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DEVELOPMENT OF AUTOMATED CONTROL SYSTEM AND REGISTRATION OF METAL IN CONTINUOUS CASTING

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ABSTRACT

Context. Modern industrial enterprises face challenges that require introduction of latest technologies to improve efficiency and competitiveness. In metallurgy, one of key stages is continuous casting, where quality of products and economic performance of enterprise depend on accuracy and efficiency of process control. Products made using continuous casting technology are widely used in various industries due to their high mechanical properties, structural uniformity and cost-effectiveness.

The development of automated metal management and registration system is becoming not only relevant, but also necessary to ensure stable and efficient production.

The problem of improving quality of metal products has always been one of most important tasks in steel industry. Imperfect technological processes, human error and equipment malfunctions can lead to defects in finished metal products. This, in turn, affects final characteristics of products, their durability and reliability.

To date, available sources have not yet found complete solution to this problem. Therefore, it is necessary to formulate problem and develop algorithm for operation of automated system for controlling and registering metal in continuous casting.

Objective. The goal of work is to develop automated metal management and registration system to improve quality of metal products.

Method. To achieve this goal, parametric model was proposed, which is formalized on basis of set theory. The model takes into account key parameters of continuous casting process: material characteristics, structural features of crystallizer, casting modes, metal level in crystallizer, and position of shot stopper.

Results. The problem was formulated and key parameters were determined, which are taken into account in system's algorithm, which made it possible to develop system for controlling parameters of continuous casting to solve problem of improving quality of metal products.

Conclusions. To improve quality of metal products and stability of casting process, parametric model was created that is comprehensive, allows optimization of key parameters and ensures accuracy of process control by integrating not only modes of product formation, but also takes into account specific properties of source material (chemical composition of material grade, etc.) and design features of casting plant. Algorithm for automated control system has been developed that takes into account relationships between certain key parameters and ensures optimal control of casting process. Based on proposed complex parametric model and algorithm, automated control and metal registration system was created. The focus of work is on quality and efficiency of metal management and registration in continuous casting, based on modern methods of computer science and engineering. A comprehensive experimental comparison of developed system with commercial analogs in real production conditions was carried out, which allowed us to objectively assess its efficiency and reliability.

KEYWORDS: automation, system, parametric model, control, registration, metal.

ABBREVIATIONS

AI – analog input;
ALOG – alarm log block;
CC – continuous casting;
CCM – continuous casting machine;
IL – industrial ladle;
GE – graphic element;
MP – metal products;
ONF – on/off control block;
PLC – programmable logic controller;
SCADA – supervisory control and data acquisition;
SL – steel ladle;
SP – stopper;
STC – steel ladle;
TMR – temperature.

NOMENCLATURE

A is a wall A of crystallizer;

${A^d}_i$ is a distance from wall A of crystallizer to opposite wall (bottom), m;

A_i^{rc} is a vibration amplitude of crystallizer, mm;

${A^{up}}_i$ is a distance from wall A of crystallizer to opposite wall (top), m;

B is a wall B of crystallizer;

${B^d}_i$ is a distance from wall B of crystallizer to opposite wall (bottom), m;

B_i is a grade of material (metal);

${B^{up}}_i$ is a distance from wall B of crystallizer to opposite wall (top), m;

Ch_{mi} is a chemical composition of material grade;

CM_i is a casting modes;

D_{bwi} is a distance between opposite walls at top and bottom of crystallizer, m;

DF_i is a design feature of crystallizer;

$[E]_i$ is a average dissolved element content in steel, %;

G_{Cci} is a metal consumption in crystallizer;

G_{Cd_i} is a metal consumption from steel ladle;

G_{CId_i} is a metal consumption from industrial ladle;

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H_{cri} is a height of crystallizer, m;

h_i^{cr} is a metal level in crystallizer, m;

h_i^{Idl} is a metal level in industrial ladle, m;

h_i^{l} is a metal level, m;

h_i^{ls} is a slag level, m;

h_i^{Stl} is a metal level in steel ladle, m;

$h^{uf}{}_i$ is a amount of underfilling of liquid metal to top of copper sleeve of crystallizer, m;

$h^{w}{}_{cri}$ is a working (active) height of crystallizer, m;

I is a number of possible alternatives;

$k^{c}{}_i$ is a hardening rate, mm/min ^{½};

k_{v} is a coefficient of workpiece pulling speed;

M_i is a material (metal);

$M^{rc}{}_i$ is a mechanism of rocking crystallizer;

$N^{rc}{}_i$ is a number of crystallizer vibrations;

$P^{hc}{}_i$ is a position of hydraulic cylinder rod;

$P^{vl}{}_i$ is a valve position;

q_i is a metal casting speed;

$Sh^{rc}{}_i$ is a shape of crystallizer vibrations;

SP_i is a position of locking mechanism;

Spl is a plane of stopper outlet, m^2;

T_{CCi} is a temperature modes, °C;

$T^{h}{}_{SCZi}$ is a temperature of hardened steel at end of secondary cooling zone, °C.

T_i is a type of material (type of metal);

$T^{ild}{}_i$ is a metal temperature in industrial ladle, °C;

$T^{ild}{}_i$ is a metal overheating temperature in industrial ladle, °C;

$T^{ld}{}_i$ is a metal temperature in steel ladle, °C;

$\Delta T^{ld}{}_i$ is a metal overheating temperature in steel ladle, °C;

T_{liqi} is a liquidus temperature of continuous casting, °C;

$T^{p}{}_{sm}$ is a solidification temperature of pure iron, °C;

$T^{s}{}_{SCZi}$ is a surface temperature of workpiece in i-th section of secondary cooling zone, °C;

$T^{wpc}{}_i$ is a temperature of crystallizer working surface, °C;

$\Delta t^{liq}{}_{Ei}$ is a amount of decrease in solidification temperature of iron when 1 % of corresponding element is introduced into it, °C;

α is a coefficient for calculating distance between opposite walls in crystallize;

μ is a consumption factor that depends on viscosity of liquid steel grade being poured;

$\rho^{m}{}_i$ is a material density, t/m^3;

$\tau^{c}{}_i$ is a curing time, min;

$\tau^{cr}{}_i$ is a length of time material stays in crystallizer;

ν_i^{rc} is a vibration frequency of crystallizer, min^{-1};

$\nu^{wcr}{}_i$ is a working speed of workpiece pulling, m/min.

INTRODUCTION

The use of metal products is extremely relevant in modern world, as metal has become main material for construction of complex and durable structures in construction, engineering, and other industries [1–3].

Metal products are characterized by high strength, resistance to wear and corrosion, durability and ability to be used in various operating conditions. In addition, metal products are efficient in recovery processes and can be recycled, making them environmentally sustainable. One of most important processes in production of metal products is continuous casting.

CC technology is used to produce wide range of metal products, including steel bars, aluminum blocks and other complex structures. It automates molding process and ensures high product quality stability through precise control of casting parameters.

Controlling and accurately recording process parameters remain challenging tasks that affect quality and stability of production. Shortcomings in control systems can lead to reduced product quality, losses, and even accidents. Therefore, solving these problems is urgent task to improve efficiency and reliability of continuous casting process.

Automated control makes it possible to precisely control process parameters such as temperature and metal casting speed, ensuring stable production conditions and preventing defects. In addition, automated system records data in real time, which simplifies maintenance of process documentation and allows for quick response to changes in process parameters.

The research tasks include development of parametric model of continuous metal casting process that will not only control process of forming metal products, but also take into account unique properties of source material and design features of casting plant. In addition, it is necessary to identify and analyze modern methods of controlling casting parameters, develop algorithm for automatic process control to optimize productivity and product quality, and implement system. These tasks are aimed at creating and implementing advanced technologies to improve continuous metal casting process. Practical tasks include implementation of algorithm and creation of automated control system for continuous casting process, implementation of real-time or scheduled process parameter recording.

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Since one of main challenges in metal forming is to improve quality of products and obtain products with high material properties. These aspects are critical to ensuring competitiveness in market and meeting requirements of modern quality standards, which is why we have chosen this topic for our research.

The initial data include results of previous studies, technical requirements for creation of automated control system [1–3]. The introduction of automation into continuous casting process by providing system with tools for controlling and recording casting parameters, optimizing production modes based on specific requirements and material properties are important tasks.

The object of research is process of control and registering metal in crystallizer.

The subject of research is continuous casting unit, or more specifically, crystallizer.

The purpose of the research is development of automated metal management and registration system to ensure quality of finished metal products.

1 PROBLEM STATEMENT

The modern steel industry is facing numerous challenges, including need to improve product quality and process stability. Continuous metal casting is critical stage in production cycle where precise parameter control and process optimization are crucial. Failure to properly control and record casting parameters can lead to defects in finished products, reduced productivity, and increased production costs.

Modern production processes are characterized by high complexity and dynamism. There is need to develop universal approaches to creating adaptive control systems that can function effectively under conditions of uncertainty and variable parameters. The key problem is development of mathematical models and algorithms that would ensure optimal control in real time.

Given all these challenges and needs of modern steel industry, it is clear that current management and control methods need to be improved to meet the growing demands on production efficiency and quality. The complexity of processes, dynamic parameters and high requirements for final product require introduction of new solutions that take into account all aspects of production cycle and provide optimal control in real time. Therefore, there is urgent need to develop automated metal management and registration system that will ensure high quality products and process stability.

The mathematical formulation includes creation of parametric model that takes into account material characteristics and specifics of production process to improve quality of metal products.

Input data for system includes crystallizer configurations and properties, as well as material parameters and casting modes.

A parametric model is proposed that formalizes key parameters for specific casting process and is necessary both for design of new plants and for existing units to optimize process of molding MP.

The input parameters for development of automated control system for MP unit are represented by model:

$M_i =< T_i, B_i, \rho^m{}_i, Ch_{mi} >,\ i=1,\ 2,\ ...,I;$

$DF_i = \ < D_{bwi}, H_{cri}, h^w{}_{cri}, h^{uf}{}_i, M^{rc}{}_i >,\ i=1,\ 2,\ ...,I;$

$M^{rc}{}_i =< N^{rc}{}_i,\ \nu_i^{rc}, A_i^{rc}, Sh^{rc}{}_i >;\ i=1,\ 2,\ ...,I;$

$CM_i = \ < T_{CCi}, q_i, \tau^{cr}{}_i,\ v^{wcr}{}_i, k_v,\ \tau^c{}_i, k^c{}_i >,$
$i = 1,\ 2,\ \ldots, I;$

$T_{CCi} = \ < T^{ld}{}_i, \Delta T^{ld}{}_i, T^{ild}{}_i, \Delta T^{ild}{}_i, T^{wpc}{}_i, T_{liqi}, T^s{}_{SCZi}, T^h{}_{SCZi} >,$

$i=1,\ 2,\ ...,I;\ \ T_{liqi} =< T^p{}_{sm},\ [E]_i, \Delta t^{liq}{}_{Ei} >,$

$i=1,\ 2,\ ...,I;\ \ D_{bwi} =< A^{up}{}_i, A^d{}_i, B^{up}{}_i, B^d{}_i >;$
$i=1,\ 2,\ ...,I.$

The distance between opposite walls: $A^{up}{}_i = (1{,}04\ \ldots 1{,}05)\times\alpha;$ $B^{up}{}_i = (1{,}02\ \ldots 1{,}03)\times\alpha;$

$A^d{}_i = (1{,}03\ \ldots 1{,}04)\times\alpha;$

$B^d{}_i = (1{,}01\ \ldots 1{,}02)\times\alpha;\ SP_i = \ < P^{hc}{}_i, P^{vl}{}_i >,$

$G_{Cd_i} =< Spl, h_i^l, h_i^{ls}, h_i^{Stl}, \mu >;\quad i=1,\ 2,\ ...,I;$

$G_{CId_i} =< Spl, h_i^l, h_i^{ls} >;\ i=1,\ 2,\ ...,I.$

As result, it is planned to obtain parametric model that will be implemented in developed automated system, which will further improve quality of metal products through accurate and stable control of casting parameters.

2 REVIEW OF THE LITERATURE

The continuous metal casting process and its control are actively studied in numerous scientific papers, with main focus on technological aspects and automation systems. The literature review of this process focuses on its efficiency, technical solutions, and innovations in controlling production parameters.

Authors of [4] describe continuous casting process, which has become main method of steel production since mid-1980s, replacing traditional ingot casting method. The authors emphasize high productivity, quality, and energy efficiency of continuous casting, as well as importance of research and development in this area to meet growing demands on steel quality, energy efficiency, and environmental aspects.

Technological aspects are described in detail in [5–8].

In [5] provides historical overview of casting methods used to produce steel sheets for various applications. The article analyzes advantages and disadvantages of modern casting methods.

In [6] analyzes machine learning methods for monitoring and controlling continuous steel casting process. The authors describe challenges, possible solutions, and future research directions in this area.

In [7], basic metallurgical principles of casting technology are discussed in detail. The authors analyze prop-

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erties of metals: cast iron, cast steel, and cast non-ferrous alloys.

In [8], we are talking about technology of two-phase zone continuous casting. The authors model flow and temperature fields at different speeds.

Quality is critical in casting, as it determines quality of final product and its properties that affect its further use in industry [9–11].

In [11], attention is focused on improving continuous casting process in steel production by optimizing design parameters of submerged casters. The authors link quality of slab production to casting mold and casting flow patterns. The study presents new optimization method called African buffalo algorithm, which was implemented in Matlab to optimize parameters such as nozzle size, port shape, length, immersion depth, etc. The authors also take into account fluid flow rate, however, they do not pay attention to specific properties of source material that directly affect process and quality of final product. In our work, one of things we plan to do is to take into account chemical composition of material grade, which affects: hardness and strength of steel, as well as melting point; improve corrosion resistance, strength, and other mechanical properties; defects in metal, such as cracks or pores.

In [12], quantification of degree of defects in continuously cast billets is presented in YOLOv5. The authors proposed network that solves problems associated with noise or dirty spots and different sizes of defects in images of these workpieces. Although innovative networks have been introduced in work, design features of casting plant, which also affect quality of resulting metal products, have not been taken into account.

In [13] discusses defects in continuous casting of steel billets and their impact on quality of finished products. The authors determined that occurrence of defects depends on temperature distribution and cooling regime in casting gating. Although authors paid attention to chemical composition of melt and secondary cooling modes, they again did not take into account design features of casting equipment. The article also notes that solutions used on one casting gating may not always be applicable to other gating due to different conditions.

Recent years have shown growing interest in new methods of monitoring and controlling this complex process, such as MP, which is reflected in work on development of automated systems based on modern technologies such as machine learning, artificial intelligence, etc. Therefore, automated systems are and will remain key area for improving quality and efficiency of metal production.

In [14] describes design of PLC-based control system for continuous casting machine. The authors use sensors to collect information about actual state of slab and then transfer it to PLC. This allows for real-time monitoring of slab quality, increasing level of automation of continuous casting process, production efficiency, and cost-effectiveness. The work also describes structure of automatic control system, which includes control, monitoring, and control levels. The authors discuss in detail various components of system, such as ladle turret, intermediate ladle slide gate control, electro-hydraulic servo system, crystallizer cooling water control, and crystallizer vibration system. The main goal of development is to increase level of automation of continuous casting process, improve quality of castings, and increase productivity. While article has concrete results, however, despite emphasis on automation, article emphasizes limited possibilities of manual control in emergency situations, which can pose potential risk to safety and reliability of process. This emphasizes need for balance between automation and possibility of manual intervention in critical situations.

References [15–17] provide overview of modern technologies and automation systems used in continuous casting processes.

In field of metals continuous casting, these works highlight key aspects that arise in process of manufacturing finished metal products.

The general trend of these scientific papers is great interest in continuous casting technologies, disclosure of issues related to quality of finished products made of metals obtained by casting. The issue of designing control system for continuous casting machine. These works cover important aspects, such as introduction of new methods for controlling parameters of continuous casting process, quantifying degree of defects, etc.

Therefore, this work focuses on control and registration of metal during continuous casting with possibility of manual control of most important parameters of MP process, which are taken into account in parametric model, if necessary, which is prerequisite for improving quality of resulting metal products.

3 MATERIALS AND METHODS

Investigate process develop comprehensive parametric model of CC.

To address key challenge of developing mathematical models and algorithms for real-time optimal control and achieving goal, our study of continuous casting process proposes parametric model. This model captures key aspects of this complex process, providing framework for optimizing control. The development of such parametric models is critical for technology improvement in various fields of science and industry [9, 18], including continuous casting, where it allows for effective real-time optimal control problems.

Moreover, definition and formalization of molding process parameters creates basis for further development of intelligent decision support systems that can integrate machine learning and big data analysis. This opens up new opportunities for use of advanced information technologies in industrial production.

The proposed model accurately reflects relationships between various parameters that affect quality and efficiency of CC production.

The necessary and sufficient parameters are represented in complex form as tuple of parameters:

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$$CC = < M_i, DF_i, CM_i, SP_i, G_{Cdi}, G_{CIdi}, G_{Cci} > . \quad (1)$$

In course of study, parametric model describing forming of metal products was created. This model is presented comprehensively as set of interrelated parameters that cover not only direct modes of molding process, but also take into account specific properties of source material. In addition, model integrates design features of casting equipment, including characteristics of crystallizer and configuration of locking mechanism.

The ultimate goal of project is to develop automated system based on created parametric model. This system is designed to efficiently manage process and accurately account for metal at forming stage of metal products. It will optimize production process, improve product quality and ensure efficient use of resources.

Describe selection and description of main parameters of metal forming process.

In this work, term «molding process» refers to process of continuous metal casting.

The selection and description of metal forming process key parameters is not only important step in solving applied problems in metallurgy, but also significant contribution to development of information technology and complex process control systems.

Our approach to decomposing complex technological process into local object-zones and identifying key control parameters demonstrates innovative method of formalizing and structuring data to create effective information models. This makes it possible to develop more accurate forecasting and optimization algorithms, which is urgent task in field of computer science.

We propose decomposition of complex technological process of molding into local objects-zones:

1) steel ladle area;
2) industrial ladle area;
3) primary cooling zone (crystallizer).

Next, let's define key control parameters that affect both metal level and quality of MP at stage of metal billet molding.

Deviations from optimal casting mode caused by various factors can lead to decrease in productivity, deterioration in metal quality, and occurrence of emergencies.

So, based on analysis of molding process, parameters and values they can take have been determined, and we will formalize these parameters below.

The first parameter is temperature of metal in industrial ladle:

$$T_i^{ild} = \begin{cases} T_1^{ild}, \text{ if } 1753 \le T^{ild} \le 1768, \\ T_2^{ild}, \text{ if } 1763 \le T^{ild} \le 1783, \\ T_3^{ild}, \text{ if } 1793 \le T^{ild} \le 1813, \\ T_4^{ild}, \text{ if } 1803 \le T^{ild} \le 1843, \\ T_5^{ild}, \text{ if } 1793 \le T^{ild} \le 1813, \\ T_6^{ild}, \text{ if } 1798 \le T^{ild} \le 1818. \end{cases} \quad (2)$$

Indexes 1, 2, 3, 4, 5, 6 in parameter T_i^{ild} here and in future – ranges of values for different steel grades: 1 – ШХ15; 2 – Ст50, 3 – Ст20–45, 4 – 12ХН3А, 5 – 40Х, 6 – Ст3сп):

Metal overheating temperature in industrial ladle:

$$\Delta T_i^{ild} = \begin{cases} T_1^{ild}, \text{ if } 1768 \le \Delta T^{ild} \le 1793, \\ T_2^{ild}, \text{ if } 1778 \le \Delta T^{ild} \le 1808, \\ T_3^{ild}, \text{ if } 1808 \le \Delta T^{ild} \le 1838, \\ T_4^{ild}, \text{ if } 1818 \le \Delta T^{ild} \le 1868, \\ T_5^{ild}, \text{ if } 1808 \le \Delta T^{ild} \le 1838, \\ T_6^{ild}, \text{ if } 1818 \le \Delta T^{ild} \le 1843. \end{cases} \quad (3)$$

The value of optimal overheating varies from 15 to 25 °C when pouring melt in closed stream for up to one hour, and in most cases, modern CCMs use closed jet to feed metal into crystallizer with melt pouring duration of no more than 60 minutes.

The second parameter is temperature of metal according to steel ladle (steel ladle is main metallurgical equipment required for receiving, transporting, processing steel in ladle and pouring molten metal):

$$T_i^{ld} = \begin{cases} T_1^{ld}, \text{ if } 1773 \le T^{ld} \le 1818, \\ T_2^{ld}, \text{ if } 1783 \le T^{ld} \le 1833, \\ T_3^{ld}, \text{ if } 1813 \le T^{ld} \le 1863, \\ T_4^{ld}, \text{ if } 1823 \le T^{ld} \le 1893, \\ T_5^{ld}, \text{ if } 1813 \le T^{ld} \le 1843, \\ T_6^{ild}, \text{ if } 1823 \le T^{ild} \le 1848. \end{cases} \quad (4)$$

Metal overheating temperature in steel ladle:

$$\Delta T_i^{ld} = \begin{cases} T_1^{ld}, \text{ if } 1787 \le \Delta T^{ld} \le 1837, \\ T_2^{ld}, \text{ if } 1793 \le \Delta T^{ld} \le 1852, \\ T_3^{ld}, \text{ if } 1827 \le \Delta T^{ld} \le 1852, \\ T_4^{ld}, \text{ if } 1837 \le \Delta T^{ld} \le 1912, \\ T_5^{ld}, \text{ if } 1827 \le \Delta T^{ld} \le 1862, \\ T_6^{ild}, \text{ if } 1837 \le \Delta T^{ild} \le 1867. \end{cases} \quad (5)$$

The third parameter is temperature of crystallizer's working surface:

$$160 \le T^{wpc}{}_i \le 180. \quad (6)$$

According to various estimates based on direct measurements, temperature of crystallizer working surface is

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usually 160–180 ^{o}C. The value of this temperature can vary depending on number of factors: thermal conductivity of crystallizer wall material, intensity of heat removal by water, thickness of crystallizer wall, composition and thickness of working coating, etc.

The steel casting rate depends on its temperature in tundish and can be described as follows:

$$2 \le q_i \le 3. \quad (7)$$

The fourth parameter is vibrations amplitude of crystallizer:

$$1 \le A_i^{rc} \le 3. \quad (8)$$

The fifth parameter, vibrations frequency of crystallizer, can be described as follows:

$$0 \le \nu_i^{rc} \le 300. \quad (9)$$

The sixth parameter is level of metal in steel ladle:

$$2.5 \le h_i^{Stl} \le 3. \quad (10)$$

The seventh parameter is level of metal in industrial ladle:

$$0.7 \le h_i^{Idl} \le 1.2. \quad (11)$$

The eighth parameter – position of stopper – is also one of main parameters that needs to be monitored because it is possible to quickly change metal consumption:

$$SP_i = \begin{cases} SP_1, \text{if } SP = [\text{open}], \\ SP_2, \text{ if } SP = [\text{close}]. \end{cases} \quad (12)$$

The ninth parameter is level of metal in crystallizer:

$$0.75 \le h_i^{cr} \le 0.85. \quad (13)$$

The rationale for selecting key control parameters is shown in Table 1.

3.3 Technical means for controlling casting parameters

In context of developing automated control and metal registration system for continuous casting, creation of effective information and measurement subsystem is a key element that requires use of modern computer science methods. This subsystem not only optimizes continuous casting process, but also provides reliable basis for automated control and accurate recording of metal parameters based on modern information technology and data processing methods.

Table 1 – Key parameters of metal CC process control: description, causes and consequences

Description	Reason	Consequences
Temperature of metal in industrial ladle	1) Unstable liquid metal temperature at furnace outlet – initial temperature affects entire casting process. 2) Heat loss during transportation. 3) Thermal insulation properties of industrial ladle. 4) The time metal stays in rolling mill (longer metal stays in rolling mill, more it cools down). 5) Additional heating (use of induction or gas heaters to maintain required metal temperature).	1) Quality of finished products. 2) The stability of CC. 3) Crystallization rate. 4) Equipment wear and tear.
Temperature of metal in steel ladle Temperature of metal in steel ladle	1) Unstable temperature of liquid metal at furnace outlet. 2) Heat loss during transportation. 3) Thermal insulation properties of steel ladle. 4) The time metal stays in ladle. 5) Additional heating. 6) The casting process (speed and uniformity of metal casting can affect temperature control).	1) Quality of finished products. 2) Crystallization process. 3) Productivity of casting process. 4) Equipment wear and tear.
Temperature of working surface of crystallizer	1) Thermal conductivity of crystallizer material. 2) Efficiency of cooling system. 3) Heat load from molten metal. 4) Coolant temperature and thermal processes in crystallizer. 6) Condition of working surface of crystallizer.	1) The process of metal crystallization. 2) Formation of primary crust. 3) Thermal stresses. 4) Wear and tear of crystallizer.
Vibrations amplitude of crystallizer Vibrations frequency of crystallizer	1) Design and characteristics of crystallizer. 2) Casting speed. 3) Viscosity and composition of metal. 4) Temperature affects metal properties, which in turn determines optimal oscillation parameters. 5) The massiveness and size of metal stream can affect optimal oscillation frequency, which ensures uniform cooling and formation of primary crust.	1) Quality of finished products. 2) Formation of primary metal cortex. 3) Smoothness and uniformity of surface of MP. 4) Thermal stresses. 5) Stable casting process, increasing productivity and reducing downtime.

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Continuation of Table 1

Description	Reason	Consequences
Level of metal in steel ladle	1) The rate at which metal is fed from furnace. 2) The rate at which metal flows out of ladle affects maintenance of stable level. 3) The level of metal. 4) The rate at which metal is drained from ladle to tap or other equipment. 5) Metal temperature. 6) Metal level depends on system pressure, which affects flow and spillage of metal.	1) Quality of finished products. 2) Stability of casting process. 3) The correct metal level reduces risk of defects such as sinks and pores.
Level of metal in steel ladle	7) The volume and shape of ladle can affect maintenance of stable metal level.	5) Cooling efficiency, which in turn affects crystallization rate and product quality.
Level of metal in industrial ladle	1) Metal feed rate from steel ladle. 2) The speed of pouring into crystallizer. 3) The temperature of metal affects its viscosity and flow rate, which can change level of metal in industrial ladle. 4) Metal level. 5) The design and dimensions of industrial ladle determine maximum and minimum metal level that can be maintained. 6) The pressure of metal in system affects its flow and, accordingly, level in industrial ladle. 7) The process of draining and filling ladle.	1) Quality of finished products. 2) Stability of casting process. 3) Avoidance of defects such as pores and cracks. 4) Ensuring optimal level of metal allows you to maintain high productivity without stops and interruptions. 5) Efficiency. 6) Equipment wear and tear.
Position of stopper	1) Casting speed. 2) Viscosity and composition of metal. 3) The level of metal in tundish. 4) Metal pressure. 5) Metal temperature. 6) The design and dimensions of stopper and crystallizer can affect precise parameters of metal flow control.	1) Quality of finished products. 2) Metal flow rate. 3) Metal level in crystallizer. 4) Pressure and turbulence of flow. 5) Avoidance of defects – cavities, sinks and cracks. 6) Stability of casting process. 7) Equipment wear and tear.
Metal level in crystallizer	1) Metal feed rate from industrial ladle. 2) The position of stopper. 3) Metal temperature. 4) Efficiency of cooling system of crystallizer. 5) Metal level. 6) Design and dimensions of crystallizer.	1) Quality of finished products. 2) Crystallization process. 3) Thermal stresses. 4) Productivity of casting process. 5) Metal level.

Our automated control system integrates variety of sensors to form comprehensive information network for real-time monitoring, analysis and control of casting parameters. This approach is based on principles of system analysis and information system design, which are key aspects of modern computer science.

Optimal control of casting parameters is critical to guaranteeing high quality of finished MPs and production safety. In this aspect, use of specialized equipment becomes mandatory, with sensors playing key role in such equipment. It is they who make it possible to accurately measure and regulate various characteristics of casting process, which ensures its effective control and management.

To begin with, measurement of metal temperatures in tundish, steel ladle and crystallizer working surface is realized thanks to CEM DT infrared pyrometer, which allows measuring high temperatures in hard-to-reach places. The device is capable of detecting temperatures above 1000 degrees (–50 °C…+1600 °C) at distance of several meters without touching object of study. Sensors can be placed at every critical point of CC process.

The amplitude of vibrations will be measured using sensor 640B01 – vibrations will be measured using sensor 640B01, industrial speed converter. It has following characteristics: speed measurement from 0 to 1 inch/sec (0 to 25,4 mm/sec); output signal from 4 to 20 mA; 2-pin connector. The frequency range for measurement is (± 10 %) from 180 to 60,000 rpm (3 to 1000 Hz).

The vibrations frequency of crystallizer can be measured using digital frequency meter 10–199,9 Hz. This device was chosen because of following characteristics: frequency measurement from 20 to 600 cycles per minute; supported voltage from 80 to 300 V; ability to measure amplitude of vibrations of crystallizer in range from 1 to 50 mm.

The metal level in steel ladle, tundish and crystallizer is monitored using special eddy current level sensor XLEV, which determines level of molten metal. The advantages include fact that this sensor measures actual level of steel and full digital signal processing.

The steel casting speed will be measured using optical metal casting speed sensor – ProSpeed LSV-2100. The advantages include: precise laser measurement; non-contact measurement method; no need for recalibration; easy integration into processes with long distances of up to 3 m.

Information about position of lock is generated by linear displacement sensor mounted on hydraulic cylinder rod of locking mechanism. To measure position of stopper, linear encoder from LTR series is used, designed for short movements and equipped with return spring. An important feature of these sensors is presence of return spring.

The integration of above sensors and measuring devices into single automated control system requires use of specialized software capable of efficiently processing and analyzing data from various sources. To solve this problem, we chose Genie software package, which provides

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comprehensive support for a wide range of industrial automation hardware. The input/output drivers included in Genie package provide support for all industrial automation hardware, including data acquisition and control modules, IBM PC-compatible MIC2000 modular co-controller, remote data acquisition and control devices, and CAN industrial bus devices with DeviceNet protocol. The data center is set of dynamic linking libraries.

Consider technical means of controlling casting parameters.

Based on analysis of parametric model (1) and taking into account parameters of metal products formation, algorithm for automated system was developed, which is shown in Fig. 1.

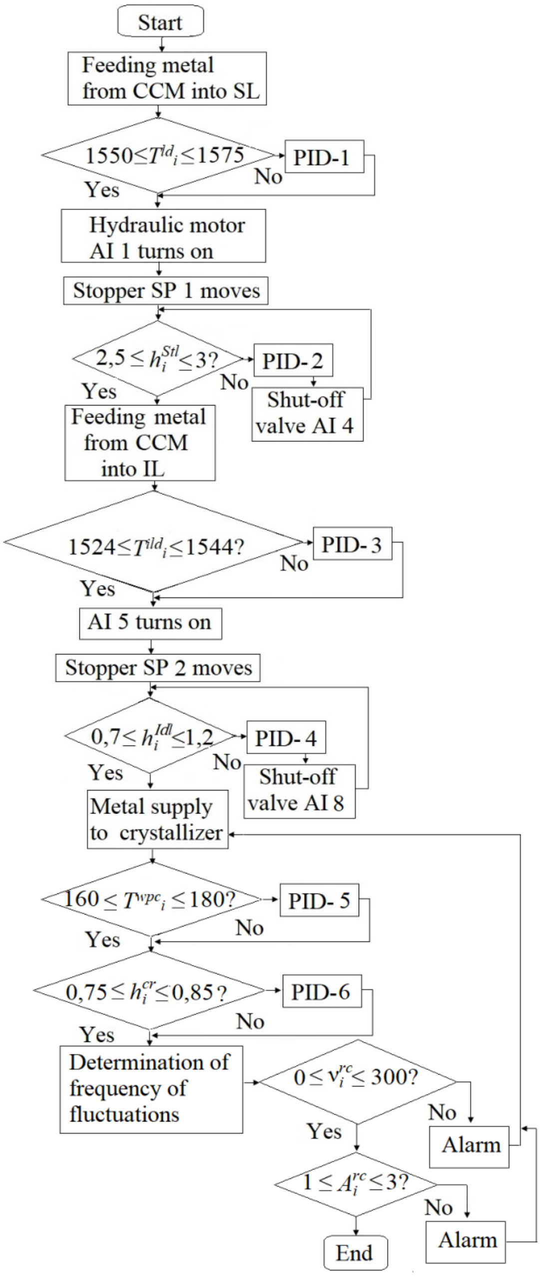

Figure 1 – Algorithm of control system operation

Stage 1: The automated system begins its operation by feeding metal (raw materials) from CCM into steel ladle.

Stage 2. Next, temperature of raw material in steel ladle is checked, if conditions are met, then hydraulic motor AI 1 is turned on, which pushes stopper in steel ladle AI 2. If conditions are not met, then control by PID 1 is required.

Stage 3. After that, level of raw materials in steel ladle is checked, if conditions are not met, then it is necessary to control AI 4 shut-off valve using PID 2. If conditions are met, then raw material enters industrial ladle.

Stage 4. Next, temperature of raw material in mill is checked, if conditions are met, then hydraulic motor AI 3 is switched on, which pushes stopper in mill SP 2. If conditions are not met, then control by PID 3 is required.

Stage 5. After that, level of raw materials in mill is checked, if conditions are not met, then it is necessary to control shut-off valve AI 8 with help of PID 4. If conditions are met, raw material enters crystallizer.

Stage 6. The algorithm is repeated, as in case of steel ladle or industrial ladle.

Stage 7. Determination of crystallizer vibrations frequency.

Stage 8. Checking conditions for vibration amplitude of crystallizer. If condition is met, then algorithm is completed, and if not, then error message (signal to indicator) is generated and algorithm returns to stage 7.

The developed algorithm is the result of formalizing a complex production process, which demonstrates the effectiveness of applying computer science methods (algorithm theory, system analysis, etc.) to model real systems.

The algorithm is built on basis of clear logical structure using conditional operators and loops, which is classical approach in algorithm theory and programming.

The algorithm implements principles of automatic control theory, in particular, use of PID controllers, which demonstrates integration of informatics methods and control theory.

Although this algorithm does not have explicit modular structure in classical sense, it has certain structuredness with successive processing and control stages, which reflects systematic approach to managing complex production process. Each stage of algorithm includes checking conditions and appropriate actions, which ensures flexibility and adaptability of control system to changes in process parameters.

4 EXPERIMENTS

Modern automated control systems are critical for industrial enterprises, as they help to increase efficiency, provide data processing for making informed decisions, and report system problems. This helps to reduce downtime and avoid shortages of both finished products and billets.

SCADA systems are backbone of many modern industries. The Genie system was chosen for development, which is one of SCADA packages.

The Genie system has module-oriented open architecture.

Development of system is reduced to user placing functional blocks in task window and establishing links

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between them, which are determined by data processing algorithm.

The openness of architecture ensures easy integration of Genie with other applications to share data during execution of strategies. Genie was chosen for this work because of its ease of use.

Based on developed algorithm, we created project that will include 2 modules:

1) Strategy, which consists of mnemonic scheme developed in «Task Editor».

2) The interface of automated system – on-screen form that is developed in «Form Editor». Connections between blocks of «Task Editor» and display elements of «Form Editor» are invisible – links.

A mnemonic scheme consisting of blocks and links between them has been created.

Task or TASK 1 – set of functional blocks displayed in Task Editor window.

TASK 1 is Task 1 window in «Task Editor», where mnemonic scheme is developed (Fig. 2).

AI units are connected to sensors that read values of measured parameters.

The AI block is designed to receive information from devices with analog signal input subsystem and transmit these signals to other blocks and display elements (Fig. 3).

Tag «Field» – name of tag in Genie system. The «Description» field is field for entering description of device (value in field is left by default). The «Device» field is used to select device to which this unit will be connected. The type of such device will be displayed in «Module» field of dialog box. The «Input Range» field is range of input signal. The «Expansion Channel» field is switch/amplifier of analog signals.

After selecting analog input device or module, set parameters of «From Channel» and «To Channel» channels (list of polled channels), from which information will be sent to analog input unit.

Some AI units are connected to ONF units via Conductor unit. It is AI 1 that receives signal from hydraulic motor.

The «Conductor» is used to establish visible connections between icons of functional blocks of task.

In Fig. 4 «ONF» block. The «ONF» block is designed to implement simplest two-position control algorithm and has input that receives feedback signal from control object and discrete output whose logical state depends on current value at input, setpoint and values of ON and OFF thresholds.

«Delta High» and «Delta Low» field – on/off threshold.

«Delta High» field – controller insensitivity zone when generating output signal that includes control object. The upper control limit is determined by summing exclusion threshold and setpoint value.

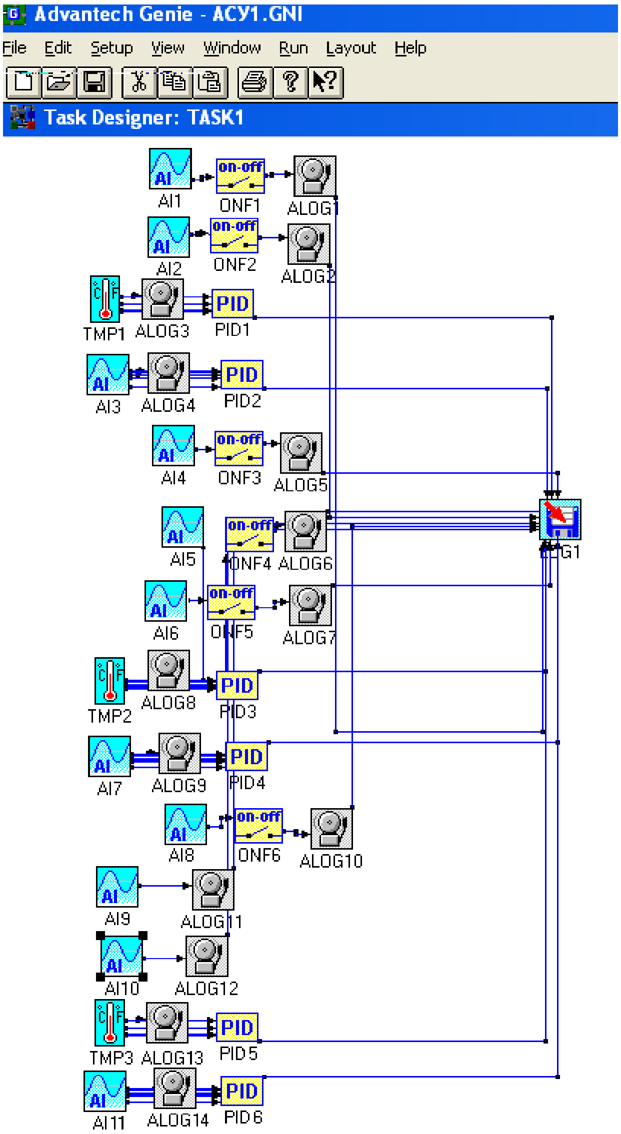

Figure 2 – Developed mnemonic scheme

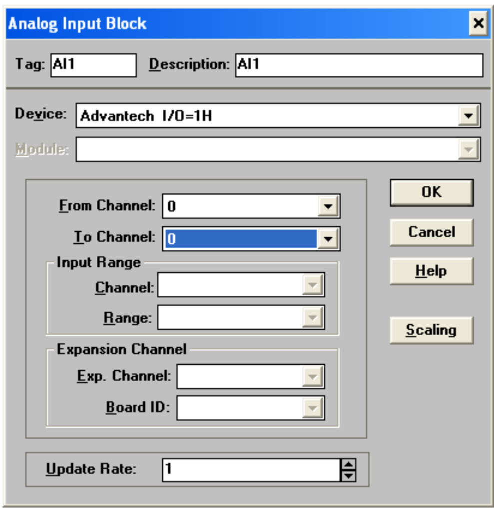

Figure 3 – Block configuration window «Analog Input Block»

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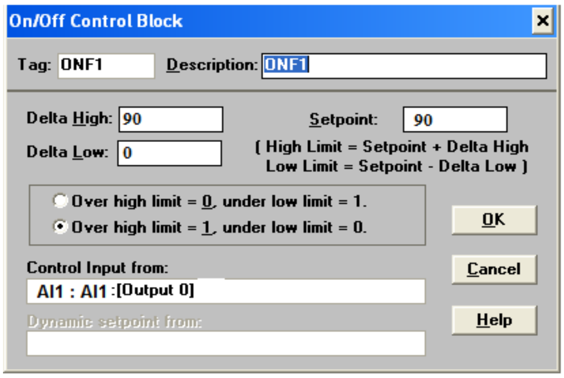

Figure 4 – Block configuration window «On/Off Control Block»

For example, «Engine» element can work in following modes: ON ($0 \to 90^\circ$) and off ($90^\circ \to 0^\circ$), then let rate be 90.

The «Setpoint» field contains value against which feedback signal at input of block is compared. The setpoint can be fixed or dynamically changed by signal from another functional block of strategy.

Field «Control Input from» – control input from output of channel 0.

Selected «Over high limit = 1, under low limit = 0» because if signal value is above upper limit, we assign value of 1 (motor is ON), and if it is below lower limit, 0 (motor is OFF).

Some «ONF» units are connected to «ALOG» (designed to store in archive information about recorded alarm events associated with signal received at input of alarm archive unit. The unit has input and output).

A description of mnemonic scheme elements connection to devices is given in Table 2.

Table 2 – Description of mnemonic elements connection

Element	Description
AI 1	Receives signal from hydraulic motor.
AI 2	Receives signal from LTR series position sensor, which detects position of stop № 1.
TMP 1	Receives signal from CEM DT, which measures temperature in steel ladle.
AI 3	Receives signal from XLEV sensor to measure level of raw materials (metal) in steel ladle.
AI 4	Receives signal from position sensor that controls shut-off valve №1.
AI 5	It receives signal from hydraulic motor, which sends signal to make stopper № 2 move.
AI 6	Receives signal from LTR series position sensor that controls position of locking mechanism №2.
TMP 2	Receives signal from CEM DT sensor, which records temperature in industrial ladle.
AI 7	Receives signal from sensor for measuring level of raw materials (metal) in IL – XLEV sensor.
AI 8	Receives signal from position sensor that controls shut-off valve № 2.
AI 9	It receives signal from sensor that measures vibrations frequency of crystallizer – digital frequency meter.
AI 10	Receives signal from sensor, measures amplitude of crystallizer vibrations – sensor 640B01.
TMP 3	Receives signal from CEM DT sensor that records temperature in crystallizer.
AI 11	Receives signal from sensor for measuring level of raw materials (metal) in crystallizer – XLEV sensor.

Blocks «TMP» 1 – 3 is connected to «ALOG» for temperature measurement.

Fig. 5 shows example of «ALOG» block configuration window.

Field «Alarm Settings» – values of alarm parameters. The values of signals at unit input fall into following ranges:

1 – above upper limit value High-High;
2 – maximum High value;
3 – below lower limit value Low-Low;
4 – minimum value Low.

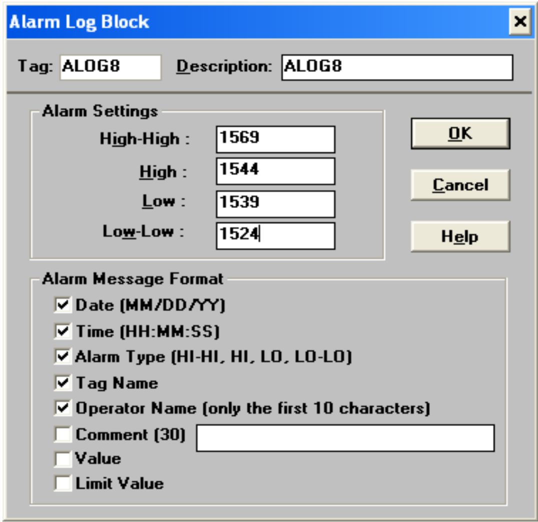

Figure 5 – Block configuration window «Alarm Log Block»

5 RESULTS

Each strategy has its own screen form – interface that is developed in «Forms Editor». The window of developed system interface consists of two displays, which are shown in Fig. 6, a, b.

As result, there are two developed interfaces: Display 1 – main and Display 2 – auxiliary for monitoring parameters of crystallizer: frequency and amplitude of vibrations.

The interface of automated system in Fig. 6 consists of elements:

– «Text string» – display has no means of communication with functional blocks and other elements of strategy display/control and is intended to display static character string on monitor screen, which is determined at stage of strategy development;

– «Display indicator» is single indicator used to display state of logical output associated with it in strategy functional block;

– «Text output field by condition» – for visualization of process in real time, provides ability to receive and transmit information;

– «Incremental regulator» – to control, in this case, temperature levels in steel casting and industrial ladles, crystallizer;

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– «Linear indicator» is used to graphically display value of parameter supplied from connected functional block of strategy;

– «Digital indicator» is used to display parameter value at output of connected functional block of strategy, as well as to display text strings coming from output of user procedure block or block of «Basic script» during strategy execution;

– «Analog regulator», which is used to control levels of raw materials;

– «Command Button (Menu Button)» is intended for creating buttons in window of display form that allow you to control process of strategy execution;

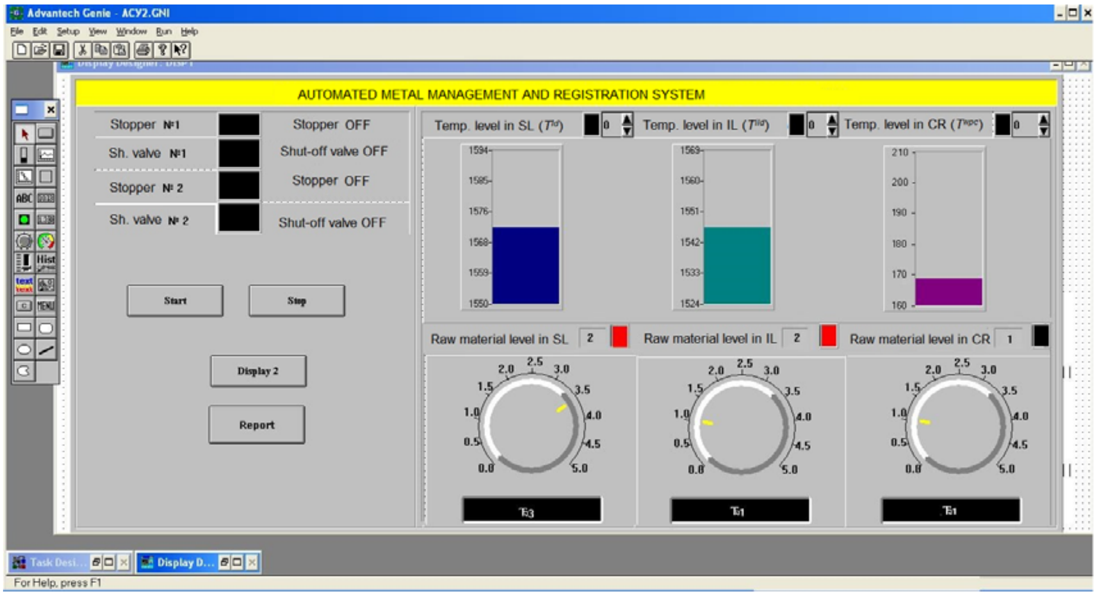
– display element «Arrow indicator» – presentation of information from associated functional block on graphical analog arrow indicator.

Thus, all elements can be classified as display and control elements.

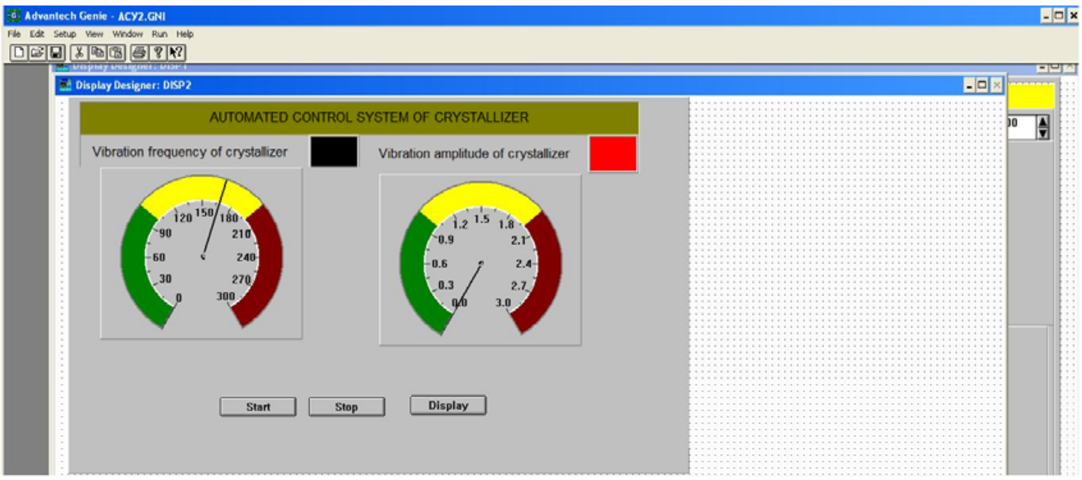
A daily report was created to record level of raw materials. Daily reports are designed to implement daily system summaries.

Fig. 7, a, b shows windows for creating report, namely. Fig. 7, a – selecting date and version of report for printing. Fig. 7, b – process of creating report configuration.

A report with particular identification number can be activated (Enabled) or blocked (Disabled). If report is blocked, it will not be printed during strategy execution.



a



b

Figure 6 – Interface to automated system for managing and registering raw materials:
a) Display 1; b) Display 2

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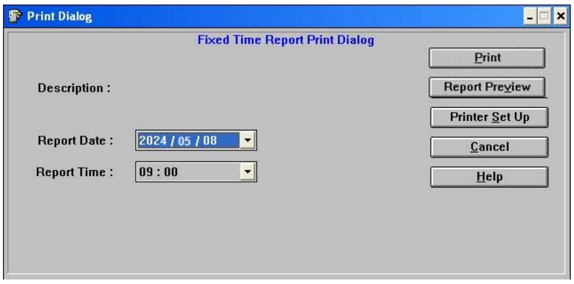
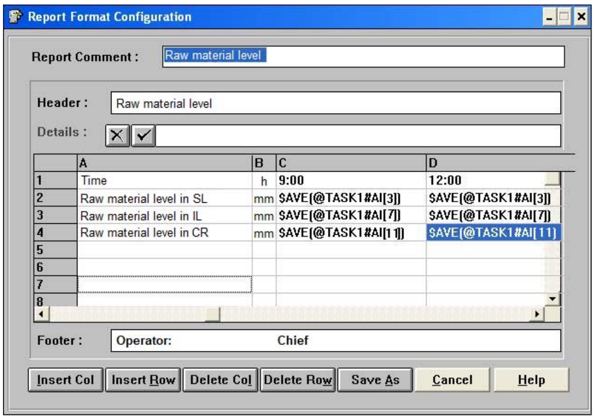


a



b

Figure 7 – Customization windows in process of creating report

The report is printed at time set in editing fields with numbers from 1 to 24 in «Report Time» parameter group.

As result, when formulating context of this work, its main goal was determined – development of automated metal management and registration system to improve quality of metal products. As result of this work, this goal has been achieved because:

– current state of production in field of continuous casting is analyzed;

– features of MP molding stages of are analyzed;

– parametric model of CC that is complex is proposed;

– key parameters of metal product molding are selected and described;

– technical means for controlling casting parameters were selected;

– algorithm for operation of proposed automated system was developed;

– developed mnemonic scheme in «Task Editor»;

– description of mnemonic elements connection to mnemonic elements is given;

– two interfaces have been developed: Display 1 – main and Display 2;

– efficiency and reliability of developed system was compared with existing commercial solutions.

The developed mathematical models and algorithm have been successfully tested on example of continuous metal casting controlling process. However, proposed approach is universal in nature and can be applied to wide class of complex production processes in various industries.

6 DISCUSSION

The developed automated system for controlling and registering metal in continuous casting is represented by complex interface consisting of two displays with elements for displaying and controlling key parameters of casting mould.

A comprehensive visual interface provides clarity and ease of navigation for operator, which is critical when working with automated control systems.

To compare development with similar systems, we selected programs used to control continuous casting machine.

The software for controlling continuous casting machine is in closed access, but there are modules for modeling metal casting.

The Electrical and Automation Systems for Continuous Casting Plants from Ingeteam [16] was chosen for consideration. This system also has its own modular automation solutions:

– MLC – raw material level monitoring;

– MWC – mold width monitoring;

– Gap monitoring – monitoring temperature of mold, predicting gaps;

– TLC – steel level control in metal casting machines;

– weight control in ladle tower, pouring trolley, product;

– measuring temperature and oxygen content in liquid steel;

– optimized billet tracking to marking devices.

Another analog is ABAX TubeStar with sets of modular automation solutions [17]:

– SprayStar Secondary and Cooling Automation provide optimal thermal profile of billet, taking into account variable casting conditions such as speed, steel composition, and overheating;

– MouldStar is module for controlling level of raw materials;

– Process Star for monitoring and collecting process data, billet quality forecasting, melt and billet reports, and equipment life tracking;

– TubeStar for monitoring condition and history of all crystallizer tubes, which is critical parameter of casting process.

Thus, system allows monitoring and displaying all necessary information for each casting mold used.

ABAX MouldStar is available as stand-alone package and can be implemented on any filling machine.

In such systems, user enters input data required to monitor molding process step by step, which can be displayed in reports.

To conduct experiment of automated control system, input data from Table 3 were used to monitor metal level during molding.

We will evaluate efficiency and reliability of developed system in comparison with existing commercial solutions.

The experiment consists of two stages, which will be compared:

1) data entry;

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2) monitoring process of forming slab product.

Therefore, it is necessary to test system's ability to correctly process input data and monitor process of forming slab product.

The main comparison criterion is number of module malfunctions detected within three days.

Fig. 8 shows results in form of diagram.

Table 3 – Input data of experimental study

Characteristics	Filling speed, m/min	Vibration frequency, rpm	Vibration amplitude, mm	Metal level in SL, mm	Metal level in IL, mm
Meaning	1	162	2	2,5	0,7
	2	163	2	2,5	0,8
	3	164	3	2,5	0,8
	4	165	3	2,7	0,9
	5	165	4	2,7	0,9
	6	165	4	2,8	1,0
	7	166	4	2,9	1,0
	8	164	5	3,0	1,2
	9	166	5	3,0	1,3
	10	166	5	3,1	1,4

In Fig. 8: – MouldStar from ABAX, – Electrical and Automation Systems for Continuous Casting Plants from Ingeteam – developed system.

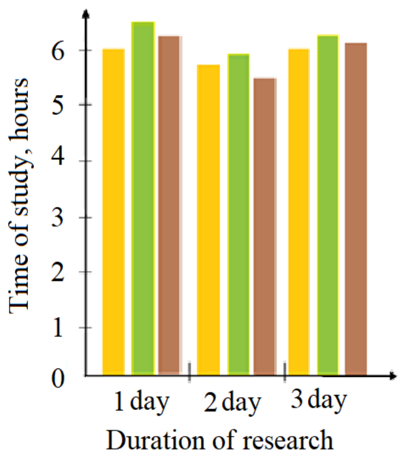

Figure 8 – Diagram comparing average operating time of developed system and analogs

As result, selected systems are stand-alone modules specialized for narrow range and designed for specific type of continuous casting machine. It was found that over three days of operation, these modules demonstrated greater reliability compared to ABAX MouldStar and Ingeteam's Electrical and Automation Systems for Continuous Casting Plants.

The system's ability to work with real data and production conditions was tested.

The developed system allows user to enter data to monitor crystallizer step by step, ensuring high stability of meniscus level, safe operation and easy operation.

The low installation and maintenance costs make this system advantageous choice for controlling continuous casting plant. Experimental results confirm advantages of this development over ABAX's MouldStar and Ingeteam's Electrical and Au-tomation Systems for Continuous Casting Plants in controlled steel casting.

CONCLUSIONS

The urgent problem of developing automated system for controlling and registering metal in continuous casting has been solved.

The scientific novelty of results obtained is that is that for first time, comprehensive parametric model of continuous metal casting process has been developed based on methods of set theory and system analysis. This model is universal tool for formalizing and optimizing processes in various industries. The proposed model integrates not only product molding modes, but also takes into account specific properties of source material and design features of the casting equipment. This model is presented as set of interrelated parameters, with each element reflecting specific aspect of casting process. The parametric model differs from existing ones in its comprehensiveness and integration of various aspects of casting process. It provides basis for developing more accurate and efficient control systems, which can potentially lead to significant improvements in product quality and production efficiency.

The practical value of results obtained is to develop automated control system that implements control of key parameters in continuous casting with ability to collect, process and record data in real time, as well as to implement control of key parameters in continuous casting. The experiments conducted using real production data demonstrate effectiveness of developed algorithm, which is result of formalizing complex production process, demonstrating effectiveness of computer science methods (algorithm theory, system analysis, etc.) for modeling real systems. Based on results of experiment to evaluate efficiency and reliability of developed system, it is possible to recommend proposed system for use in practice.

The results obtained make significant contribution to development of information systems for managing and monitoring complex production processes. They ensure improved product quality and optimization of production processes through introduction of user-friendly system for visualizing and controlling key parameters. The developed system, which includes two informative screens (Display 1 and 2), allows operators to more effectively monitor and control casting process, resulting in reduction in defects and increase in overall production efficiency. These achievements create solid foundation for further technological improvements in steel industry.

Prospects for further research are to investigate new methods of secondary cooling to improve surface quality and internal structure of workpieces. In addition, there is area for improving non-destructive testing methods to detect defects in real time during casting process. The developed automated system creates basis for further im-

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provement of management technologies in steel industry, in particular, for introduction of machine learning and predictive analytics methods to predict product quality and optimize production parameters.

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РОЗРОБКА АВТОМАТИЗОВАНОЇ СИСТЕМИ УПРАВЛІННЯ ТА РЕЄСТРАЦІЇ МЕТАЛУ ПРИ БЕЗПЕРЕРВНОМУ ЛИТТІ

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АНОТАЦІЯ

Актуальність. Сучасні промислові підприємства стикаються з викликами, які вимагають впровадження новітніх технологій для підвищення ефективності та конкурентоспроможності. У металургії одним із ключових етапів є безперервне лиття, де від точності та оперативності управління процесом залежить якість виробів та економічні показники підприємства. Вироби, отримані за технологією безперервного лиття, знаходять широке застосування у різних галузях промисловості завдяки своїм високим механічним властивостям, однорідності структури та економічній ефективності.

Розробка автоматизованої системи управління та реєстрації металу стає не лише актуальною, але й необхідною для забезпечення стабільного та ефективного виробництва.

Проблема підвищення якості виробів з металу завжди була однією з найважливіших завдань металургійної галузі. Недосконалість технологічних процесів, людський фактор, а також збої в роботі обладнання можуть призводити до виникнення дефектів у готових металевих виробах. Це, у свою чергу, впливає на кінцеві характеристики виробів, їх довговічність та надійність.

На сьогоднішній день у наявних джерелах ця проблема ще не знайшла повного вирішення. Тому необхідно здійснити постановку задачі та розробити алгоритм роботи автоматизованої системи управління та реєстрації металу при безперервному литті.

Мета. Метою дослідження є розробка автоматизованої системи управління та реєстрації металу для підвищення якості металевих виробів.

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Метод. Для щоб досягти поставленої мети, була запропонована комплексна параметрична модель, яка формалізована на базі теорії множин. Модель враховує ключові параметри процесу безперервного лиття: матеріал, конструкційні особливості кристалізатору, режими розливання, рівень металу в кристалізаторі та положення стопора промковшу.

Результати. Здійснена постановка задачі та визначені ключові параметри, які враховані в алгоритмі роботи системи, а це дало можливість розробити систему управління установкою безперервного лиття для вирішення задачі підвищення якості отриманої заготовки.

Висновки. Для підвищення якості отриманих виробів з металу та стабільності процесу лиття створено параметричну модель, яка є комплексною, дозволяє оптимізувати ключові параметри та забезпечує точність керування процесом за рахунок того, що інтегрує не лише режими формування виробів, але й враховує специфічні властивості вихідного матеріалу (хімічний склад марки матеріалу і т.п.) та конструктивні особливості установки для лиття. Розроблено алгоритм роботи автоматизованої системи управління, який враховує взаємозв'язки між визначеними ключовими параметрами та забезпечує оптимальне керування процесом лиття. На базі запропонованої параметричної моделі та алгоритму створено автоматизовану систему управління та реєстрації металу. Фокус роботи направлений на якість та ефективність управління та реєстрації металу при безперервному литті, що базується на сучасних методах інформатики та обчислювальної техніки. Проведено комплексне експериментальне порівняння розробленої системи з комерційними аналогами в умовах реального виробництва, що дозволило об'єктивно оцінити її ефективність та надійність.

КЛЮЧОВІ СЛОВА: автоматизація, система, параметрична модель, управляння, реєстрація, метал.

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