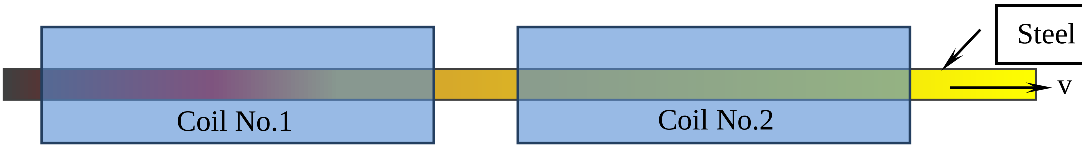
## OPTIMIZATION OF FORGING INDUCTION HEATER

**Real story:** Forging Company has an induction heater for continuous heating of steel bar Dia. 40 mm.

- Heater has two connected in parallel coils. Coils have length of 1200 mm with 96 turns in each coil made of rectangular tubing A × T × t = 8 × 12 × 1.5 mm (A and T – axial and radial dimensions, t – wall thickness). Coil ID = 86 mm, refractory cylinder ID = 60 mm. Material – ceramics.
- Coil voltage is app. 800 V at 1000 Hz.
- Coils have 12 branches for water cooling each; total water flow rate is around 300 lt/min.




ELTA 5.5 (6.0) was used to find a possibility to improve the heater.

**Notes:**

1. Main block of ELTA calculates heating history of the part in batch heating mode. For continuous heating a selected part length must be equal to the coil length. Calculations are made in time, which is related to position of the test point on the part surface in a real process of heating and cooling as t = v/x, with v – speed of the part transportation and x – position of the point at time t starting from the beginning of its treatment (entering into the coil). This method allows us to obtain correct temperature field in the part. However the coil parameters will change in time due to substitution of batch heating for a continuous mode. Correct values of the coils parameters correspond to average (mean) values of calculated parameters during the heating cycle. ELTA gives these values in report and on the screen (on demand when clicking sign of integral ∫). Multiple tests proved that this approach gives quite accurate results.
2. Coils may be connected in series (same current), in parallel (same coil head voltage) or be independent. Independent coils may have different dimensions, turn numbers, etc., as well as be generated by individual power supplies with different frequencies and operation modes. The only restriction for continuous heating is the same length of all coils. For batch heating this restriction isn't necessary.

**A. Analysis of existing system** gave the following results:

1. A set of calculation showed that with coil voltage 800 V, the 40 mm bar could reach final temperature of 1250 ± 50 °C when its speed is 44.5 mm/sec. It means that heating time in each coil is 27 sec and with a space between the coils of 130 mm a "cooling" stage time in the gap is 3 sec. Production rate is 1.56 t/hr.
2. Bar surface temperature (Ts) is app. 1000 °C at the exit from the first coil, drops to 980 °C during transportation between the coils and raises to 1270 °C in the second coil.
3. Heating in the second coil is low efficient (el. efficiency is 0.35 compared to 0.64 for the first coil). Thermal efficiency is also lower (0.85 and 0.95 respectively) due to higher surface temperature.
4. Temperature gradient in radius is rather small and temperature equalizes in 3-4 sec.

5. Part of the report automatically generated by ELTA is presented below.

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Version: 6.0 Project: Forge-T

Radd: 0 W; Ladd: 0 mH

**Processing Stages:**

1. "Heating/Voltage", duration: 27 s.
   f= 1000 Hz, U= 800 V.
   Media temperature:
   $T_{ext.surf}$= 20 °C.
   $a_{outside}$= "Natural".

2. "Cooling", duration: 3 s.
   Media temperature:
   $T_{ext.surf}$= 20 °C.
   $a_{outside}$= "Natural".

3. "Heating/Voltage", duration: 27 s.
   f= 1000 Hz, U= 800 V.
   Media temperature:
   $T_{ext.surf}$= 20 °C.
   $a_{outside}$= "Natural".

4. "Cooling", duration: 3 s.
   Media temperature:
   $T_{ext.surf}$= 20 °C.
   $a_{outside}$= "Natural".

**Integral parameters:**

**Stage N1**

| | |
|---|---|
| Coil Voltage = 800 V | Generator Voltage = 800 V |
| Coil Current = 2107.6 A | Generator Current = 671.38 A |
| Coil Impedance = 0.38942 W | Generator Impedance = 1.3015 W |
| Coil Power Factor = 0.28114 | Generator Power Factor = 0.81819 |
| Workpiece Power = 3.1619E5 W | Coil Power = 4.4908E5 W |
| Generator Power = 4.4908E5 W | Electrical Efficiency = 0.63924 |
| Thermal Efficiency = 0.94175 | Total Efficiency = 0.61167 |
| Field Strength = 1633.5 A/cm | Magnetic Flux Density = 0 T |

**Coil Cooling Parameters**

Input Temperature= 20 °C; Output Temperature= 40 °C.

Water Flow Rate= 108.34 lt/min; Sections Number= 6 ; Pressure Drop= 0.25467 MPa.

**Stage N3**

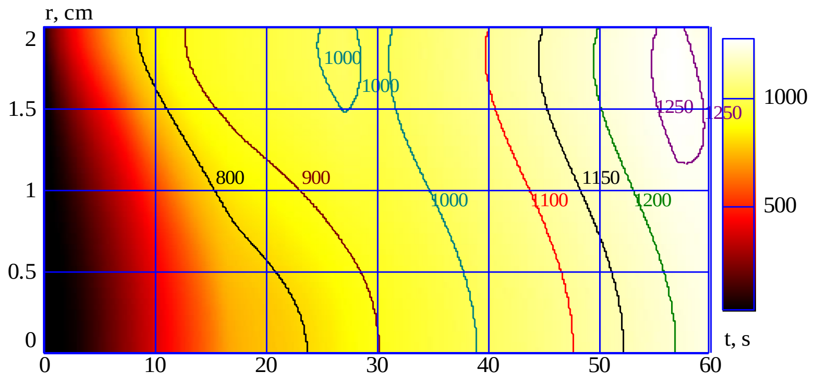
| | |
|---|---|
| Coil Voltage = 800 V | Generator Voltage = 800 V |
| Coil Current = 2280 A | Generator Current = 317.62 A |
| Coil Impedance = 0.35088 W | Generator Impedance = 2.5188 W |
| Coil Power Factor = 0.13931 | Generator Power Factor = 0.99999 |
| Workpiece Power = 1.018E5 W | Coil Power = 2.5409E5 W |
| Generator Power = 2.5409E5 W | Electrical Efficiency = 0.40061 |
| Thermal Efficiency = 0.82016 | Total Efficiency = 0.32864 |
| Field Strength = 1769.1 A/cm | Magnetic Flux Density = 0 T |

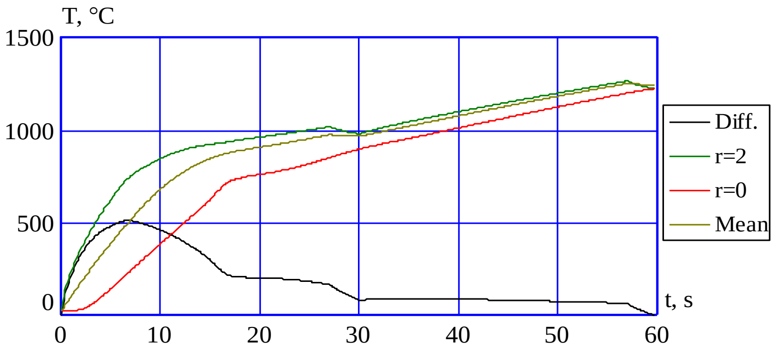
**Coil Cooling Parameters**

Input Temperature= 20 °C; Output Temperature= 40 °C.

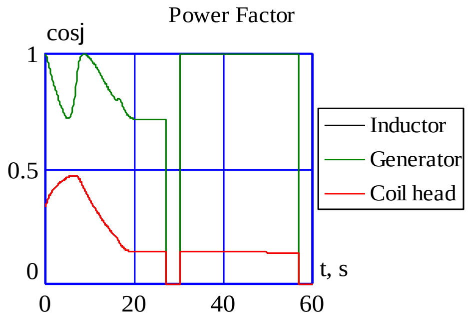
Water Flow Rate= 137.94 lt/min; Sections Number= 7 ; Pressure Drop= 0.26 MPa.

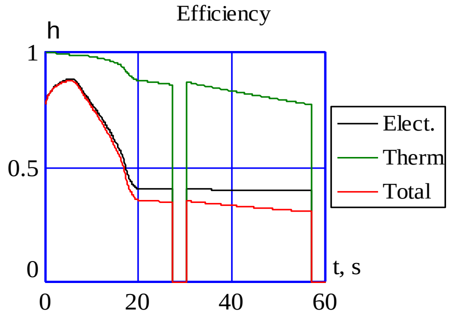
**Results of simulation**




Temperature dynamics during the process




Results of analysis:

1. Results of simulation are very close to measured parameters of the existing installation.
2. Specific energy for heating bar is around 450 kWh/t, which is 2 times higher than minimum required energy (enthalpy) for heating to 1250 °C (245 kWh/t).
3. In existing installation number of water cooling branches may be reduces to 7. However for higher input water temperature (e.g. 30 °C) number of branches must be at least 10 – 12 as it is at present time.

**B. Modified heater**

Because two coils are too long for heating at 1000 Hz, it is a good idea to remove the second coil and modify the first coil. With several iterations it was found that the coil winding must be made of 68 turns of tubing 16 × 16 × 1.6 mm in order to have minimum power demand for the same production rate. The results are presented below.

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Version: 6.0

Project: Forge-T

Radd: 0 W; Ladd: 0 mH

**Processing Stages:**

1. "Heating/Voltage", duration: 27 s.
   f= 1000 Hz, U= 760 V.
   Media temperature:

   $T_{ext.surf}$= 20 °C.

   $a_{outside}$= "Natural".

2. "Cooling", duration: 8 s.
   Media temperature:
   $T_{ext.surf}$= 20 °C.

   $a_{outside}$= "Natural".

**Integral parameters:**

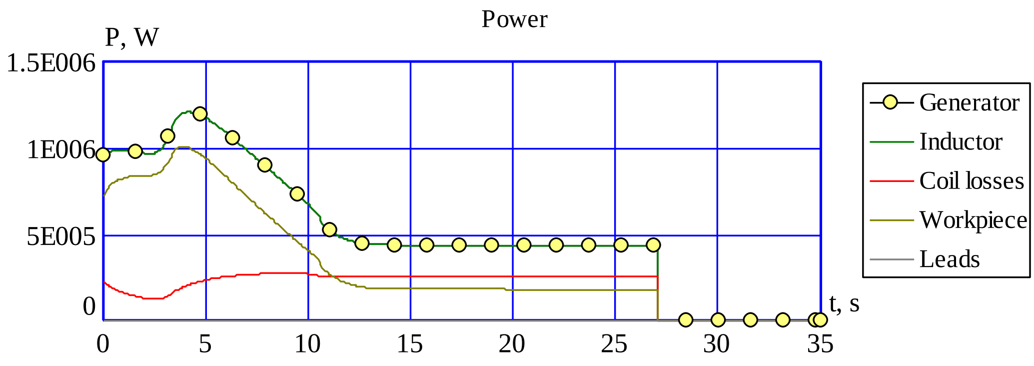
**Stage N1**

Coil Voltage = 760 V
Coil Current = 4197.5 A
Coil Impedance = 0.18275 W
Coil Power Factor = 0.21119
Workpiece Power = 4.1185E5 W
Generator Power = 6.5223E5 W
Thermal Efficiency = 0.92851
Field Strength = 2306.3 A/cm

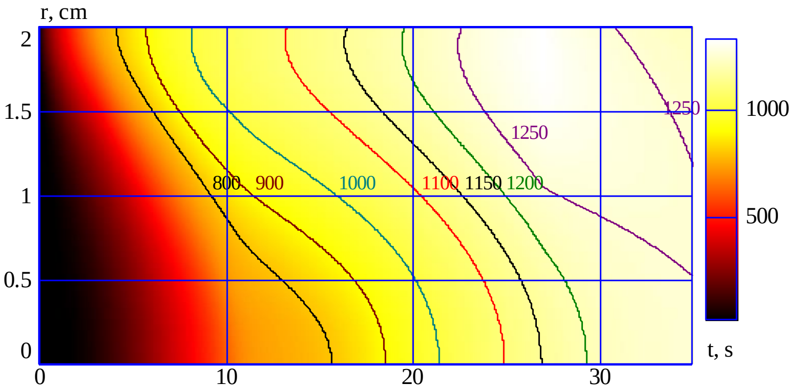
Generator Voltage = 760 V
Generator Current = 973.72 A
Generator Impedance = 0.88627 W
Generator Power Factor = 0.87093
Coil Power = 6.5223E5 W
Electrical Efficiency = 0.55904
Total Efficiency = 0.52718
Magnetic Flux Density = 0 T

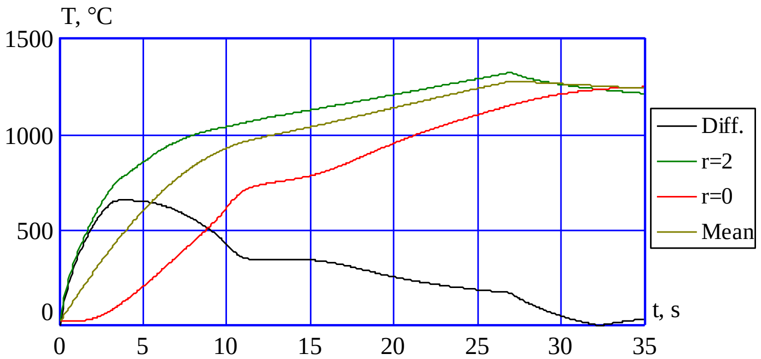
**Coil Cooling Parameters**

Input Temperature= 20 °C; Output Temperature= 40 °C.
Water Flow Rate= 196.42 lt/min; Sections Number= 4 ; Pressure Drop= 0.2887 MPa.

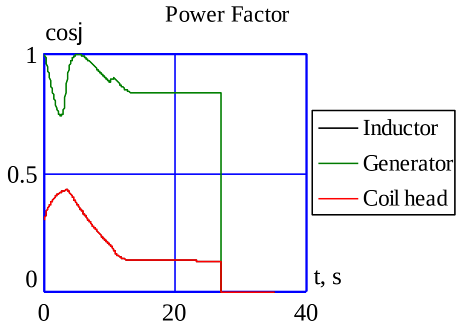


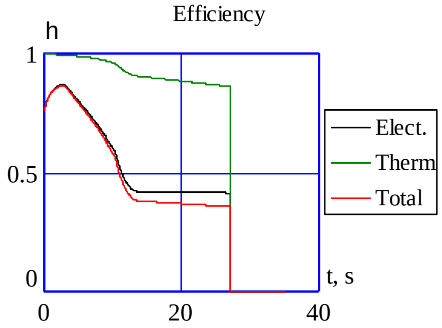
## Results of simulation




Temperature dynamics during the process




## Improvements:

1. Shorter heater length and lower price (one coil instead of two).
2. Higher efficiency (electrical efficiency 0.56, total 0.52).
3. Lower water demand (200 lt/min instead of 300 lt/min).
4. Smaller and cheaper capacitor battery.
5. Total required power is 652 kW compared to initial 703 kW, i.e. reduced by 7.5 %.

Further improvements may be achieved if we increase frequency.

## C. Heating at frequency 1500 Hz

Reference depth for hot steel at 1000 Hz is 16 mm, i.e. only 1.25 times smaller than the bar radius. It means that coefficient of power absorption G equals to 0.3 and is far from a threshold value which equals to 1 at high frequency. Optimal frequency for a bar with diameter 40 mm must be 3 – 4 kHz; in this range an absorption coefficient is about 0.8. Frequency change from 1 to 3 or 4 kHz may demand purchase of a new power supply. It will require also longer coil in order to provide uniform heating. We can assume that the existing thyristor power supply for 1000 Hz may be turned to 1500 Hz. Simulation below showed that even this simple change can result in significant improvement of efficiency.

### Results of simulation at 1500 Hz:

**Integral parameters:**

**Stage N1**

| | |
|---|---|
| Coil Voltage = 800 V | Generator Voltage = 800 V |
| Coil Current = 1865.9 A | Generator Current = 584.69 A |
| Coil Impedance = 0.43997 W | Generator Impedance = 1.4793 W |
| Coil Power Factor = 0.27565 | Generator Power Factor = 0.82184 |
| Workpiece Power = 3.0283E5 W | Coil Power = 3.9036E5 W |
| Generator Power = 3.9036E5 W | Electrical Efficiency = 0.73435 |
| Thermal Efficiency = 0.95485 | Total Efficiency = 0.70626 |
| Field Strength = 1281.8 A/cm | Magnetic Flux Density = 0 T |

**Coil Cooling Parameters**

Input Temperature= 20 °C; Output Temperature= 40 °C.
Water Flow Rate= 75.063 lt/min; Sections Number= 4 ; Pressure Drop= 0.16009 MPa.

**Stage N3**

| | |
|---|---|
| Coil Voltage = 800 V | Generator Voltage = 800 V |
| Coil Current = 1992.8 A | Generator Current = 265.5 A |
| Coil Impedance = 0.40144 W | Generator Impedance = 3.0133 W |
| Coil Power Factor = 0.13322 | Generator Power Factor = 0.99996 |
| Workpiece Power = 1.1468E5 W | Coil Power = 2.1239E5 W |
| Generator Power = 2.1239E5 W | Electrical Efficiency = 0.53991 |
| Thermal Efficiency = 0.84358 | Total Efficiency = 0.45551 |
| Field Strength = 1370.1 A/cm | Magnetic Flux Density = 0 T |

**Coil Cooling Parameters**

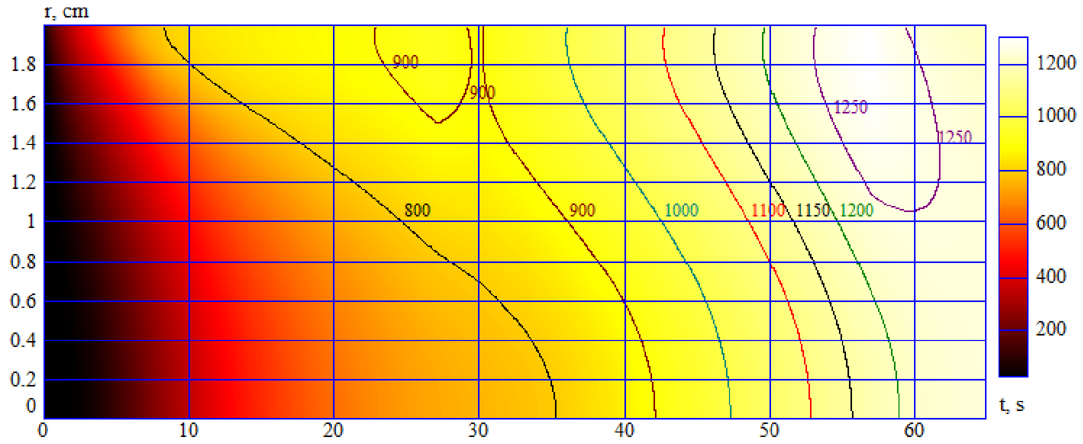
Input Temperature= 20 °C; Output Temperature= 40 °C.
Water Flow Rate= 98.077 lt/min; Sections Number= 4 ; Pressure Drop= 0.27329 MPa.

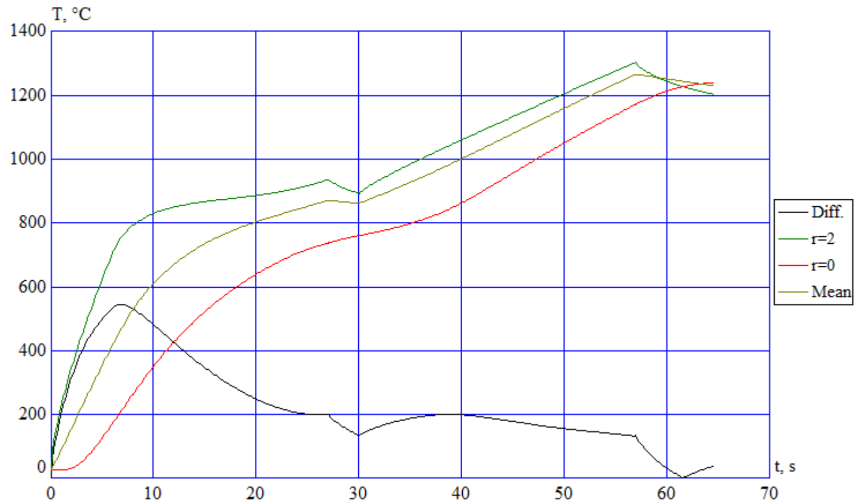
### Improvements:

1. Using two modified coils same as in case A but with turn number 85, it is possible to heat bar with the same production rate using only 602 kW instead of 703 for initial design! Maximum surface temperature is 1270  C.
2. Lower need in water (173 lt/min instead of 300 lt/min) with only 4 branches of cooling.

## D. Heating at frequency 4000 Hz

We can use two coils 1000 mm long with 51 turns to heat bar with required uniformity. Coils may be fed in parallel from one power supply. Temperature color map and temperature dynamics chart are presented below.




**Improvements:**

1. Total required power is only 457 kW, i.e. 1.54 time lower than in the existing installation.
2. Lower water demand (110 lt/min instead of 300 lt/min in existing installation) with only 2 branches of cooling for each coil.
3. Smaller and cheaper capacitor battery.

**Overall conclusions:**

Table. Installation parameters for the same production rate of 1.56 t/hr

| Version | Number of coils | Frequency, kHz | Power, kW | | | Water, lt/min | Reactive power, kVAr |
|---|---|---|---|---|---|---|---|
| | | | Coil 1 | Coil2 | Total | | |
| A | 2 | 1.0 | 449 | 254 | 703 | 245 | 3410 |
| B | 1 | 1.0 | 652 | - | 652 | 198 | 3100 |
| C | 2 | 1.5 | 390 | 212 | 602 | 173 | 3000 |
| D | 2 | 4.0 | 282 | 175 | 457 | 110 | 2900 |

- Simulation of the existing system (case A) gave results very close to measured in practice both for electrical and cooling parameters.
- Using ELTA it is possible to simulate different heating regimes and heater designs.

- Though ELTA has no automatic optimization procedure, an operator can effectively optimize the process and system in several iterations with account for multiple restrictions and several goal functions.
- Operator-guided design can provide big savings in capital investments, energy and cooling water demand.