AN OPTIMAL RELATIONSHIP BETWEEN CASTING SPEED AND HEAT TRANSFER COEFFICIENTS FOR CONTINUOUS CASTING PROCESS

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Abstract

The quality of steel slabs produced by continuous casting is influenced by many various factors. Casting speed, cooling rates and surface temperatures are the factors with very strong impacts to the process and that is why we focus on a determination of their optimal relationship. More precisely, this paper investigates how cooling rates depend on the chosen speed of casting. For finding this relationship we built our original 2D numerical model of the continuous casting process and by regulation algorithm we acquire the specific cooling for producing the steel slabs with predefined quality. The numerical model is based on enthalpy approach, which can simulate phase and structural changes of steel with arbitrary chemical composition, and the regulated cooling are included in its boundary conditions in the form of heat transfer coefficients. The heat transfer coefficients are obtained by an original heuristic self-regulating algorithm based on the idea of simulated annealing. By repeatedly fixing casting speed to different values and finding its associated cooling, we receive the investigated relationship.

Key Words: Continuous casting process, heuristic optimization, secondary cooling

1. INTRODUCTION

Nowadays, continuous casting is the predominant way of producing steel in the world. Every year, steel industry processes millions of tons of liquid steel into semi-finished products such as slabs, blooms, and billets. Schematic representation of the continuous slab casting installation is shown in **Fig. 1.** Steel production ratio via continuous casting process in Czech Republic is comparable with industrialized European countries. The focus on high quality products require production innovations and an application of new approaches supported by technological development [1]. Industrial trials are very expensive and time-consuming, thus the more economical way is to use numerical simulations of the casting process.

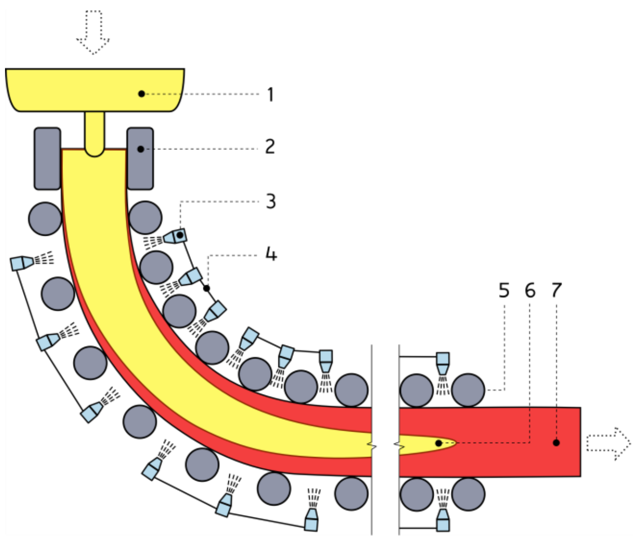

Fig. 1. Scheme of continuous casting. 1 - tundish; 2 – mould; 3 - nozzle; 4 - coolant circuit; 5 - roller; 6 - liquid material; 7 - solid material.

This paper deals with the determination of optimal relationship among casting control parameters with focus on high quality final product. Particularly, we investigate the optimal cooling proportion as a function of casting speed. The contemporary practices in many foundries are that the setting of the cooling intensity for particular grades of steel and casting speed depends on an expert judgment and moreover, it is usually described as a simple linear function.

Unfortunately, this approach need not correspond with the real behavior for most of steels and we show how the real relationships look like.

Previous works were generally based on simplified temperature field models and were optimized by mathematical programming [2], neural networks or genetic algorithm [3]. These models describe the casting process very roughly and therefore their results are not satisfactory for deep investigations. Our original numerical model of the temperature field is inspired by the real caster geometry from EVRAZ VÍTKOVICE STEEL with twelve coolant circuits. The original heuristic self-regulating algorithm is used for black-box optimization of the model.

2. DEFINITION OF THE PROBLEM

The goal is to determine the real relationship between casting speed and cooling rates in the secondary cooling zone under certain metallurgical criteria. These metallurgical criteria are formulated as a series of constraints that represent the quality of slab products and process feasibility. The courses of the surface temperature field have to be decreasing in the most of the profile and the temperature in the straightening area must be in the given range. The values for these constraints depend on the grade of employed steel and an expert's decision. The evaluation in this paper is executed on steel grade S355J0H, nevertheless this study can be easily generalized by changing the chemical composition directly in the numerical model via the enthalpy function. The cooling phenomena are expressed by the values of the heat transfer coefficients (HTCs) [4]. To obtain the desired relationship we have created both the original heuristic algorithm and the numerical model of the temperature field. In the real casting conditions, it is not possible to keep the heat transfers coefficients exactly in fixed values but in some tolerance range. Thus, repeated computations for every casting speed are the appropriate way. The obtained data can be fit by the regression analysis and the investigated relation is based on its results.

3. MATHEMATICAL MODEL OF TEMPERATURE FIELD

The temperature distribution through the casting process is described by the mathematical equation in differential form. There are three basic mechanisms of heat transfer, the conduction mechanism plays the dominant role inside the body of cast steel, whereas convection and radiation take place only in the secondary and tertiary cooling zone, where they form boundary conditions. The temperature field of the slab is described by Fourier-Kirchhoff equation [5, 6], where the velocity component v_y [m/s] is considered only in the direction of casting. Phase and structural changes are included in the model by the use of a thermo-dynamical function of volume enthalpy H [J/m^3]. The method is also called the enthalpy approach [6].

$$\frac{\partial H}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) + v_y \frac{\partial H}{\partial y}, \tag{1}$$

$$\frac{\partial H}{\partial \tau} = \frac{1}{r}\frac{\partial}{\partial r}\left(\lambda r \frac{\partial T}{\partial r}\right) + \frac{1}{r^2}\frac{\partial}{\partial \varphi}\left(\lambda \frac{\partial T}{\partial \varphi}\right) + v_y \frac{1}{r}\frac{\partial H}{\partial \varphi}. \tag{2}$$

The equations (1-2) describe unsteady-state 2D heat transfer (Fourier-Kirchhoff) equation written in Cartesian and cylindrical coordinates, where λ is thermal conductivity [W/m·K], T is temperature [K], H is volume enthalpy [J/m^3], τ is time [s], x, y, r, φ are spatial coordinates. In order to have a well-posed problem, initial and boundary conditions must be provided. The boundary conditions include the heat flux in the mould and under the rollers, forced convection under the nozzles, and free convection and radiation in tertiary cooling zone.

$T = T_{casting}$ the level of steel, (3)

$-\lambda \frac{\partial T}{\partial n} = 0$ the plane of symmetry, (4)

$-\lambda \frac{\partial T}{\partial n} = \dot{q}$ in the mould and beneath the rollers, (5)

$-\lambda \frac{\partial T}{\partial n} = h_{tc}\left(T_{surface} - T_{amb}\right) + \sigma\varepsilon\left(T_{surface}^4 - T_{amb}^4\right)$ within the secondary and tertiary zones. (6)

The equations (1-2) are discretized by the finite difference method [3, 4] using an explicit formula for the time derivative. The mesh for the finite difference scheme is non-equidistant and its nodes are adapted to the real rollers and nozzles positions. The equations (1-2) contain both the enthalpy and temperature, so during the simulation the corresponding temperature must be calculated from the enthalpy for each node at each time step. This numerical model allows us to apply various enthalpy-temperature functions (**Fig. 2.**) and thermal conductivity-temperature curves, thus the temperature field can be calculated for various steels only by defining their chemical composition.

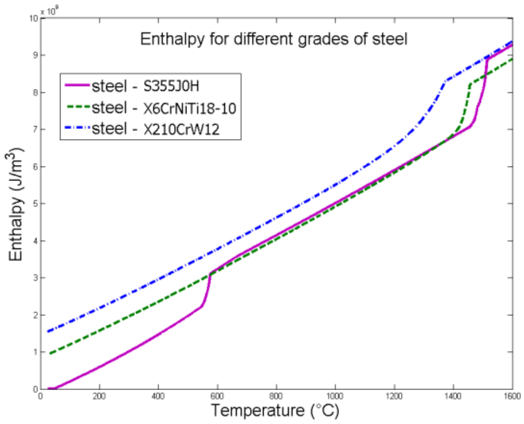

Fig. 2. Relationship between temperature and enthalpy for three grades of steel

4. THE SELF-REGULATING ALGORITHM

The aforementioned model has the cooling rates of nozzles in boundary conditions and we need to find their values such that the predefined material quality is satisfied. The quality is characterized by a set of temperatures in the particular points on the surface of cast slabs. Therefore the aim of the algorithm is to find the cooling rates which cause that the points on the surface are in given temperature range.

In the beginning, the algorithm generates random value for each nozzle. These values are uniformly distributed in a given range, and therefore, the initial configuration of the whole system need not to fulfill any of the prescribed material conditions. By repetitive regulation over the heat transfer coefficients, we can find the configuration which meets all the conditions and which ensures desired qualities of the final material.

The iterative regulation takes into account only fundamental aspects of the numerical model and thereby it makes the algorithm robust with respect to various classes of steels. The main idea of the regulation is based on the principle how the nozzles affect temperature field. Each nozzle can influence only material which is after the nozzle (in the sense of the direction of casting), and its strongest cooling impact is in close neighborhood. The closer the point is, the higher impact the nozzle has. It means that if we want to change a temperature in some particular point, we can regulate only a few nozzles before this controlled point. The crucial idea of the algorithm is that we define a few points along the whole temperature field and we watch over their temperature. If the temperature is above the prescribed boundary, then we decrease the heat transfer coefficients in two preceding nozzles and vice versa.

Similarly, to make the temperature field to be in a decreasing trend, we define pairs of points whose temperatures have to be descending. If the first point of the defined pair has lower temperature than the other one, we reduce HTC of the nozzle before the first point and increase HTC after it. These two simple techniques completely determine which of the HTCs should be decreased and which ones should be increased.

The only remaining question is how intensively the HTC should be changed. Our algorithm uses a mechanism which is similar to the idea of simulated annealing [7]. At the beginning, the intensity of the modifications is very high, and with increasing number of iterations the intensity exponentially decreases. Thereby, this mechanism lets the algorithm smoothly converge to the steady state.

The real value used for modification of particular HTC is computed as a product of the actual intensity, weight-dependent on the distance from the controlled point, and a small random disturbance. Because each nozzle can register several different requests (from different controlled points), we pick only the one with the highest absolute value.

Our particular implementation has the initial intensity equal to 1000 and after each iteration, the intensity is multiplied by constant value 0.8. For the controlling of the temperature in the given points, we assigned weight to the closest nozzle to 0.8 and for the second closest nozzle is the weight 0.2. The weights, associated with nozzles regulate decreasing trend, are chosen to 0.5 for both of them (the one before and after the first control point in the defined pair). The schematic pseudo-code of the algorithm is show in the **Fig. 3.**

```
intensity = 1000
while all is not statisfied do:
    for each controlled point do:
        if temperature(point)>boundary:
            request = intensity * weight * rand(0.95, 1.05)
            append request for increasing htc in previous nozzles

        if temperature(point)<boundary:
            request = intensity * weight * rand(0.95, 1.05)
            append request for decreasing htc in previous nozzles
    end for

    for each controlled pair do:
        if temperature(pair[0])<temperature(pair[1]):
            request = intensity * weight * rand(0.95, 1.05)
            append requests for increasing and decreasing nozzles
    end for

    for each nozzle do:
        modify htc by the highest absolute value of the all appended requests
    end for

    evaluate model with new htc setting
    intensity = 0.8*intensity
end while
```

Fig. 3. Pseudo-code of optimization algorithm

5. RESULTS AND DISCUSSION

The relationship, we are looking for, describes how to set HTC intensity for each nozzle in order to reach equivalent surface temperature profiles for arbitrary casting speed. These temperature profiles are shown in **Fig. 4.** and they were chosen on experts advices to achieve the best quality of the final material. The material temperature in the first section of the caster (up to 13 m) has to be in the range from 1080 °C to 1100 °C due to the minimization of cracks caused by straightening of steel. In a similar way, smoothly decreasing trend of the surface temperatures has also a positive influence on the quality of material. The value of the surface temperatures in exit area is defined to be between 750 °C and 800 °C. Feasibility of the numerical solution is qualified by the limitation of metallurgical length and the limitation of HTC intensity. For instance, if we constrain the metallurgical length to 20 meters, the final solution is infeasible for higher values of casting speed (**Fig. 4.** right).

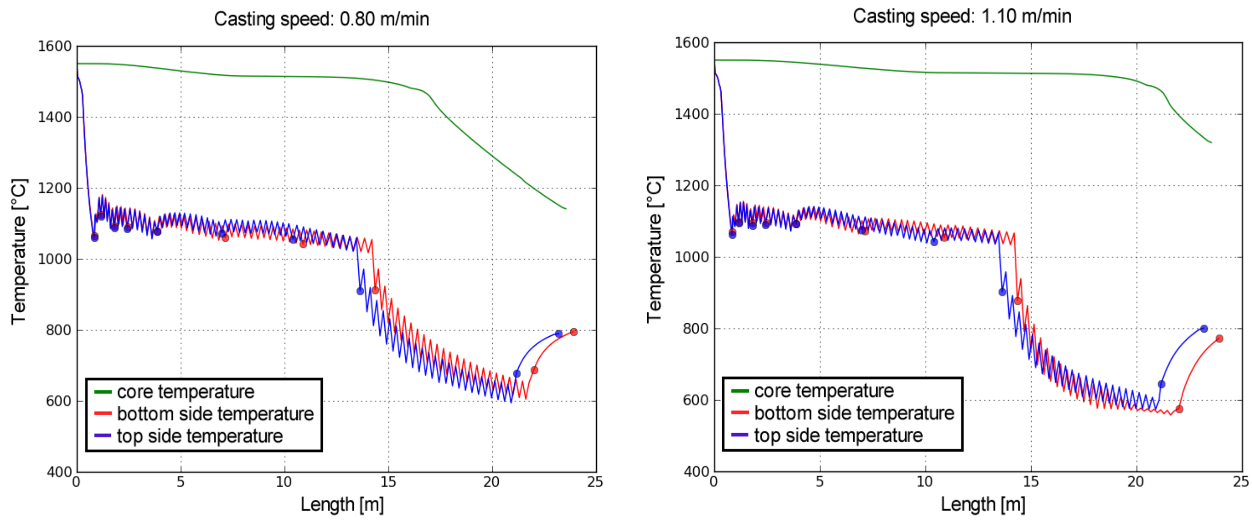

Fig. 4. Surface and core temperature trends for different casting speeds

In order to make the desiderative relationship robust, we executed several computations of the mentioned models and performed their statistical evaluation. There were taken ten independent algorithm runs for each casting speed between 0.5 m/min and 1.2 m/min (with step size 0.05 m/min). All together, 150 evaluations were used for the determination of investigated function of HTC with respect to the values of casting speed.

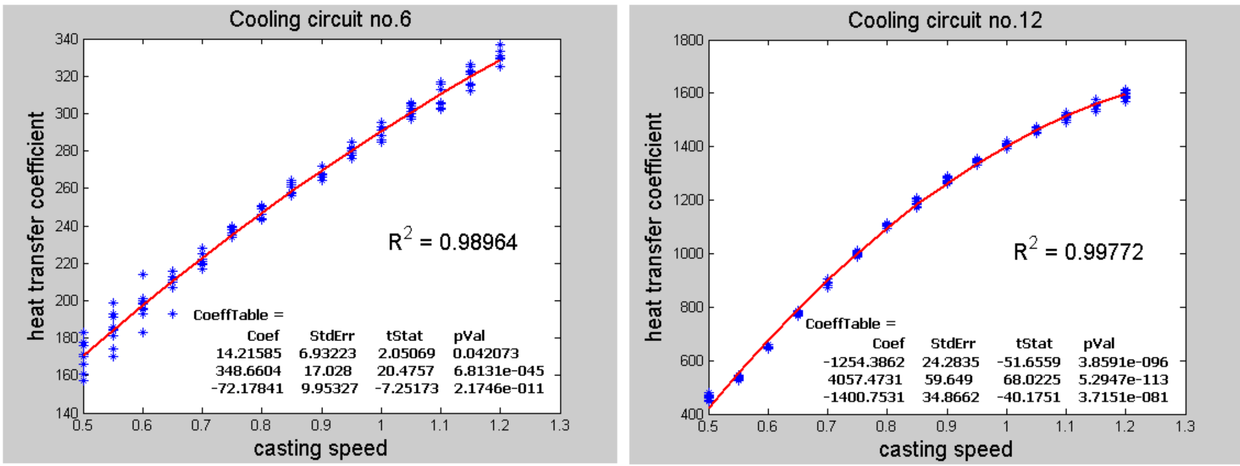

Fig. 5. Linear regression curves for selected cooling circuits

The obtained data were fitted by various linear regression models (linear, polynomial …) [8] and the most promising one of them was the model in the quadratic form (7). This form can suitably fit the desired relations for all cooling circuits.

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 , \qquad (7)$$

where *x* represents the casting speed and *y* HTC.

The results of the linear regression and their graphic representation for selected coolant circuits can be seen in **Fig. 5** and we can there observe a different cooling behavior in different coolant circuits. The regression curves for all the cooling circuits are depicted in **Fig. 6.** The appropriate way can be the use of specific regression model for particular cooling circuit. In other to have applicable model for real casting process, we should enlarge the numerical model by additional relationship between cooling intensity and HTC for particular cooling circuits.

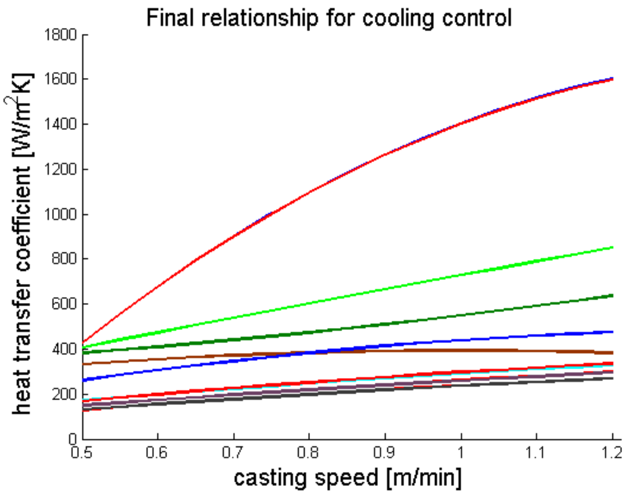

Fig. 6. Linear regression curves for all cooling circuits

Table 1. The obtained HTCs [W/m^2·K] for each cooling circuit and selected casting speeds [m/min].

Speed\circuit	1	2	3	4	5	6	7	8	9	10	11	12
0,5	332	407	383	261	168	171	148	149	129	131	425	424
0,6	354	473	410	306	198	197	173	173	154	155	677	676
0,7	371	539	440	347	226	223	196	196	177	177	901	900
0,8	383	603	474	382	251	247	219	218	199	198	1097	1095
0,9	390	666	510	413	275	270	240	239	219	218	1265	1263
1,0	393	729	549	439	297	291	261	259	237	236	1406	1402
1,1	390	790	592	460	316	310	280	278	254	252	1518	1514
1,2	383	850	637	476	334	329	298	295	268	267	1603	1598

Table 1 gathers HTCs in particulars coolant circuits calculated by using the regression for selected casting speeds. These results were verified for their feasibility and therefore they correctly show how to control the casting process in the optimal way.

6. CONCLUSION

The paper deals with the determination of the optimal relationship between the casting speed and cooling in the continuous slab casting process of steel grade S355J0H. This relation assigns heat transfer coefficients for each particular nozzle in such a way that the cast slab reaches the prescribed material quality. The obtained HTC intensities follow mostly quadratic dependencies on the casting speed and they are computed for each individual cooling circle by the numerical-optimization algorithm and subsequent regression analysis. The whole technique has very general nature and therefore, it can be easily modified for arbitrary grade of steel, quality conditions or specific caster geometry including rollers and nozzles positions. The established relationships should be mainly used as a support tool for setting the optimal cooling by caster operators, but they are also very useful for designing new optimal caster geometry or deeper understanding of behavior and interaction between individual process parameters. Further research will be focused on making the algorithm more precise, which includes an incorporating 3D numerical model and also more accurate specifications of the final material quality.

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REFERENCES

[1] NORMSNTON, A. S., et al. Improving surface quality of continuously cast semis by an understanding of shell development and growth. Final report, Technical steel research series, Luxembourg, (2005), 349 p., ISBN 92-79-00066-1.

[2] MAUDER, T., NOVOTNÝ, J. Two mathematical approaches for optimal control of the continuous slab casting process. In Mendel 2010 - 16th International Conference on Soft Computing, Brno, Brno University of Technology, (2010), pp. 395 – 400, ISBN 978-80-214-4120-0.

[3] SANTOS, C. A., SPIM, J. A., GARCIA, A. Mathematical modeling and optimization strategies (genetic algorithm and knowledge base) applied to the continuous casting of steel. Engineering Applications of Artificial Intelligence 16, (2003), pp. 511–527, ISSN-1: 0952976.

[4] PŘÍHODA, M., MOLINEK, J., PYSZKO, R., VELICKA, M., VACULÍK, M., BURDA, J. Heat Transfer during Cooling of Hot Surfaces by Water Nozzles. Metalurgia=Metallurgy, vol. 48, (4), 2009, P. 235-238.

[5] ŠTĚTINA, J., KAVIČKA, F., DOBROVSKÁ, J., CAMEK, L., MASARIK, M. Optimization of a concasting technology via a dynamic solidification model of a slab caster. Materials Science Forum, (2005), 475-479(5), pp. 3831 – 3834, ISSN 0255-5476.

[6] STEFANESCU, D. M. Science and Engineering of Casting Solidification. Second Edition, New York, Springer Science, (2009), 402 p., ISBN 978-0-387-74609-8.

[7] KIRKPATRICK, S., GELATT, C. D., VECCHI, M. P. Optimization by Simulated Annealing. In Science New Series, Vol. 220, No. 4598 (May 13, 1983), pp. 671-680

[8] FOX, J. Applied regression analysis, linear models, and related methods. California, Sage publications, (1997), 599 p., ISBN 0-8039-4540-X.