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VERIFICATION OF NON-STANDARD F-CURVES DURING STEEL INTERMIXING IN A TUNDISH

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Minimization of intermixing length during continuous casting of steel is a crucial step towards higher productivity and yield of a continuous casting technology. For such a complex mass transfer problem, physical simulation using scaled-down water models might become indispensable tool to quantify the liquid steel parameters in the tundish. In this paper, such an advanced, water-based model of tundish from Železiarne Podbrezová, a. s. is used to model the intermixing process of two consecutive heats with different chemical composition. Obtaining the non-standard F-curves while manipulating the liquid level and the casting speed simultaneously gave us a valuable insight into the process of intermixing and allowed us to make preliminary conclusions on the intermixing optimization problem.

Key words: steel, continuous casting, physical simulation, tundish, flow

INTRODUCTION

Physical modelling of steel flow in a three-strand, T-type, twelve-ton tundish used in Železiarne Podbrezová, a. s. (ŽP, a. s.) is the key modelling process of the joint laboratory SimConT, cooperatively built by ŽP VVC, s. r. o. and Faculty of Materials, Metallurgy and Recycling (FMMR), Technical University of Košice in 2016 – 2018. This laboratory is located at the Institute of Metallurgy, FMMR TU Košice and is based on a scaled-down (1:2) water model of tundish in ŽP, a. s. (hereinafter referred to as "tundish"). The model itself is equipped with a comprehensive sensing and control system to perform automated series of steady - state as well as transient steel flow experiments, Figure 1 [1]. In this paper, physical simulation of experimental steel intermixing in the tundish during continuous casting is described and evaluated. During the experimental intermixing process, steel level in the tundish was deliberately manipulated so to minimize the intermixing length in the casting strands.

In SimConT laboratory, the high level of automation and control system allowed us to fully control both the steel level and the casting speed. This made possible the full reconstruction of the non-trivial transient flow process in the real tundish and evaluate rigorously the intermixing process using well-proven water modelling analogy.

For the validity of the tundish water model, obtaining the RTD (Residence Time Distribution) curves for all casting strands and comparing them to the ones obtained during actual casting is of funda -mental importance. These curves represent the basic characteristics of the steel flow in the tundish and correlate strongly with the final quality of the cast steel [2-4]. The F-curves characterize the flow dynamics during transient casting state, i.e., when the steel level rises during filling from a set minimum to the nominal value. From F-curve can be directly predicted length of slab transition area [5-6]. This part of slab is in many cases, depending on chemical composition of casted steel qualities, does not meet with standards required for given steel quality. Therefore, we need to know allocation and length of this transition area, especially in multiple strand continuous casting machine (CCM). For the validation of F-curves for the tundish model, a series of experiments were performed in ŽP, a. s., where two consecutive heats with different chemical compositions were cast so that the F-curves could be reconstructed from the longi-

Figure 1 SimConT laboratory with operator's control station (front left), water model of ŽP tundish (right) and water model of U. S. Steel tundish (rear left)

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tudinal concentration profile of the target chemical element in the casting strands.

EXPERIMENTAL WORK

Evaluation of the intermixing process in a real tundish. The aim of the experiment was to analyze the concentration transient phenomenon in the tundish during casting of two consecutive heats (No. 2775 and 2774) with different chemical composition. Since it is not possible to take synchronous steel samples from the molds during casting, it was decided to use additional chemical analysis of the cast billets. Chromium (Cr) and molybdenum (Mo) were used as tracking elements. [7] On the basis of the time relations during casting and the lengths of individual billets it was possible to reconstruct the longitudinal concentration profiles in all three strands from the beginning of the casting (i.e., opening the 2774 - heat).

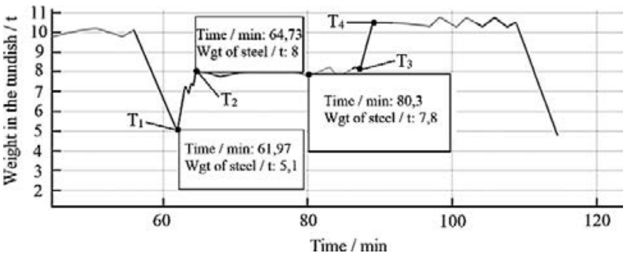

Figure 2 Steel weight in the tundish during the intermixing phase, with time intervals T_1 - T_4

In Figure 2 we can see the graphical representation of the intermixing casting phase in the tundish. Each color segment of the weight curve represents the "virtual billet", i.e., the material to be solidified in the given billet and subsequently cut from the casting strand. Prior to opening the 2774 - ladle (62 nd minute) the steel weight in the tundish was reduced to approx. 5 tonnes. After opening, filling of the tundish commenced, reaching the weight level of 8 tonnes (65th minute), changing the casting speed and hold time until the concentration changed to the desired level (80th min.) Finally, the reference weight of steel in the tundish (10 – 11 tonnes) was reached. During 18 minutes of transition casting, approximately 18,9 m of billets were cast on the 1st strand. The changes in casting speed were different for each strand, Table 1.

Table 1 **Casting parameters during intermixing**

Parameters in the transient casting phase				
Time intervals	T_1	T_2	T_3	T_4
Absolute time / min	62	65	87,1	89,2
Level Change / t	T_1	T_2-T_3		T_4
	5	8		10 – 11
Casting speed / m/min	v_0 (- T_2)		v_1 (T_2 -)	
Strand No. 1	0,9		1,05	
Strand No. 2	0,9		0,95	
Strand No. 3	0,9		1,15	

Transient characteristics have been created for every casting strand and compared with the real data on the level and casting speed. For clarity, characteristics of casting speed are shown for 1st strand only in Figure3.

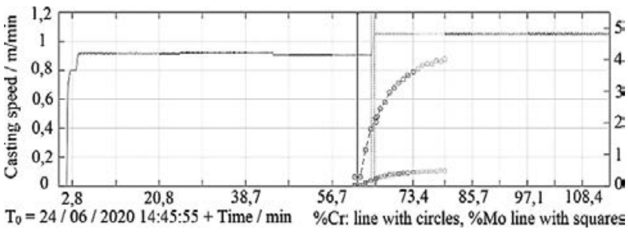

Figure 3 Casting speed during actual casting, with corresponding transition phase in the billets, strand No. 1, change in casting speed from 0,95 to 1,05 m/min at t_1 = 64,75 to t_2 = 65,35 / min

Modelling of the intermixing phase of continuous casting using tundish water model. Intermixing of two consecutive and chemically different heats in the tundish has been evaluated via F-curves. Using these curves, it is possible to determine the location and length of the transition area under specific conditions (casting speed, tundish configuration, liquid steel level at which tundish filling begins, and tundish filling mode) [8-9]. For each F-curve, it is possible to calculate at which time, under the given conditions, the concentration of the monitored element decreased or increased to the desired value. It is also possible to calculate, how much steel has been cast and where the transition area is located. An example of an F-curve is shown in Figure 4.

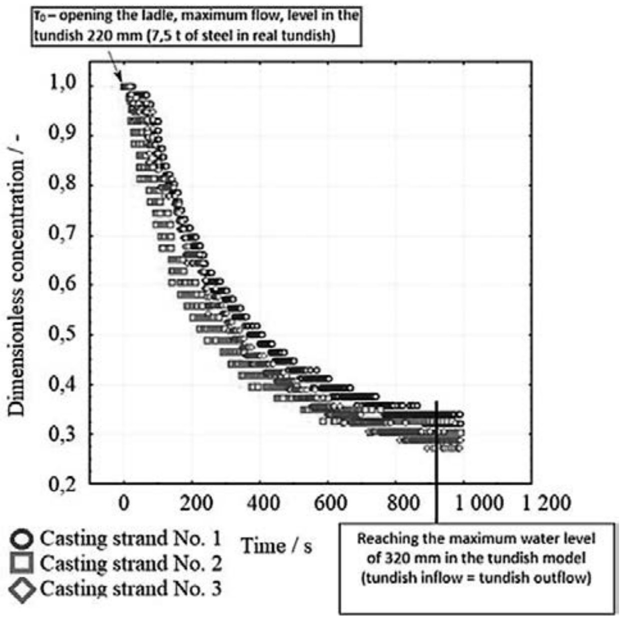

Figure 4 Example of F-curves for a three-strand tundish

It is necessary to know the dimensions of the mold, which together with the casting speed, are used to calculate the amount of steel cast per unit of time. The second option is to directly enter the cast amount of steel per unit of time (machine productivity per hour or minute). It is also necessary to consider the change in the volume of steel during the transition from liquid to solid state (i.e., specific weight difference), which may differ depending on the cast quality. Using the similarity criterions, we can deduce outcomes as in [10–11]. For a scaled-down (1:2) physical model of the tundish, the length scale M1 = 0,5 and the volume scale MQ = 0,176. The volumetric flow through the tundish will be Qv * MQ * 1 000.

For the tundish model experiment, it was necessary to recalculate the parameters from the real tundish to the model. The recalculated values are in Table 2. Due to the non-standard procedure of filling the tundish from the B-ladle while keeping the reduced liquid steel level and changing the casting speed of the strands simultaneously, the correct conversion of flow parameters using similarity criteria was crucial. In general, flow measurements can be made even with user-defined flow and liquid level courses; we obtain the so-called non-standard F-curves. The three measurements above faithfully copied the casting process during the measurement of the F-curve on the real tundish according to the compared data.

Table 2 **Description of physical simulation parameters for a steady flow**

Selected physical model parameters for a constant-level steel flow in the tundish				
Time intervals	T_1	T_2	T_3	T_4
Theoretical Time / s	0	127	1 066	1 152,6
Level change / mm	T_1	$T_2 - T_3$		T_4
	155	230		280
Water flow / l/m	(… – T_2)		(T_2 – …)	
1st casting strand	7,3		8,5	
2nd casting strand	7,3		7,7	
3rd casting strand	7,3		9,3	

RESULTS AND DISCUSSION

The theoretical and real time required to refill the tundish from 155 mm to 230 mm water level is given in Table 3. The theoretical time was deter-mined based on the data provided by ŽP, a. s. and recalculated according to the similarity criteria for the physical model. Flow rates were recalculated accordingly.

In Figures 6 – 8 is graphical comparison of F-curves (water conductivity measurement) measured on water model with dimensionless concentration of Cr in real conti - cast slab. It must be taken into account that presented measurement outputs are unique, involving not only a change in the height of the steel level in the tundish, but also changes in the casting speed of the individual casting strands. In practice, it is very difficult to exactly identify points on slabs that correspond exactly to the critical time period.

Table 3 **Length of the time period of the water level in-crease from the value of 155 mm to 230 mm and the flow rate at the tundish inlet – Measurement No. 1**

Theoretical time / s	127	
Actual time / s	135	
Change of input speed when the time changes	T_1	T_2
Inlet flow / l/min	46,20	29,3

Figure 5 shows a scheme of the tundish water model, through which the measurements of verification F-curves with real data were carried out.

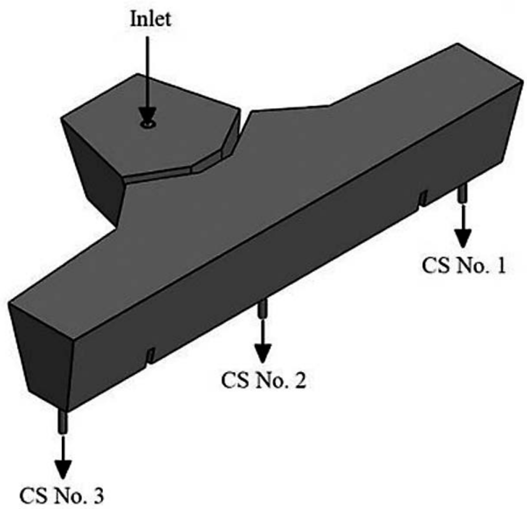

Figure 5 Geometry of 3-strand T-shaped tundish water model and its parameters

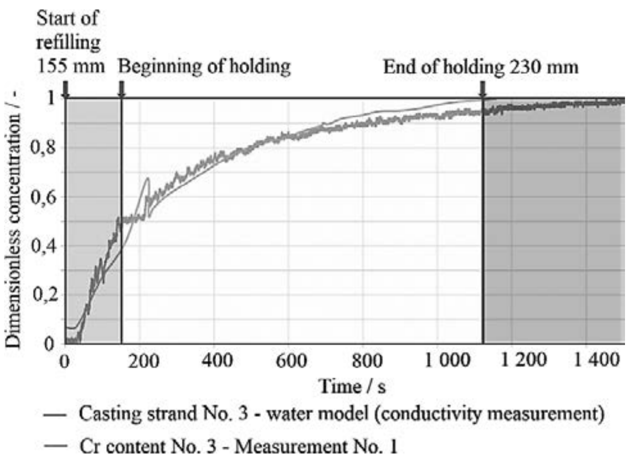

Figure 6 Conductivity measurement / Cr content Strand No. 3 - Measurement No. 1

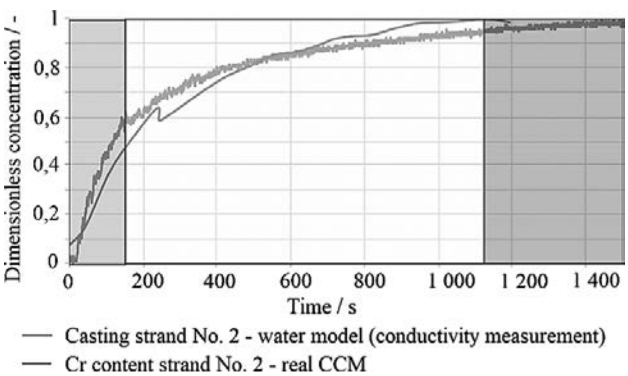

Figure 7 Conductivity measurement / Cr content Strand No. 2 - Measurement No. 1

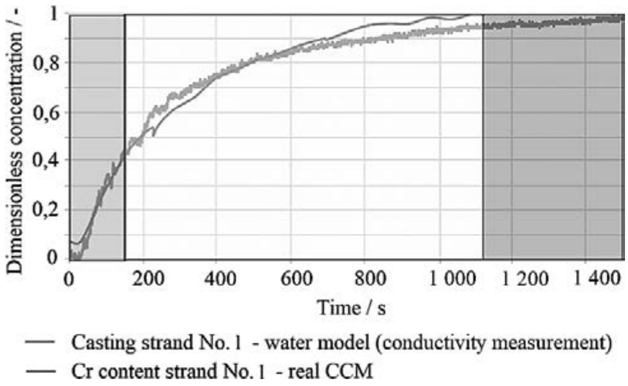

Figure 8 Conductivity measurement / Cr content Strand No. 1 - Measurement No. 1

CONCLUSION

Based on the tracer concentration characteristics obtained on the tundish water model and their comparison with the tracer element (Cr) concentration profiles on the real billets, it is possible to conclude:

- The recalculation of flow rate, liquid level and simulation time based on similarity criteria is correct
- Evolution of the concentration of the tracer during physical simulation, despite the complexity of the measurement, copies the real-world values quite precisely
- Measurements of selected quantities during simulated casting on the SimConT water model accurately represent transients on the real tundish
- During measurements on the real tundish as well as on the model, there is a disordered swirling of steel / water in the ladle (due to a change in the casting speed), which causes significant variance in the measured data. For further verifications, it would be advisable not to change the casting speed during the experiment.

In conclusion, it seems that holding the steel level down while intermixing two successive heats does not lower the intermixing length. This is contrary to what had been expected so far.

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Note: The responsible for the translation to English is Miriam Valčáková – Translations and interpreting, Košice, Slovakia.