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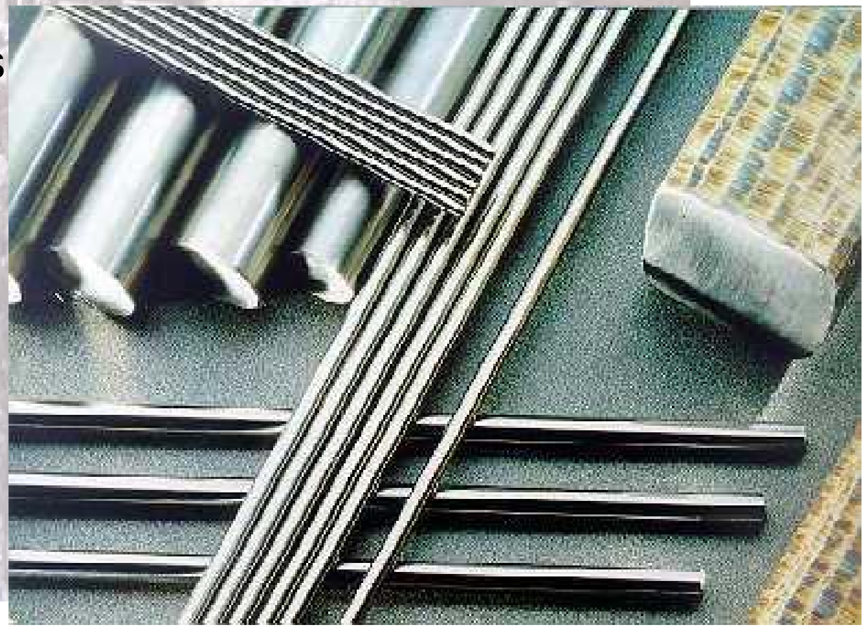
A Heat Transfer Model for Ugitech's Continuous Casting Machine

C. Deville-Cavellin

A Heat Transfer Model for Ugitech's Continuous Casting Machine

- Ugitech:
  - Member of the S+B Group
  - Dedicated to Stainless Steels Long Products
- The Continuous Casting Machine:
  - Technological features
  - Problems to be solved
- Numerical Simulation:
  - The heat transfer model
  - Some results / comparisons with measurements
  - Recent developments : mechanical model
- Conclusion:
  - Work in constant progress
  - Generalization of numerical simulation



Ugitech S.A

UGITECH, a main industrial stainless steel long products actor based on a famous legacy

1908 – Paul Girod begins the production of alloyed steels at Ugine

1925 – First heat with the Ugine Perrin Process

1972 – Merger of Ugine the Pechiney Group to form Ugine Aciers

1978 – Foundation of Sprint Metal through the merger of the wire drawing Facilities of Ugine Aciers and Creusot-Loire

1986 – Merger of Usinor and Sacilor. Ugine Aciers is renamed Ugine-Savoie

1990 – Ugine-Savoie acquires Bedini

1991 – New dust cleaning Machine in Ugine

2002 – Merger of Usinor, Arbed and Aceralia to create Arcelor

2003 – Ugitech creation to merger of Ugine-Savoie Imphy and Sprint Metal

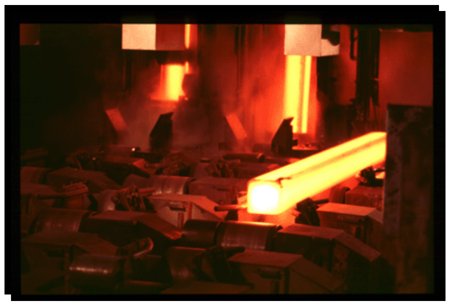
2006 – Schmolz & Bickenbach acquires Ugitech

Dedicated to stainless steels long products

UGITECH Operations

Production / R&D

UGITECH (Ugine)
- Melting Shop
- Remelting Furnace



Transformation

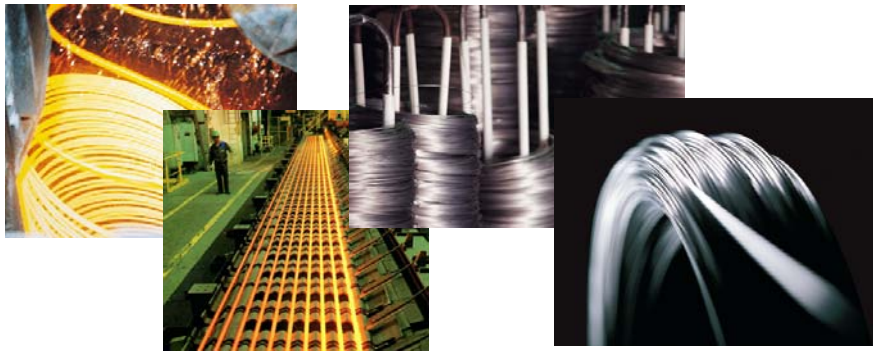
Bar Drawing
- UGITECH (Ugine)
- Trafilerie Bedini (Milan)

Wire Drawing
- UGITECH (Bourg-en-Bresse)
- UGITECH (Brionne)
- UGITECH (Imphy)
- SMEZ (Reichshof)
- SMEZ (Brumby)

Distribution + Services

SCHMOLZ + BICKENBACH Network

UGITECH (Grigny – Rouen – Marignier)
UGITECH Srl (Milan)
UGITECH GmbH (Renningen)



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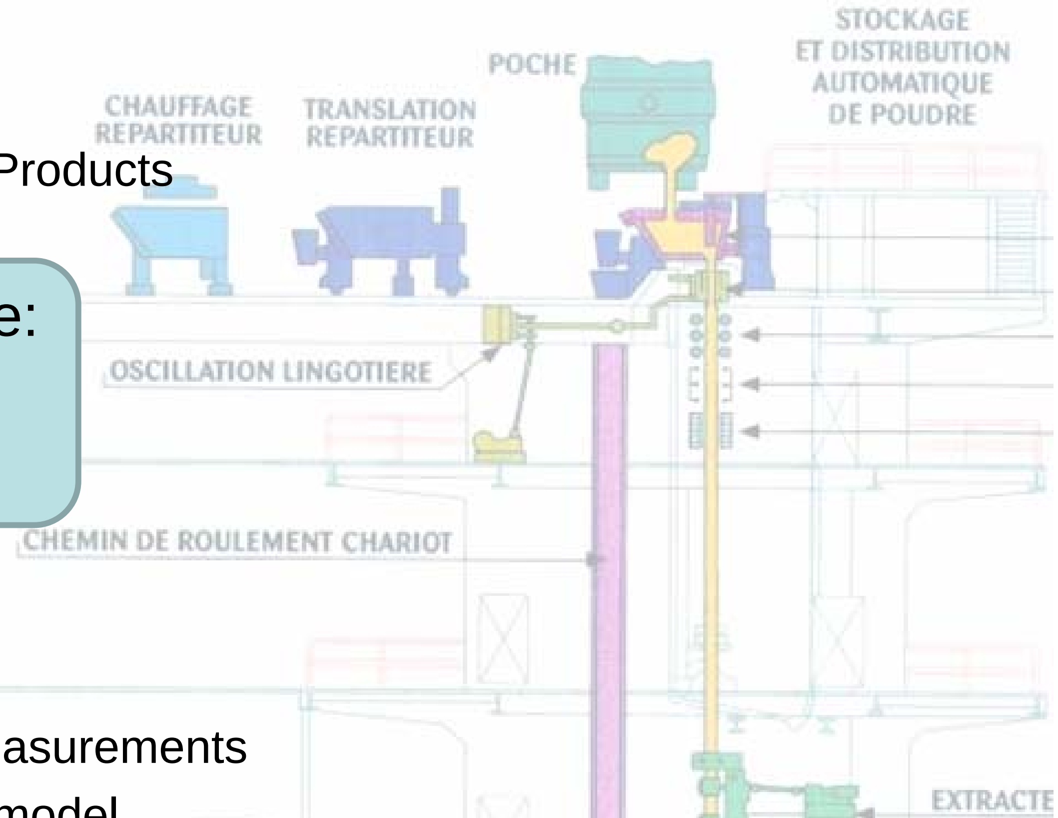
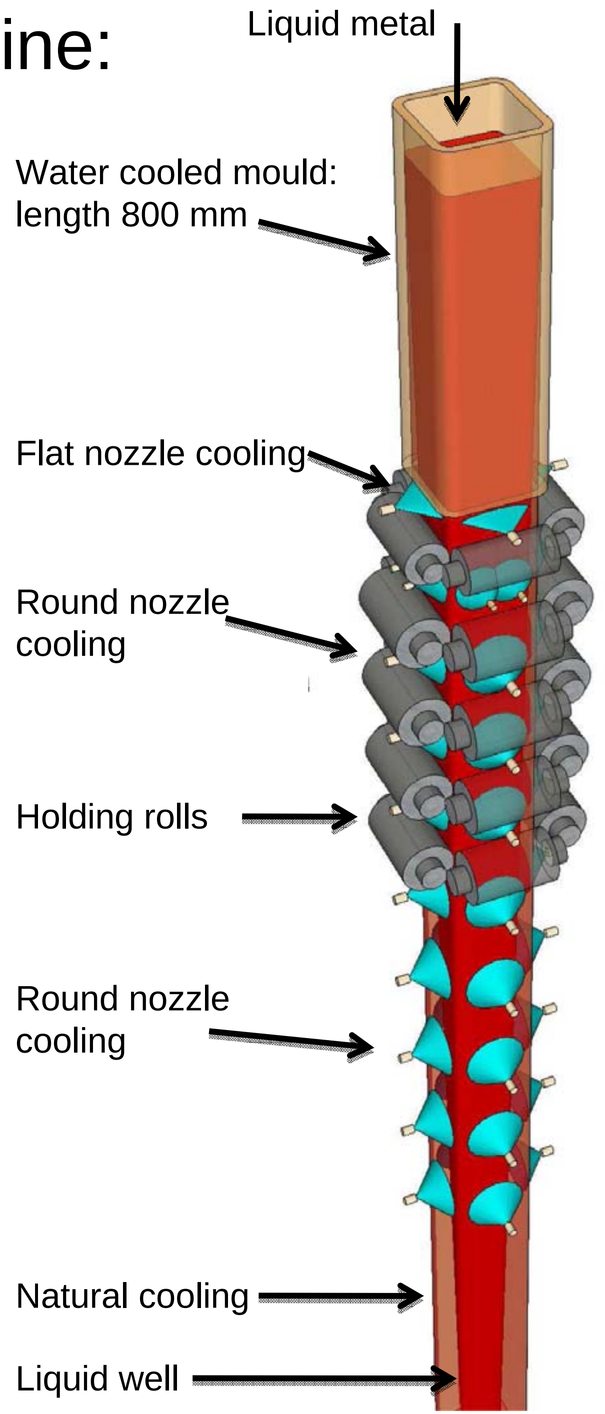


The Continuous Casting Machine:

- Technological features:
  - A 3-strand fully vertical machine
  - Bloom 205² mm with ∅40 mm rounded corners
  - Casting of stainless steels (any grade)
  - Casting speed around 1 m/min
  - Lubrication with mineral mould flux
  - Metallurgical length: 14 m

- Phenomena
  - Casting of superheated liquid steel: +40°C (≅1400°C)
  - First solidification within the mould, through a thin layer of infiltrated molten mould flux
  - Passing through several water cooling nozzles
  - End of solidification through radiation mainly

The blooms are torch-cut after 14 m, in lengths about 3,4 m. This constitutes a maximum limit we cannot exceed as far as the end of solidification is concerned.



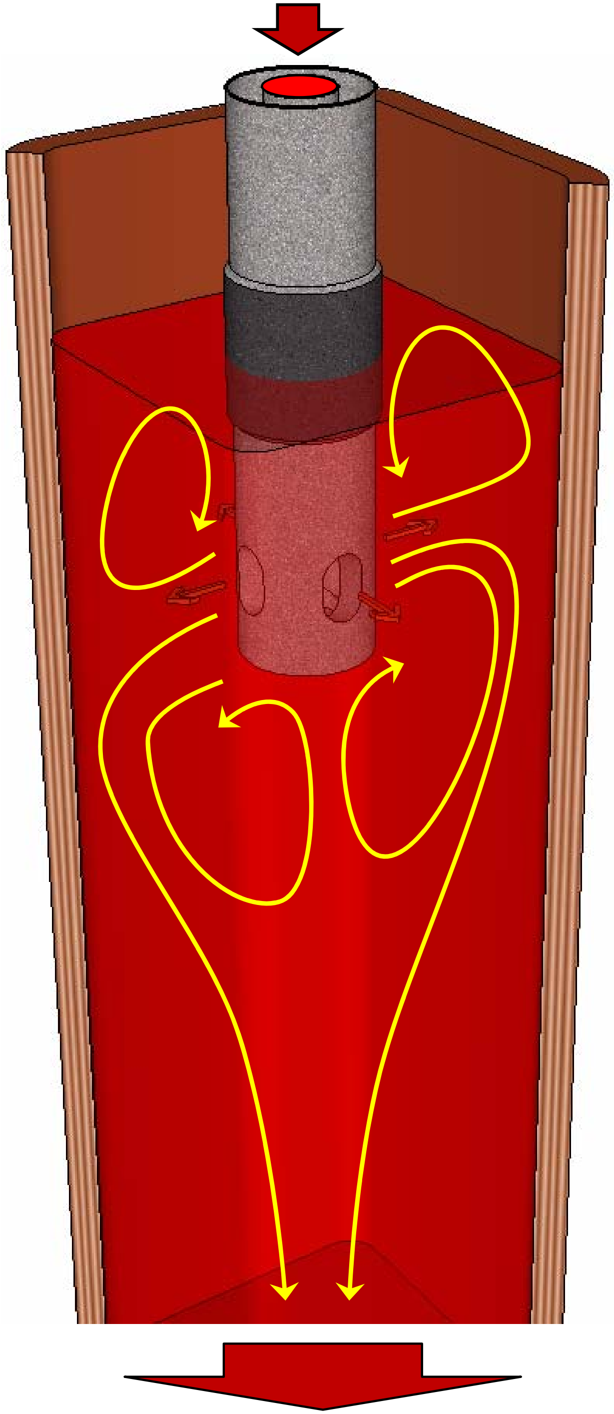
UGITECH
Providing special steel solutions

Problems to be solved

- Physical phenomena
  - Turbulent fluid flow before solidification
  - Heat transfer, with or without convection
  - Mechanical stresses and strains after solidification

As a matter of fact, all these phenomena are tightly coupled and extremely non-linear. Solidification and mechanical contacts (mould/rollers) are a modelling difficulty.

- Model simplifications
  - The fluid flow is calculated separately to check the vertical extend of the radial convection. Only a local increase in the heat conductivity brings the convection influence in the model
    - Only the upper part of the mould content is affected by convection
  - All the heat exchanges are in the horizontal plane
    - This is not true in the upper part... But we verify that the overall heat extracted through the mould is correct, compared with measurements
  - All the stresses and strains are in the horizontal plane
    - Fairly correct if one considers that things change slowly along the *z* axis.



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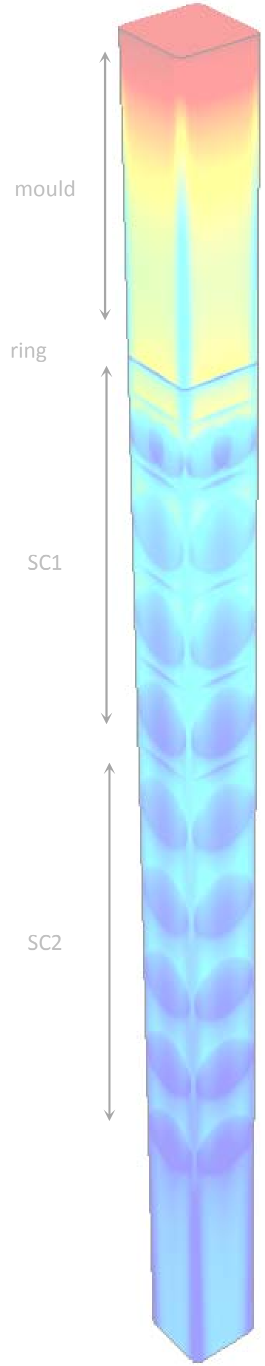
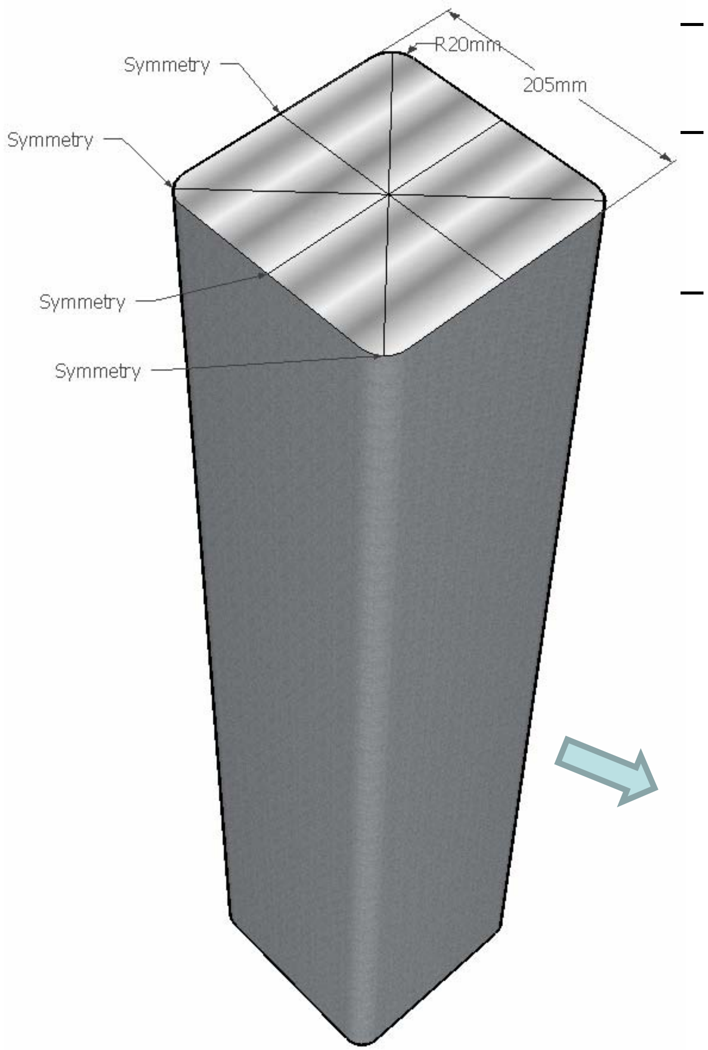
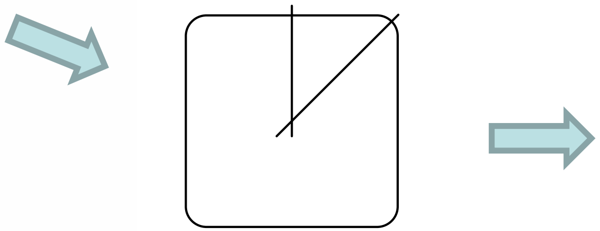
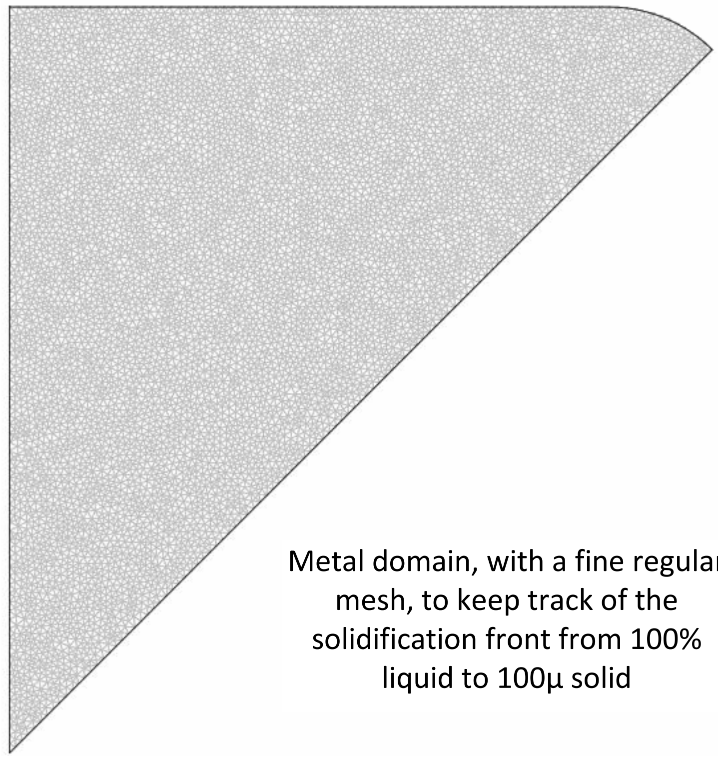


The heat transfer model (1)

- A 2D model : *geometry and meshing*
  - Considering the geometry of the problem, the heat is supposed to flow within the section of the bloom
  - We neglect the 3D aspects…
    - *True* along the length of the product
    - *To be corrected* near the top meniscus
  - The symmetries are used whenever possible
    - Only one eighth of the section is meshed
    - Whenever required, we can use a full section mesh







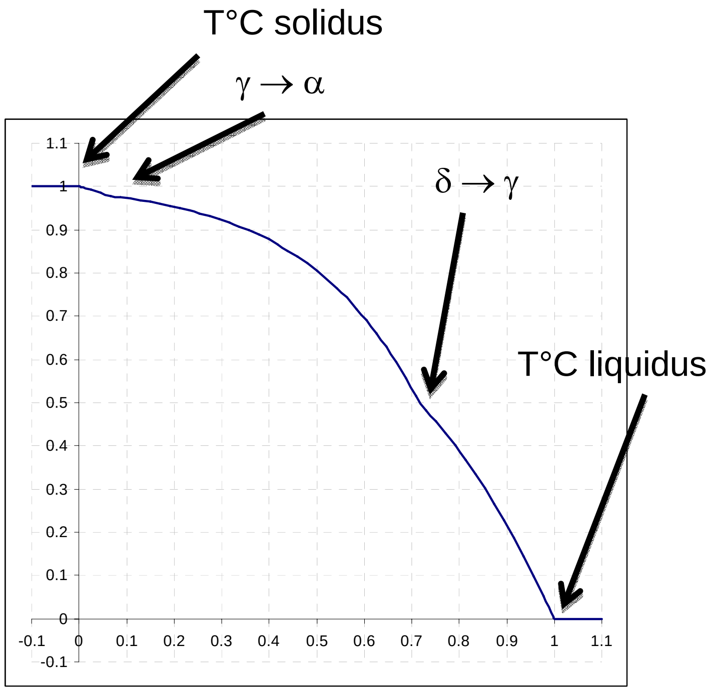
Metal domain, with a fine regular mesh, to keep track of the solidification front from 100% liquid to 100µ solid

The heat transfer model (2)

- *Domain settings*
  - The solidifying stainless steels undergo different phase changes, often involving more than one solid phase (δ and α ferrite, γ austenite)
  - The solidification interval is modelled using equilibrium thermo-dynamic calculation. A solid fraction is used to calculate the thermo-physical data as a composite between liquid, and solid.
  - For the time being, the local solidification time is not taken into account

    ... but it's part of our projects... Or thermo-chemistry software allows for it.
  - The curves are fed in Comsol Multiphysics either as:
    - Direct scalar expressions
    - Formal derivative against T
    - Tables
    - or a mixture of all

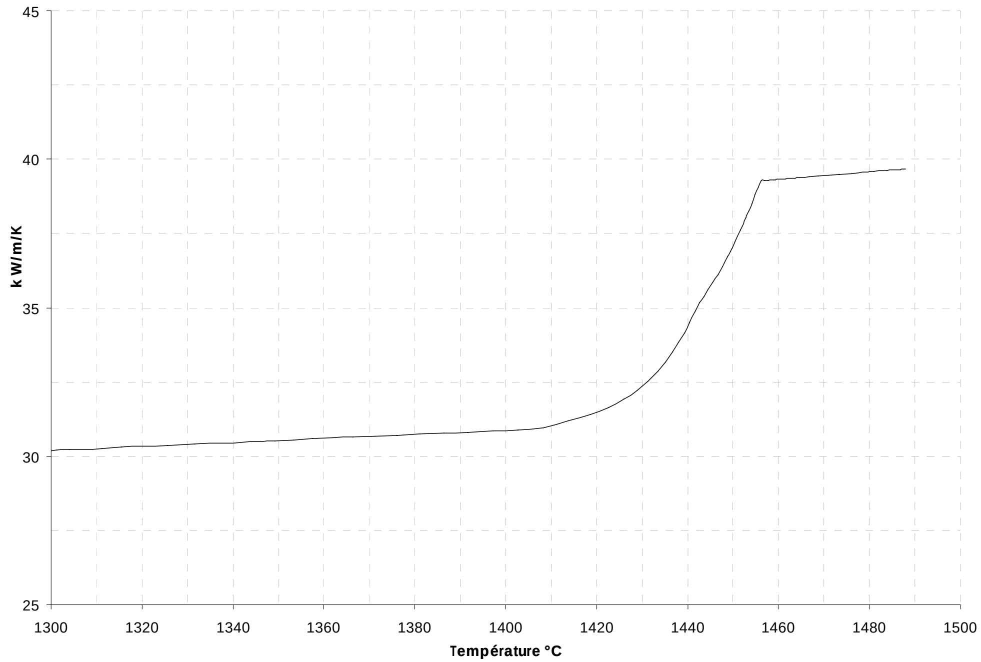
T_liq	1456.06[degC]	Liquidus temperature
T_sol	1407.76[degC]	Solidus temperature
DelT	T_liq-T_sol	Solidification range
Tadim	(T-T_sol)/DelT	Adimensional temperature
cp_Sc	3197.685121[J/(kg*K)]	Solid heat capacity (order 0)
cp_Lc	107.528668[J/(kg*K)]	Liquid heat capacity(order 0)



Adimensional solid fraction as a function of the adimensional temperature

The heat transfer model (3)

- Some thermo-physical data



Heat conductivity W/m/K

$$k_{calc} = (k_{SP}T + k_{SC})\, f_{fra} + k_{mouvL}((k_{LP}T + k_{LC})(1 - f_{fra}))$$

k solid

Solid fraction

k liquid

$$k_{mouvL} = 1 + (MouvL - 1)\, flc2hs(M_{\lim} - Position, M_{liss})$$

Correction factor for convection effects

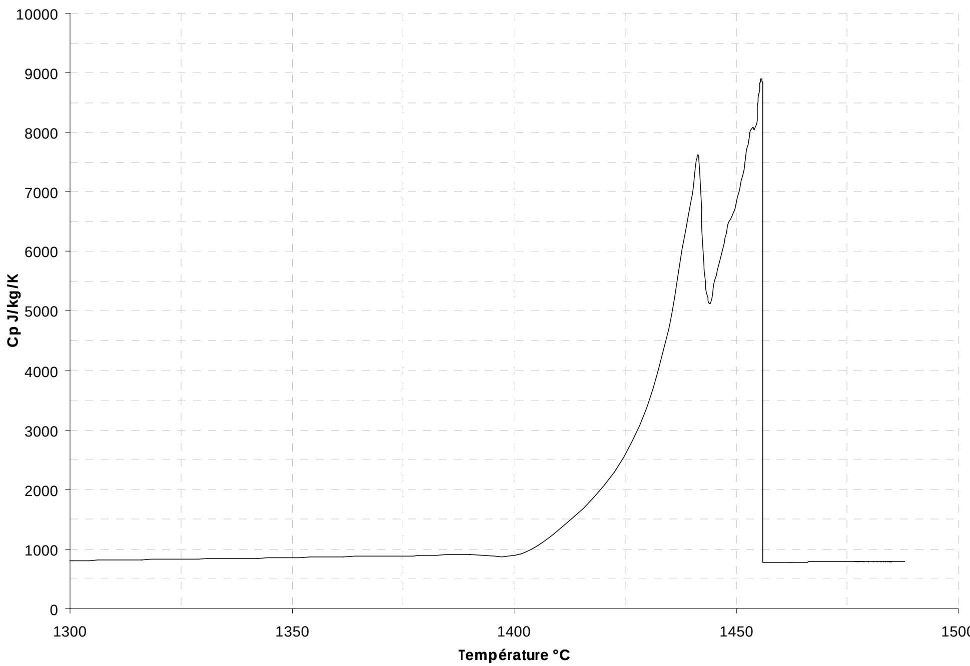
$$H_S = Cp_{SC}(T - T_{sol}) + Cp_{SP}\frac{T^2 - T_{sol}^2}{2} + Cp_{Sp2}\frac{T^3 - T_{sol}^3}{3}$$

$$H_L = Cp_{LC}(T - T_{liq}) + Cp_{LP}\frac{T^2 - T_{liq}^2}{2} + dHsol$$

$$H_{calc} = f_{fra}H_S + (1 - f_{fra})H_L$$

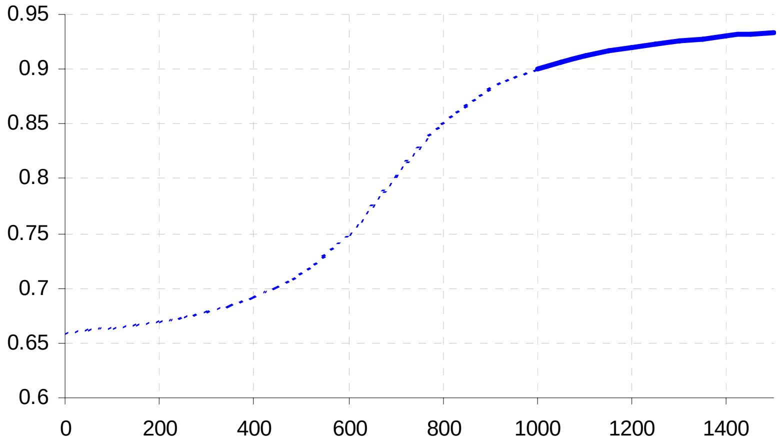
$$Cp(T) = \left.\frac{\partial H}{\partial T}\right|_p$$

Heat capacity J/kg/K



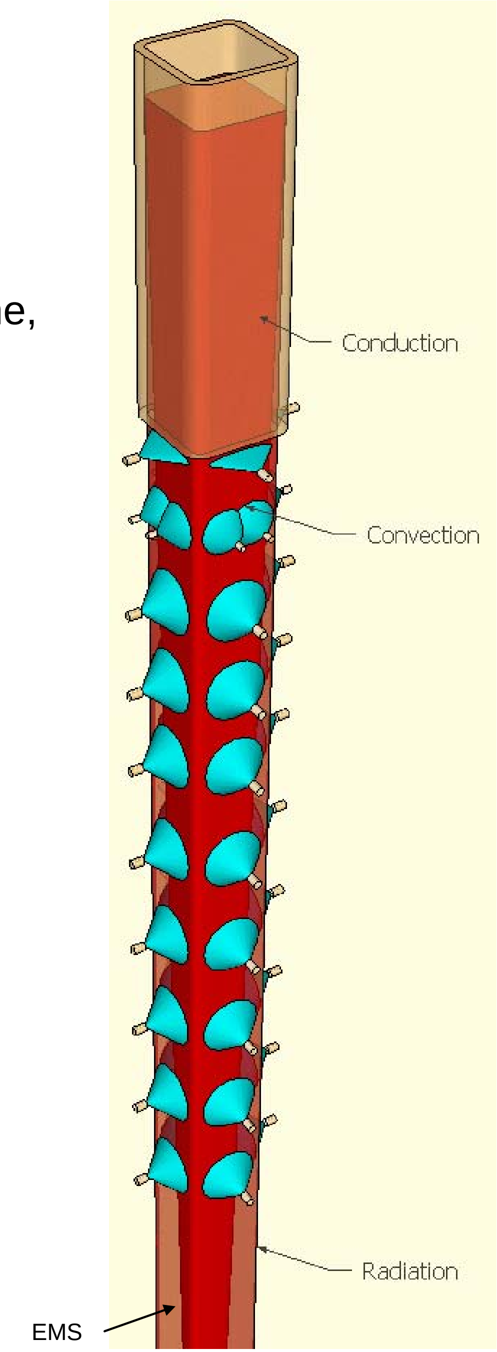
The heat transfer model (4)

- *Boundary conditions*
  - Depending on time
    - Since the simulation is 2D, the bloom section is translated within the machine, at the casting speed… The boundary conditions vary in time, to rebuilt the history of the section.
  - Four kinds
    - *Conduction* in contact with the upper copper mould
      - A simple extracted flux equation depending on the *z/t* axis
    - *Radiation* along the free length
      - A temperature dependant equation



Surface emissivity as a function of surface temperature

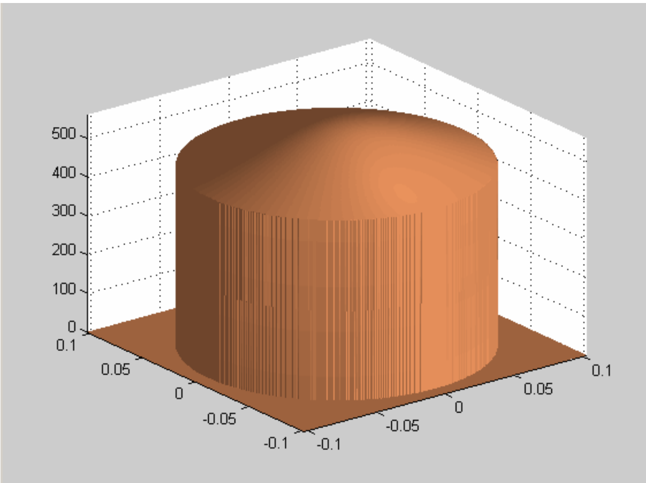
    - Volumic heat flux
      - Flux generated by an electromagnetic stirring device



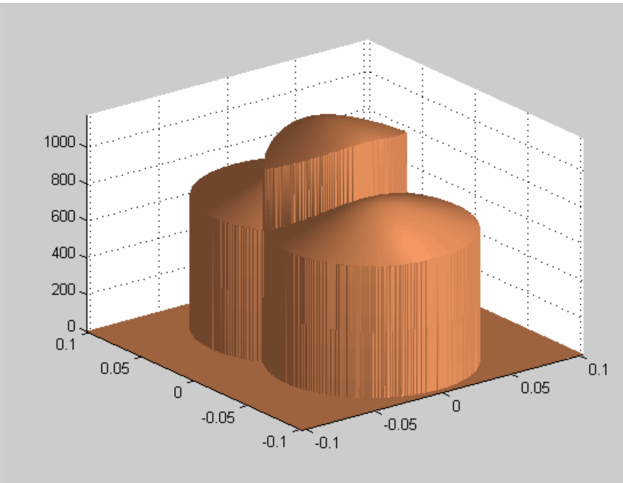
The heat transfer model (5)

- *Convection:*
  - The capacity of Comsol to handle large equations allows us to describe each cooling nozzle independently. The (huge) equation used, gives the value of the heat transfer coefficient as a function of *x* (horizontal coordinate on the bloom surface), *z/t* (vertical position), the water flow rate, and the geometrical characteristics of the nozzle. Each nozzle has its own equation...

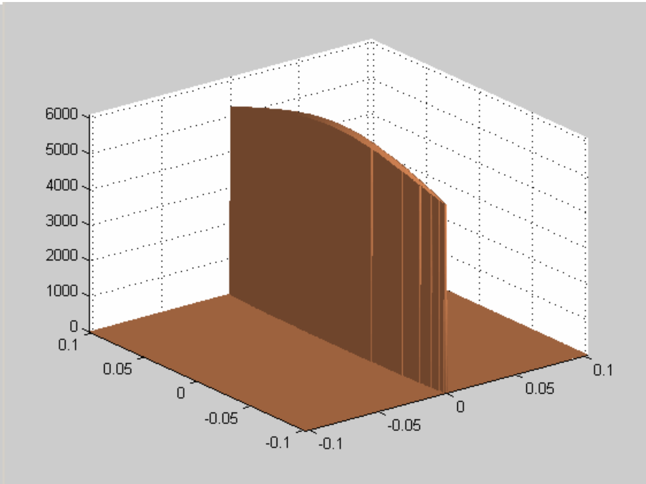
```
hLocal=1570*(((((((((x+(Nspray-1)/2*dSpray)/(Dist.*tan(AngH*pi/360))).^2+(t/(Dist.*tan(AngV*pi/360)))^2)<=1)).*(cos(atan
(sqrt(((x-(-(Nspray-1)/2)*dSpray).^2)+t^2)/Dist)))+(Nspray==2)*((((((x-(1-(Nspray-1)/2)*dSpray)/(Dist.*tan(AngH*pi/360))
).^2+(t/(Dist.*tan(AngV*pi/360)))^2)<=1)).*(cos(atan(sqrt(((x-((Nspray-1)/2)*dSpray).^2)+t^2)/Dist)))))/(2*pi*(Dist^2)*N
spray*(Dist.*tan(AngV*pi/360))/(Dist.*tan(AngH*pi/360))*(sin(AngH*pi/360)*tan(AngH*pi/360)+(cos(AngH*pi/360)-1)))*Qeau*N
spray*0.06))/3.6).^0.55*(1-0.0075*(Teau-273.15))/4
```



Round nozzle



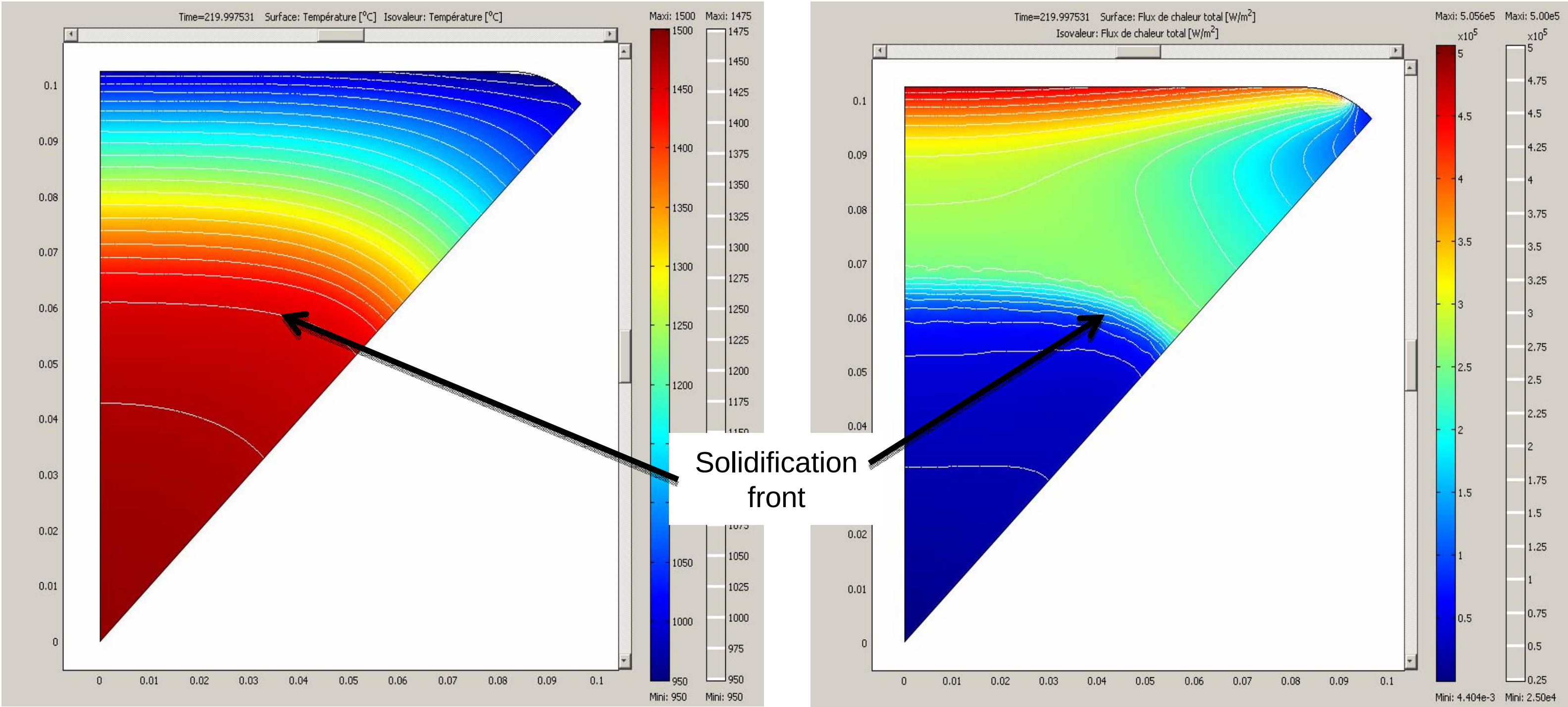
Paired round nozzles



Flat nozzle

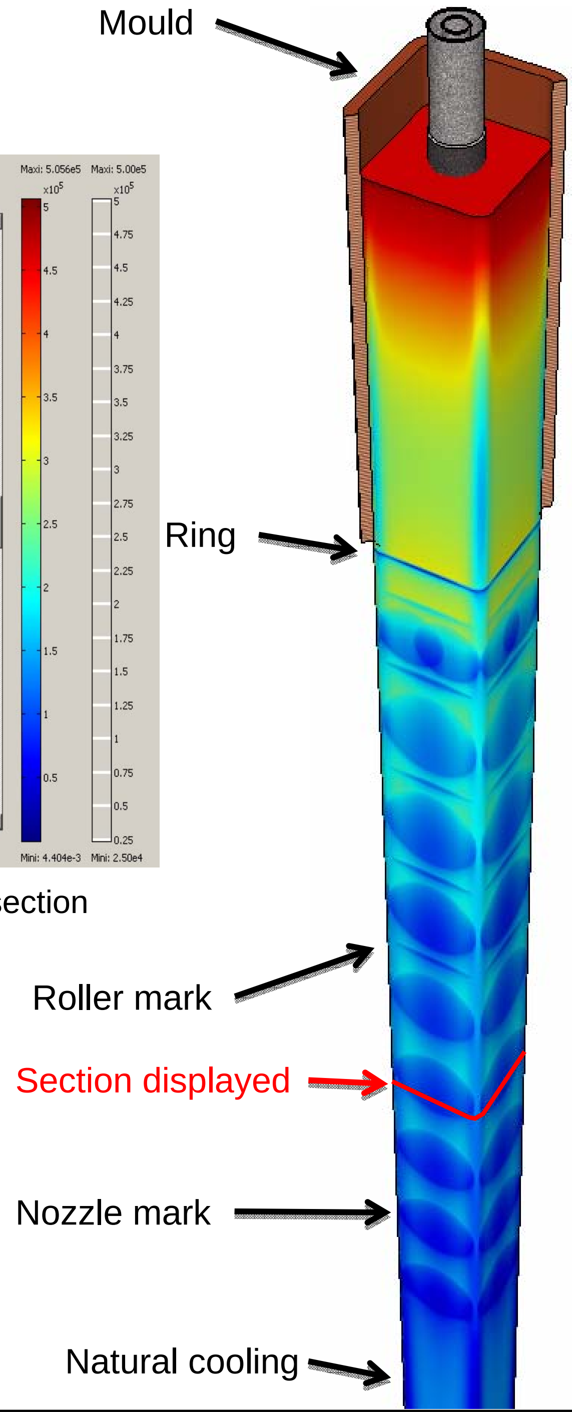
Values of *h* -- convection coefficient -- as a function of *x* and *z*

Some results … (1)



Temperature profile in an 8th of a bloom section

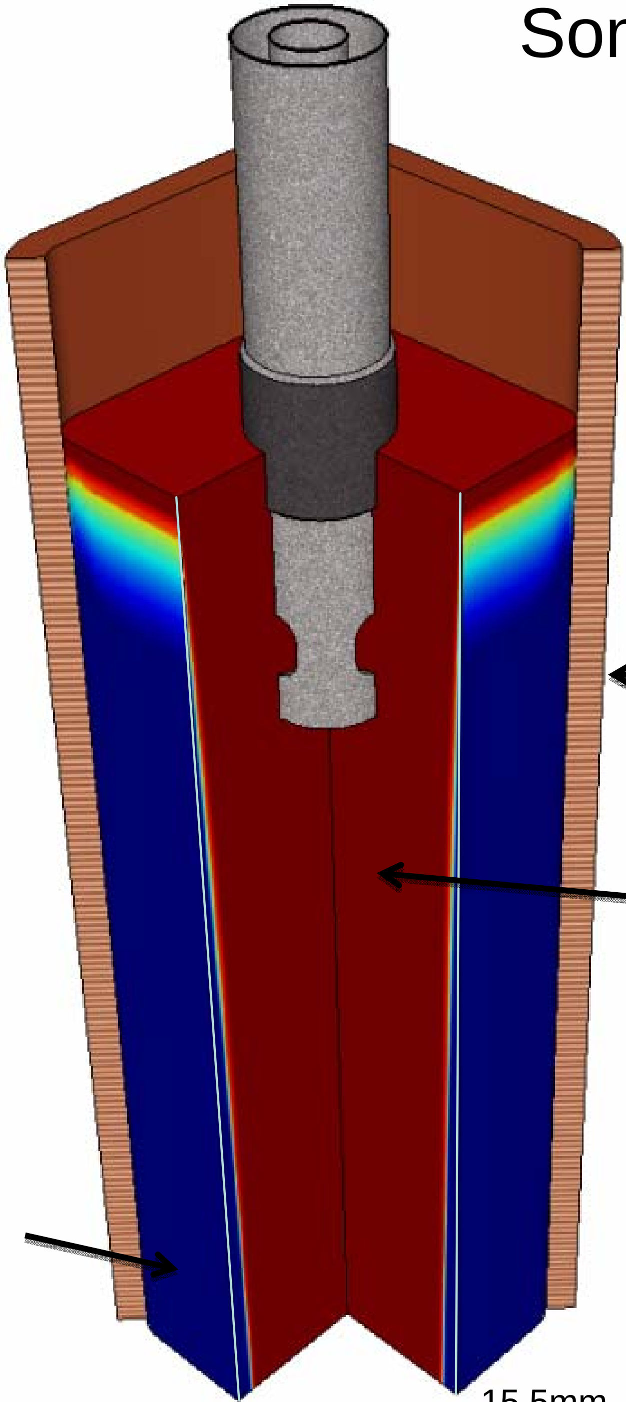
Heat flux profile in an 8th of a bloom section



Grade 304L
Casting speed 1,12m/min

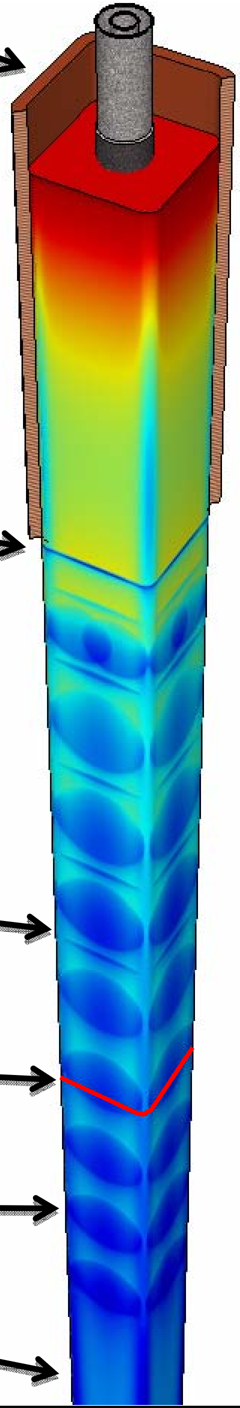
The calculation time is about 1000s

Some results … (2)



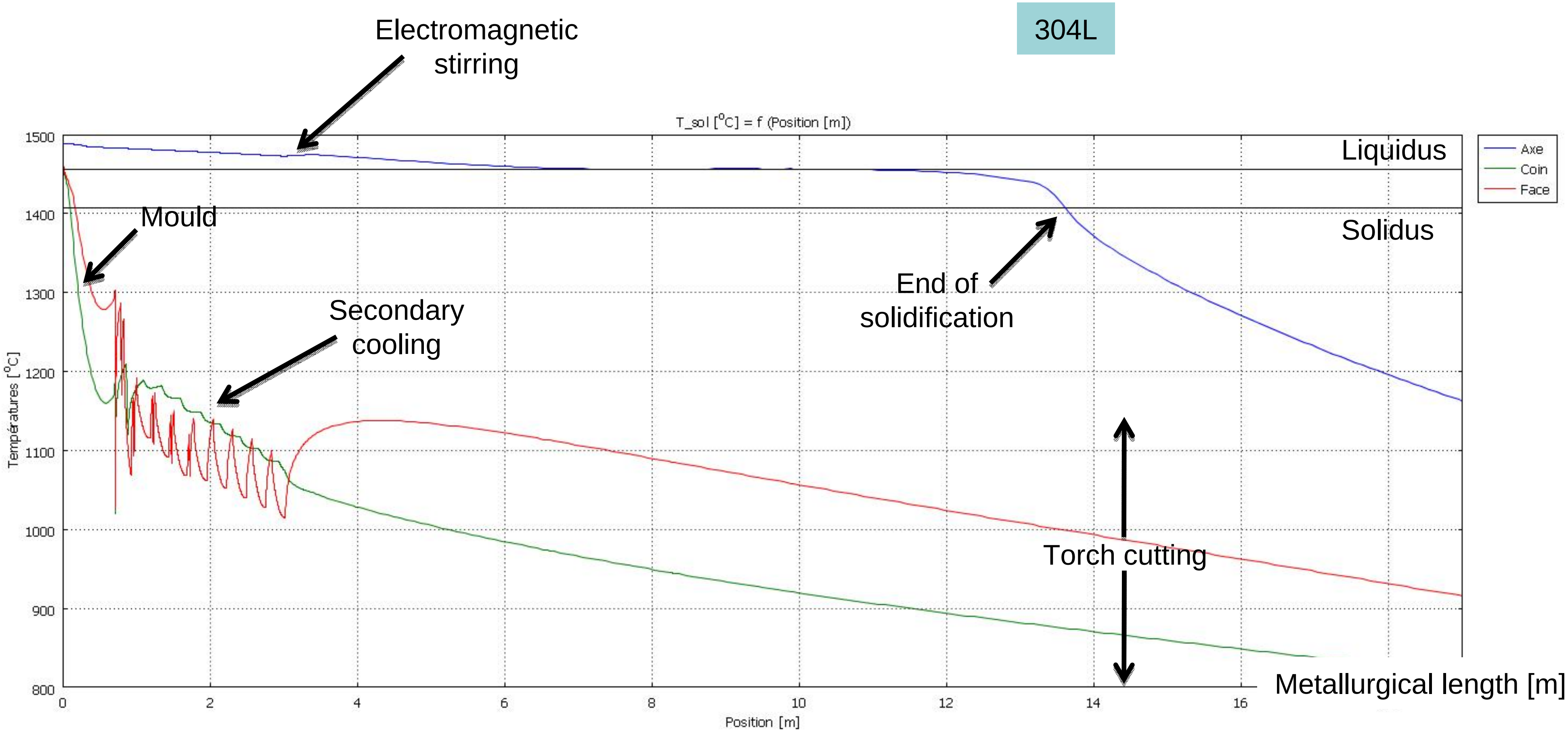
Liquid & Solid fractions

Grade 304L
Casting speed 1,12m/min



Some results … (3)

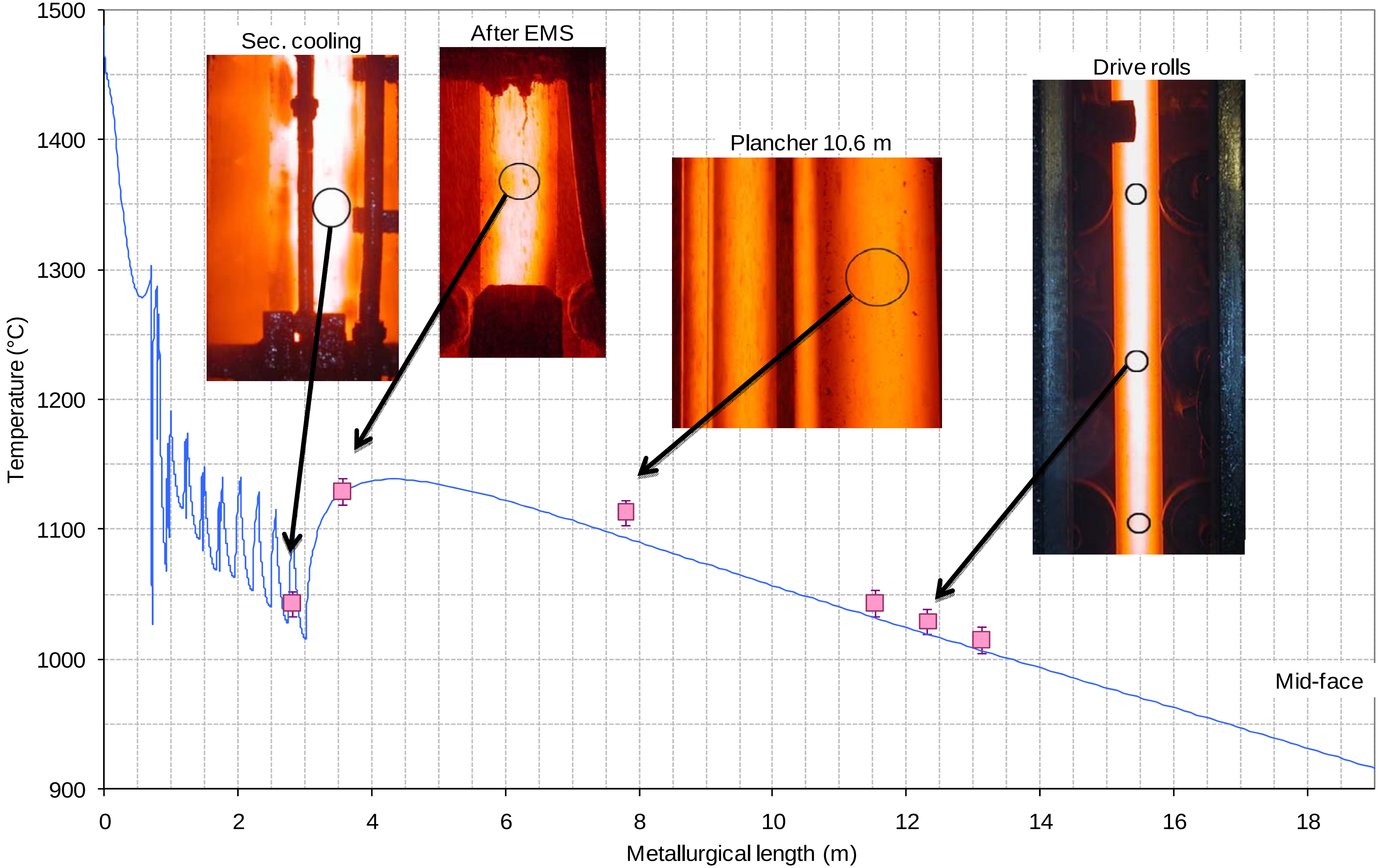
- The length of the liquid well (end of solidification at the axis) can be calculated: any torch cutting on the liquid is avoided.
- The surface defects are also correlated with the temperature gradient and evolution



Temperatures along the strand at the corner, at mid-face and at this axis

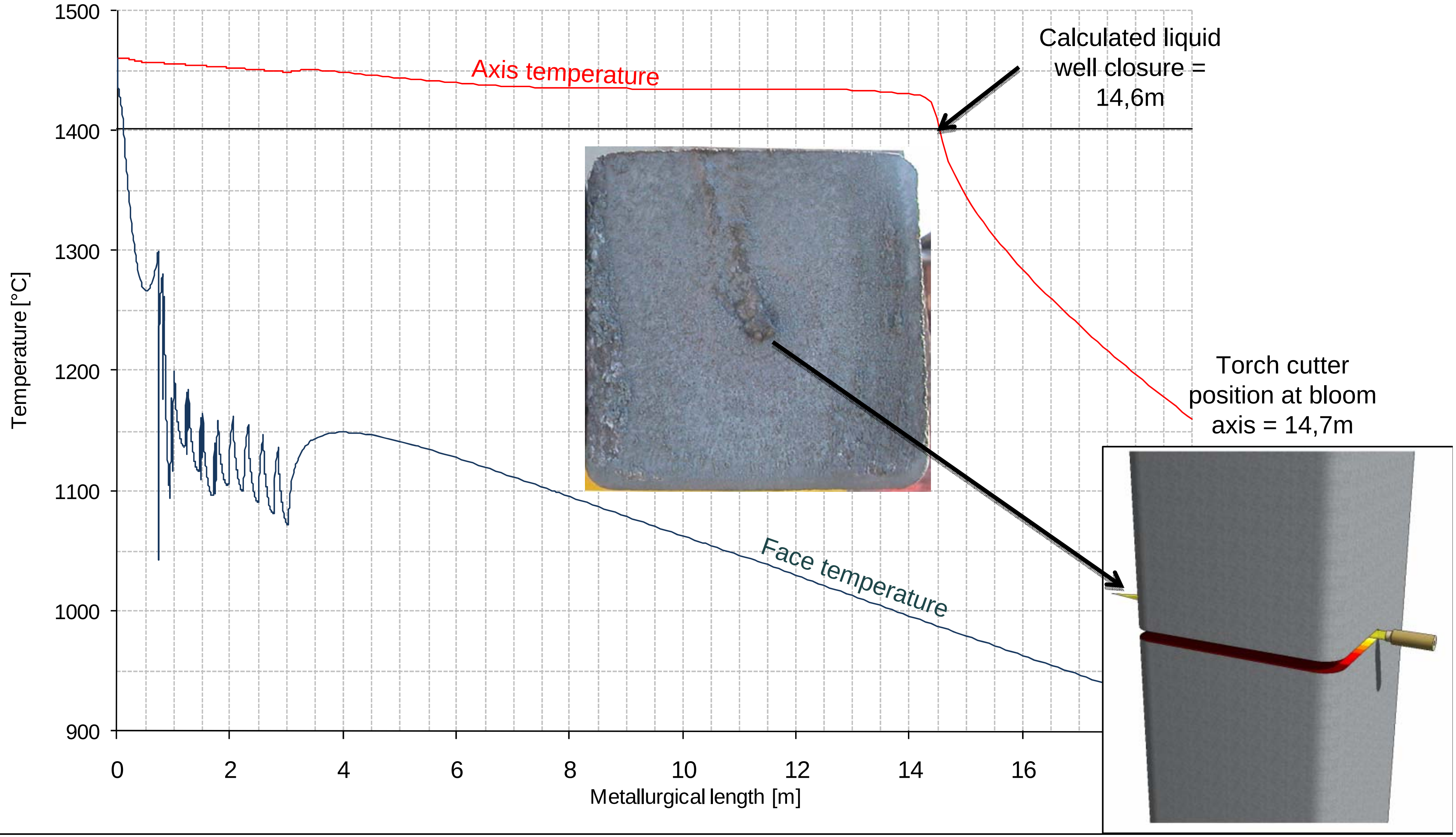
… and comparisons with measurements (1)

- Pyrometric measures have been taken along the CC strand and fall within ± 10°C from the forecast. The surface temperature is well calculated



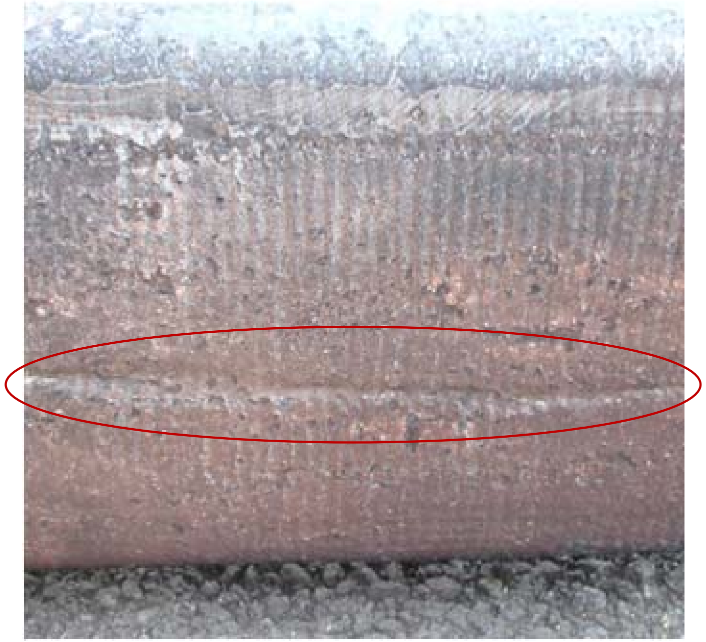
… and comparisons with measurements (2)

- An incidental torch cutting displaying a liquid metal drop, confronted with the casting conditions shows that the liquid well position is also correct.



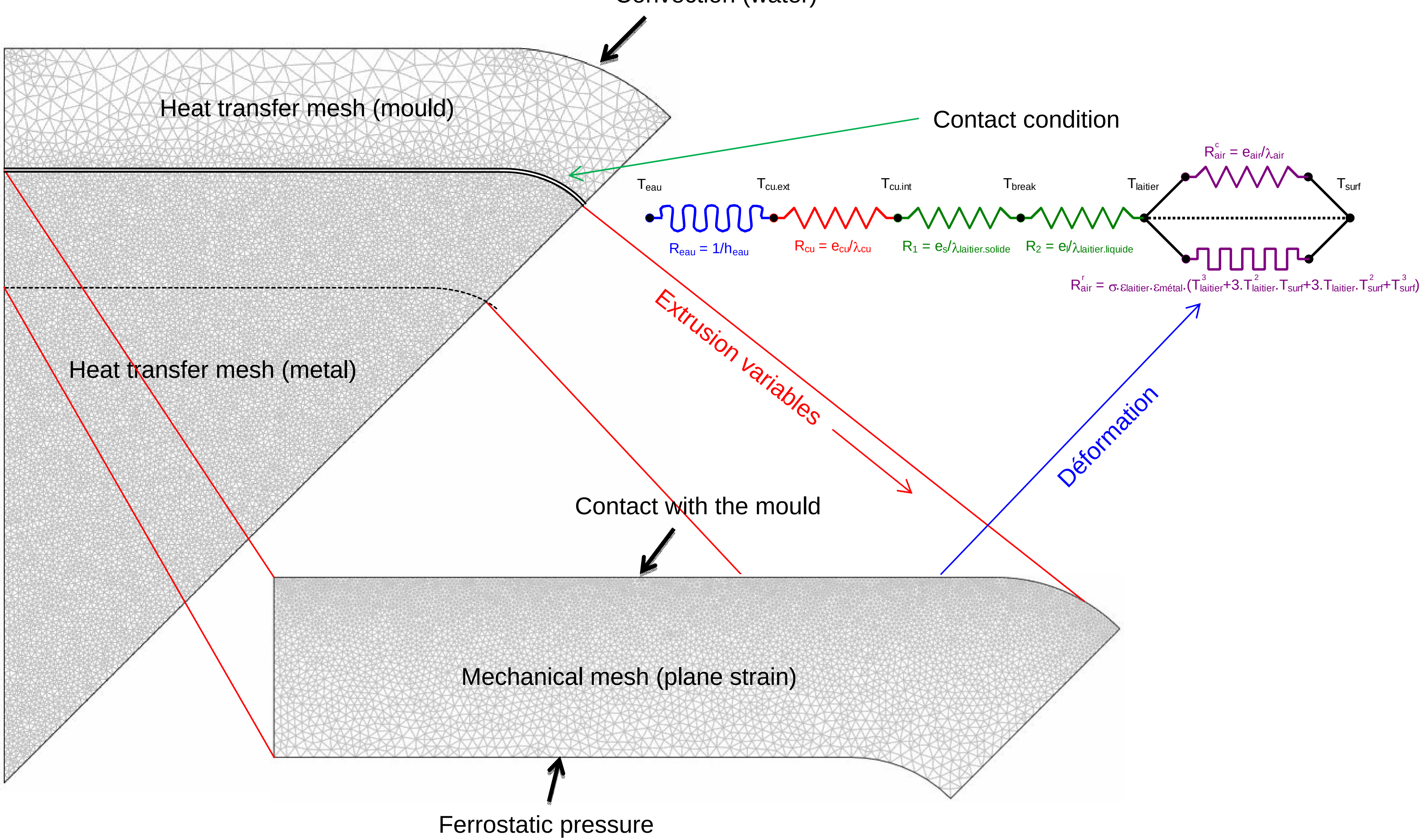
Recent developments : thermo-mechanical model (1)

- The most difficult part of the model resides in the mould, where one creates the solid phase, and where all the phenomena occur:
  - Fluid flow (which changes the heat fluxes locally)
  - Phase change which induces volume changes
  - Variable, non-linear surface contact between mould and metal
- Most of the defects are coming from this early solidification
  - Cracks
  - Segregations near the product's skin
  - Depressions
  - Oscillations marks
- If not to give an exact forecast, at least does a model assist the researcher in understanding the process



Thermo-mechanical model (2)

- Two dialoging meshes:

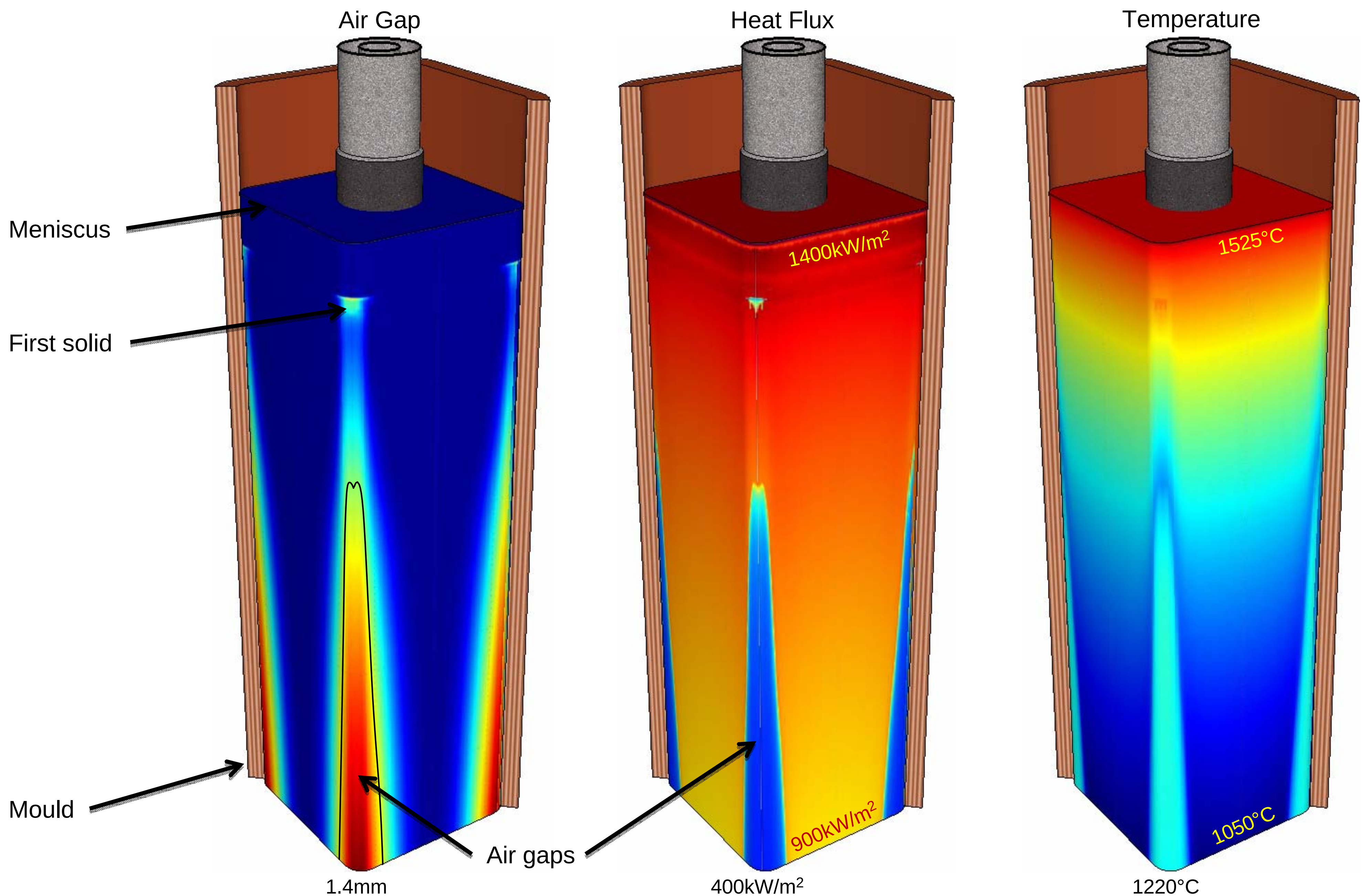


Thermo-mechanical model (3)

- Material:
  - Elasto-plastic material, with a perfect plastic behaviour in the solid phase
    - *This is a theme for our current work... A visco-plastic behaviour would be better...*
  - Purely elastic behaviour, with a very low Young modulus in the liquid phase
    - This does not modify the results since the Yong modulus chosen is several orders of magnitude lower than in the solid phase
    - This assumption avoids strain accumulation in the liquid, while transmitting correctly the pressure at the solidification front

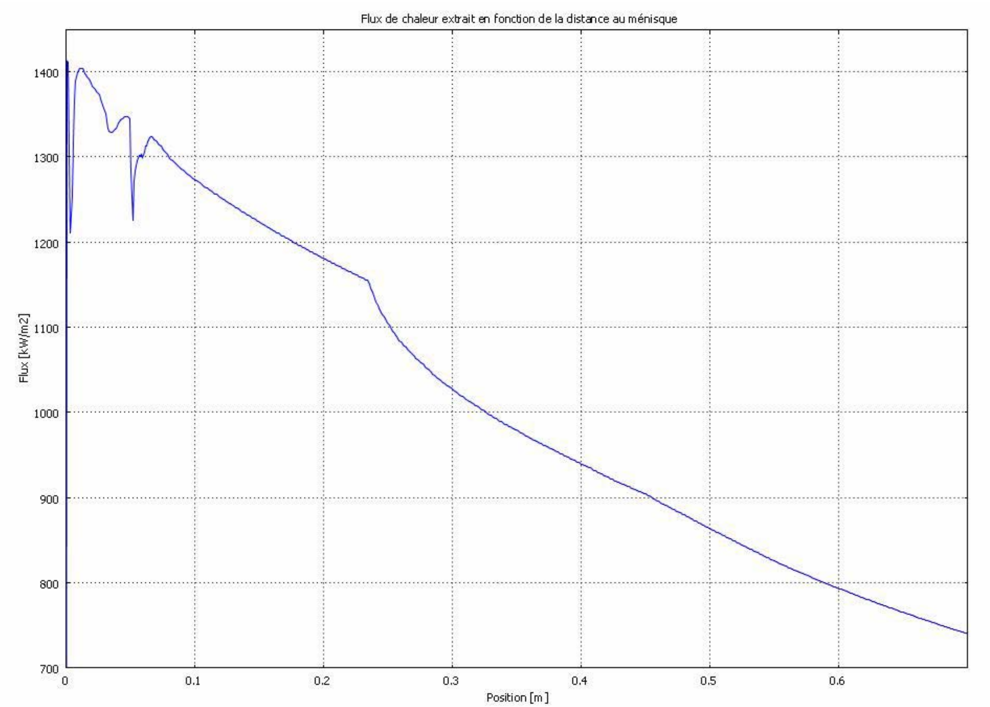
- Boundary conditions
  - Symmetries (conventional BC)
  - Convection coefficient at the external boundary of the mould.
  - Ferrostatic pressure at the inner boundary of the mechanical mesh
  - Thermal resistance between mould and metal
    - Taking into account the mould flux properties and thickness
    - Taking into account the eventual air gap deduced from the deformations of the surface
  - Contact condition at the surface of the metal
    - Hand built to accommodate the transient calculation
    - Based on a smoothed reaction force proportional to the ferrostatic pressure

Thermo-mechanical model (4)

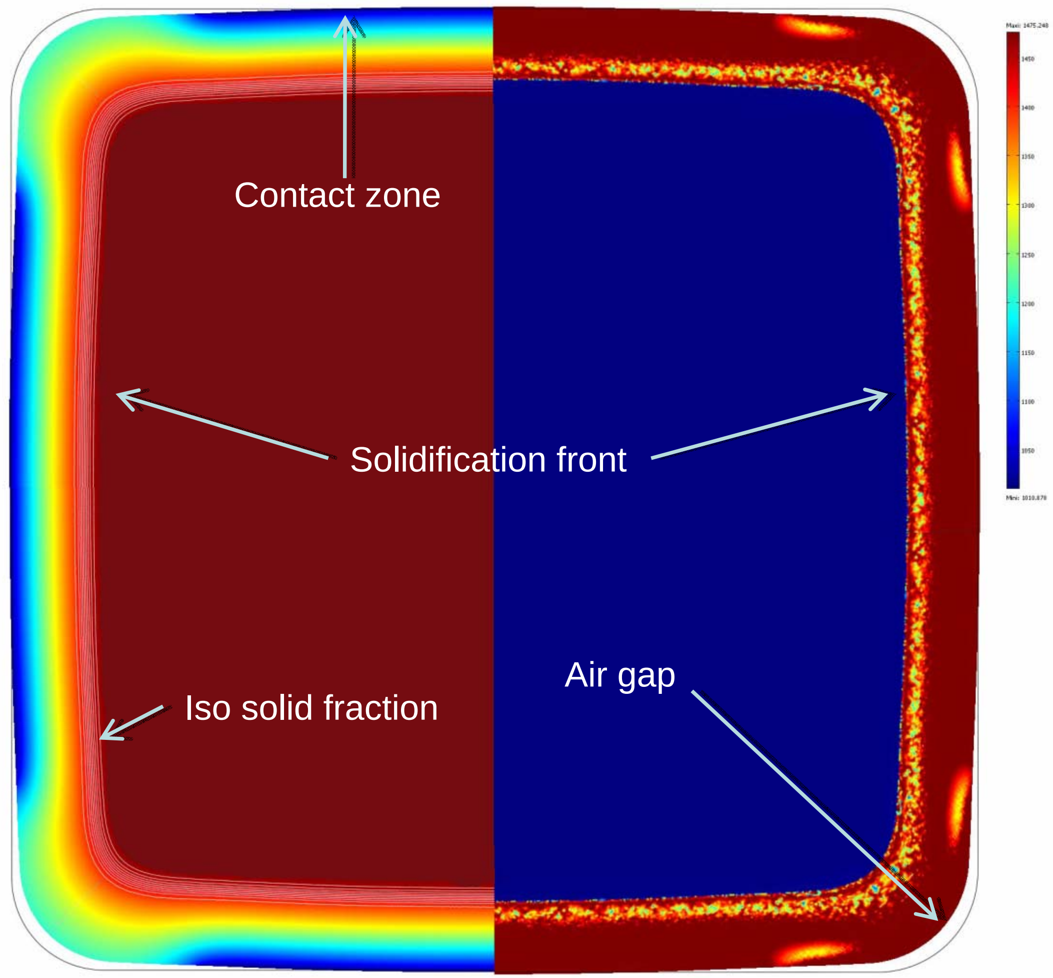


Thermo-mechanical model (5)

- Results:



Heat fluxes along the length of the mould



Section of the product at the mould exit

- These results are qualitative for the time being. The big difficulty of convergence and numerical stability has been overcome and work is still in progress regarding the constitutive laws of the near melting solid

- The calculation time is about 5 hours

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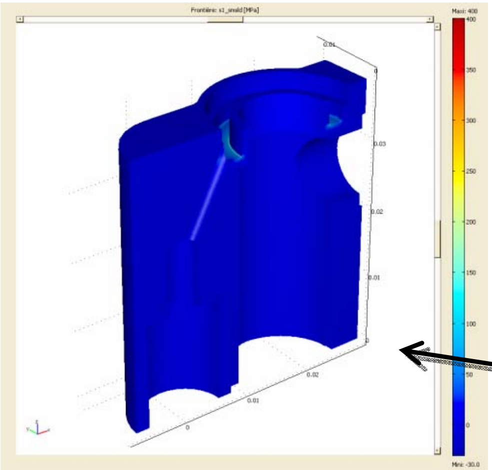
Conclusion (1)

- Using our current thermodynamical knowledge, and Comsol:
  - We can calculate the heat transfer of any heat's solidification
  - Our heat transfer model is accurate enough to track the liquid well
    - It has been checked against real data on two grade families
  - We have first results regarding the interfacial heat transfers in the mould

- Constant progress on three battle fronts:
  - Apply the use of the model to more and more case studies
    - Casting speed limits,
    - Format changes
    - Asymmetry
    - New grade families
  - Feed the model(s) with accurate data (thermo-physical data acquisition)
    - Increase our current databases further than 304, 326, 420, etc.
    - Measure ρ, Cp, λ, solidification enthalpy for new grades
    - Improve the nozzles description
  - Improve the model itself
    - constitutive laws for near melting steels
    - 3D ??

Conclusion (2)



- Considering the success of this model, we are extending our numerical simulation effort to other fields:
  - Ladle simulation (2D-axi heat transfer, 3D-CFD)
  - Localised stresses on a machined part (3D elastic)
  - ESR heating (3D AC-DC + heat transfer)
  - Bloom cooling after CC (3D heat transfer)
  - Tundish simulation (3D k-ε CFD)