TAPER PREDICTION IN SLAB AND THIN SLAB CASTING MOLDS

Claudio Ojeda

Department of Mechanical Engineering
University of Illinois at Urbana-Champaign

October 15, 2002

Introduction

- **Taper plays an important role to ensure good contact and heat exchange between mold wall and shell surface.**
  - **Shell growth uniformity**

- **Problems**
  - **Excessive taper causes:**
    - ☞ Narrow face wearing.
    - ☞ Extra tensile stress causes transverse cracking.
    - ☞ Buckling of the shell wide face, causes “gutter” and longitudinal cracks.
  - **Insufficient taper causes:**
    - ☞ Breakouts in the steel shell.
    - ☞ Bulging below mold causing subsurface longitudinal cracks.

Objectives

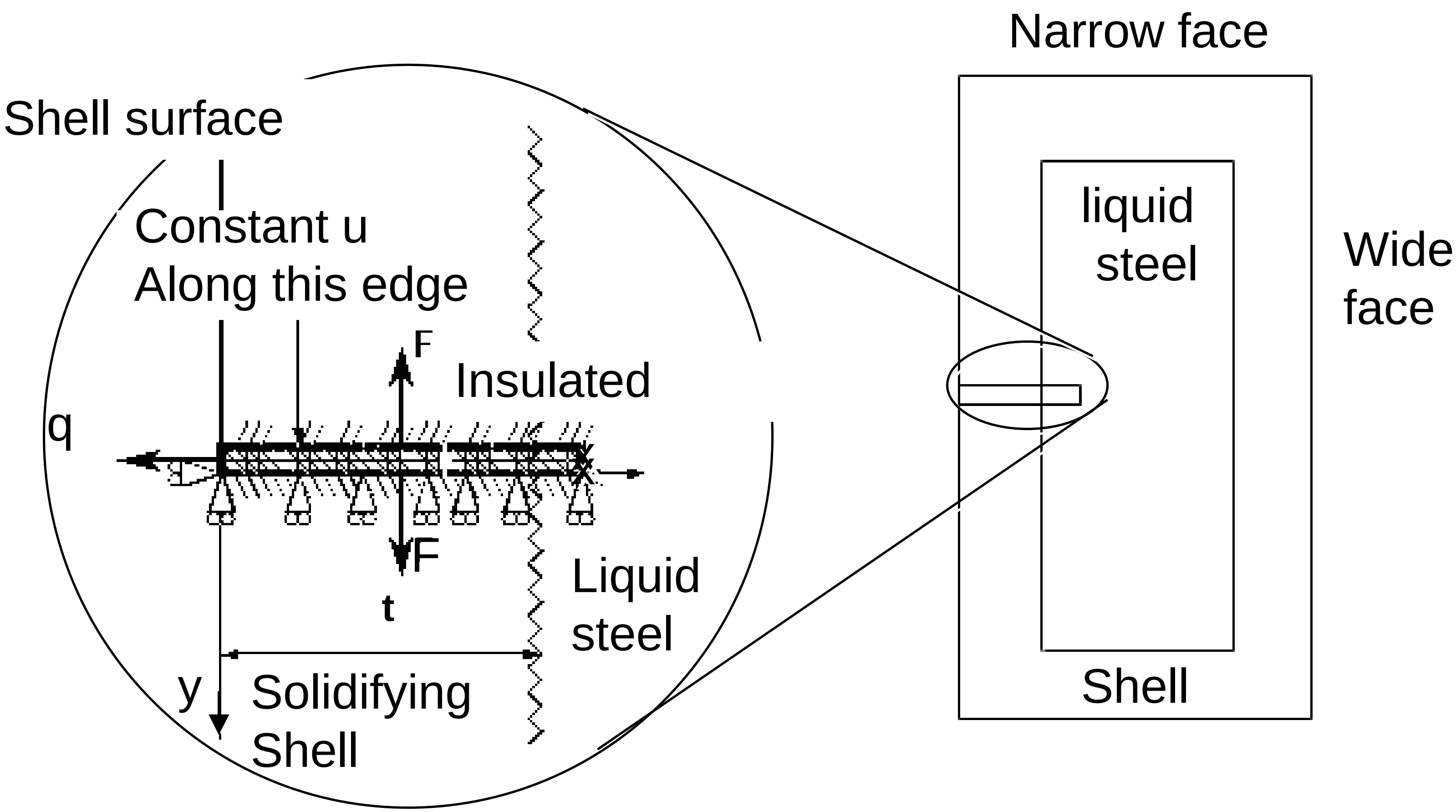
- Calculate ideal taper including the effects of:
  - Shell shrinkage
  - Mold distortion
  - Flux layer thickness
  - Funnel extra length (thin slabs)

- Investigate the effect of heat flux profile on Ideal Taper in conventional and thin slabs as affected by
  - Heat flux profile
  - Casting speed
  - Steel grade
  - Powder type
  - Mold length

Model description

- Finite difference heat transfer and solidification model (CON1D).
- 2D Finite element elastic-viscoplastic thermal-stress model (CON2D).
- 1D slice-domain representing the behavior of a longitudinal slice through the centerline of the shell moving down the mold.
- Heat flux boundary condition is applied in the shell surface.

Model description



Definition of ideal taper

- Billet molds

IT= Shell shrinkage(z) – (Mold distortion(z) – Mold distortion meniscus)

- Slab molds

IT= Shell shrinkage(z) – (Mold distortion(z) – Mold distortion meniscus)
– (flux thickness(z) – flux thickness meniscus)

- Thin slab molds

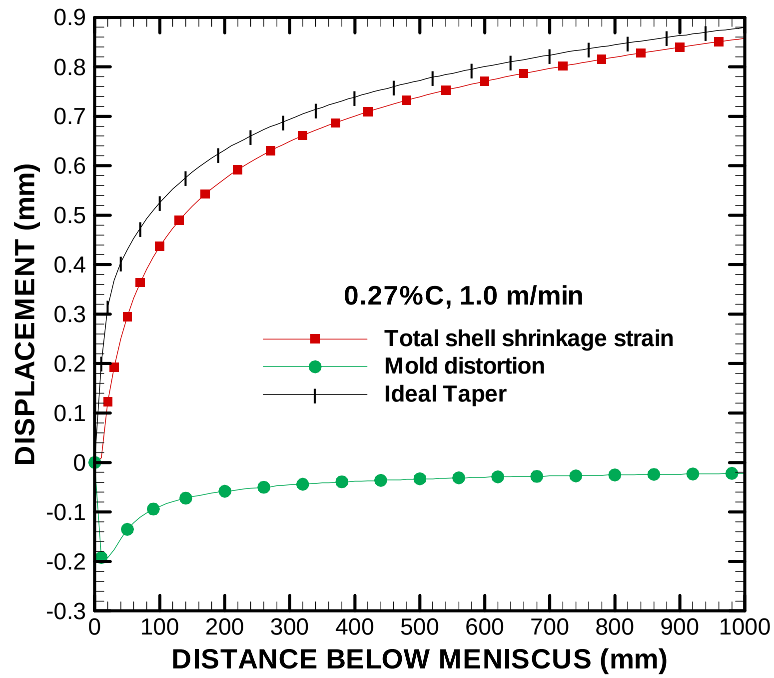
IT= Shell shrinkage(z) – (Mold distortion(z) – Mold distortion meniscus)
– (flux thickness(z) – flux thickness meniscus)
– (funnel extra length meniscus – funnel extra length(z))

Billet Mold distortion

Billet casting operating conditions

Mold geometry	
Slab width	120 mm
Slab thickness	120 mm
Mold height	1100 mm
Cu plate thickness	10.15 mm
Copper properties	
Thermal conductivity	360 W $m^{-1}K^{-1}$
Elastic modulus	117 Gpa
Poisson ratio	0.343
Thermal expansion coefficient	$16.0*10^{-6}K^{-1}$
Density	8940 kg m^{-3}
Operating conditions	
Pour temperature	1540 C
Water slot heat transfer coefficient	35 kW $m^{-2}K^{-1}$
Water temperature, T_w	30 C
Ambient temperature	25 C
Meniscus level (below top mold)	100 mm

- Samarasekera, Brimacombe, Ironmaking and Steel making, 1982, Vol. 9, Issue 1, pp 1-15



Slab Mold distortion

Mold distortion = Wide face expansion + Narrow face distortion

– Wide face expansion
  - ☞ Transmitted by clamping forces
  - ☞ Linearized temperatures of hot and cold plate faces

$$\Delta x_{WF} = \alpha_{mold}\left(\frac{moldwidth}{2}\right)\left(\frac{T_{coldmen} + T_{hotmen}}{2} - \frac{T_{cold} + T_{hot}}{2}\right)$$

– Narrow face distortion
  - ☞ Linearized temperatures of hot and cold plate faces
  - ☞ Water jacket stiffness

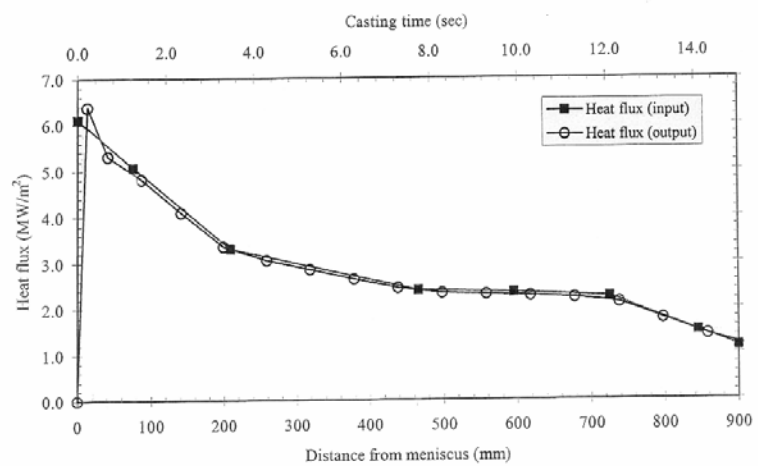
$$\Delta x_{NF} = \frac{3(\alpha_{hot} - \alpha_{cold})\left(\bar{T}_{hot} - \bar{T}_{cold}\right)(t_{hot} + t_{cold})}{t_{cold}^2 K_1}\left[Lx - x^2\right]$$

Validation of Thin-slab mold distortion

Thin Slab operating conditions

Mold geometry	
Slab width	1260 mm
Slab thickness	75 mm
Mold height	1000 mm
Cu plate thickness	60 mm
Water slot depth – shallow slots	35 mm
Water slot thickness	5 mm
Distance between most slots	4.6 mm
Copper properties	
Thermal conductivity	350 W $m^{-1}K^{-1}$
Elastic modulus	115 Gpa
Poisson ratio	0.34
Thermal expansion coefficient	$17.7*10^{-6}K^{-1}$
Density	8960 kg m^{-3}
Operating conditions	
Water slot heat transfer coefficient	38.45 kW $m^{-2}K^{-1}$
Water temperature, T_w	37.8 C
Ambient temperature	35 C
Meniscus level (below top mold)	100 mm

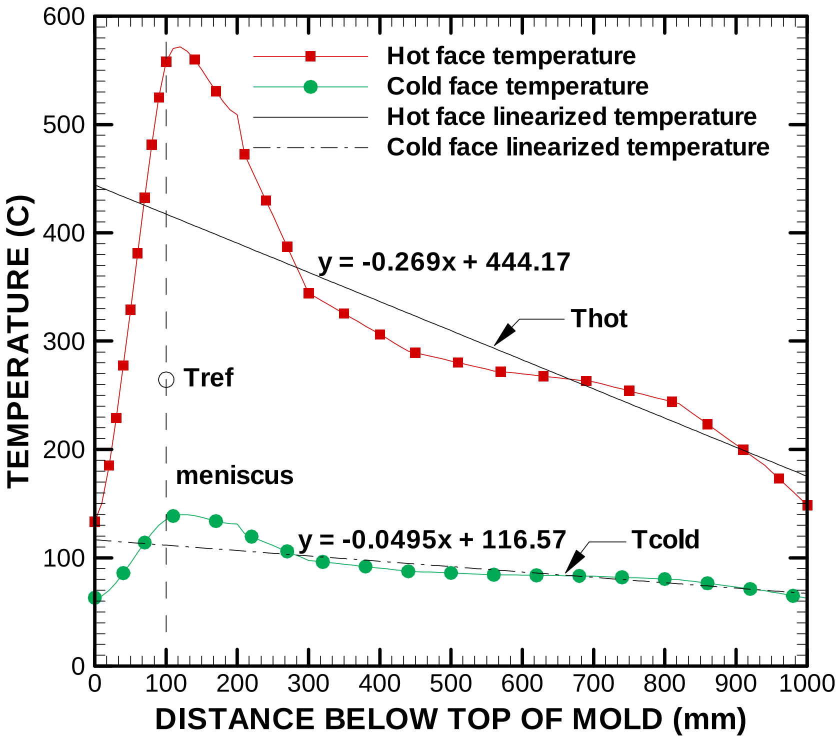
Heat flux profile

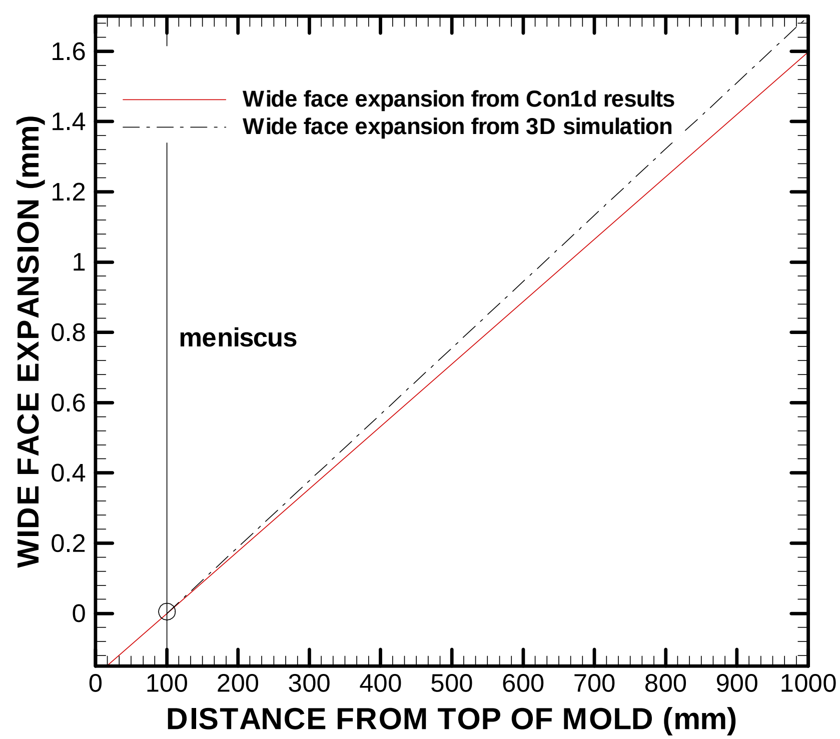


1. Joong Kil Park, Brian G. Thomas, Indira V. Samarasekera, and U. Sok Yoon, Metallurgical and Materials Transactions B, 2002, vol. 33B, pp 425-436.
2. Joong Kil Park, Brian G. Thomas, Indira V. Samarasekera, and U. Sok Yoon, Metallurgical and Materials Transactions B, 2002, vol. 33B, pp 437-449.

Validation of Thin-slab Mold distortion

Wide face temperature | Wide face expansion





Validation conventional slab mold distortion

Conventional Slab operating cond.

Mold geometry	
Slab width	914 mm
Slab thickness	220 mm
Mold height	700 mm
Cu plate thickness	60 mm
Water slot depth – shallow slots	25 mm
Water slot thickness	5 mm
Distance between most slots	35 mm
Copper properties	
Thermal conductivity	374 W $m^{-1}K^{-1}$
Elastic modulus	117 Gpa
Poisson ratio	0.343
Thermal expansion coefficient	$17.7*10^{-6}K^{-1}$
Density	8940 kg m^{-3}
Operating conditions	
Water slot heat transfer coefficient	35 kW $m^{-2}K^{-1}$
Water temperature, T_w	15 C
Ambient temperature	35 C
Meniscus level (below top mold)	84 mm

Heat flux profile

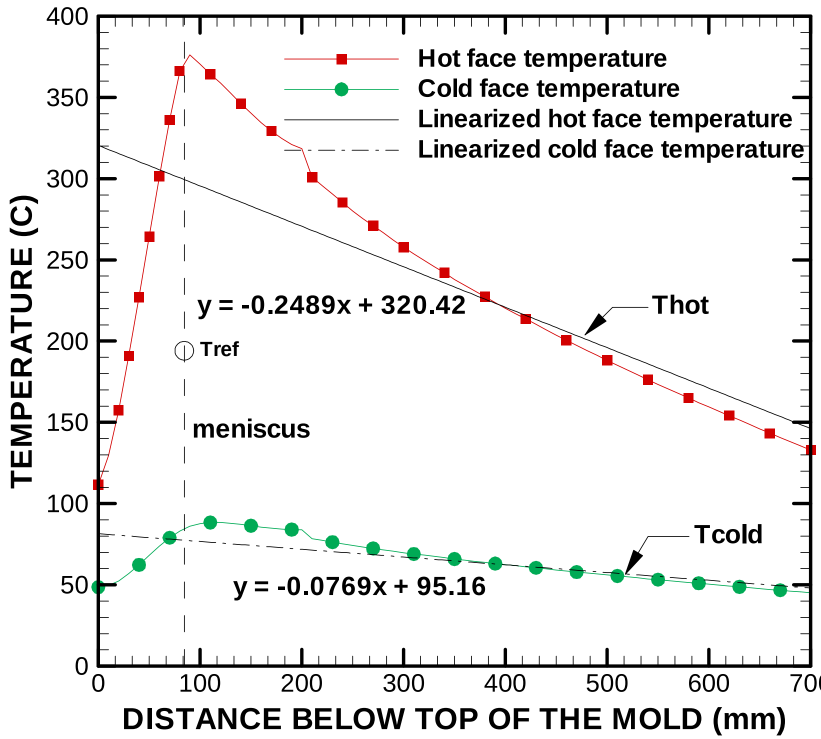
$$q = 2.68 - 31.9(0.084 - z) \qquad 0.0<z<0.084\text{m}$$

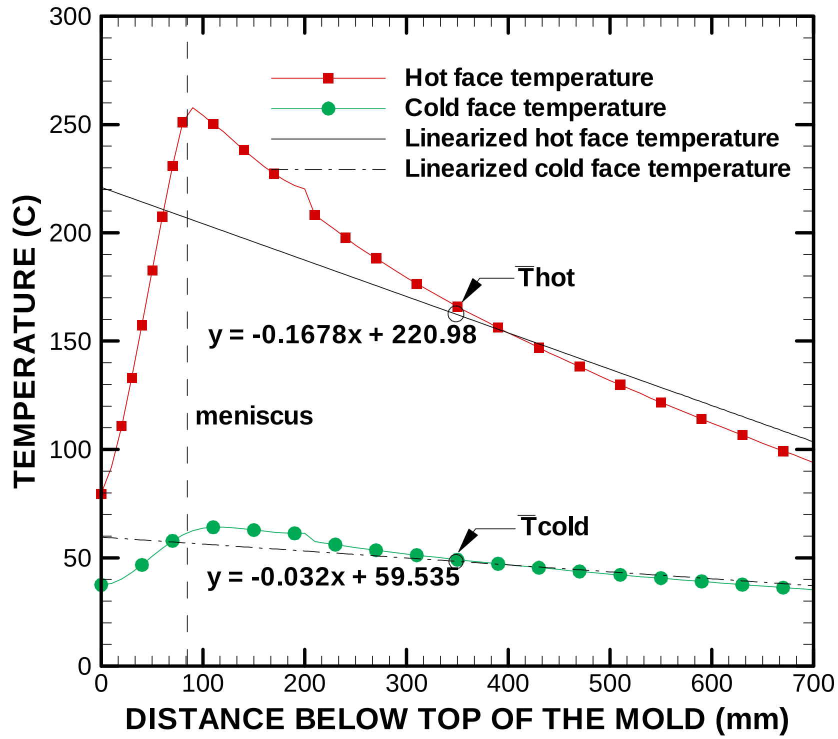
$$q = 2.68 - 2.58\sqrt{z - 0.084} \qquad 0.084<z<0.7\text{m}$$

B.G.Thomas, G. Li, A. Moitra and D. Habing: ISS transactions, October 1998, pp 125-143.

Validation conventional slab mold distortion

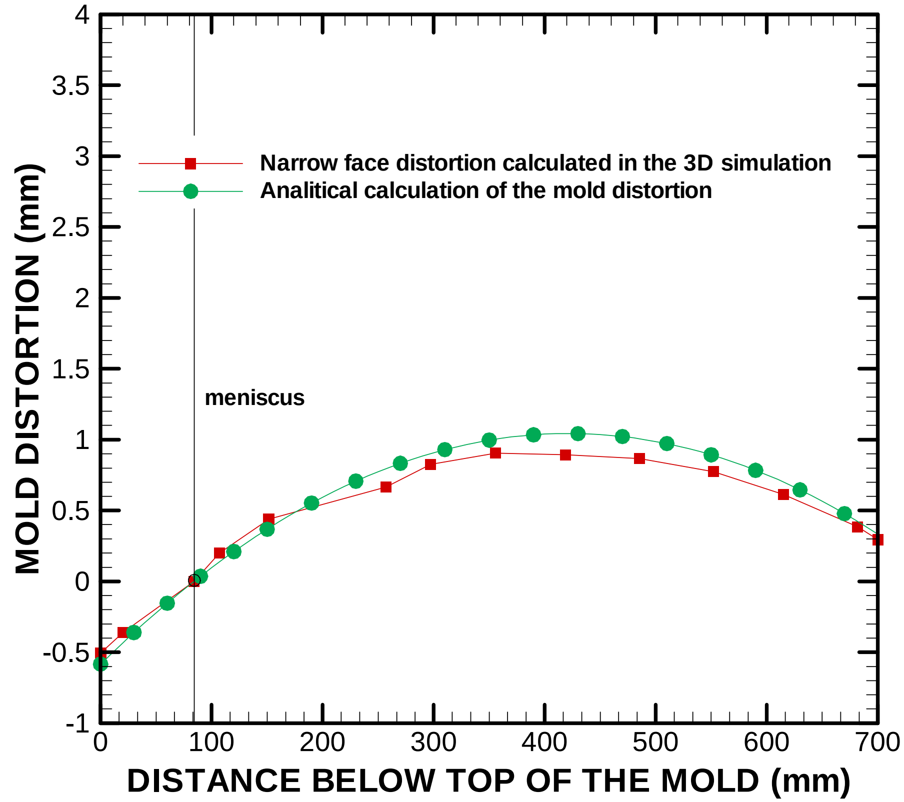
Wide face temperature   Narrow face temperature





Validation conventional slab mold distortion

Wide face expansion + Narrow face distortion



Shell shrinkage

- Heat flux profile
  - Importance of changes in meniscus area
- Casting speed
  - Increasing casting speed increases instantaneous and average heat flux but decreases time for shrinkage.
- Mold length
  - For the same conditions higher mold length causes higher shrinkage
- Steel grade
  - Differences between low, peritectic and high carbon content steels
- Mold Powder composition
  - Differences in solidification temperature

Effect of heat flux profile

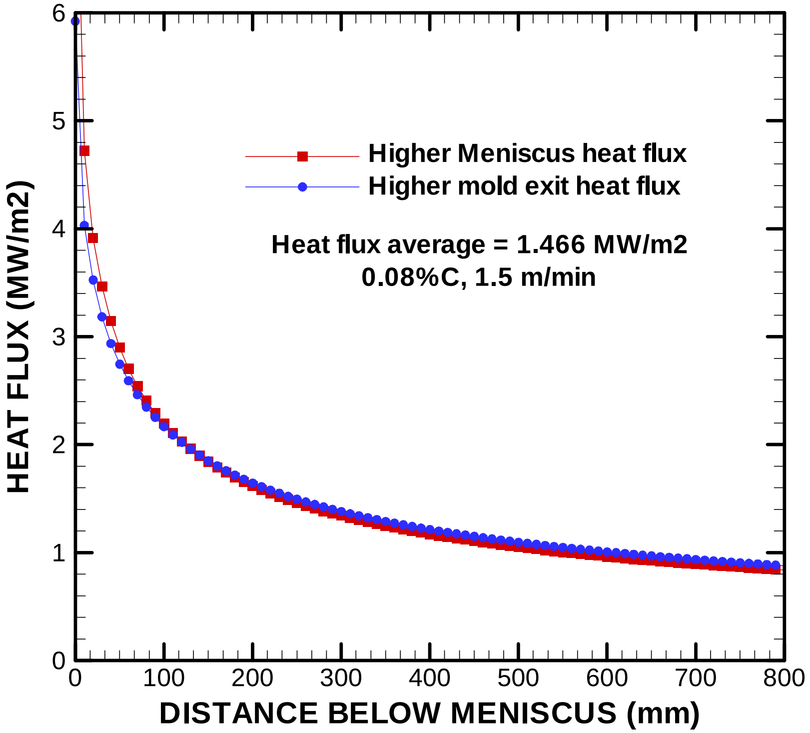
- Shell shrinkage controlled by heat flux profile.
- Higher heat flux causes more shrinkage.
- Shell shrinkage sensitive to minor changes specially near the meniscus.
- Mean heat flux determined with*:

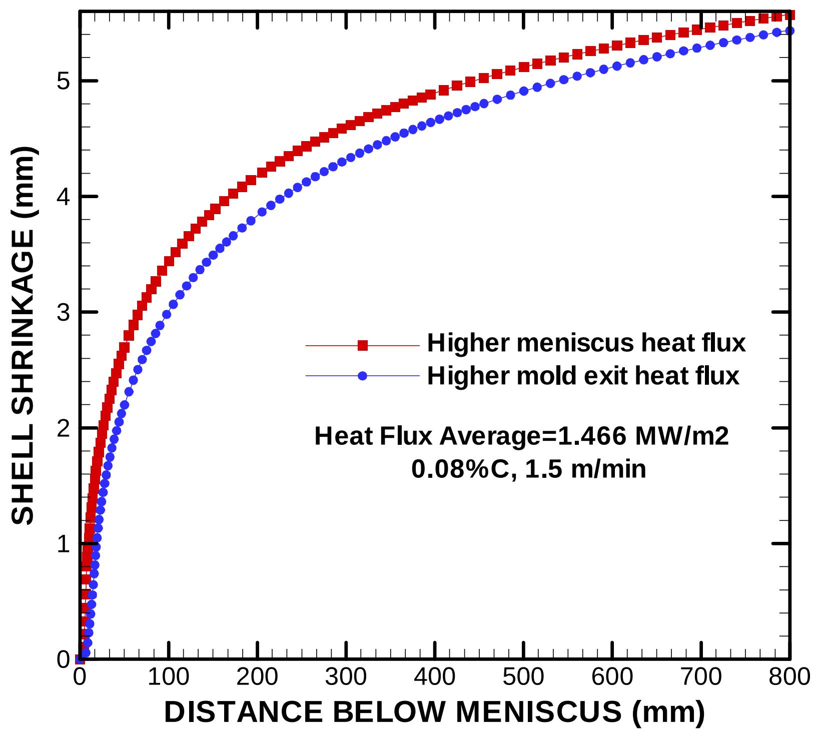
$$Q_G = 4.63 \cdot 10^6 \mu^{-0.09} T_{flow}^{-1.19} V_C^{0.47} \left\{ 1 - 0.152 \exp\left[-\left(\frac{0.107 - \%C}{0.027} \right)^2 \right] \right\}$$

Q_G is the mean heat flux (MW/m^2), μ is the powder viscosity at 1300 ^oC, (Pa-s), T_{flow} is the melting temperature of the mold flux (^oC), V_c is the casting speed (m/min), and %C is the carbon content

– *C. Cicutti, M. Valdez and T. Perez, "Mould Thermal Evaluation in a Slab Continuous Casting Machine," 85th Steelmaking Conference, (Nashville, TE, USA), Iron and Steel Society, Inc. (USA), Vol. 85, 2002, 97-107.

Effect of heat flux

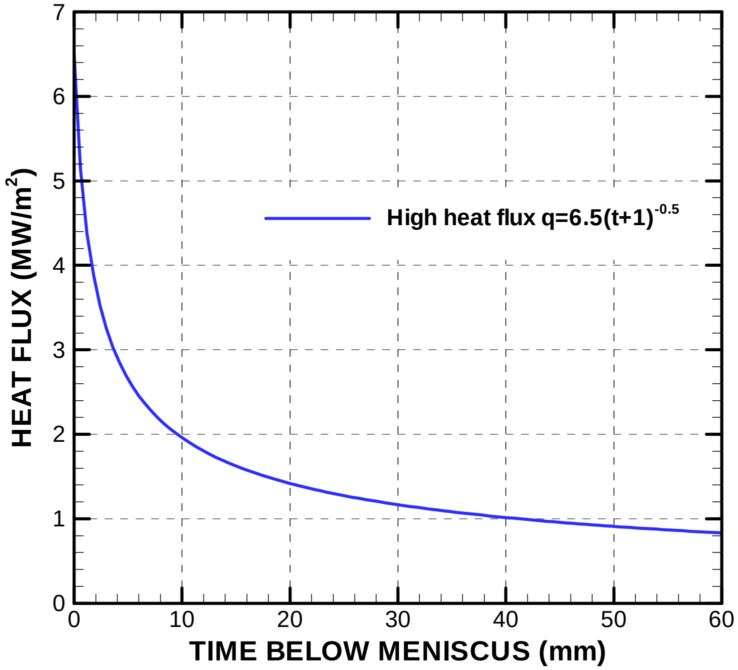


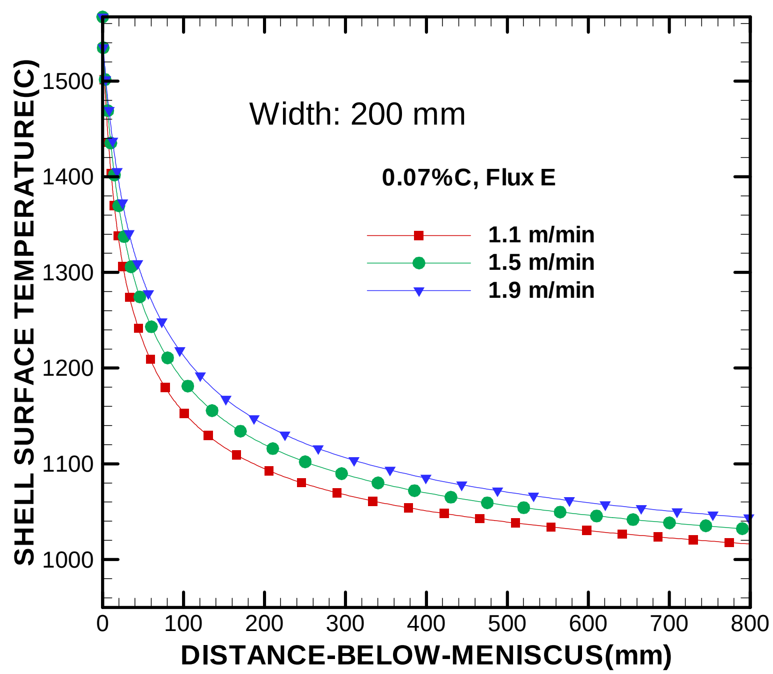


Effect of casting speed

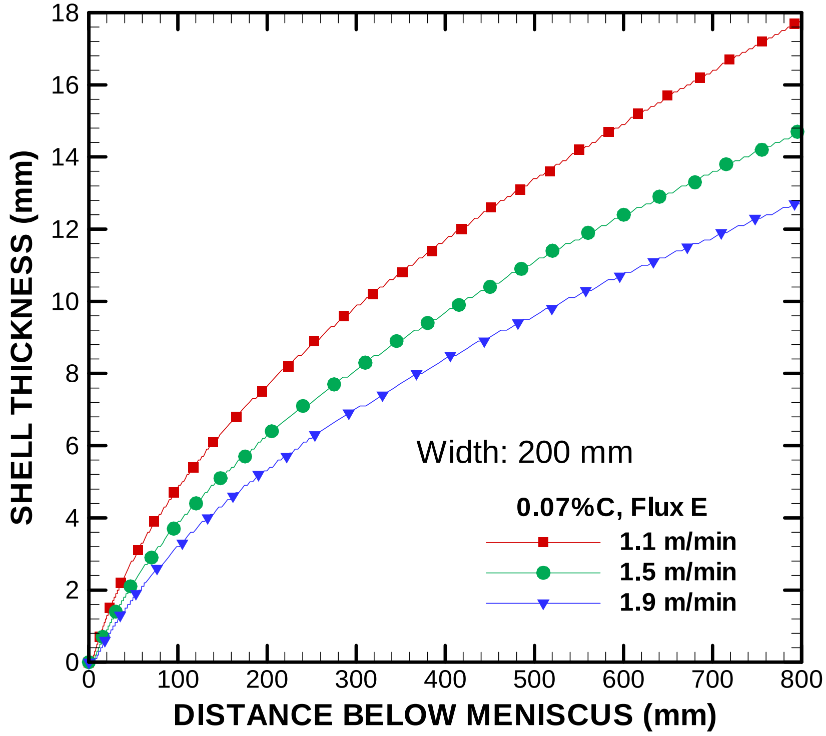
– Higher casting speed causes higher heat flux (more shrinkage) but less dwell time (less shrinkage).

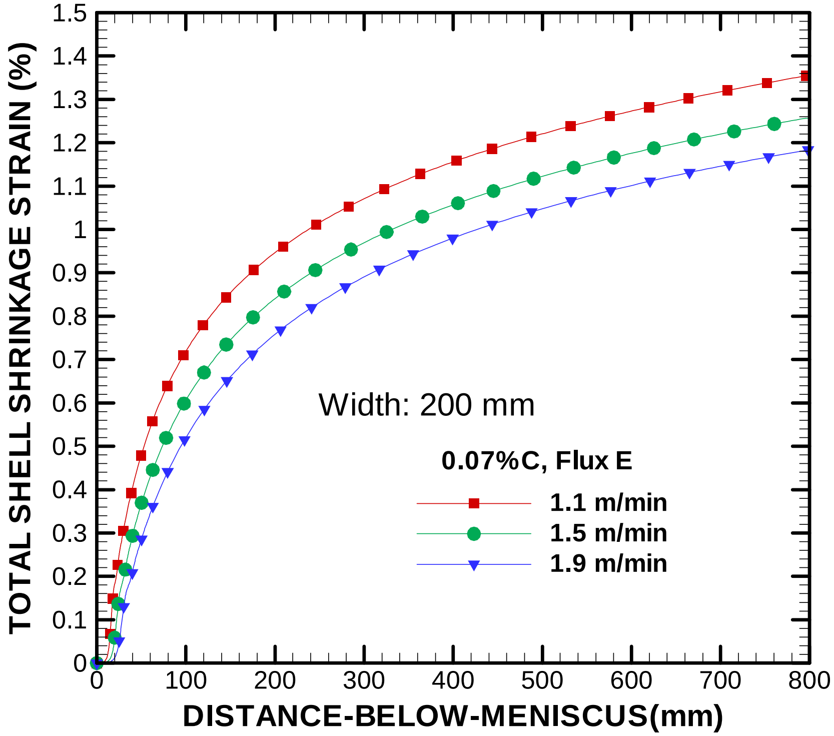
Net effect: less shrinkage





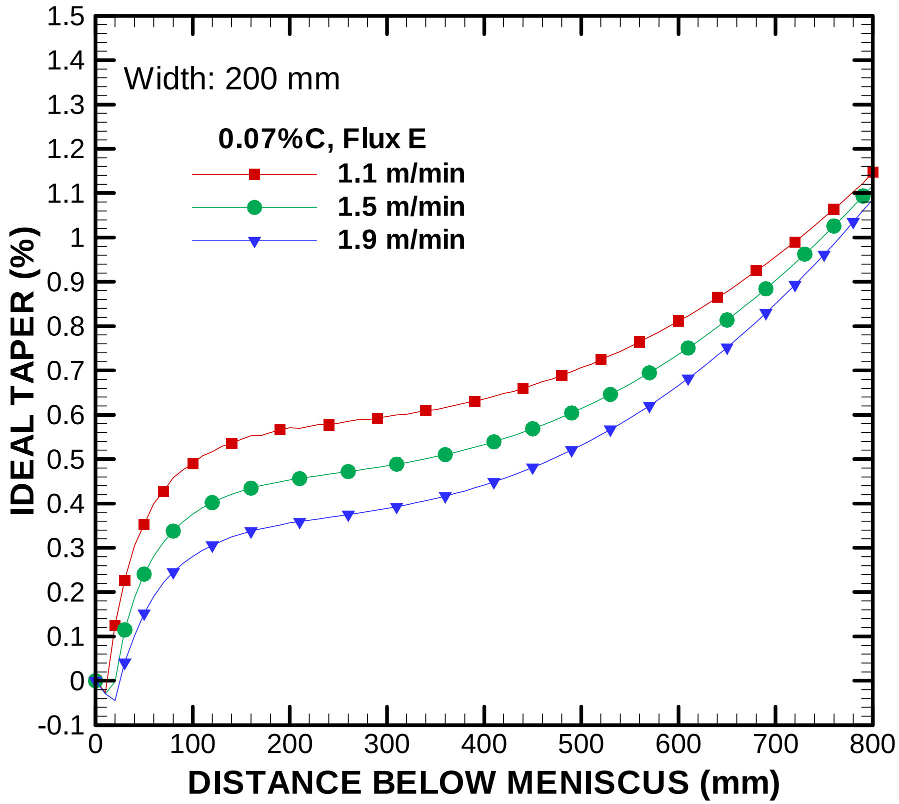
Effect of casting speed





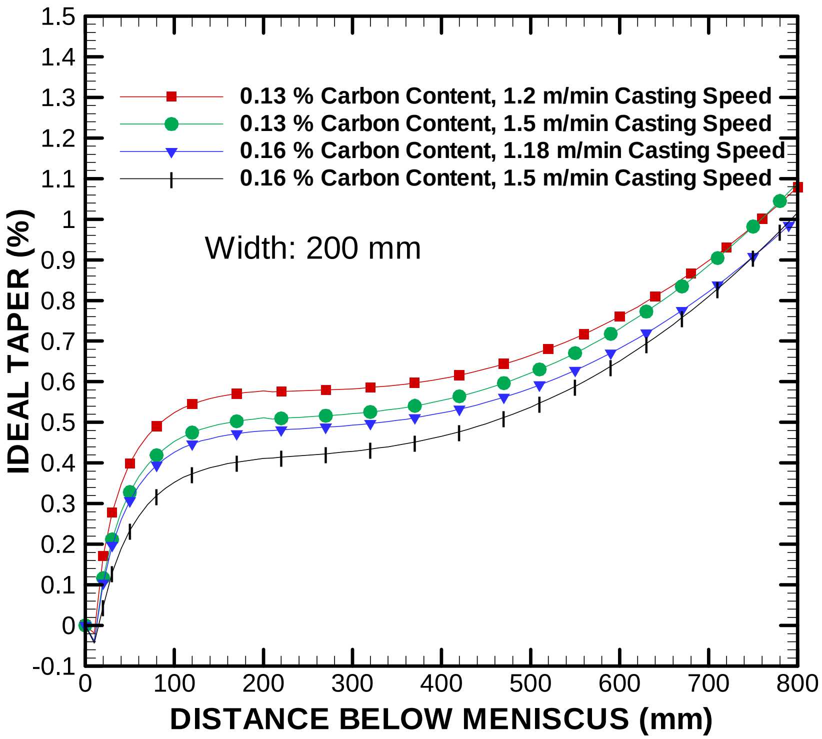
Effect of casting speed

- Effect of casting speed on Ideal taper

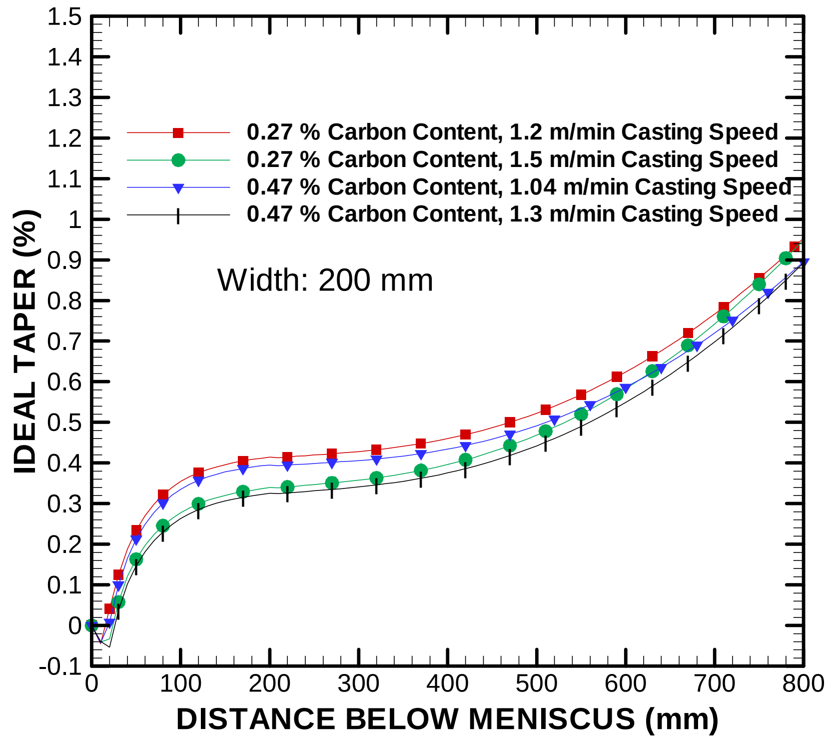


Effect of casting speed

Peritectic steels



High carbon steels



Effect of casting speed

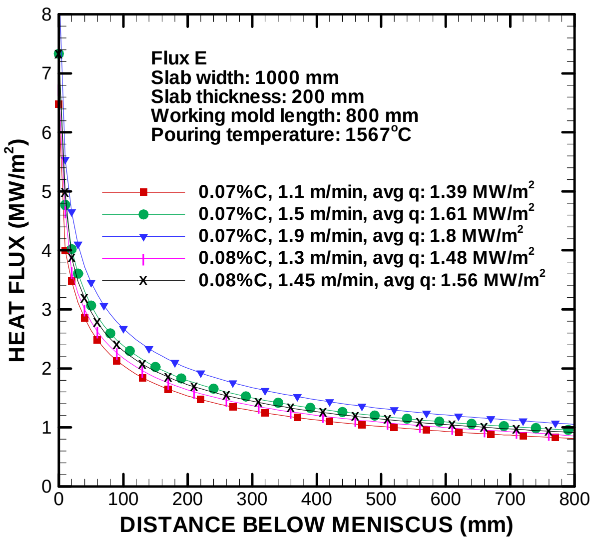
Cases	0B	1B	2B	3B	4B	5B	6B	7B	8B	9B	10B	11B	12B
Grade	low carbon			peritectic		medium carbon		medium carbon		high carbon		high carbon	
Tliquidus	1527			1527		1521		1517				1490	
Carbon content	0.07%			0.08%		0.13%		0.16%		0.27%		0.47%	
%Mn, %Si	.3%, .03%			0.42%, 0.01%		.57%, .22%		.87%, .14%				.75%, .22%	
%P, %S	.01%, .007%			.07%, .07%		.07%, .07%		.007%, .005%				.018%, .007%	
Powder type	E (220)			E (220)		C (666)		C (666)		E(220)		E (220)	
Viscosity (Pa-s)	0.083			0.083		0.192		0.192		0.083		0.083	
sol. Temp (C)	1120			1120		1215		1215		1120		1120	
Casting Speed (m/min)	1.1	1.5	1.9	1.3	1.45	1.2	1.5	1.18	1.5	1.2	1.5	1.04	1.3
Tundish temp (C)	1567			1555		1555		1559		1559		1542	
Heat Flux (MW/m2)													
Heat Average (MW/m2)	**1.70**	**1.94**	**2.13**	**1.83**	**1.94**	**1.77**	**1.94**	**1.76**	**1.94**	**1.77**	**1.94**	**1.67**	**1.83**
Surf Temp (exit (C)	1016	1032	1044	1005	1010	1001	1012	1006	1018	1006	1018	972	984
Shrinkage (mm) CON1D	13.18	12.36	11.74	8.98	8.68	8.30	7.84	11.03	10.47	8.64	8.16	8.09	7.17
Shrinkage 50mm CON2D	2.40	1.84	1.41	2.47	2.27	2.87	2.47	2.36	1.96	1.94	1.56	1.81	1.46
Shrinkage (mm) CON2D	6.80	6.29	5.92	6.98	6.81	7.42	7.08	6.79	6.44	6.29	5.96	6.05	5.73
Taper (%/mold) CON2D	1.36	1.26	1.18	1.40	1.36	1.48	1.42	1.36	1.29	1.26	1.19	1.21	1.15
Flux layer (mm)	1.47	1.25	1.14	1.39	1.33	2.34	2.07	2.23	1.91	1.99	1.76	1.99	1.76
Mold distortion+expansion (mm	-0.43	-0.55	-0.65	-0.49	-0.55	-0.46	-0.55	-0.46	-0.55	-0.46	-0.55	-0.41	-0.49
Ideal NF (mm)	***5.70***	***5.60***	***5.45***	***6.05***	***6.05***	***5.55***	***5.55***	***5.00***	***5.10***	***4.75***	***4.75***	***4.50***	***4.45***
Ideal NF (%)	***1.14***	***1.12***	***1.09***	***1.21***	***1.21***	***1.11***	***1.11***	***1.00***	***1.02***	***0.95***	***0.95***	***0.90***	***0.89***

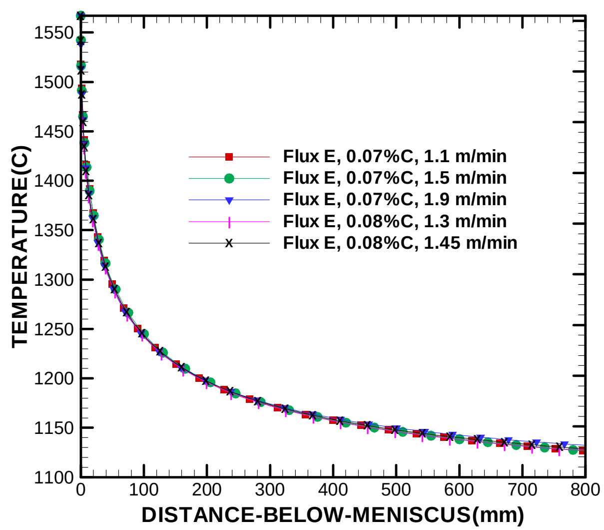
Effect of casting speed

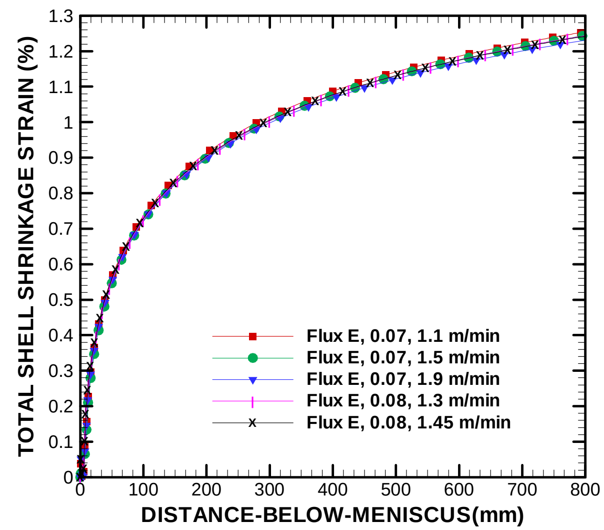
Higher casting speed causes higher heat flux (more shrinkage) but less dwell time (less shrinkage).

Measured data of heat flux*

Net effect: no change in shrinkage





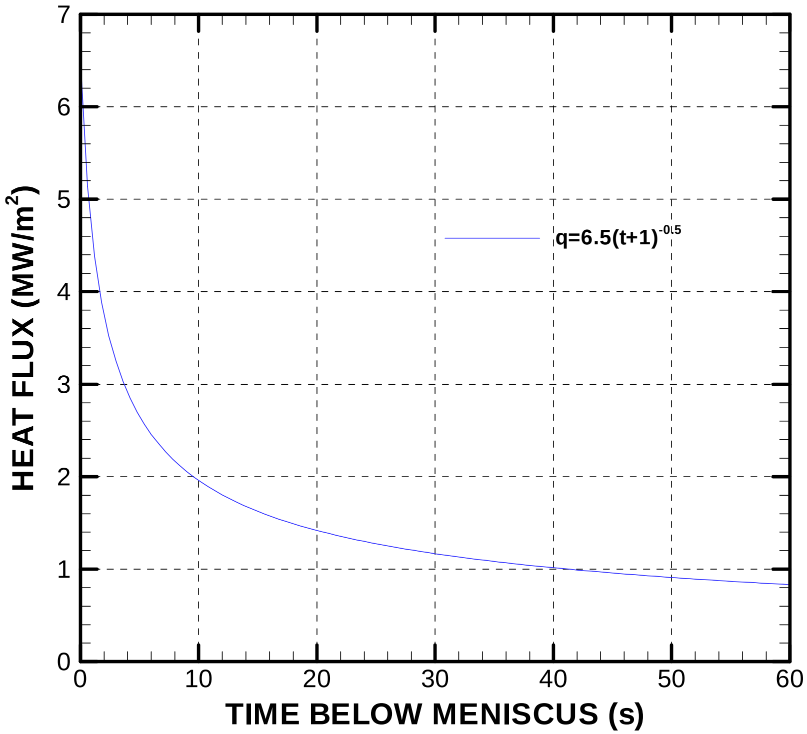


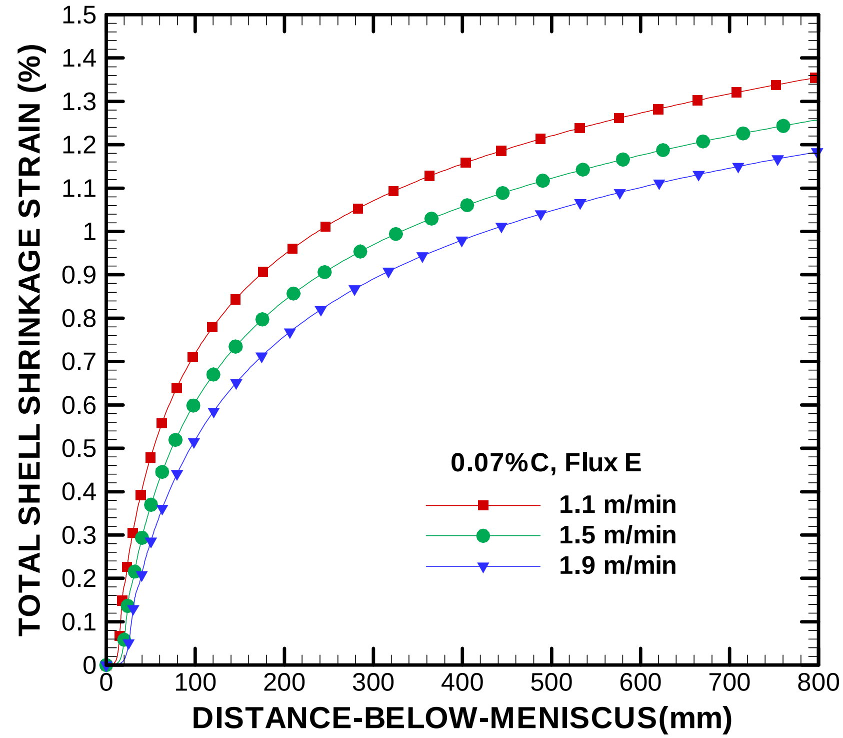
- *C. Cicutti, M. Valdez and T. Perez, "Mould Thermal Evaluation in a Slab Continuous Casting Machine," 85th Steelmaking Conference, (Nashville, TE, USA), Iron and Steel Society, Inc. (USA), Vol. 85, 2002, 97-107.

Effect of mold length

- Mold length
  - For the same conditions (including heat flux), shell shrinkage strains for different mold lengths can be approximated with the same curve
  - Shell shrinkage for different mold lengths can be obtained truncating the curves at the desired working mold length

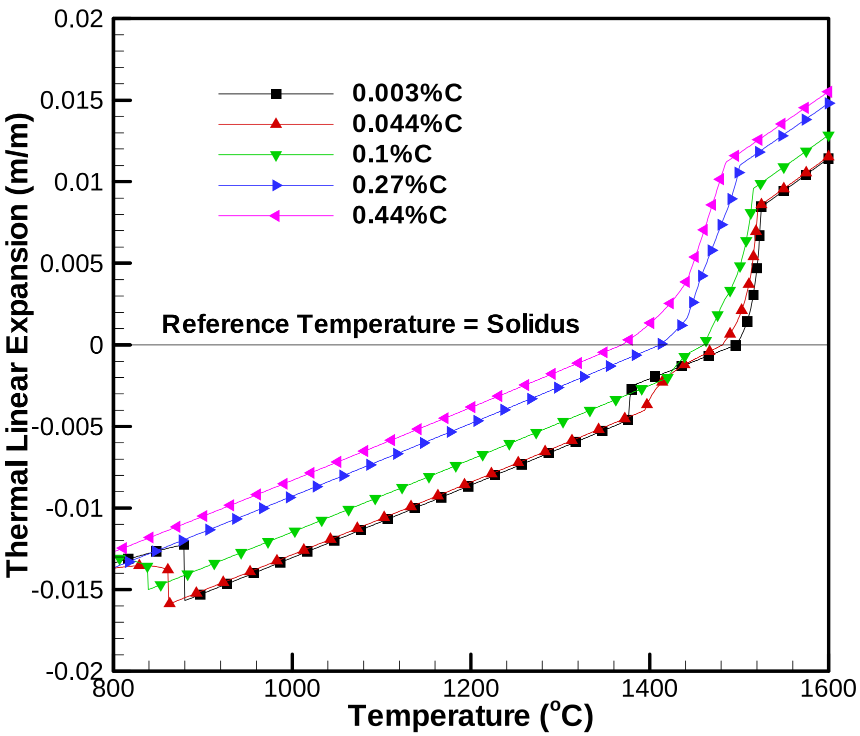
Effect of mold length





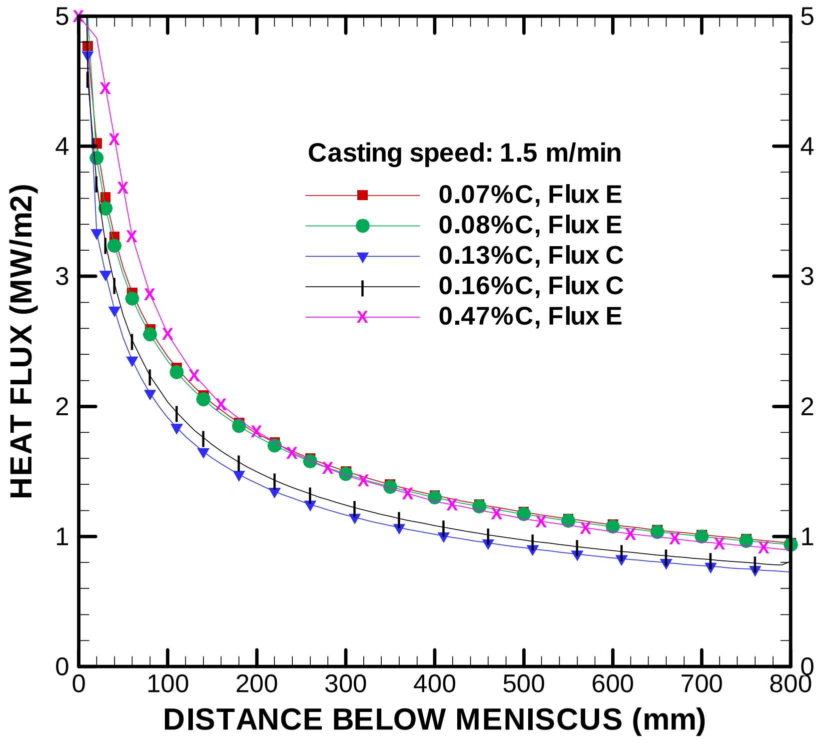
Effect of steel grade

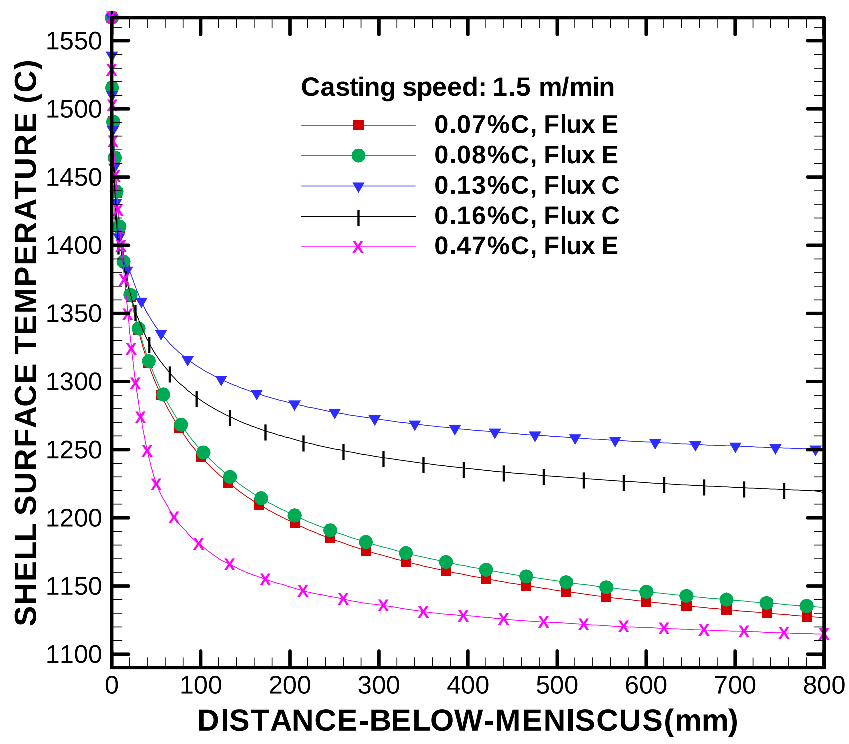
- **Steel grade effect**



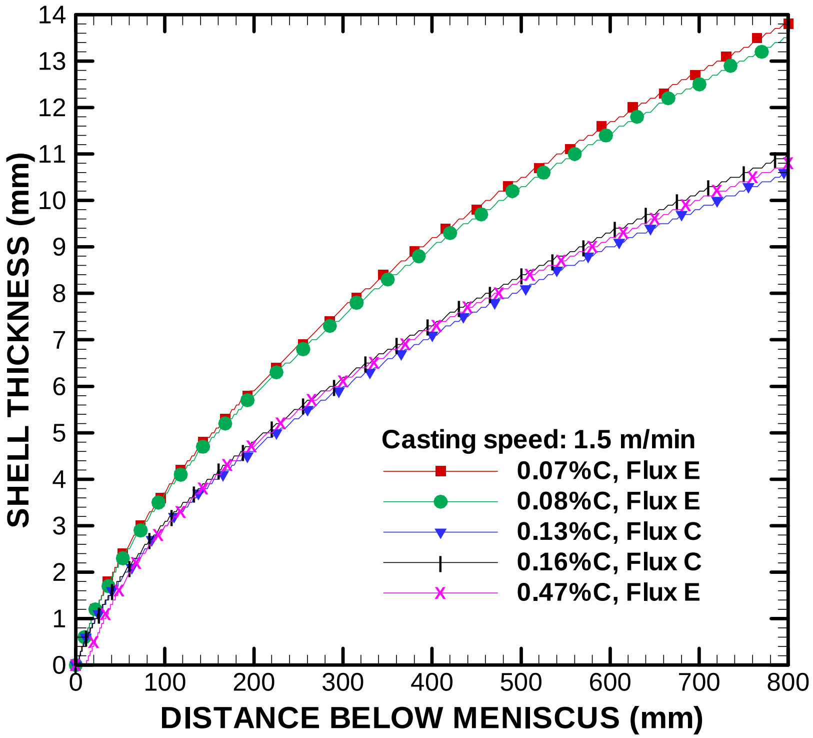
- Low carbon steels (>0.08%C)
  - Higher plastic strain
  - Higher thermal expansion
- Peritectic steels (🕔0.1%)
  - Deeper oscillation marks causes lower heat flux
  - Higher thermal expansion
  - Final result the smallest shell shrinkages
- High carbon steels (>0.2%)
  - Shallow oscillation marks Higher heat flux
  - Small inelastic strain Thermal strain
  - Heat flux and shell shrinkage similar to low carbon steels

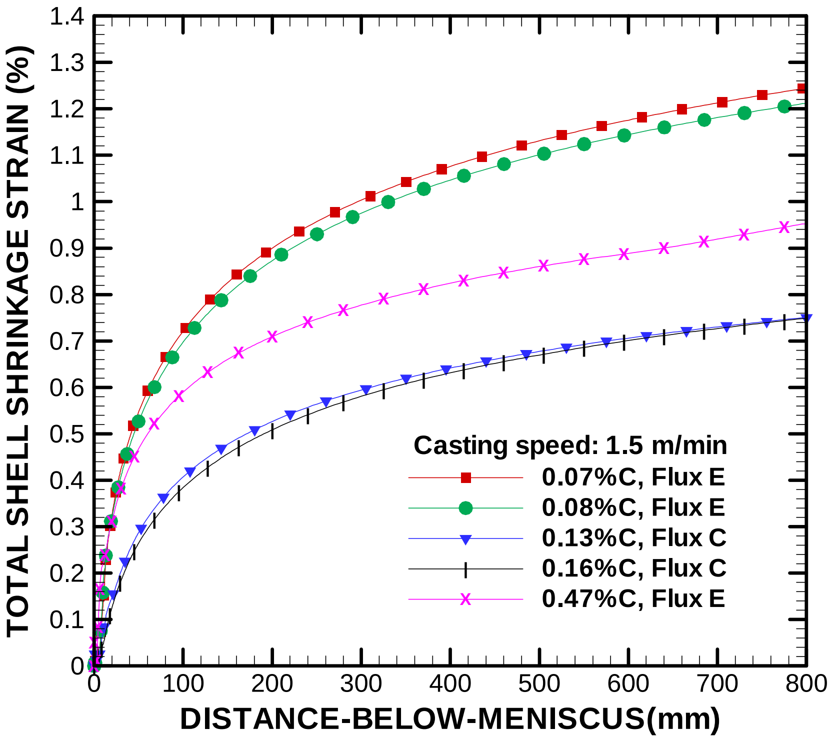
Effect of steel grade



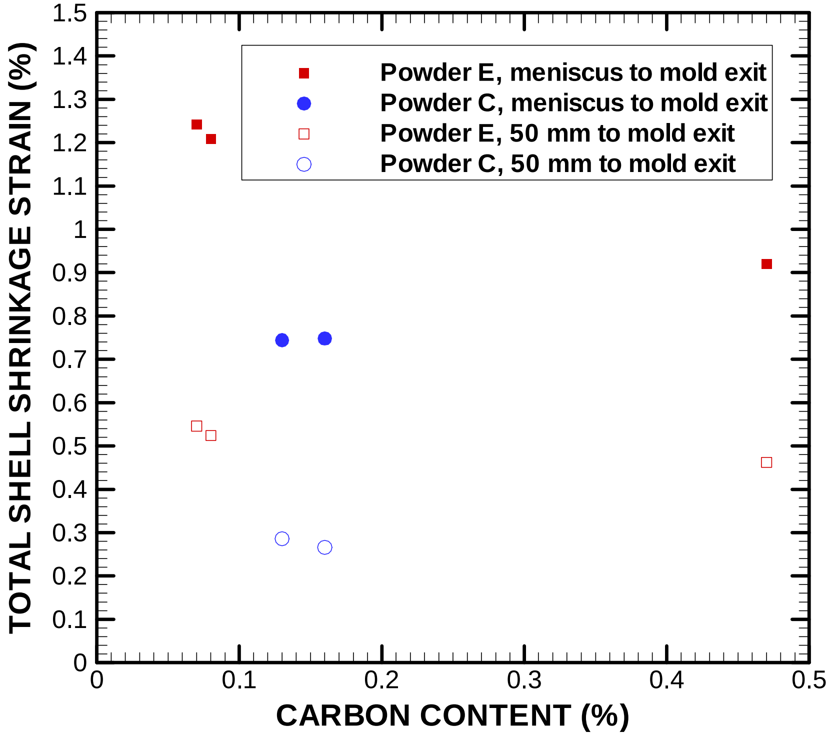


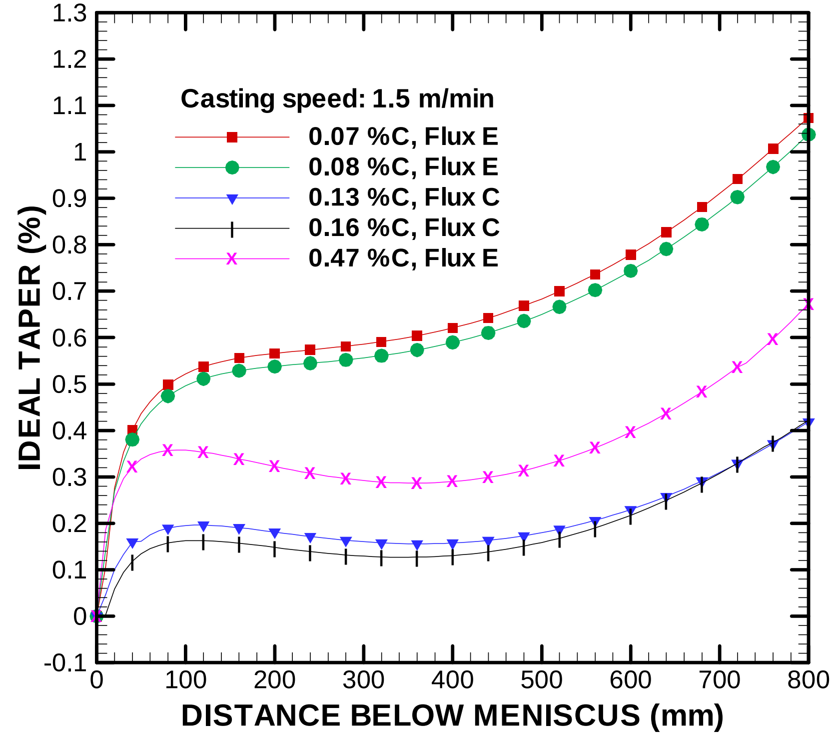
Effect of steel grade





Effect of steel grade





Continuous Casting Consortium

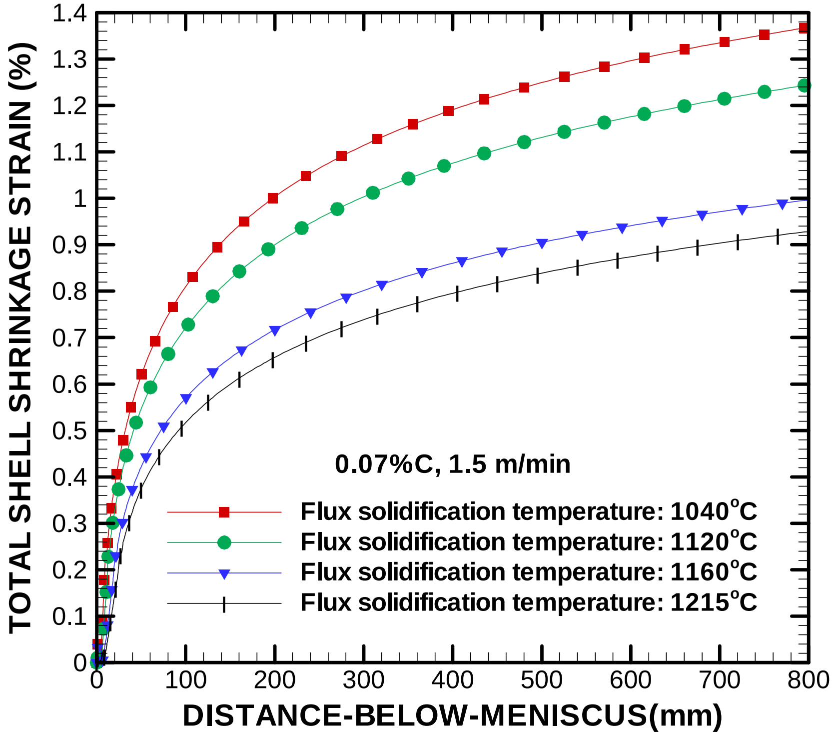
Effect of steel grade

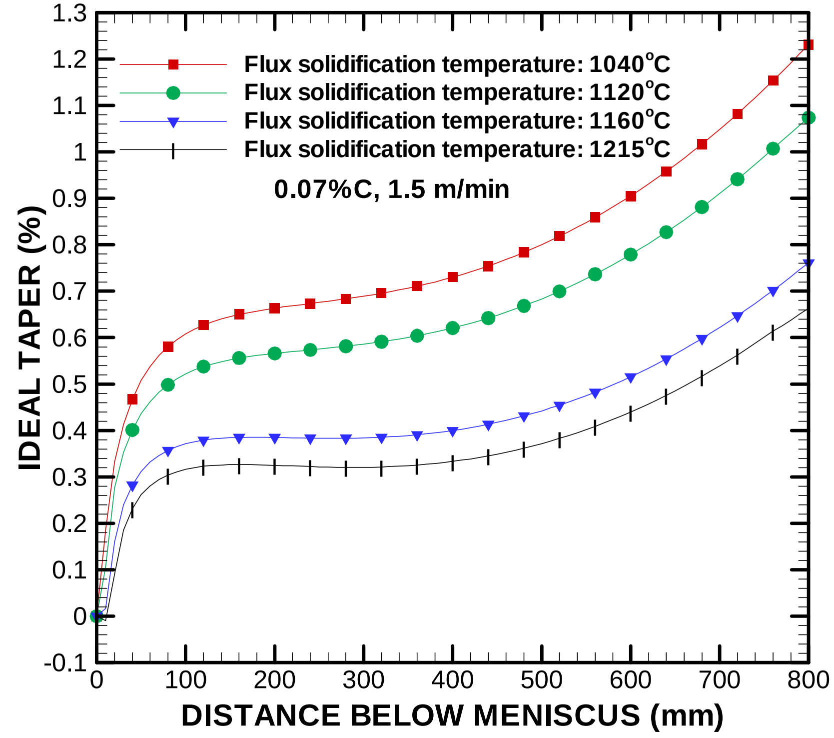
Grade	low carbon	peritectic	medium carbon	medium carbon	high carbon
Tliquidus	1527	1527	1521	1517	1490
Carbon content	0.07%	0.08%	0.13%	0.16%	0.47%
%Mn, %Si	.3%, .03%	0.42%, 0.01%	.57%, .22%	.87%, .14%	.75%, .22%
%P, %S	.01%, .007%	.07%, .07%	.07%, .07%	.007%, .005%	.018%, .007%
Powder type	E (220)	E (220)	C (666)	C (666)	E (220)
viscosity (Pa-s)	0.083	0.083	0.192	0.192	0.083
sol. Temp (C)	1120	1120	1215	1215	1120
Flux comsumption rate (kg/t)	0.245	0.245	0.245	0.245	0.05
Solid flux velocity ratio (V/Vc)	0.02	0.0185	0.0026	0.0091	0.009
Oscilation mark depth (mm)	0.24	0.24	0.34	0.34	0.05
Casting Speed (m/min)	1.5	1.5	1.5	1.5	1.5
Tundish temp (C)	1567	1567	1567	1567	1567
Heat flux average (MW/m^2)	**1.61**	**1.59**	**1.29**	**1.37**	**1.64**
Surf Temp (exit (C)	1126.7	1134.3	1250.2	1218	1114.7
Shrinkage (mm) CON1D	9.40	5.96	3.12	6.52	4.96
Shrinkage 50mm CON2D	2.73	2.62	1.43	1.33	2.31
Shrinkage (mm) CON2D	6.21	6.04	3.72	3.74	4.61
Taper (%/mold) CON2D	1.24	1.21	0.74	0.75	0.92
Flux layer (mm)	1.30	1.31	1.98	1.97	1.51
Narrow face distortion (mm)	-1.54	-1.51	-1.32	-1.35	-1.71
Wide face expansion (mm)	1.07	1.06	0.96	1.01	1.45
Ideal NF (mm)	**5.37**	**5.19**	**2.09**	**2.11**	**3.36**
Ideal NF (%)	**1.0737**	**1.037**	**0.418**	**0.421**	**0.672**

Effect of mold flux composition

- Study of the effect of Powder composition in shell shrinkage
  - Mold powder viscosity
    - ☞ Slight changes in shell shrinkage
  - Mold powder Solidification temperature
    - ☞ Higher solidification temperature causes a lower heat flux and consequently lower shell shrinkage

Effect of mold flux composition





Effect of mold flux composition

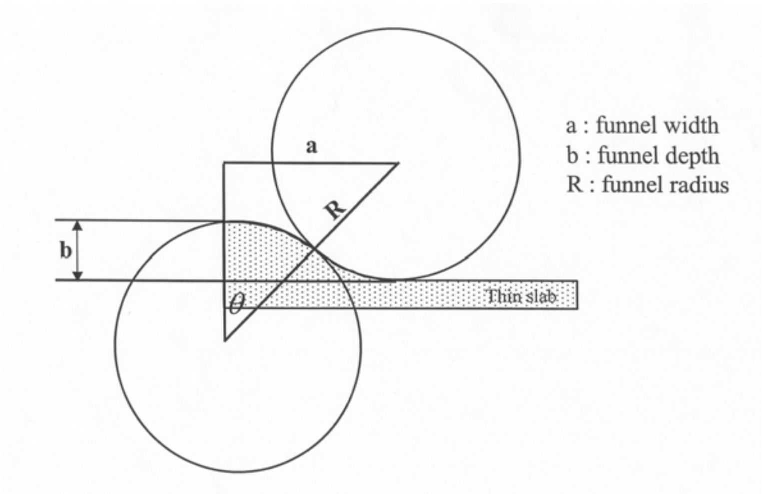
Grade	low carbon			
Tliquidus	1527			
Carbon content	0.07%			
%Mn, %Si	.3%, .03%			
%P, %S	.01%, .007%			
Powder type	A (RB1 - B)	C (666)	D (155)	E (220)
viscosity (Pa-s)	0.225	0.192	0.115	0.083
sol. Temp (C)	1160	1215	1040	1120
Flux comsumption rate (kg/t)	0.25	0.25	0.25	0.25
Solid flux velocity ratio (V/Vc)	0.008	0.015	0.011	0.020
Oscillation mark depth (mm)	0.24	0.24	0.24	0.24
Casting Speed (m/min)	1.5	1.5	1.5	1.5
Tundish temp (C)	1567	1567	1567	1567
Heat Flux average (MW/m^2)	**1.41**	**1.36**	**1.71**	**1.61**
Surf Temp (exit (C)	1202.1	1220	1090	1126.7
Shrinkage (mm) CON1D	7.72	7.24	10.36	9.40
Shrinkage 50 mm CON2D	2.12	1.88	3.08	2.73
Shrinkage (mm) CON2D	4.98	4.64	6.82	6.21
Taper (%/mold) CON2D	1.00	0.93	1.36	1.24
Flux layer (mm)	1.59	1.73	1.12	1.30
Narrow face distortion (mm)	-1.36	-1.29	-1.65	-1.54
Wide face expansion (mm)	0.94	0.88	1.17	1.07
Ideal NF (mm)	**3.81**	**3.32**	**6.15**	**5.37**
Ideal NF (%)	**0.76**	**0.66**	**1.23**	**1.07**

Conclusions

- More taper is needed near the top of the mold to compensate the more shrinkage of the steel shell.
- As casting speed increases, shrinkage decreases.
- Shell shrinkage depends mainly of the heat flux profile which depends of the casting speed and interface conditions.
- Peritectic steels generally requires smaller taper (due to the lower heat flux caused by bigger oscillation marks).
- Mold powders with higher solidification temperatures require less taper (due to lower heat flux).

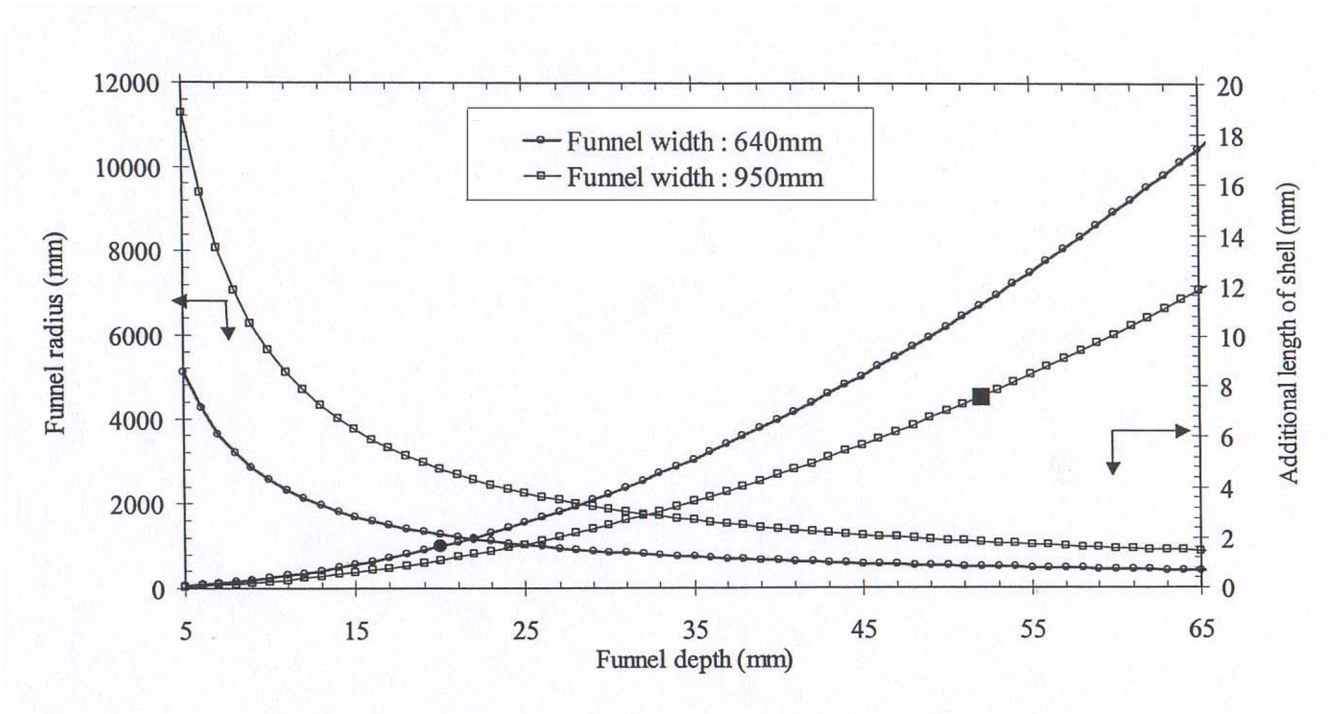
Extra length in Funnel

- In thin slab casting there is a taper induced by the change in perimeter of the wide face, because of the funnel shape.



$$EL = 2\left\{\left[\frac{a^2+b^2}{2b}\sin^{-1}\left(\frac{2ab}{a^2+b^2}\right)\right]-a\right\}$$

Extra length in funnel



Thin slab casting ideal taper

- Higher casting speeds than conventional slab casting.
- Funnel shape effect.

IT= Shell shrinkage(z) – (Mold distortion(z) – Mold distortion meniscus)
– (flux thickness(z) – flux thickness meniscus)
– (funnel extra length meniscus – funnel extra length(z))

Thin slab casting conditions

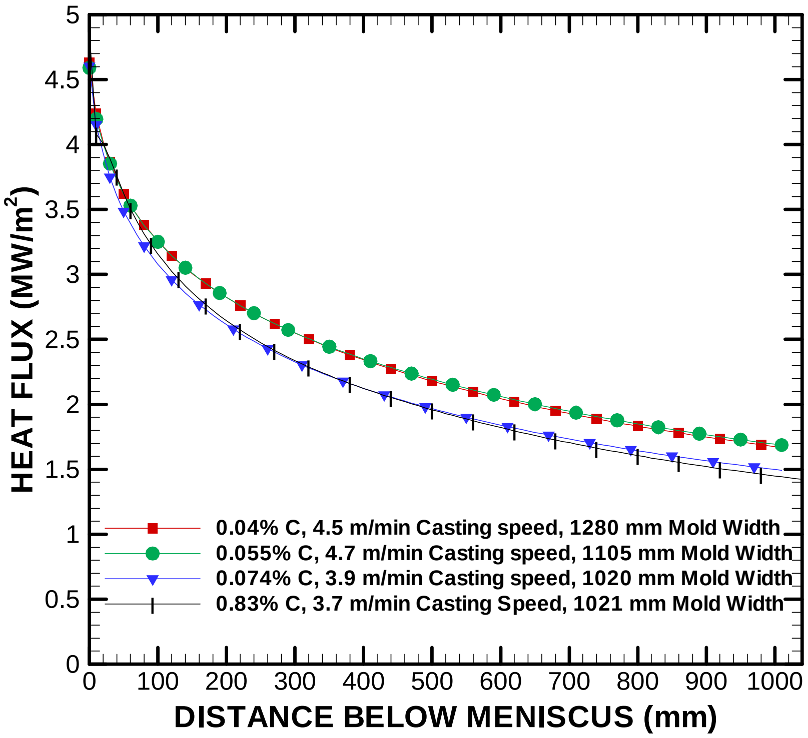
- Operating Conditions.

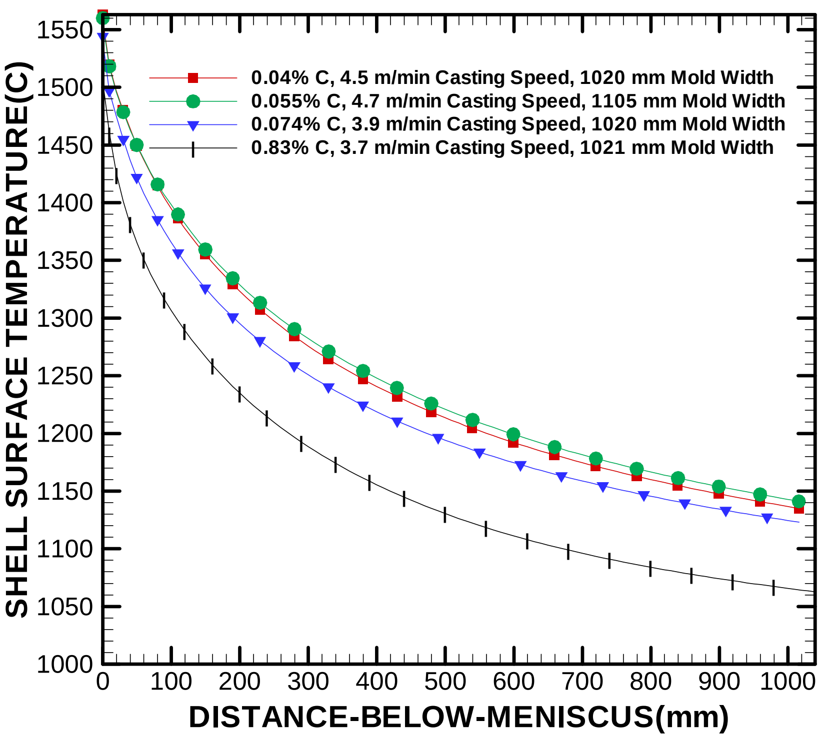
Mold geometry	
Slab thickness	49.78 mm
Mold Heigth	1100 mm
Cu plate thickness	121 mm
Funnel	
Funnel width: a	1020 mm
Funnel depth at top: b	60 mm
Funnel heigth	750 mm

Description	Carbon Content	Casting Speed	Mold Width	Meniscus level
Difficult to cast low carbon	0.04%	4.5 m/min	1280 mm	83 mm
Low Carbon	0.06%	4.7 m/min	1100 mm	83 mm
Approximately Peritectic	0.074%	3.9 m/min	1020 mm	83 mm
High Carbon	0.83%	4 m/min	1020 mm	58 mm

Thin slab casting ideal taper

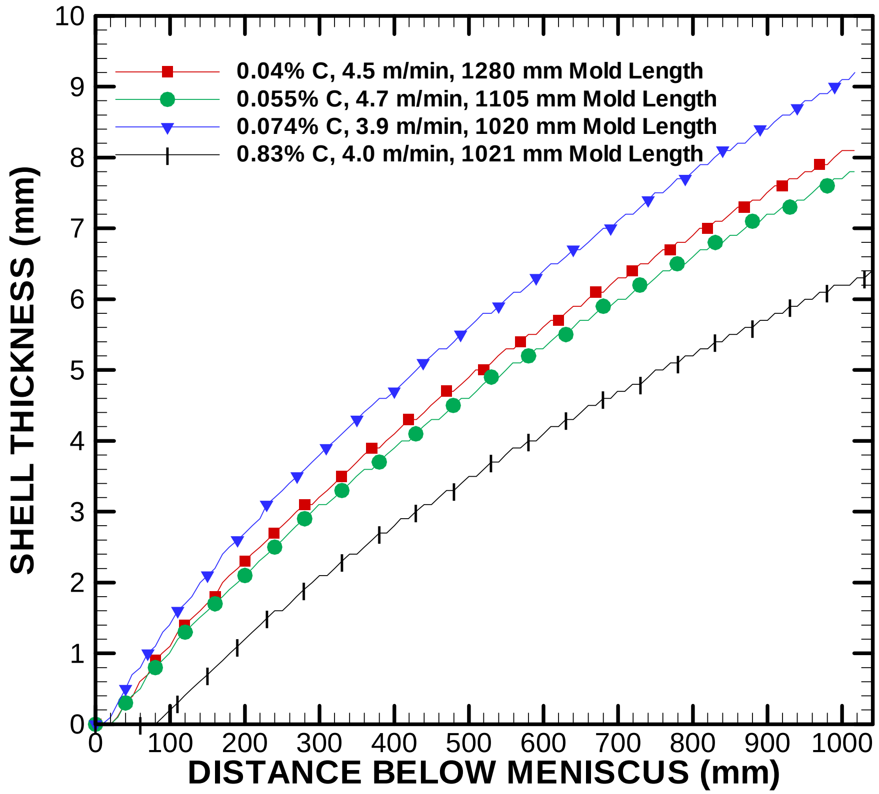
- Heat flux and surface temperatures





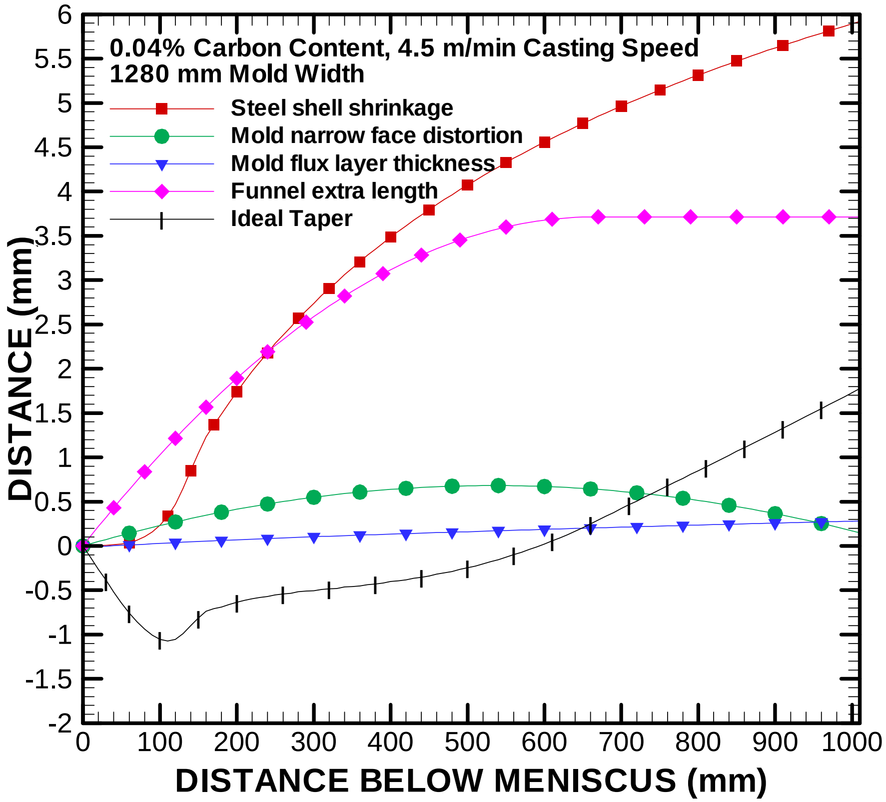
Thin slab casting ideal taper

- Solidified steel shell thickness



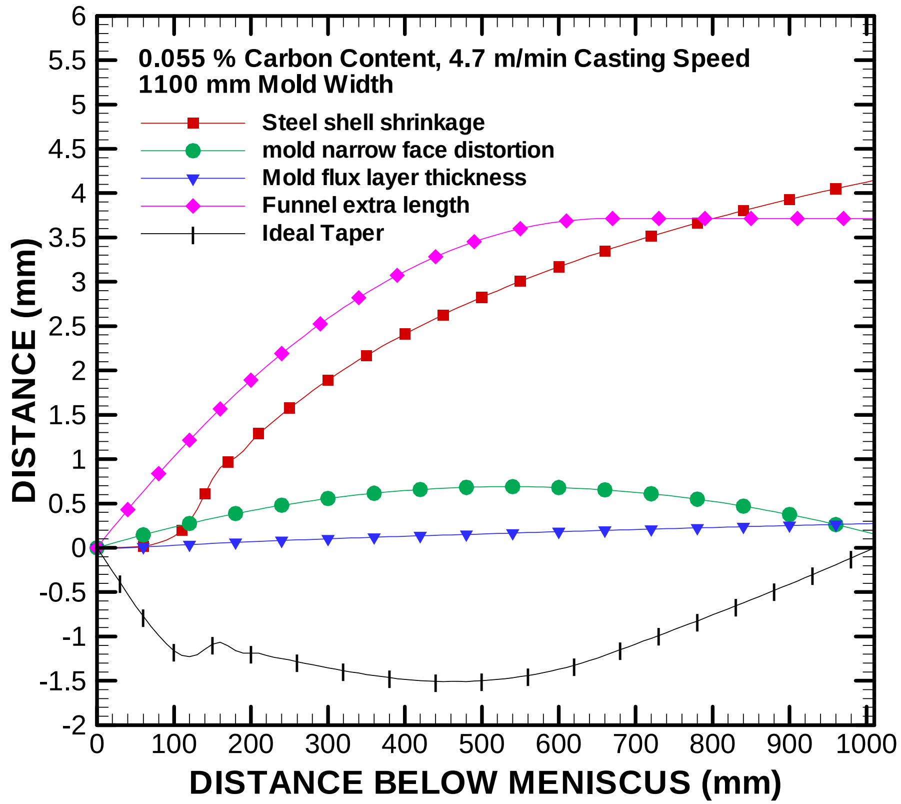
Thin slab casting ideal taper

- Difficult to cast low carbon



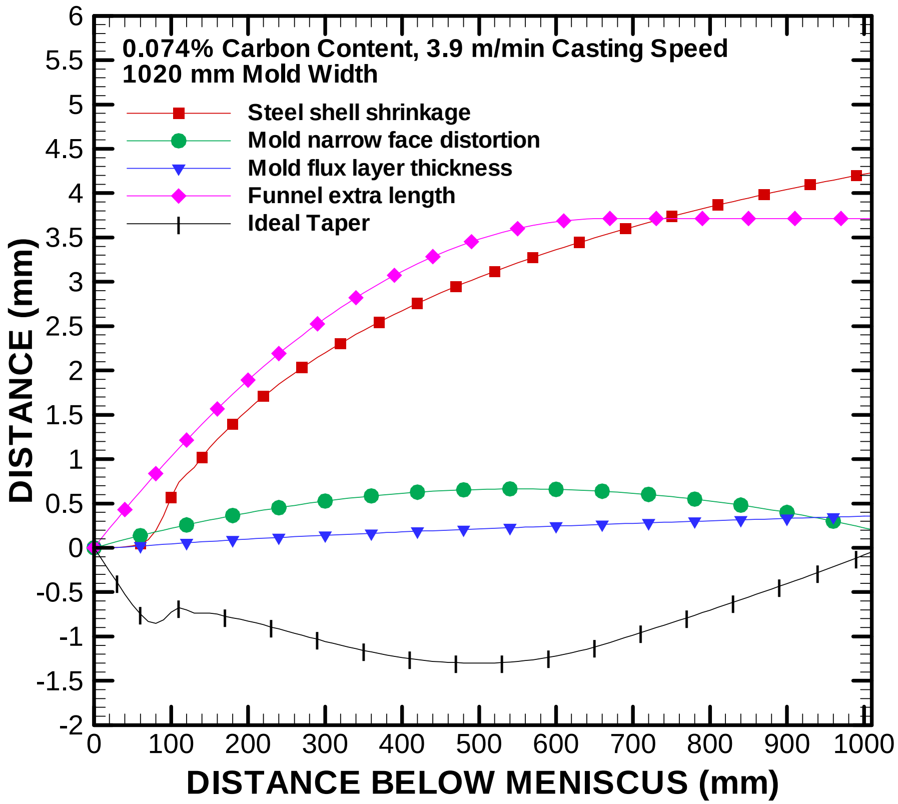
Thin slab casting ideal taper

- Common low carbon steel



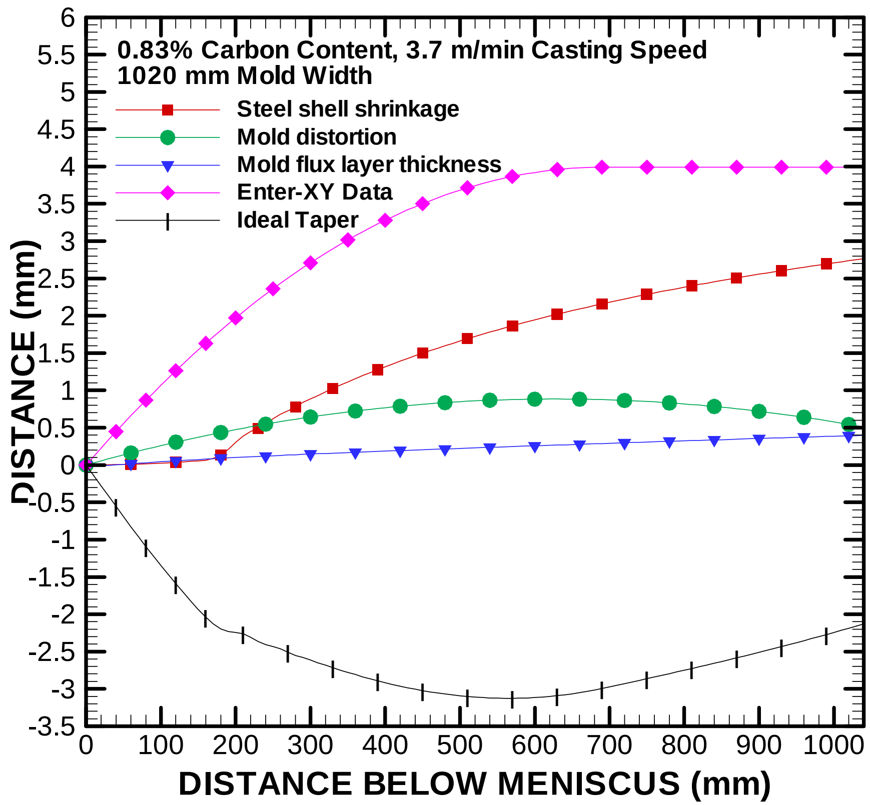
Thin slab casting ideal taper

- Approximately peritectic steel

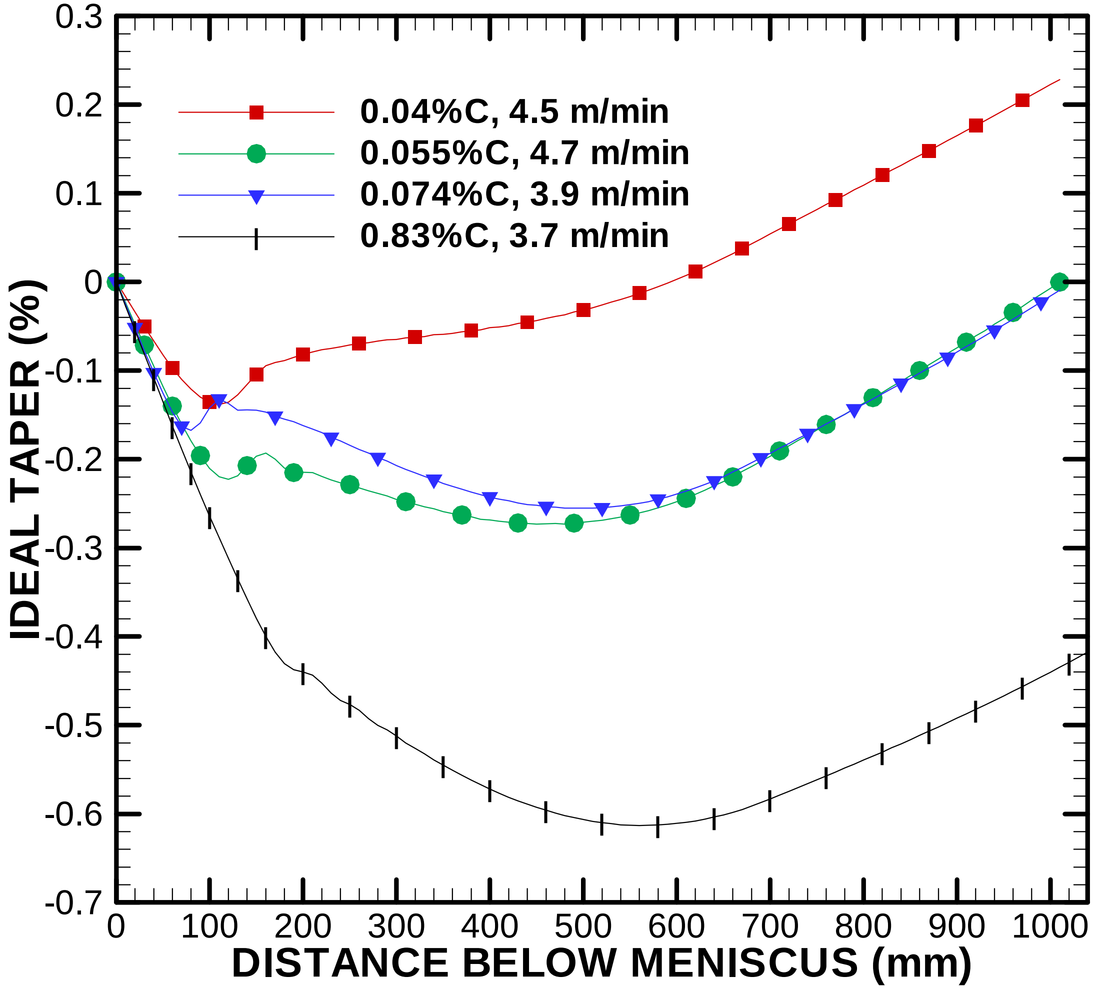


Thin slab casting ideal taper

- High carbon steel



Thin slab casting ideal taper



Thin slab casting ideal taper

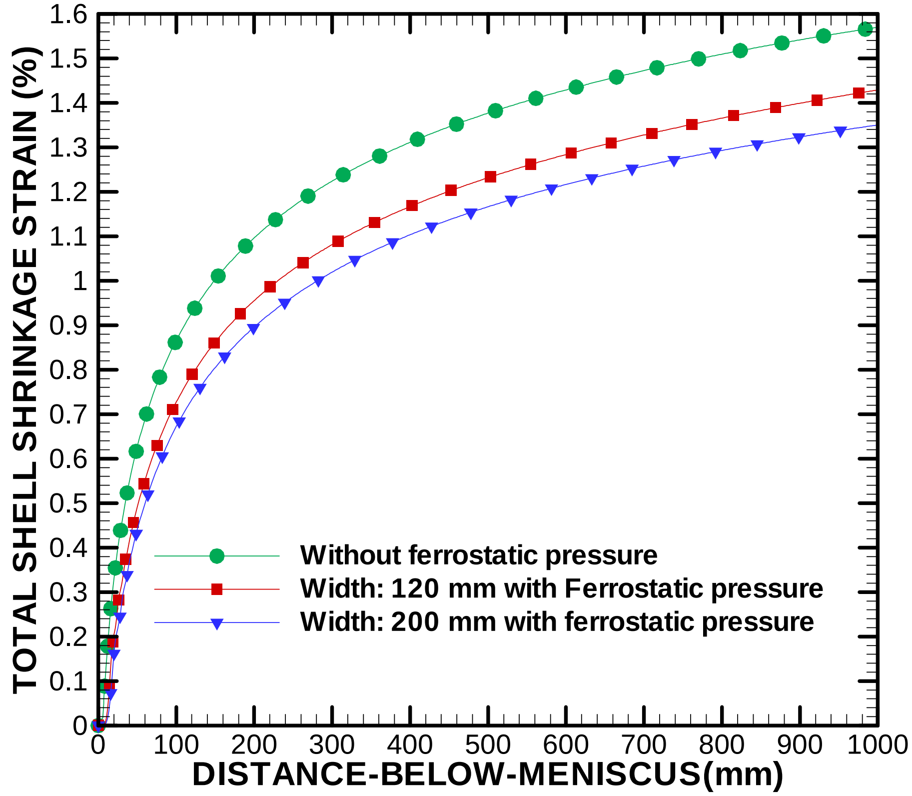
- Results

Case (carbon content %)	Recorded ΔT (° C)	Recorded Heat Flux (kW/m^2)	Computed ΔT (° C)	Computed Heat Flux (kW/m^2)	Suggested Taper from Calculations (%/mold)	Taper used currently (%/mould)
0.04	11.66	2732.48	9.44	2346	0.23	0.85
0.055	8.33	2310	9.79	2355	0.0	0.95
0.074	7.22	2177	8.67	2152	-0.01	0.95
0.83	7.88	2310	7.98	2149	-0.42	1.2

Thin slab casting ideal taper

- Results
  - The shell shrinks more on the top of the mold than in the bottom of the mold, so it is difficult to match the shrinkage of the shell shell with a linear Taper.
  - Mold distortion, flux layer thickness and extra length of funnel significantly affect the Ideal taper.
  - The Ideal Taper predicted is for all cases smaller than the taper used currently.

Effect of ferrostatic pressure



Conclusions

- More taper is needed near the top of the mold, such as achieved using parabolic taper.
- As casting speed increases, shrinkage decreases (for same conditions and heat flux profile).
- Mold length affects the taper only by extending the nonlinear curve (for the same conditions and heat flux profile).
- Mold taper depends mainly on the heat flux profile, which in turn depends on the casting speed and interface conditions (powder, steel grade, etc.).
- Peritectic steels generally require slightly less taper than either low or high carbon steels, owing to their lower heat flux.
- Mold powders with higher solidification temperature have lower heat flux (compared with both oil lubrication or low solidification temperature powders) and consequently have less shrinkage and less ideal taper (other conditions staying the same).
- Flux layer thickness, mold distortion and extra length of funnel (thin slabs) make important contributions to Ideal Taper.