Numerical Coupling Plasma - Weldpool applied to GTA Welding

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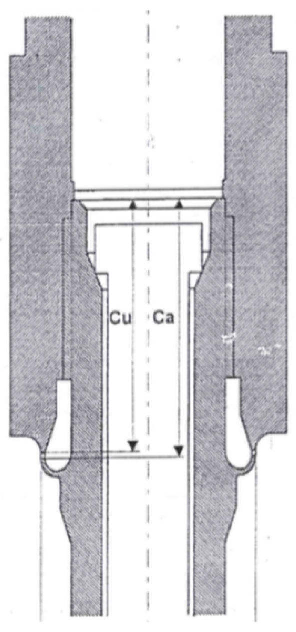
Abstract

In order to realise case studies about repair process on the nuclear park, this PhD thesis aims to build up engineering tools by developing a numerical model enabling the simulation of welding operating process by fusion. Hence, a numerical coupling of two models is needed in order to enhance the thermal transfer from the plasma model to the weldpool model and thus, enables the prediction of the weld bead shape.

1. Industrial context



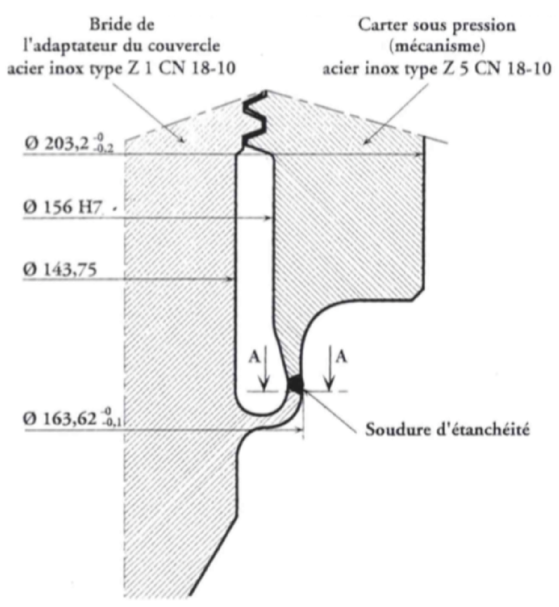


Figure 1: *Weling process*

- Welding ensuring the sealing of control rods between reactor vessel head and containment building
- Repair process: Replacements of control rods or reactor vessel heads

The main issue:

- Weldpool deviation due to the difference in chemical compositions of the workpieces
  ⇒ Surfactant element concentration within the alloy i.e. Sulfur
- Impossible to perform non-destructive testing of the geometry below the welding
- Fragile weldings yielding important outflows

- **Solution**: Numerical simulation in order to prevent repair process

2. Governing equations

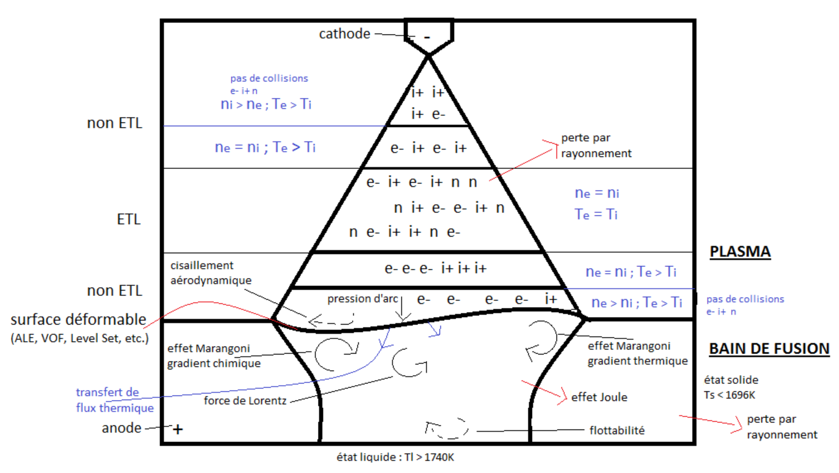


Figure 2: *Physical phenomena in welding modelling*

$$
\begin{cases}
\text{div}(\rho \mathbf{u}) = 0 \\
\frac{\partial}{\partial t}(\rho \mathbf{u}) + \textbf{div}(\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \textbf{div}(\mu(\underline{\underline{\nabla}}\mathbf{u} + \underline{\underline{\nabla}}\mathbf{u}^T)) + \mathbf{j} \times \mathbf{B} + \mathbf{ST}_w \\
\frac{\partial}{\partial t}(\rho h) + \text{div}(\rho \mathbf{u} h) = \text{div}\left(\frac{\lambda}{C_p}\nabla h\right) + \mathbf{j}\cdot\mathbf{E} - \Phi_v + \mathbf{ST}_p \\
\text{div}(\sigma \nabla P_R) = 0 \\
\Delta \mathbf{A} = -\mu_0 \mathbf{j} \\
\mathbf{E} = -\nabla P_R \\
\mathbf{B} = \textbf{rot}(\mathbf{A}) \\
\mathbf{j} = \sigma \mathbf{E}
\end{cases}
$$

3. Weldpool model

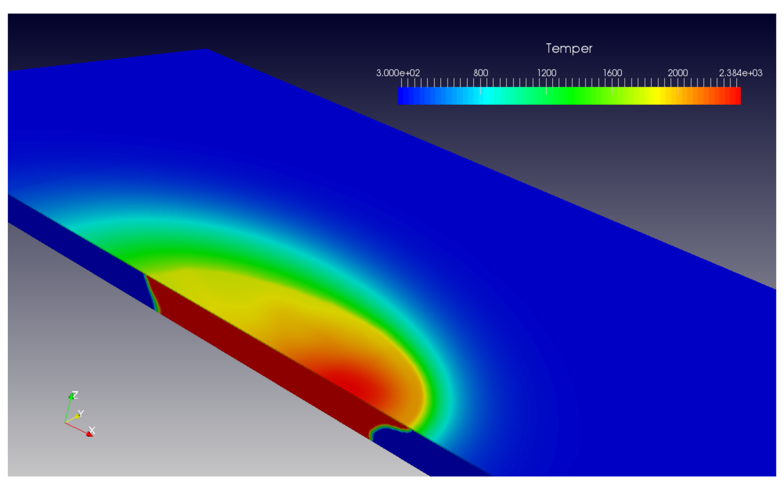


Figure 3: *Weldpool simulation with Code_Saturne 4.1: T and liquid fraction*

- $\gamma(a_s, T)$: Surface tension (Marangoni effect): microscopic disequilibria at a free surface
- Boundary condition on velocity :

$$\mu\frac{\partial \mathbf{u}}{\partial n} = f_L\frac{\partial \gamma}{\partial T}(\mathbf{c}, T)\nabla T + f_L\sum_i \frac{\partial \gamma}{\partial c_i}(\mathbf{c}, T)\nabla c_i$$

- Boundary condition on enthalpy and electric potential:

$$\frac{\lambda}{C_p}\frac{\partial h}{\partial n} = \frac{\eta U I}{2\pi {r_h}^2} exp\left(-\frac{r^2}{2{r_h}^2}\right) + \epsilon\sigma(T^4 - T_0^4) + h(T - T_0)$$

$$\sigma\frac{\partial P_R}{\partial n} = \frac{I}{2\pi {r_j}^2} exp\left(-\frac{r^2}{2{r_j}^2}\right)$$

- Sulfur transport-reaction equation: $\partial_t(\rho Y_s) + \text{div}(\rho \mathbf{u} Y_s) = \text{div}(\rho \mathbf{D}^S_{304L}\nabla Y_s) - K(T)\rho Y_i Y_j + S^{Y_i}_{vap}$
  (Y_s: mass fraction, $\mathbf{D}^S_{304L}$: Sulfur-to-Stain diffusive coefficient, $K(T)$: collision frequency factor)
- Problem 1: Operating parameters obtained from experimental scaling
- Problem 2: Non-gaussian thermal fluxes

- **Solution**: Numerical coupling of two models: plasma - weldpool

4. Plasma model

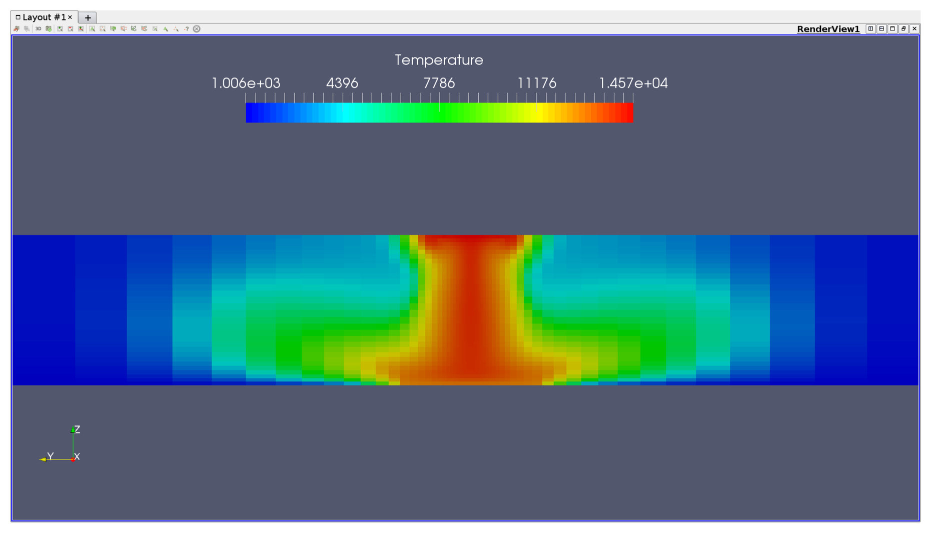


Figure 4: *Plasma simulation: Temperature*

Vapour transport-reaction equation: $\partial_t(\rho X_i) + \text{div}(\rho \mathbf{u} X_i) = \text{div}(\rho \mathbf{D}_{vap}\nabla X_i) - \frac{\rho}{\tau}(X_i - X_{i_0})$

(X_i: mass fraction, $\mathbf{D}_{vap}$: vapour diffusive coefficient, τ: time constant, X_{i_0}: vapour mass fraction)

Energy balance at the anode and the cathode ($\mathbf{ST}_p$):

$$-\lambda_a\frac{\partial T_a}{\partial n} = -\lambda_p\frac{\partial T_p}{\partial n} + \frac{L_a}{X_i - 1}\rho D_{vap}\frac{\partial X_i}{\partial n} - j_e\left(\frac{5k_B}{2e}(T_p - T_a) + \Delta V_a + W_a\right) + \chi_a q_{ray} - \epsilon_a\sigma_B T_a^4$$

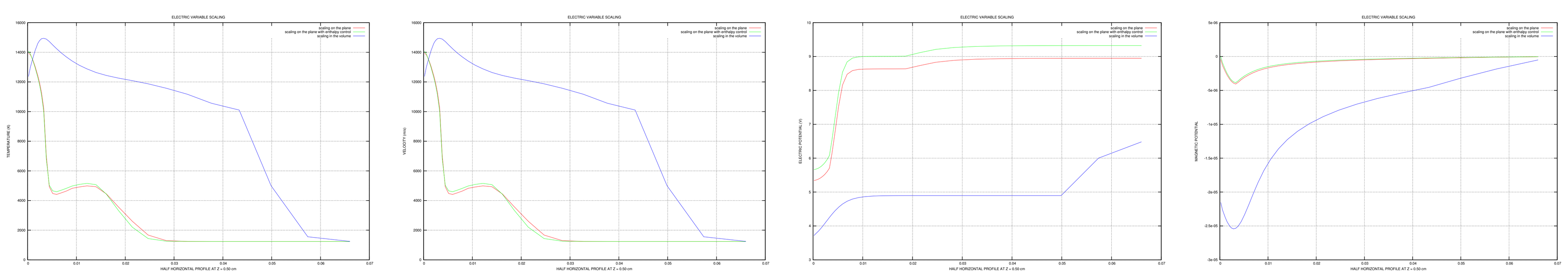
$$-\lambda_c\frac{\partial T_c}{\partial n} = -\lambda_p\frac{\partial T_p}{\partial n} + j_i\left(\frac{5k_B}{2e}T_c + \Delta V_c + V_i\right) - j_e\left(\frac{2k_B}{e}T_c + W_c\right) + \chi_c q_{rad} - \epsilon_c\sigma_B T_c^4$$

with $\Delta V_{a,c} = \frac{k_B T_e}{e} ln\left(\frac{n}{n_e}\right)$ *(L_a vapour latent heat, D_{vap} Iron-to-gas diffusive coefficient)*

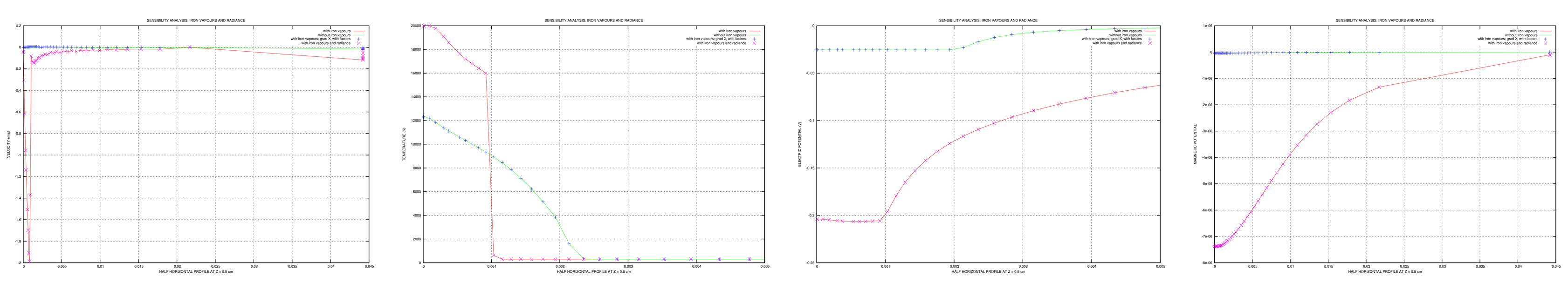
4.1 Some results on the plasma model with *Code_Saturne* 4.1: Sensibility analysis

1) Electrical scaling

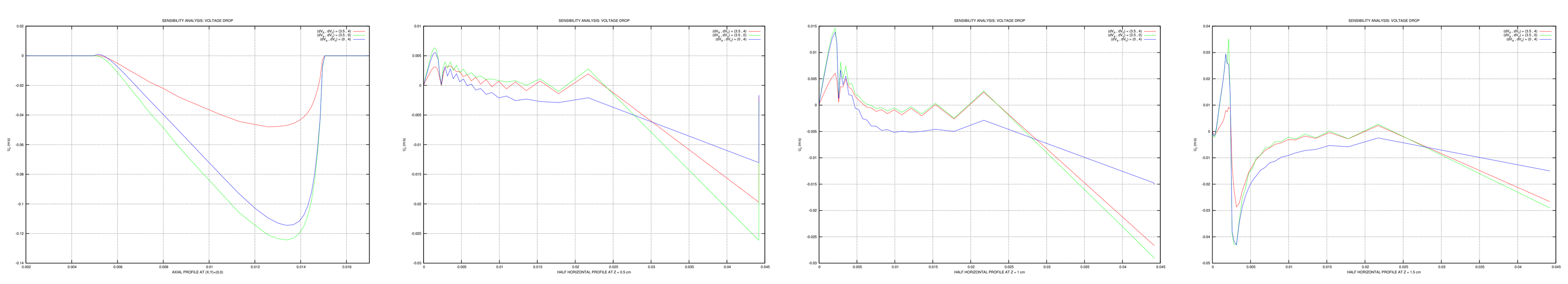
- Electric potential (P_R) scaled in order to converge towards imposed current intensity (I)
- P_R and I computed from Laplace forces and Joule effect



2) Iron vapours and radiance



3) Voltage falls



- No significant variations for enthalpy
- Radiance must be taken into account for further sensibility analysis of voltage drop

5. Perspectives

1) Suppress equivalent thermal source boundary conditions
⇒ *Numerical coupling of plasma and weldpool models*

2) Enhance the model of surface physical phenomena for optimal vertical welding
⇒ *Implementation of an interface tracking method (e.g. ALE)*

3) Enhance thermal transfers within the plasma sheaths
⇒ Implementation of non-LTE plasma model (e.g. Two-temperature Hall-MHD) in order to obtain separately ion and electron temperatures (T_i, T_e) and densities (n_i, n_e) to estimate the anode fall (ΔV_a)