CCC Annual Report

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Correlation for mold heat flux measured in slab casters

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Background

- Previous work shows that mold heat transfer is primarily influenced by casting speed, steel composition, properties of of mold powder, and strand width such as

$$Q(kW/m^2) = 4.63 \cdot 10^6 \cdot \mu^{-0.09} \cdot T_{Flow}^{-1.19} \cdot V_c^{0.47} \cdot \left(1 - 0.152 \cdot \exp\left(-\left(\frac{0.107 - \%C}{0.027}\right)^2\right)\right)$$

Cicutti Equation[1]

$$Q(MW/m^2) = 3.128 \cdot 10^5 \cdot V_c^{0.620} \cdot T_{break}^{-1.845} \cdot W^{0.072} \cdot \mu^{-0.017} \cdot \left(1 - 0.152 \cdot \exp\left(-0.021 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right)^2\right)\right)$$

Decatur Equation[2]

- Decatur equation was developed for a thin slab caster at Nucor Decatur Steel mill in Alabama based on 2.5 years of measurements comprising 10556 heats [2]

- Similar methodology is being implemented to Nucor Tuscaloosa steel mill to investigate the effect of various casting variables

Objectives

Based on statistical analysis of measurements of slab casters of Nucor steel mills at Decatur and Tuscaloosa,

1. Investigate the effect of various casting variables on mold heat flux of wide face of Nucor Tuscaloosa caster

2. Develop equations to predict mold heat flux as a function of casting variables based on Tuscaloosa caster alone, and on both Decatur and Tuscaloosa casters

3. Evaluate the performance of mold heat flux equations (current and previous) for Decatur and Tuscaloosa casters

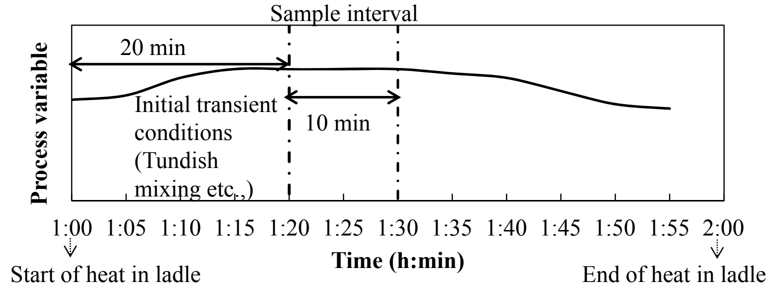
Outline

1. **Data extraction**
   - Use SQL query to collect measurements from plant database*
2. **Data preprocessing**
   - Apply “primary filters” to remove unreliable and unsteady heats
   - Investigate the effect of individual casting variables on heat flux with “secondary filters”
3. **Model development**
   - Validate: test method on a known relationship[2]
   - Apply method to determine mold heat flux equation
     - Choose structure of the equation
     - Determine best fit parameters for different combinations
     - Select the best model based on statistical measures
4. **Model evaluation**
   - Compare the performance of the model with existing models
   - Test the performance of the model for other data sets

(*Provided by Daniel Green for Nucor Tuscaloosa caster)

Data extraction:
Nucor Tuscaloosa mill

- Nucor Tuscaloosa has 136.1 mm thick slab caster with a working mold length of 812.8 mm and adjustable width of 2565.4 to 1016.0 mm
- SQL query is employed to collect 11 months of measurements comprising 9729 heats
- From each heat (typically lasts for 50 minutes), starting 20 minutes after the ladle is opened, average values of measurements for 10 minutes are collected



- Special thanks to Daniel Green, Bob Williams, and others at Nucor Steel Tuscaloosa for providing data and valuable guidance for this project

Data extraction:
Casting variables analyzed

1. Casting speed
2. Composition of steel (C, C_A, C_B)
3. Viscosity of mold powder
4. Break point temperature of mold powder
5. Basicity of mold powder (CaO/SiO_2)
6. Super heat
7. Width
8. Mold plate thickness
9. Mold level standard deviation

- Grade of the steel[3] can be determined as peritectic based on whether C is within the interval $[C_A, C_B]$:

$$C_A = 0.0896 + 0.0458 * Al - 0.0205 * Mn - 0.0077 * Si + 0.0223 * Al * Al - 0.0239 * Ni + 0.0106 * Mo + 0.0134 * V - 0.0032 * Cr + 0.00059 * Cr * Cr + 0.0197 * W$$

$$C_B = 0.1967 + 0.0036 * Al - 0.0316 * Mn - 0.0103 * Si + 0.1411 * Al * Al + 0.05 * Al * Si - 0.0401 * Ni + 0.03255 * Mo + 0.0603 * V + 0.0024 * Cr + 0.00142 * Cr * Cr - 0.00059 * Cr * Ni + 0.0266 * W$$

where C, Mn etc., represent the element mass concentration (%)

Effect of Silicon term on C_A is observed in plant to be opposite of Blazek equation given here (ie positive) so should be considered in calculating peritectic range

Data extraction: Calculation of mold heat flux

- Heat flux across a mold hot face is calculated as

$$Q = \frac{G \cdot \rho_w \cdot C_w \cdot \Delta T}{W \cdot Z}$$

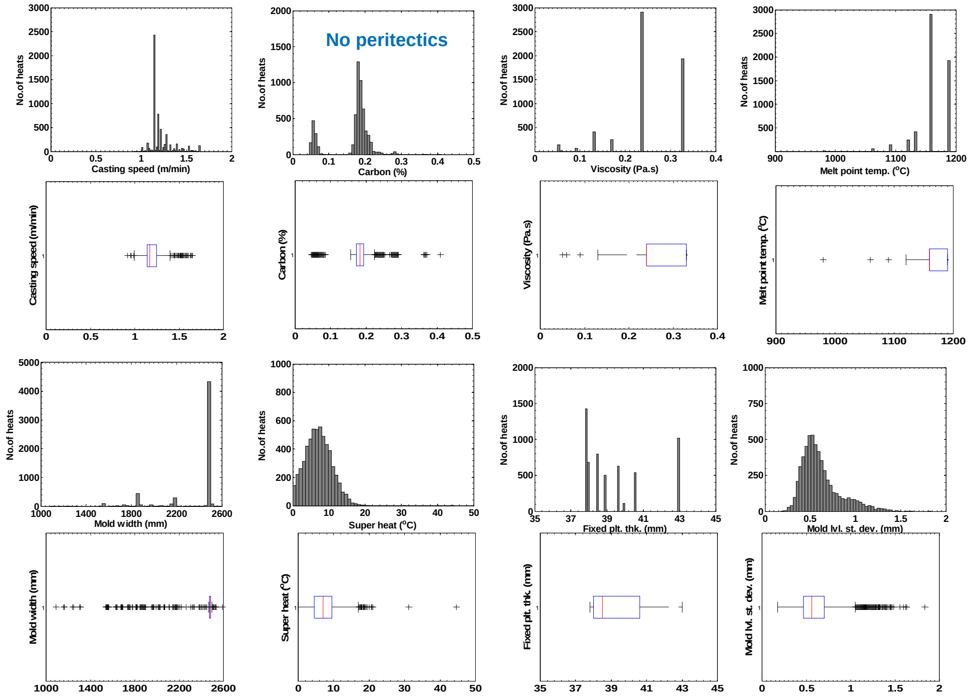
Q - heat flux
G - water flow rate
ρ_w - density of water
C_w - specific heat capacity of water
ΔT - temperature rise of the cooling water
Z - mold working length
W - strand width

Data preprocessing: Tuscaloosa caster-Primary filters

- Apply "primary filters" to remove incomplete, noisy, and inconsistent data

Casting variable	**Filter criterion**	**Remaining heats (of 9729 total)**
Blanks with insufficient data		8489
Constant casting speed	variation in $V_c \leq 2$ mm/s	8060
Mold powder type	excluding trial powders	7981
Constant mold width	variation in $W \leq 10$ mm	6173
Realistic super heat	$0 \leq s \leq 50$ °C	5704
Realistic mold level standard deviation	$l \leq 3$ mm	5704

Data preprocessing: Data visualization of Tuscaloosa measurements (5704 heats)



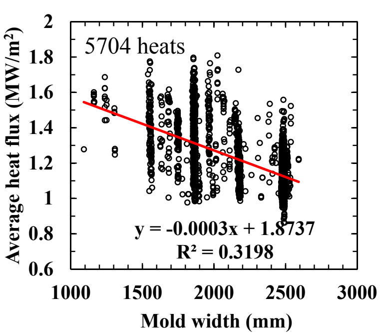
Data preprocessing: Tuscaloosa caster- Importance of Secondary filters

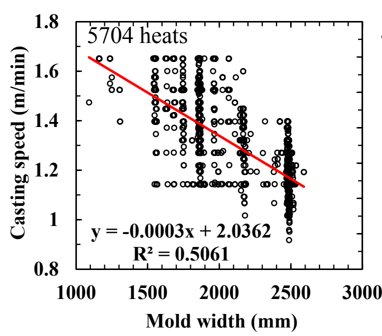
- There is multicollinearity between many of the variables

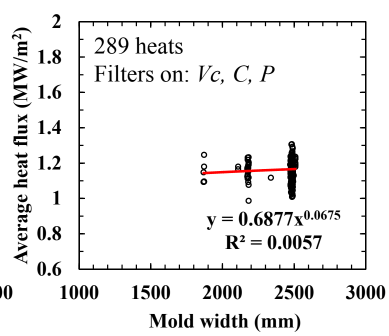
Mold heat flux decreases with mold width for all heats…

… but to maintain a constant throughput, casting speed decreases with mold width, which decreases heat flux…

… so, with a constant casting speed, a little effect of mold width on heat flux is observed





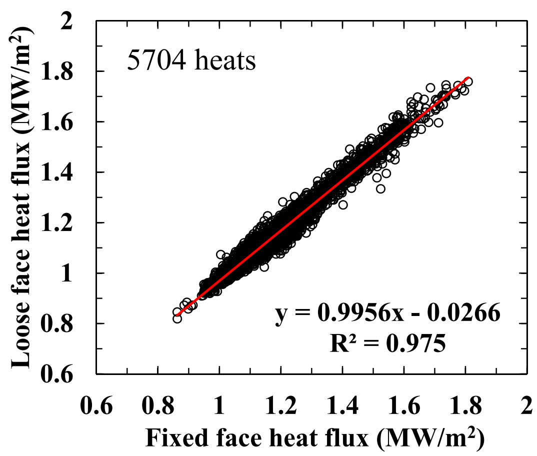


Data preprocessing: Tuscaloosa caster-Secondary filters

- While investigating the effect of individual casting variables on mold heat flux, secondary filters are chosen to retain maximum number of heats with filtering of other variables

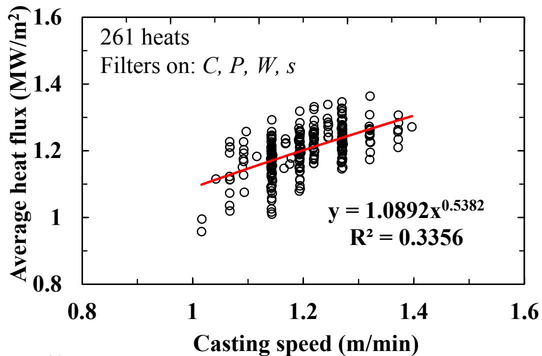
Casting variable	Measurement range (after primary filters)	Range for secondary filter
Casting speed (m/min)	0.917- 1.652	1.14-1.15
Carbon percent (%)	0.046-0.41	0.177-0.191
Mold powder	8 powders	P (2D)
Mold width (mm)	1091.2-2590.8	2470-2500
Super heat (°C)	0-44.611	5.35-8
Mold plate thickness (mm)	37.8-43	43
Mold level standard deviation (mm)	0.178-1.836	0.476-0.543

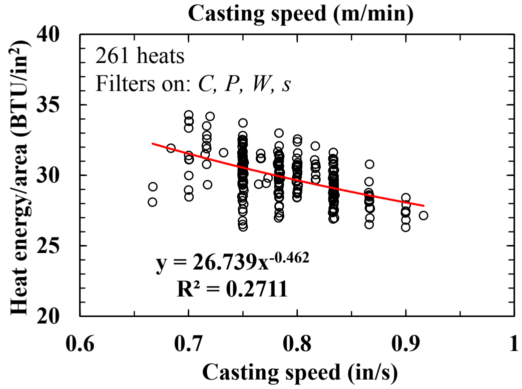
Tuscaloosa caster: Comparison of heat flux across mold wide faces



- No significant difference in average mold heat flux between fixed and loose wide faces
- Therefore, fixed wide face is employed for the rest of the analysis and model development

Tuscaloosa caster: Influence of casting speed





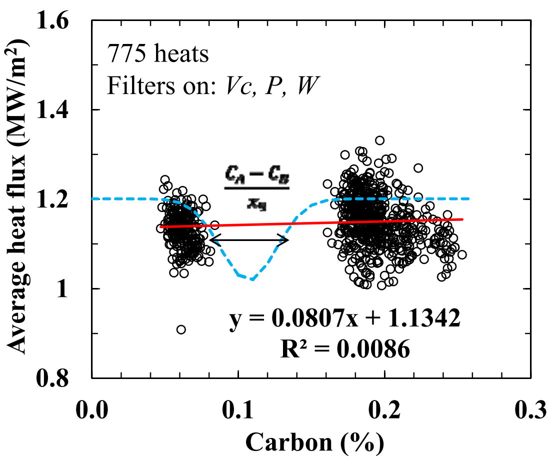
OBSERVED:

- **As casting speed increases,**
  - **mold heat flux increases**
  - **mold heat energy per unit area decreases**
- Most significant variable on heat flux

AS EXPECTED:

- As ***casting speed increases,***
  - residence time of steel in mold decreases, solidifying shell becomes thinner leading to steeper temperature gradients, resulting in ***higher heat flux***[1,2,4-10]
  - mold powder consumption drops, resistance to heat flow across gap decreases, resulting in ***higher heat flux***[4]
  - depth of oscillation marks decreases, lesser resistance across gap, thus ***higher heat flux***[5]
  - energy removal decreases because shell gets thinner

Tuscaloosa caster: Influence of steel composition



OBSERVED:

- **Nucor Tuscaloosa does not cast peritectics.**
- So, peritectic heat flux drop is not observed due to lack of data

EXPECTED:

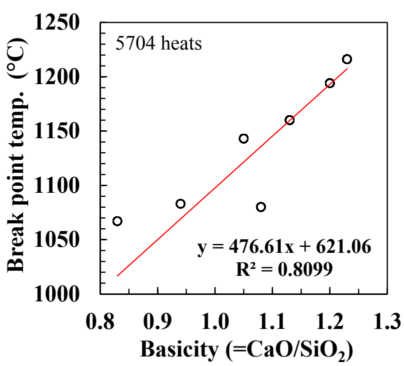
- The larger contraction of the steel during the peritectic phase change associated with shrinkages from δ to γ transformations increases the gap between the shell and mold face resulting in ***lower heat flux*** for ***peritectic steels*** compared to low and high carbon steels[1,3,6,9,10]

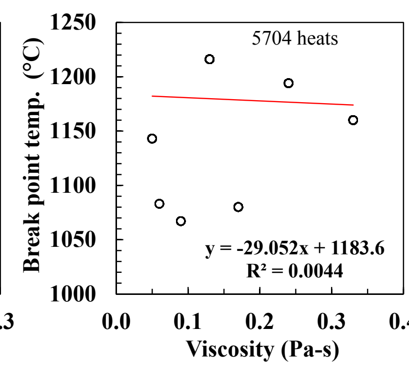
Mold powder properties employed at Tuscaloosa caster

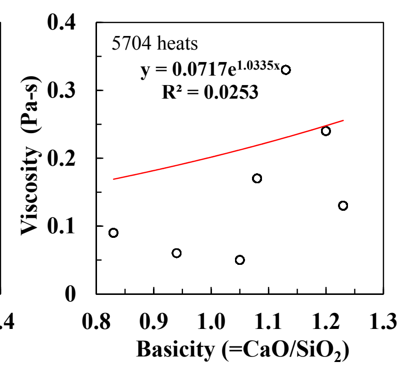
- For Tuscaloosa data studied, mold powders are from only two different manufacturers M-1 & M-2

Manufacturer	Mold powder	IRSID Viscosity1300°C (pa-s)	Solidification temperature (°C)	Softening point (°C)	Melt point (°C)	Flow point (°C)	Break point temperature (°C)	Basicity (CaO/SiO_2)	No. of heats (~9729)
M-1	1A	0.13	1080		1098			1.08	
	1B	0.17	1080		1120			1.08	522
	1C	0.33	1160		1190			1.13	2924
M-2	2A	0.05		1070	1090	1110	1143	1.05	300
	2B	0.06		960	980	1000	1083	0.94	60
	2C	0.13		1110	1135	1160	1216	1.23	842
	2D	0.24		1140	1160	1180	1194	1.2	4836
	2E	0.21		1140	1160	1180	1205	1.25	
	2F	0.05		1070	1090	1110	1147	1.05	146
	2G	0.09		1050	1060	1070	1067	0.83	122
	2H								93

Tuscaloosa caster: Influence of mold powder properties

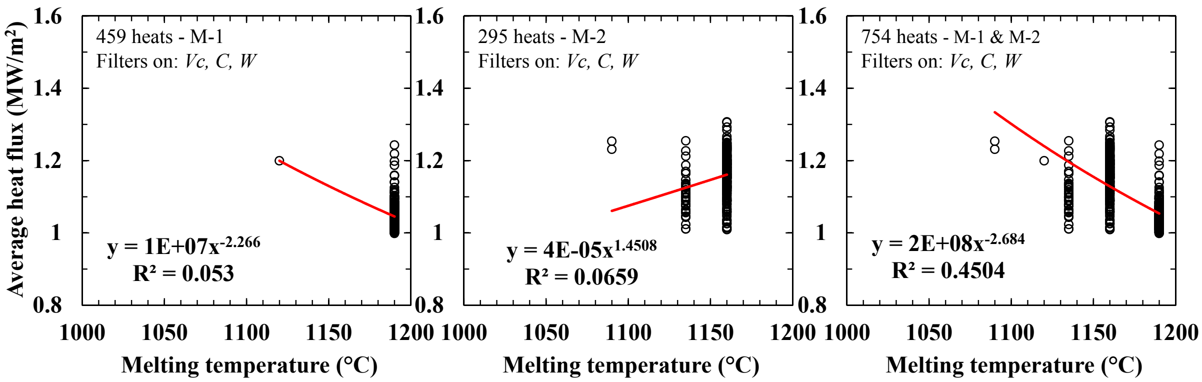






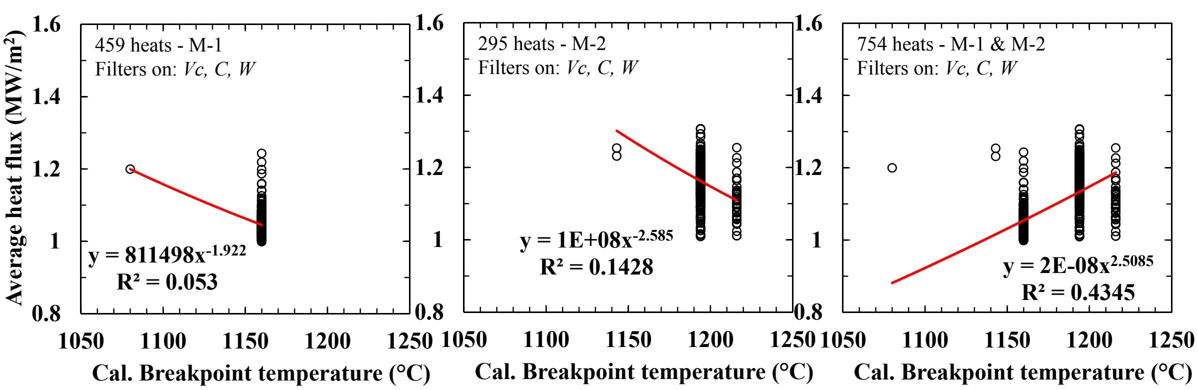
- Mold powder acts a lubrication layer between strand and mold and known to have considerable influence on mold heat flux
- A strong positive correlation is observed between break point temperature and basicity. Hence inclusion of both properties in the correlation is not needed
- Thus, break point temperature and viscosity are considered in the model development

Tuscaloosa caster: Influence of melting temperature of mold powder



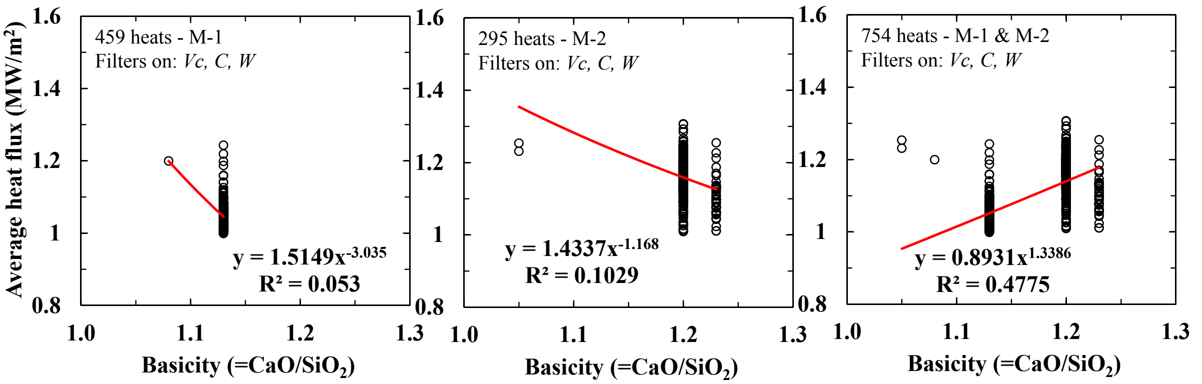
- The influence of melting temperature of mold powder on mold heat flux is different for different powder manufacturers M-1 & M-2
- This might be due to differences in measurement methodology of powder properties from the different manufacturers. Or, melting temperature is not much related to heat transfer which depends more on crystallization during cooling
- But difficult to conclude owing to high uneven distribution of heats (1 & 458 heats in M-1 and 2, 47 & 246 heats in M-2)
- Thus, melting temperature was considered not as good as other properties (break point temperature and viscosity) to characterize mold heat transfer.

Tuscaloosa caster: Influence of break point temperature of mold powder



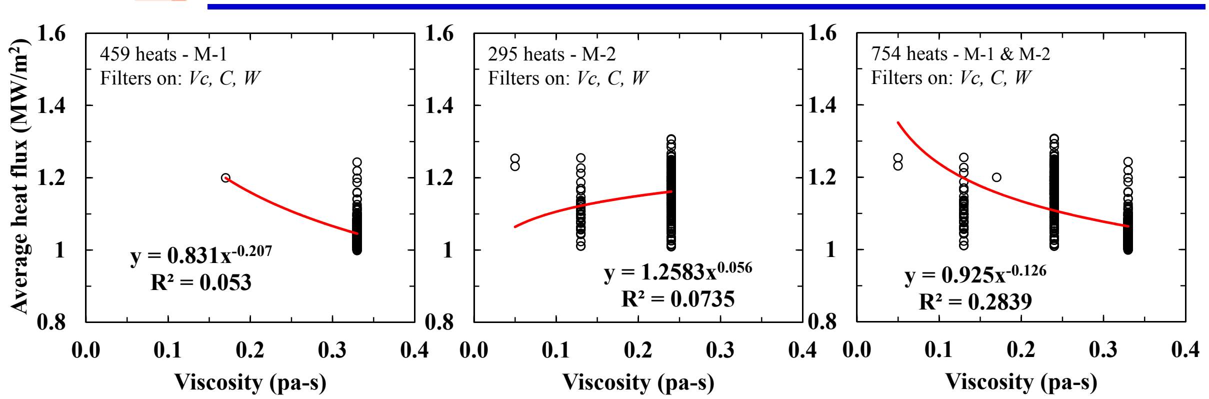
- Individually, for both manufacturers M-1 & M-2, mold heat flux decreases with increasing break point temperature as expected.
- But including both together produces an opposite correlation, due **to the differences in measurement techniques of break point temperature for the different manufacturers**
- So, only powders from one manufacturer were used for the rest of the analysis

Tuscaloosa caster: Influence of basicity of mold powder



- Similar to break point temperature, mold heat flux is decreasing with basicity individually but both together is producing an opposite correlation

Tuscaloosa caster: Influence of viscosity of mold powder

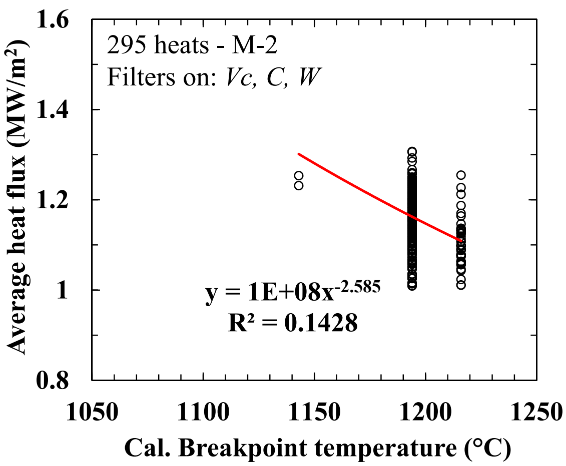


- The effect of viscosity on mold heat flux is varying for two different manufacturers

- But high uneven distribution of heats makes it difficult to conclude which manufacturers data can be considered

- Owing to availability of data pertaining to different mold powders, M-2 is considered for the rest of the analysis

Tuscaloosa caster: Influence of break point temperature of mold powder



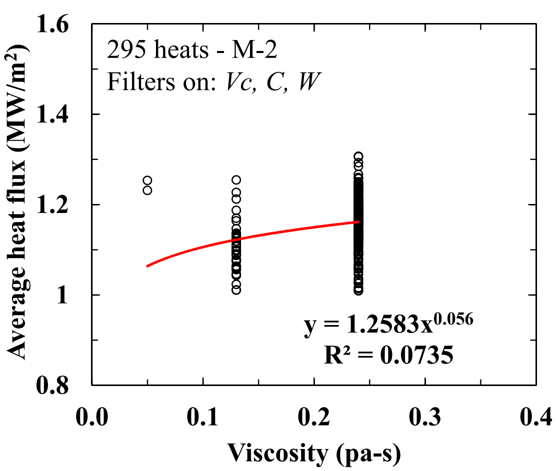
OBSERVED:

- **Mold heat flux is decreasing with increase in break point temperature**

AS EXPECTED:

- Known to influence molten flux rate into gap and thus slag thickness
- ***Lower the break point temperature***,
  - thinner the solidified slag layer, lesser the gap resistance, ***higher the mold heat flux***
  - easier the steel flow resulting in lesser depth in oscillation marks and hooks, thus ***higher the mold heat flux***[1,2,5,7-10]

Tuscaloosa caster: Influence of viscosity of mold powder



OBSERVED:

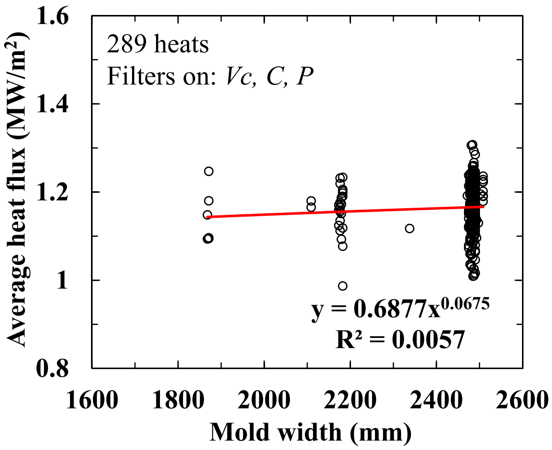
- **Mold heat flux is increasing with viscosity**

- The observed effect is opposite to that of previous literature. But difficult to conclude owing to availability of less mold powders and their calculation/ measurement techniques

EXPECTED:

- Similar to break point temperature***, lower viscosity*** helps for easy flow of liquid slag in the casting gap, thus ***higher mold heat flux***[1,5,7-10]

Tuscaloosa caster: Influence of mold width



OBSERVED:

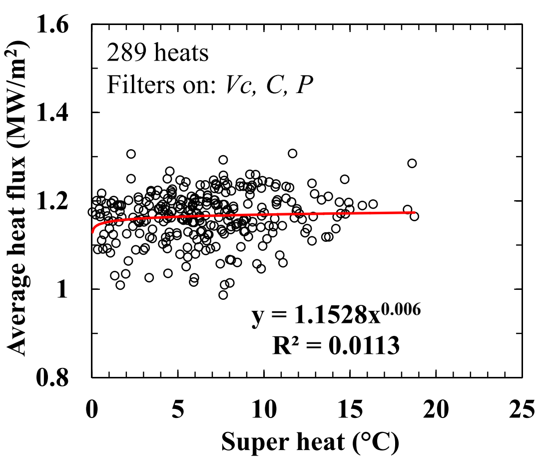
- **Mold heat flux is slightly increasing with mold width**

- Owing to multicollinearity with casting speed, multiple regression analysis is needed to capture the effect of width

AS EXPECTED:

- ***Increasing width*** makes the low heat flux in corners less important and increasing the region of good contact, thus an ***increase in heat flux*** is expected

Tuscaloosa caster: Influence of superheat



OBSERVED:

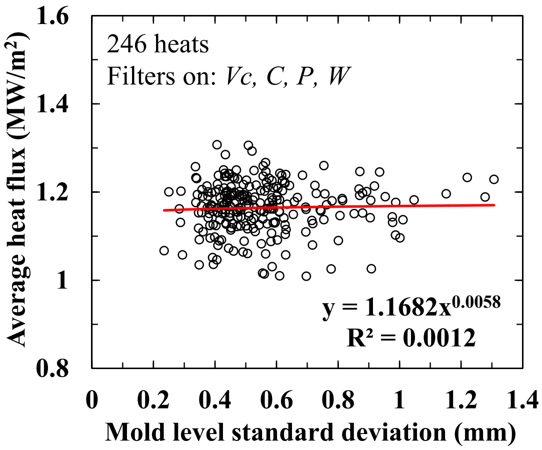
- **Mold heat flux is very slightly increasing with super heat**

- Measurements in tundish which comprises mixture of batches of steel might be contributing to some scatter

AS EXPECTED:

- ***Higher liquid temperatures*** at the top surface should lessen meniscus freezing and hook formation, leading to shallower oscillation marks and less gap resistance, resulting in ***higher mold heat flux***[2,10]

Tuscaloosa caster: Influence of mold level standard deviation



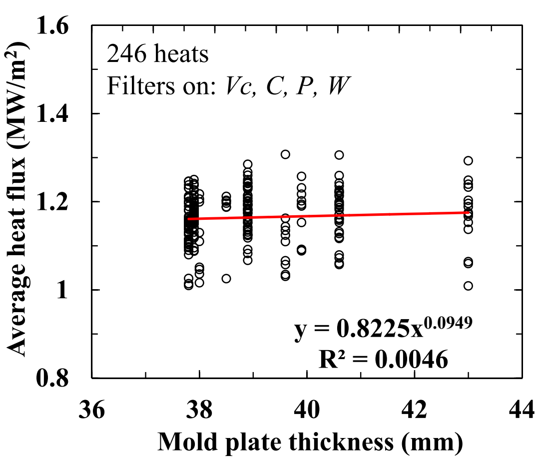
OBSERVED:

- **The effect of mold level standard deviations on mold heat flux is very small**
- This may be due to the way mold level signals are recorded and filtering of mold level deviations before entering the database

EXPECTED:

- ***Higher mold level fluctuations*** result in deeper oscillation marks, thus increasing gap resistance ***lowers heat flux****[1,8,11]*

Tuscaloosa caster: Influence of mold plate thickness



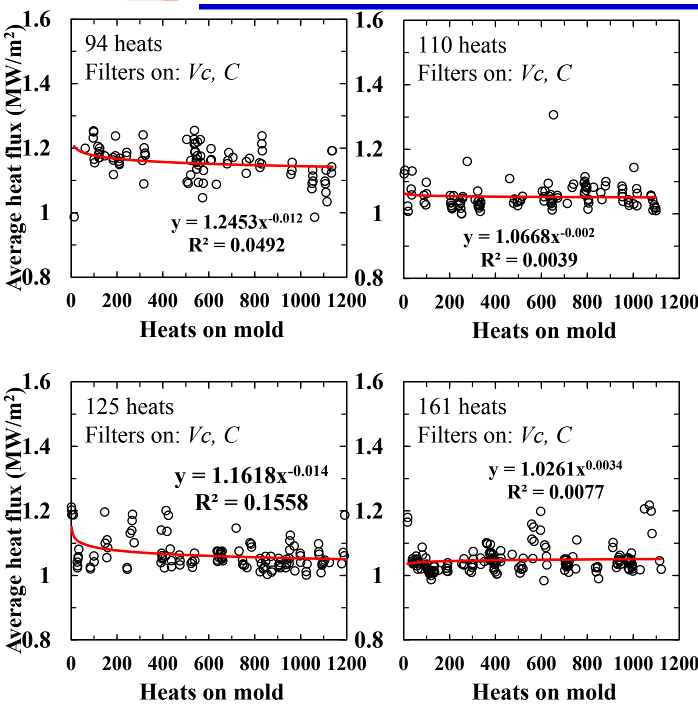
OBSERVED:

- **Mold plate thickness has little effect on mold heat flux**
- Adjusting water flow rates with plate thickness and not accounting for mold wear during campaign may affect trend

EXPECTED:

- As ***mold plate thickness decreases***,
  - hot face temperature decreases, solid slag layer velocity increases, thus decreasing solid slag layer thickness and its resistance across gap resulting in ***higher mold heat flux***[4]
  - thinner mould resistance also slightly contributes to ***higher heat flux***
  - Alternatively, solidifies thicker slag layer, with more crystallization, increasing gap resistance, so ***decreasing heat flux***[5]
- ***So: different trends are observed***

Tuscaloosa caster: Influence of mold wear during a campaign



OBSERVED:

- Heat flux **decreases** slightly with increasing heats and wear

AS EXPECTED:

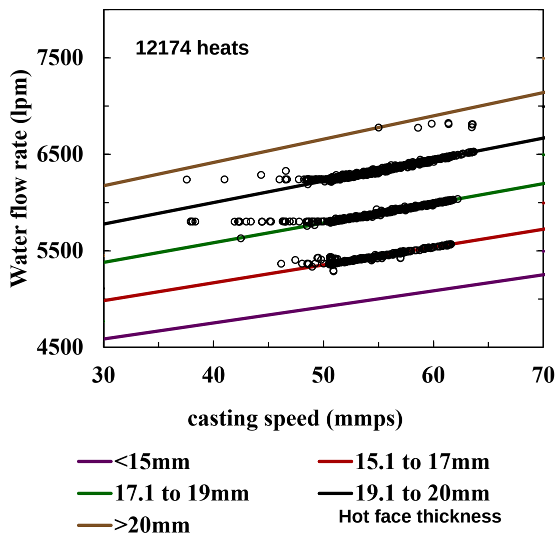
Increasing heats on mold, during a campaign causes:

- surface roughness increases due to wear, increasing contact resistance resulting in ***lower heat flux***
- thermal fatigue cracks and wear may increase adherence of solid flux film leading to more crystallization and **lowering heat flux**

Nucor Decatur Caster: Effect of hot face thickness and hot face temperature

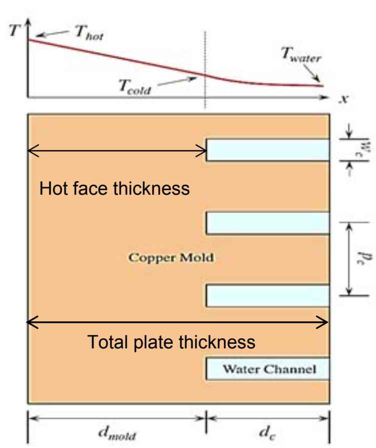
Nucor Decatur caster: Water curves

- Relation between water flow rates and mold plate thickness are investigated for Nucor Decatur caster
- From water curve table[12], water flow rates in the mold channels are adjusted based on
    1. Hot face thickness (≈ 15-21 mm): Higher the thickness, higher the flow rates
    2. Casting speed: Higher flow rates for increasing speeds
    3. Mold copper geometry: Higher flow rates for 15 mm slots than 20 mm slots
    4. Grade: Higher flow rates for low carbon steel



Calculation of hot face thickness and hot face temperature

- Nucor Decatur has 15 mm slot (depth of water channel) mold geometry
- **Total Plate thickness** ≈ 31 - 36.5 mm
- **Hot face thickness** ≈ 15 - 21 mm
- Hot face thickness values for heats are obtained from plant reports



Mold geometry[13]

Hot face temperature[13-Eqns 5-12] is calculated as:

- $T_{hot} = T_{water} + q_{hot}\left(\frac{1}{h_{cold}} + \frac{d_{mold}}{k_{mold}}\right)$
- $q_{hot} = 2.1\ kW/m^2$ - considered as a constant
- $\frac{1}{h_{cold}} = \frac{d_{scale}}{k_{scale}} + \frac{1}{h_w}$
- d_{scale}= 0 – assumed as there no measurements

$$h_w = h_{water}\frac{w_c}{p_c} + \frac{1}{p_c}\sqrt{2(p_c - w_c)h_{water}k_{mold}}\tanh\left(d_c\sqrt{\frac{2}{(p_c - w_c)}\frac{h_{water}}{k_{mold}}}\right)$$

- But measurements are available only for T_{inlet} and ΔT, from which T_{water} is calculated as

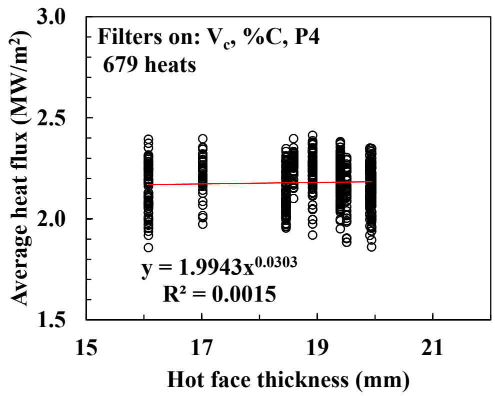
$$T_{water} = T_{inlet} + 0.5*(\Delta T)$$
$$T_{cold} = 58.98\ °C\ [13]$$
$$T_{film} = 0.5*(T_{cold} + T_{water})$$

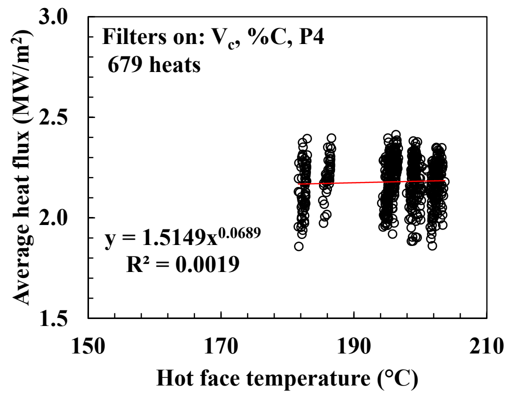
Filters on Nucor Decatur caster

- Following filters are applied on Nucor North caster to investigate the effect of hot face thickness and hot face temperature

Casting variable	Filter criterion	Remaining heats (of 14,137 total)
With HFT values		12174
Constant casting speed	variation in $V_c \leq 2$ mm/s	11288
Mold powder type	excluding trial powders	11276
Constant mold width	variation in $W \leq 1$ mm	9178
Realistic super heat	$0 \leq s \leq 50$ °C	9041
Realistic mold level standard deviation	$l \leq 3$ mm	9039
Slot depth	$14.90 \leq d_c$ (TPT-HFT) ≤ 15.1 mm	4783
Water flow rates following water curve table	$Q_w \leq 6600$lpm	4776
Casting speeds following water curve table	$V_c \geq 50$ mm/s	4730
Casting speed	3.02-3.05 m/min	
Carbon percent(%)	0.0348-0.0545	Secondary filters
Mold powder	P4	

Nucor Caster: Effect of hot face thickness and hot face temperature





- The results showed that there is a little effect of hot face thickness and hot face temperature on mold heat flux

- Hence, they are not included in the model development

Model development: Non-linear regression

- Based on combined data of ***Nucor casters*** { Decatur (9022 heats) and Tuscaloosa (3531 heats) }, non-linear regression analysis is performed in MATLAB to develop the equation

- **Residual function:** The difference between each measured heat flux and predicted value

$$R(x) = Q_{meas,i} - Q_{pred,i}(x)$$

- The objective is to find a minimum for the residual function

- ***Fminsearch*** function based on Nelder-Mead Simplex (search) algorithm is employed for unconstrained nonlinear optimization of residual function

Model development

- **Stepwise forward selection** is performed in developing models with different combinations

- For each structure, best fit parameters are determined with 100 different initial guesses

- **Model Selection:**

  Model is selected based on statistical measures

  1. Residual sum of squares (RSS): The smaller the RSS, the better the model.

  $$RSS = \sum_{i=1}^{n}(y_i - f(x_i))^2$$

  2. Akaike Information Criterion (AIC): AIC measures the trade-off between the goodness of fit and complexity of the model.

  A smaller AIC indicates a better model.

  $$AIC = -2L + 2k$$

Model development: Structure of the equation

Structure of the equation assumed is

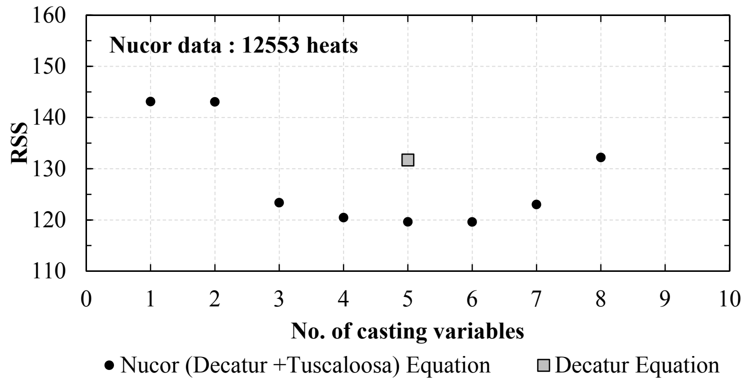
$$Q = x_1 \cdot V_c^{x_2} \cdot T_{break}^{x_3} \cdot W^{x_4} \cdot \mu^{x_5} \cdot s^{x_6} \cdot t^{x_7} \cdot l^{x_8} \left(1 - 0.152 \cdot \exp\left(-x_9 \left(\frac{\left(\frac{C_A + C_B}{2}\right) - \%C}{C_B - C_A} \right)^2 \right) \right)$$

- Q - predicted mold heat flux (MW/m^2)
- V_c - casting speed (m/min)
- T_{break} - break point temperature of the powder (°C)
- W - width of the slab (mm)
- μ - mold slag viscosity (Pa-s)
- S - superheat (°C)
- t - thickness of the mold plate (mm)
- l - standard deviation of the mold level (mm)
- $\%C$ - carbon amount (weight %), C_A & C_B – Peritectic predictors
- x_i, $i = 1, 2, .., 9$ - fitting parameters

Nucor data (Decatur + Tuscaloosa) : Models with statistical measures

Model	RSS	AIC
$Q = 1.059 \cdot V_c^{0.646}$	143.110	-56159.363
$Q = 1.247 \cdot V_c^{0.645} \cdot \left(1 - 0.152 \times \exp\left(-0.115 \times \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	143.054	-56162.298
$Q = 28.272 \cdot 10^3 \cdot V_c^{0.570} \cdot T_{break}^{-1.414} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	123.379	-58017.657
$Q = 15.285 \cdot 10^3 \cdot V_c^{0.609} \cdot T_{break}^{-1.403} \cdot W^{0.068} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	120.455	-58316.780
$Q = 37.594 \cdot 10^3 \cdot V_c^{0.590} \cdot T_{break}^{-1.529} \cdot W^{0.066} \cdot \mu^{-0.010} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	119.626	-58401.385
$Q = 39.263 \cdot 10^3 \cdot V_c^{0.588} \cdot T_{break}^{-1.529} \cdot W^{0.065} \cdot \mu^{-0.01} \cdot t^{-0.011} \cdot \left(1 - 0.152 \cdot \exp\left(0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	119.616	-58400.473
$Q = 35.262 \cdot 10^3 \cdot V_c^{0.586} \cdot T_{break}^{-1.498} \cdot W^{0.061} \cdot \mu^{-0.008} \cdot t^{-0.032} \cdot l^{0.012} \cdot \left(1 - 0.152 \cdot \exp\left(0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	123.009	-58047.386
$Q = 30.07 \cdot 10^3 \cdot V_c^{0.591} \cdot T_{break}^{-1.492} \cdot W^{0.062} \cdot \mu^{-0.008} \cdot l^{0.012} \cdot t^{-0.003} \cdot s^{0.00} \left(1 - 0.152 \cdot \exp\left(0.061 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$	132.194	-57141.347

Nucor data: Models with statistical measures



- Thus, for Nucor data, ***model with 5 casting variables*** is the best model before the jump in RSS and from now is referred as ***Nucor Equation***

$$Q = 37.594 \cdot 10^3 \cdot V_c^{0.590} \cdot T_{break}^{-1.529} \cdot W^{0.066} \cdot \mu^{-0.010} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right)^2\right)\right)$$

Tuscaloosa data: Best model

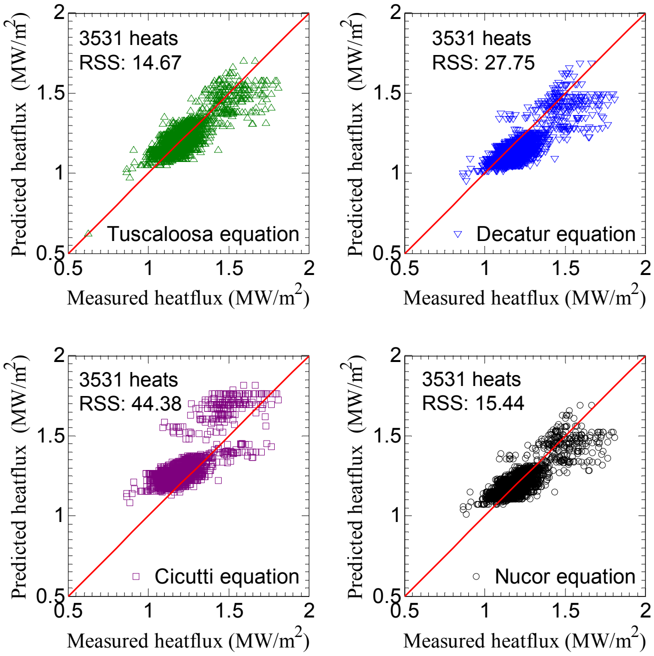
- Similarly, the recommended form of mold heat flux predicting equation based on Tuscaloosa caster (3531 heats) alone is

$$Q = 2.676 \cdot 10^3 \cdot V_c^{0.740} \cdot T_{break}^{-1.188} \cdot W^{0.09} \cdot \mu^{-0.014} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right)^2\right)\right)$$

RSS = 14.67 and R^2 =0.69

Q - predicted mold heat flux (MW/m^2)
V_c - casting speed (m/min)
T_{break} - break point temperature of the powder (°C)
W - width of the slab (mm)
μ - mold slag viscosity (Pa-s)
$\%C$ - carbon amount (weight %)
C_A, C_B - Peritectic predictors

Performance of different predicting equations on Tuscaloosa data

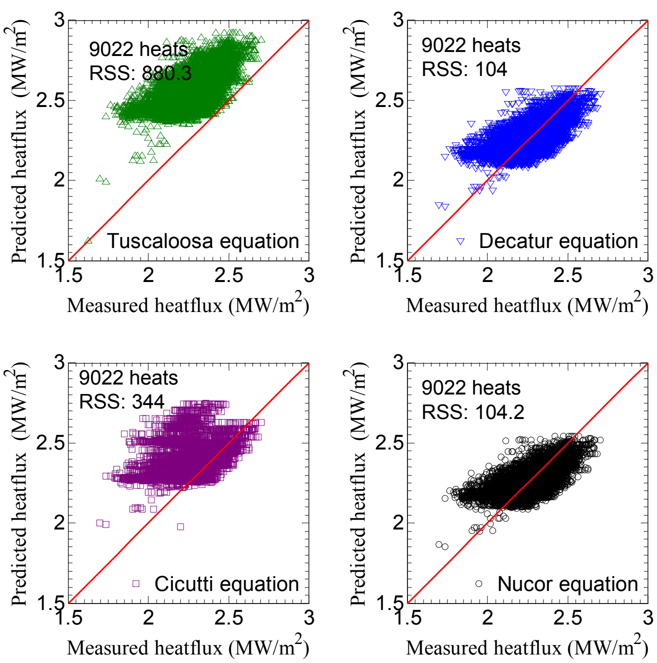


Tuscaloosa caster (3531 heats)

	RSS	R^2	AIC
Tuscaloosa	14.67	0.69	-19352
Decatur	27.75	0.414	-17102
Nucor	15.44	0.674	-19173
Cicutti	44.38	0.063	-15446

- Tuscaloosa equation performs ~same as Nucor equation
- Decatur equation is underpredicting heat flux
- On Tuscaloosa caster, Nucor equation is performing better than Decatur and Cicutti equations

Performance of different predicting equations on Decatur data



Decatur caster (9022 heats)

	RSS	R2	AIC
Tuscaloosa	880.3	-3.75	-20986
Decatur	104	0.439	-40259
Nucor	104.2	0.438	-40239
Cicutti	344	-0.86	-29464

- On Decatur caster, Tuscaloosa equation is overpredicting heat flux
- Nucor equation performs ~same as Decatur equation and much better than Cicutti equation

Mold heat flux: predicting equation

- Thus, the recommended form of mold heat flux predicting equation for any plant is

$$Q = 37.594 \cdot 10^3 \cdot V_c^{0.590} \cdot T_{break}^{-1.529} \cdot W^{0.066} \cdot \mu^{-0.010} \cdot \left(1 - 0.152 \cdot \exp\left(-0.0 \cdot \left(\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)} \right)^2 \right) \right)$$

Q - predicted mold heat flux (MW/m^2)

V_c - casting speed (m/min)

T_{break} - break point temperature of the powder (°C)

W - width of the slab (mm)

μ - mold slag viscosity (Pa-s)

$\%C$ - carbon amount (weight %)

C_A, C_B - Peritectic predictors

Conclusions

1. Average mold heat flux over the wide face of a slab caster at Nucor Tuscaloosa steel mill with 9,700 heats is investigated using measurements of nine casting variables.

2. Equations to predict mold heat flux as a function of casting variables are developed.

   The recommended "Nucor" equation performs well on both casters and better than the Cicutti equation originally developed for a thick slab caster

Conclusions for individual trends

1. Casting speed has a clear, strong influence, positively correlating with heat flux.
2. The influence of carbon content is not observed because of non-availability of data for peritectic steels but incorporated for general application of the model to other casters.
3. Mold powder properties differ between measurement methods and manufacturers. In addition, only a few different mold powders were investigated, and mold powder property data was limited. More work is needed on mold powder effect.
4. There is a strong correlation between break point temperature and basicity of mold powder. Thus only break point temperature and viscosity or mold powder are considered in the model development. Compared to break point temperature, viscosity of mold powder has a weaker effect
5. Though not evident in individual trends, regression analysis showed that mold width has an effect on mold heat flux
6. The effects of superheat, mold plate thickness, and mold level standard deviation are not evident in the data

Future work

- Apply rigorous statistical techniques presented here to evaluate other important relationships using *big data* - base analysis
- Especially needed is information on peritectic grades and additional mold powders
- Evaluate new equation at other casters

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