Modeling of Induction Heating of Steel Billets for DPS Control Design Purposes

J. Kapusta[1], J. Camber[1], G. Hulkó[1]
1. Institute of Automation, Measurement and Applied Informatics, Faculty of Mechanical Engineering,
Slovak University of Technology in Bratislava, Slovak Republic.
juraj.kapusta@stuba.sk, juraj.camber@stuba.sk, gabriel.hulko@stuba.sk

Introduction: All real-life systems can be described as distributed parameters systems (DPS) in terms of control, especially heavy industrial devices, such as gas/electrical furnaces, induction heating or continuous casting processes. Simple time-dependent identification may not be sufficient for modern, robust and highly efficient control. Most of the controlled thermal processes are nonlinear, complex and changing in time and space (Hulkó, G. et al., 1998). Fortunately, for modern design there is no longer necessary to deal with physical identification of process. The computer aided modeling (CAM) software become useful assistant in exploring thermal analysis and dynamics of wide range of applications when using properly. Advanced multi-physical modeling, investigation of time-spatial dynamic characteristics of system and finally the Simulink/DPS Blockset control circuit suited for induction heating are described in this poster.

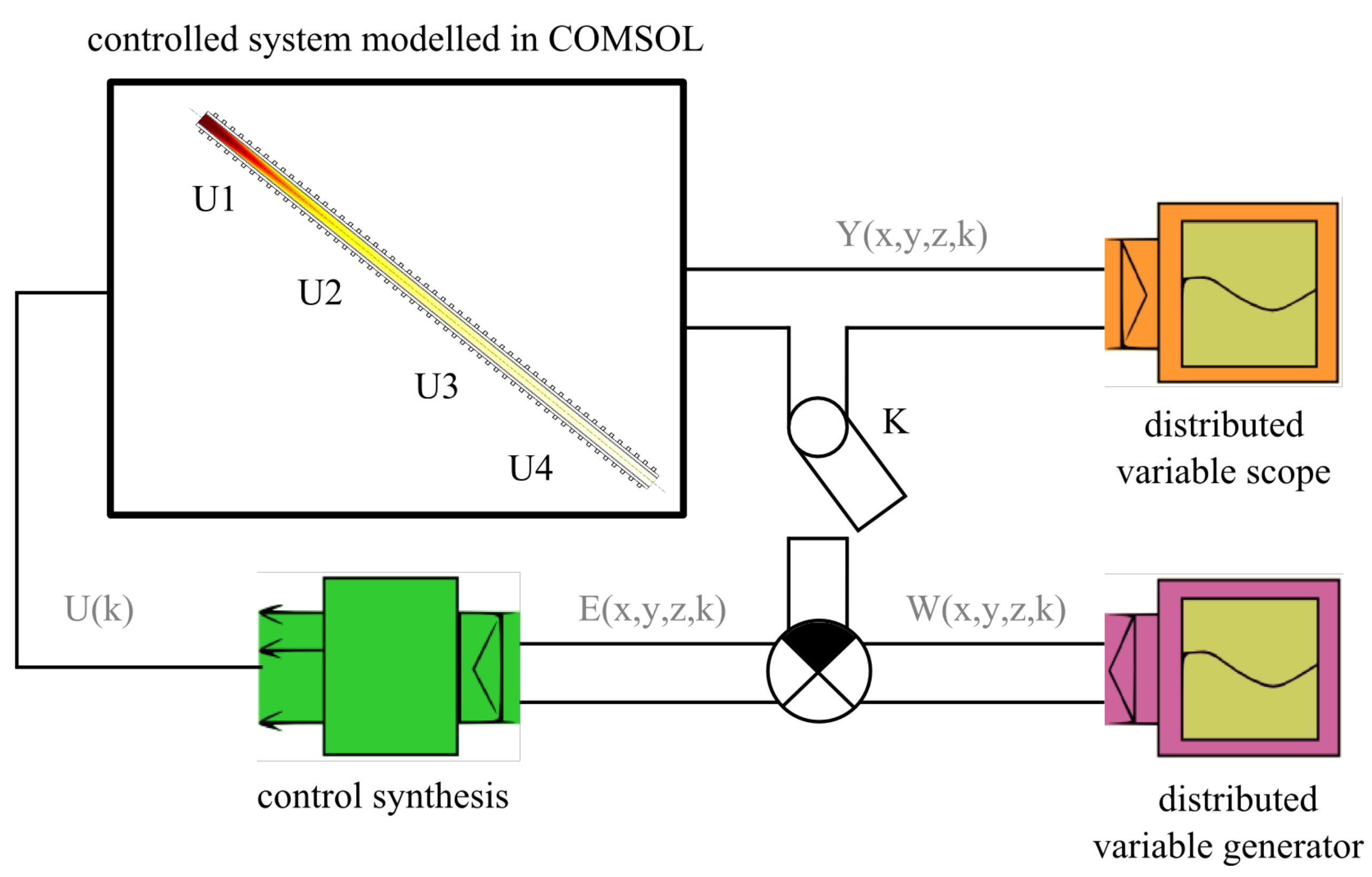

Figure 1. Simple schematic of DPS Blockset control circuit

Computational Methods: Material properties of heated steel billets are non-linear temperature dependent, which means they are changing during heating cycle. It is necessary to take it into account in model preparation. Magnetic vector potential **A** for axially symmetric cylindrical system can be written as

$$\frac{1}{\mu_0\mu_r}\left(\frac{\partial^2\mathbf{A}}{\partial r^2}+\frac{1}{r}\frac{\partial\mathbf{A}}{\partial r}+\frac{\partial^2\mathbf{A}}{\partial r^2}-\frac{\mathbf{A}}{r^2}\right)=-\mathbf{J}_{\mathrm{source}}+i\omega\sigma\mathbf{E}$$

where $\mu_0 = 4\pi\cdot10^{-7}$ [H·m^{-1}] is permeability of vacuum, μ_r is relative permeability, $J_{source} = -\sigma\,\phi$ drive current density in the coil, σ electrical conductivity and **E** represents the vector of electric field intensity. Boundary condition is set as a standard Dirichlet boundary condition **A** = 0, or as a gradient of vector **A**, which is negligible small in space (Neumann boundary condition *grad***A** = 0). In case of cylinder body heat it is necessary to consider a modified two-dimensional Fourier equation of the heat transfer in axial symmetry form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(\lambda(T)r\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right)=-q(T)+c(T)\rho\frac{\partial T}{\partial t}$$

where T is temperature, ρ density of material, c specific heat capacity, λ thermal conductivity coefficient of material and q is the density of heat flow, which is produced by heating of the body due to eddy currents. It should be noted that two variables c and λ are nonlinear functions of temperature dependent and their replacement by a constant value can increase the error of calculation.

The heating process of large diameter steel billets (above 80mm radius) for forging industry takes about several minutes to achieve an optimal steady state, depending on heated material, production stage cycle and desired temperature profile as well. In our model situation based on real engineering application, the billets are constantly moving through the coil tunnel with velocity of 1cm/s, which means, approximately every 25 seconds the properly heated billet drops out. To simplify a calculation and to reduce solving time, there was considered a moving bar instead of number of separate involving billets. The desired forming temperature of steel billet in the end of inductor should be around 1450K, including the minimal core-to-surface temperature variation. In practice, the forging temperature may vary depending on forming technology and heated material.

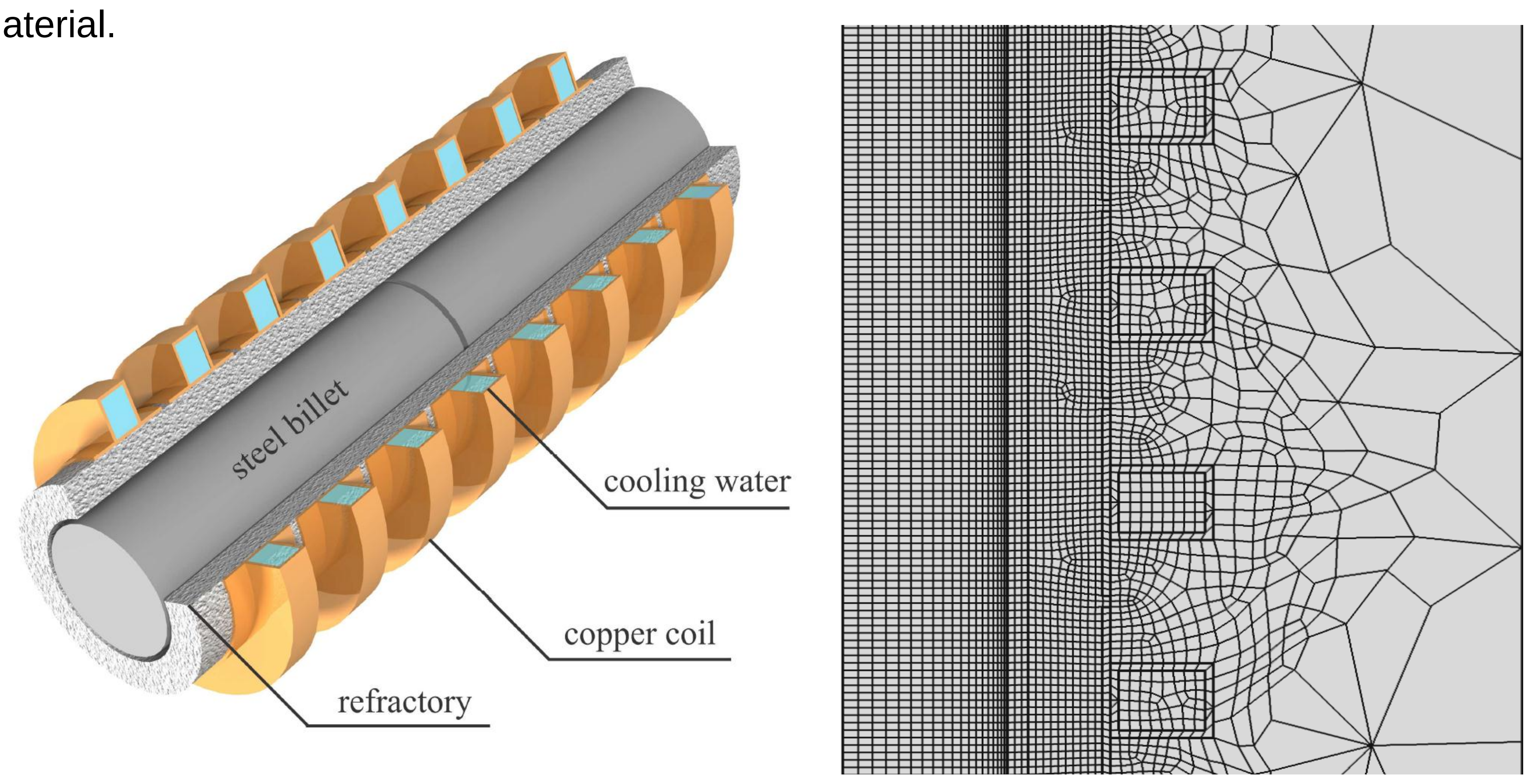

Figure 2. Part detail of complete 3D-model and custom finite element mesh in 2D axisymetric

Results: Solving time was set up to t=800s, which makes the steady-state clearly visible. The expected forming temperature around 1450K in the end of inductor has been achieved during time of approximately 400s with billet moving velocity of 1cm/s.The desired time-dependent temperature distribution in billets through whole inductor length gives a fairly accurate view on induced heat to the surface of billet and to the core as well (see **Fig. 3**). Solved steady state temperature-to-time profile of four-module inductor was measured by ten virtual probes symmetrically placed on whole length of inductor, as shown Fon **Fig. 4**. The solved time-spatial distribution of temperature solved by COMSOL, represents both components of dynamics, therefore it was used as steady-state system representation for DPS control circuit design. In other words, in terms of DPS theory, it represents the essential dynamic characteristic of system. It was exported in matrix form from COMSOL and loaded into MATLAB interface for DPS control design purposes via DPS Blockset Toolbox (see **Fig.1**).

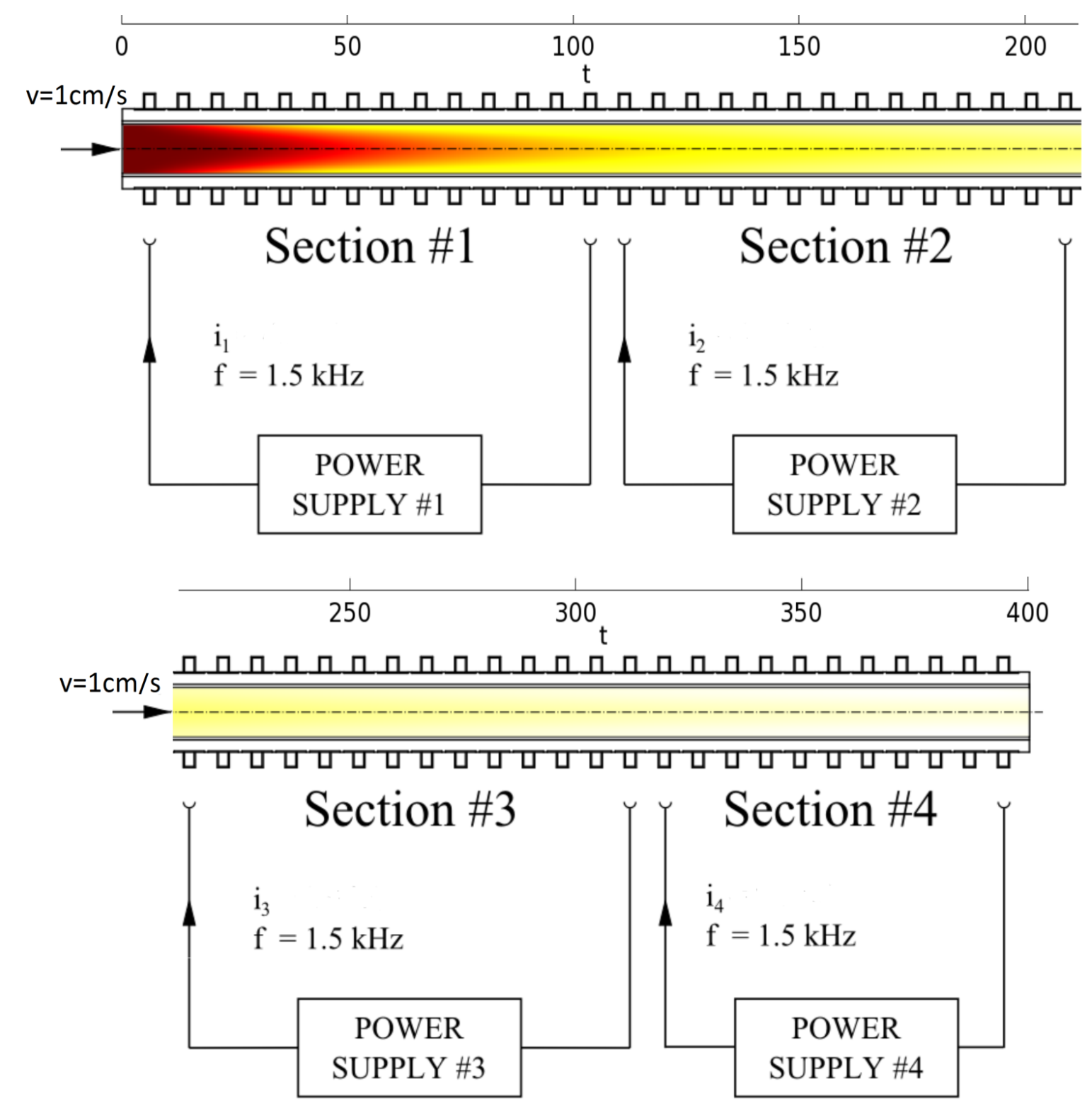

Figure 3. Solved temperature-to-time distribution in billets through whole inductor length

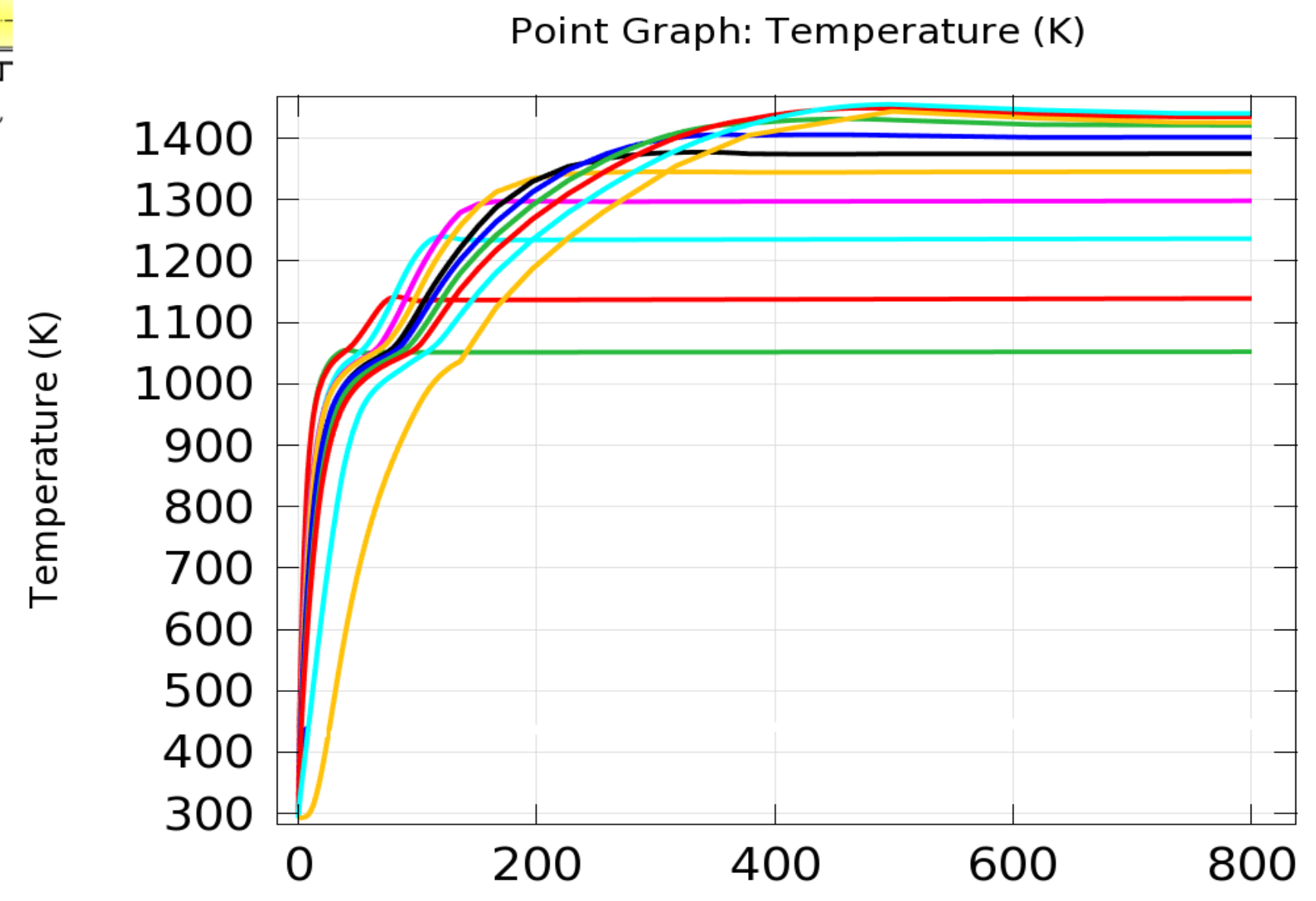

Figure 4. Steady-state temperature-to-time profile

Four coils generate heat in the billet separately, making it a typical lumped-input and distributed-parameter-output system. Dynamic characteristic of the induction heating process has been obtained on numerical model in COMSOL. In a linearized region around the steady-state let us consider a model situation of a step change – the need to raise the temperature of billets by 30K in full length of inductor in time t=100s. The DPS PID Control Synthesis block operates with properly tuned PI regulator and uploaded dynamic characteristic of model solved by COMSOL, is able to achieve new required time-spatial temperature profile within 400s by changing the actuation quantities U_1-U_4. The U_1-U_4 simply represents the coil currents.

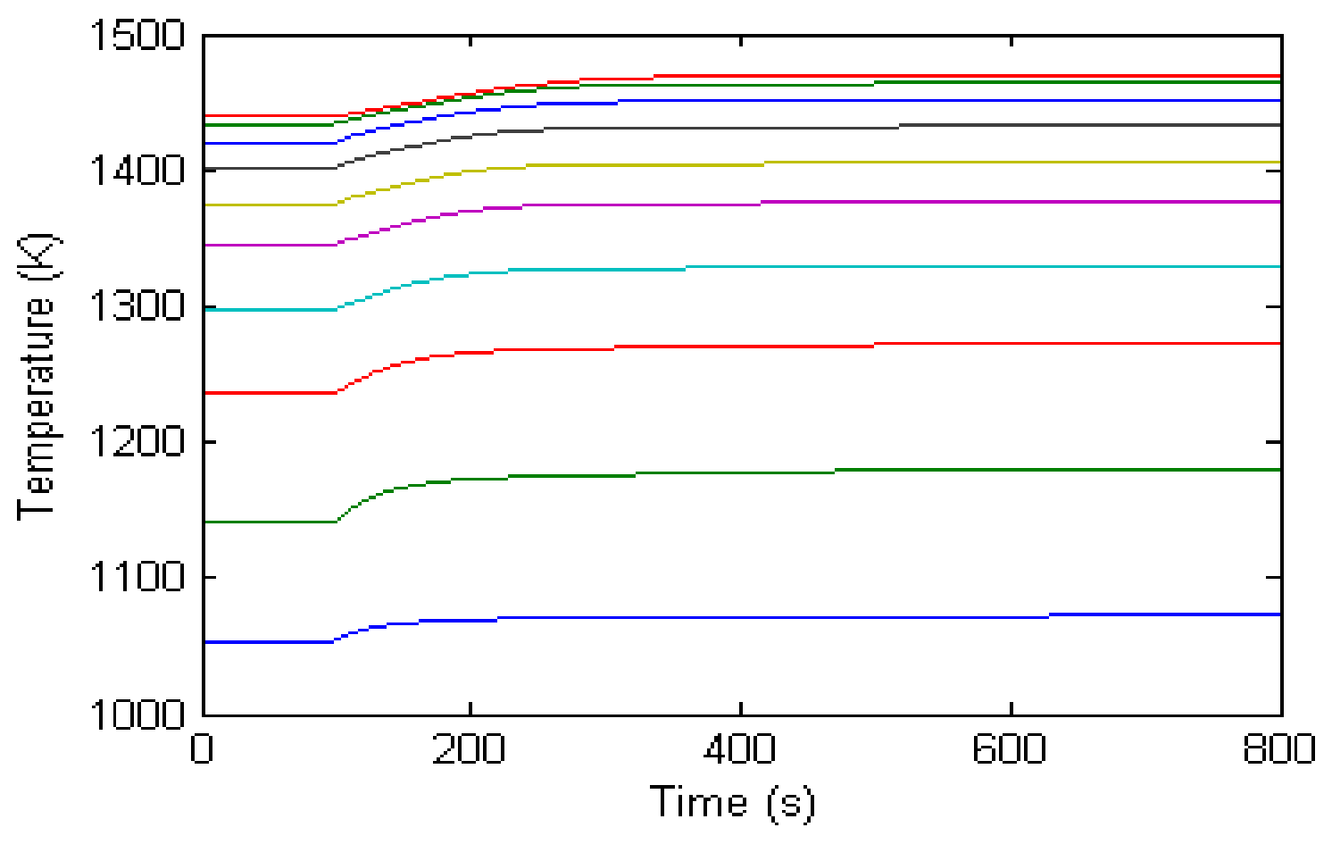

Figure 5. Temperature-to-time profile of controlled system

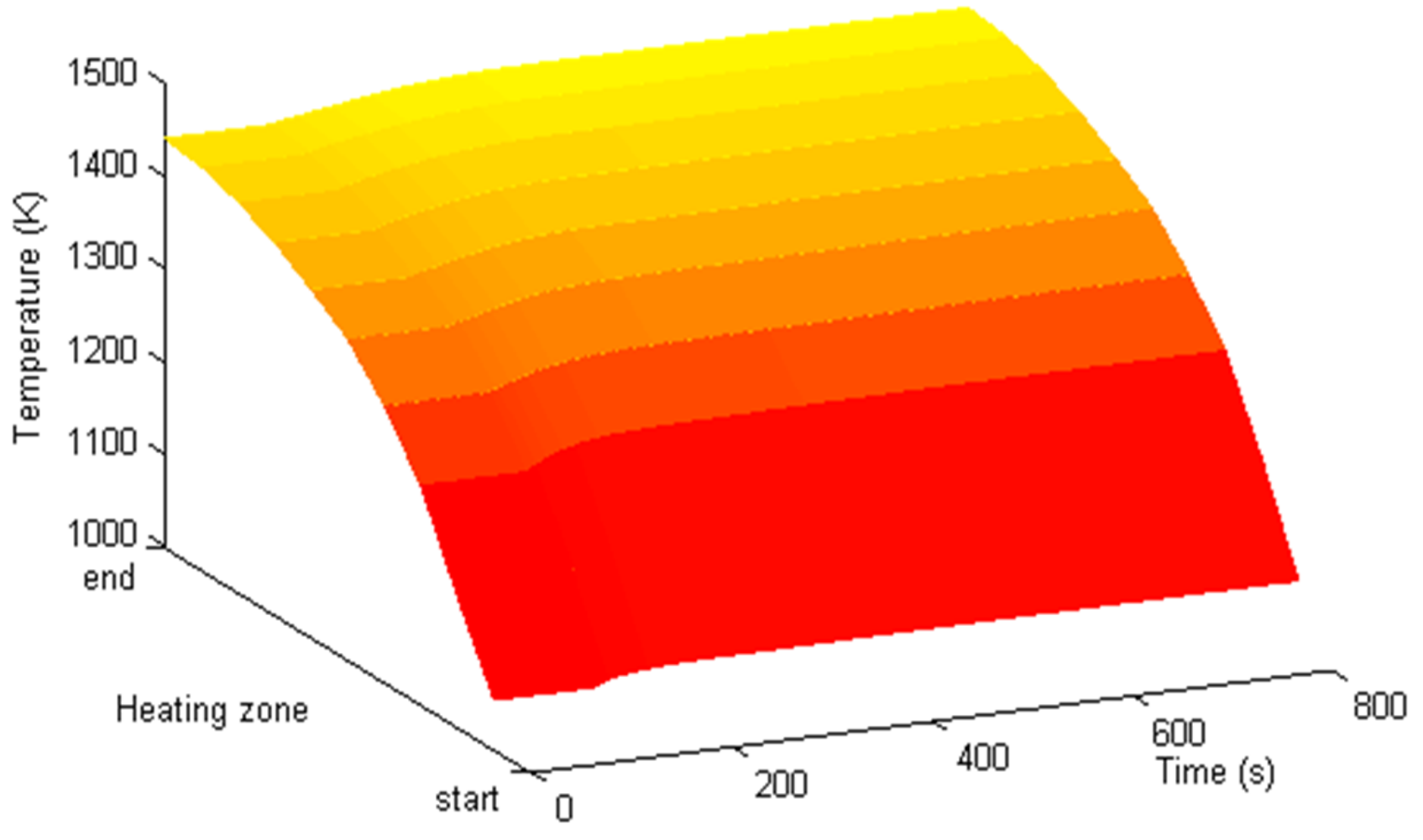

Figure 6. Time-spatial temperature profile

In time t=100s, there is a step change from steady-state to +30K on full length of inductor. **Fig. 5** represents the ability of four controlled actuators (coil currents) to achieve required temperature rise measured by same ten virtual probes; **Fig. 6** shows the time-spatial temperature distribution given by actuation of four coil currents.

Conclusions: The control of distributed parameter systems on the basis of lumped-input/distributed-output systems (LDS) seems to work properly for multi-coil induction heating processes in off-line mode. There is an ambition to replace the „off-line“ model by on-line thermal models in the near future.

Obtaining the desired dynamic characteristics by COMSOL Multiphysics was very quick, the solving of model takes about one hour on computer based on i5- 2300 equipped with 16GB RAM. Great cooperation and copatibility with MATLAB interface was also very useful.

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