CCC Annual Report

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# PREDICTION OF MOLD HEAT FLUX FROM CASTING PARAMETERS


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## Background

- Heat transfer in the continuous casting mold has a critical influence on strand surface quality, casting productivity and operating safety[1]
- Previous studies by Cicuitti et al [2] have shown that mold heat transfer is mainly influenced by casting speed, steel carbon content and the properties of mold powder

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

where $\mu$ is the mold slag viscosity (Pa-s), $T_{melt}$ is the melting temperature of the powder (°C), $V_c$ is the casting speed (m/min) and $\%C$ is the weight percent of carbon

# Objectives

**Based on statistical analysis of extensive plant measurements,**

1. Investigate the effect of various casting parameters on the thermal behavior of mold

2. Develop an expression to predict total heat flux in the mold as a function of casting parameters

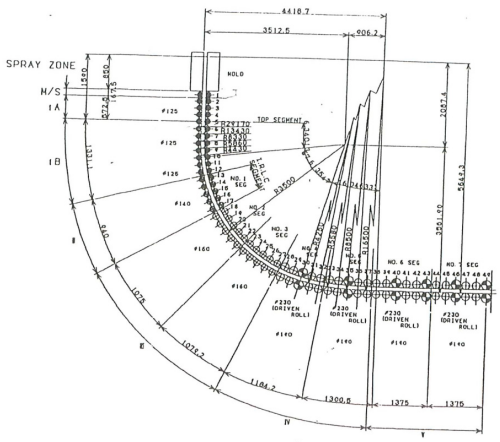


# Outline

- **Procurement of data from the plant database**
  - Use SQL query to collect data from 2.5 years of measurements
  - Apply “primary filters” to remove unreliable heats
- **Effect of individual casting parameters on heat flux**
  - Apply “secondary filters” to isolate the effect of individual parameters
  - Evaluate trends
- **Non-linear Multiple Regression**
  - Validate: test method on a known relationship
  - Apply to determine mold heat flux equation
    - Choose form of nonlinear equation
    - Optimize parameters based on “primary filtered” data
    - Analyze results

# Measured mold heat flux data: Nucor Steel Decatur, AL

1. Nucor Decatur has two casters (North and South)
   - Thin (90mm) CSP slab casters
   - Parallel mold with working length 850 mm
2. Nucor Decatur keeps a wide data base of measurements recorded at 10 sec intervals
3. Special thanks to Ron O'Malley, Bob Williams, and others at Nucor Steel Decatur for providing access and valuable guidance for this project




**Nucor Decatur caster**

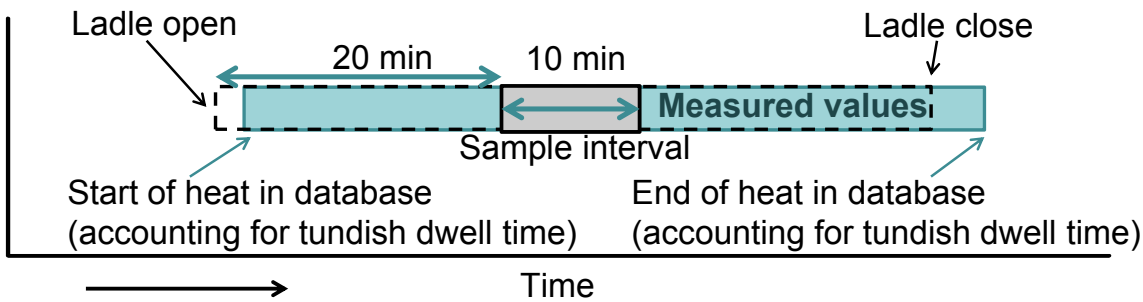


# Nucor Decatur SQL database query: Sample interval

**DATA:**

| Caster | Period | No. of Heats |
|---|---|---|
| North Caster | 01/01/2011 to 06/20/2013 | 16,197 |
| South Caster | 01/01/2011 to 06/20/2013 | 16,348 |

- From each heat, (typically 50 minutes), select 10 min of data, starting 20 min after the ladle is opened
- Extract average, maximum and minimum values of each parameter



# Nucor Decatur SQL database query: Location of measured parameters

| Database | Variables | | Units |
|---|---|---|---|
| prod_live.. caster_heat_data | ladle_open_dt | Date | Yr day |
| | ladle_close_dt | | Hr,m,s |
| measured_values.. caster_mv | caster_id | | |
| | heat_no | | |
| | **actual_cast_speed** | | mm/s |
| | mold_water_flow_1 | Water flow rate (1-Fixed face, 2-Loose face) | lpm |
| | mold_water_flow_2 | | |
| | delta_t1, delta_t2 | Raise in water temperature | °C |
| | **mold_width_hot** | | cm |
| | inlet_temperature | | °C |
| | tundish_temperature1_cont | | °C |
| | **superheat_cont** | | °C |
| | mold_level_dev,mold_level | | cm |
| | **st.dev** from mold_level_dev | formal standard deviation of mold level calculated from 60 points (10 min of data at 10 s intervals) | cm |
| prod_live.. heat_chemistry | **C_amount** | | wt % |
| | **$C_{Eq}$, $C_A$, $C_B$** | Calculated from the composition of steel | % |
| prod_live.. caster_report_cast_info | mold_no | | |
| | **main_powder** | Viscosity & Melting temperature of the mold powder are taken from the summary sheet supplied by Nucor Decatur metallurgists | |
| | heats_on_mold | | |
| | **fixed_value** | Mold plate thickness of fixed face | mm |
| | loose_value | Mold plate thickness of loose face | mm |

* Parameters in bold are possible independent variables for finding correlations



# Database query: Calculated parameters

- (Total) Mold heat flux[2] was calculated as

$$Q = \frac{0.00006794 * G * \Delta T}{W * Z}$$

where $Q$ = heat flux (MW/m$^2$)
$G$ = mold water flow rate (l/min)
$\Delta T$ = temperature rise of mold water (°C)
$W$ = width of the slab (m)
$Z$ = working length of the mold (m)

- Equivalent Carbon[1] (for predicting peritectic grades) is calculated as

$$C_{Eq} = C + 0.02 * Mn - 0.037 * Si + 0.023 * Ni - 0.0189 * Mo - 0.7 * S + 0.0414 * P + 0.003 * Cu - 0.0254 * Cr - 0.0276 * Ti + 0.7 * N$$

# Database query: Calculated parameters

- Grade of the steel[3] can also 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 concentration in mass-%.

*Tungsten not recorded in database



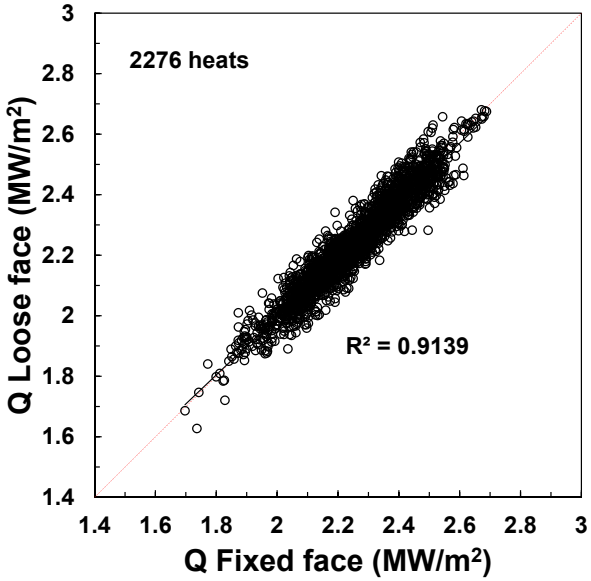
# Filtering of raw data

- **Primary Filters**: used to select "reliable" heats with only realistic and reasonable variations of the casting parameters in the 10 min time interval

| | | Out of 16196 total heats |
|---|---|---|
| A. | Excluding trial mold powders | **16123** |
| B. | Constant casting speed (variation ≤ 2 mm/s) | **14792** |
| C. | Constant mold width (variation ≤ 0.1 cm) | **12122** |
| D. | Realistic super heat (≤ 150 °C) | **11999** |
| E. | Within first 100 heats on a mold (to ensure measurement of mold plate thickness is still accurate) | **2276** |

- **Secondary Filters**: to isolate effect of each parameter by keeping other parameters constant. Filters change for each parameter. Common secondary filters:
  - Low carbon content (%C < $C_A$)
  - Super heat (25 to 40°C)
  - Mold width (125-130 cm)
  - Particular mold powder

# Effect of mold face on heat flux

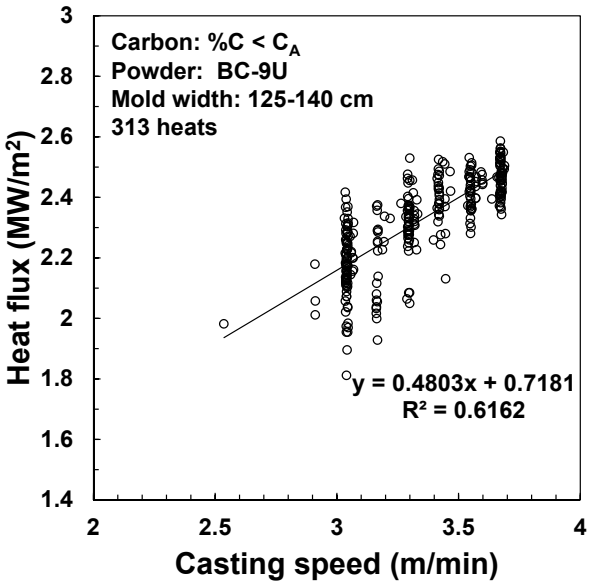



No significant difference in the heat flux extracted between the fixed and loose wide faces

**Thus, fixed face is considered for analysis**



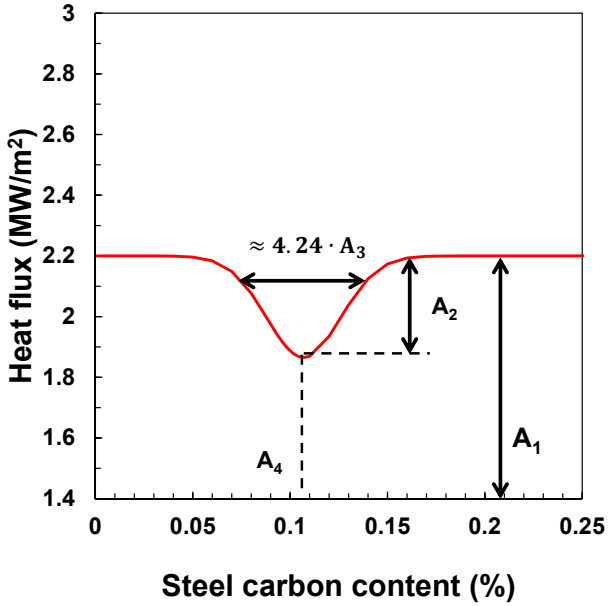
# Effect of casting speed




| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Low Carbon (%C < $C_A$) | 1651 |
| Mold powder BC-9U | 1532 |
| Mold width between 125 and 130 cm | 313 |

**Heat flux increases with casting speed**

# Effect of carbon content



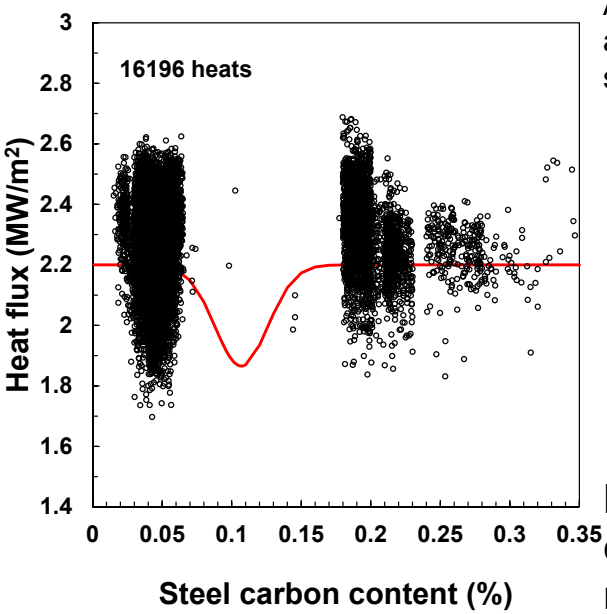

Cicuitti et al [2] use a nonlinear formula to account for the drop in heat flux for peritectic steels:

$$Q = A_1\left\{1 - \left(\frac{A_2}{A_1}\right) exp\left[-\left(\frac{A_4 - \%C}{A_3}\right)^2\right]\right\}$$

- $A_1$: average heat flux far away from peritectic
- $A_2$: maximum drop in heat flux in peritectics
- $A_3$: parameter describing the width of the heat flux drop
- $A_4$: "critical" steel composition where heat flux is smallest



# Effect of carbon content (16196 heats)




Adapting Cicuitti et al[2] formula to account for heat flux with peritectic steels:

$$Q = A_1\left\{1 - \left(\frac{A_2}{A_1}\right) exp\left[-\left(\frac{A_4 - \%C}{A_3}\right)^2\right]\right\}$$

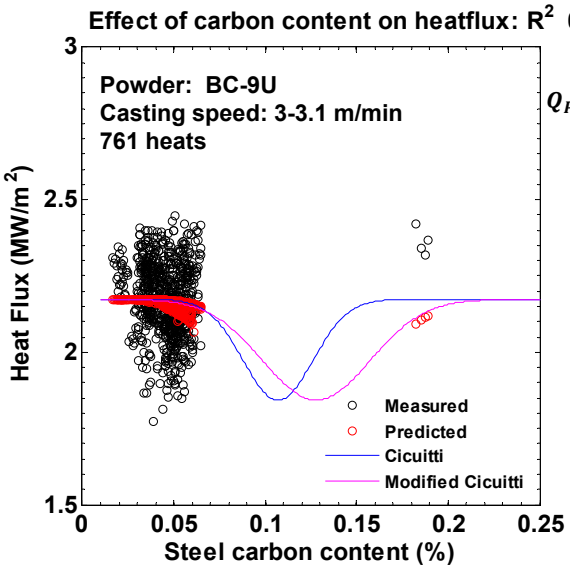
$A_1 \approx 2.2\ \mathrm{M}\frac{W}{m^2}$ (changed from [2] to reflect average heat flux at Nucor Decatur)

$\frac{A_2}{A_1}$ = 0.152; $A_3$ = 0.027; $A_4$ = 0.107;

(all the same as [2])

**Nucor Decatur does not cast peritectics, so there is no data on the heat flux drop**

# Effect of carbon content: in terms of $C_A$ and $C_B$




$$Q_{Pred} = Q_{mean} \cdot \left\{ 1 - 0.152 \cdot exp\left[ -A_5 \left( \frac{\frac{C_A + C_B}{2} - \%C}{C_B - C_A} \right)^2 \right] \right\}$$

- Cicuitti's formula for heat flux drop in peritectics was modified with terms using $C_A$ and $C_B$, with an additional coefficient $A_5$ to describe the width of the heat flux drop
- The optimum value of $A_5$ was determined to be 2.405
- **This structure is employed in predicting heat flux to include the effect of carbon**



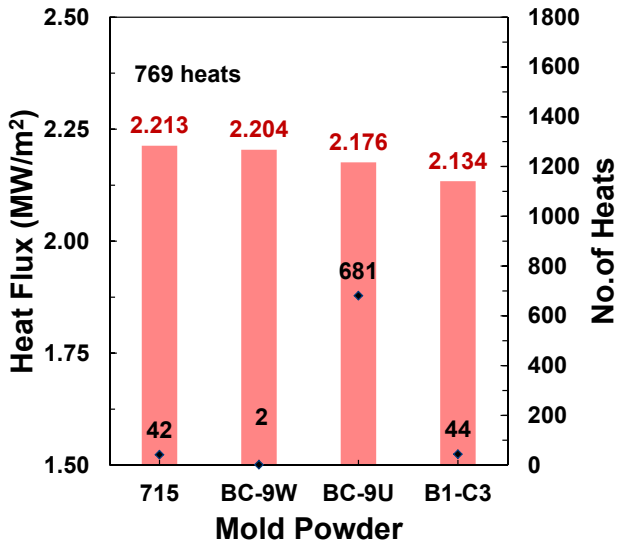
# Effect of mold powder

| Powder Name | Basicity | $SiO_2$ | CaO | F | Viscosity dPa-s @ 1300 °C | Calculated Break Point / Crystallization Temp, °C | Heat flux (MW/m²) | No. of heats |
|---|---|---|---|---|---|---|---|---|
| 715 | 1.09 | 29.2 | 31.8 | 9.1 | 0.70 | 1108 | 2.375 | 367 |
| BC-9U | 1.00 | 31.3 | 31.3 | 7.7 | 0.80 | 1129 | 2.249 | 1677 |
| BC-9W | 1.05 | 30.9 | 32.5 | 7.7 | 0.80 | 1147 | 2.235 | 4 |
| B1-C3 | 1.33 | 26.4 | 35.2 | 10.3 | 0.20 | 1158 | 2.194 | 195 |
| AHG-40X | 1.25 | 30.7 | 38.4 | 9.0 | 0.5 | 1100 | 2.122 | 34 |

| Of 2276 heats after primary filtering | Low | Peritectic | High |
|---|---|---|---|
| 715 | 65 | 33 | 269 |
| BC-9U | 1662 | 5 | 10 |
| BC-9W | 4 | | |
| B1-C3 | 95 | 4 | 95 |
| AHG-40X | 1 | 3 | 30 |

- **Carbon grade and mold powder are related.**
- **BC- 9U is the common mold powder for low carbon steels**

# Effect of mold powder

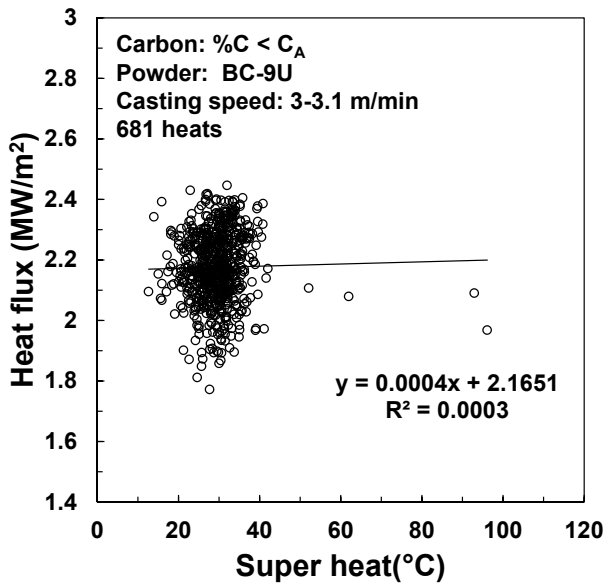



| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Casting speed 3-3.1m/min | 1043 |
| Low Carbon (%C < $C_A$) | 769 |

- **With 42 heats each, heat extraction of powder 715 is higher than that of B1-C3**
- **Owing to fewer/unequal number of data here, the effect of viscosity and melting temperature of mold powder on heat flux cannot be observed**



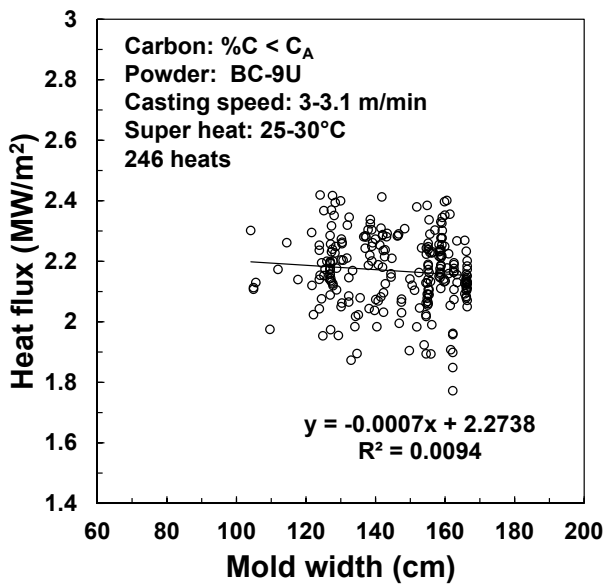
# Effect of superheat




| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Low Carbon (%C < $C_A$) | 1651 |
| Mold powder BC-9U | 1532 |
| Casting speed 3-3.1m/min | 681 |

**There is little correlation between super heat and heat flux**

# Effect of mold width

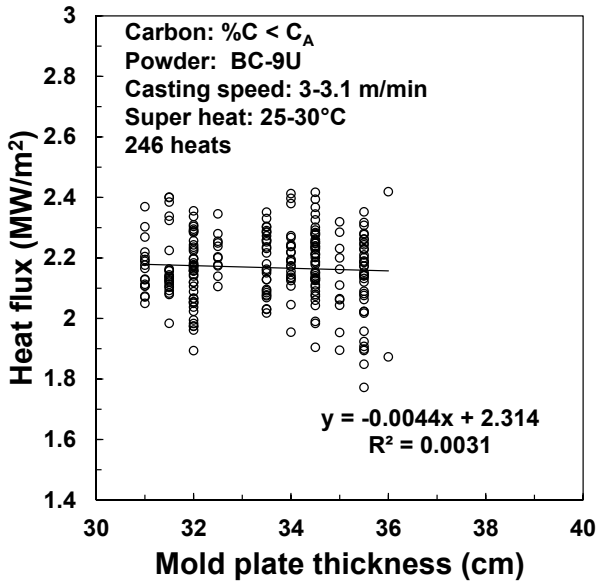



| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Low Carbon (%C < $C_A$) | 1651 |
| Mold powder BC-9U | 1532 |
| Casting speed 3-3.1m/min | 681 |
| Super heat 25-30°C | 246 |

- Increasing width makes the low heat flux in corners less important, thus should increase heat flux
- BUT: we don't see this because of cross correlation with speed:
- Narrower slabs tend to be cast with higher speed, which has higher heat flux
- Multiple regression is needed to properly resolve this issue



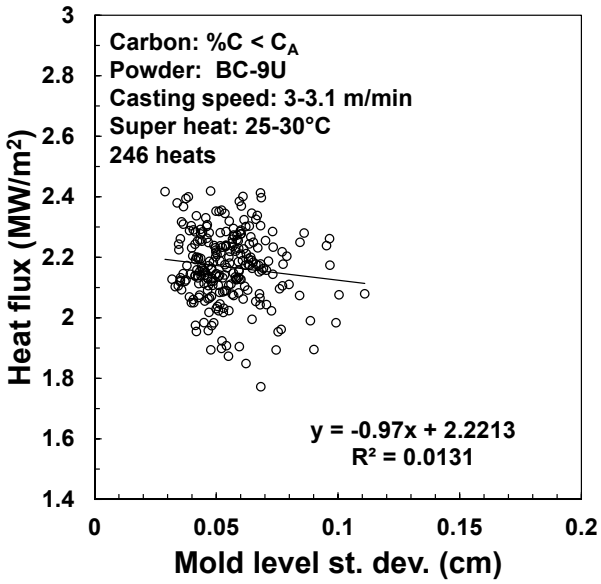
# Effect of mold plate thickness




| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Low Carbon (%C < $C_A$) | 1651 |
| Mold powder BC-9U | 1532 |
| Casting speed 3-3.1m/min | 681 |
| Super heat 25-30°C | 246 |

**Little correlation between mold plate thickness and heat flux**

# Effect of mold level variation (Standard deviation)

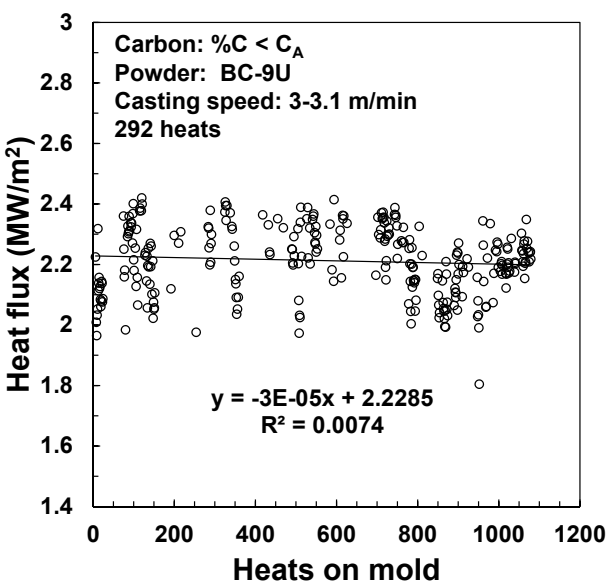



| Secondary filters | Remaining heats |
|---|---|
| After primary filters | 2276 |
| Low Carbon (%C < $C_A$) | 1651 |
| Mold powder BC-9U | 1532 |
| Casting speed 3-3.1m/min | 681 |
| Super heat 25-30°C | 246 |

**Higher mold level fluctuations make deeper oscillation marks and lower heat flux, but effect is small.**



# Effect of Heats on mold

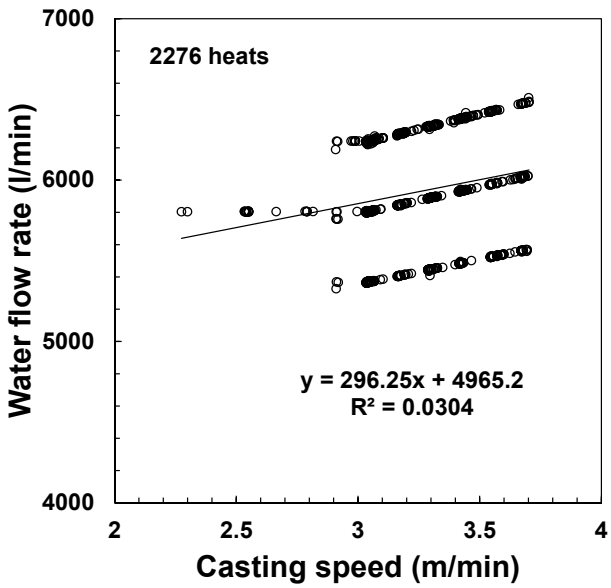



| Filters | Remaining heats |
|---|---|
| One mold "campaign" | 845* |
| After primary filtering | 845 |
| Low Carbon (%C < $C_A$) | 619 |
| Mold powder BC-9U | 607 |
| Casting speed 3-3.1m/min | 292 |

- **As the thickness of the mold plate decreases (with increase in the number of heats on a mold), heat flux might drop due to thicker slag layer and deeper oscillation marks**
- **But large scatter with low $R^2$ value indicates little correlation**

* Not all heats from the campaign are in the database

# Cross correlation: Water flow rate increases with casting speed

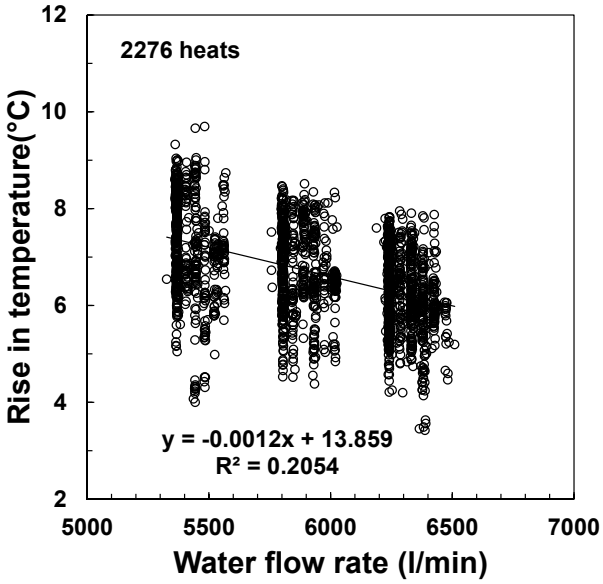



There are three clearly separate "patterns" that are used in the data

For all three patterns, as casting speed increases, water flow rate is also increased.



# Cross correlation: Water temp. rise decreases with increased flow rates




Rise in water temperature is lower at higher water flow rates

(because heat flux – multiple of the two – is generally constant with water flow rate)

Due to previous result, temperature rise also decreases with increasing casting speed

# Regression: Introduction

- **Coefficient of determination ($R^2$):** $R^2 = 1 - \frac{SS_{res}}{SS_{tot}}$

  where Sum of squares of residuals: $SS_{res} = \sum_{i=1}^{n}(y_i - f_i)^2$

  Total sum of squares: $SS_{tot} = \sum_{i=1}^{n}(y_i - \bar{y})^2$

- **Adjusted $R^2$**: Adj. $R^2 = 1 - \left(\frac{Total\ df}{Residual\ df}\right)\frac{SS_{res}}{SS_{tot}}$

  $Total\ df = n - 1$ and $Residual\ df = n - p - 1$

$n$ is number of observed data points; $p$ is the number of independent variables

- **fminsearch**[4] function in MATLAB is employed to find the minimum of the scalar function: Residual equation = $\sum(Q_{Act} - Q_{Pred})^2$
  - It is an unconstrained nonlinear optimization tool based on Nelder-Mead simplex algorithm which evaluates the local minimum of a scalar function of several variables, starting at an initial estimate.

- Coefficients obtained in regression analysis of Excel are given as initial guess*



# Validation of MATLAB Nonlinear Multiple Regression Tools

- Before using MATLAB regression to find best coefficients for the heat flux prediction equation, need to validate the method
- **Test problem:** Use MATLAB to find the known heat flux equation, without giving it the constant and exponents:

$$Q = \frac{0.00006794 * G * \Delta T}{W * Z}$$

where Dependent variable is:

$Q$ = heat flux (MW/m$^2$)

Independent variables are:

$G$ = mold water flow rate (l/min)

$\Delta T$ = temperature rise of mold water (°C)

$W$ = width of the slab (m)

$Z$ = working length of the mold (m)

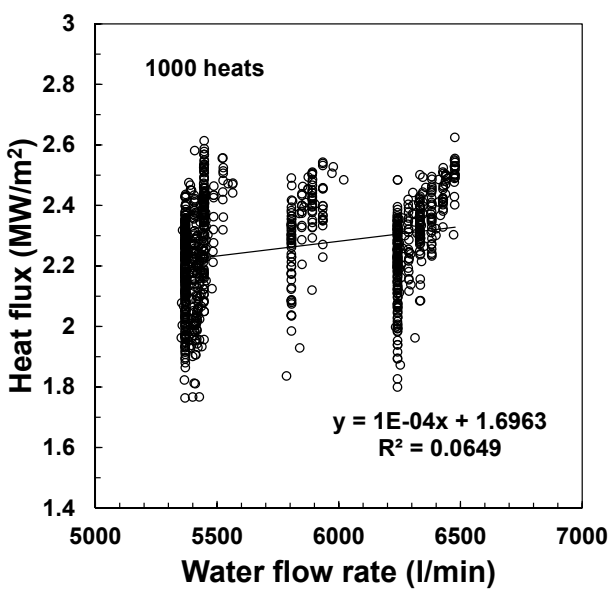
- Apply MATLAB regression (fminsearch function)
  - Assuming equation structure: $Q = x_1 * G^{x_2} * \Delta T^{x_3} * W^{x_4} * Z^{x_5}$
  - Minimize residuals to find best values of: $(x_1, x_2, x_3, x_4, x_5)$

# Validation: Matlab Code

```
clc; clear all; close all;
%Reading measured input x and y data from Excel sheet
Northcaster=xlsread('Sanity check Nucor North.xlsx','Input');
len=length(Northcaster); data=Northcaster(1:len,2:6);
G=data(:,1);dT=data(:,2);W=data(:,3);Z=data(:,4); %Independent variables on the Right hand side
ActQ=data(:,5);
Q = @(x,data)x(1)*(G.^x(2)).*(dT.^x(3)).*(W.^x(4)).*(Z.^x(5)); %Structure of the proposed
equation
reseqn = @(x) (Q(x)-ActQ)'*(Q(x)-ActQ);
x0=[0.00005 0.9 0.9 -0.9 -0.9]; %Initial guess
options=optimset('Display','iter','TolFun',1e-12,'TolX',1e-
12,'MaxFunEvals',100000,'MaxIter',10000)
[x,fval,exitflag]=fminsearch(reseqn,x0,options); %Determining the coefficients using fminsearch
function
PredQ=x(1)*G.^x(2).*dT.^x(3).*W.^x(4).*Z.^x(5);
%Calculating Regression parameters
sstot =0;ssres=0;
n=len;p=length(x);
for i=1:len
    sstot=sstot+(ActQ(i)-mean(ActQ))^2;
    ssres=ssres+(PredQ(i)-ActQ(i))^2;
end
R2=1-(ssres/sstot)
aR2=1-(1-R2)*(n-1)/(n-p-1)
%Plotting
X=1.5;Y=3;xp =X:0.1:Y;yp=xp;
set(gca,'FontSize',18,'FontWeight','bold');
plot(ActQ,PredQ,'b*'),xlim([X Y]),ylim([X Y]),xlabel('Actual heat flux
(MW/m^2)','FontSize',15,'FontWeight','bold'),ylabel('Predicted heat flux
(MW/m^2)','FontSize',15,'FontWeight','bold'), title(sprintf('Predicted Vs Actual heatflux - Adj.
R^2  %0.2f ',aR2),'FontSize',18,'FontWeight','bold')
hold on;plot(xp,yp,'k-');set(gca,'XMinorTick','on','YMinorTick','on');axis square
```



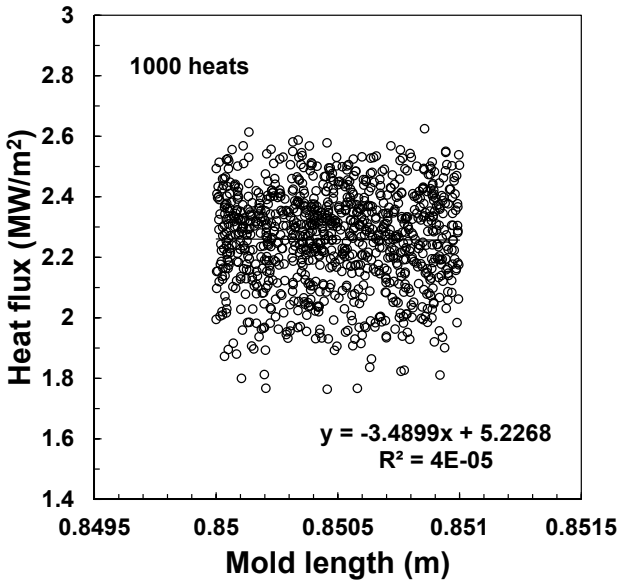
# Validation: Results for individual parameters




**Weak overall correlation between water flow rate and heat flux**

**There is a clear positive relationship when limited to a single mold water pattern, but this is likely due to the cross-correlation with casting speed.**

# Validation: Results for individual parameters




(with added uniform random noise between 0 and 0.001)

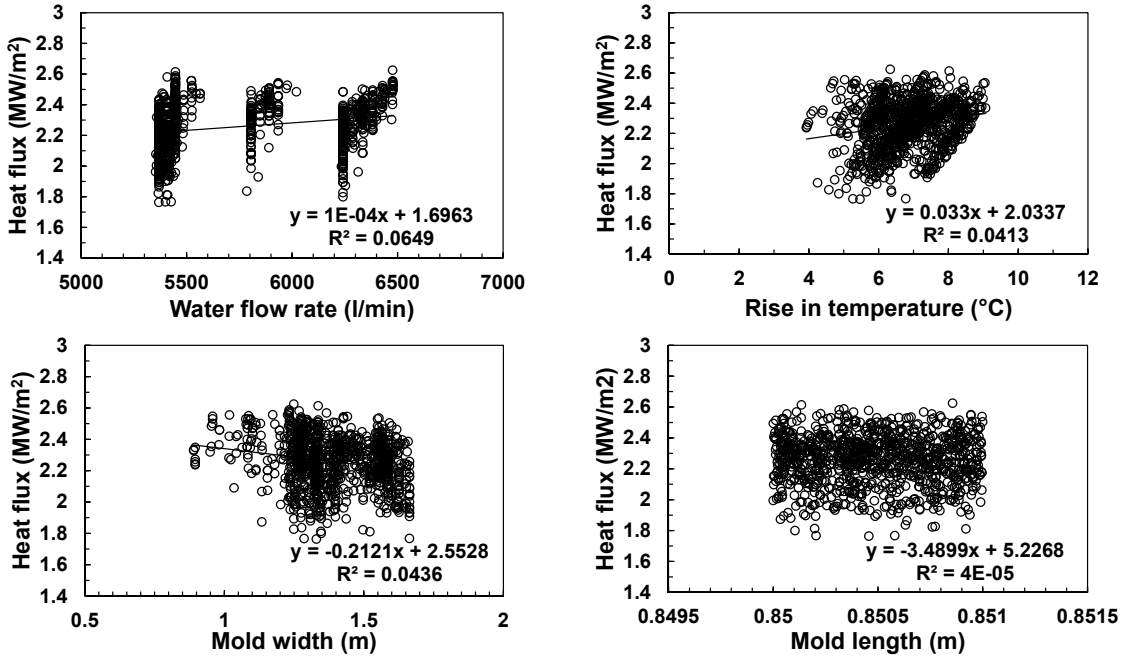
**A constant working mold length of 850 mm is assumed for calculating heat flux from the database measurements.**

**However, for the validation case, random noise was added because the optimization function failed to converge if a constant is treated as a variable.**



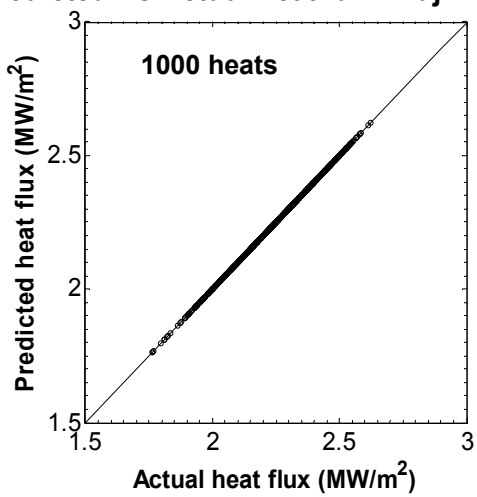
# Validation: Results for individual parameters

**Weak correlation between individual parameters and mold heat flux**



# Validation: Results for multiple regression

**Predicted Vs Actual heatflux - Adj. $R^2$ 1.00**




$$Q = x_1 * G^{x_2} * \Delta T^{x_3} * W^{x_4} * Z^{x_5}$$

| $x_1$ | $x_2$ | $x_3$ | $x_4$ | $x_5$ |
|---|---|---|---|---|
| 67.94e-006 | 1 | 1 | -1 | -1 |

$R^2$ = 1
Adj. $R^2$ = 1
which matches with the original equation

$$Q = \frac{0.00006794 * G * \Delta T}{W * Z}$$

**Output of MATLAB nonlinear multiple regression exactly matches actual data:**
**Method is being used properly**



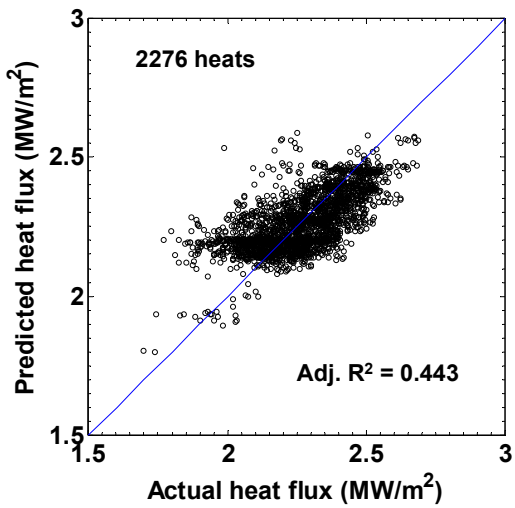
# Structure of the proposed heat flux equation

- $$\boldsymbol{Q = x_1 * V_c^{x_2} * \mu^{x_3} * T_{melt}^{x_4} * W^{x_5} * s^{x_6} * t^{x_7} * l^{x_8} * \left\{1 - \left(\frac{A_2}{A_1}\right) * \exp\left[-x_9\left(\frac{\frac{C_A+C_B}{2} - \%C}{(C_B - C_A)}\right)^2\right]\right\}}$$

Where $Q$ = heat flux (MW/m$^2$)
$V_c$ = casting speed (m/min)
$\mu$ = mold slag viscosity (Pa-s)
$T_{melt}$ = melting temperature of the powder (°C)
$W$ = width of the slab (mm)
$s$ = superheat (°C)
$t$ = thickness of the mold plate (mm)
$l$ = mold level standard deviation (mm)

# Non-linear multiple regression-MATLAB: All 8 variables

$$Q = 1.35 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.756} * s^{0.018} * W^{0.085} * t^{-0.004} * l^{0.006} * \left\{1 - 0.152 * exp\left[-\left(0.193\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$



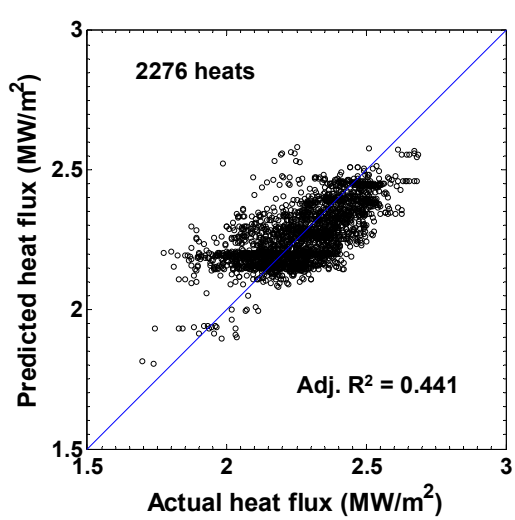

- All 8 proposed casting parameters as variables
- Note: Small exponents on –
  - Superheat ($s$)
  - Mold plate thickness ($t$)
  - Mold level standard deviation ($l$)

indicate they might be insignificant for prediction of heat flux



# Non-linear multiple regression-MATLAB: $V_C, \mu, T_{melt}, W, \%C$

$$Q = 1.24 * 10^5 * V_c^{0.69} * \mu^{-0.016} * T_{melt}^{-1.746} * W^{0.093} * \left\{1 - 0.152 * exp\left[-\left(0.203\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$

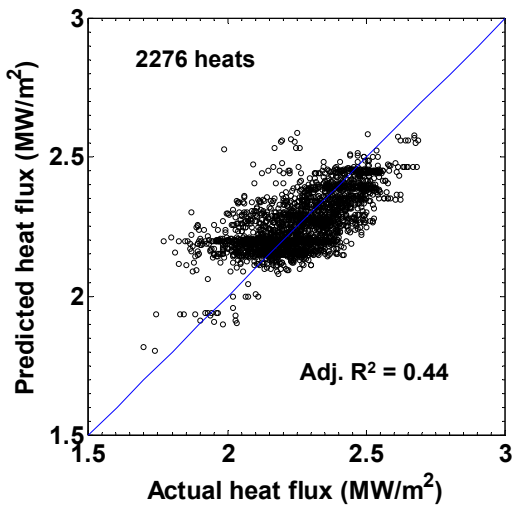



Dropped:
- Superheat ($s$)
- Mold plate thickness ($t$)
- Mold level standard deviation ($l$)

- Adj. $R^2$ changed hardly from 0.443 to 0.441 indicating little correlation of the dropped variables with heat flux

# Non-linear multiple regression-MATLAB: $V_C, \mu, T_{melt}, W$

$$Q = 0.949 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.728} * W^{0.090}$$

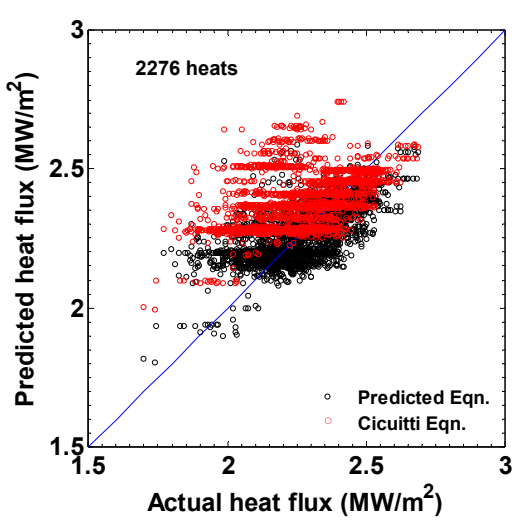



- Drop grade (%C) term
- Adj.$R^2$ barely changed
- For Nucor data without peritectics, inclusion of carbon term in the equation is not necessary
- Thus, prediction of heat flux as a function of speed, viscosity, melting temperature and width is appropriate



# Comparison of developed equation with Cicuitti Equation

$$Q = 0.949 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.728} * W^{0.090}$$




- New equation based on Nucor steel database predicts better than the Cicuitti equation
- Owing to lack of data on peritectics, heat flux can be predicted with a simpler function of only speed, viscosity, melting temperature and width, for the Nucor Decatur data base

# Mold heat flux: Predicting equation

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

$$Q = 1.24 * 10^5 * V_c^{0.69} * \mu^{-0.016} * T_{melt}^{-1.746} * W^{0.093} * \left\{1 - 0.152 * exp\left[-\left(0.203\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$

Where $Q$ = heat flux (MW/m$^2$)

$V_c$ = casting speed (m/min)

$\mu$ = mold slag viscosity (Pa-s)

$T_{melt}$ = melting temperature of the powder (°C)

$W$ = width of the slab (mm)

$\%C$ = Carbon weight percentage

$C_A, C_B$ = Peritectic predictors [3]



# Conclusions

- Starting with 16,000 heat database from Nucor Steel Decatur, non-linear multiple regression analysis with MATLAB "fminsearch" produced an empirical equation to predict mold heat flux (MW/m$^2$) with $R^2$ of 0.44 :

$$Q = 0.949 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.728} * W^{0.090}$$

- Higher casting speed strongly correlates to increasing heat flux.
- When looking at parameters with cross-correlations individually, the trends are very weak.
- Owing to insufficient data, strong cross-correlations, and weak effect on heat flux, there is little effect of steel grade, powder properties, super heat, mold width, thickness of the mold plate or mold level standard deviation
- Fits better than original Cicuitti equation, but there is still room for improvement

# Future work

- Regression analysis can be performed with different structures of the equation to try to better predict the heat flux
- Advanced non-linear optimization tools, like genetic algorithm or simulated annealing, might be employed
- The performance of the predicting equation can be studied with other casters in different mills
  - Especially needed is information on peritectic grades and additional mold powders



# References

[1] G. Xia et al, “Investigation of mould thermal behaviour by means of mould instrumentation”, Iron making and steelmaking, 2004, Vol.31, No.5

[2] C. Cicutti et al, “Mould Thermal Evaluation in a slab continuous casting machine”, Steelmaking Conf. Proc., 2002, P.97-107

[3] Blazek, Kenneth E., et al. "Calculation of the peritectic range for steel alloys." Iron & steel technology 5.7 (2008): 80-85

[4]MATLAB Help file

http://www.mathworks.com/help/matlab/ref/fminsearch.html

http://www.mathworks.com/help/matlab/math/optimizing-nonlinear-functions.html#bsgpq6p-11

# Acknowledgements


- Continuous Casting Consortium Members (ABB, ArcelorMittal, Baosteel, Magnesita Refractories, Nippon Steel and Sumitomo Metal Corp, Nucor Steel, Postech/ Posco, Severstal, SSAB, Tata Steel, ANSYS/ Fluent)
- Nucor Steel Decatur (Ron O'Malley, Bob Williams, and others)
- Professor Brian Thomas and graduate student Bryan Petrus for the valuable guidance

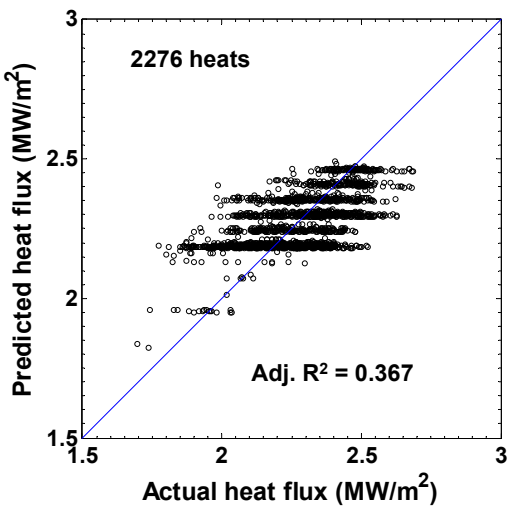



# Appendix

- Regression with different combinations of casting parameters [43-49]
- Regression with fewer primary filtering operations [50-53]

# Non-linear multiple regression: 2276 heats ($V_C$)

$$Q = 1.091 * V_c^{0.625}$$

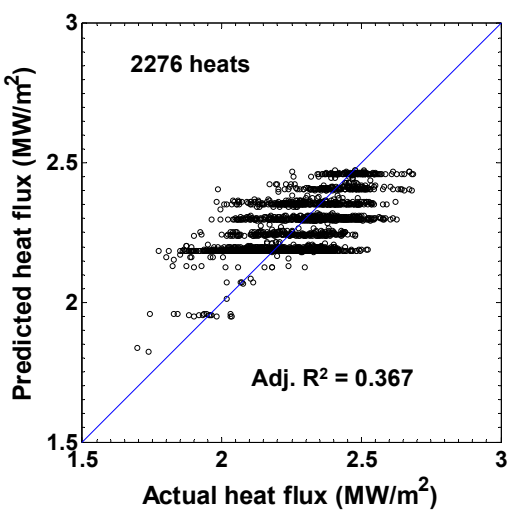



- Heat flux as a function of speed alone
- In spite of scatter, an adj.$R^2$ of 0.367 shows casting speed alone is a reasonably good indicator of heat flux



# Non-linear multiple regression: 2276 heats ($V_C$, $\%C$)

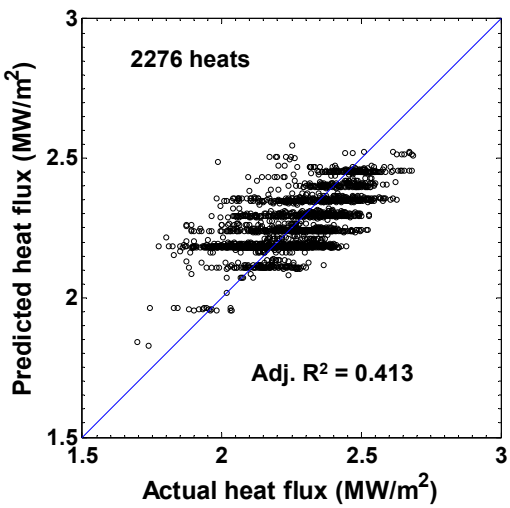
$$Q = 1.285 * V_c^{0.624} * \left\{1 - 0.152 * exp\left[-\left(0.143\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- Heat flux as a function of speed and grade
- No change in Adj. $R^2$ value even with inclusion of grade
- This equation might predict heat flux better at plants that cast peritectics

# Non-linear multiple regression: 2276 heats ($V_C, \%C, Tmelt$)

$$Q = 0.22 * 10^5 * V_c^{0.611} * T_{melt}^{-1.385} * \left\{1 - 0.152 * exp\left[-\left(0.107\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$

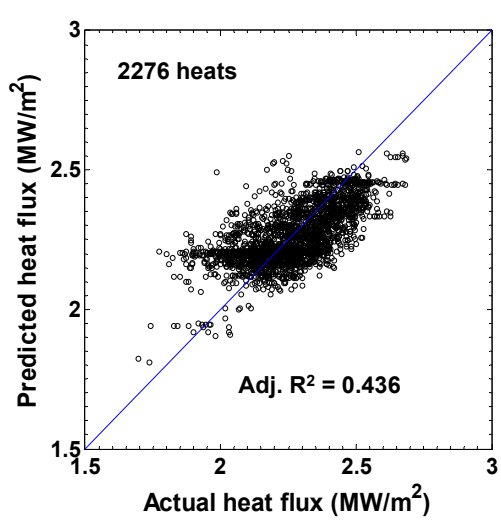



- Heat flux as a function of speed, grade and melting temperature of mold powder
- Improvement in Adj. $R^2$ value from 0.367 to 0.413 indicates significant effect of melting temperature of mold powder on heat flux



# Non-linear multiple regression: 2276 heats ($V_C, Tme_{lt}, W\ \%C$)

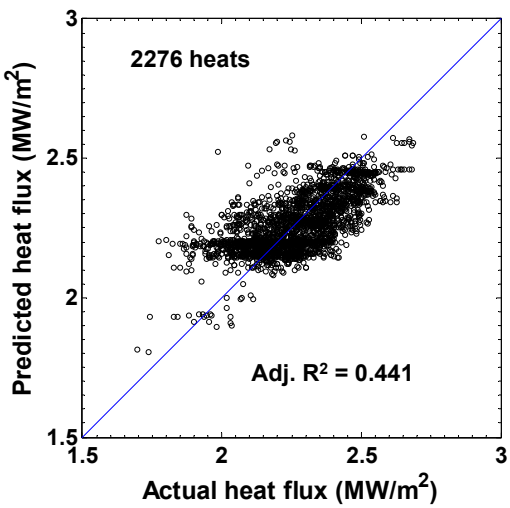
$$Q = 0.144 * 10^5 * V_c^{0.688} * T_{melt}^{-1.433} * W^{0.093} * \left\{1 - 0.168 * exp\left[-\left(0.168\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- Heat flux as a function of speed, grade, melting temperature and mold width
- Improvement in Adj. $R^2$ value from 0.413 to 0.436 indicates noticeable effect of mold width on heat flux

# Non-linear multiple regression: 2276 heats ($V_C, \mu, Tmelt, W\ \%C$)

$$Q = 1.24 * 10^5 * V_c^{0.69} * \mu^{-0.016} * T_{melt}^{-1.746} * W^{0.093} * \left\{1 - 0.152 * exp\left[-\left(0.203\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$

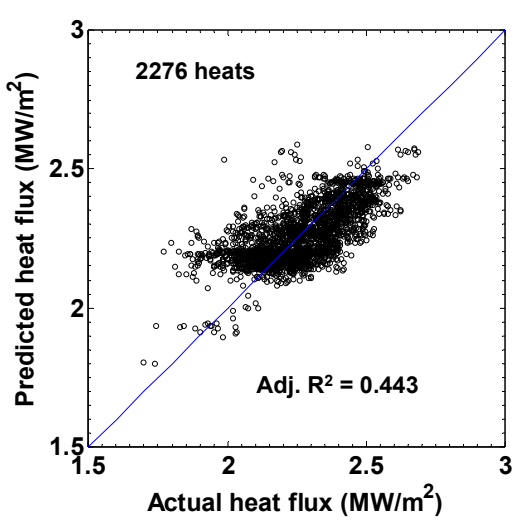



- Heat flux as a function of speed, grade, melting temperature and mold width
- Improvement in Adj. $R^2$ value from 0.436 to 0.441 indicates noticeable effect of powder viscosity on heat flux



# Non-linear multiple regression: 2276 heats ( All 8 variables)

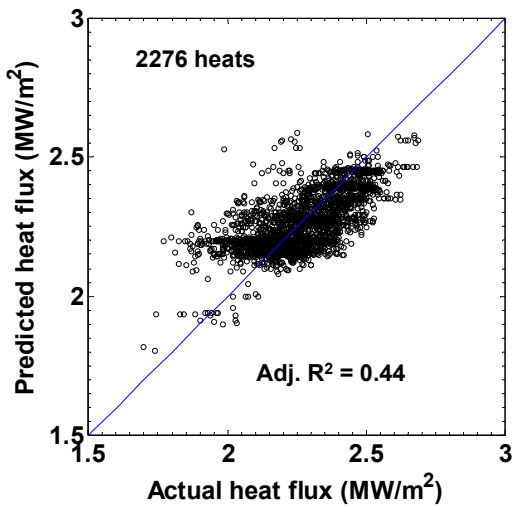
$$Q = 1.35 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.756} * s^{0.018} * W^{0.085} * t^{-0.004} * l^{0.006} * \left\{1 - 0.152 * exp\left[-\left(0.193\left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- Besides 5 variables of previous case, superheat, mold plate thickness and mold level standard deviation are considered
- Increase in Adj. $R^2$ value from 0.441 to 0.443 indicates little effect of the newly added variables in predicting heat flux

# Non-linear multiple regression: 2276 heats ($V_C, \mu, T_{melt}, W$)

$$Q = 0.949 * 10^5 * V_c^{0.691} * \mu^{-0.015} * T_{melt}^{-1.728} * W^{0.090}$$

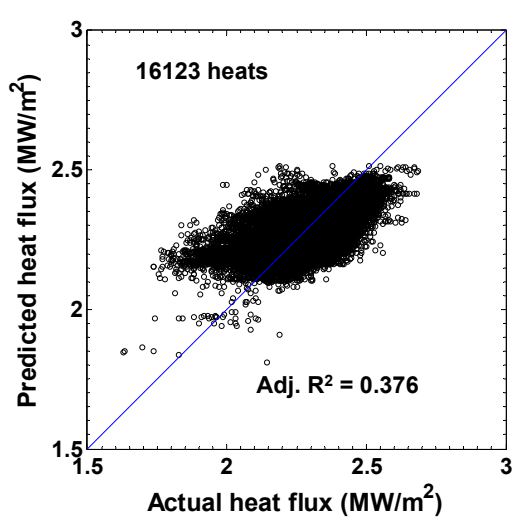



- Heat flux as a function of speed, viscosity, melting temperature and mold width
- Owing to lack of data on peritectics, prediction of heat flux as a function of speed, viscosity, melting temperature and width is appropriate



# Non-linear multiple regression: All heats

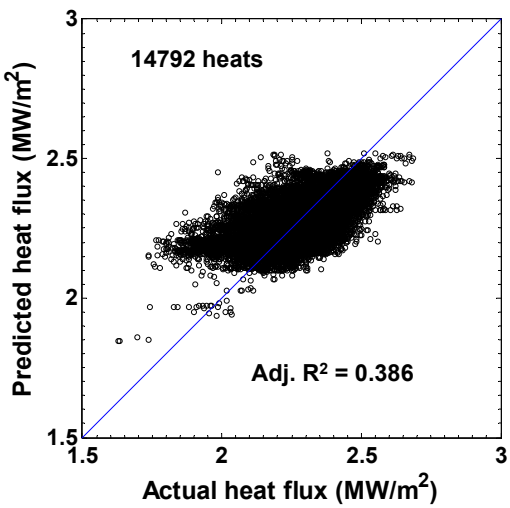
$$Q = 1053.903 * V_c^{0.610} * T_{melt}^{-1.034} * W^{0.079} * \left\{1 - 0.152 * exp\left[-\left(0 * \left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- All the data procured from database was used to find the equation
- Heat flux as a function of speed, grade, melting temperature and mold width
- $x_9$ is determined as 0. Thus for the Nucor data with no peritectics, effect of grade of carbon on heat flux is not observed.

# Non-linear multiple regression: Only filtering for constant speed

$$Q = 1367.693 * V_c^{0.614} * T_{melt}^{-1.071} * W^{0.079} * \left\{1 - 0.152 * exp\left[-\left(0 * \left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$

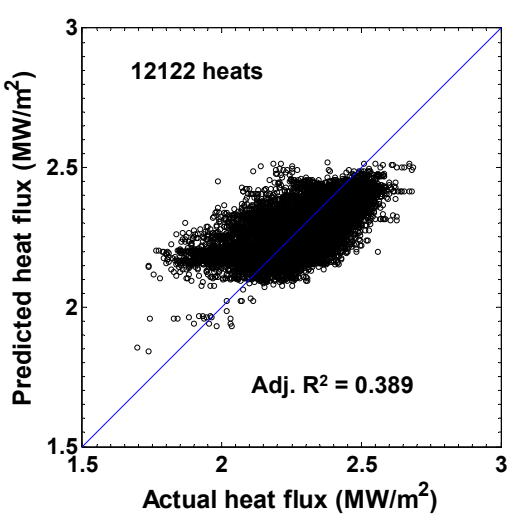



- For the same structure, apply primary filter A (drop variations in $V_c$ > 2 mm/s)
- Again, $x_9$ is determined as 0



# Non-linear multiple regression: Constant speed and width

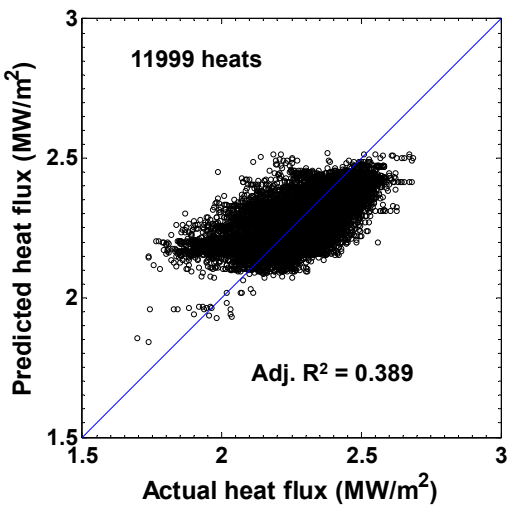
$$Q = 1545.444 * V_c^{0.621} * T_{melt}^{-1.089} * W^{0.078} * \left\{1 - 0.152 * exp\left[-\left(0 * \left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- For the same structure, apply primary filters B & C (drop variations in $V_c$ and mold width)
- Again, $x_9$ is determined as 0

# Non-linear multiple regression: Filters for speed, width, superheat

$$Q = 1528.799 * V_c^{0.622} * T_{melt}^{-1.089} * W^{0.079} * \left\{1 - 0.152 * exp\left[-\left(0 * \left[\frac{\frac{C_A + C_B}{2} - \%C}{(C_B - C_A)}\right]\right)^2\right]\right\}$$




- For the same structure, apply primary filters B,C & D (drop unrealistic superheats and variations in cast speed and mold width)
- With each filter, improvement in Adj.$R^2$ is small.
- But the exponent defining the effect of each variable is almost the same.