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Dynamic On-line Model of Temperature Field for Continuous Steel Billet Casting and its Integration into the Control System of the Caster

Dynamický on-line model teplotního pole plynule odlévaného ocelového sochoru a jeho začlenění do řídicího systému ZPO

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The on-line version of the 3D dynamic model of the transient temperature field of a billet caster is based on its off-line version. It enables the simulation of the temperature field of the caster in real time. The model receives the data from the first and second level of control of the caster via an interface program, evaluates the measured data and carries out a calculation of the temperature field and other aggregated quantities that are sent back to the information system of the steelworks/plant. It aims to enhance the quality and accuracy of the input data, the mutual connections between them and the qualitative parameters, including the establishing of their limit values. This creates a system that not only quickly but also very accurately displays the temperature field of the blank during the course of the actual process, including all necessary technological data from the caster. The dynamic model was integrated into the casting control system. This suggests its usefulness for real deployment, the application and robustness of the used numerical methods and other software parts.

Key words*: dynamic solidification model; casting control system; control computer; monitor of an operator; cooling optimization; statistical data processing*

On-line verze 3D dynamického modelu nestacionárního teplotního pole sochorového ZPO je založena na jeho off-line verzi. Umožňuje simulaci teplotního pole ZPO v reálném čase nebo v čase kratším. Mnohonásobné zvýšení rychlosti výpočtu teplotního pole sochoru umožňuje nejen využití výkonnějšího výpočetního hardware, ale především software. V takto krátkém čase tak lze sledovat vývoj teplotního pole v oblasti krystalizátoru, sekundárního i terciálního chlazení a tyto informace využít pro optimální řízení ZPO jako celku i jednotlivých jeho klíčových uzlů. Model přijímá data z první a druhé úrovni řízení ZPO přes rozhraní, vyhodnocuje naměřená data a provádí výpočet teplotního pole a dalších agregovaných veličin, které jsou odesílány zpět do informačního systému ocelárny. Cílem je zvýšení kvality a přesnosti vstupních údajů, vzájemných vazeb mezi nimi a kvalitativními parametry, včetně stanovení jejich mezních hodnot. To vytváří systém, který nejen rychle, ale také velmi přesně zobrazuje teplotní pole sochoru během daného procesu, včetně všech potřebných technologických dat ze ZPO. Funkčnost on-line modelu je podmíněna dostupností on-line vstupních dat, jako jsou licí teplota, rozměr sochoru, chemické složení lité oceli, licí rychlost, poloha hladiny v krystalizátoru, teploty ve stěně krystalizátoru, teploty chladicí vody v krystalizátoru na vstupu a výstupu, průtok vody, nastavení průtoků a tlaku vody v sekundárním chlazení, teploty z pyrometrů v sekundárním chlazení. Tato data poskytuje modelu teplotního pole vyvinutý separátní program se standardním rozhraním. Rozhraní je naprogramováno dle aktuálního stavu řízení a je ve zdrojových textech k dispozici odběrateli, aby si mohl při změně řízení interface modifikovat. Dynamický model byl začleněn do systému řízení ZPO. Svědčí to o jeho užitečnosti pro reálné nasazení, o spolehlivosti i robustnosti použitých numerických metod i dalších softwarových částí.

Klíčová slova*: dynamický model tuhnutí; řídicí systém ocelárny; řídicí počítač; operátorská obrazovka; optimalizace chlazení; statistické zpracování dat*

Brno University of Technology, Faculty of Mechanical Engineering collaborated on the solution of the project of the Ministry of Industry and Trade of Czech Republic (MIT) with the steelmaking company Třinecké železárny, a.s. as the principal investigator. During the creation of off-line and on-line versions of the temperature field model, it was inevitable to choose a modern development tool and object-oriented language [1] for programming. The model was therefore programmed in Delphi 2007 (Object Pascal programming language). The Firebird database, a modern SQL client/server database, was used for storage of data. We separated the data and the program. All input data, such as the location of the cooling nozzles, rollers, experiment parameters, properties of cast steels, etc., were stored in the SQL database. Similarly, the results of the simulation were entered into the SQL database. This solution allowed making changes without having to intervene in the program code. This was the only possible way because the programs in the model were from the outset developed with a view for their deployment in real-world operation, where maintenance of the computer will be ensured by network managers. All changes to data, configurations, and technology standard operating procedures (SOP) were made in one database.

The resulting product was developed as a unit of three independent programs BrWatch, BrCaster and BrCCMEx that will be discussed in subchapters 1.1 through 1.3. At present, the Brno Dynamic Model of Solidification, commercially offered by the Brno University of Technology, is registered under the single name of Brno Dynamic Solidification Models (BrDSM) (trademark EU 015723893).

1. Three independent programs for temperature field system

1.1 BrWatch program

Data acquisition program BrWatch was run on the DASFOS server and it was programmed in Delphi 2007 (Fig. 1). It loaded the configuration from the local database Firebird (position 4), it communicated with the application InTouch (position 3) via dll, and it communicated with the central database using ADO/ODBC (position 6). On the basis of these communications, it constructed a vector of real numbers at regular intervals (5 to 10 seconds on request of the on-line model). The vector was transferred via the TCP/IP server using the protocol HTTP/XML (position 2) to BrCaster (on-line model). It picked the values calculated by BrWatch program characterizing the temperature field, i.e. surface temperatures, metallurgical length, etc., as well as the results of recommended values for casting rate and water flow rates for the zones I, II, III, and IV from BrCaster via TCP/IP using the HTTP/XML protocol (position 2).

The graphical environment of the data acquisition program made it possible to quickly check the collected data and set the parameters of the on-line temperature model (Fig. 2). The system administrator used this program for influencing the parameters and behaviour of the on-line model. The thermal model is a numerical calculation that works with a fixed time step. It always had to have all the data at every step. Any deficit of the quantity might have caused numerical instability and crash of calculation. It was possible to replace the missing or incorrect quantities by either a previous valid value or a so-called standard value. The set time step, in which the calculated data was provided, was 10 s.

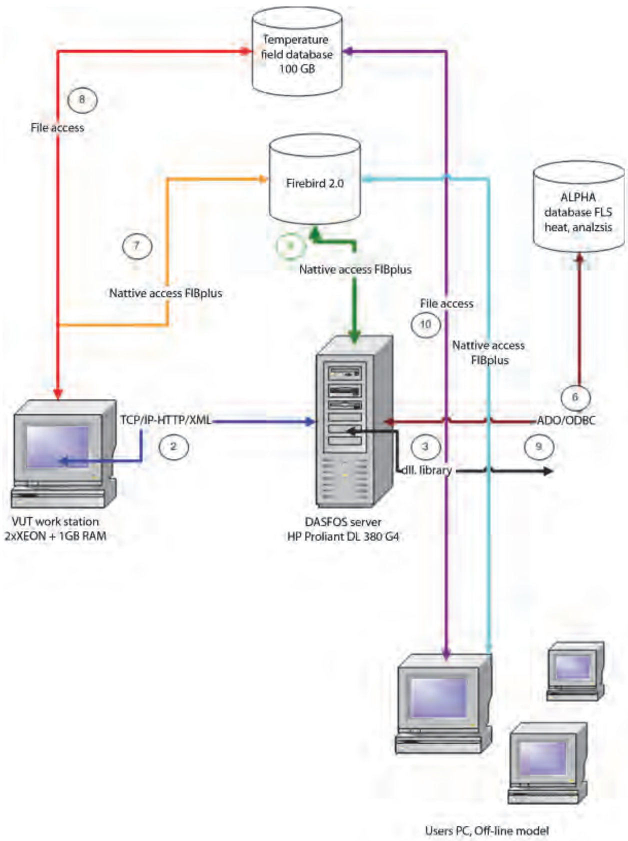

Fig. 1 Scheme of the communication between the different parts of the dynamic model
Obr. 1 Schéma komunikace mezi jednotlivými částmi dynamického modelu

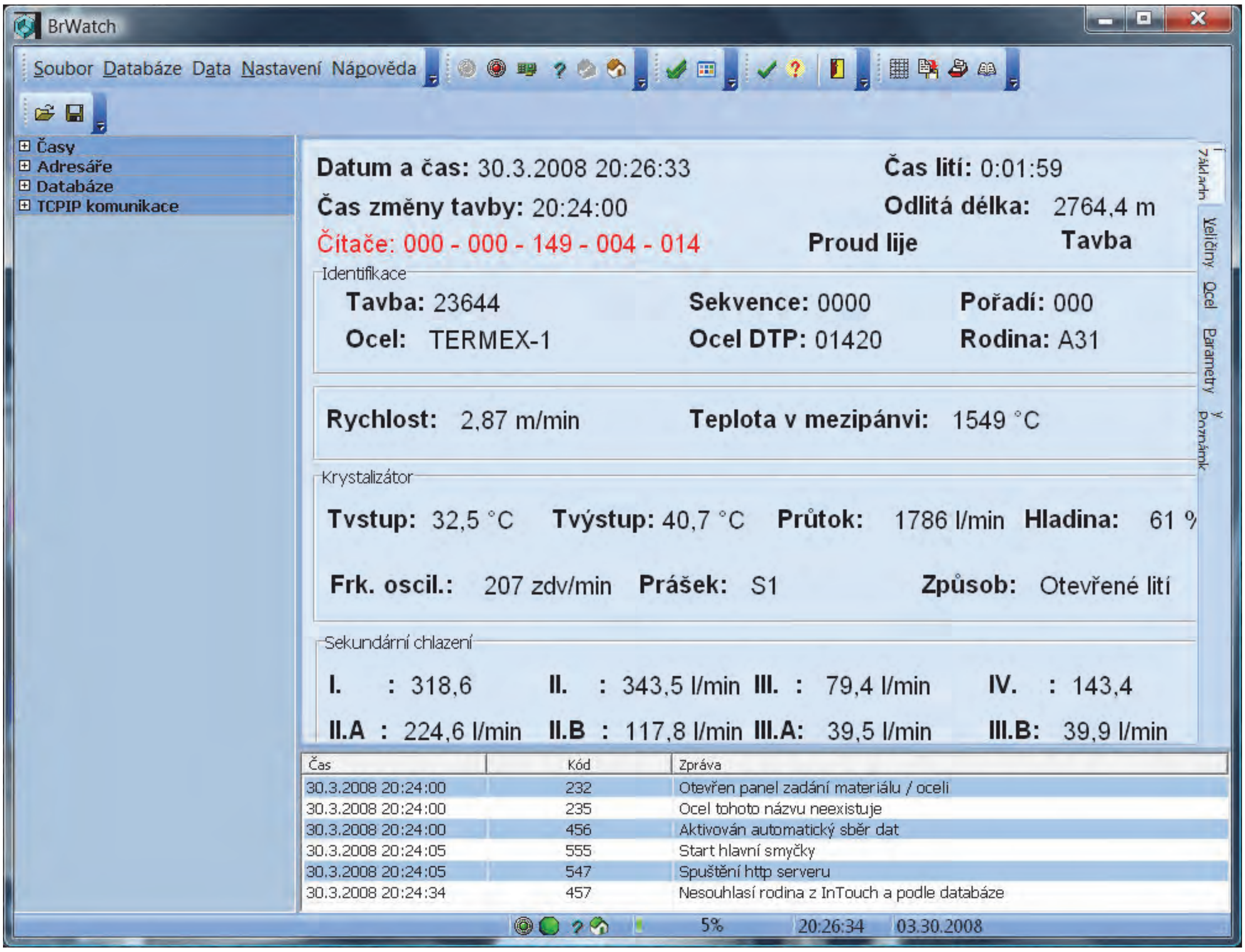

Fig. 2 Graphical interface of the program BrWatch
Obr. 2 Grafické rozhraní programu BrWatch

1.2 Program BrCaster, on-line model

The on-line model was run on a two-processor PC, visualization was available in the control room for continuous casting machine 2 (CCM2). The numerically demanding multithreaded model solved the following functions: it read configuration from the Firebird database, same as BrWatch (Fig. 1, position 7); it received the vector of valid input values via TCP/IP sockets (position 2); it performed calculation of boundary conditions and thermo-physical parameters; it calculated the temperature field; it visualized the temperature field on the computer monitor in the control room; it calculated the controlled quantities (required casting speeds, water flows for the zones I, II, III and IV); it saved the calculated temperature field (position 8); it provided the current temperature field data to the operating information system for all its users (web server).

The program was based on the off-line version, picked the data from the first and second levels of the hierarchically structured CCM control system via the BrWatch interfacing program, it performed the calculation of the temperature field and of other aggregated quantities (Fig. 3) which were sent back to the information system of the steel plant. Another goal of the on-line version was to increase the quality and accuracy of the input data, of mutual links between them and of the qualitative parameters, including the setting of limit values. In this way, a system was created that displayed not only very quickly but also as accurately as possible the real temperature field of the continuously cast billet (CCB) during the process, as well as all the necessary technological data from the CCM. One of the great advantages was the fact that the program had integrated the so-called web server, i.e. other users of the computer network of the steel plant could see individual operator screens of the online model via an ordinary Internet browser (Fig. 4).

Fig. 5 shows screens of the dynamic temperature model. Most of them are the same as for its off-line version. Fig. 5a presents basic parameters of casting both in numerical form and in the form of barographs and graphs of history. The basic screen of the model is in Fig. 3, where the metallurgical length is emphasized in addition to the temperature field. Fig. 5b shows the temperature history of the indicated points of cross-section during its progress through the entire CCM. Data from secondary cooling, including the temperatures measured by a pyrometer and calculated temperatures at the same points, are shown in Fig. 5c. The screen in Fig. 5d shows the evolution of iso-liquidus and iso-solidus in longitudinal axial sections, and Fig. 5e shows the evolution of surface temperatures at the place of the built-in pyrometers. The graph of the local time of solidification (the time, during which temperature of the given point was within the interval of solidification) in individual points of the profile is shown in Fig. 5f. The last screen shows the heat output volume in the individual zones (Fig. 5g).

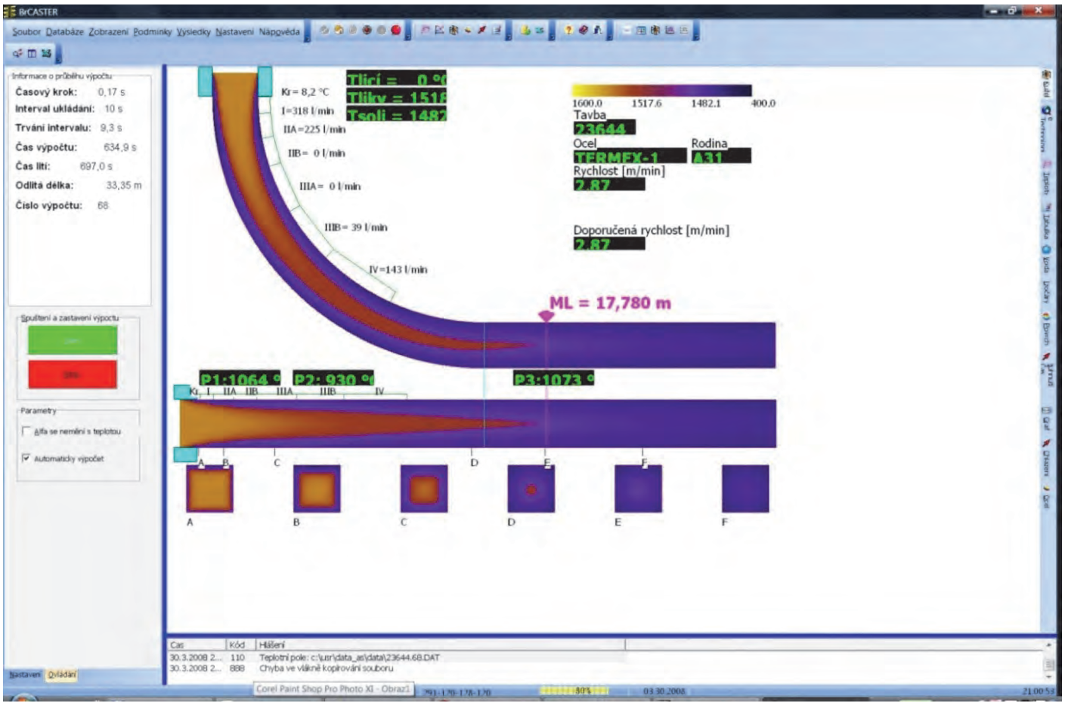

Fig. 3 Graphical interface of the on-line program with an example of the temperature field

Obr. 3 Grafické rozhraní on-line programu s příkladem zobrazení teplotního pole

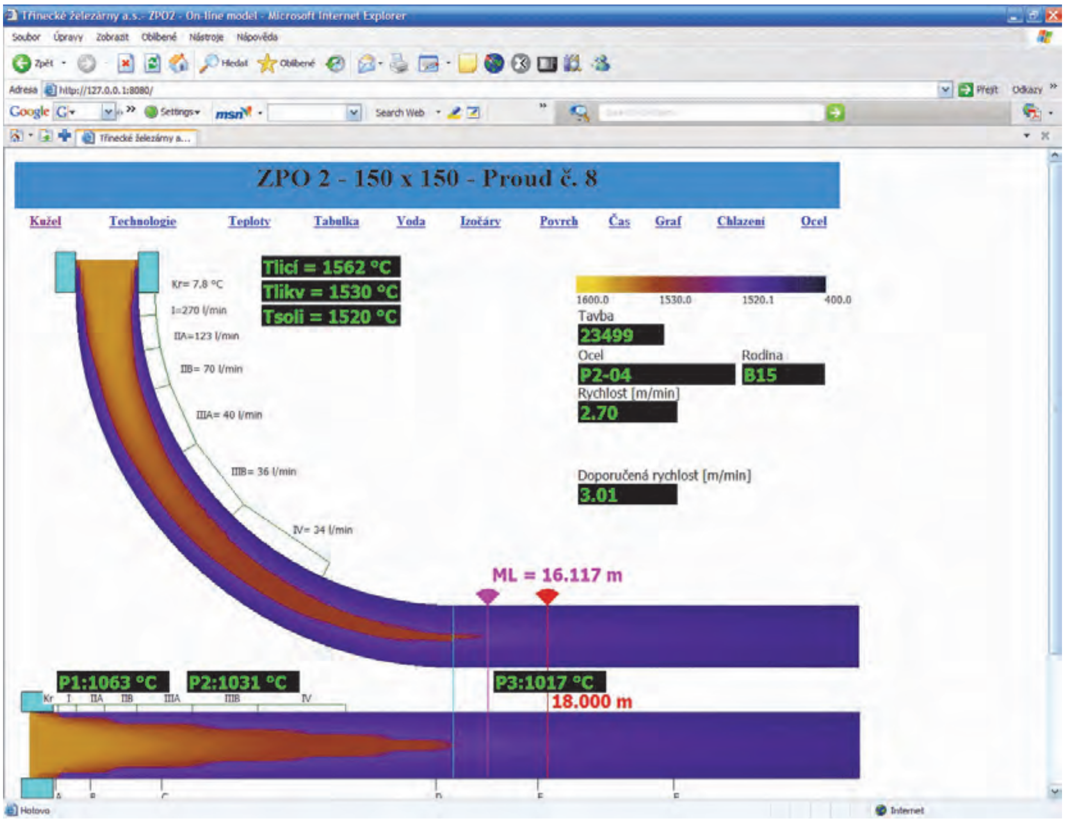

Fig. 4 Example of the results of the on-line model via the information system

Obr. 4 Příklad zobrazení výsledků on-line modelu přes informační systém

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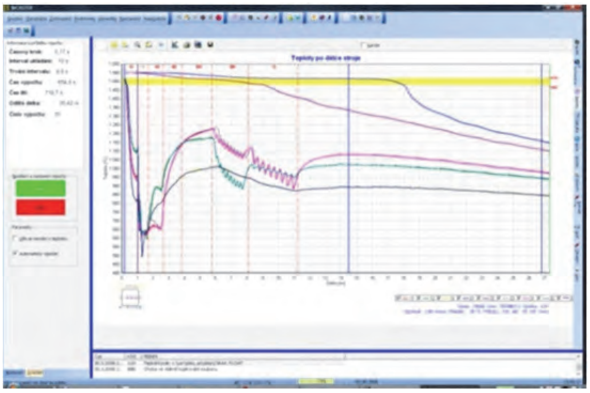
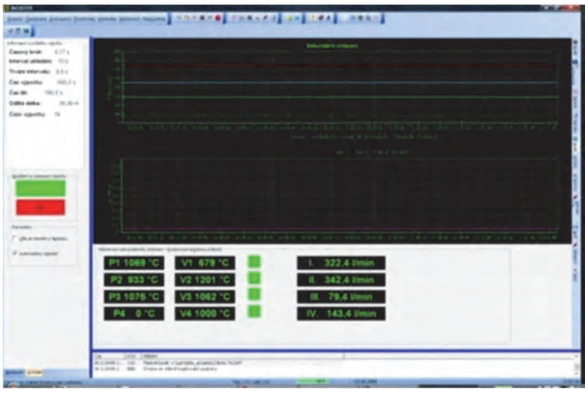
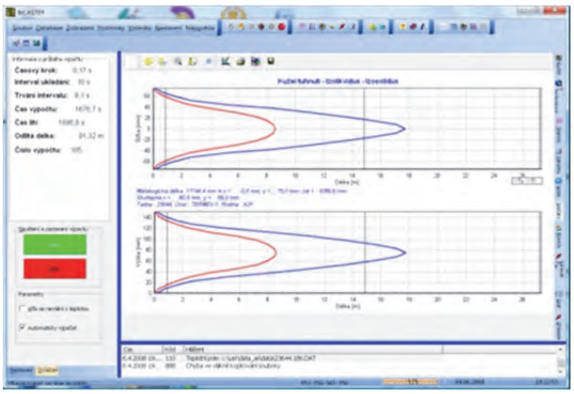
a) Basic parameters of the casting
a) Základní parametry lití



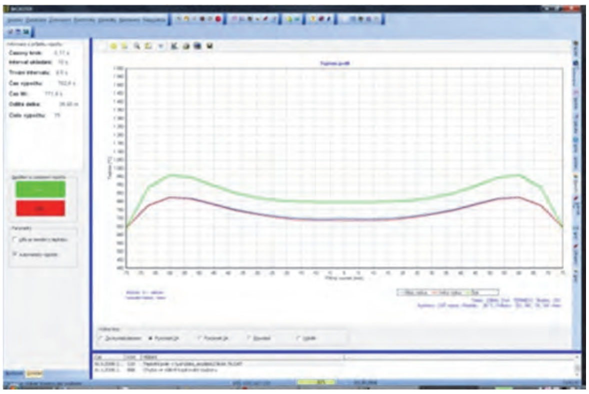
b) Temperature history along the caster
b) Historie teplot podél ZPO



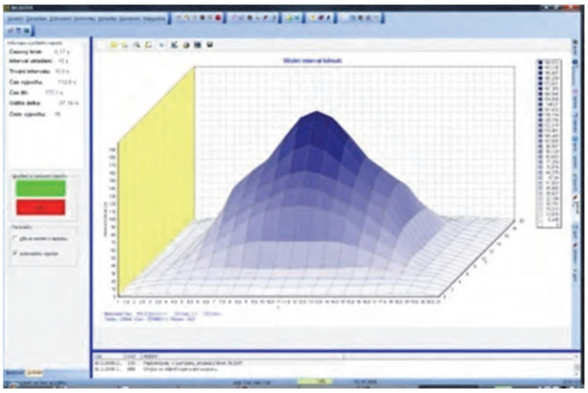
c) Data of the secondary cooling
c) Data sekundárního chlazení



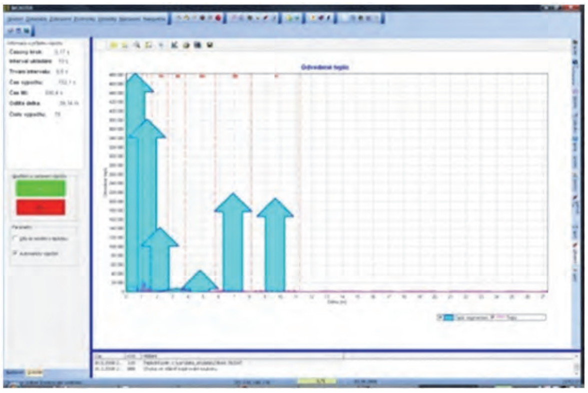
d) Evolution of iso-liquidus and iso-solidus in the axial longitudinal sections
d) Průběh izolikvidy a izosolidy v podélných osových řezech



e) Surface temperatures in the place of built-in pyrometers
e) Povrchové teploty v místě zabudovaných pyrometrů



f) Local solidification time
f) Místní doba tuhnutí



g) Heat flows diverted in the zones
g) Tepelné toky odvedené v zónách

Fig. 5 Operator monitor of the dynamic model of the temperature field

Obr. 5 Operátorské obrazovky dynamického modelu teplotního pole

1.3 Program BrCCMEx, off-line model

The off-line temperature model, which was run on any industrial PC, had the following options: loading the configuration and data from the central Firebird database (position 9); editing Firebird Configuration Database on the Server (position 9); retrieving data from an online server, such as trends (position 9); viewing files (position 10); and it performs calculations of the temperature field.

The off-line model, which was developed first, enables the user to design even a non-traditional file or combination of technological interventions for the optimal formation of the temperature field with the aim of enhancing the quality of the concasting while maintaining or even raising the volume of production. The basic screen MS Windows is shown in Fig. 6.

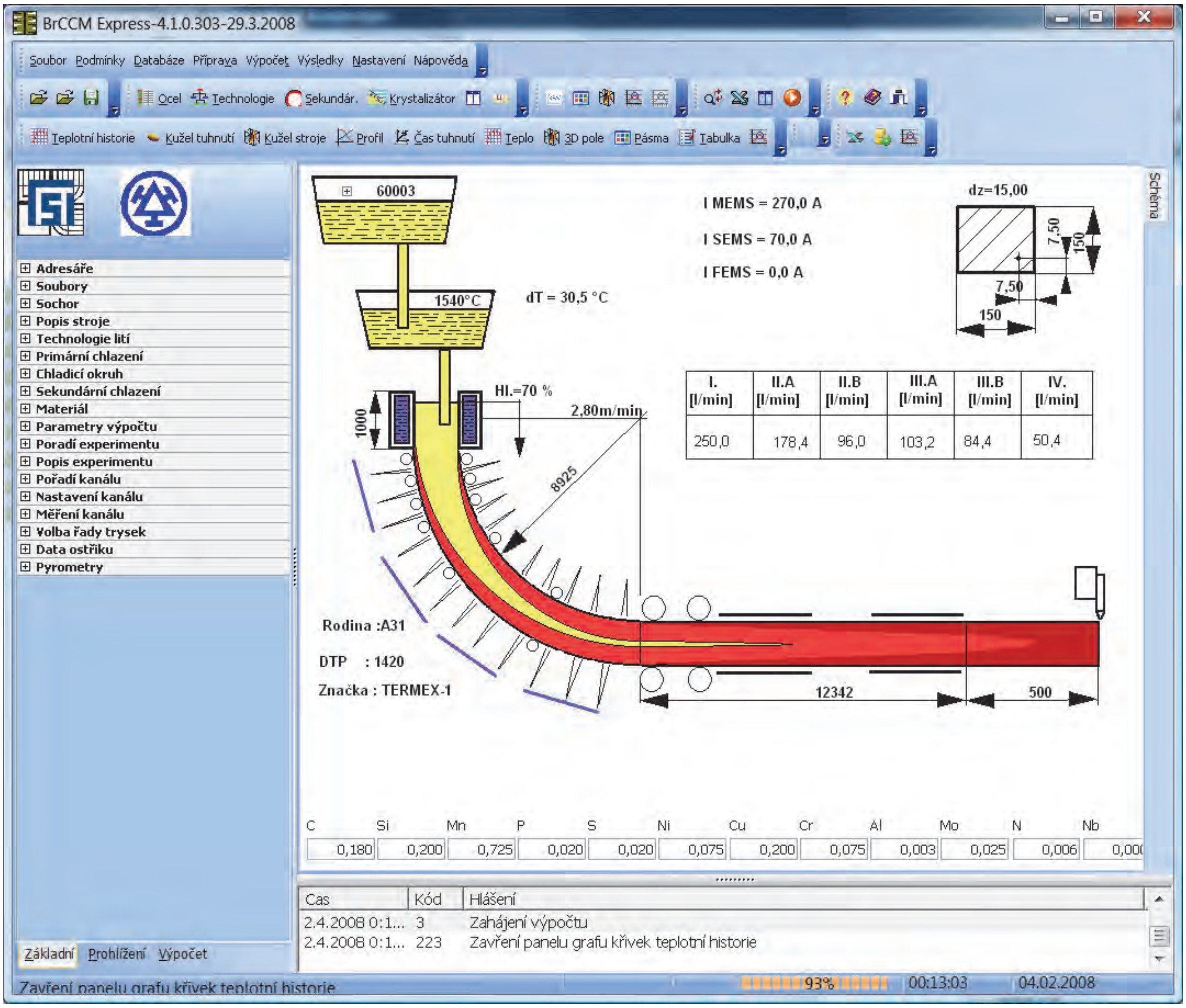


Fig. 6 Basic screen of the off-line model
Obr. 6 Základní obrazovka off-line modelu

Users (technologists) had the opportunity to upload the current live data from the on-line model to their off-line temperature field model, to make some changes in input parameters (e.g. to adjust secondary cooling, change the casting speed, etc.). After performing an off-line simulation, they found out how the temperature field would be created under such changed conditions. The off-line version can be also successfully used in the case of occurrence of defects on billets. The user has downloaded calculated thermal fields from the archive server and he/she could analyse, with the use of the off-line model, probable causes of defects and prepare measures in order to avoid repeating of defects. The off-line model will in future allow also for download of quantities from the application server, and it will make possible to use statistical methods and links between variables and defects for the search of the cause of defects in the formation of the original temperature field of the billet from a problematic heat.

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2. Dynamic model activity

Two independent control loops worked in a dynamic on-line model. The first served for the setting of calculation of the temperature field according to the current state of CCM and operating conditions. This control loop used temperature values measured by three (or possibly four) installed pyrometers for calculation of the control deviation. Location of the pyrometers is schematically illustrated in Fig. 7 with black dots. Temperatures from the pyrometers were compared with the calculated temperatures at the same locations and correction of the heat transfer coefficients in the respective zones before the pyrometers was performed. If the difference between the measured and calculated temperatures and the correction factor was within acceptable limits (± 50 °C), the green LED signal lamp indicated correspondence of the model with the reality (Fig. 5d). In the event of a major disagreement, the red light warned that the situation should be analysed.

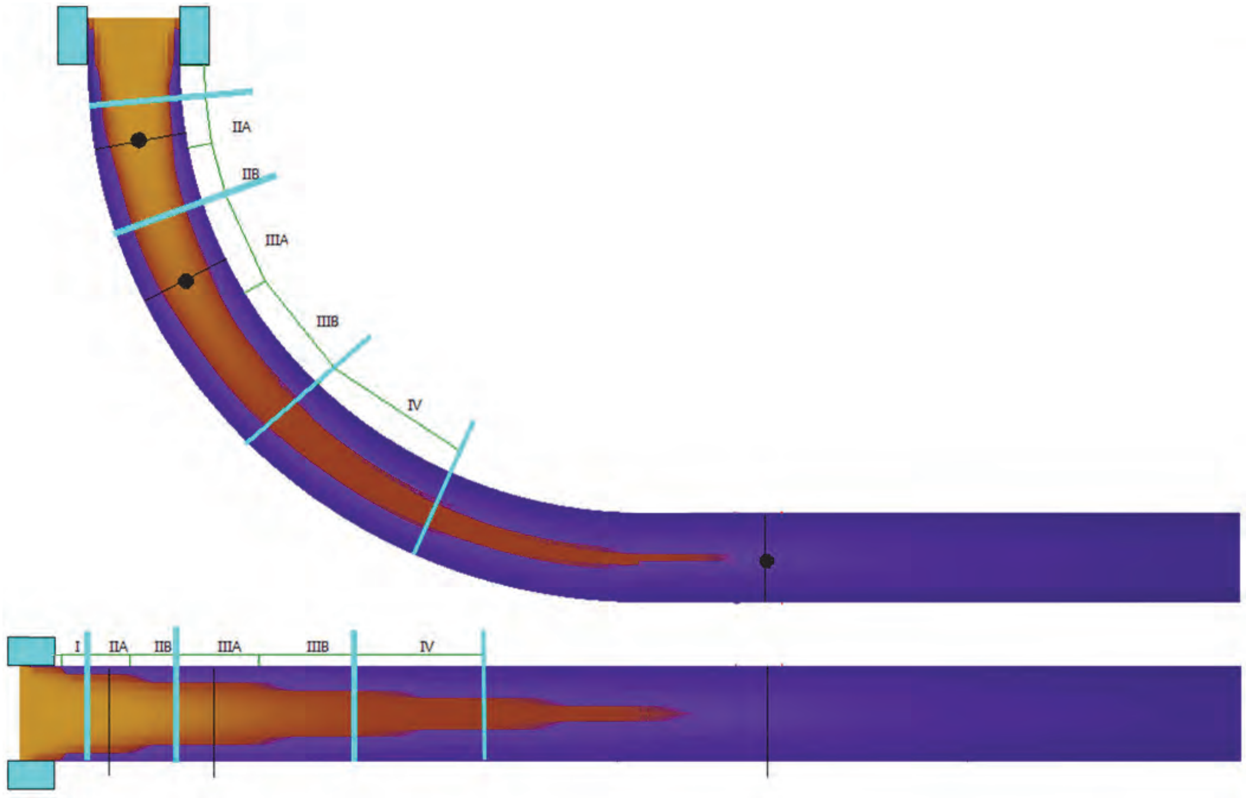

Fig. 7 Location of the pyrometers and places with target temperatures
Obr. 7 Umístění pyrometrů a míst s cílovými teplotami

The second control loop was the recommendation of optimal casting speed and flow rates in the zones I, II, III and IV using the temperature model. Optimisation criteria can be in general the following ones:

- metallurgical length, which should extend into the not-bent part,
- limitation of reheating between zones,
- cooling rate limitation,
- limitation of surface temperature at the point of straightening,
- limitation of temperature behind individual zones,
- limitation of temperature fluctuations in the cooling zone.

Due to the fact that the optimal values of these parameters are unknown, only the following parameters were selected for this project:

- metallurgical length, which should approach the specified value,
- surface temperatures at four locations (between zones), marked in Fig. 7 with cyan boundary lines); temperature values must be within the specified interval.

Fig. 8 shows a diagram of the control operation for one zone controller (in this case zone III). Similar control loops must be implemented for all four zones.

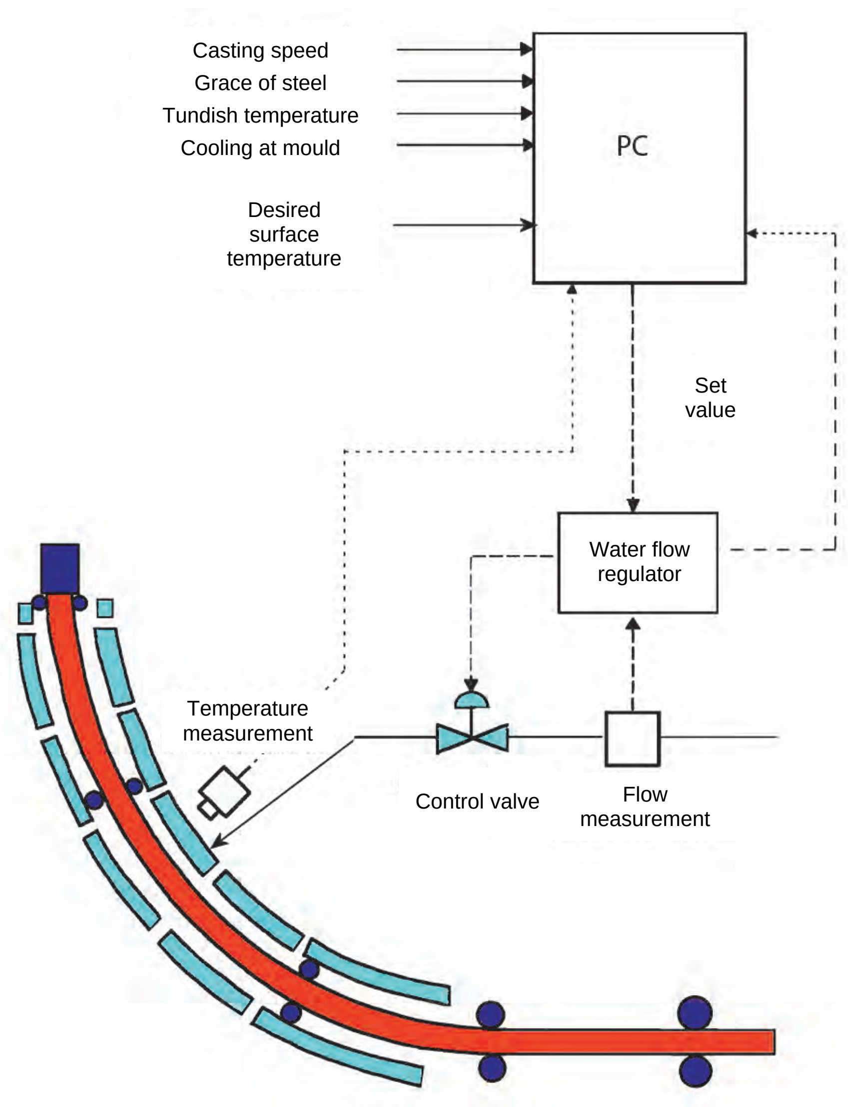

Fig. 8 Scheme of the regulation of the water flow in the one cooling zone
Obr. 8 Schéma regulace průtoku vody v jedné chladicí zóně

Since the number of cast steel grades was large, we used their classification in 4 groups [2, 3], for which the casting conditions should be the same. The database of conditions for each group contains:

- recommended metallurgical length,
- minimum and maximum temperature at the point 1 (behind zone I),
- minimum and maximum temperature at the point 2 (behind zone II),
- minimum and maximum temperature at the point 3 (beyond zone III),
- minimum and maximum temperature at the point 4 (behind zone IV).

Determination of these optimal values is a very challenging and long-term task. Therefore, in the first stage of deployment of the on-line model, the actual achieved values and the metallurgical length for casting conditions taken from the standard operating procedure for the respective group were used as initial values.

3. Outline of statistical processing of data from dynamic on-line model

In addition to graphical results presented here, statistical methods can also be used for the analysis of data from the on-line model of the temperature field. For each melt, the following statistical variables were determined for all measured and calculated values of the technological parameters: mean value (arithmetic mean), minimum value, maximum value, variance, standard deviation, slope coefficient and coefficient of acuity.

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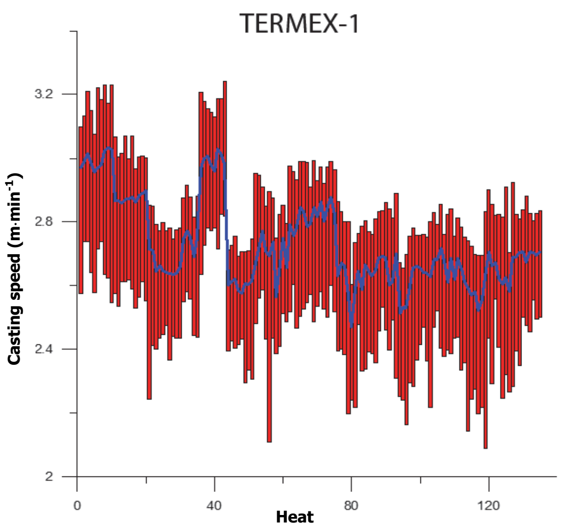
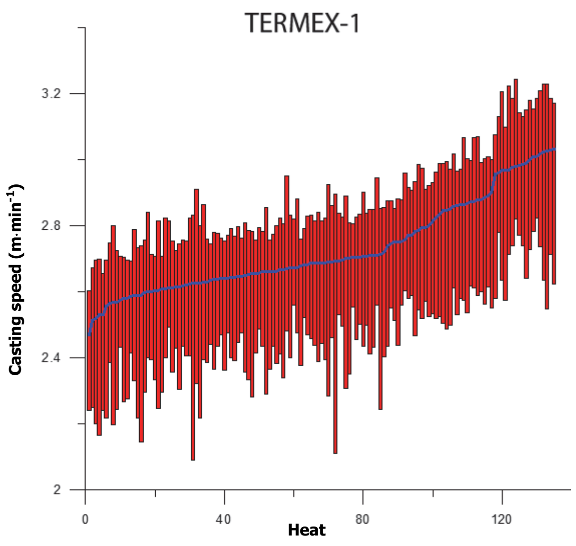


a) Sorted according to the time
a) Seřazeno podle času



b) Sorted according to the average casting speed
b) Seřazeno podle průměrné licí rychlosti

Fig. 9 Casting speed in the individual heats, the minimum, maximum and average value
Obr. 9 Licí rychlost u jednotlivých taveb, minimální, maximální a průměrná hodnota

These statistical variables were evaluated for all 400 data files that are stored by the temperature model in the database. It was possible to further evaluate these quantities using graphs for the given period. The graphs presented here correspond to the six-month operation of the CCM when a total of 140 heats of TERMEX-1 steel grade were cast.

Fig. 9 depicts the casting speed for TERMEX-1 steel grades. The minimum and maximum casting speeds and averaged speed are plotted here. Fig. 9a shows the temperature of individual heats in the order in which they were cast. Fig. 9b shows the temperatures of heat ordered according to the average casting speed of these heats.

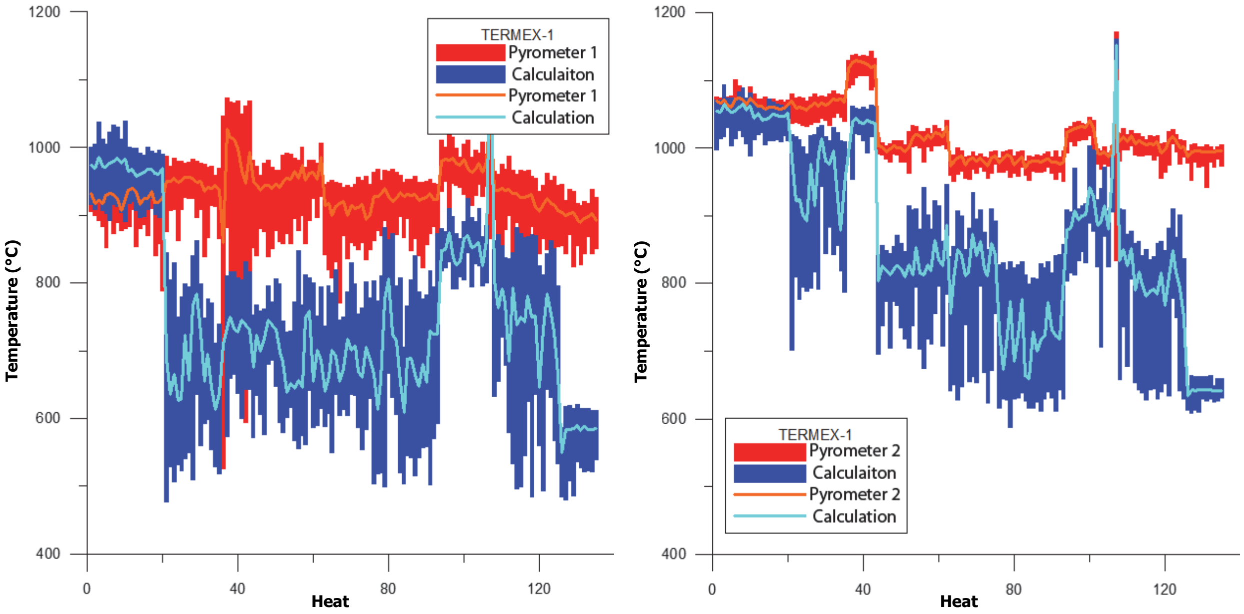


Fig. 10 Surface temperature measured by the pyrometers and calculated in the same places
Obr. 10 Povrchová teplota měřená pyrometry a vypočtená ve stejných místech

Fig. 10 shows a similarly structured graph of the measured surface temperature determined by the pyrometers 1 and 2. The graph also shows an evolution of the temperatures calculated at the same points. Figure 10 shows a good match between the measured and calculated values for the first 20 heats. The calculation results showed that surface temperature was higher only by 5% in comparison to the temperatures measured by the pyrometer 1. The 5% variance is a very good result for the operating conditions. After that the nozzles in the first zone were replaced by a different type which is in the graphs manifested by an increased 22% difference between the measured and calculated temperature values.

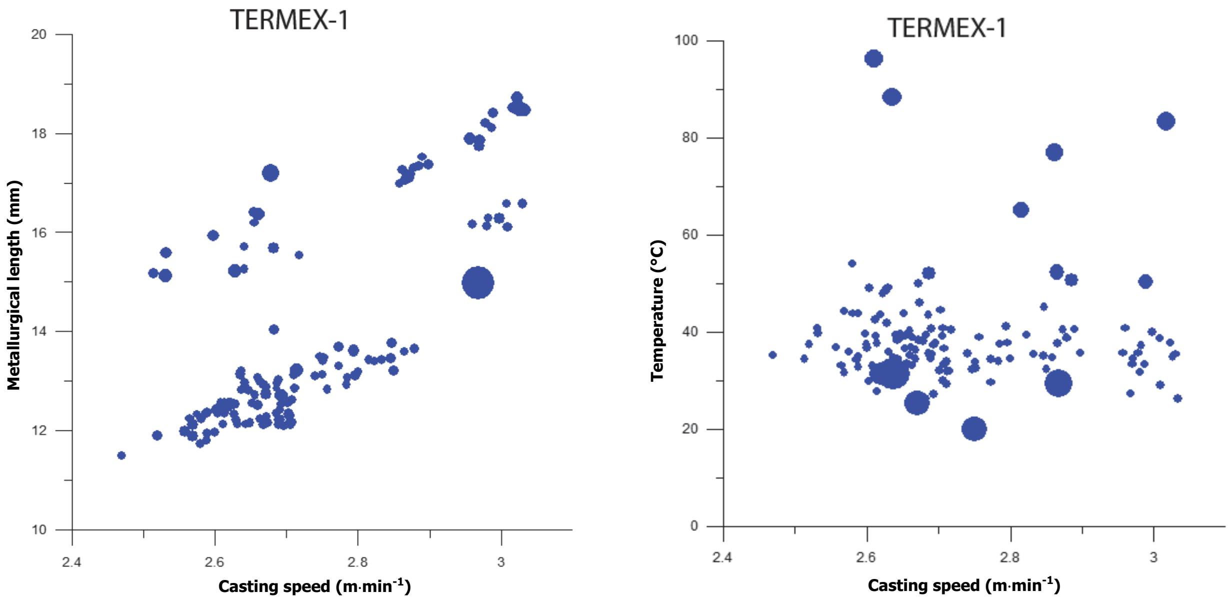


Fig. 11 Metallurgical length and the temperature of the overheating depending on the casting speed for steel TERMEX-1
Obr. 11 Metalurgická délka a teplota přehřátí v závislosti na rychlosti lití pro ocel TERMEX-1

The graphs in Fig. 11 present the value of metallurgical length and the overheating temperature in dependence on the casting speed. These parameters from each heat are expressed by one blue circle, the radius of which corresponds to the standard deviation. It can be seen from Fig. 11 that approximately linear dependence exists between the metallurgical length and the casting speed, which corresponds to the relevant solidification constant. Due to the replacement of the nozzle, the results of heats were divided into two linear dependencies, which were reflected in the graph by two fields of the observed cases. A functional dependence was also expected between the overheating temperature and the casting speed. This, however, was not confirmed in real heats, as it is shown in the right graph in Fig. 11.

The graphs of statistical variables are an example how it is possible to use the data from the on-line model for an analysis of the CCM behaviour and for optimisation of its operation.

Conclusions

A numerical model of a non-stationary temperature field of a steel billet 150 × 150 mm cast by continuous casting was developed and tuned in off-line and on-line versions. Presentation of the results shows how it is possible to use both versions for optimisation of casting parameters. The online version was in the steelworks Třinecké železárny, a.s. incorporated directly into the CCM control system. The results show significant differences between the temperature field model of continuously cast slabs and billets. In the case of the casting of billets, the intervals of input parameters are much wider including a larger number of types of steels. A particular problem is also the use of conical water nozzles in the secondary cooling zone where the heat transfer coefficient under the nozzle is markedly dependent on the surface temperature of the billet. By using the model, it is possible to achieve faster and easier implementation and mastering of new types of steel (according to immediate customer requirements with reduced risk of production losses), but mainly to achieve higher qualitative parameters of steel casting including stability of their production, i.e. narrowing the difference between the qualitative properties of individual heats of the same steel grades and to achieve a repeatability. Improving the quality means moreover a reduction of power consumption per ton of final product. This reduces also the volume of flue gasses for the production of the final product and it will thus reduce the ecological exposure of the work environment.

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EU šetření proti pěti zemím kvůli ocelovému dumpingu před ukončením

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Od léta 2016 běžící vyšetřování Evropské komise proti Srbsku a čtyřem dalším zemím kvůli obvinění, že exportují ocel do EU za dumpingové ceny, by mělo být co nevidět uzavřeno, výsledky by měly být předloženy v květnu. Určitý předběžný výsledek je ale znám již teď. Srbská ocelárna ve Smederevu, patřící od července 2016 čínskému koncernu HBIS, svoje exporty oceli do EU od srpna do listopadu 2016 nezvýšila. EK provádí šetření ale také proti Rusku, Iránu, Brazílii a Ukrajině, poté co si v květnu 2016 stěžoval evropský ocelářský svaz EUROFER. EUROFER tvrdil, že zmíněných pět zemí prodává svoji ocel o minimálně 20 % pod tržními cenami. Evropské šetření ukázalo, že exporty oceli pěti vyšetřovaných zemí do EU stouply v příslušném období o 14 %. Rusko zvýšilo export do EU o 73 %, Brazílie o 23 %. Irán a Ukrajina svoje exporty do EU zredukovaly, u Srbska nedošlo k žádné změně.

ArcelorMittal spřádá plány pro Itálii

Frankfurter Allgemeine *22.03.2017*

ArcelorMittal počítá ještě minimálně do konce roku 2018 s trvající robustní ocelářskou konjunkturou. Frank Schulz, šéf největšího ocelářského koncernu na světě pro Německo, poukazuje na dobrou poptávku po oceli od odvětví, jako je výroba automobilů, stavebnictví a strojírenství. Spotřeba oceli v Německu by měla letos vzrůst o 1 procento, v příštím roce předběžně o 1,5 procenta. Na roky 2017 a 2018 se díváme s opravdovým optimismem, řekl Schulz v Düsseldorfu. Také ceny se výrazně zvýšily, v průměru o dobrý dvoumístný procentuelní nárůst. Jenže stouply také ceny železné rudy a koksovatelného uhlí. Samozřejmě zůstávají obavy z obrovských přebytečných kapacit. Konsolidaci předpovídá Schulz i pro Evropu. Že se koncern snaží získat existující, deficitní a obrovskými ekologickými problémy zatíženou ocelárnu ILVA v Tarantu, není pro Schulze žádný protimluv. Říká, že by to bylo nové řešení pro Evropu. Schulz je toho názoru, že v této největší evropské ocelárně by bylo možné vyrábět vysoce kvalitní oceli nejen pro Evropu, ale také pro trhy v severní Africe a v Turecku.