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Heat Transfer and Ideal Shrinkage for Soft Reduction Modeling

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Phenomena governing macrosegregation / ideal soft reduction

- turbulent, transient **fluid flow** in a complex geometry (inlet nozzle and strand liquid pool), affected by argon gas bubbles, thermal and solutal buoyancies
- transport of **superheat** through the turbulent molten steel
- transport of **solute** on microscopic (between dendrites), mesoscopic (between grains, columnar-equiaxed regions, etc.) & macroscopic scales (center to surface)
- coupled **segregation** (including micro, meso, and macro scales)
- **solidification** of the steel shell, including the growth of dendrites, grains and microstructures, phase transformations, and microsegregation
- **microstructure** evolution, including columnar-equiaxed transition, nucleation of solid crystals, both in the melt and against mold walls
- **shrinkage** of the solidifying steel shell, due to thermal contraction, phase transformations, and internal stresses
- thermal-mechanical deformation of the **mushy-zone**, and its effective **permeability**, which control transport of solute-rich fluid
- **stress** in the solidifying shell, due to loading from external forces, (mold friction, **bulging** between support rolls, withdrawal, gravity pressure) thermal strains, creep, and plasticity (which varies with temperature, steel composition, and cooling rate)
- **thermal-distortion**, warping, misalignment, and wear of the support and drive **rolls**

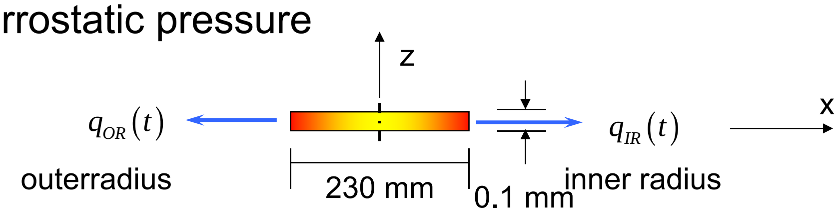
Simple ideal soft-reduction model

1) 1-D Heat transfer model of entire strand (CON1D, validated with 1D and 2D ABAQUS)
2) 1-D & 2-D Thermo-mechanical models of free-shrinkage of solidifying shell, including the liquid
   - Assume shell deforms exactly to match liquid shrinkage; avoiding fluid flow and also macrosegregation
3) 3-D thermal-mechanical model of shell in mushy zone (ignoring liquid), to calculate:
   soft-reduction efficiency = liquid-core reduction / surface reduction

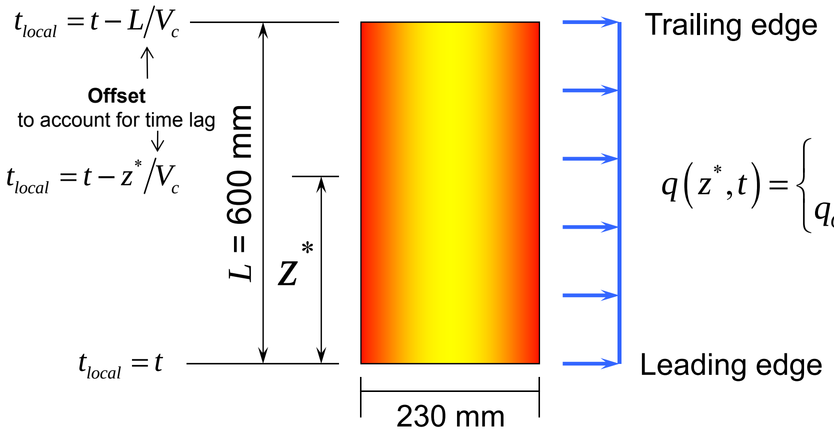
accounts for:
bulging of narrow faces, plastic strain,
bulging of wide faces between rolls, etc.

Lagrangian Slice Model of Thermal Strain through Thickness

- Calibrate CON1D to match typical thick-slab caster
- Heat flux time-history from CON1D as heat loads to Abaqus
  - Independent inner and outer radius
  - Top and bottom edges insulated
- x-displacement fixed at centerline
- Generalized plane strain finite elements (quad)
- Generalized plane strain imposed in z-direction
  - Fix top edge z-displacement
  - Constraint equations on bottom edge z-displacements
- No ferrostatic pressure



2D Lagrangian Longitudinal Slice Model

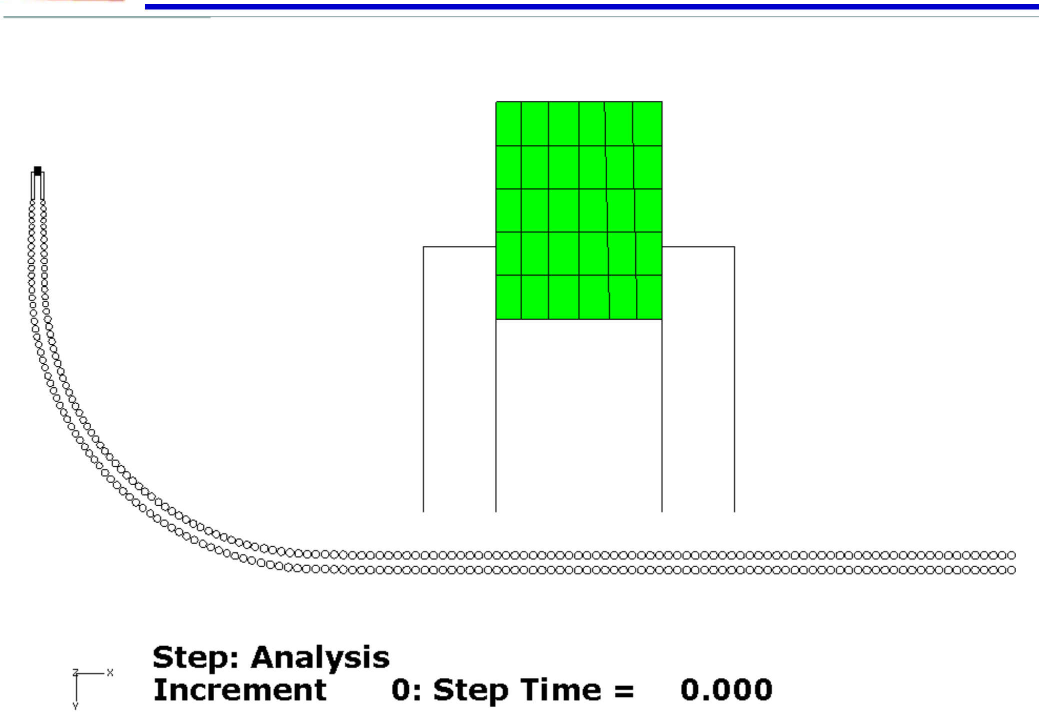


$$q(z^*, t) = \begin{cases} 0 & t_{local} < 0 \\ q_{CON1D}(t_{local}) & \text{otherwise} \end{cases}$$

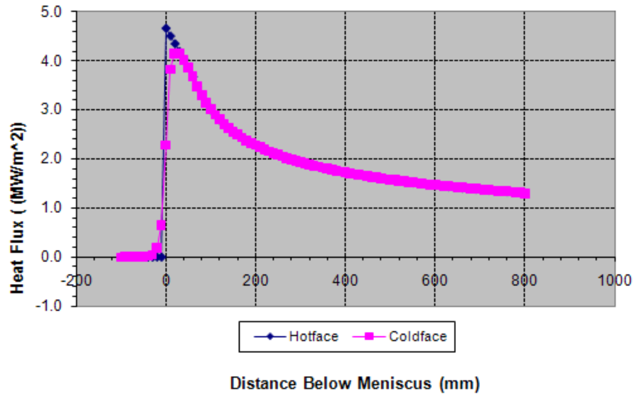
The heat flux time-history from CON1D is shifted to account for the finite domain thickness in the casting direction

- Independent inner and outer radius heat loads
- Assumes constant casting speed

Baosteel Caster Simulation



Thermal model (mold): Heat Flux boundary condition

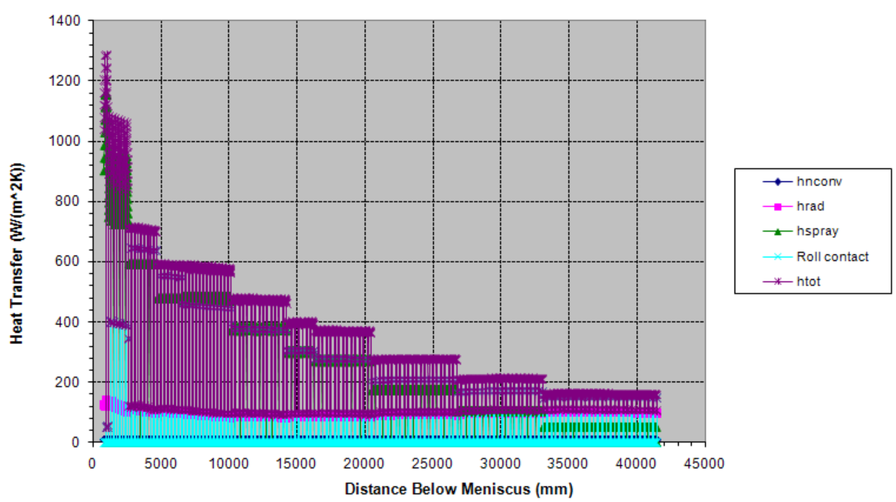


Heat Flux in the mold

In this case, heat flux based on the mold water temperature increase.

Y. Wang, 2010

Thermal model (spray zones): Convection boundary condition

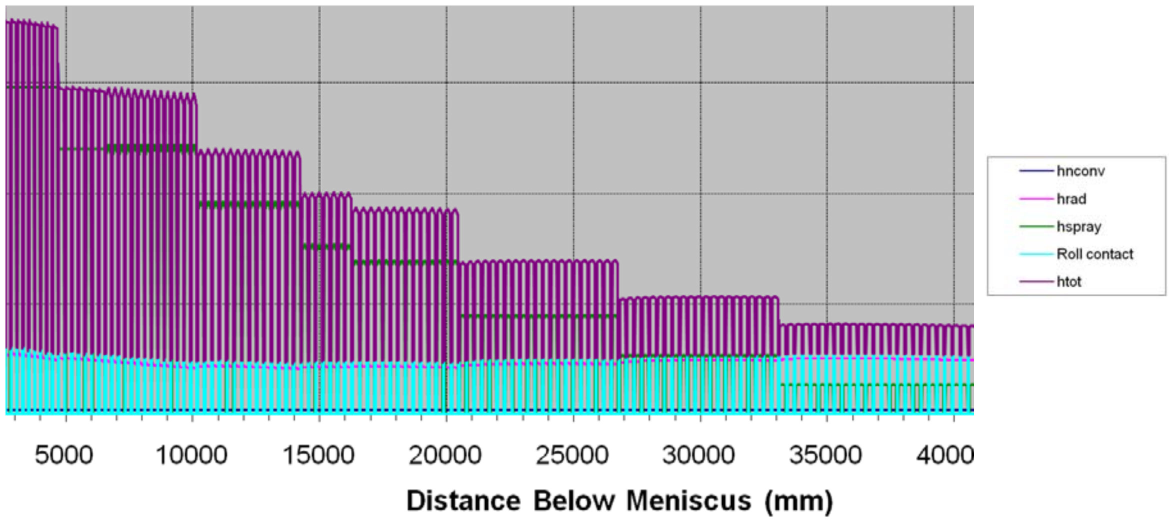


Heat transfer Coefficient in Secondary cooling zones

Secondary cooling zone includes four heat transfer methods: Radiation, spray, roll contact and convection.

Y. Wang, 2010

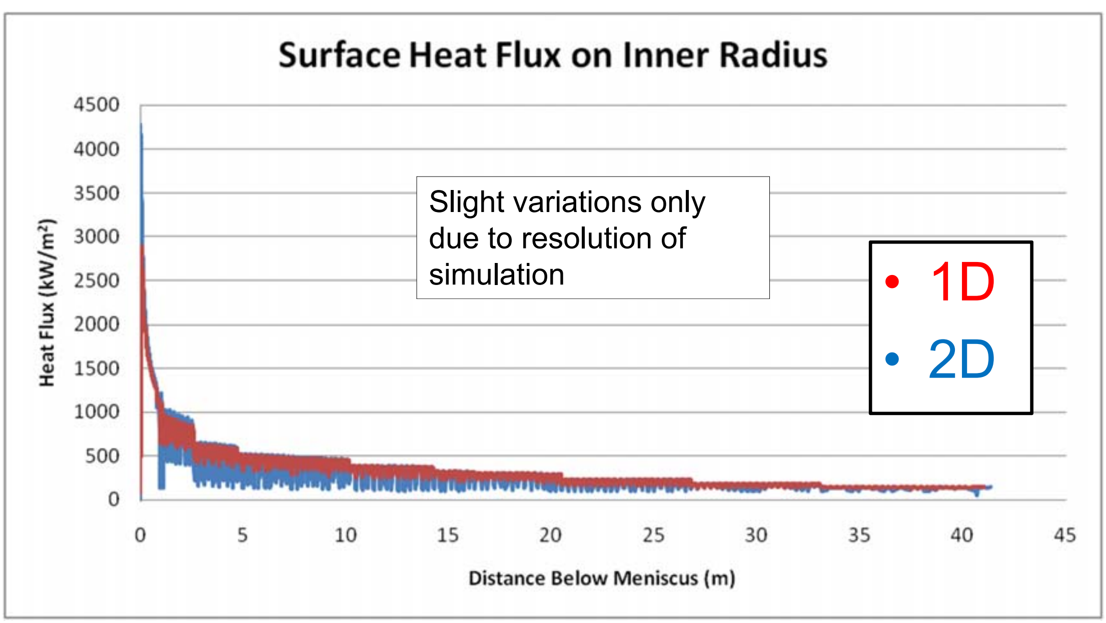
Temperature BC: heat transfer coefficient



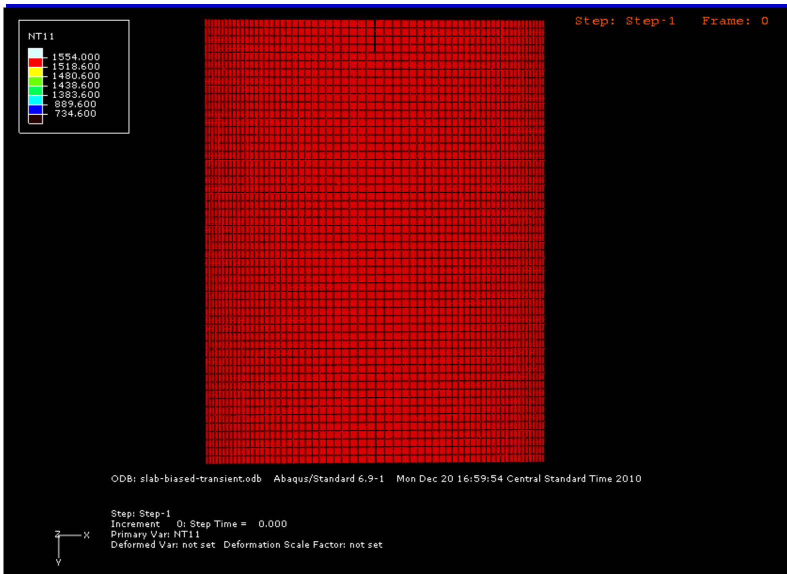
Part ZOOM IN

Y. Wang, 2010

Surface Heat Flux



Temperature Profile Development

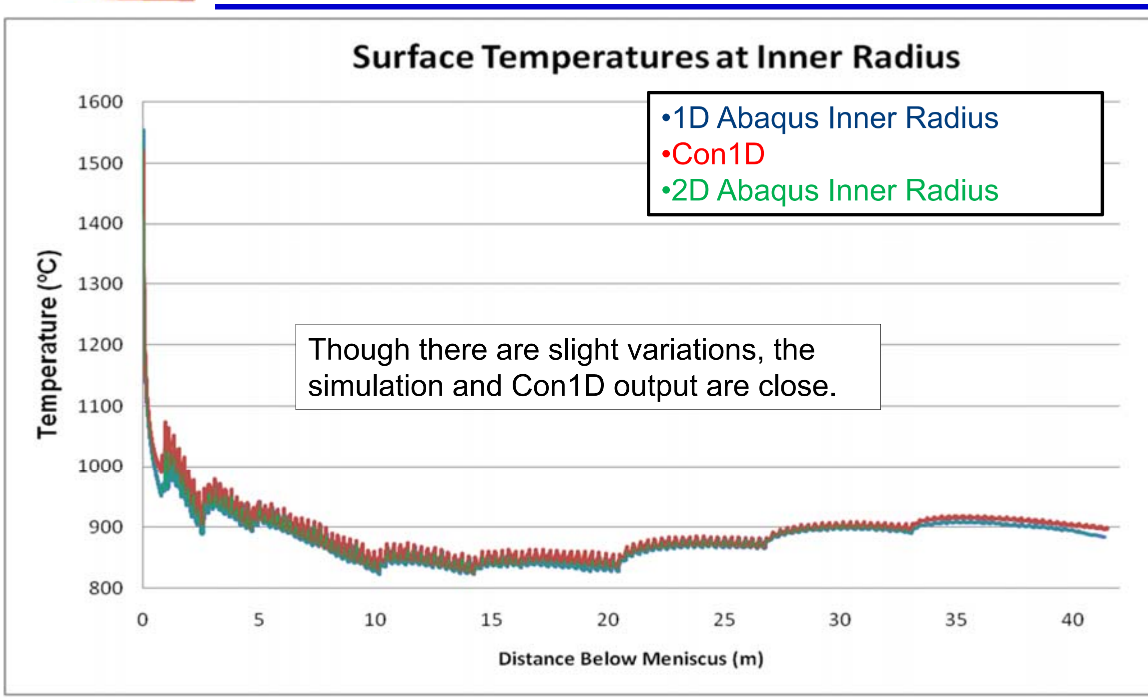


Temperatures indicate phase fractions

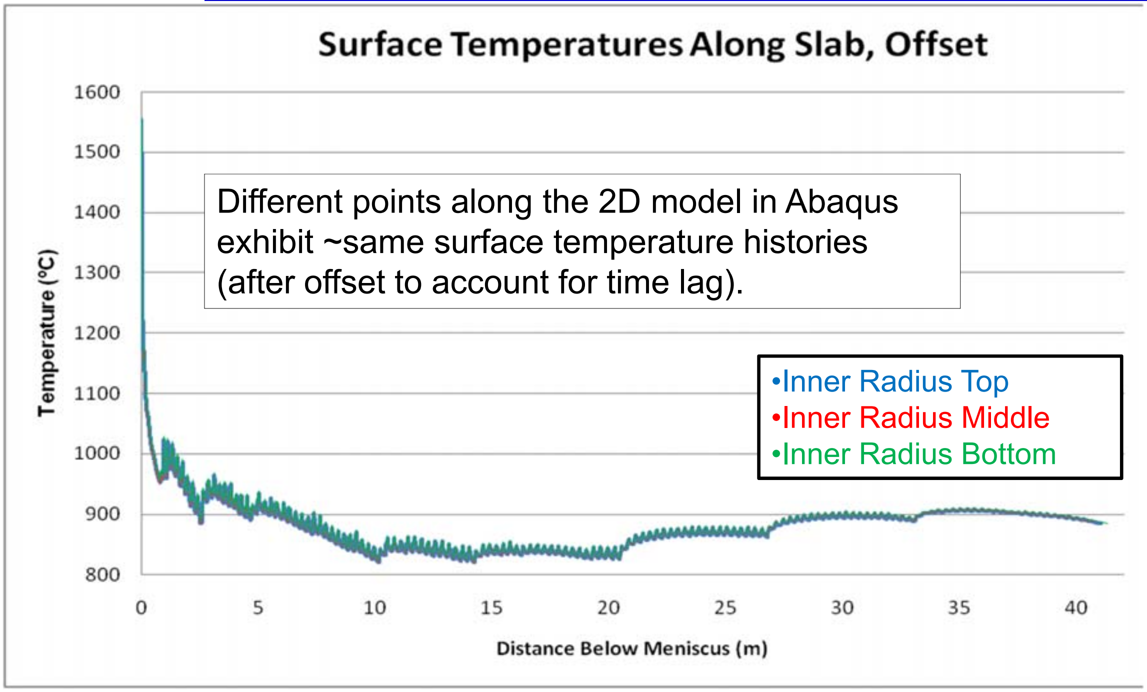
liquid | mush | δ | δ & γ | γ | γ & α | α + Fe_3C

1518.6°C 1480.6°C 1438.6°C 1383.6°C 889.6°C 734.6°C

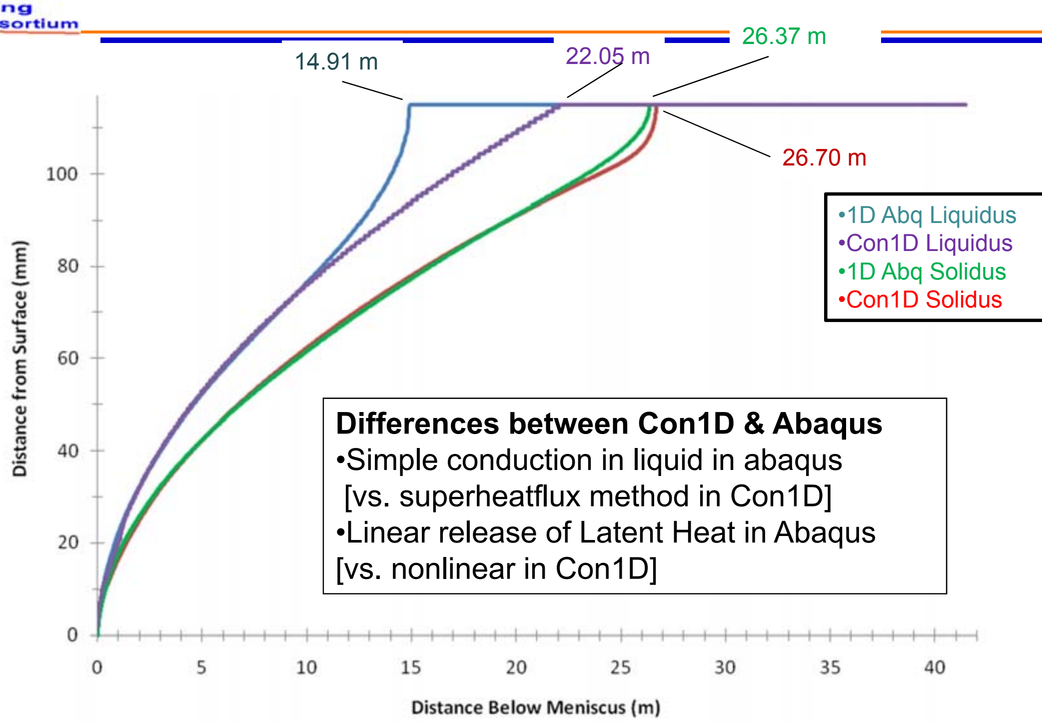
Surface Temperatures



2D Surface Temperatures

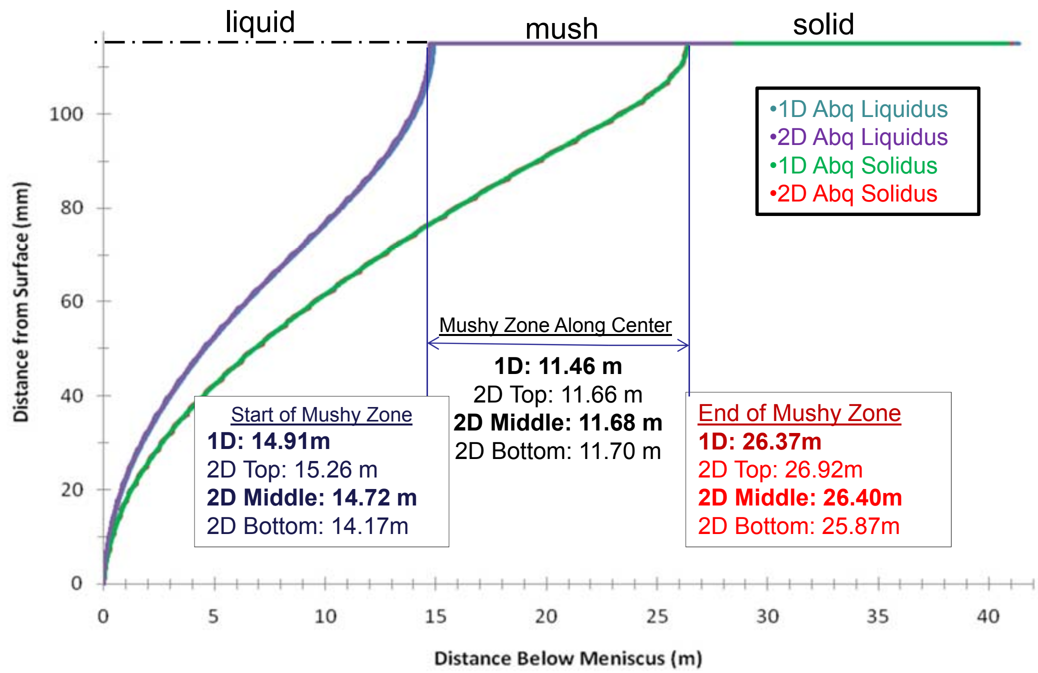


Shell Thickness Comparison

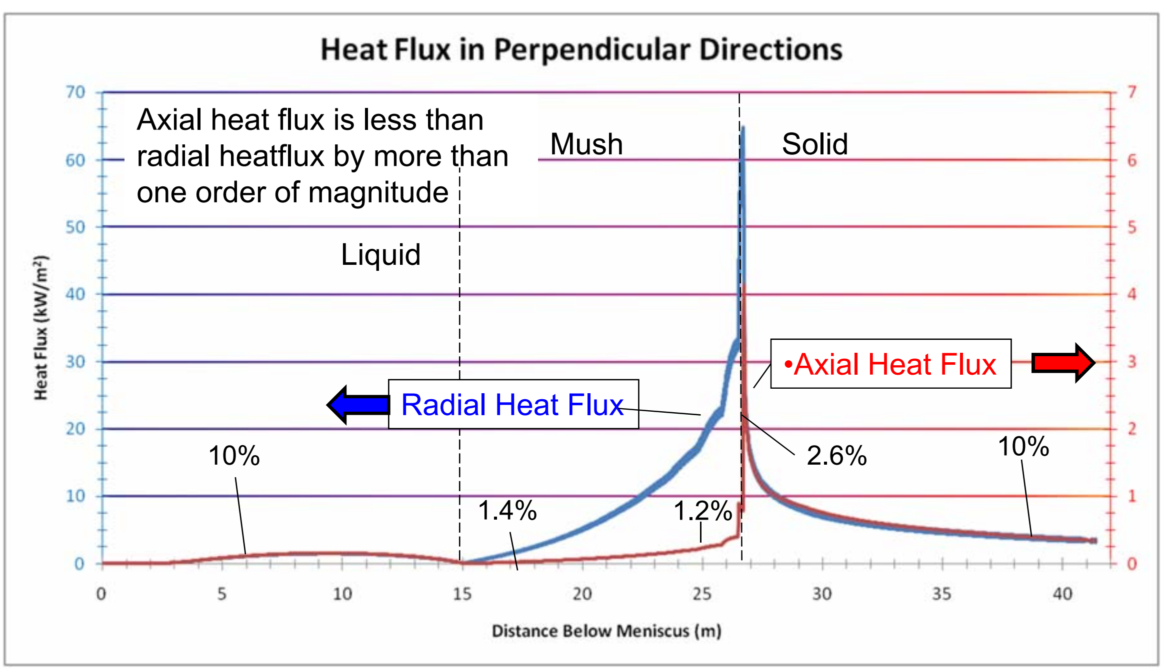


Differences between Con1D & Abaqus
- Simple conduction in liquid in abaqus [vs. superheatflux method in Con1D]
- Linear release of Latent Heat in Abaqus [vs. nonlinear in Con1D]

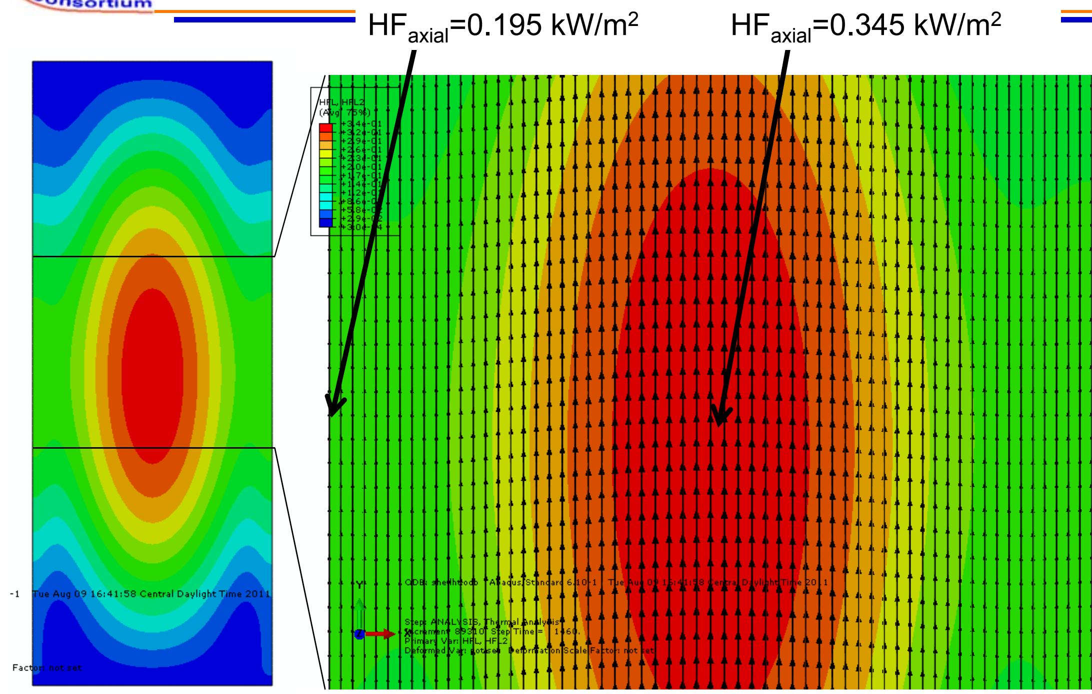
1D & 2D Shell Comparison in Abaqus



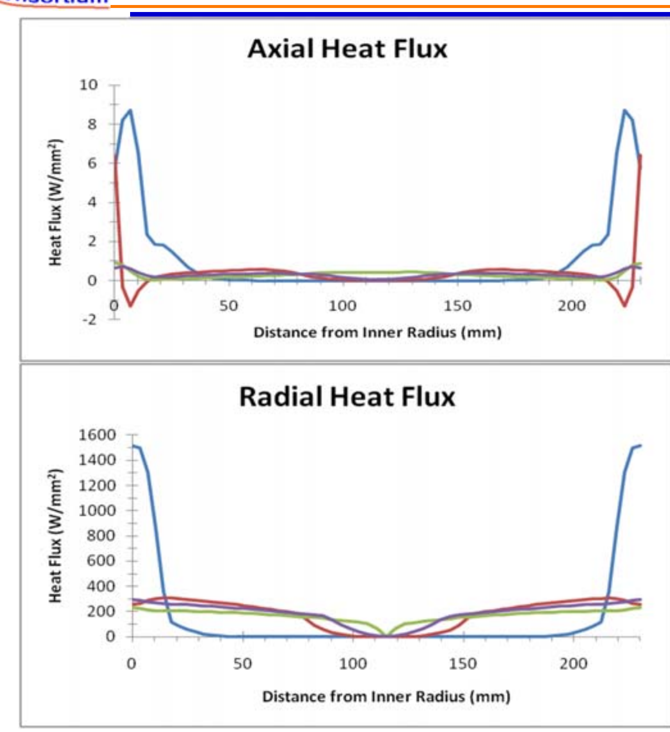
Heat Flux at Center of 2D Slab



Axial Heat Flux



Heat Flux Through Width



(Middle of 2D Domain)

Distance Below Meniscus
- 0.766974 m (Mold Exit)
- 14.92866 m (Liquid/Mush)
- 19.83 m (Mushy Zone)
- 26.37802 m (Mush/Solid)

- In solid shell, Axial Heat Flux is always less than 1% of the Radial heat flux

- 2D domains valid for thermal model because axial heat conduction can be neglected

2D Lagrangian Transverse Domain

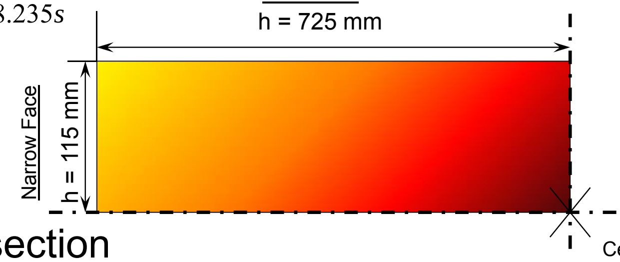
$$q_{NF}(t) = \begin{cases} 0 & t < 0 \\ 0.85 q_{WF}(t) & 28.235s > t \geq 0 \\ \varepsilon_{steel}\sigma(T_s^4 - T_{air}^4) & t > 28.235s \end{cases}$$

$$q_{WF}(t) = \begin{cases} 0 & t < 0 \\ q_{CON1D}(t) & t \geq 0 \end{cases}$$

$\varepsilon_{steel} \approx 0.8$

$\sigma = 5.67\times10^{-8}$ W/(m^{-2}K^{-4})

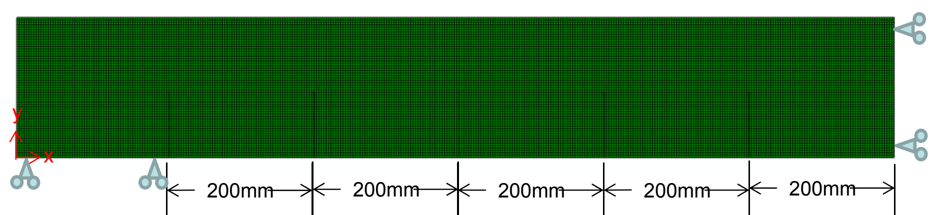
Only radiative heat transfer is applied to narrow face after mold exit



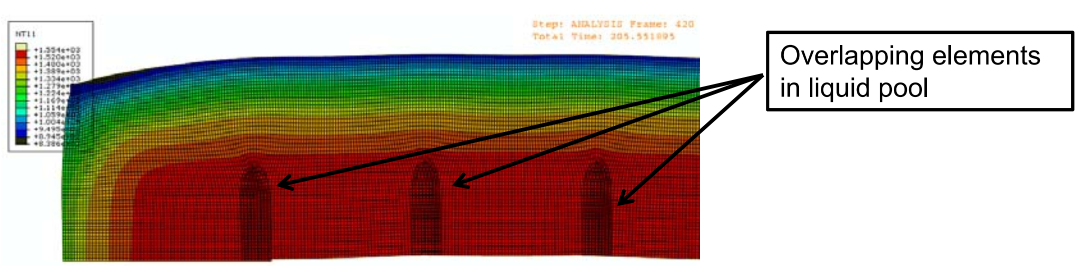
- Transverse cross-section
- Quarter Slice utilizing symmetry through width and thickness
- Boundaries:
  - Thermal: insulated central axes
  - Mechanical: No displacement of central axes

Mesh Geometry

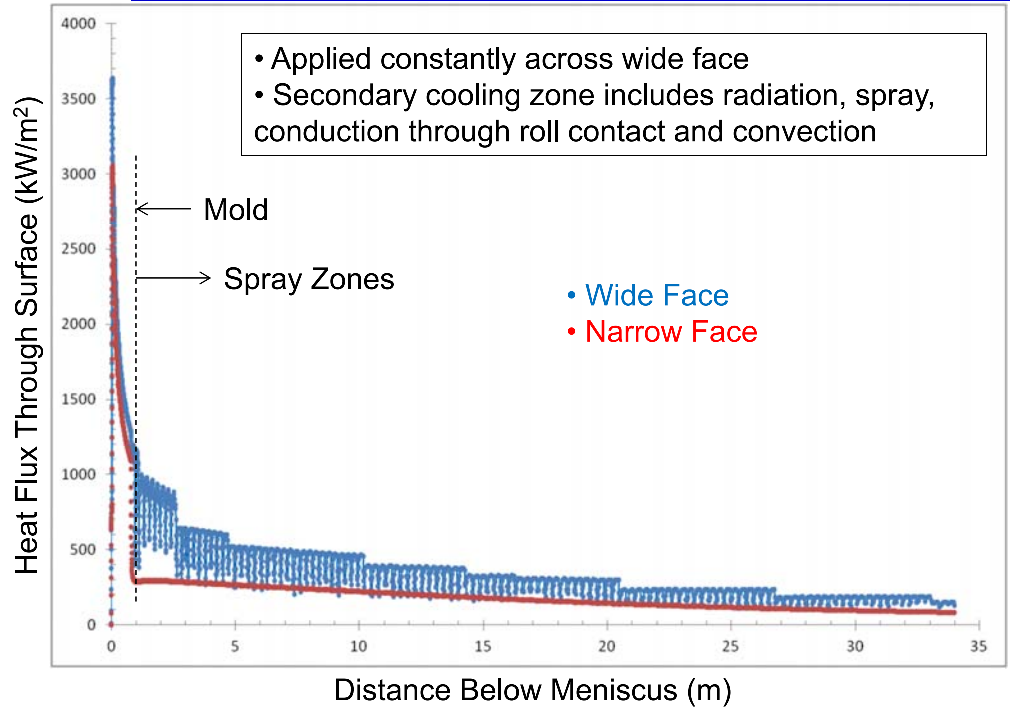
- 362 x 57 generalized plane-strain elements; approx. 2x2mm each



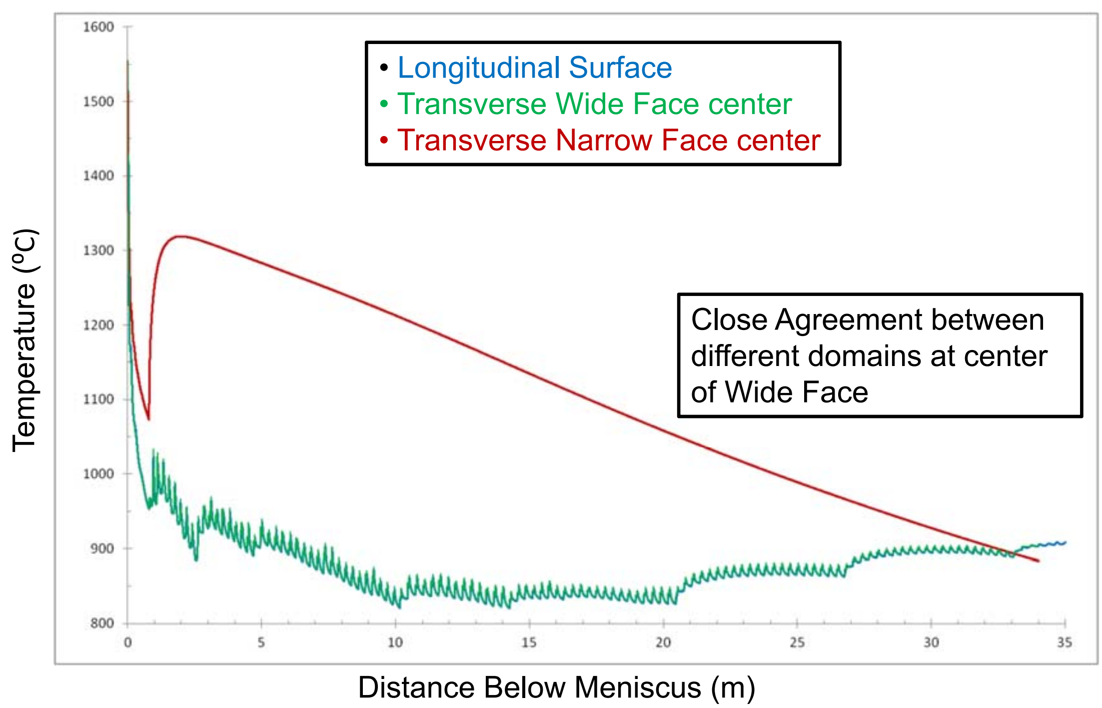
- Liquid region has 5 lines of 27 uncoupled elements each to allow liquid elements to expand and overlap to mimic the flow of liquid out of liquid pool domain



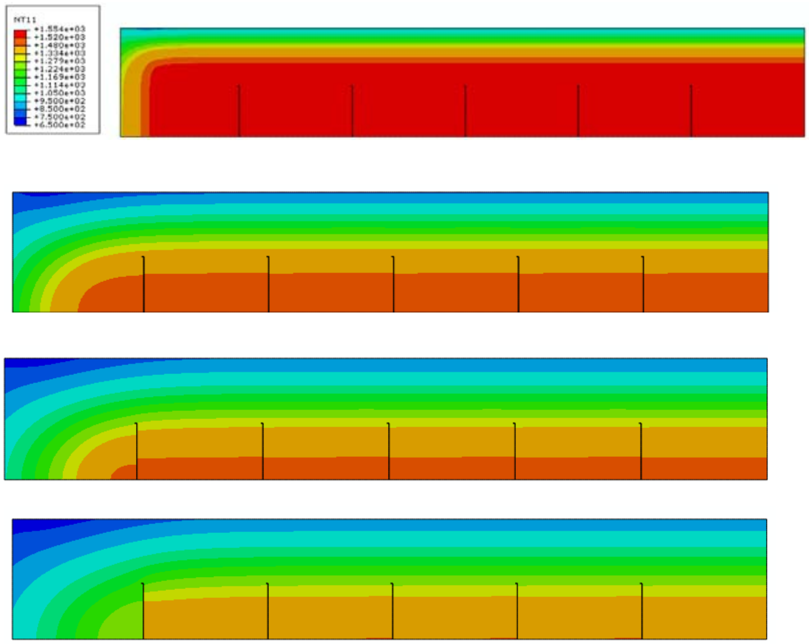
Applied Heat Fluxes



Surface Temperatures



Temperature Development



Spray Zone
100s, 2.83m

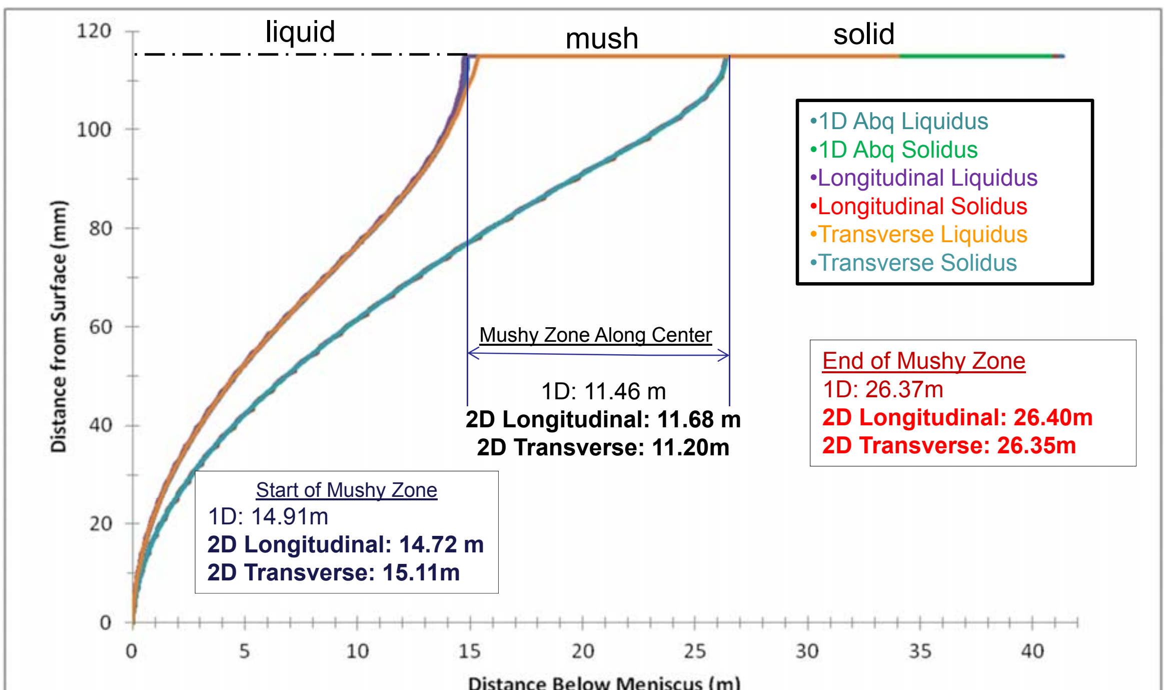
Red = Liquid
Orange = Mush

Liquid Pool End
532s, 15.1m

Mushy Zone
740s, 21.0m

Solidification End
932s, 26.4m

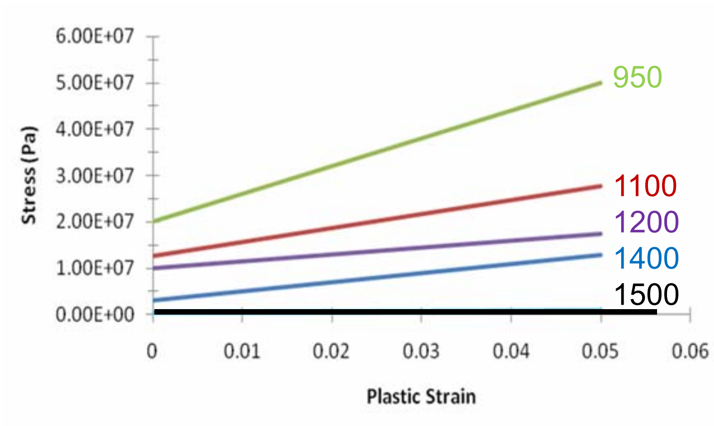
Longitudinal and Transverse Shell Comparison in Abaqus



Thermal-Elastic-Plastic Stress Analysis

(Temperature-Dependent Property Data in Abaqus)

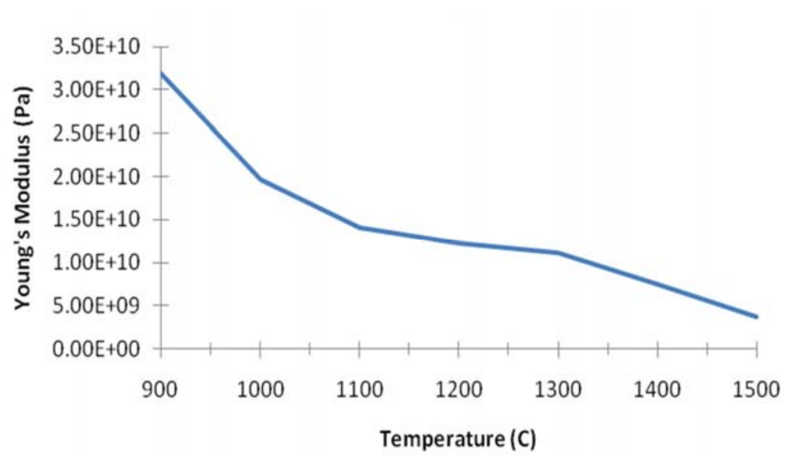
Yield Stress versus Plastic Strain data
For Elastic-Thermal-Plastic Analysis in Abaqus



Plastic Stress (Pa)	Plastic Strain	Temperature (C)
2.00E+07	0	950
5.00E+07	0.05	950
1.27E+07	0	1100
2.77E+07	0.05	1100
1.00E+07	0	1200
1.75E+07	0.05	1200
3.00E+06	0	1400
1.30E+07	0.05	1400
5.00E+05	0	1500
1.00E+06	0.05	1500

Elastic Modulus

(Temperature-Dependent Property Data in Abaqus)

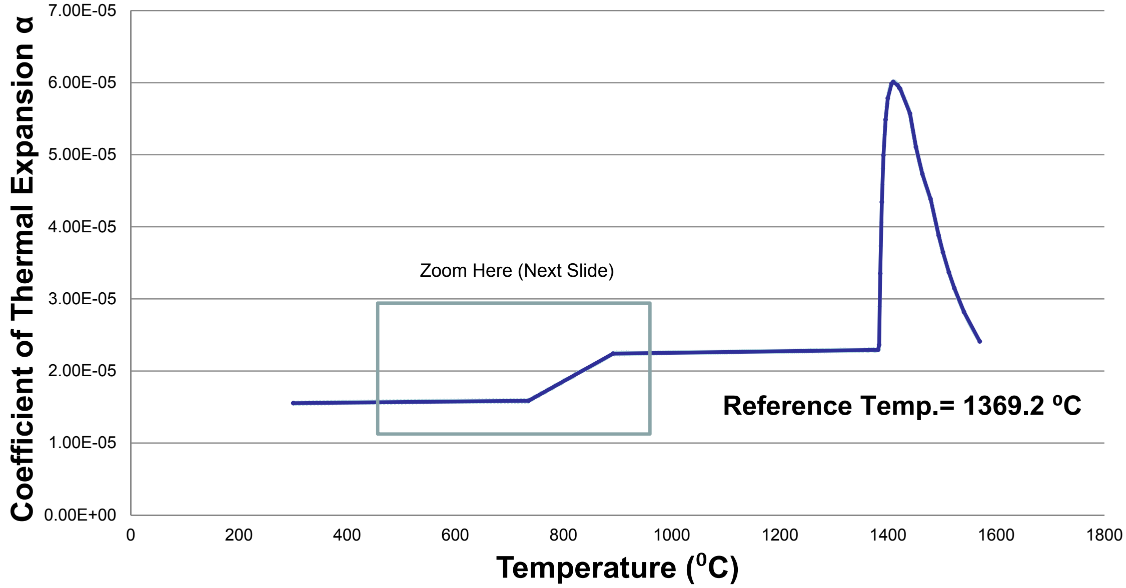


Young's Modulus (Pa)	Temperature (C)
3.20E+10	900
1.96E+10	1000
1.40E+10	1100
1.22E+10	1200
1.11E+10	1300
7.51E+09	1400
3.75E+09	1500

Poisson Ratio = 0.3

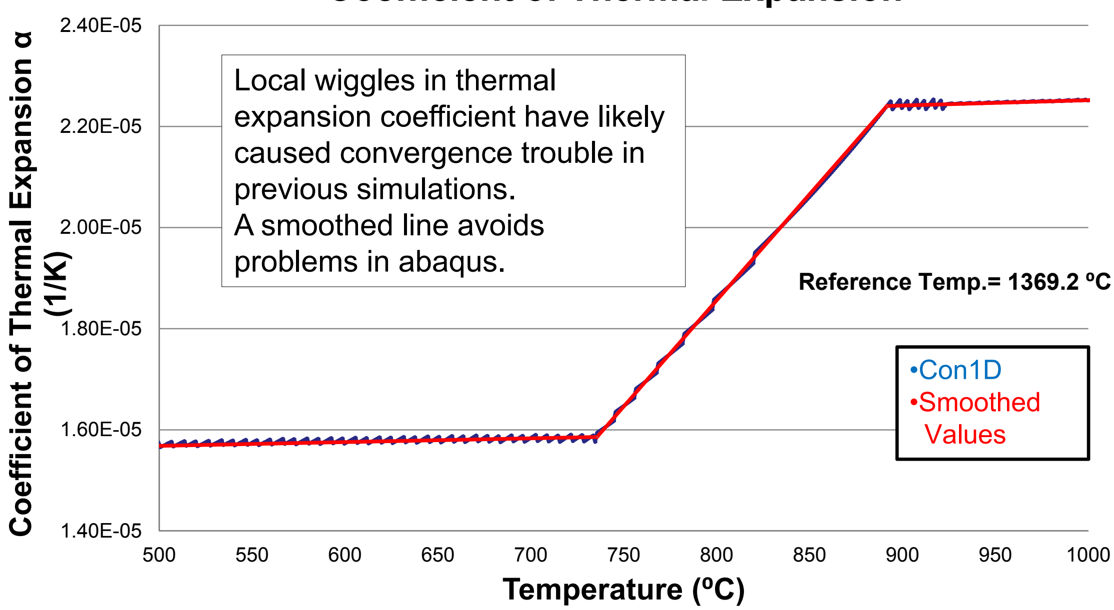
Thermal Expansion Coefficient

Coefficient of Thermal Expansion

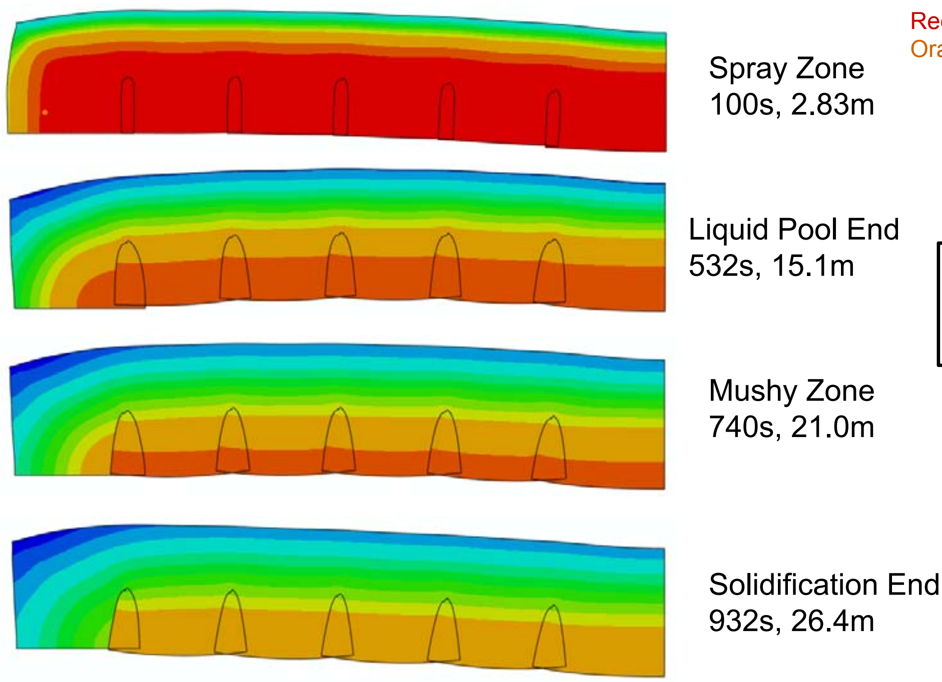


Variations in α

Coefficient of Thermal Expansion



Deformation

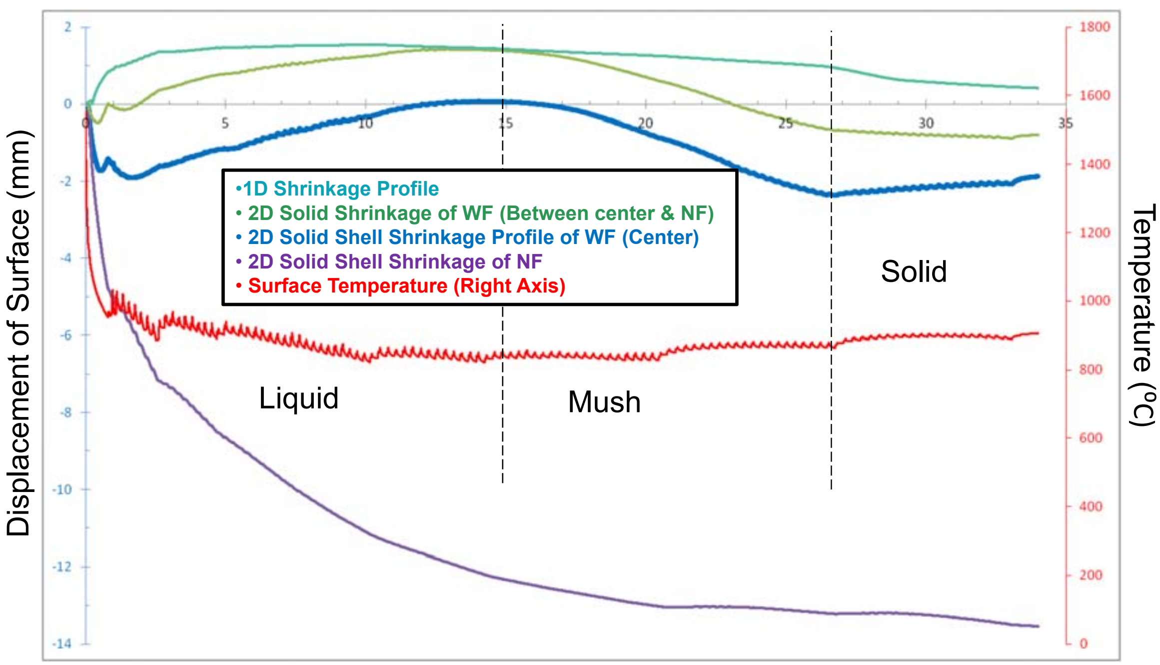


Red = Liquid
Orange = Mush

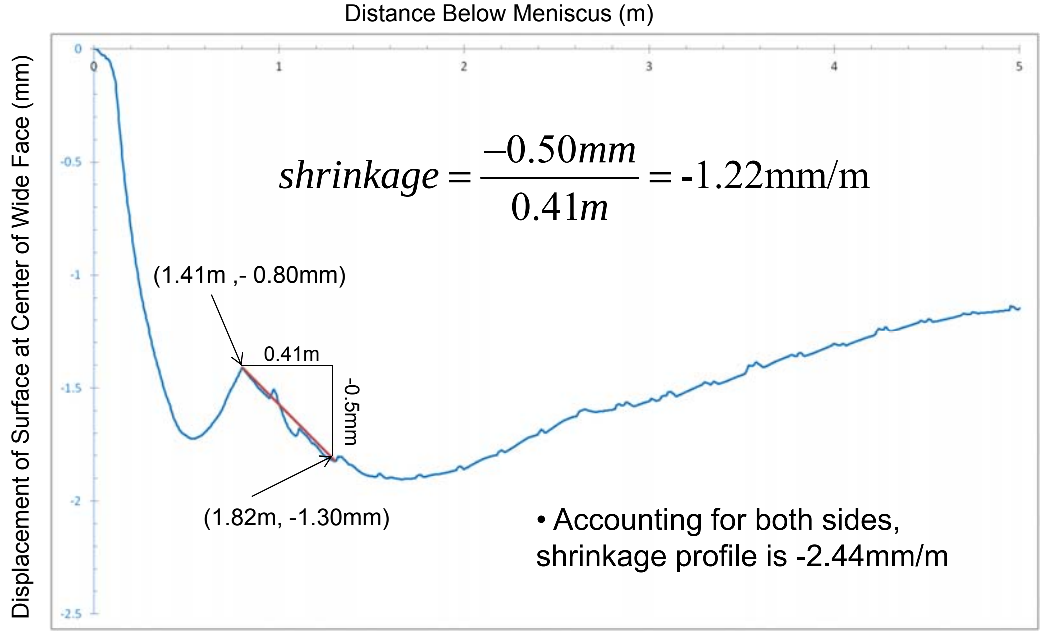
Deformation Scale Factor=10

Displacement of Surface

Ideal surface shape of 2D Wide Face = Machine taper / soft reduction profile



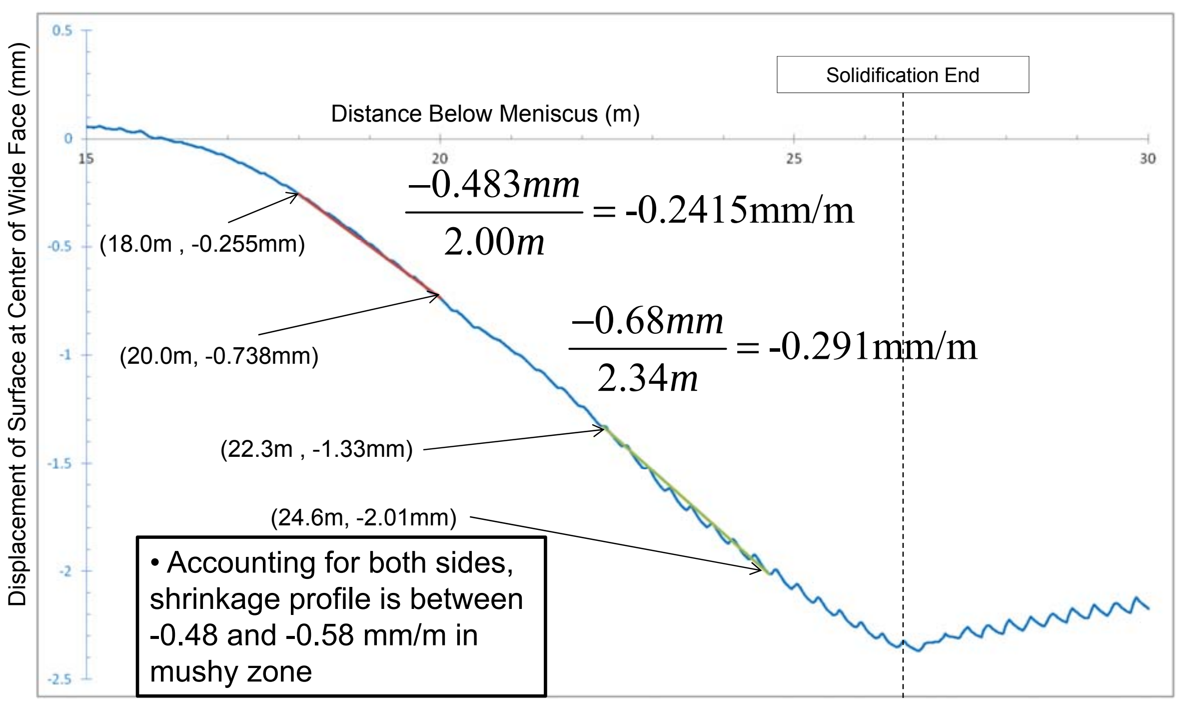
Shell Shrinkage After Mold Exit



$$shrinkage = \frac{-0.50mm}{0.41m} = \text{-1.22mm/m}$$

• Accounting for both sides, shrinkage profile is -2.44mm/m

Shell Shrinkage in Mushy Zone



$$\frac{-0.483mm}{2.00m} = \text{-0.2415mm/m}$$

$$\frac{-0.68mm}{2.34m} = \text{-0.291mm/m}$$

• Accounting for both sides, shrinkage profile is between -0.48 and -0.58 mm/m in mushy zone

Conclusion

- Rapid fluctuations in material properties may cause convergence problems in simulations
- One-dimensional simulation matches two-dimensional for high-Pe thermal problems
- Axial heat transfer is 100X smaller than radial heat flux near surface, but only 10X smaller in the liquid and solid center where temperature gradients are very small.
- Accelerated shrinkage occurs after liquid pool depth, before final solidification (in the mushy zone)

Future Work

- Two Dimensional Mechanical Model
  - Rollers modeled
  - Proper bending and rotation
  - Thorough stress analysis
- Three Dimensional thermal-mechanical model of shell in mushy zone (ignoring liquid)

  Calculating Soft Reduction Efficiency to account for NF Bulging, WF Bulging, and plasticity effects
- Analysis of liquid strain to determine volume displacement of liquid pool

Acknowledgements

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- Brian Thomas, UIUC