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Prevent of clogging via a mathematical model of heat transfer in submerged entry nozzle

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Abstract
Clogging of the steel in the submerged entry nozzle (SEN) is mainly due to the agglomeration and/or interaction of the steel with the SEN refractory material. However, the continuous casting steel also leads to clogging - the freezing of the steel in the SEN at the beginning of the casting. The freezing of the steel in the SEN results mainly in the change in the geometry, the low casting temperature of steel, the insufficient preheating of the SEN and the low initial casting speed. To eliminate the problems of steel freezing at the beginning of continuous casting, the authors solved them using a mathematical model of heat transfer in the SEN. Using the mathematical model, it is possible to simulate the layout of temperatures in the SEN and the temperature of the steel at the interface of steel - the inner surface of the SEN. To determine the temperature layout in the SEN after installation on the tundish, a method of measuring the decreased average temperatures of the SEN by free convection after heating was used. Based on the analysis of the current state using simulations in a mathematical model, it is possible to define conditions for preventing the freezing of steel in the SEN when the wall thickness or isolation thickness is changing.

Keywords
Submerged entry nozzle, continuous casting, temperature layout, freezing, clogging

Introduction

There are 4 types of clogging, each with a different origin. They can cause clogging alone but also as a combination of individual types (Rackers & Thomas, 1995). Clogging is produced by the agglomeration of oxidation products of aluminium, titanium, or zirconium with a size of 1-20 microns (Ogibayashi, 1994; Shin et al., 1988; Singh, 1974; Tehovnik, 2015). The sintered oxidation products are then formed by bonding (Singh, 1974; Cameron, 1992; Tai et al., 1985; Uemura et al., 1992). It is also produced by the agglomeration of complex oxides containing non-metallic materials (Rackers & Thomas, 1995). Clogging created by the composition of deoxidation products is stored in the film. These are reactions with air drawn in the nozzle (Tai et al., 1985; Fukuda et al., 1992), oxygen from steel (Louhenkilpi, 2014), or oxygen formed from silica (Tai et al., 1985; Uemura et al., 1992; Fukuda et al., 1992; Saxena et al., 1978; Li et al., 2020). It may also be caused by unforeseeable failures or operational errors (Ikäheimonen et al., 2002). Clogging-type freezing occurs when the steel preheating is low, and at the same time, the heat flux from the steel flow is high (Szekely & DiNovo, 1974).

Nowadays, mathematical models are used to solve many problems. In the field of continuous steel casting, much of the scientific work is devoted to the clogging of steel in SEN using mathematical modelling based on water models (Kato et al., 2007) or computer flow dynamics (CFD) (Mizobe et al., 2017; Sun et al., 2018) in 1, 2 or 3 dimensions. Scientific interest is primarily oriented towards the area of mathematical modelling of flow and heat transfer of molten steel in tundish (Warzecha, 2014; Huang et al., 2019) and inside SEN (Cheng et al., 2019; Lu et al., 2019; Yan et al., 2020).

In the design of new SEN geometry, in addition to modelling steel flow and inclusions agglomeration, the solution of heat loss through the SEN wall is also needed (Rackers, 1995).

Clogging can occur when optimizing the cost of SEN in the continuous casting of steel, which is dependent on SEN material and geometry (especially wall thickness and isolation material thickness). To use mathematical modelling to solve and eliminate unwanted conditions, knowledge of the production process, production processes and technological operations is necessary, including casting temperatures, casting velocity at the beginning, temperature layout in SEN and others.

After the design of the SEN geometry modifications, mathematical models are used to model a solution (e.g. modification of production processes) that avoids the problems of steel freezing at the start of casting. The comparison is related to the SEN design that avoids operational problems.

Material and Methods

Solution methodology

To solve the problem, it was necessary to:

- measure the course of the SEN temperatures profile during cooling after preheating,
- create a mathematical model that defines:
  - heat loss from SEN during cooling,
  - average temperature change course SEN during cooling,
  - temperature layout in individual layers of SEN in a stationary state during steel casting,
  - loss of heat into the environment at a stationary state,
  - calculation of the outlet steel temperature from the SEN at the start of casting and at stationary state.

In developing the mathematical model, 3 different SEN models were used, one as a comparison with a thicker wall model 0 and two others with a thinner wall model 1 and model 2. Model 2 has 2 variations in external isolation thickness. Model 2/2 with 2mm thickness and model 2/4 with 4mm isolation thickness. The chemical composition of the SENs was comparable. However, models 1 and 2 differed in the geometry of the inlet throat.

Temperature measurement by free cooling

For the analysis of SEN from a thermotechnical point of view, a method of measuring the decrease of mean temperatures by free convection after heating in the gas furnace was proposed. Continuous measurement with thermo-vision Micro-epsilon thermoIMAGER TIM 400 (Temperature range 200 – 1500 °C; System accuracy ±2 °C or ± 2%) was performed. The surface temperature was monitored for free cooling of selected SEN types after removal from the gas furnace and placing the tubes in the racks. Fig. 1 shows a diagram of the distribution of the analyzed temperature layout and a visualization of the temperature distribution of measured temperature regions.

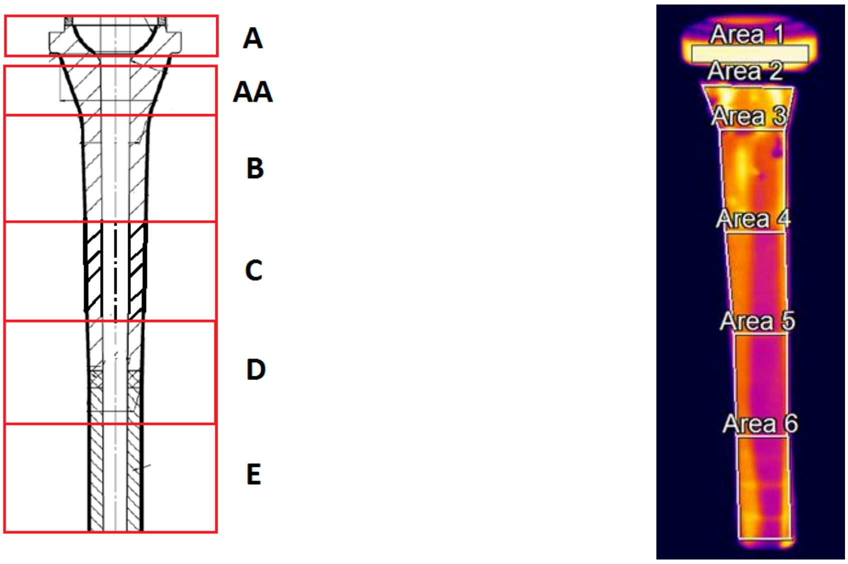

Fig. 1. Scheme of the temperature layout SEN (a); visualization of the distribution of measured temperature regions into SEN(b).

Based on the analysis of the measurement of the change in average surface temperatures of SEN, the graphs for various SEN were constructed; see Figs. 2-5.

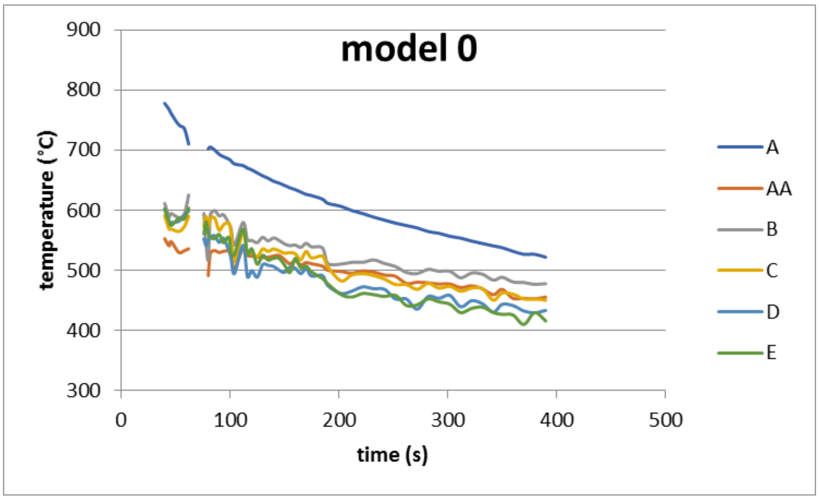

Fig. 2. Average surface temperature change for SEN, model 0.

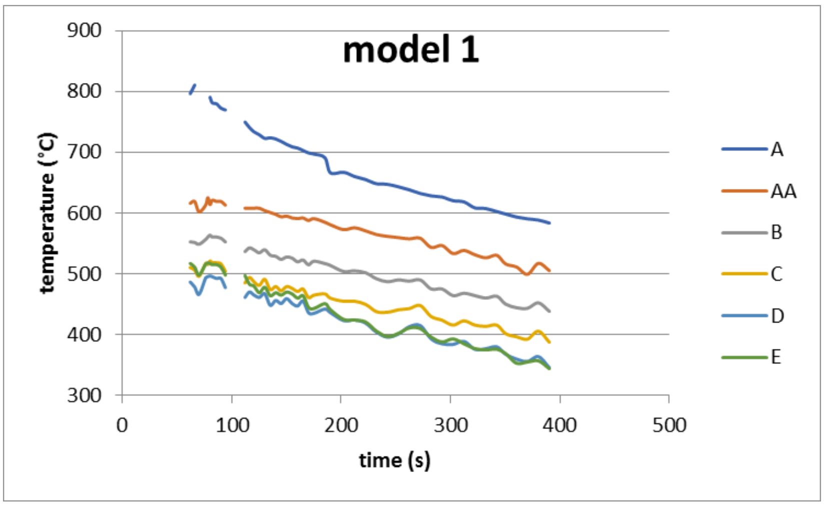

Fig. 3. Average surface temperature change for SEN, model 1.

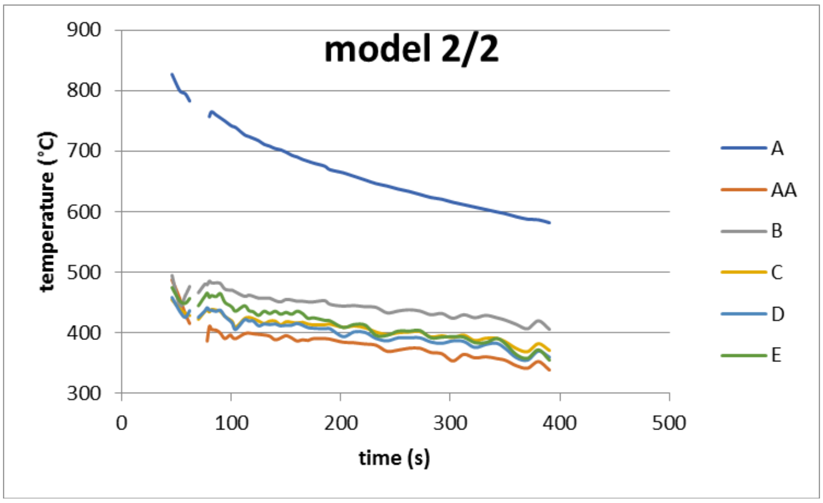

Fig. 4. Average surface temperature change for SEN, model 2/2.

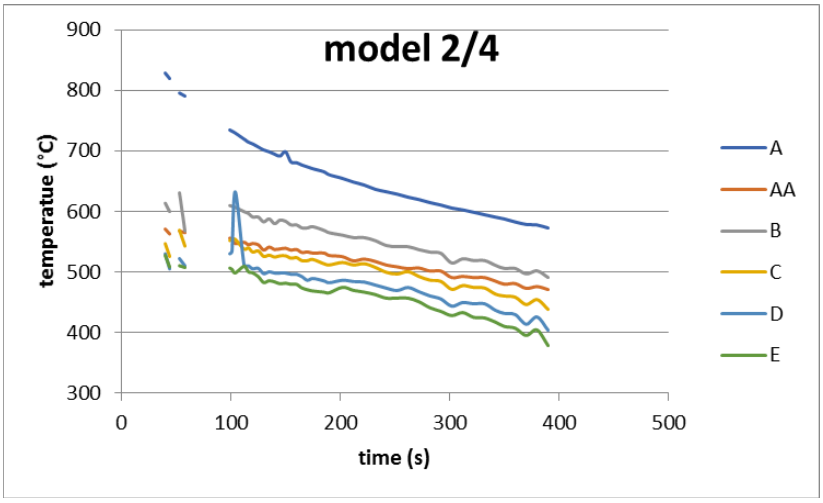

Fig. 5. Average surface temperature change for SEN model, 2/4.

Mathematical model - algorithm

Geometric parameters, material data sheets (composition, density), and free cooling temperatures were used to develop a 2-dimensional mathematical model for determining average temperatures along the height and diameter of SEN. The basic parameters of the materials used are in Table 1.

Tab. 1. The basic parameters of the used materials.

	SEN	Isolation	STEEL
THERMAL CONDUCTIVITY (W.m^{-1}.K^{-1})	1,5	= 0,0003t + 0,015	= - 0,034t + 54,293 (up to 800°C) = 26,5 (above 800°C)
BULK DENSYTY (kg.m^{-3})	2340	300	= - 0,4366t + 7923,8
SPECIFIC HEAT CAPACITY (J.kg^{-1}.K^{-1})	= -0,0000003t^2 + 0,0007t + 0,5269	1035	820
EMISSIVITY (-)	0,7	0,7	-

The basis of the mathematical model is the kinetics of heat transfer and the law of energy conservation. The algorithm is based on a zonal iterative heat transfer and energy balance calculation. The iterative calculation of heat transfer is governed by the designed algorithm described below. The calculation is performed as follows according to the elaborated Petri model in Fig. 6.

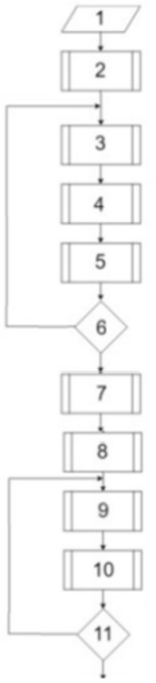

Fig. 6. Petri flowchart of mathematical model.1 = loading input data; 2 = surface temperature estimation; 3 = calculation of physical and optical parameters; 4 = calculation of thermal losses by walls to the environment; 5 = calculation of heat flows through SEN layers; 6 = verification of surface temperature; 7 = calculation of temperature layout; 8 = estimation of steel outlet temperature; 9 = calculation of heat flow from steel to ceramics; 10 = calculation of heat flow through ceramics; 11 = verification of the steel outlet temperature from the zone.

Results and discussion

The result from the mathematical model

Based on the measurement of the mean temperature change on the SEN surface, the mean temperature distribution over the height and cross-section of the SEN over time was calculated. The mathematical model was modelling the distribution of mean temperatures across the cross-section and the height of SEN when steel flows through them. The results of these models show a difference that can be considered as causing problems at the start of casting and hence the reason why steel can freeze in SEN. In simplified terms, this can described based on the diagram in Fig. 7.

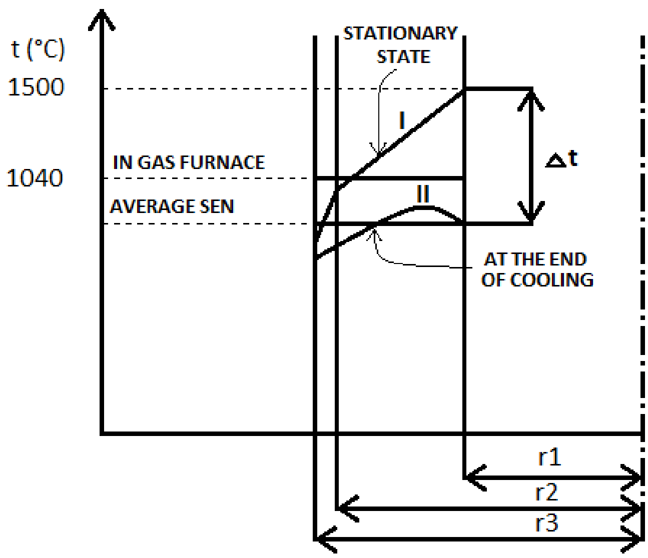

Fig. 7. Temperature diagram.

The cooling of the SEN occurs from the moment they are removed from the gas furnace, placed in a ladle and started casting. During this time, heat is dissipated from the SEN, and the average temperature across the SEN cross-section has an approximate shape as the curve II. During casting, the mean SEN temperatures must then be increased up to the steady state described by curve I. The difference between these curves is the amount of heat that the SEN must accumulate to compensate for heat losses to the environment. This energy or heat to the SEN is taken from the steel, and the steel temperature at the surface of the SEN walls decreases. The amount of energy required depends not only on the different average temperatures between SEN and steel but also on the physic-chemical properties of the SEN, the wall thickness and the thickness of the mineral isolation. The mean temperature courses for both model situations and for different SENs are shown in Tables 2-4 below.

Based on the measured data, the outlet temperature of the steel from the SEN at the start of the casting and at the optimal casting speed was calculated by a mathematical model. SEN model 0, which does not usually cause steel to freeze, can be considered a comparison tube. The results of mathematical simulations point to lower steel outlet temperatures in tubes with thinner wall thickness. Although the differences are not significant (up to 5°C difference in the steel temperature at the outlet of the SEN), the temperature drop over the comparative tube can cause an unwanted state of freezing of the steel at the SEN walls depending on the steel grade (characteristic liquid temperature).

Tab. 2. Outlet temperature of steel from SEN at the beginning and at the normal state of casting.

SEN MODEL	0	1	2/2	2/4
	BEGINNING			
CASTING VELOCITY ($m.min^{-1}$)	0,7	2,3	2,3	2,3
VELOCITY IN SEN ($m.s^{-1}$)	0,8	0,687	0,687	0,687
INLET TEMPERATURE – STEEL (°C)	1550	1550	1550	1550
OUTLET TEMPERATURE – STEEL (°C)	**1530**	**1526**	**1526**	**1527**
	NORMAL STATE			
CASTING VELOCITY ($m.min^{-1}$)	0,95	3,5	3,5	3,5
VELOCITY IN SEN ($m.s^{-1}$)	1,08	1,04	1,04	1,04
INLET TEMPERATURE – STEEL (°C)	1550	1550	1550	1550
OUTLET TEMPERATURE – STEEL (°C)	**1534**	**1532**	**1532**	**1533**

After the steel casting starts, the casting speed gradually increases, and the SEN accumulates heat until the temperature field in the SEN stabilizes within a certain time (within 2-3 minutes). The steel temperature drop was calculated for the various tubes at the optimum casting speed. In the optimum operating condition, there is only a minimal drop in the steel outlet temperature, at a drop of 1.5 °C.

One of the important factors influencing the initial steel outlet temperature at the start of casting is the mean tube temperature in each region dependent on heat loss as a function of time, obtained by analyzing the surface temperature drop during free cooling. From the mean temperatures, it is possible to determine the total heat loss from the SEN recess to the start of casting, defined by the time of

350 seconds; see Table 3. The more energy was discharged into the environment, the tube must accumulate more energy up to the operating state (normal state). This heat is supplied to the tube to be contained in the steel.

Tab. 3. Heat loss to the environment and mean tube temperature at the end of cooling.

COOLING TIME 350 SECONDS							TOTAL LOSS / AVERAGE TEMP.
SEN ZONE	**A**	**AA**	**B**	**C**	**D**	**E**	
SEN MODEL	**0**						
HEAT LOSS (J)	293 272	290 032	215 015	195 785	130 403	264 604	1 389 111
AVERAGE TEMPERATURE – CERAMICS (°C)	777	863	859	863	869	865	**852**
SEN MODEL	**1**						
HEAT LOSS (J)	380 662	358 483	179 400	141 277	119 136	191 676	1 370 634
AVERAGE TEMPERATURE – CERAMICS (°C)	720	818	872	886	886	834	**829**
SEN MODEL	**2/2**						
HEAT LOSS (J)	566 820	190 545	211 622	164 725	139 989	201 739	1 475 440
AVERAGE TEMPERATURE – CERAMICS (°C)	557	925	839	858	856	821	**811**

SEN MODEL	2/4						
HEAT LOSS (J)	583 525	130 425	149 802	121 428	111 199	181 290	1 277 669
AVERAGE TEMPERATURE – CERAMICS (°C)	549	970	911	919	909	862	**853**

At the operating casting speed, the distribution of average SEN temperatures is stable, and their values are given in Table 4. At these average temperatures, it is possible to determine the total loss of the tube and calculate the temperature of the steel on the inner surface. The basis for the calculation and determination of temperatures is the heat balance of the individual tube areas.

Tab. 4. Heat loss to the environment and SEN temperature at normal state.

SEN ZONE	**A**	**AA**	**B**	**C**	**D**	**E**	TOTAL LOSS
SEN MODEL	**0**						
HEAT LOSS (W)	429	452	732	732	529	1 059	**3 933**
OUTSIDE TEMPERATURE SEN (°C)	738	624	727	736	741	741	
TEMPERATURE ISOLATION/CERAMICS (°C)	738	785	927	940	946	946	
INSIDE TEMPERATURE SEN (°C)	1 505	1 497	1 529	1 529	1 529	1 529	
SEN MODEL	**1**						
HEAT LOSS (W)	324	518	714	704	693	1 089	**4 043**
OUTSIDE TEMPERATURE SEN (°C)	738	627	752	768	786	793	
TEMPERATURE ISOLATION/CERAMICS (°C)	738	790	963	987	1014	1 026	
INSIDE TEMPERATURE SEN (°C)	1 502	1 494	1 525	1 525	1 525	1 525	
SEN MODEL	**2/2**						
HEAT LOSS (W)	324	516	714	703	692	1 087	**4 036**
OUTSIDE TEMPERATURE SEN (°C)	738	627	752	768	786	793	
TEMPERATURE ISOLATION/CERAMICS (°C)	738	790	963	987	1 014	1 026	
INSIDE TEMPERATURE SEN (°C)	1 502	1 494	1 525	1 525	1 525	1 525	
SEN MODEL	**2/4**						
HEAT LOSS (W)	324	463	613	601	587	919	**3 508**
OUTSIDE TEMPERATURE SEN (°C)	738	592	697	710	726	729	
TEMPERATURE ISOLATION/CERAMICS (°C)	738	870	1045	1 068	1 094	1 106	
INSIDE TEMPERATURE SEN (°C)	1 502	1 502	1 526	1 526	1 526	1 527	

Discussion

The aim of mathematical modelling is to find a solution that would prevent the unwanted state of freezing of steel in SEN. Based on previous analysis, one of the possible solutions is to increase the temperature of preheating SEN. The SEN preheating temperature sought must meet the following requirement: - the mean temperature of the SEN after cooling must be such that, at the start of casting, it will not draw off the amount of heat from the steel, which could cause the steel to freeze against the walls of the tube.

SEN model 2 with 2 mm isolation (model 2/2) and 4 mm isolation (model 2/4) was selected for modelling. When comparing these submerged entry nozzles, the tube with thicker isolation has a higher mean temperature and lower losses. However, even when the preheating temperature of this SEN is increased up to 1100 ° C, the steel outlet temperature will be lower at the start casting rate than at the comparator SEN model 0. Therefore, the modelling of the increase of the casting starting speed was also accepted. The results of the simulations are shown in Table 5.

Tab. 5. Heat loss to the environment and temperature in the tubes under standard conditions.

SEN ZONE	**A**	**AA**	**B**	**C**	**D**	**E**	TOTAL HEAT LOSS / AVER. TEMPERATURE / CASTING SPEED
SEN MODEL	**2/2**						
PREHEATING TEMPERATURE (°C)	**1 040**						

HEAT LOSS (J)	566 820	190 545	211 622	164 725	139 989	201 739	1 475 440
AVERAGE TEMPERATURE – CERAMICS (°C)	557	925	839	858	856	821	**811**
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 544	1 539	1 535	1 532	**1 526**	W=2.3
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 545	1 542	1 539	1 536	**1 532**	W=3.5
SEN MODEL	**2/4**						
PREHEATING TEMPERATURE (°C)	**1 040**						
HEAT LOSS (J)	583 525	130 425	149 802	121 428	111 199	181 290	1 277 669
AVERAGE TEMPERATURE – CERAMICS (°C)	549	970	911	919	909	862	**853**
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 544	1 541	1 537	1 533	**1 527**	W=2.3
OUTLET TEMPERATURE – STEEL (°C)	1 548	1 546	1 543	1 540	1 537	**1 533**	W=3.5
SEN MODEL	**2/4**						
PREHEATING TEMPERATURE (°C)	**1 060**						
HEAT LOSS (J)	587 107	132 866	152 198	123 665	113 277	184 474	1 293 586
AVERAGE TEMPERATURE – CERAMICS (°C)	567	989	929	938	927	879	**872**
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 545	1 541	1 537	1 534	**1 528**	W=2.3
OUTLET TEMPERATURE – STEEL (°C)	1 548	1 546	1 543	1 540	1 538	**1 533**	W=3.5
SEN MODEL	**2/4**						
PREHEATING TEMPERATURE (°C)	**1 080**						
HEAT LOSS (J)	590 829	135 417	154 701	126 002	115 448	187 801	1 310 198
AVERAGE TEMPERATURE – CERAMICS (°C)	585	1 008	947	956	945	897	**890**
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 545	1 541	1 538	1 534	**1 529**	W=2.3
OUTLET TEMPERATURE – STEEL (°C)	1 548	1 546	1 543	1 541	1 538	**1 534**	W=3.5
SEN MODEL	**2/4**						
PREHEATING TEMPERATURE (°C)	**1 100**						
HEAT LOSS (J)	594 694	138 081	157 316	128 444	117 716	191 275	1 327 527
AVERAGE TEMPERATURE – CERAMICS (°C)	603	1 026	966	974	962	914	**908**
OUTLET TEMPERATURE – STEEL (°C)	1 547	1 545	1 541	1 538	1 535	**1 529**	W=2.3
OUTLET TEMPERATURE – STEEL (°C)	1 548	1 546	1 543	1541	1 538	**1534**	W=3.5

As a result of mathematical modelling to prevent freezing, not only the preheating temperature of the Model 2 SEN with a 4 mm isolation thickness but also an increase in the steel casting starting speed, as seen in the graph in Fig. 8.

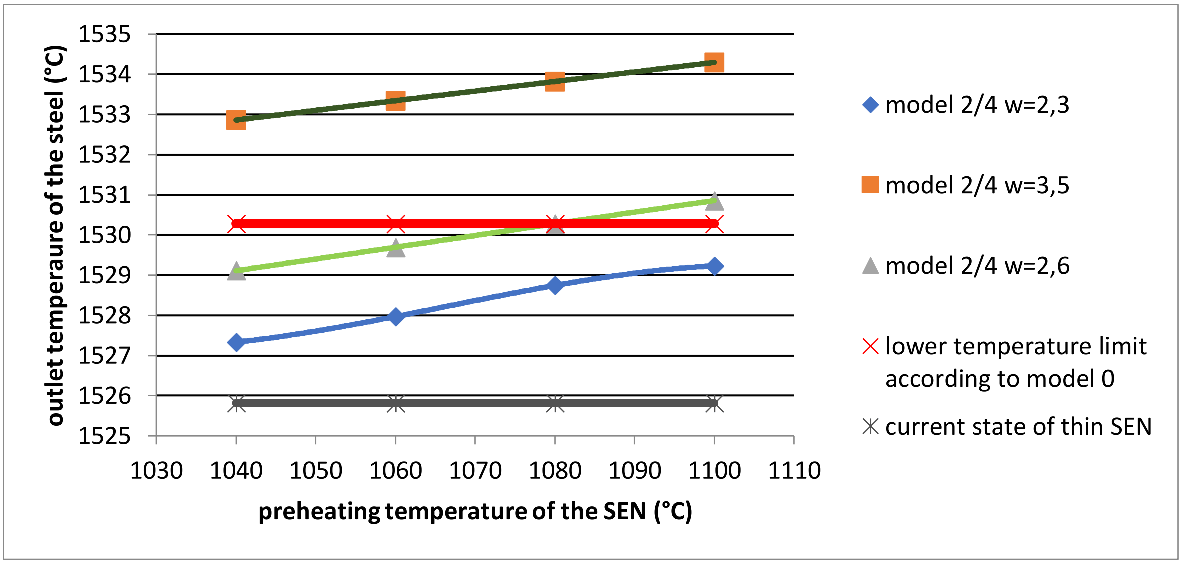

Fig. 8. Graph of output steel dependence on preheating temperature and casting speed.

The results of the mathematical model indicate qualitative trends. Quantitatively they will already depend on the type and composition of the steel. In order to prevent the steel from freezing in the SEN, it is necessary to ensure a minimum temperature of the steel at the outlet of the SEN. By modelling the growth of the preheating temperature of SEN and the growth of the starting casting speed, it is possible to exceed the minimum limit resulting from the comparison tube model 0, the values of which have been recalculated to a state where the steel does not freeze. In steel casting, the temperatures of the incoming melted steel as well as the set temperature, are also important.

Conclusion

The problem of steel freezing in a submerged entry nozzle is considered an undesirable condition in steel casting. The temperature at which the steel begins to solidify at the SEN walls is not constant but depends on the composition of the steel. Mathematical modelling was oriented to prevent steel freezing in SEN through casting operation requirements. The accuracy of the calculation is influenced by the amount and quality of the information available. The analysis performed does not focus on the temperature at which the steel begins to solidify but on achieving a condition where the steel does not freeze in the SEN (using SEN model 0). When using SEN with a thinner wall, it is necessary to ensure a temperature increase of SEN preheating, an increase of starting speed of steel drawing, use of thicker insulation (ceramic fibre), and an increase of temperature of incoming steel, either alone or by the combination of individual measures.

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