

Cooling and Solidification of Metal

Introduction

This example is a model of a continuous casting process. Liquid metal is poured into a mold of uniform cross section. The outside of the mold is cooled and the metal solidifies as it flows through the mold. When the metal leaves the mold, it is completely solidified on the outside but still liquid inside. The metal then continues to cool and eventually solidify completely, at which point it can be cut into sections. This tutorial simplifies the problem somewhat by not computing the flow field of the liquid metal and assuming there is no volume change during solidification. It is also assumed that the velocity of the metal is constant and uniform throughout the modeling domain. The phase transition from molten to solid state is modeled via the apparent heat capacity formulation. Issues of convergence and mesh refinement are addressed for this highly nonlinear model.

The Continuous Casting — Arbitrary Lagrangian-Eulerian Method model is similar to this one, except that the velocity is computed from the Laminar Flow interface instead of being considered constant and uniform. For a detailed description of the application, see Continuous Casting — Arbitrary Lagrangian-Eulerian Method.



Figure 1: A continuous casting process. The section where the metal is solidifying is being modeled.

Model Overview

The model simplifies the 3D geometry of the continuous casting to a 2D axisymmetric model composed of two rectangular regions: one representing the strand within the mold, and one the spray cooled region outside of the mold, prior to the saw cutoff. In the second section, there is also significant cooling via radiation to the ambient. In this region it is assumed that the molten metal is in a hydrostatic state, that the only motion in the fluid is due to the bulk downward motion of the strand. This simplification allows the assumption of bulk motion throughout the domain.

Since this is a continuous process, the system can be modeled at steady state. The heat transport is described by the equation:

$$\rho C_{p} \mathbf{u} \cdot \nabla T + \nabla \cdot (-k \nabla T) = 0$$

where k and C_p denote thermal conductivity and specific heat, respectively. The velocity, **u**, is the fixed casting speed of the metal in both liquid and solid states.

As the metal cools down in the mold, it solidifies. During the phase transition, a significant amount of latent heat is released. The total amount of heat released per unit mass of alloy during the transition is given by the change in enthalpy, ΔH . In addition, the specific heat capacity, C_p , also changes considerably during the transition.

As opposed to pure metals, an alloy generally undergoes a broad temperature transition zone, over several kelvins, in which a mixture of both solid and molten material coexist in a "mushy" zone. To account for the latent heat related to the phase transition, the Apparent Heat capacity method is used through the Heat Transfer with Phase Change domain condition. The objective of the analysis is to make ΔT , the half-width of the transition interval small, such that the solidification front location is well defined.

Table 1 reviews the material properties in this tutorial.

PROPERTY	SYMBOL	MELT	SOLID
Density	$\rho \text{ (kg/m}^3)$	8500	8500
Heat capacity at constant pressure	$C_p \; (J/(kg\cdot K))$	530	380
Thermal conductivity	k (W/(m⋅K))	150	300

TABLE I: MATERIAL PROPERTIES.

The melting temperature, $T_{\rm m}$, and enthalpy, ΔH , are 1356 K and 205 kJ/kg, respectively.

This example is a highly nonlinear problem and benefits from taking an iterative approach to finding the solution. The location of the transition between the molten and solid state is a strong function of the casting velocity, the cooling rate in the mold, and the cooling rate in the spray cooled region. A fine mesh is needed across the solidification front to resolve the change in material properties. However, it is not known where this front will be.

By starting with a gradual transition between liquid and solid, it is possible to find a solution even on a relatively coarse mesh. This solution can be used as the starting point for the next step in the solution procedure, which uses a sharper transition from liquid to solid. This is done using the continuation method. Given a monotonic list of values to solve for, the continuation method uses the solution to the last case as the starting condition for the next. Once a solution is found for the smallest desired ΔT , the adaptive mesh refinement algorithm is used to refine the mesh to put more elements around the transition region. This finer mesh is then used to find a solution with an even sharper transition. This can be repeated as needed to get better and better resolution of the location of the solidification front.

In this example, the parameter ΔT is first ramped down from 300 K to 75 K, then the adaptive mesh refinement is used such that a finer mesh is used around the solidification front. The resultant solution and mesh are then used as starting points for a second study, where the parameter ΔT is further ramped down from 50 K to 25 K.

Results and Discussion

The solidification front computed with the coarsest mesh, and for $\Delta T = 75$ K, is shown in Figure 2. A wide transition between the molten and solid state is observed. The adaptive mesh refinement algorithm then refines the mesh along the solidification front because this is the region where the results are strongly dependent upon mesh size. This solution, and refined mesh, are used as the starting point for the next solution, which ramps the ΔT parameter down to 25 K. These results are shown in Figure 3.

The point of complete solidification moves slightly as the transition zone is made smaller. As the transition zone becomes smaller, a finer mesh is needed, otherwise the model might not converge. If it is desired to get an even better resolution of the solidification front, the solution procedure used here should be repeated to get an even finer mesh, and further ramp down the ΔT parameter.

The solid phase fraction is plotted along the *r*-direction at the line at the bottom of the mold in Figure 4, and Figure 5 shows the solid fraction along the centerline of the strand.

For smaller values of ΔT , the transition becomes sharper, and the model gives confidence that the metal is completely solidified before the strand is cut.



Figure 2: The fraction of solid phase for $\Delta T = 75$ K shows a gradual transition between the liquid and solid phase.



Figure 3: The fraction of solid phase for $\Delta T = 25$ K shows a sharp transition between the liquid and solid phase.



Figure 4: The fraction of solid phase through the radius for all values of ΔT . For smaller values of ΔT , the transition is sharper.



Figure 5: The fraction of solid phase along the centerline for all values of ΔT . For smaller values of ΔT , the transition is sharper.

Application Library path: Heat_Transfer_Module/Thermal_Processing/ cooling_solidification_metal

Modeling Instructions

From the File menu, choose New.

NEW

In the New window, click 🚳 Model Wizard.

MODEL WIZARD

- I In the Model Wizard window, click 🕋 2D Axisymmetric.
- 2 In the Select Physics tree, select Heat Transfer>Heat Transfer in Fluids (ht).
- 3 Click Add.
- 4 Click \bigcirc Study.

5 In the Select Study tree, select General Studies>Stationary.

6 Click 🗹 Done.

GLOBAL DEFINITIONS

First, set up the parameters and variables needed for this simulation of a continuous casting process.

Parameters 1

I In the Model Builder window, under Global Definitions click Parameters I.

- 2 In the Settings window for Parameters, locate the Parameters section.
- **3** Click **b** Load from File.
- **4** Browse to the model's Application Libraries folder and double-click the file cooling_solidification_metal_parameters.txt.

GEOMETRY I

Create two rectangles representing the strand within the mold, and the spray cooled region outside of the mold.

Rectangle 1 (r1)

- I In the Geometry toolbar, click Rectangle.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- **3** In the **Width** text field, type **0.1**.
- 4 In the **Height** text field, type 0.6.

Rectangle 2 (r2)

- I In the **Geometry** toolbar, click Rectangle.
- 2 In the Settings window for Rectangle, locate the Size and Shape section.
- **3** In the **Width** text field, type **0.1**.
- 4 In the **Height** text field, type 0.2.
- 5 Locate the **Position** section. In the **z** text field, type 0.6.
- 6 Click 🟢 Build All Objects.



MATERIALS

Solid Metal Alloy

- I In the Materials toolbar, click **Blank Material**.
- 2 In the Settings window for Material, type Solid Metal Alloy in the Label text field.

3	Locate the Mate	rial Contents section.	In the table	, enter the f	ollowing	settings
				,		

Property	Variable	Value	Unit	Property group
Heat capacity at constant pressure	Ср	Cp_S	J/(kg·K)	Basic
Density	rho	8500	kg/m³	Basic
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	300	W/(m·K)	Basic

Liquid Metal Alloy

- I In the Materials toolbar, click 🚦 Blank Material.
- 2 In the Settings window for Material, type Liquid Metal Alloy in the Label text field.
- 3 Click in the Graphics window and then press Ctrl+A to select both domains.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Heat capacity at constant pressure	Ср	Cp_L	J/(kg·K)	Basic
Density	rho	8500	kg/m³	Basic
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	150	W/(m·K)	Basic

Set up the physics.

HEAT TRANSFER IN FLUIDS (HT)

Initial Values 1

- I In the Model Builder window, under Component I (compl)>Heat Transfer in Fluids (ht) click Initial Values I.
- 2 In the Settings window for Initial Values, locate the Initial Values section.
- **3** In the *T* text field, type T_in.

Fluid I

- I In the Model Builder window, click Fluid I.
- 2 In the Settings window for Fluid, locate the Heat Convection section.
- **3** Specify the **u** vector as

0		r
- V	cast	z

Phase Change Material I

- I In the Physics toolbar, click Attributes and choose Phase Change Material.
- 2 In the Settings window for Phase Change Material, locate the Phase Change section.
- **3** In the $T_{\text{pc},1\rightarrow 2}$ text field, type T_m.
- **4** In the $\Delta T_{1 \rightarrow 2}$ text field, type dT.
- **5** In the $L_{1 \rightarrow 2}$ text field, type dH.
- 6 Locate the Phase I section. From the Material, phase I list, choose Solid Metal Alloy (mat1).
- 7 Locate the Phase 2 section. From the Material, phase 2 list, choose Liquid Metal Alloy (mat2).

Inflow I

- I In the Physics toolbar, click Boundaries and choose Inflow.
- **2** Select Boundary 5 only.



3 In the Settings window for Inflow, locate the Upstream Properties section.

4 In the T_{ustr} text field, type T_in.

Heat Flux 1

I In the Physics toolbar, click — Boundaries and choose Heat Flux.





- 3 In the Settings window for Heat Flux, locate the Heat Flux section.
- 4 From the Flux type list, choose Convective heat flux.
- **5** In the *h* text field, type h_mold.
- **6** In the T_{ext} text field, type T0.

Heat Flux 2

I In the Physics toolbar, click — Boundaries and choose Heat Flux.

2 Select Boundary 6 only.



- 3 In the Settings window for Heat Flux, locate the Heat Flux section.
- 4 From the Flux type list, choose Convective heat flux.
- **5** In the *h* text field, type h_spray.
- **6** In the T_{ext} text field, type T0.

Surface-to-Ambient Radiation I

- I In the Physics toolbar, click Boundaries and choose Surface-to-Ambient Radiation.
- **2** Select Boundary 6 only.
- **3** In the Settings window for Surface-to-Ambient Radiation, locate the Surface-to-Ambient Radiation section.
- **4** From the ε list, choose **User defined**. In the associated text field, type eps_s.
- **5** In the T_{amb} text field, type T0.

Outflow I

I In the Physics toolbar, click — Boundaries and choose Outflow.

2 Select Boundary 2 only.



MESH I



2 In the Settings window for Mesh, locate the Physics-Controlled Mesh section.

3 From the Element size list, choose Extremely fine.

STUDY I

- I In the Model Builder window, click Study I.
- 2 In the Settings window for Study, locate the Study Settings section.
- 3 Clear the Generate default plots check box.

Step 1: Stationary

Set up an auxiliary continuation sweep for the dT parameter.

- I In the Model Builder window, under Study I click Step I: Stationary.
- 2 In the Settings window for Stationary, click to expand the Study Extensions section.
- **3** Select the **Auxiliary sweep** check box.
- 4 Click + Add.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
dT (Temperature transition zone half width)	300 200 150 100 75	К

- 6 Click to expand the Adaptation and Error Estimates section. From the Adaptation and error estimates list, choose Adaptation and error estimates.
- 7 Find the Mesh adaptation subsection. From the Adaptation method list, choose Rebuild mesh.
- 8 In the Home toolbar, click **=** Compute.

RESULTS

Solid and Liquid Phases (Adaptive Mesh)

- I In the Home toolbar, click 🚛 Add Plot Group and choose 2D Plot Group.
- 2 In the Settings window for 2D Plot Group, type Solid and Liquid Phases (Adaptive Mesh) in the Label text field.

Surface 1

- I In the Solid and Liquid Phases (Adaptive Mesh) toolbar, click Surface.
- In the Settings window for Surface, click Replace Expression in the upper-right corner of the Expression section. From the menu, choose Component I (compl)>
 Heat Transfer in Fluids>Phase change>ht.thetal Phase indicator, phase I.
- 3 In the Solid and Liquid Phases (Adaptive Mesh) toolbar, click 💿 Plot.

The reproduced figure describes the fraction of solid phase for $\Delta T = 75$ K.

ADD STUDY

- I In the Home toolbar, click $\sim\sim$ Add Study to open the Add Study window.
- 2 Go to the Add Study window.
- 3 Find the Studies subsection. In the Select Study tree, select General Studies>Stationary.
- 4 Click Add Study in the window toolbar.
- 5 In the Home toolbar, click ~ 2 Add Study to close the Add Study window.

STUDY 2

- I In the Model Builder window, click Study 2.
- 2 In the Settings window for Study, locate the Study Settings section.

3 Clear the Generate default plots check box.

Step 1: Stationary

- I In the Model Builder window, under Study 2 click Step I: Stationary.
- **2** In the **Settings** window for **Stationary**, click to expand the **Values of Dependent Variables** section.
- **3** Find the **Initial values of variables solved for** subsection. From the **Settings** list, choose **User controlled**.
- 4 From the Method list, choose Solution.
- 5 From the Study list, choose Study I, Stationary.
- 6 From the Solution list, choose Adaptive Mesh Refinement Solutions I (sol2).
- 7 From the Use list, choose Level 2 Refined Solution 5 (sol5).
- 8 From the Parameter value (dT (K)) list, choose 75 K.
- **9** Click to expand the **Mesh Selection** section. Locate the **Study Extensions** section. Select the **Auxiliary sweep** check box.
- IO Click + Add.

II In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
dT (Temperature transition zone	50 25	К
half width)		

Solution 6 (sol6)

I In the Study toolbar, click **The Show Default Solver**.

Use a tighter relative tolerance to capture the phase change effect also for the small phase transition temperature interval.

- 2 In the Model Builder window, expand the Solution 6 (sol6) node, then click Stationary Solver 1.
- 3 In the Settings window for Stationary Solver, locate the General section.
- 4 In the **Relative tolerance** text field, type 1e-5.
- **5** In the **Study** toolbar, click **= Compute**.

RESULTS

Solid and Liquid Phases

I In the Home toolbar, click 🚛 Add Plot Group and choose 2D Plot Group.

- 2 In the Settings window for 2D Plot Group, type Solid and Liquid Phases in the Label text field.
- 3 Locate the Data section. From the Dataset list, choose Study 2/Solution 6 (sol6).

Surface 1

- I In the Solid and Liquid Phases toolbar, click Surface.
- In the Settings window for Surface, click Replace Expression in the upper-right corner of the Expression section. From the menu, choose Component I (compl)>
 Heat Transfer in Fluids>Phase change>ht.thetal Phase indicator, phase I.
- 3 In the Solid and Liquid Phases toolbar, click 🗿 Plot.

This shows the fraction of solid phase for $\Delta T = 25$ K.

Phase Indicator at Symmetry Axis

- I In the Home toolbar, click 🚛 Add Plot Group and choose ID Plot Group.
- 2 In the Settings window for ID Plot Group, type Phase Indicator at Symmetry Axis in the Label text field.

Line Graph I

- I In the Phase Indicator at Symmetry Axis toolbar, click 📐 Line Graph.
- 2 Select Boundaries 1 and 3 only.
- 3 In the Settings window for Line Graph, click Replace Expression in the upper-right corner of the y-Axis Data section. From the menu, choose Component I (compl)> Heat Transfer in Fluids>Phase change>ht.thetal Phase indicator, phase I.
- 4 Locate the x-Axis Data section. From the Parameter list, choose Expression.
- **5** In the **Expression** text field, type **z**.
- 6 Click to expand the Legends section. Select the Show legends check box.

Line Graph 2

- I Right-click Line Graph I and choose Duplicate.
- 2 In the Settings window for Line Graph, locate the Data section.
- 3 From the Dataset list, choose Study 2/Solution 6 (sol6).
- 4 Click to expand the Title section. From the Title type list, choose None.
- 5 In the Phase Indicator at Symmetry Axis toolbar, click on Plot.

Compare the resulting plot with Figure 5 showing the fraction of solid phase through the centerline for all values of Δ T.

Phase Indicator through Radius

- I In the Model Builder window, right-click Phase Indicator at Symmetry Axis and choose Duplicate.
- 2 In the Settings window for ID Plot Group, type Phase Indicator through Radius in the Label text field.

Line Graph 1

- I In the Model Builder window, expand the Phase Indicator through Radius node, then click Line Graph I.
- 2 In the Settings window for Line Graph, locate the Selection section.
- 3 Click Clear Selection.
- 4 Select Boundary 4 only.
- 5 Locate the x-Axis Data section. In the Expression text field, type r.
- 6 In the Phase Indicator through Radius toolbar, click 🗿 Plot.

Line Graph 2

- I In the Model Builder window, click Line Graph 2.
- 2 In the Settings window for Line Graph, locate the Selection section.
- 3 Click Clear Selection.
- **4** Select Boundary 4 only.
- 5 Locate the x-Axis Data section. In the Expression text field, type r.

Phase Indicator through Radius

- I In the Model Builder window, click Phase Indicator through Radius.
- 2 In the Settings window for ID Plot Group, locate the Legend section.
- 3 From the Position list, choose Upper left.
- 4 In the Phase Indicator through Radius toolbar, click on Plot.

Compare the resulting plot with Figure 4 showing the fraction of solid phase through the radius for all values of Δ T.

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