STUDY OF THE HEAT LOSSES AT THE CONTINUOUS CASTING OF SLABS

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Abstract

The paper presents the study of the heat losses which occur at the continuous casting of slabs, along the path casting ladle - distributor - crystallizer - secondary cooling, as a function of technological factors such as: slab temperature, chemical composition, liquid steel weight, environmental temperature, etc. On the basis of these correlations it has been established the optimal level of the heat losses on each important zone of the path so that the continuous casting should be efficient (defect-free slabs, high productivity).

1. INTRODUCTION

The liquid steel evacuated from the oxygen converter suffers in time, on the path LD converter-continuous casting unit, a loss of temperature (IVANESCU A. 2004, IVANESCU L. 2004). We propose ourselves to calculate these losses of heat (temperature) with the aid of a mathematical model on the main stages of the path (IVANESCU A., 2007):

- the steel evacuation from the converter in the casting ladle;
- the transportation of the casting ladle from the LD converter to the continuous casting unit;
- the bubbling of the steel with argon;
- the distributor;
- the crystallizer;
- the secondary cooling;
- the cooling in the atmosphere.

The steel evacuation from the converter in the casting ladle determines a decrease of the temperature 
\[ \Delta \delta_0 = \theta_o - \theta_1 \] where \( \Delta \delta_0 \) is the temperature loss generated by the evacuation of steel in the casting ladle, \( \theta_o \) is the temperature of evacuation in the converter and \( \theta_1 \) is the steel temperature in the casting ladle after the evacuation. The value of this temperature loss is determined by:

- the duration of the steel evacuation, in minutes;
- the liquid steel temperature before the evacuation;
- the thermal state of the refractory lining of the casting ladle;
- the quantity of ferro-alloys necessary to deoxidation and alloying.

The transportation of the casting ladle from the converter to the rotative tower determines a decrease of the temperature 
\[ \Delta \delta_1 = \theta_1 - \theta_2 \] where \( \theta_2 \) is the steel temperature in the casting ladle at the arrival to the rotative tower. After the bubbling with argon the steel suffers a decrease of the temperature 
\[ \Delta \delta_2 = \theta_2 - \theta_3 \] where \( \theta_3 \) is the liquid steel temperature after the bubbling with argon. The decrease of the temperature corresponding to the ladle opening maneuvers is 
\[ \Delta \delta_3 = \theta_3 - \theta_4 \] where \( \theta_4 \) is the steel temperature in the jet that flows in distributor. The decrease of the temperature in the distributor is 
\[ \Delta \delta_4 = \theta_4 - \theta_5 \] where \( \theta_5 \) is the steel average temperature in the distributor in the moment of casting start in the crystallizer. The decrease of the temperature in the crystallizer is 
\[ \Delta \delta_5 = \theta_5 - \theta_6 \] where \( \theta_6 \) is the steel temperature in the crystallizer. It can be written:
\[ v_t \cdot c_o (\theta_5 - \theta_6) = D_{H_2O} \cdot c_{H_2O} (t_2 - t_1) + Q_p \]  
(1)

where:  
\( v_t \) is the casting speed;  
\( c_o \) – the liquid steel specific heat;  
\( D_{H_2O} \) – represents the cooling water flow rate;  
\( c_{H_2O} \) – the water specific heat;  
\( t_2 \) – the cooling water temperature at the exit of the crystallizer;  
\( t_1 \) – the cooling water temperature at the entering the crystallizer;  
\( Q_p \) - the heat lost by radiation and conduction of the crystallizer.

The decrease of the temperature in the secondary cooling system is \( \Delta \theta_6 = \theta_6 - \theta_7 \) where \( \theta_7 \) is the slab average temperature at the exit of the splashing zone. The decrease of the temperature in the atmosphere is \( \Delta \theta_8 = \theta_7 - \theta_8 \) where \( \theta_8 \) is the slab average temperature at the cutting unit.

From the relation (1) it can be calculated \( \theta_6 \)

\[ \theta_6 = \frac{v_t \cdot c_o \theta_5 - D_{H_2O} \cdot c_{H_2O} (t_2 - t_1) - Q_p}{v_t \cdot c_o} \]  
(2)

The values of \( \theta_7 \) and \( \theta_8 \) are determined as arithmetic means of three values measured with thermocouples along the slab width.

2. THE MATHEMATICAL MODELLING OF THE HEAT LOSSES

The establishing of the mathematical model is based on the balance of the heat on the precinct contour where the liquid metal is found (casting ladle, distributor, crystallizer) (MUNTEANU 2005):

\[ Q_p = m \cdot c_{m_o} (\theta_{t_i} - \theta_{t_i+1}) \text{ in [J]} \]  
(3)

where:  
\( Q_p \) – represents the heat loss of the metal which is found in the casting ladle, distributor or crystallizer, in the period \( (t_{i+1} - t_i) \);  
\( m \) – the mass of the liquid metal;  
\( c_{m_o} \) – the liquid metal specific heat;  
\( \theta_{t_i} \) – the metal temperature at the beginning of the maintaining period;  
\( \theta_{t_i+1} \) – the metal temperature at the end of the maintaining period;

The heat losses \( (Q_p) \) equation is:

\[ Q_p = Q_{p\text{rad}} + Q_{p\text{cond}} + Q_{p\text{barb}} + Q_{p\text{ar}} \]  
(4)

where:  
\( Q_{p\text{rad}} \) – the heat lost by radiation of the liquid metal in the period \( (t_{i}, t_{i+1}) \);  
\( Q_{p\text{cond}} \) – the heat lost by thermal conductivity in the period \( (t_{i}, t_{i+1}) \);  
\( Q_{p\text{barb}} \) – the heat lost by bubbling;  
\( Q_{p\text{ar}} \) – the heat lost in cooling water.

The heat lost by radiation is:

\[ Q_{p\text{rad}} = \varepsilon c_o S_i \left( \frac{T_{\text{met}} t_i}{100} \right)^4 - \left( \frac{T_{\text{met}} t_{i+1}}{100} \right)^4 \right) (t_{i+1} - t_i) \text{ [J]} \]  
(5)

where:

\( \varepsilon \) - blackness coefficient;
\[ c_o \] - coefficient of blackbody radiation;
\[ S_j \] - the area of the radiation, with \( i=1 \) for the casting ladle, \( i=2 \) for distributor, \( i=3 \) for crystallizer;
\[ T_{met} \tau_i \] - the liquid metal temperature at the beginning of the maintaining period \( \tau_i \);
\[ T_{met} \tau_{i+1} \] - the liquid metal temperature at the beginning of the maintaining period \( \tau_{i+1} \).

The heat lost by thermal conductibility is:
\[
Q_{p\,cond}^{\text{wall}} = Q_{p\,cond}^{\text{base}}
\]
where:
\[
Q_{p\,cond}^{\text{wall}} = \frac{2\pi \lambda h (\theta_i \text{med} - \theta_{mm})}{\ln \frac{d_e}{d_i}} (\tau_{i+1} - \tau_i) \quad \text{in [J]} \quad (7)
\]
\[
Q_{p\,cond}^{\text{base}} = \frac{\lambda (\theta_i \text{med} - \theta_{mm})}{\delta} S_i (\tau_{i+1} - \tau_i) \quad \text{in [J]} \quad (8)
\]
where:
\( \lambda \) - the coefficient of thermal conductibility, in [J/m.s.grd];
\( h \) - the depth of the liquid metal, in [m];
\( \theta_i \text{med} \) - the medium temperature of the liquid metal in the period \( \tau_i, \tau_{i+1} \);
\( \theta_{mm} \) - the medium temperature of the precinct mantle in the period \( \tau_i, \tau_{i+1} \);
\( d_e \) - the average exterior diameter, in [m];
\( d_i \) - the average interior diameter, in [m];
\( \delta \) - the thickness of the thermal isolation.

The heat lost by bubbling is:
\[
Q_{p\,barb} = D_{Ar} \cdot c_{sAr} (\theta_i - \theta_{Ar}) \tau_{barb} \quad \text{in [J]} \quad (9)
\]
where: \( D_{Ar} \) - represents the argon flow rate, in [m³/min];
\( c_{sAr} \) - the argon specific heat;
\( \theta_i \) - the liquid metal temperature at the beginning of the bubbling;
\( \theta_{Ar} \) - the argon temperature at the introduction in the liquid metal;
\( \tau_{barb} \) - the bubbling duration.

The heat lost in the cooling water is:
\[
Q_{p\,ar} = D_{H_2O} \cdot c_{sH_2O} (t_2 - t_1) (\tau_{i+1} - \tau_i) \quad \text{in [J]} \quad (10)
\]
where: \( D_{H_2O} \) - represents the cooling water flow rate, in [m³/min];
\( c_{sH_2O} \) - the water specific heat;
\( t_2 \) - the cooling water temperature at the exit of the crystallizer, in [°C];
\( t_1 \) - the cooling water temperature at the entering the crystallizer, in [°C];
\[
\tau_i - \text{the hour of starting the casting in the crystallizer;}
\]
\[
\tau_{i+1} - \text{the hour of ending the casting in the crystallizer;}
\]

The mathematical model of the temperature loss has the expression:

\[
\Delta \theta = \theta_i - \theta_{i+1} = \frac{l}{m \cdot c_{m_i}} \left[ \frac{T_{\text{met}} \tau_i}{100} - \frac{T_{\text{met}} \tau_{i+1}}{100} \right] + \frac{2 \pi \lambda (\theta_{i \text{med}} - \theta_{m \text{m}})}{\ln \frac{d_e}{d_i}} + \frac{\dot{\lambda} (\theta_{i \text{med}} - \theta_{m \text{m}})}{\delta} S_j + D_{\text{Ar}} c_{S\text{Ar}} (\theta_0 - \theta_{\text{Ar}}) + D_{H_2O} c_{S\text{H}_2\text{O}} (\theta_2 - \theta_1) \Delta \tau
\]

and

\[
w_\theta = \frac{\Delta \theta}{\Delta \tau} = \frac{l}{m \cdot c_{m_i}} \left[ \frac{T_{\text{met}} \tau_i}{100} - \frac{T_{\text{met}} \tau_{i+1}}{100} \right] + \frac{2 \pi \lambda (\theta_{i \text{med}} - \theta_{m \text{m}})}{\ln \frac{d_e}{d_i}} + \frac{\dot{\lambda} (\theta_{i \text{med}} - \theta_{m \text{m}})}{\delta} S_j + D_{\text{Ar}} c_{S\text{Ar}} (\theta_0 - \theta_{\text{Ar}}) + D_{H_2O} c_{S\text{H}_2\text{O}} (\theta_2 - \theta_1) \Delta \tau
\]

where:

\[
w_\theta - \text{is the velocity of the temperature loss;}
\]
\[
\Delta \tau - \text{is the metal temperature loss.}
\]

3. INDUSTRIAL EXPERIMENTATIONS

There have been studied five steel charges elaborated in LD converter and casted in the Continuous Casting Unit (CCU) at Mittal Steel Galati, Romania. The corresponding technological parameters are presented in Tables 1 and 2.

### Table 1

<table>
<thead>
<tr>
<th>Charge no.</th>
<th>( \theta_0 ) [°C]</th>
<th>( \theta_1 ) [°C]</th>
<th>( \tau_{e_v} ) [min]</th>
<th>( \tau_1 ) [min]</th>
<th>( \tau_2 ) [min]</th>
<th>( \tau_3 ) [min]</th>
<th>( \tau_4 ) [min]</th>
<th>( \tau_5 ) [min]</th>
<th>( \tau_6 ) [min]</th>
<th>( D_{H_2O} ) [l/min]</th>
<th>( \theta_0 ) [°C/min]</th>
<th>( \theta_1 ) [°C/min]</th>
<th>( \theta_2 ) [°C/min]</th>
<th>( \theta_3 ) [°C/min]</th>
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<td>1680</td>
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<td>0.76</td>
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<td>0.53</td>
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<td>10.4</td>
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<td>1613</td>
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<td>27</td>
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<td>1580</td>
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<td>1620</td>
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<td>1575</td>
<td>14</td>
<td>28</td>
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<td>0.73</td>
<td>314</td>
<td>21</td>
<td>33</td>
<td>0.73</td>
</tr>
</tbody>
</table>

### Table 2

<table>
<thead>
<tr>
<th>Charge no.</th>
<th>( \Delta \delta_0 )</th>
<th>( \Delta \delta_1 )</th>
<th>( \Delta \delta_2 )</th>
<th>( \Delta \delta_3 )</th>
<th>( w_0 ) [°C/min]</th>
<th>( w_1 ) [°C/min]</th>
<th>( w_2 ) [°C/min]</th>
<th>( w_3 ) [°C/min]</th>
</tr>
</thead>
<tbody>
<tr>
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<td>60</td>
<td>33</td>
<td>43</td>
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<td>0.76</td>
<td>1.375</td>
<td>14.33</td>
</tr>
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<td>45</td>
<td>21</td>
<td>37</td>
<td>26</td>
<td>7.50</td>
<td>0.53</td>
<td>7.4</td>
<td>8.67</td>
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<td>26</td>
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<td>10.4</td>
</tr>
<tr>
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<td>35</td>
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<td>5.71</td>
<td>0.33</td>
<td>3.21</td>
<td>8.33</td>
</tr>
</tbody>
</table>

We have used the following notations:

\( \tau_{e_v} \) - the duration of the steel evacuation from the converter in the casting ladle, in [min];
\( \tau_i \) - the duration of the casting ladle transportation from the LD converter to the rotative tower, including the bubbling through porous cork, in [min];
τ₀ – the duration of bubbling with argon, including the cooling minutes for the slab, in [min];
τ₃ – the duration of the distributor filling, in [min];
w₀ – the temperature loss at the steel evacuation from the converter, in [°C/min];
w₁ – the temperature loss at the casting ladle transportation from the converter to CCU, in [°C/min];
w₂ – the temperature loss at the bubbling with argon, including the introducing of the cooling slab, in [°C/min];
w₃ – the temperature loss at the distributor filling, in [°C/min];

Using the mathematical model there have been calculated the speeds of the steel temperature decreasing and the corresponding errors, the results being presented in Table 3. For the studied five charges the errors of the mathematical model are below 10%.

<table>
<thead>
<tr>
<th>Charge no.</th>
<th>w₀, calc [°C/min]</th>
<th>e₀, calc [%]</th>
<th>w₁ [°C/min]</th>
<th>e₁ [%]</th>
<th>w₂ [°C/min]</th>
<th>e₂ [%]</th>
<th>w₃ [°C/min]</th>
<th>e₃ [%]</th>
</tr>
</thead>
<tbody>
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<td>0.71</td>
<td>6.5</td>
<td>1.5</td>
<td>8.3</td>
<td>13.1</td>
<td>8.5</td>
</tr>
<tr>
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<td>6.8</td>
<td>9.3</td>
<td>0.58</td>
<td>8.6</td>
<td>6.8</td>
<td>8.0</td>
<td>9.01</td>
<td>3.77</td>
</tr>
<tr>
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<td>8.4</td>
<td>0.71</td>
<td>4.2</td>
<td>2.4</td>
<td>9.1</td>
<td>11.3</td>
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<td>7.5</td>
<td>10.9</td>
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<td>3.51</td>
<td>8.5</td>
<td>9.0</td>
<td>7.44</td>
</tr>
</tbody>
</table>

4. CONCLUSIONS
The greatest temperature (heat) losses are registered at the distributor filling and at the charge evacuation from the converter: w₃ > w₀ > w₂ > w₁. The errors obtained at the calculation of the temperature (heat) losses of the mathematical model are below 10%. It is searched for the improving of the mathematical model so that the errors should be below 5%. With the aid of this mathematical model there can be determined the allowed ranges of the temperature losses, so that the continuous casting should develop in optimal conditions. Also, the obtained results using the mathematical model can constitute useful information for warning the operator for the eventual unframed values in the allowed ranges, in order to take appropriate rectifying measures.

LITERATURE REFERENCES
IVANESCU A., 2004, The mass transfer at the metallic materials processing (in Romanian), Editura Didactica si Pedagogica, Bucharest.