Time-dependent simulation of temperature field in SPS by the use of a PID temperature controller in a coupled thermoelectric finite element model

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Introduction : The purpose of this study is to create a numerical model able to reproduce the dynamic thermoelectric behaviour of the SPS process. This model should allow to analyse the temperature field as a function of time. In the real machine, the controller is configured so as to follow the reference temperature cycle introduced by the operator. In the same way, we implement a temperature PID controller in the coupled thermoelectric finite element model of the SPS machine. Simulation results are compared with recordings coming from the real SPS machine.

Coupled thermoelectric FEM model

General domain equations

Fourier-Kirchhoff law

$$\rho C_{p(T)} \frac{\partial T}{\partial t} - \nabla\bullet\left(k_{(T)} \nabla T\right) = q$$

$$q = \boldsymbol{E}\bullet\boldsymbol{J}$$

Thermic to electric coupling

Electric to thermic coupling : Joule power

Ohm law :

$$\boldsymbol{J} = \sigma_{(T)} \boldsymbol{E}$$

$$\boldsymbol{E} = -\nabla V$$

Boudary conditions and specific domain characteristics

The source of the electric problem is the effective potential difference between electrodes $U = \frac{U^{in}}{2}$

Feedback temperature = mean temperature at the bottom surface of axial hole T^{fb}

Graphite tools : Temperature dependence of thermic and electric characteristics

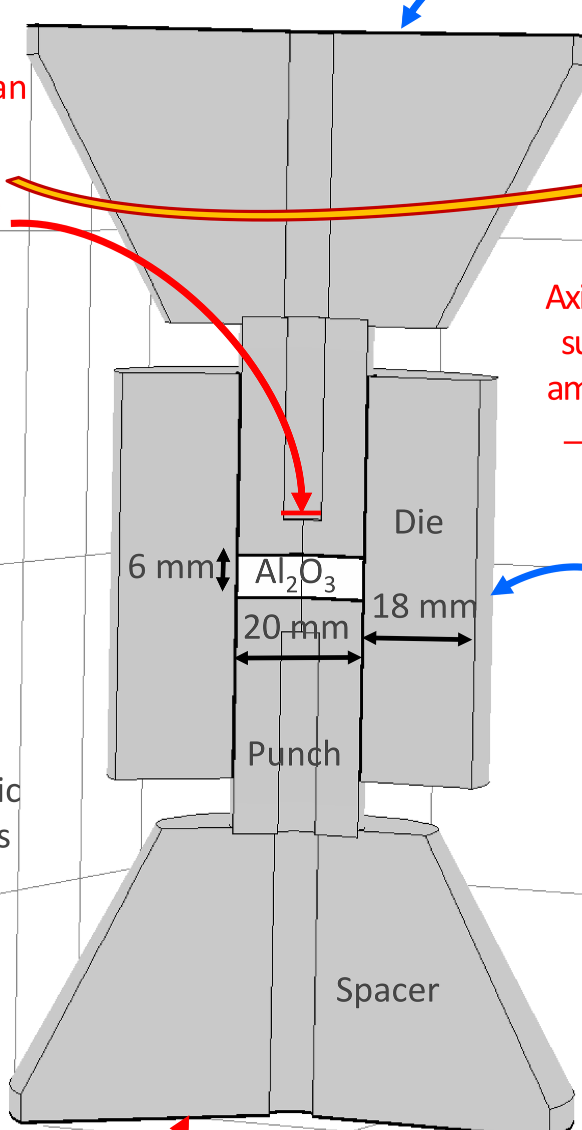
— 0.35 mm Graphite foil → anisotropy → σ and k = diagonal tensors.

Contact between objets : electric and thermic contact resistances

$$\boldsymbol{n}\bullet\boldsymbol{J} = \frac{1}{\rho_s}(V_1 - V_2)$$

$$\boldsymbol{n}\bullet\boldsymbol{\varphi}_s = k_s(T_2 - T_1)$$

Contact with water cooled electrode => constant temperature $T = T_e$



Axial hole and external surfaces → surface to surface and surface to ambiance radiation heat exchange $-\boldsymbol{n}.(-k\nabla T) = \varepsilon\left(G - \sigma T^4\right)$

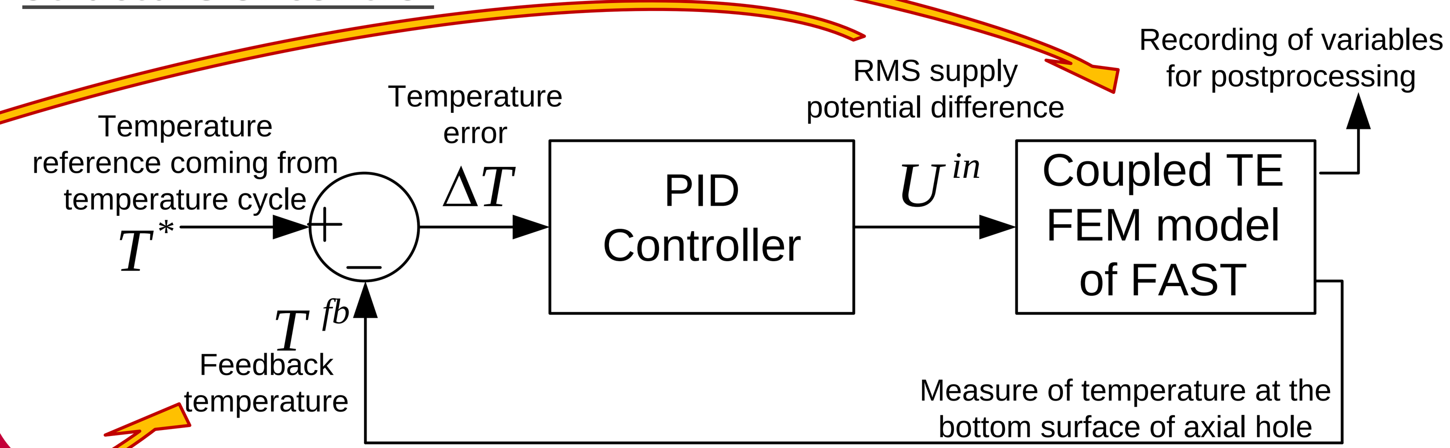
External surfaces => Electric insulation $\boldsymbol{n}\bullet\boldsymbol{J} = 0$

Process in vaccum → No convection and no conduction in gaz heat exchange

$U = -\frac{U^{in}}{2}$

PID temperature controller

Structure of control



Mathematical forms of PID controller

Transfer function : series formulation

$$C_s(s) = G_c \frac{(1 + sT_i)(1 + sT_d)}{sT_i(1 + s\lambda_s T_d)}$$

Transfer function : parallel formulation

$$C_{\|}(s) = K_p \left(1 + \frac{1}{s\tau_i} + \frac{s\tau_d}{1 + s\lambda_{\|}\tau_d}\right)$$

General gain — Proportional component — Integral component — Differential component

Integrodifferential equations

$$\begin{cases} U^{in}(t) = K_p\left(\Delta T(t) + \frac{1}{\tau_i}\int_0^t \Delta T(t)\,dt + v(t)\right) \\ v(t) + \lambda_{\|}\tau_d \frac{dv(t)}{dt} = \tau_d \frac{d\Delta T(t)}{dt} \end{cases}$$

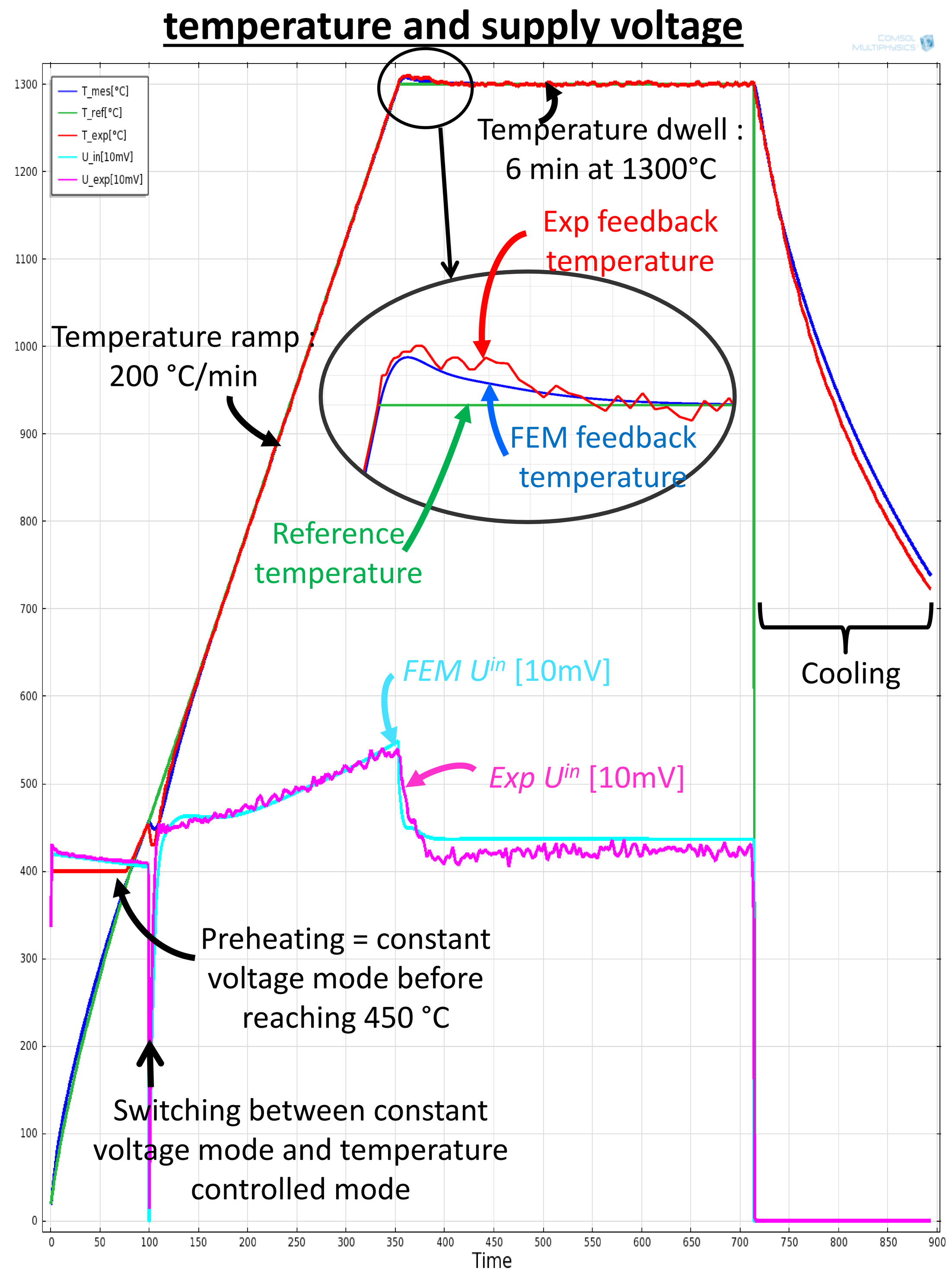
Configuration of solver :

- Time-dependent solver
- Segregated solver : (1) PID controller DAEs (2) Electric PDEs (3) Thermic PDEs
- Inside time step : repeating of segregated solver until convergence

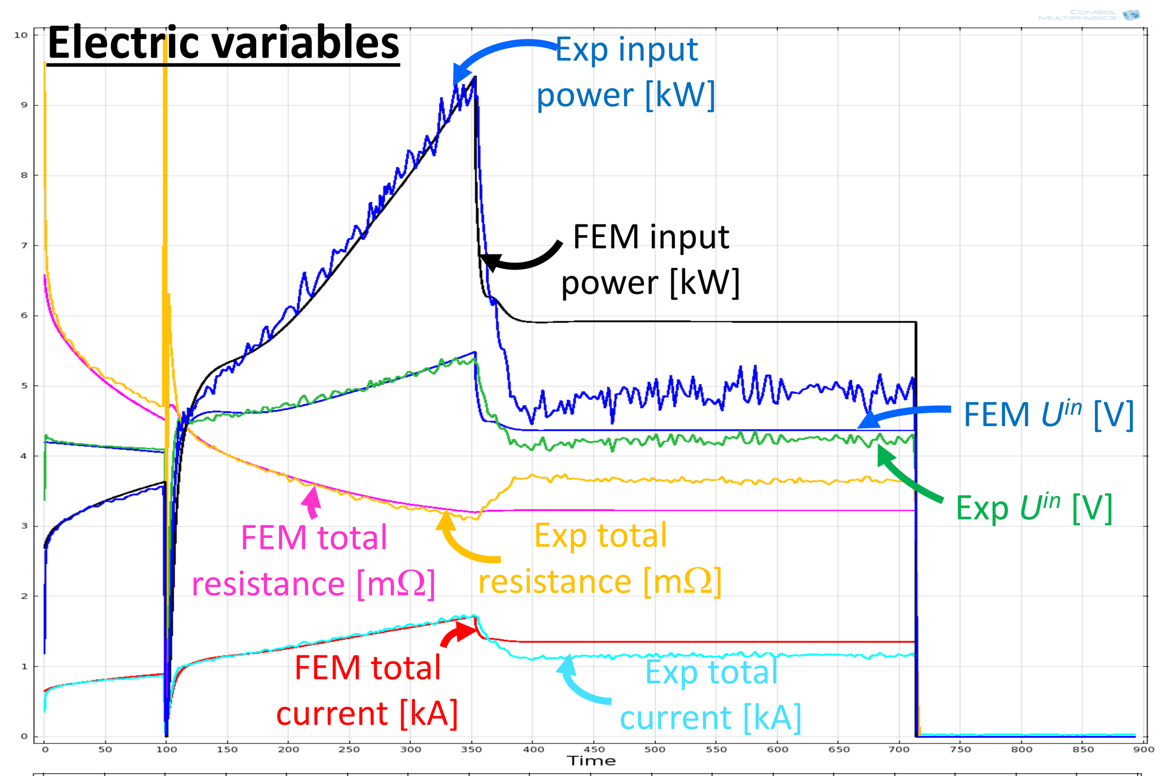
Parametrization of PID controller : To get with the FEM model the same dynamics as in real machine recordings.

Validation : comparison between model (FEM) and experimental (Exp) results - Sintering of alumina compacts

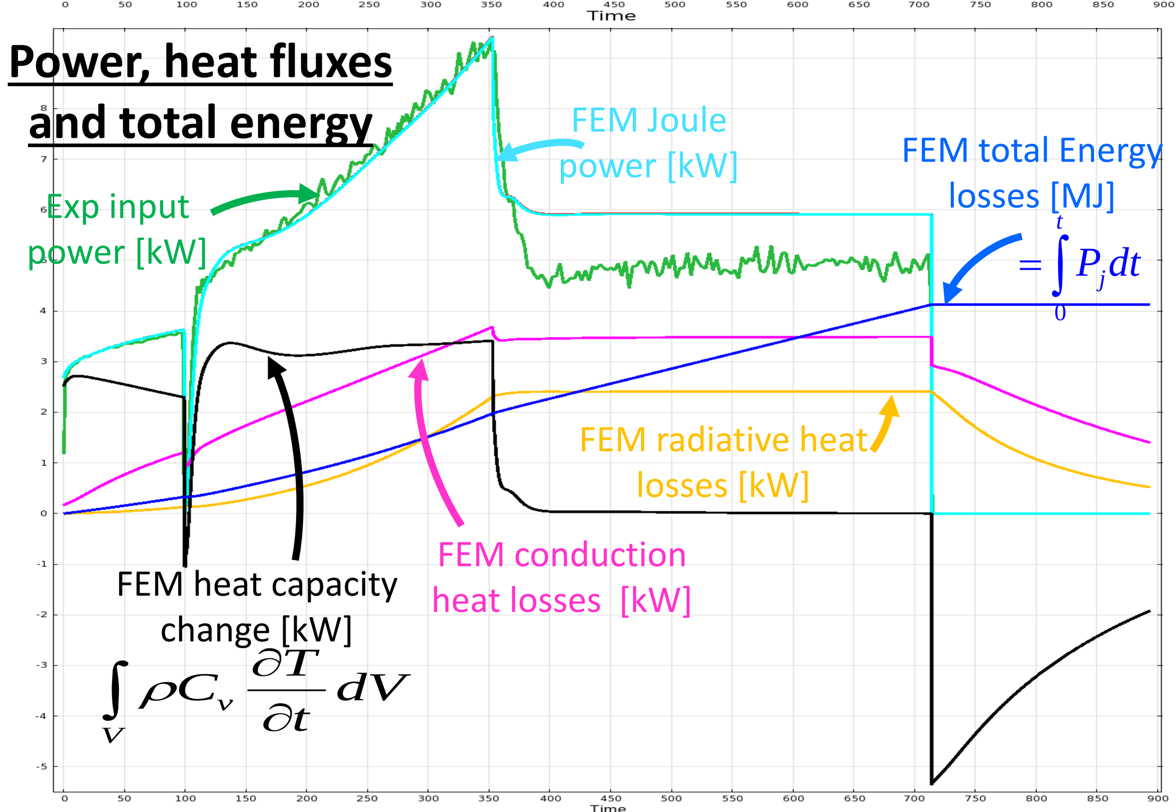
Reference temperature cycle, feedback temperature and supply voltage



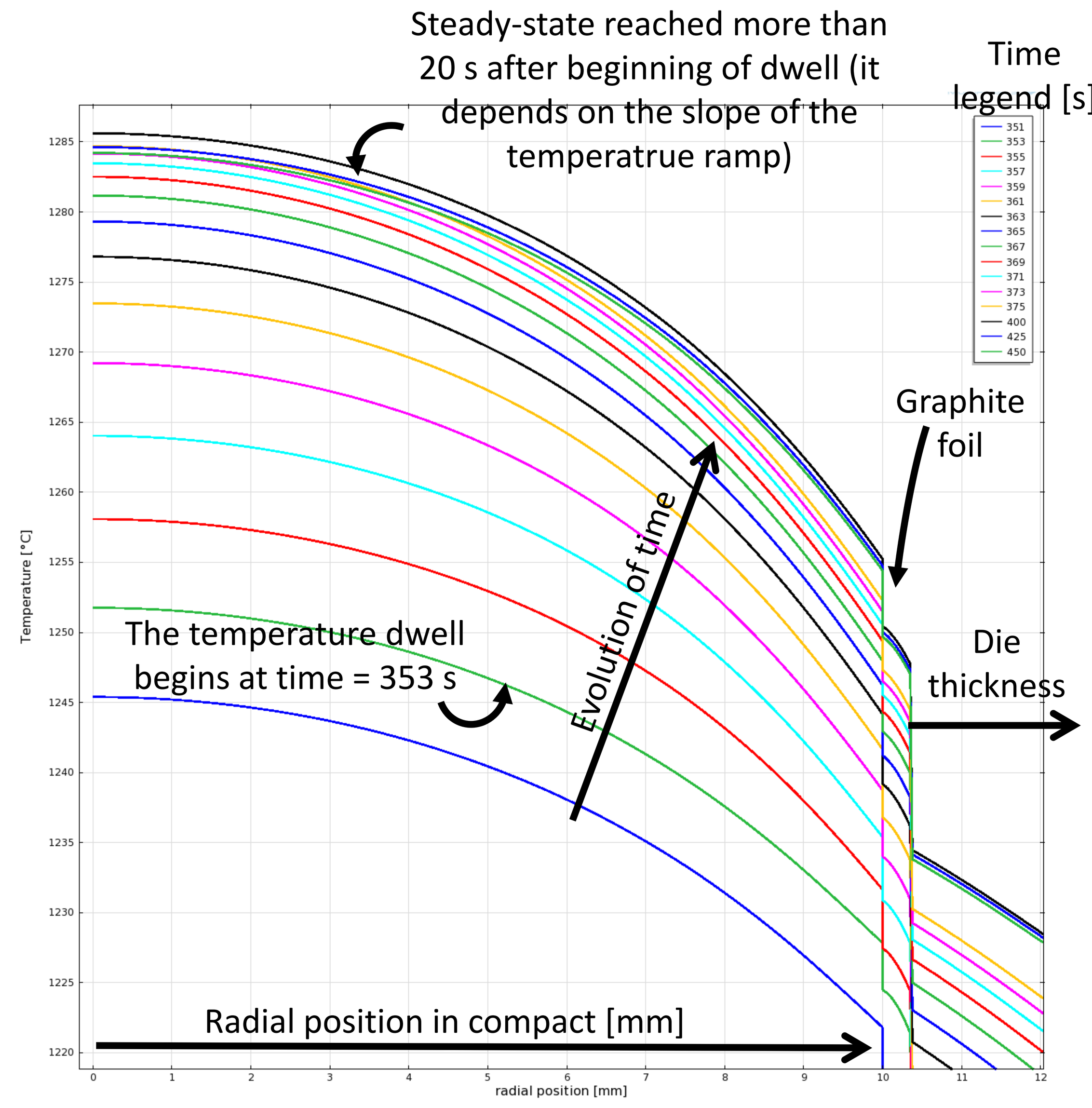
Electric variables



Power, heat fluxes and total energy



Temperature in the center of the compact in function of radial position in the beginning of dwell period



Conclusions

- Reproduction of real thermal behaviour of SPS → Successful implementation of PID temperature controller in coupled thermoelectric FEM of SPS
- Good results compared to experimental measures → Validation of model
- It allows → to study dynamic evolution of temperature field in compact → to understand evolution of heat fluxes in function of time

Perspectives

- Taking into account characteristic changes with relative density
- Application : Optimization of sintering conditions (design of tools, temperature cycle)

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