. It has been developed as continuation of program ELTA for two-dimensional calculation of temperature in cylindrical workpieces. Despite a lot of commercial 2D programs which can be used for induction heating of cylindrical workpieces 2DELTA is the best in this field first of all for technological specialists, developers of induction heating equipments and students due to its some advantages.

The main features of this program are:

- 2DELTA has “Model View”, i.e. the system of geometrical visualization for main elements of technological line, that permits to control the preprocessing;
- 2DELTA provides the great opportunities for visualization of output parameters in the form of graphs and tables, i.e. the advanced post processing;
- Program has very friendly user interface;
- 2DELTA is relatively simple program for understanding and realization; the boundary conditions in the problem of calculating the electrical and thermal parameters can be set automatically;
- Many typical technological heating lines with simultaneous, non-stationary semi-continuous and continuous processes can be simulated from start to stationary finish;
- 2DELTA can simulate the heating process with one, two or three layer induction coils;
- User may select from many variants of resonant circuits with different schemes of compensation: parallel; parallel with transformer; series; series with transformer; series-parallel; series-parallel with transformer; parallel-series; parallel-series with transformer, etc.;
- 2DELTA can take into account circuits with series connected induction coils and simultaneously multi frequency power sources for circuits;
- There is a special cooling diagram: applying the Time-Temperature Transformation curves (Continuous Cooling Transformation diagram, Isothermal Transformation diagram or other types of diagram) to this graph, the user can find the structural transformations in the cross-section of workpiece including the case depth and hardness;
- Program has a special block EDF for calculation of electrodynamic (electromagnetic) forces acting on the workpieces, induction coils and magnetic concentrators.
- 2DELTA has a built-in report with report templates created by users and can export

the results in a Word format.

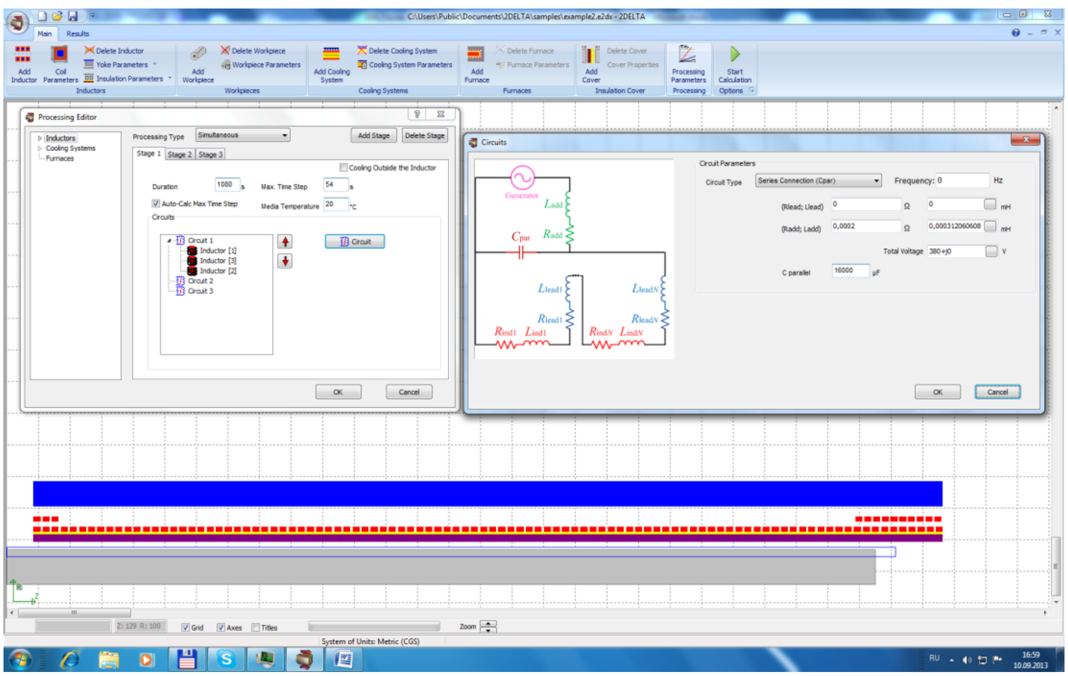
2DELTA program provides a two dimensional simulation of electromagnetic and thermal fields in cylindrical induction heating using both integral and differential numerical methods.

2DELTA can simulate a wide range of electrothermal processes in cylindrical workpieces and may be simply and effectively used by students, scientists, industrial researchers and users of induction technology in multiple applications.

Simultaneous processing

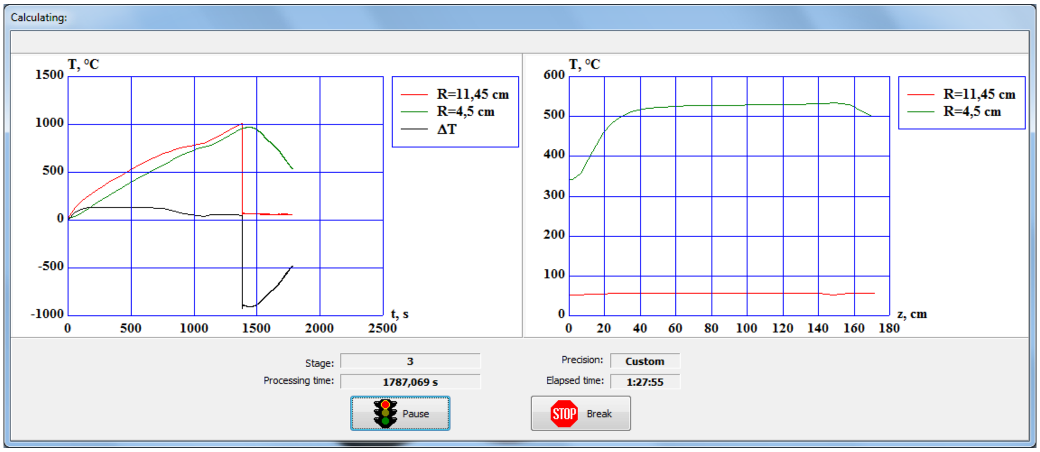
Simultaneous heating process is the process when the workpiece is located in stationary position without any moving. There are two other types of processing (semi-continuous and continuous) when workpiece can move throughout the technological line. Even in simultaneous processing 2DELTA provides numerous variants to investigate. For example the induction heater has the main induction coil and two additional coils located at the end parts of main coil. These coils may be used to compensate the well known negative “end” effects of workpiece and inductor in the ferromagnetic stage. If you use the additional coils in nonmagnetic stage the distribution of temperature along the surface is very non-uniform due to high specific power at the end parts. In this case the additional coils can be switch off to reduce the overheating of end parts of the load.

The example of such variant is presented below.



The first stage has three series connected induction coils to compensate the end effects of inductor and load up to Curie point. In the second, no ferromagnetic, stage one induction coil is switched on and two other additional coils are switched off to prevent the overheating of end parts of workpiece.

Cooling system is used after second stage for hardening of steel.

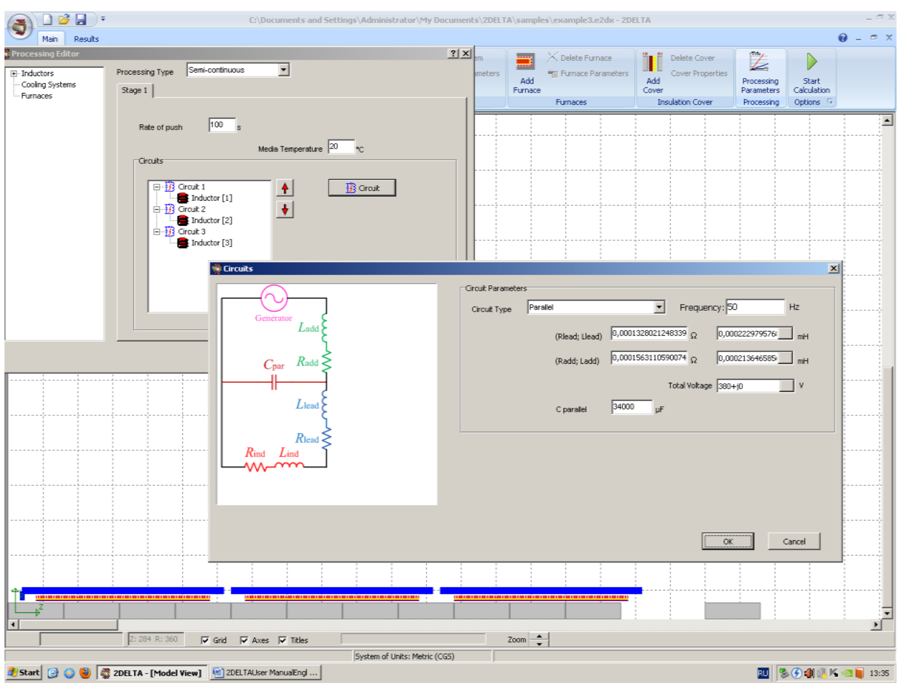


Inductors 1, 2 and 3 are switched off, cooling system is switched on.

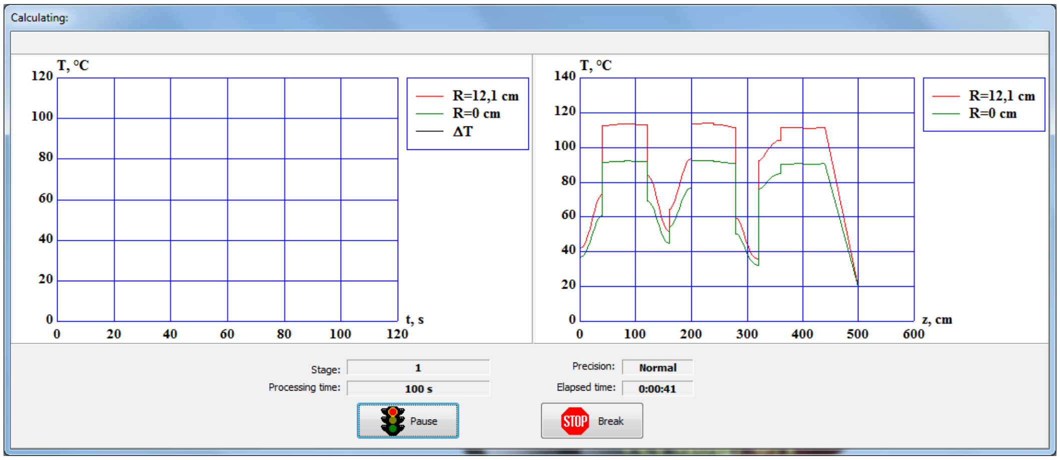
Simi-continuous processing

Semi-continuous heating process is the process when the workpieces are moving with determined step of push. 2DELTA can calculate the technological line with one workpiece or two and more workpieces. The second variant is more complicated from technological point of view. The process is non-stationary. 2DELTA provides to investigate the process from initial temperature of all workpieces, for example 20 °C, to final. In this case parameters of inductors can change sufficiently.

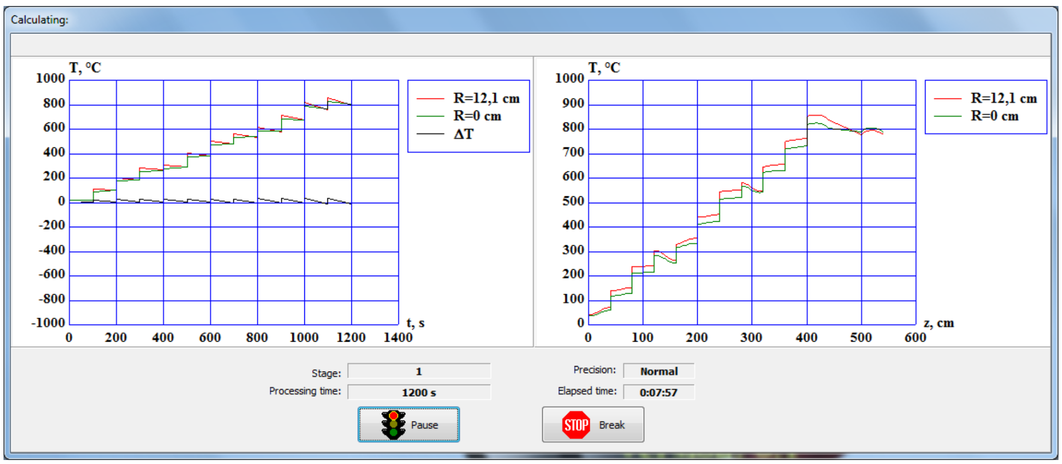
Example 3 is the semi-continuous variant of industrial induction heating line for copper workpieces.



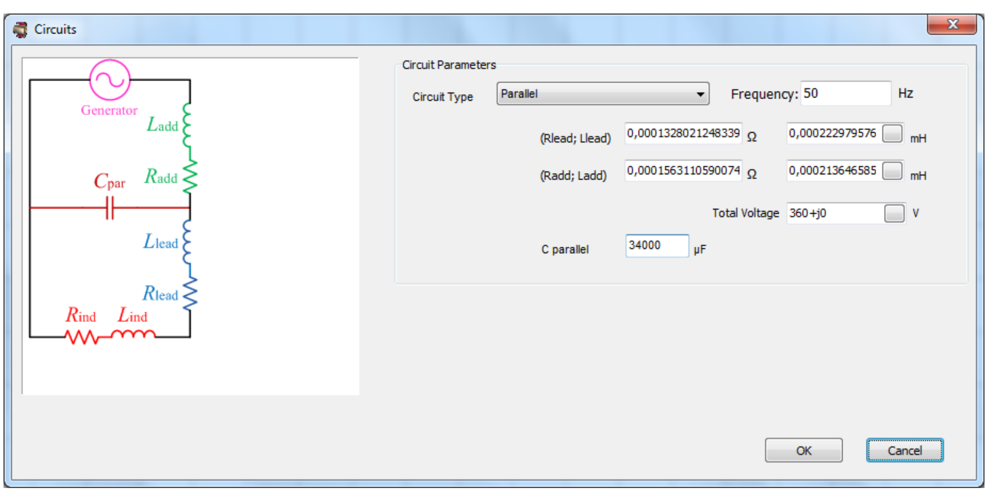
11 workpieces are located inside the 3 phase induction heater. One workpiece is out the inductors on the air. Rate of push is 100 s.

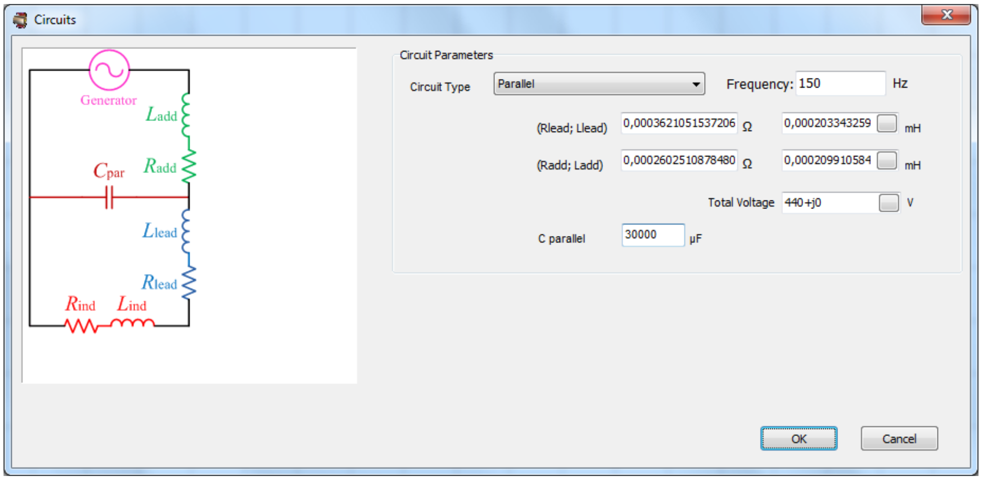


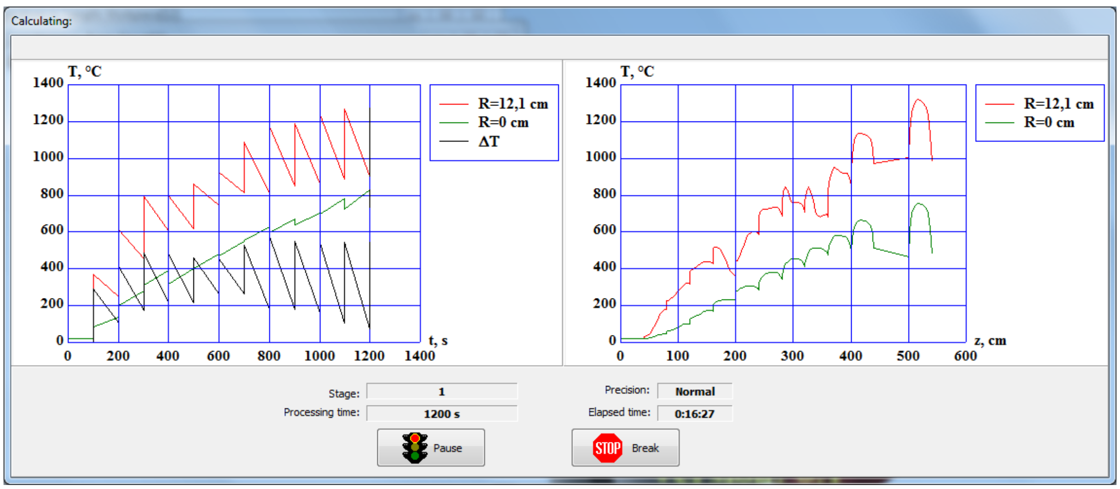
The temperature of each workpiece increases from the first stage of push 100 s to final stage 1200 s. Non-stationary process of heating is finished and you can see the stationary process when the parameters of inductors do not change sufficiently.



2DELTA provides to investigate the process used simultaneously multi frequency power sources, for example 2 frequencies 50 and 150 Hz. In this case the heating sources of workpiece summarize. Example 4 is the semi-continuous variant of two frequencies induction heating line for steel workpieces.







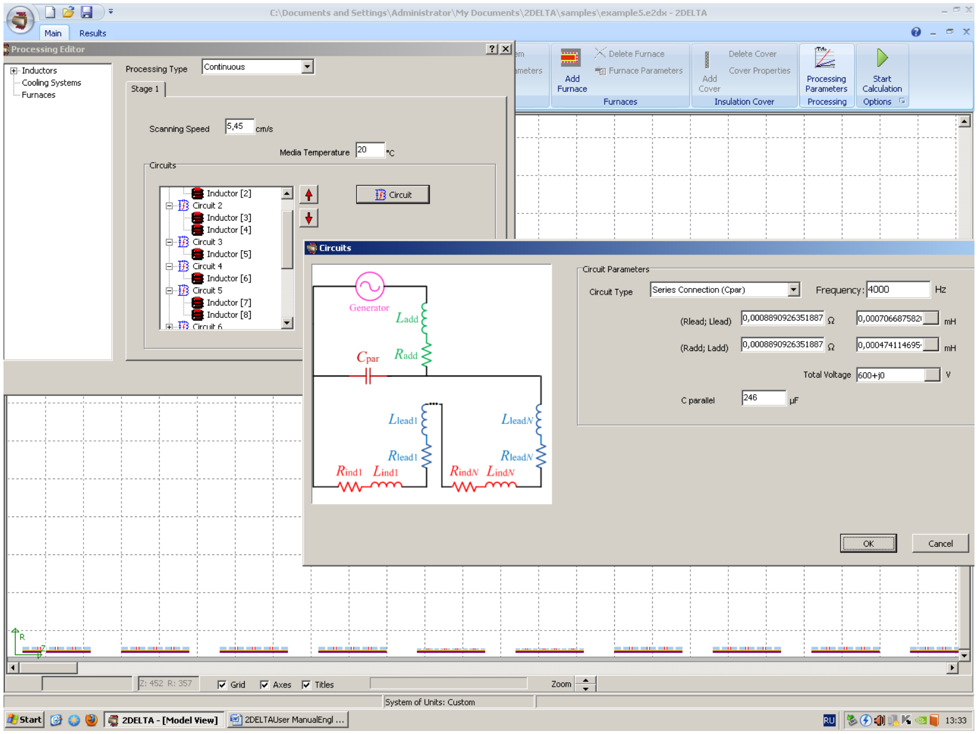
To reduce the time of calculation during the investigation process you may save the temperature distribution after firs calculation and use it in the future.

2DELTA writes file of temperature and you may open it after you will open the task. In this case the heating process will be stationary instead of no stationary one investigated in the first calculation.

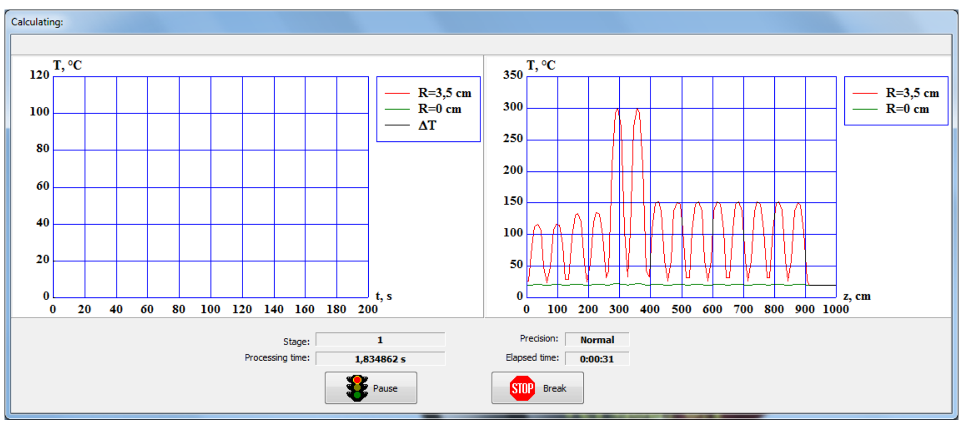
Continuous processing

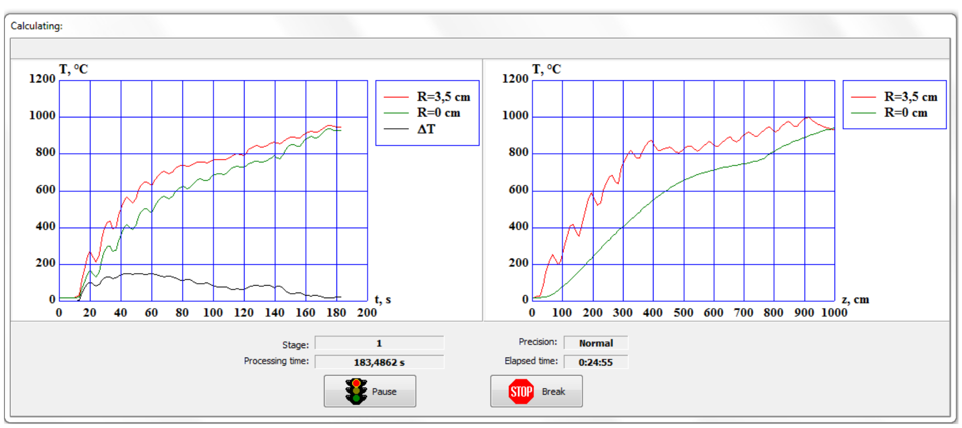
Continuous heating process is the process when the very long workpiece moves with determinate speed. 2DELTA can calculate the technological line with one workpiece. The process is non-stationary. 2DELTA provides to investigate the process from initial temperature of workpiece, for example 20 °C, to final. In this case parameters of inductors can change sufficiently.

Example 5 is the continuous variant of induction heating line for steel workpiece. Often some inductors have series connection and parallel circuit to compensate the reactive power. In this example there are 8 circuits. The circuits 1, 2, 5, 6, 7 and 8 have two series connected induction coils. Both the circuits 3 and 4 have only 1 induction coil.



The temperatures along Z coordinate of the workpiece change from non-stationary to stationary distribution.





2DELTA provides to investigate the process used simultaneously multi frequency power sources. Often frequency in non-ferromagnetic stage must be more than in ferromagnetic. You may increase the electrical efficiency if induction coils 10, 11, 12 and 13 will have frequency 10 kHz instead 4 kHz.

Many types of data presentation are available in 2DELTA.

1. **Temperature vs. Length** (at any radius and at any time).
2. **Temperature vs. Radius** (at any length and at any time).
3. **Temperature vs. Time** (at any radius and at any length).
4. **Temperature Difference vs. Length** (at any radius and at any time) for any workpiece. This graph shows **Surface** and **Core** temperatures plus **Differential** and **Average** temperatures in the load cross-section at any instant of the process.
5. **Temperature Difference vs. Time** (at any radius and at any length) for any workpiece.
6. **Efficiency** for any Circuit (series connected inductors). This graph shows the electrical, thermal and total efficiency of the circuit for the full range of time.

10. **Power Factor** for any circuit and generator. This graph shows power factor of the Circuit and generator over the full range of time. Keep in mind that **2DELTA does not show a sign of the power factor (inductive or capacitive reaction)**. Obviously it is inductive for the very coils but not for the whole circuit. Power factor of the generator load can be inductive or capacitive and even more, it can change sign during processing time
11. **Impedance** for any Circuit. This graph shows the real, imaginary and total circuit impedance and impedance of primary of transformer over the full range of time.

14. **Voltage** for any Circuit. This graph shows voltage of the circuit and on the generator terminals over the full range of time. The voltage is calculated for the circuit including the buswork.
15. **Current** for any Circuit. This graph shows the current of circuit and generator over the range of time.
16. **Power** for any Circuit. This graph shows the power input to the circuit, the power dissipated in the inductors of circuit, and the power reaching the workpiece over the full range of time. It shows too the power output of generator.
17. **Reactive Power** for any Circuit. This graph shows the reactive power of circuit over the full range of time.
18. **Frequency** for any Circuit. This graph shows frequency variation during the process of heating.
19. **Thermal Losses** of the workpieces inside the any inductor and total losses. This graph shows the power losses of workpieces surface area.
20. **Capacitance**. This graph shows the real and resonant capacitance required for compensation of the Circuit (series connected inductors) reactive power for some circuits.
21. **Field Strength vs. Length** (at any radius and at any time). This graph shows the magnetic field strength of any workpiece, over the full range of length.
22. **Field Strength vs. Radius** (at any length and at any time). This graph shows the magnetic field strength of any workpiece, over the full range of radius.
23. **Field Strength vs. Time** (at any radius and at any length). This graph shows the magnetic field strength of any workpiece, over the full range of time.
24. **Heat Sources Density vs. Length** (at any radius and at any time). This graph shows the heat sources density of any workpiece, over the full range of length.
25. **Heat Sources Density vs. Radius** (at any length and at any time). This graph shows the heat sources density of any workpiece, over the full range of radius.

26. **Heat Sources Density vs. Time** (at any radius and at any length). This graph shows the heat sources density of any workpiece, over the full range of time.

27. **Current Density vs. Length** (at any radius and at any time). This graph shows the current density of any workpiece, over the full range of length.

28. **Current Density vs. Radius** (at any length and at any time). This graph shows the current density of any workpiece, over the full range of radius.

29. **Current Density vs. Time** (at any radius and at any length). This graph shows the current density of any workpiece, over the full range of time.

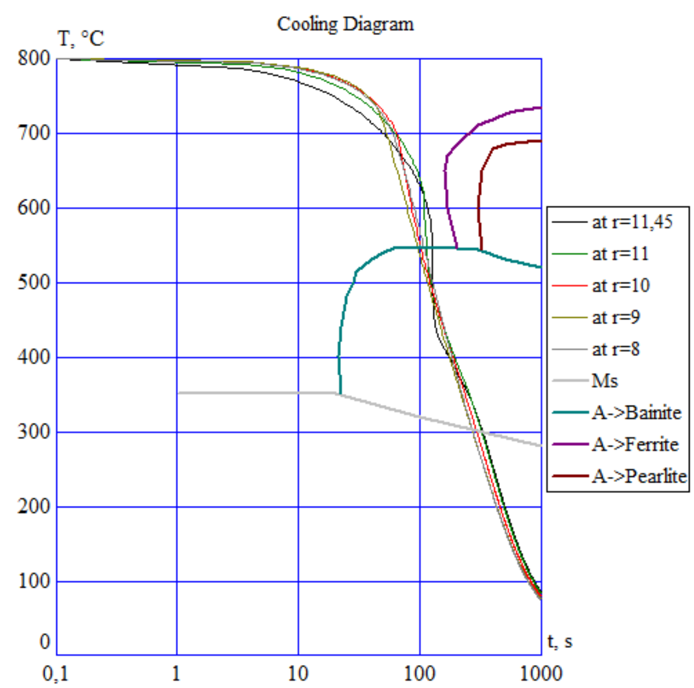
30. **Electrodynamic Forces**. This graph shows the value of axial electrodynamic force on the workpiece vs. air gap during the displacement at the end of process.

Cooling diagrams apply only to processes with cooling stages. This diagram shows temperature dynamics at selected part points during the process of cooling. In 2DELTA, all cooling curves start at the time when the local temperature crosses a line of the designated temperature specified by the user. **It means that zero point of the time scale is individual for each element of the cross-section.**

The A_r temperature may be used as a characteristic temperature for heat treating processes. This graph may be displayed in normal or logarithmic scales. Use Add New Curve under the 2D **Graph** menu to add additional curves to the graph. The program informs you if the designated point does not meet specified requirements (crossing the specified temperature line).

Applying the Time-Temperature Transformation curves (Continuous Cooling Transformation diagram or Isothermal Transformation diagram) to this graph, the user can find the structural transformations in the part cross-section including the case depth and hardness.

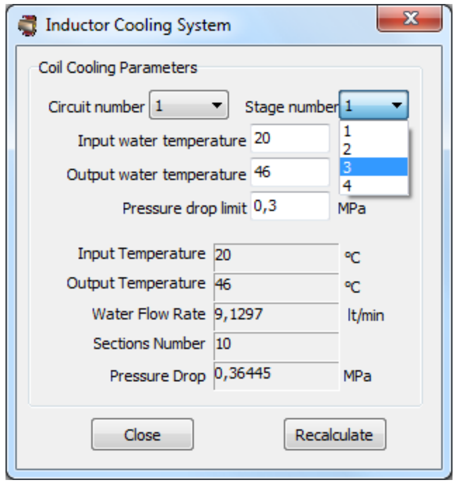
Right click mouse button on the Cooling Diagram and click Import Data From… . Find *.txt file (for example AISI 4140 (42CrMoS4).txt) in directory. The curves of Ms, A->Bainite, A->Ferrite, A->Pearlite are appeared.



The M_s temperature may be used as a characteristic (start temperature) for transformation of austenite into martensite. This diagram can predict the quality of hardening process that depends on the quality of cooling media and parameters of steel.

If user has the data of hardness for example in HV, it may create txt file and Import Data From this file too.

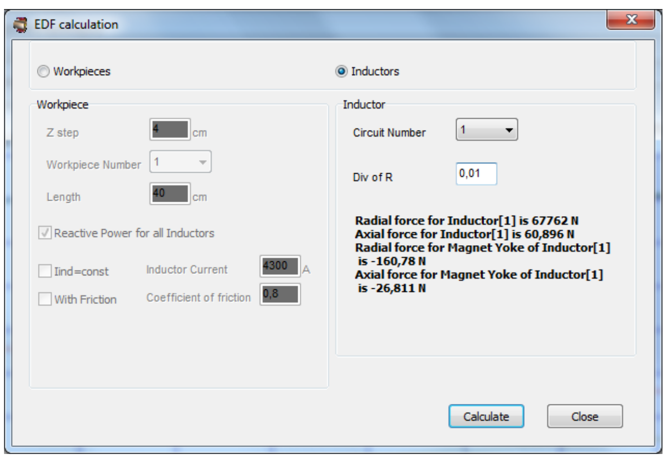
2DELTA makes hydraulic calculations for water cooling of the inductor. The program calculates required Water Flow Rate, Section Number (parallel branches of water), and Pressure Drop for each stage and each circuit number. You may change the Input or Output water temperature, the Pressure drop limit, click the button Recalculate to show immediately the new results.



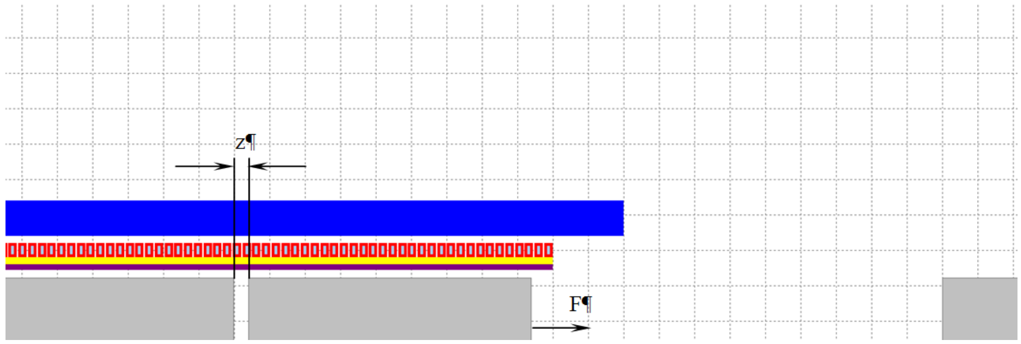
Electrodynamic Forces

You may calculate EDF of workpiece or EDF of inductor.

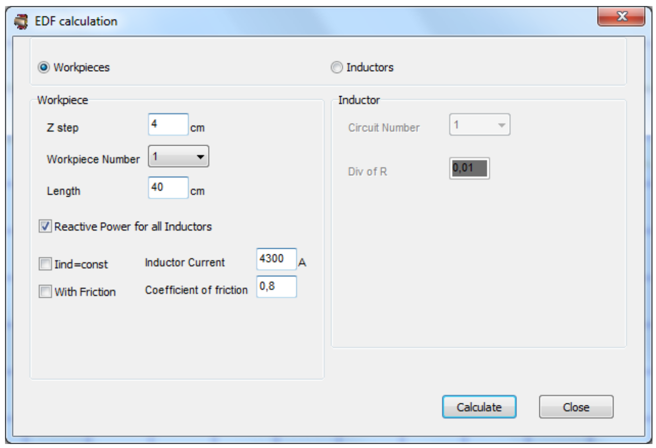
Small window prompts you to calculate the Radial and Axial Forces of Inductors, Magnet Concentrators and Axial Forces of workpiece.

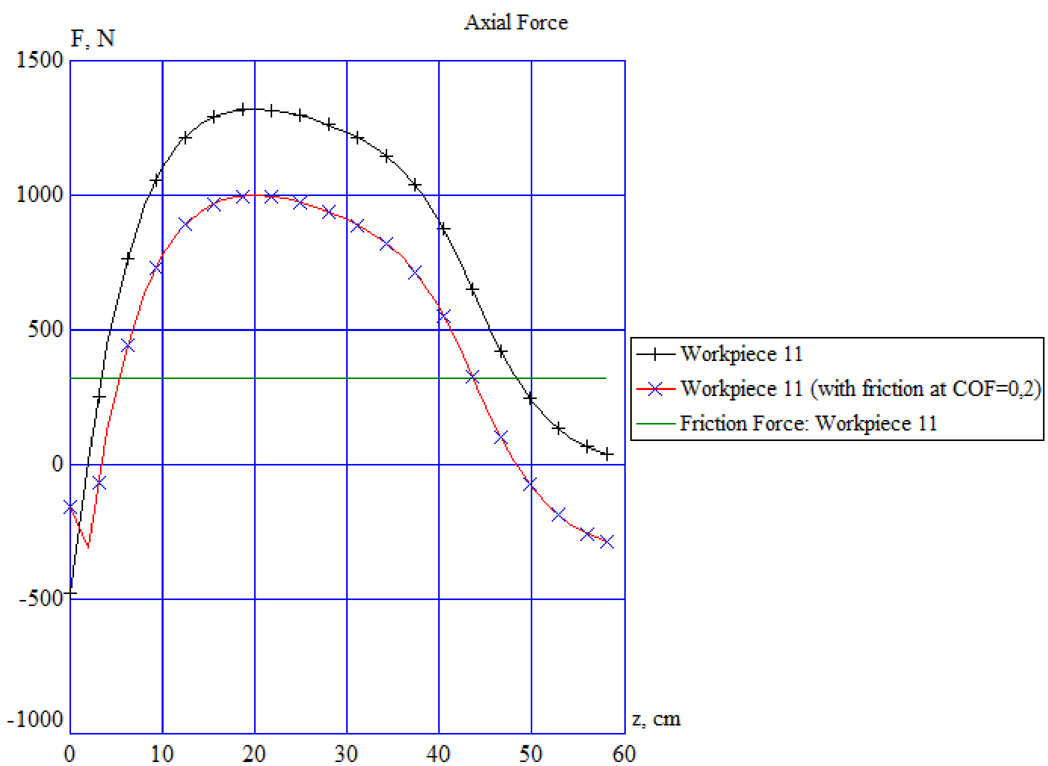


For example you want to investigate the EDF and very strong problem of spontaneous unloading the workpiece from inductor. Workpiece number 11 moves inside the inductor number 3 with increased air gap (see picture).



You may click the **Workpieces** button, choose the Workpiece Number 11, Length of moving and step of displacement Z step (for example 60 cm and 2 cm), change Coefficient of friction 0.2, calculate and wait the result in 2D graph form.





The obtained result of axial force can give you the useful information about the problem of spontaneous unloading the workpiece (in the picture the positive value of force with friction at coefficient of friction COF=0.2).

1. Ivanov A., Bukanin V., Zenkov A. *Advancements in Program ELTA for calculation of induction heating systems.* Proc. of the Int. Conf. on Heating by EM Sources, Padua, May 21-24, 2013.