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TRANSITION PHENOMENA IN TUNDISH DURING GRADE CHANGE OF CC-STEEL – PART 1

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ABSTRACT:
The paper deals with the possibilities and results of the transition processes modelling in a four-strand billet caster tundish with a change in the chemical composition of the continuously cast steel during sequence casting. The simulations were done using both *numerical modelling* (CFD Fluent programme) and *physical modelling* (1:3 length scale tundish model). The paper presents the data obtained on the extent of the transition zone for various boundary conditions of steel casting, and the results obtained from the two modelling methods used are mutually compared.

KEY WORDS:
steel, continuous casting, grade change, tundish, modelling.

INTRODUCTION

When casting two different steel grades in a sequence, the steels tend to get mixed in the tundish and, in certain cases, also in the liquid cores of the solidifying blanks. That leads to the emergence of chemistries that correspond neither to the previous nor to the following steel grade cast. A so-called mixed or transition zone occurs in the continuously cast blanks as a results, with the chemical composition out of the tolerance specified for either of the steel grades cast. Verification and minimisation of these transition zones is an important pre-requisite to increasing the productivity of CCMs.

In order to verify the extent of the transition zone, both direct operational measurements and results obtained from physical or numerical modelling tools may be considered. On one previous occasion, when addressing a project assigned by the Grant Agency of the Czech Republic, a numerical simulation was undertaken to establish the extent of a transition zone in continuously cast 108x108mm billets related to the particular conditions provided by the billet caster no. 2 at TŽ, a.s. using a CFD Fluent software package. The results of this simulation, which are given in papers [1-3], have for instance proved a very significant effect of the weight of steel in the tundish and the flow pattern conditions on the extent of the transition zone and led to more accurate data on the number of emerging transition billets.

As the CCM no. 2 at TŽ, a.s. has practically moved to the casting of 150x150mm billets only it was necessary to adapt the simulations to these conditions, too. Special attention was devoted to the evaluation of

- tundish steel weight at ladle change,
- the effects of the temperature difference between the steel present in the tundish and newly supplied steel,
- the effects of stoppage of some casting strands,
- the effects of weight steel flow into the tundish being refilled.

1. Fundamental Technological Methods of Minimising the Extent of Transition Zones

There are three well-known technological procedures employed to address the issue of elimination or minimisation of the transition zones when casting different steel grades in a sequence. The first option involves the so-called flying tundish change where the tundish is changed along with the casting ladle so that the new upcoming steel grade does not get mixed up with the previous grade. The other fundamental solution involves the use of so-called grade-separators plates inserted in the mould to physically separate the original and upcoming steel grades. When inserting the separators, the blank drag speed is reduced to a minimum, or the casting process is altogether stopped. The easiest of the three methods consists in employing the same procedure when casting steels of different grades as when casting a single-grade sequence. This method does not have the effect of reducing the productivity of the machine, but compared to the above methods it leads to the emergence of major transition zones inside the blanks cast. When employing this method, however, the casting conditions can be modified to keep the extent of the transition zones as minimised as possible.

2. Main Factors Affecting the Transition Zone Extent

The extent of the transition zone is closely related to the liquid steel flow pattern observed in the tundish and thus is dependent upon the retention times, which is a period of time for which the steel is kept in the tundish. These retention times are directly related to the weight (amount) of steel in the tundish, the inner tundish configuration and the casting speed. Chemical composition of the two consecutive steel grades cast has a huge influence upon the extent of the resultant transition zone. Within a certain period of time after the tundish began to be filled with a new steel grade, the impact of the change in the concentration of chemical elements at the tundish outlet is characterised by a certain dependency which essentially corresponds to a so-called *transition curve*. If we use these graphs to represent the concentration in dimensionless form, then the value 0 denotes the composition of the former steel grade, whereas the value 1 stands for the latter steel grade cast. It is very suitable to represent the change in concentrating of chemical elements in the dimensionless form as the resultant chart may subsequently be employed for any element and, essentially, for varying absolute ranges of compositions of the steels cast (provided that the effects of molecular diffusion under the conditions of steel flow in the tundish are neglected).

The shape of the transition curve obtained from physical or numerical modelling can be then used to reversely deduct the basic data on the transition zone extent [4-7]. The transition zones are most commonly defined as restricted areas within the blanks where the chemical composition is out of the tolerance specified for the individual steel grades cast. If the tolerances are available, it is recommended that so-called *dimensionless specifications* of the chemical compositions be established for both the old and new steel grades, these taking values falling to a range stretching from 0 to 1.

$$\tilde{c}_{old,i} = \max\left\{\frac{c_{old,i} - c_{old,i,min}}{c_{old,i} - c_{new,i}}, \frac{c_{old,i} - c_{old,i,max}}{c_{old,i} - c_{new,i}}\right\} \quad (1)$$

$$\tilde{c}_{new,i} = \min\left\{\frac{c_{old,i} - c_{new,i,min}}{c_{old,i} - c_{new,i}}, \frac{c_{old,i} - c_{new,i,max}}{c_{old,i} - c_{new,i}}\right\} \quad (2)$$

where:

$\tilde{c}_{old,i}$ – dimensionless specification of element *i* for the old steel grade (previous heat), -

$\tilde{c}_{new,i}$ – dimensionless specification of element *i* for the new steel grade (following heat), -

$c_{old,i}$ $c_{new,i}$ – real concentration of the given element *i* in old and new steel grades (for example heat analysis), %wt.

$c_{old,i,\min}$ $c_{old,i,\max}$ – minimum and maximum permissible concentration for the given element *i* in the old steel grade, %wt.

$c_{new,i,\min}$ $c_{new,i,\max}$ – minimum and maximum permissible concentration for the given element *i* in the new steel grade, %wt.

The dimensionless specifications must be calculated for all relevant elements so that it could be possible to establish the critical element displaying the highest $\tilde{c}_{new}$ - $\tilde{c}_{old}$ variance value thus determining the maximum possible extent of the transition zone. The transition steel and the corresponding transition zone will be localised between these $\tilde{c}_{old}$ and $\tilde{c}_{new}$ values.

The equations (1) and (2) moreover imply that the $\tilde{c}_{old,i}$ and $\tilde{c}_{new,i}$ values not only depend on the tolerances of the chemical composition of the two steels, but also on the actual $c_{old,i}$ and $c_{new,i}$ values. The closer the two values are to one another, the smaller area of transitional chemical composition will arise. If small differences occur, the transition zone does not need to emerge, as its chemical composition is within the tolerances specified for both the old and new steels. On the contrary, major differences in the chemical compositions of the steels combined with tight tolerance ranges specified for the two steels may cause the value of $\tilde{c}_{old}$ to approach zero and the value of $\tilde{c}_{new}$ to approach 1, which will essentially lead to enormous growth of the transition zone extent. As suggested by the above observations, a lot of potential may then be found inside the range between these two extremities. Dimensionless specifications of the chemical composition may be in advance allocated to particular steel grades and then the corresponding transition curves may be employed to determine the extent of the resultant transition curve. When performing the calculations the deviation of the real chemical composition from the required composition must be taken into account.

3. Conditions Applying to the Numerical Modelling of Transition Zone Extent

The basis of the numerical modelling of the extent of transition zones was a simulation of the processes occurring in the tundish along with a change in chemical composition of incoming steel. At this stage, the effect of the subsequent mixing of the liquid phases in the mould was not taken into account. These processes may have an essential role to play with larger moulds, i.e. especially where slabs and blanks are cast. In continuous casting of billets, the effect of this intermixing will not be significant as shown in literature.

The steel grade change was simulated by a step shift in the dimensionless concentration of the component in question from value 0 to value 1, while the changes in concentration and temperature were monitored at the individual tundish outlets. The simulations were carried out in a regime of a non-stationary problem with convergence at each time level. As stated beforehand, the modelling of the transition zone origin was carried out subject to the casting of 150x150mm billets at CCM no. 2 at TŘINECKÉ ŽELEZÁRNY, a.s. for the tundish steel weights of 15, 12, 10, and 8 t given the current tundish configuration. The casting speeds corresponding to the above weights are given in **table 1**.

Two fundamental variants were considered for the simulations. The first variant considered isothermal bath flow in the tundish, which may arise under the conditions present when the temperature of the newly supplied steel is identical as that of the steel present in the tundish. The other variant was characterised by non-isothermal tundish bath flow. In that case, the temperature of the newly supplied steel was considered to be 30°C higher than the temperature of steel already present in the tundish.

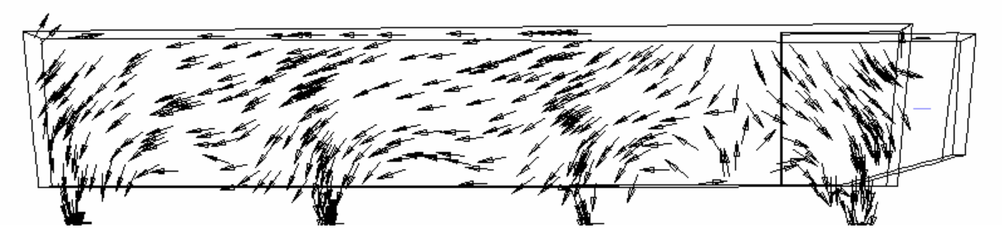

Figure 1: Tundish steel flow pattern represented by velocity vectors in the vertical plane passing through tundish nozzles under *isothermal* conditions

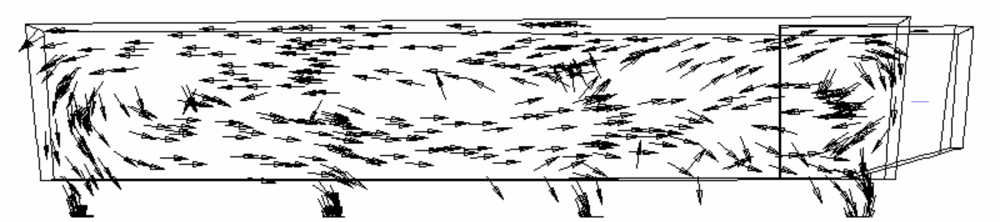

Figure 2: Tundish steel flow pattern represented by velocity vectors in the vertical plane passing through tundish nozzles under *non-isothermal* conditions.
(Approximately 200 s after the incoming steel concentration was changed)

Figures 1 and 2 clearly show the difference between the tundish flow patterns observed under isothermal and non-isothermal conditions. The arrows in the figures represent the speed vectors in the vertical plane passing through the tundish nozzles. Under non-isothermal conditions, buoyancy forces emerge as a result of varying densities of the steel present in the tundish and that which is being supplied. These buoyancy forces lead to the development of the so-called reverse flowing. The flow is directed to the surface layers of the tundish bath against the opposite wall where they turn downwards toward to discharge junction of the nozzle no. 8 and proceed in a reverse fashion back to the nozzle no. 5. - see figure 3. The results obtained from numerical simulations correspond to the results achieved when physical modelling in isothermal conditions was performed [8,9].

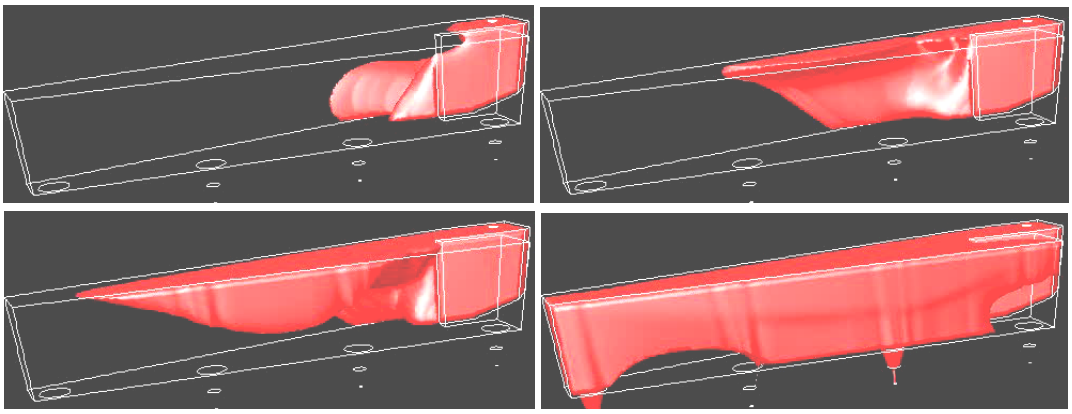

Figure 3: Steel spread in the tundish under ***non-isothermal*** conditions

4. Results of Numerical Modelling of Transition Zone Extent

Figure 4 shows the transition curves characterising the process of concentration changes observed at the tundish outlets subject to a step concentration change at the tundish inlet under isothermal and non-isothermal flow and stable tundish steel weight of 12 t.

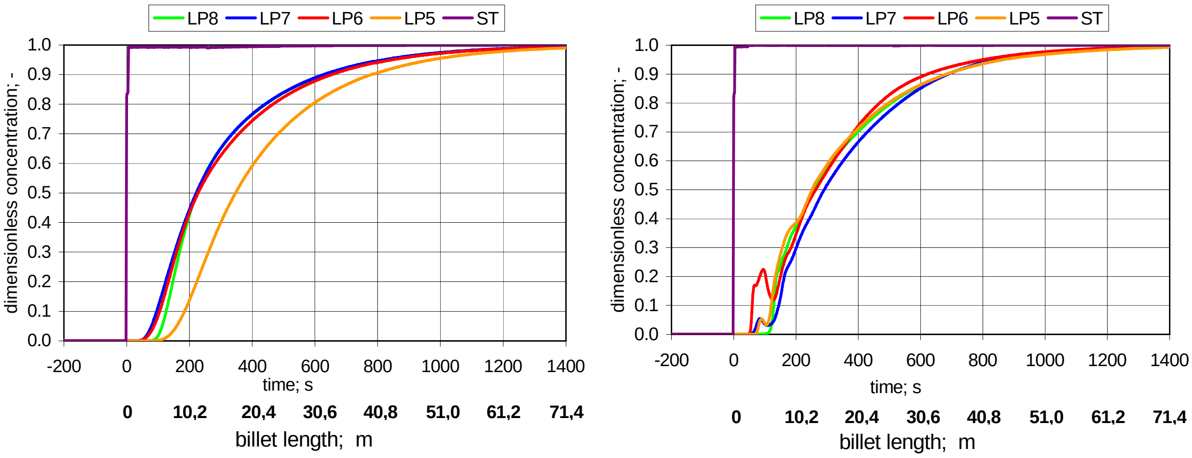

Figure 4: Transition curves characterizing a change in the chemical composition of liquid steel at the individual tundish nozzles (LP5, LP6, LP7, LP8) after a change in the concentration of a steel component at tundish inlet under conditions of *isothermal* flow and *non-isothermal* flow at tundish steel weight of 12 t

Major concentration increase was observed between 100 and 400 s after the concentration was changed at the tundish inlet. The steepness of the individual curves subsequently diminishes and the concentration begins to be stabilised in a more continuous fashion before it gets almost totally homogeneous at all casting strands at 1200 s after the concentration change, which corresponds to almost one third of the casting time allotted to a single heat (190 t). Under non-isothermal conditions, the pattern of transition curves as well as the order of concentration growths at the individual nozzles changes along with a change in the flow pattern. The onsets of the transition curves are characterised by fluctuating concentration changes occurring as a result of the mutual interaction of inertia and buoyancy forces with subsequent changes in the flow pattern. As a function of the gradual stabilisation of the temperature field in the tundish bath, the flow pattern gets closer to the isothermal flow pattern where inertia forces dominate.

Figure 5 shows the transition curves under isothermal and non-isothermal conditions and at stable tundish steel weight of 8 t. Lower steel weights observed in free casting where identical calibrated nozzles were employed have led to lower casting speeds – in this case 2,7 m.min^{-1}. Lower tundish steel weights have a pronounced effect on the increased steepness of the transition curves. The region of steep concentration increase is observed between 100 and 300 s after the concentration was changed at the tundish inlet. After that it becomes almost totally stabilised at all casting strands at 800 s, which corresponds to approximately a quarter of the heat casting time. Even at the tundish steel weight of 8 t, the onset of the transition curves under non-isothermal conditions is characterised by fluctuating concentration changes, which implies that buoyancy force dominated the flow pattern.

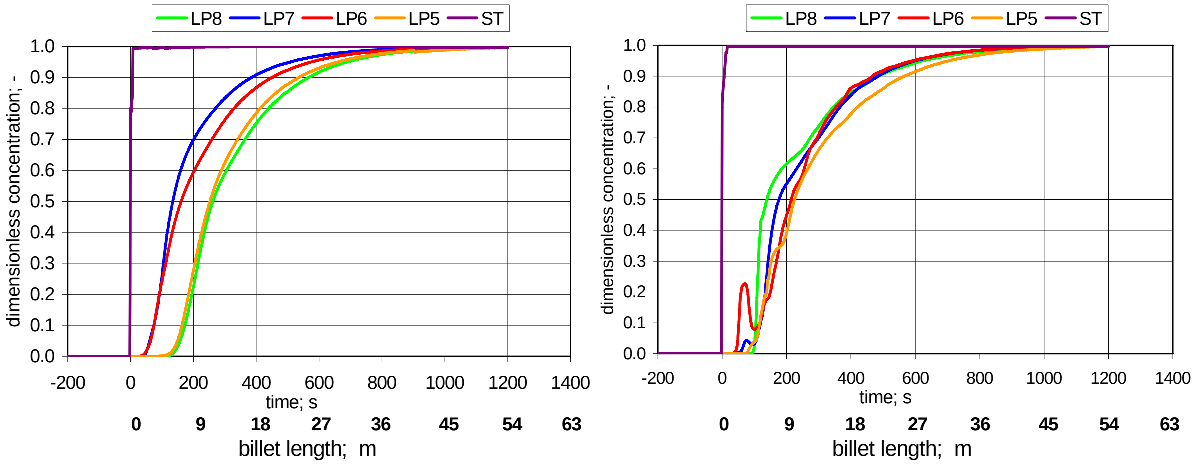

Figure 5: Transition curves characterizing a change in the chemical composition of liquid steel at the individual tundish nozzles (LP5, LP6, LP7, LP8) after a change in the concentration of a steel component at tundish inlet under conditions of *isothermal* flow and *non-isothermal* flow at tundish steel weight of 8 t

It is also worthwhile to save a few words about the behaviour of the steel bath temperatures at the tundish outlets in simulation of non-isothermal conditions – see figure 6. As stated above, the temperature was increased from 1510°C to 1540°C at the tundish inlet along with a composition (concentration) change, i.e. a temperature step change by 30°C. As shown in figure 7, the progression of the curves corresponds relatively well to the transition curves in figure 5. The divergence in the temperature of steel entering the tundish and leaving the tundish has been caused by the considered heat losses through the tundish lining and away from the bath level in the tundish. These losses were simulated in the Fluent environment by the corresponding heat fluxes. Temperature drops of approximately 2°C were observed for nozzles no. 6 and no.7, and as far as the outer nozzles no. 5 and 8 are concerned, the temperature was observed to drop by approximately 4°C. The as-verified obtained values may serve to more accurately establish the optimum casting speed at the individual casting strands.

The results obtained from an analysis of the transition curves are summarised in table I, which gives data on the extent of the transition zone for four basic tundish steel weights (15 t, 12 t, 10 t and 8 t). Both isothermal and non-isothermal flow conditions were simulated for each of the above steel weights (temperature difference of 30°C). The transition zone is expressed in each of these instances for two $\tilde{c}_{old}$ and $\tilde{c}_{new}$ value ranges, both for the "stricter" variant {0,1; 0,9} and the "milder" variant {0,3; 0,7}. The real values of these dimensionless specifications of the chemical composition may be obtained by applying the above procedure on the basis of analytical data on the chemical composition of both steel cast and permissible tolerance deviations from the specified composition.

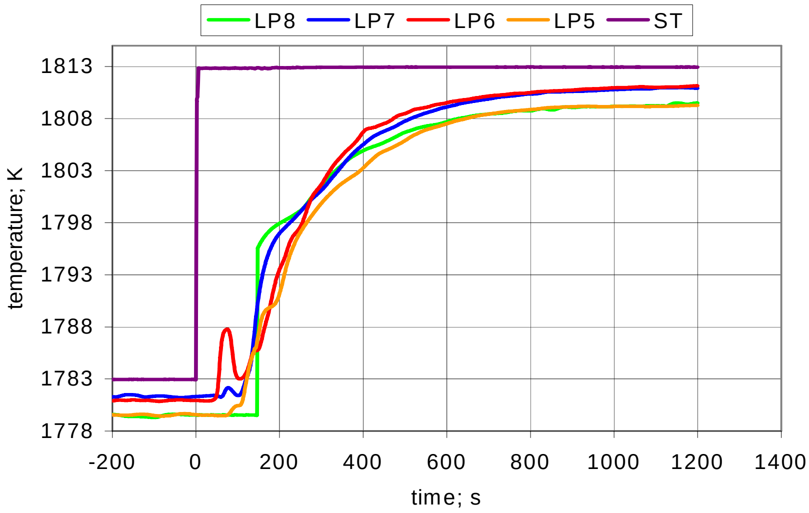

Figure 6: Changes in steel temperature at individual tundish nozzles (LP5, LP6, LP7, LP8) after a change in the temperature of the steel from 1783 K to 1813 K at the tundish steel weight of 8 t

The above table may used to derive information on the extent of the transition zone of the casting strands LP5 to LP8 (and LP4 to LP1). Considering the fact that it has so far not been possible reflect these data on field scale for various separations of billets from each casting strand, a so-called *reference maximum length* of the transition zone was calculated, essentially expressing its maximum possible extent valid for any casting strand if, at the same, it has been complied with the requirement that the steel outside this transition zone has to have a required chemical composition fully corresponding to the tolerance range specified for the "old" (previous) or "new" (following) steel grade. Based on these data, the maximum possible emergent weight of the transition zone was summarised for all of the eight casting strands.

Inter alia, the above table shows that under the conditions of isothermal flow and the "stricter" dimensionless specification {0,1; 0,9} 64 tonnes of transition steel may be expected to emerge upon changing the grade at the tundish steel weight of 15 t. With the "milder" specification {0,3; 0,7}, the amount of transition steel decreased to approximately 29 t. The table also shows a certain effect of non-isothermal flow on the extent of the transition zone. With the "stricter" dimensionless specification, the extent dropped to 56,5 t (i.e. by approximately 12 %), and with the "milder "dimensionless specification, it remained unchanged.

Table I further implies that once the steel grade has been changed, meaning the concentration of the steel's critical component at the tundish inlet was changed, the critical change in the composition at the tundish outlet did not occur before after 118 s and 164 s with the "stricter" and "milder" specification, respectively, which, converted to the billet length cast at a single casting strand, corresponds to 6,5 m and 9 m, respectively. Hence, this length may still be considered to consist of the old (previous) steel grade, as it complies with its dimensionless specification.

Table I: Results of simulation of the extent of transition zone in 150x150mm CC-billets using CFD Fluent

Conditions			Transition Zone Extent					
Weight of steel in tundish, t	Casting speed, $m.min^{-1}$	Temperature difference, °C	$\tilde{c}_{old}$	$\tilde{c}_{new}$	Units	min/max	Max. ref. length at 1 casting strand, m	Total weight at 8 casting strands, t
15	3.3	0	0.1	0.9	s	118/952		64
					m	6.49/52.36	45.87	
			0.3	0.7	s	164/544		29.2
					m	9.02/29.92	20.9	
		30	0.1	0.9	s	114/850		56.5
					m	6.27/46.75	40.48	
			0.3	0.7	s	144/522		29
					m	7.92/28.71	20.79	
12	3.1	0	0.1	0.9	s	94/778		48.68
					m	4.79/39.68	34.89	
			0.3	0.7	s	152/482		23.48
					m	7.75/24.58	16.83	
		30	0.1	0.9	s	120/688		40.42
					m	6.12/35.09	28.97	
			0.3	0.7	s	156/428		19.35
					m	7.96/21.83	13.87	
10	2.9	0	0.1	0.9	s	90/702		40.99
					m	4.32/33.7	29.38	
			0.3	0.7	s	140/462		21.57
					m	6.72/22.18	15.46	
		30	0.1	0.9	s	110/626		34.56
					m	5.28/30.05	24.77	
			0.3	0.7	s	136/374		15.93
					m	6.53/17.95	11.42	
8	2.7	0	0.1	0.9	s	72/566		31.02
					m	3.24/25.47	22.23	
			0.3	0.7	s	104/364		16.3
					m	4.68/16.4	11.7	
		30	0.1	0.9	s	104/566		29.01
					m	4.68/25.47	20.79	
			0.3	0.7	s	112/326		13.44
					m	5,04/14,67	9,63	

Identical tendencies may also be observed for lower tundish steel weights which are closer to the real technological practice at ladle change related to the transition to a different steel grade. With lower steel weights in the tundish, the process of mutual intermixing of the two steels accelerates, which results in a noticeably increased steepness (inclination) of the individual transition curves. The increased steepness has a very beneficial effect on the extent of the resultant transition zone. For instance, given the lowest considered steel weight of 8t in the tundish, it was found out that with the "stricter" dimensionless specification {0,1; 0,9} only about 31 t of transition steel could be expected to emerge, which is almost a half of the amount determined for 15 t of steel in the tundish. A similarly positive trend may be observed where "milder" specification applies {0,3; 0,7}, with the amount of transition steel dropping to approximately 16 t. Even here, a beneficial effect of non-isothermal flow upon the extent of the transition zone may be observed: compared to the isothermal conditions, the resultant zone is smaller by 6 to 15 %.

A comparison of the results obtained from numerical simulations of the transition zones emerging in 150x150mm billets for isothermal tundish flow conditions and tundish steel weights of 12 and 8 t is shown in figure 7.

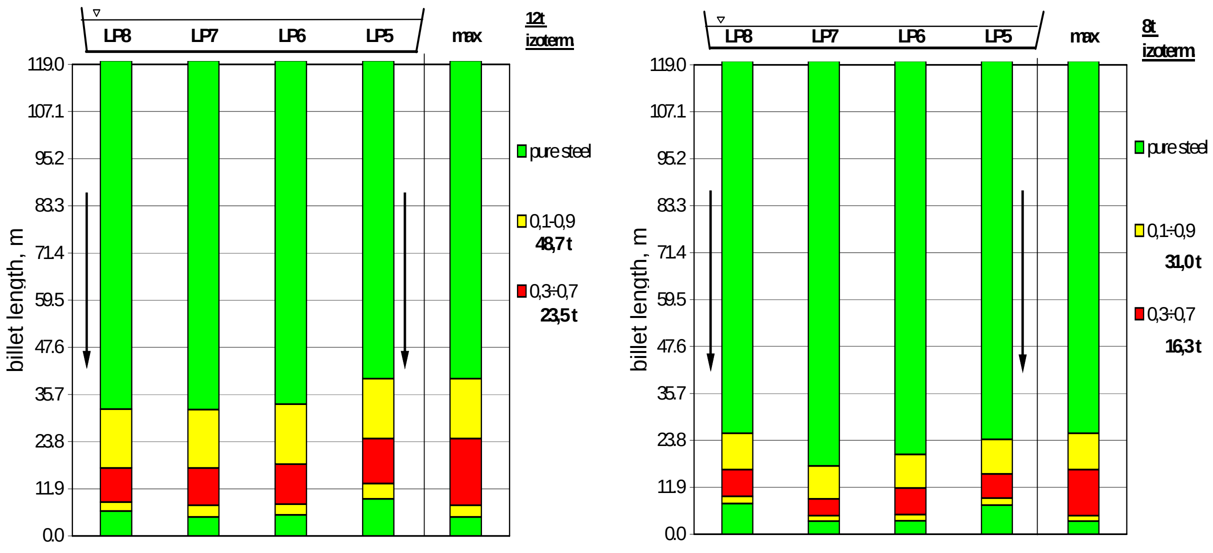

Figure 7: Graphical representation of the transition zone extent in 150x150 mm billets under isothermal bath flow and at the tundish steel weight of *12 t* and *8 t*

Zero bloom length (axis x) corresponds to the moment when new (following) heat begins to flow into the tundish. First, the charts show an apparent area of pure steel (previous grade), after which the transition steel zone sets in with the "stricter" dimensionless specification within which there is also a smaller zone with the "milder" specification. After the end of the transition zone, pure steel follows (following grade). A comparison of the charts on the abovementioned figures reveals an apparent effect of the decreasing weight of steel in the tundish on the extent of the transition zone. The charts also imply that the transition zone cannot reach as far as a bloom cast before the onset of the steel flow from a new casting ladle. Considering the fact that after that the bloom gets generally cut 11,9 m lengths, the transition zone may extend even to the billets that originated before the new ladle steel began to be discharged into the tundish. This fact needs to be considered when deciding which billets originated from the transition zone. Figure shows that given the tundish steel weight of 8 t the maximum of three 11,9 m-long billets may be expected to be inflicted with a transition zone under the least favouring conditions, i.e. at the dimensionless specification {0,1 - 0,9}. The specified dimensionless specifications will, however be more favourable in a majority of cases, which could further reduce the extent of the transition zone.

5. Physical Modelling of Transition Zone Extent and Comparison with Results of Numerical Modelling

The tundish transition processes that affect the emergence and extent of the transition zone in continuously cast billets were also covered by the experimental simulations using the physical modelling method. The physical modelling method is widely used in metallurgy, being based on the use of the theory of similarity of processes occurring in a real facility (tundish) and its model. The steel flow pattern at the CCM 2 tundish at TŽ, a.s. [10] had already been optimised previously by changing its internal configuration using the above method.

When performing the physical modelling of transition processes, the condition of Fr identity and Tu criteria for the facility and the model were adhered to. The physical tundish model was made of organic glass at the length scale of M_l=1:3 – see Figure 8.

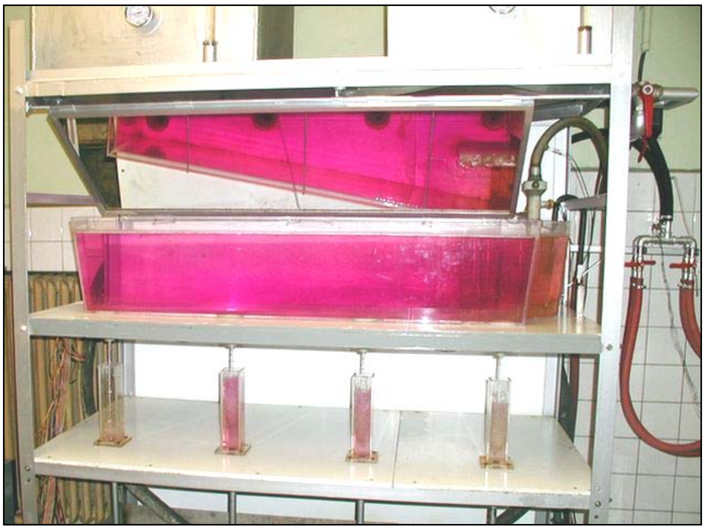

Figure 8: View of the physical model installation on scale 1:3 with colored fluid

The steel grade change was simulated on the model by changing the flow of KCl water solution with a different concentration, and/or even with a different temperature. The trend in changes of conductivity and temperature of the solution at the tundish outlets was scanned using combined conductivity/temperature sensors. The measured solution conductivity values were set off to a reference temperature on line, and then the values were converted to the real solution concentration. The physical model was used to simulate analogical variants as was the case with the numerical modelling, while at the same time the effect of identical boundary conditions were monitored.

Figures 9 and 10 compare the trends in transition curves obtained from numerical and physical modelling for 8 t and 15 t of steel in the tundish and non-isothermal flow pattern in casting strands 6 and 7.

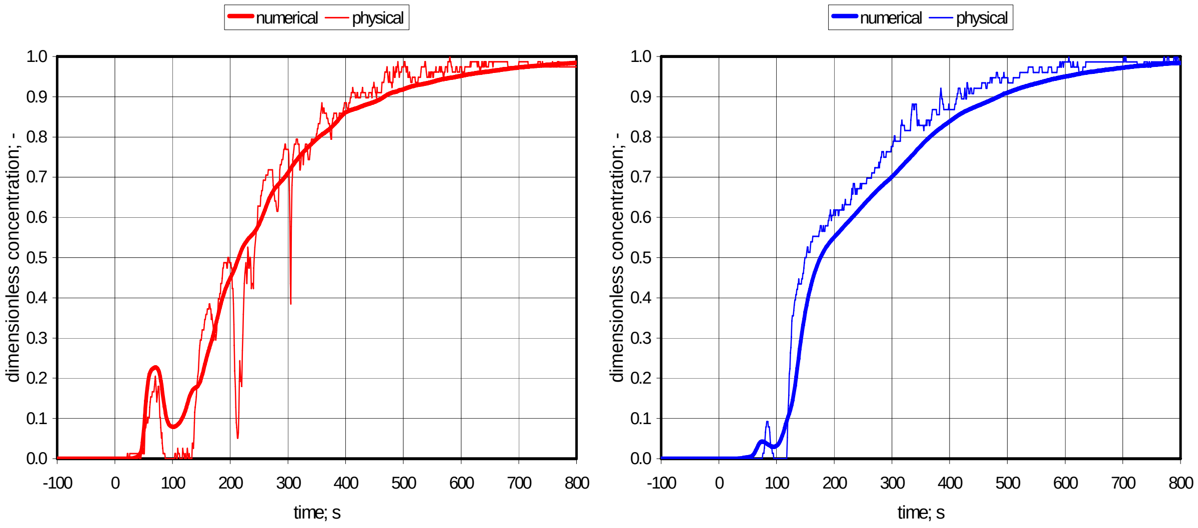

Figure 9: The comparison of the numerical and physical modelling results of the transition phenomena at non-isothermal conditions and with the tundish steel weight of *8 t* for casting strand *no.6* and *no.7*

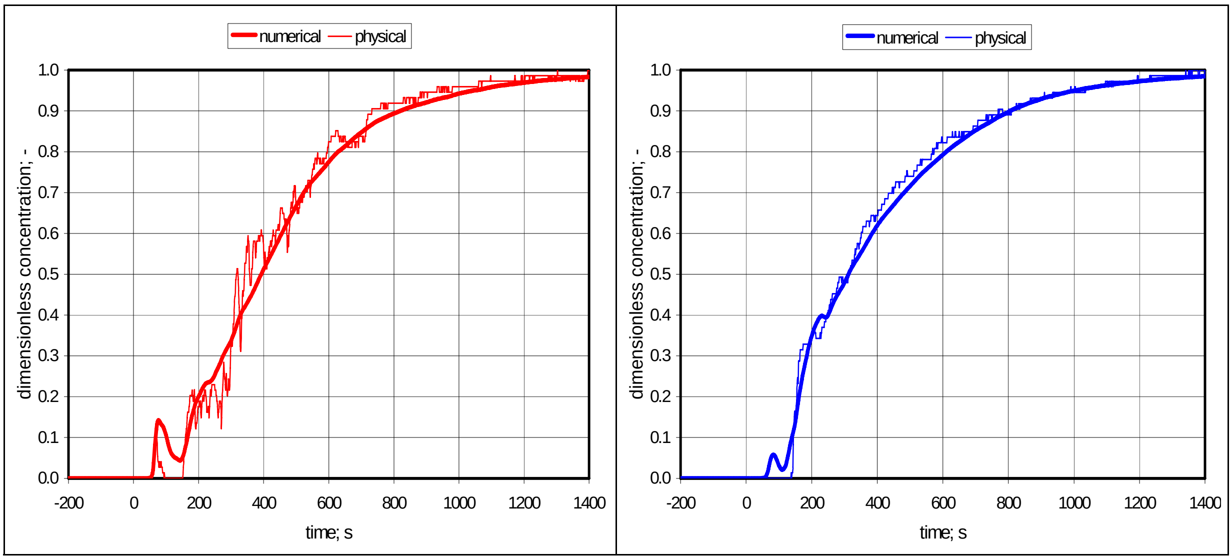

Figure 10: The comparison of the numerical and physical modelling results of the transition phenomena at non-isothermal conditions and with the tundish steel weight of *15 t* for casting strand *no.6* and *no.7*

The figures clearly show not only the good correlation of time relations, but also the correlation of curves, which proves that analogical flow pattern was achieved in the physical model and in the numerical simulation environment. The same correlation was also achieved for other casting strands and also for the isothermal flow conditions. The results obtained from the physical modelling were used to ensure better accuracy of the numerical modelling results and to verify them.

6. Conclusion

The physical and mathematical modelling of bath flow in a four-strand tundish at CCM no. 2 at TŽ, a.s. was primarily focused upon the simulation of the transition zone extent in finished billets originating as a result of sequence casting of two different steel grades. Results of these simulations also led to the draft of the so-called transition curves applying to individual casting strands, on the basis of which the extent of the transition zones may be predicted for a range of verifying casting conditions and dimensionless specifications of chemical composition of steels. The results obtained from the simulations imply that the transition zone is much smaller than that inherent in state-of-the-art practice applied for CCM 2.

The next study will be devoted to the modelling of non-standard casting conditions (obstruction of casting strands, refilling mode with increased flow rate). Finally will be modelling results compare with plant experiment.

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