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ORIGINAL ARTICLE

Intelligent system for prediction of liquid metal breakouts under a mold of slab continuous casting machines

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Abstract Increase in efficiency of a continuous casting machine is directly related to reduction of a shutdown period to repair and to eliminate accident consequences. One of the most widespread and severe accidents on the machine is the strand shell breakout under a mold. This article presents results of development and operation of the intelligent system for prediction of liquid metal breakouts under the mold of slab continuous casting machines. The most significant scientific results of the study are: mathematical model of copper mold wall temperatures values distributed on the mold perimeter, diagnostic criteria for strand shell sticking in the mold, and techniques and algorithms of strand shell sticking in the mold. Applying the listed results at development of continuous casting machine automation systems allow to reduce the number of accidents on continuous casting process, what is very important for the steel industry.

Keywords Continuous casting machine · Diagnosis · Prediction · Mold · Liquid metal breakout · Strand shell

1 Introduction

Slab continuous casting machines (CCM) are currently an integral part of a metallurgical process flow. The scope for increased efficiency of CCM includes inter alia, reduction of its shutdown period to repair and to eliminate accident consequences resulting from breakouts of liquid metal under the mold. A key reason for liquid metal breakout is "sticking" of a part of the strand shell to mold walls ("strand shell sticking" as defined in technical literature) [1–5].

Modern CCM applies monitoring systems for thermal processes of billet primary crystallization and resulting technical diagnostic systems (TDS) for strand shell sticking. In a real-time mode, TDS identifies deviations in the course of solidification of the shell in the mold and ensures intelligent support of making decisions on adjustment of main parameters of steel continuous casting to increase the quality of the billet and prevent accidents. Thermal process monitoring and strand shell sticking diagnostic systems mainly use a method based on analysis of temperature changes on copper mold walls. Temperature is measured with thermocouples built in mold walls in several rows along its perimeter [6, 7].

Operation of thermocouples on CCM at OJSC Magnitogorsk Iron and Steel Works (MMK), OJSC Asha Metallurgical Plant, OJSC Severstal, and OJSC Novolipetsk Steel showed that in conditions of increased vibration and severe environment, some thermocouples were broken directly during steel casting, and it was not practical to replace faulty thermocouples while the machine was in operation.

Formal mathematical processing or rejections of temperature values of copper mold walls received from faulty thermocouples results in a significant misrepresentation of diagnostics information and, consequently, a decrease in reliability of the thermal process monitoring system. The possibility of wrong diagnoses may achieve 90 % (for CCM of MMK). Moreover, there are liquid metal breakouts resulting from strand shell sticking not identified by TDS [5, 7].

In the area of theory and practice of development and design of monitoring and diagnostic systems for billet primary crystallization based on analysis of changes in temperatures of mold walls, considerable experience was gained as reflected in publications of Russian and foreign scientists Sorokin, Kaznov, Delektorsky, and Emiling [8, 9]. Results of such studies are patented by world leading manufacturers of

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metallurgical equipment: SMS Siemag, Voest AG, Nippon Steel [10, 11].

However, in spite of performed research and a considerable number of publications on thermal control of billet primary crystallization on CCM, the following problems are of current importance:

- The lack of techniques for collection and processing of data on copper mold wall temperatures ensuring high reliability when thermocouples are broken
- The lack of prediction models with highly reliable prognoses on liquid metal breakouts

The objective of this research is to increase performance of CCM by decreasing wrong diagnoses on strand shell sticking in the mold when applying automated TDS based on the intelligent thermal process control system for billet primary crystallization.

To achieve this objective, the authors had to do the following:

- Perform a statistical analysis of time diagrams on temperatures of copper mold walls in a regular steel casting mode and during strand shell sticking, classify faults of thermocouples, set limit conditions for changes in values of faultless and faulty thermocouples
- Prepare a mathematical model of instantaneous values of copper mold wall temperatures distributed on the mold perimeter based on an original triangulation of a mold coordinate grid and further 2D interpolation of temperature values
- Determine diagnostic criteria for strand shell sticking in the mold subject to changes in temperatures of copper mold walls
- Develop diagnostic techniques and algorithms of strand shell sticking in the mold by testing a set of diagnostics criteria
- Give an experimental evaluation of developed techniques and technical solutions on operating CCMs

2 Experimental methodology

A thermocouple installation diagram (along the perimeter of the mold) which is mainly characteristic of slab CCMs in Russia and abroad is shown by an example of CCM-1 of MMK. Walls of every mold of CCM-1 have 108 built-in thermocouples, while a range of their installation is vertically and horizontally non-uniform. One narrow wall and wide wall of the mold are shown in Fig. 1.

Analog signals are transmitted from thermocouples to a data collection system which digitizes them and initially processes. Regular time diagrams of temperatures of mold copper walls received from faultless thermocouples in steady-state conditions of steel casting are given in Fig. 2.

Characteristic types of faults of thermocouples (Fig. 3) are short circuit in an electric circuit of the thermocouple (diagram 1), open circuit (diagram 2), and a high interference level evidencing thermocouple or recorder failure (diagram 3). In addition to failures of thermocouples of circuits of recorders, we classified a defect related to incorrect installation of thermocouple in mold walls, namely, the lack of a reliable thermal contact of a sensitive thermocouple junction with the surface of the copper mold wall (Fig. 3, diagram 4). The stated defect is revealed as low temperatures of the faulty thermocouple as compared to values of a neighboring thermocouple (diagram 5) having a reliable contact with a mold wall.

Thermocouples with the said faults (defects) are to be excluded from processing.

Having analyzed time diagrams of copper mold wall temperatures in a regular mode of billet cooling in the mold and during strand shell sticking and statistics of changes in temperature, we established that strand shell sticking in the mold

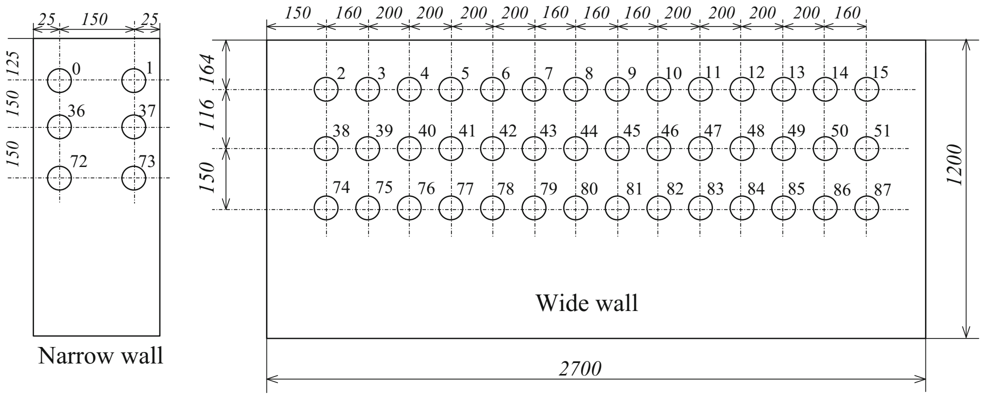


Fig. 1 Thermocouples position coordinates on the walls of the mold

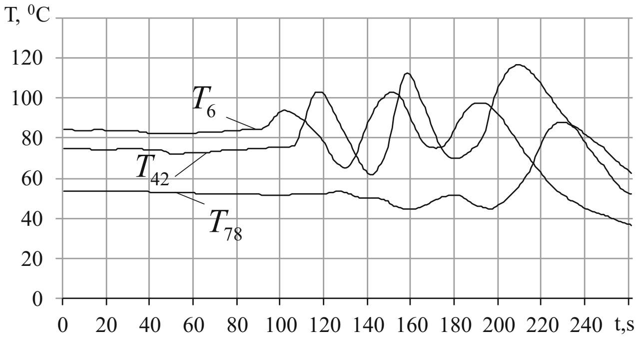


Fig. 2 Time diagrams of the copper mold wall temperatures: T_6, T_{42}, T_{78}—diagrams of actual temperatures from the 6th, 42nd, and 78th thermocouples

entailed changes in temperature in a sticking zone as well as on neighboring vertical and horizontal parts of copper mold walls (Fig. 4a).

As a result of the statistic analysis of some thermocouples and temperature distribution along the perimeter of the mold, it was found that the time-temperature curve of some thermocouples did not comply with a normal law of distribution, depriving of application of statistic methods based on the stated law of distribution. It is feasible to analyze thermal processes in the mold by time change of the rate of copper mold wall temperature changes (Fig. 4b), which are distributed in compliance with the normal law. Time change of values of different thermocouples is non-uniform; therefore, it is not practical to get common values reflecting correct changes in temperature on various parts of copper mold walls. Failure of one or

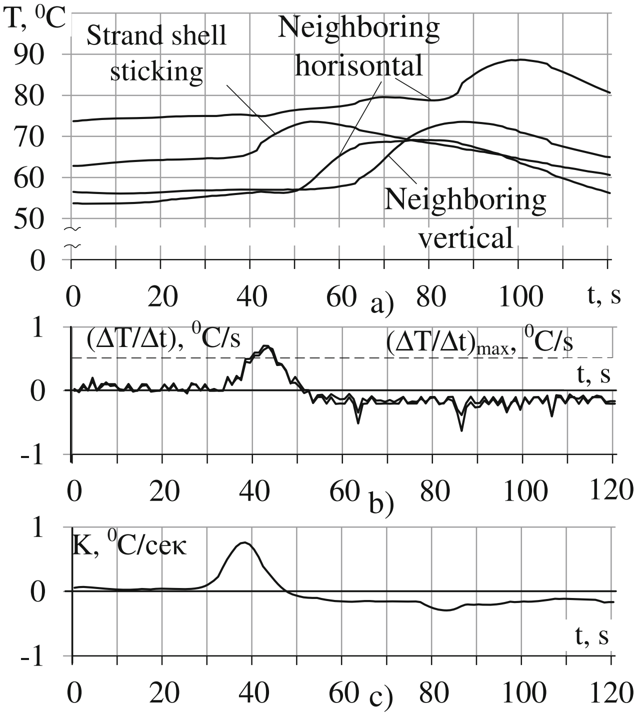
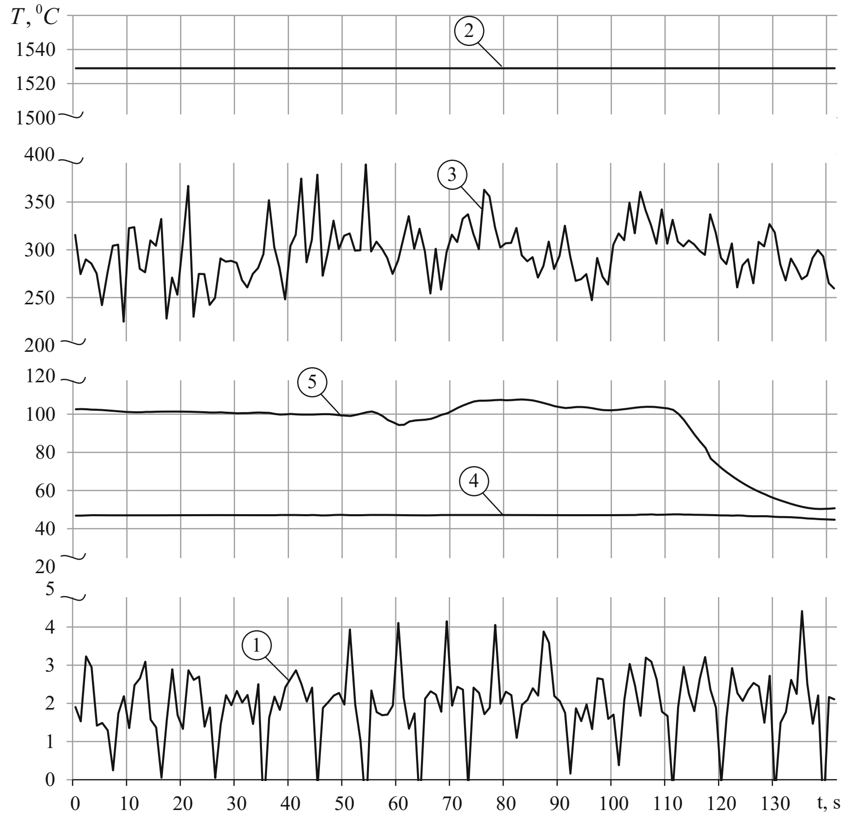


Fig. 4 Time diagrams of the copper mold wall temperatures: **a** absolute values of the copper mold wall temperatures, **b** relative values of the copper mold wall temperatures, and **c** linear fit coefficient

Fig. 3 Time diagrams of the thermocouples signals: *1* –short circuit, *2* open circuit, *3* thermocouple or recorder failure, *4* thermal contact of thermocouple and the wall surface of the mold failure, and *5* thermocouple normal mode



several thermocouples contributes to a significant extent to a wrong diagnosis; therefore, to increase reliability of the diagnosis, it is feasible to analyze temperatures by interpolated temperature values, not by thermocouple values [3].

3 Triangulation of a coordinate grid

A mathematical model of distribution of faultless thermocouple temperatures on parts of walls with faulty thermocouples factoring into non-uniform installation of thermocouples in mold walls is produced by initial triangulation of a 2D coordinate grid of the mold and further plotting of interpolated temperature values along the applicate axis based on location of an anticipated coordinate along axes of a new basis, namely coordinates in a triangle.

Triangulation of the coordinate grid of thermocouples is made in accordance with the Delaunay condition: neither of vertices of generated triangles can be located inside a circumference built on three vertices of any of the stated triangles (Fig. 5). To make the triangulation, we applied a simple iterative algorithm [12].

The triangulation of the coordinate grid of horizontally scanned thermocouples on CCM-1 of MMK complying with the Delaunay condition is given in Fig. 5.

Interpolating polynomial $T^*(x,y)$ in terms of variables of the triangle is [13]:

$$T^*(x,y)=\sum_{j=1}^{3}\left[T_j(x,y)\cdot q_j(x,y)+\left(\frac{\partial}{\partial x}T(x,y)\right)_j+r_i(x,y)+\left(\frac{\partial}{\partial y}T(x,y)\right)_j\cdot S_j(x,y)\right], \tag{1}$$

where $T_j(x,y)$—temperature of the copper mold wall in the vertex of the triangle having the coordinates x,y-;$\frac{\partial}{\partial x}T(x,y)$, $\frac{\partial}{\partial y}T(x,y)$—temperature gradients in a direction of a relevant coordinate; and i, j, and k—random interchange from vertices 1, 2, and 3 of triangles (Fig. 5).

The expression (1) contains the following adopted contractions:

$$q_j=-2p_j^3+3p_j^2+2p_jp_kp_i;\quad p_j(x,y)=\frac{D_{ki}}{C_{ki}};$$
$$r_j(x,y)=p_j^2\left(p_j\cdot\xi_{ij}+p_k\xi_{kj}\right)+\frac{1}{2}p_jp_kp_i\left(\xi_{ij}+\xi_{ki}\right);$$
$$S_j(x,y)=p_j^2\left(p_j\cdot\eta_{ij}+p_k\eta_{kj}\right)+\frac{1}{2}p_jp_kp_i\left(\eta_{ij}+\eta_{ki}\right);$$
$$D_{ki}=\begin{vmatrix}1 & x & y\\ 1 & x_k & y_k\\ 1 & x_i & y_i\end{vmatrix};\quad C_{ki}=\begin{vmatrix}1 & x_j & y_j\\ 1 & x_k & y_k\\ 1 & x_i & y_i\end{vmatrix};\quad \xi_{ij}=x_i-x_j;\quad \eta_{ij}=y_i-y_j.$$

To achieve continuous temperature gradients along the coordinate x on the left and right boundaries of the mold coordinate grid, the mold perimeter was symmetrically reflected to the left and to the right, and triangulation was performed for a triple perimeter of the mold.

Coordinates x and y for the interpolating polynomial are selected by the following principle: an operating perimeter of the mold is presented as a grid with a regular step horizontally and distribution of lines in three rows vertically; a vertical step is selected subject to a maximum approximation of interpolated value coordinates $T^*(x,y)$ to coordinates of installed thermocouples which are the most frequently used in an operating perimeter of the mold.

An example of the diagram of interpolated values of temperatures in a horizontal section (150 mm from the top) of a mold-operating perimeter having a horizontal step of $\Delta l=$ 50 mm is given in Fig. 6.

Having selected temperature values (similar to Fig. 6) on a mold-operating perimeter in different steel casting modes, we checked correspondence of distribution of instantaneous interpolated temperature values to distribution of instantaneous measured temperature values in case of several faulty

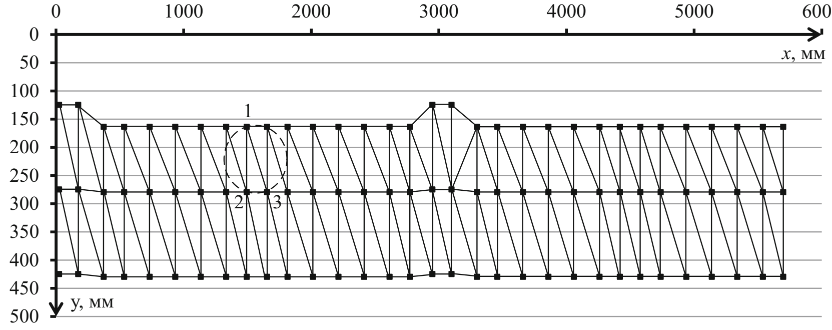
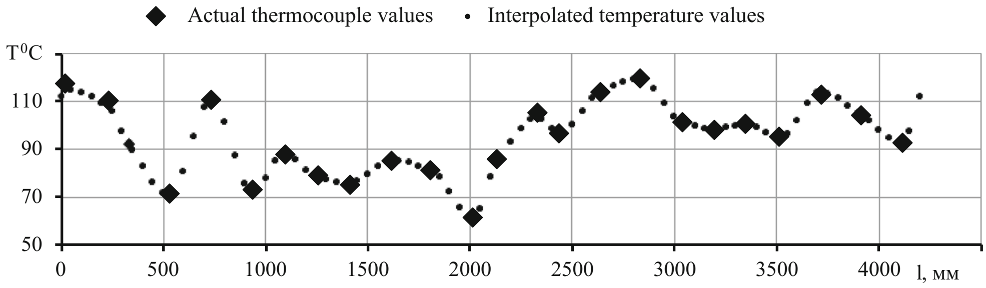


Fig. 5 Thermocouple positions coordinate system of the Delaunay triangulation *1*, *2*, and *3*—vertices of the triangles of the Delaunay triangulation

Fig. 6 Distribution of temperature values on the mold perimeter



thermocouples. The character of changes and calculated interpolated values of copper mold wall temperatures corresponds to current conditions of continuous steel casting. Moreover, coefficients of pair correlation and a maximum value of relative accuracy between series of measured and interpolated temperature values in every control point of a mold-operating surface within a period of 120 s or longer (with a discrete value of 1 s) are 0.96 and 0.3, correspondingly. The latter proves that interpolated temperature values have a non-significant statistical difference from measured ones.

To make a time analyze of temperature values $T^*_{i,j}$, it was suggested that a three-dimensional shift array $\Theta[3, N_{\mathrm{col}}, N_{\mathrm{buf}}]$ be created and updated every moment of thermocouple sampling. The structure of the array and its mnemonic diagram is given in Fig. 7.

The number of D elements in the data array is:

$$D = 3 \times N_{\mathrm{col}} \times N_{\mathrm{buf}}, \tag{2}$$

where N_{col}—number of columns in the array and Θ, N_{buf}—*number of arrays* Θ_k *in the array* Θ *(length of the array* Θ*).*

The length N_{buf} of the array is selected subject to the condition: temperature values of copper mold walls shall be stored in the data arrays during billet movement from a top row of thermocouples to a bottom one at an operating speed of billet pulling:

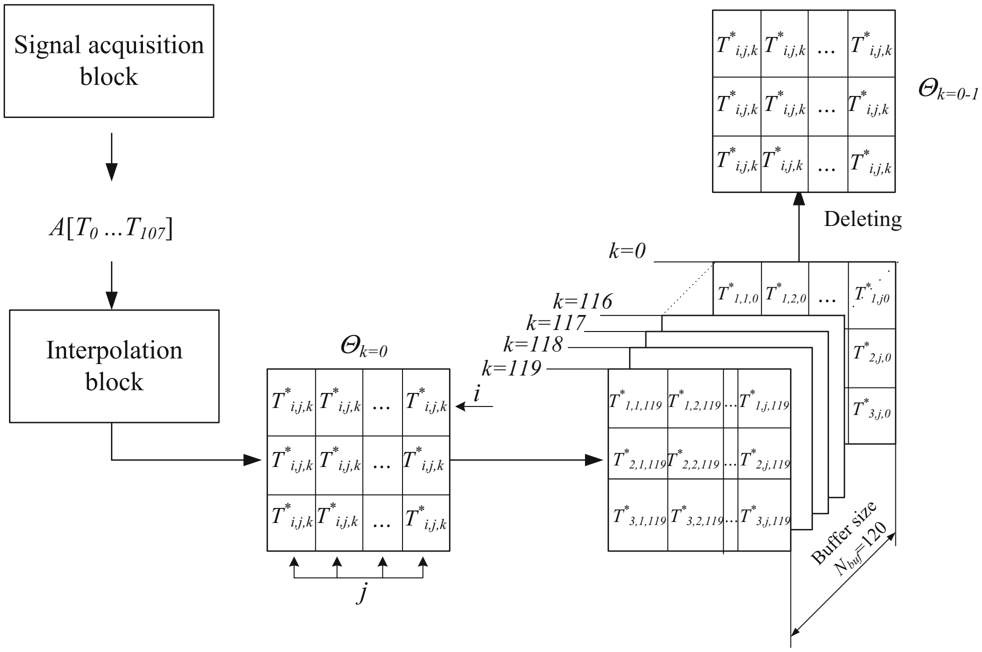
$$N_{\mathrm{buf}} > \frac{(y_3 - y_1)\cdot 60}{Vp_{\min}\cdot \Delta t}, \tag{3}$$

where y_1, y_3—maximum and minimum ordinate of the mold coordinate grid (Fig. 5), m, Δt—time of thermocouple signal digitization, s, $Vp_{\min}$—minimum operating speed of billet pulling, m/min.

The length of the array $\Theta[3, N_{\mathrm{col}}, N_{\mathrm{buf}}]$ calculated by the expression (2) for CCM-1 of MMK is $N_{\mathrm{buf}} = 120$.

Having analyzed temperature changes in a normal steel casting mode, it was found that when changing such technological factors as billet pulling speed, level of steel in the mold, and period of use of mold assembly units, temperature of some parts of copper mold walls changed significantly, similar to Fig. 4a [14]. Therefore, strand shell sticking in the

Fig. 7 Data array origination mnemonic diagram $A[T_0 \ldots T_{107}]$ input array of temperature data; Θ 3D shift array of mold temperature values; i, j, k Θ array element indexes



mold should be diagnosed by a set of the following four diagnostic indicators, not by one of parameters:

1. Increase in the temperature of two adjacent parts of the copper mold wall measured by ith and (i+1th) thermocouples assessed as increase in the rate of time changes of the stated temperatures (Fig. 4b) to $(\Delta T/\Delta t)_{\mathrm{MAX}}$:

$$\begin{cases} \left(\Delta T\middle/\Delta t\right)_{i,j} > \left(\Delta T\middle/\Delta t\right)_{i,j\mathrm{MAX}}; \\ \left(\Delta T\middle/\Delta t\right)_{i,j+1} > \left(\Delta T\middle/\Delta t\right)_{i,j+1\mathrm{MAX}}, \end{cases} \tag{4}$$

where $(\Delta T/\Delta t)_{i,j\mathrm{MAX}} = \overline{(\Delta T/\Delta t)}_{i,j} + 2 \cdot \sigma_{(\Delta T/\Delta t)_{i,j}}$—threshold value for the rate of temperature changes on parts of copper mold walls, $\overline{(\Delta T/\Delta t)}_{i,j} = \frac{1}{N_{\text{буф}}} \sum_{k}^{N_{\text{буф}}} (\Delta T/\Delta t)_{i,j,k}$—estimated mathematical expectation of the rate of temperature changes on parts of copper mold walls, and $\sigma_{(\Delta T/\Delta t)_{i,j}} = \sqrt{\frac{1}{N_{\text{буф}}-1} \sum_{k}^{N_{\text{буф}}-1} \left(\overline{(\Delta T/\Delta t)} - (\Delta T/\Delta t)_{i,j,k}\right)^2}$—estimated mean square deviation of the rate of temperature changes on parts of copper mold walls.

2. Decrease in the temperature of a copper mold wall measured by ith thermocouple in a specified period relative to the event stated in p. 1, estimated by the decreased coefficient $K_{i,j}<0$ of the approximating line (Fig. 4c):

$$T^*_{i,j}(k) = k_{i,j} \cdot K_{i,j}, \tag{5}$$

where $K_{i,j} = \frac{N \cdot \left(\sum_{k=1}^{N} k_{i,j,k} \cdot T_{\overrightarrow{i,j,k}}\right) - \left(\sum_{k=1}^{N} T_{\overrightarrow{i,j,k}}\right) \cdot \left(\sum_{k=1}^{N} k_{i,j,k}\right)}{N \cdot \left(\sum_{k=1}^{N} k^2_{i,j,k}\right) - \left(\sum_{k=1}^{N} k_{i,j,k}\right)^2}$—tangent of an angle between the approximating line and the time axis (Fig. 4)

3. Increase in the temperature of parts of copper mold walls measured by thermocouples adjacent to ith horizontally in a specified time interval relative to the event stated in p. 1 (Fig. 4a).
4. Increase in the temperature of copper mold walls measured by thermocouples adjacent to ith vertically in a specified time interval relative to the event stated in p. 1. The stated range is proportional to the distance ΔS [m] covered by the billet in the mold during Δt:

$$\Delta S = \int_{t1}^{t2} Vp(t)dt \approx \sum_{k=k1}^{k2} \frac{Vp_k \cdot \Delta t}{60}, \tag{6}$$

where Vp—billet pulling speed, m/min, and Δt—time of signal digitization, s.

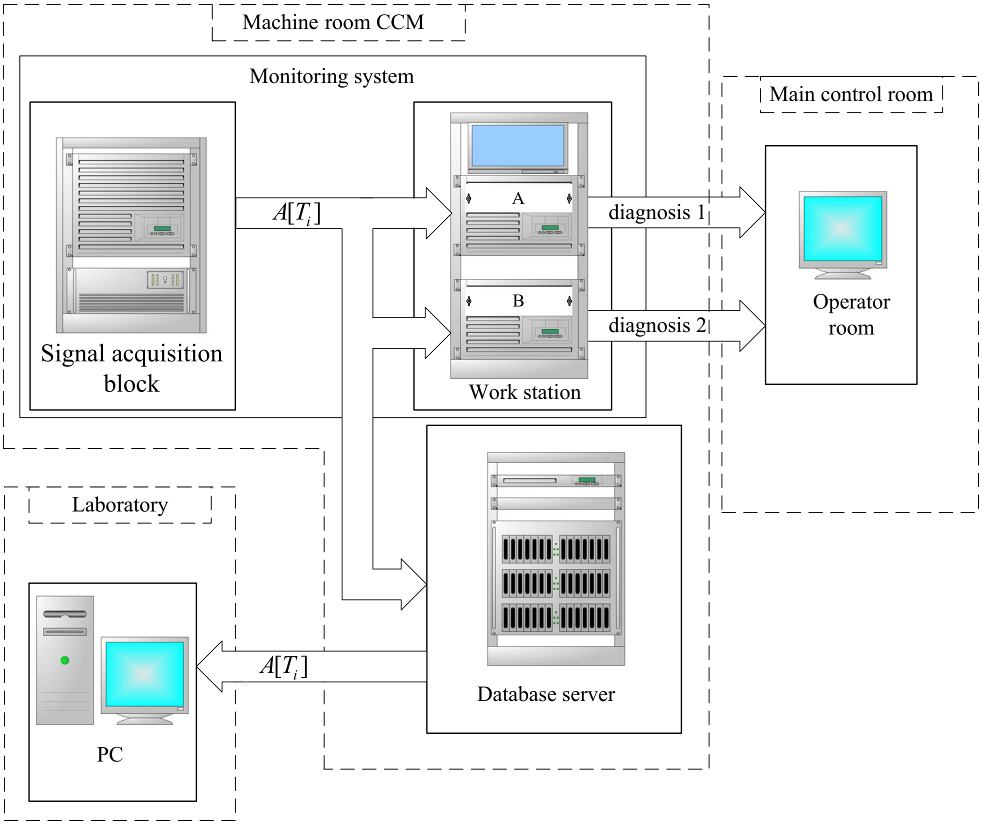


Fig. 8 Monitoring system functional scheme *A* software module “A”, *B* software module “B”, *PC* personal computer, $A[T_i]$ input array of mold temperature values

In case of strand shell sticking, ΔS is within the range of:

$$0,75\cdot\Delta Y_j \le \Delta S \le 2\cdot\Delta Y_j, \qquad (7)$$

where ΔY_j—distances between adjacent lines of the mold coordinate grid (Fig. 5); 0.75, 2—empirical coefficients.

The presented set of indicators is characterized by the lack of fixed limit values of diagnostic features. Limit values are flexible; they are set and adjusted factoring into changes of continuous casting parameters directly during the process.

A functional chart of the technical diagnostic system is given in Fig. 8. To reduce capital expenditure for modernization of the available diagnostic system, it was resolved to implement the developed system on hardware of the workstation for the regular diagnostic system A as a separate program module B. A new system may operate at the same time with the current system A; preliminary completion of the algorithm and the diagnostic program in a laboratory on PC are ensured.

4 Conclusions

We developed and optimized a diagnosis algorithm and program based on control of a set of diagnostic indicators factoring into changes of CCM operating modes, location of operating thermocouples during casting billets of a specific section, and number of operating thermocouples. The developed program was debugged and tested in the laboratory. To evaluate performance of the diagnosis, we selected data on temperature changes on copper mold walls in case of strand shell sticking on a server of the database of PCS of CCMs #1, 5 at MMK. Besides, following historical data received from Severstal and the Asha Metallurgical Plant, we selected eight events of strand shell sticking in the mold. In a read-only mode, we diagnosed such sticking on the said CCMs. Program B identified strand shell sticking in all events. In July of 2008, program B was introduced into pilot operation on two strands of CCM-5, and in April of 2009, on four strands of CCM-1 at MMK. Within the period of its pilot operation, all events of strand shell sticking were identified, while the number of wrong diagnoses (one wrong diagnosis per strand per month on the average) was less as compared to system A. It is proved that the number of wrong diagnoses on system B is 12 times less than in system A.

5 Summary

Having analyzed time diagrams of temperatures on parts of mold copper walls, it was found that four indicators of changes of the stated temperatures measured in a zone of strand shell sticking as well as on adjacent parts of copper mold walls could be used as diagnostic criteria for strand shell sticking in the mold. We developed a mathematical model relevant to experimental data to calculate distribution of instantaneous values of copper wall temperatures along the perimeter of the mold allowing interpolation-based definition of temperature on parts of mold copper walls with faulty thermocouples. We defined a set of diagnostic indicators contributing to a diagnosis of strand shell sticking in the mold. A diagnostic program was developed and introduced into pilot operation on CCMs #1, 5 at MMK. Within 1.5 years of operation, the said program showed a relatively high reliability of diagnoses: due to early detecting of strand shell sticking in the mold; 44 out of 44 probable cases of breakout liquid metal was prevented. The number of wrong diagnoses as compared to the regular diagnostic system for strand shell sticking in molds of CCM #1, 5 was decreased 12 times.

Compliance with ethical standards The team of authors composed of S.I. Luk'yanov, E.S. Suspitsyn, S.S. Krasilnikov, and D.V. Shvidchenko confirm that they have no conflict of interest.

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