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Gas Tungsten Arc Welding heat transfer and fluid flow simulation

1. The GTAW Heat transfer-Fluid flow problem:

The GTA Welding or TIG (Tungsten Inert Gas) process is studied in a simple case involving only two physical phenomena: Heat transfer and Fluid Flow (Navier-Stokes equations). This document describes the coefficients used in the two states equations and their boundary conditions in order to understand the gtaw.sif attached to the post (as well as the mesh files…). This is just a preliminary work. I hope to add the electromagnetism equations in order to take into account the Lorentz force and the free surface deformation on the weld-pool surface. Figure 1, here below, depicts all the phenomena involved in GTA Welding.

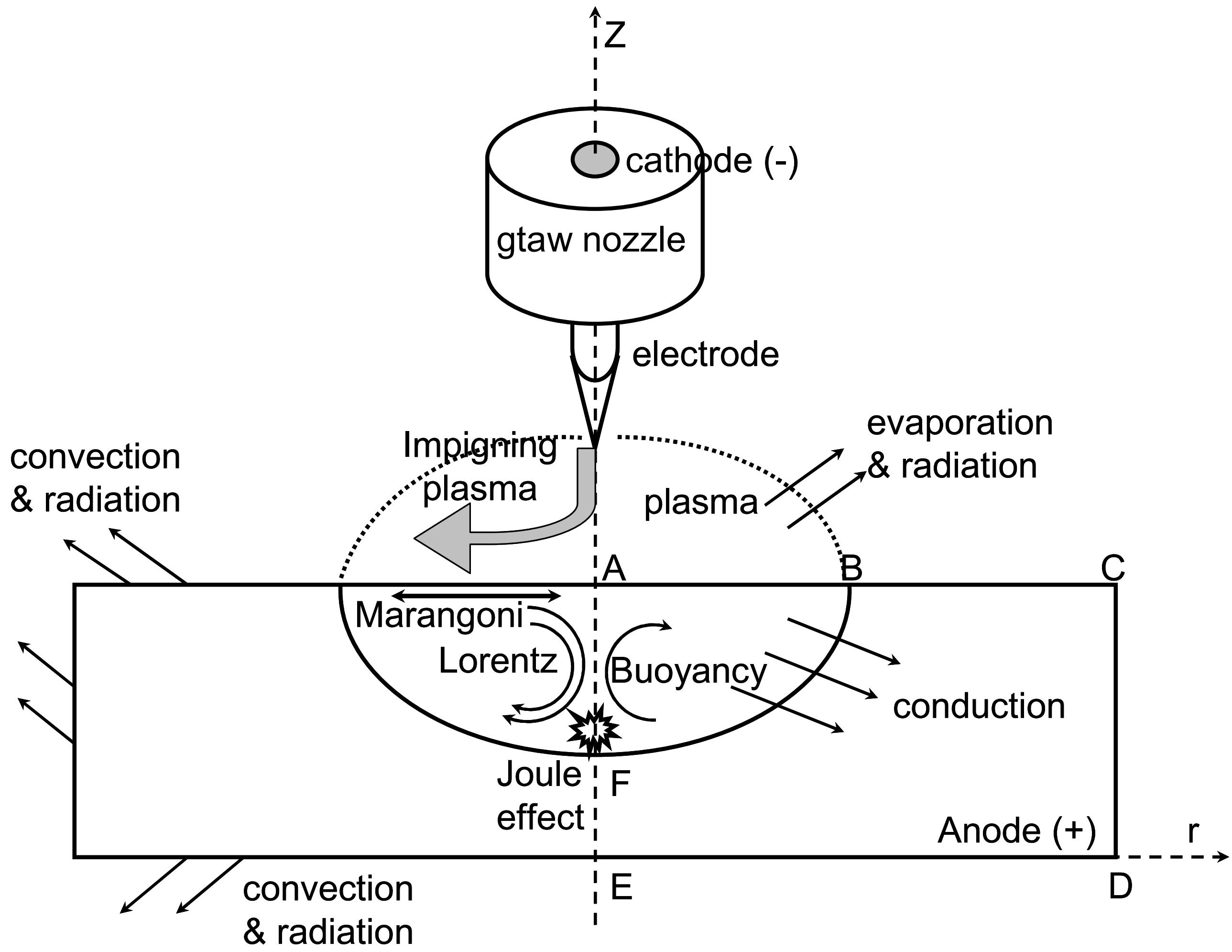

Figure 1: magneto-hydrodynamic problem involved in GTAW.

In order to simplify the problem, the following assumptions are considered:

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- The study is restricted to GTA spot welding, => axis ymmetric coordinate system, figure 2.
- The flow is laminar and incompressible (Buoyancy, Marangoni and Arc drag Shear Froces are considered).
- The Molten metal surface tension coefficient is temperature dependent (for the Marangoni Force) and the latent heat of fusion is taken into account in the specific heat coefficient.
- The electromagnetism is not considered so no Lorentz force plays in the molten metal.
- No free surface for the weld pool.

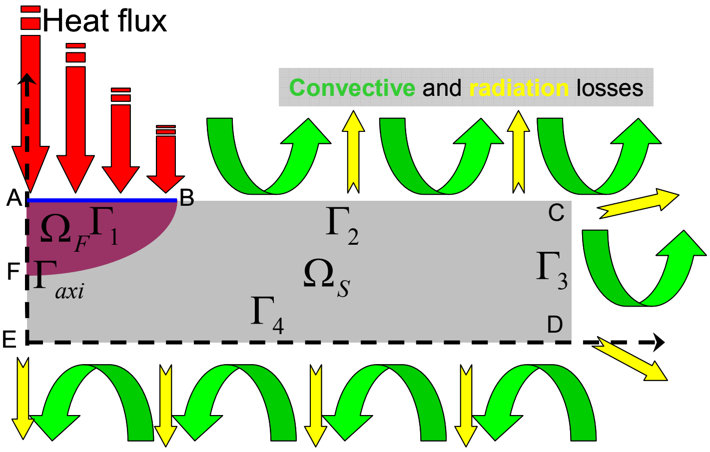

Figure 2 : axisymmetric domain and heat transfer modelling.

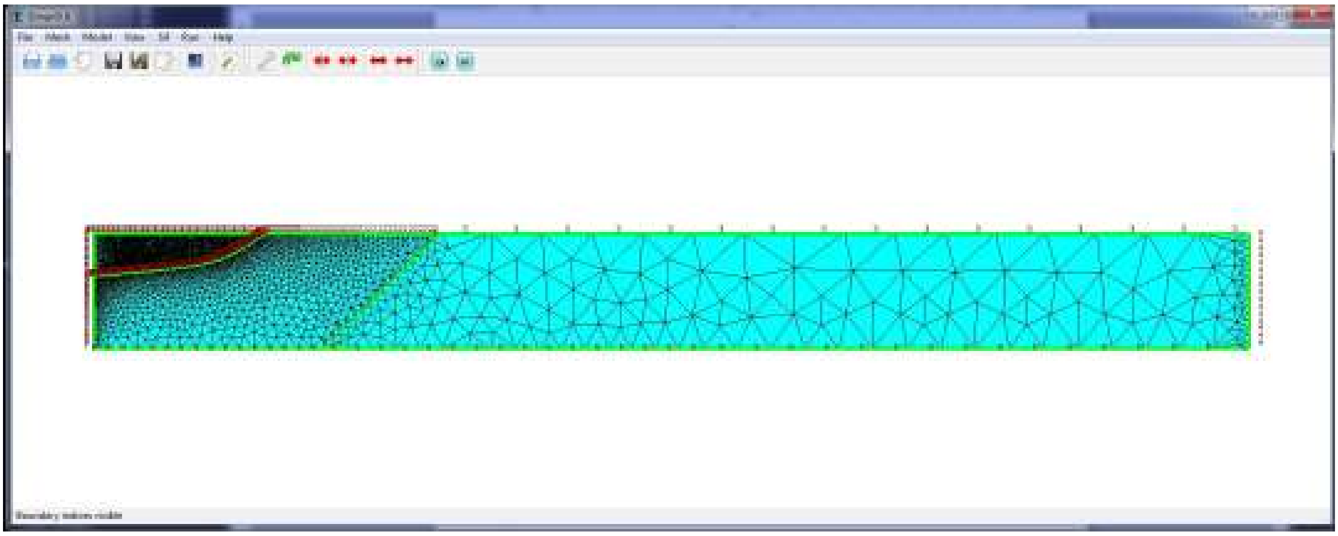

Figure 3: mesh used (radius = 20mm and thickness = 4 mm). On the top, the boundary numbers are 1, 2 and 3; the right vertical is 4, the bottom ones are 5 and 6. The left vertical (symmetry axis) are 7 and 8. the inner ones are (from center to outward) 10 and 9.

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THE HEAT TRANSFER & FLUID FLOW MODELLING:

- **Energy conservation (for the computation of the temperature T):**

$$\rho C_p^{eq}\frac{\partial T}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(r\rho C_p^{eq}uT-r\lambda\frac{\partial T}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho C_p^{eq}wT-\lambda\frac{\partial T}{\partial z}\right)=Q$$

With T is the temperature field. ρ, C_P and λ are respectively the mass density, specific heat and thermal conductivity of the Stainless Steel Metal. u and w are the fluid flow velocities computed with the Navier-Stokes equations.

The heat transfer boundary conditions are (it refers to figure 2):

→ On the top surface $\Gamma_1\cup\Gamma_2$: $-\lambda\dfrac{\partial T}{\partial z}=-\Phi(r,t)+h(T-T_0)+\varepsilon\sigma\left(T^4-T_0^4\right)$

→ On the lateral side Γ_3: $-\lambda\dfrac{\partial T}{\partial r}=h(T-T_0)+\varepsilon\sigma\left(T^4-T_0^4\right)$

→ On the bottom surface Γ_4: $\lambda\dfrac{\partial T}{\partial z}=h(T-T_0)+\varepsilon\sigma\left(T^4-T_0^4\right)$

→ On the symmetry axis : $-\lambda\dfrac{\partial T}{\partial r}=0$

→ The initial condition is: $T(r,t=0)=T_0$

$\Phi(r)$ is a surface heat flux exchanged between the plasma arc and the work-piece. We will assume that this heat flux distribution obey to a Gaussian distribution. So it can be written as follows: $\Phi(r,t)=\eta\dfrac{1}{2}\dfrac{Us.Is}{\pi r_b^2}e^{-\frac{1}{2}\left(\frac{r}{r_b}\right)^2}$ where Us is the welding tension, Is is the welding intensity, η is the GTAW efficiency and r_b is called the Gaussian radius.

- **The classical Navier-Stokes equations which govern the fluid flow in the weld pool can be expressed as follows:**

  - **Mass conservation:** $\nabla.\vec{v}=\dfrac{1}{r}\dfrac{\partial(\rho ru)}{\partial r}+\dfrac{\partial(\rho w)}{\partial z}=0$ as the fluid is assumed to be incompressible ($\rho=cste$), this becomes: $\dfrac{1}{r}\dfrac{\partial(ru)}{\partial r}+\dfrac{\partial w}{\partial z}=0$.

  - **Momentum conservation:**

$$\rho\frac{\partial u}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(\rho ruu-\mu r\frac{\partial u}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho uw-\mu\frac{\partial u}{\partial z}\right)=-\frac{\partial P}{\partial r}-\mu\frac{u}{r^2}$$

$$\rho\frac{\partial w}{\partial t}+\frac{1}{r}\frac{\partial}{\partial r}\left(\rho ruw-\mu r\frac{\partial w}{\partial r}\right)+\frac{\partial}{\partial z}\left(\rho rww-\mu\frac{\partial w}{\partial z}\right)=-\frac{\partial P}{\partial z}+F_{buoyancy}$$

$F_{Buoyancy}$ represents body forces in the weld pool, namely the buoyancy force (or Boussinesq approximation) and it could be expressed as: $\vec{F}_{buoyancy}=\rho_0\left(1-\beta\left(T-T_{ref}\right)\right)\vec{g}$

where $\vec{v}$ is the velocity vector field in the weld pool, t is the time, ρ is the density, μ is the viscosity, p is the pressure, $\vec{g}$ is the gravity, T_{ref} is the reference temperature taken as the solidus temperature of the considered alloy.

The boundary conditions associated to the momentum equation are:

- On the free surface Γ_1, the surface tension Marangoni-driven flow is taken into account with the condition: $\mu\frac{\partial u}{\partial z}=f_L\frac{\partial\gamma}{\partial T}\frac{\partial T}{\partial r}$ and $w=0$.

The temperature coefficient of surface tension $\frac{\partial\gamma}{\partial T}$ for pure metals is negative. The presence of Sulfur in the weld pool can lead to positive value of $\frac{\partial\gamma}{\partial T}$. It exists some formula which takes into account both temperature and Sulfur activity on the surface tension such as:

$$\gamma=\gamma_m-A_\gamma\left(T-T_L\right)-R_gT\Gamma_S\ln\left(1+K(T)a_S\right)\text{ with }K(T)=k_1\exp\left(-\frac{\Delta H_0}{R_gT}\right)$$

(From: P. Sahoo, T. DebRoy, M.T. McNallan, Surface tension of binary metal surface active solute systems under conditions relevant to welding metallurgy. Metall. Trans. B 19B (1988) 483-491.)

- On the symmetry axis Γ_{axi}: $u=0$.
- Along the liquid-interface: $u=0$ and $w=0$.
- The initial condition is: $u(r,t=0)=0$ and $w(r,t=0)=0$.