Chemical Technology, Control and Management

Manuscript 1506

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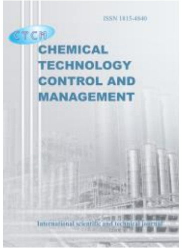
ISSN 1815-4840, E-ISSN 2181-1105
Himičeskaâ tehnologiâ. Kontrol' i upravlenie
**CHEMICAL TECHNOLOGY. CONTROL AND MANAGEMENT**
**2023, №5 (113) pp.63-75.**
International scientific and technical journal
*journal homepage:* https://ijctcm.researchcommons.org/journal/




**Article history:** Received 07 September 2023; Received in revised form 30 October 2023; Accepted 31 October 2023; Available online 07 December 2023

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# TRENDS IN THE DEVELOPMENT AND IMPROVEMENT OF GLASS FURNACES AND MONITORING AND CONTROL SYSTEMS

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***Abstract:*** *The theory and practice of establishing industrial automation systems for glass furnaces and installations as they are right now are taken into consideration. Comparative analysis is based on publications over the last 20 years in the field being studied. On the basis of an analysis of the review materials, generalizations are made that form the basis for proposals aimed at modernizing and improving the technology and instrumentation of fuel combustion processes in gas-burning furnaces and installations, as well as monitoring and control systems for technological processes occurring in glass furnaces and installations.*

***Keywords:*** *glass melting furnaces and installations, monitoring and control system, fuel combustion process, mathematical modeling and optimization of complex heat and mass transfer processes.*

***Annotatsiya:*** *Shisha eritish pechlari va qurilmalarining sanoat avtomatlashtirish tizimlarini amalga oshirish nazariyasi va amaliyotining zamonaviy holati ko'rib chiqilgan. Qiyosiy tahlil o'rganilayotgan soha bo'yicha so'ngi 20 yil davomida chop etilgan nashrlarga asoslangan. Analitik sharh materiallarini umumlashtirish asosida gaz yoquvchi pechlar va qurilmalarda yoqilg'i yoqish jarayonlarining texnologiyasi va qurilmalarini shakllantirilishining, shuningdek, shisha eritish pechlari va qurilmalarida kechadigan texnologik jarayonlarni nazorat qilish va boshqarish tizimlarini modernizatsiyalash va takomillashtirishga qaratilgan takliflar shakllantirilgan.*

***Tayanch so'zlar:*** *shisha eritish pechlari va qurilmalari, nazorat qilish va boshqarish tizimi, yoqilg'ining yonish jarayoni, murakkab issiqlik va massa almashinish jarayonlarini matematik modellashtirish va optimallashtirish.*

***Аннотация:*** *Рассмотрено современное состояние теории и практики реализации систем индустриальной автоматизации стекловаренных печей и установок. Сравнительный анализ опирается на публикации в рассматриваемой предметной области за последние два десятилетия. На основе обобщения материалов аналитического обзора сформулированы предложения, направленные на модернизацию и совершенствование технологии и аппаратурного оформления процессов сжигания топлива в газосжигающих печах и установках, а также систем контроля и управления технологическими процессами, протекающими в стекловаренных печах и установках.*

***Ключевые слова:*** *Стекловаренные печи и установки, система контроля и управления, процесс горения топлива, математическое моделирование и оптимизация сложных тепло- и массообменных процессов.*

## Introduction

The glass industry, one of the sectors with the fastest growth, creates a wide range of goods, including insulating fiberglass, different lighting chandeliers and lamps, windows and glass for cars and buildings, video screens, kitchen appliances, spotlights, jupiters, lamps and among others. [1-8].

The evolution of culture and social life in human society is directly correlated with the manufacturing of glass. The technology for preparing raw materials, manufacturing, and primary processing of glass melting products, drying, and firing, followed by the final formation of completed goods, serve as a gauge of this industry's level of development. The importance of glass products in people's life throughout history and into the present day predicts the high level of interest in advancing technology, hardware design, and the adoption of industrial automation systems.

The level of development of technical, algorithmic, mathematical and information systems for automated control of technological processes in the glass industry existing in the world indicates insufficient use of the rich opportunities for implementing high-performance control systems for complex technological processes, which would take into account all the main and measurable technological parameters in real time.

In this regard, the improvement of methods and algorithms for controlling fuel combustion processes in glass melting furnaces, as well as the application of promising principles for constructing intelligent control systems for the fuel combustion process in glass melting furnaces, taking into account the complexity of taking into account disturbances, incompleteness and uncertainty of initial information about the progress of technological processes of burning the fuel under study, Improving the safety and technical and economic performance of glass furnaces is a pressing and important issue today [9-13].

For glass melting furnaces, lowering fuel consumption through the application of tried-and-true automatic monitoring and control techniques is a critical concern. A crucial aspect in boosting the competitiveness of an industrial firm and the welfare of the populace, from a contemporary perspective, is the quest for innovative techniques, methods, and tools that lead to the efficient and ecologically friendly use of energy, raw materials, and the human factor.

One of the expensive and most challenging technological procedures in the glass industry is fuel combustion. For this reason, it is crucial for science and practice to increase non-stationary conjugate heat exchange between the hot environment of the combustion chambers of heating units and the glass product.

In order to find logical solutions for the design of furnace units and the organization of thermal technological regimes in them, it is possible to more thoroughly study non-stationary heat, mass transfer, and hydrodynamic processes using mathematical and computer modelling, which are well-established scientific and applied methods and tools.

**Analysis of the current state of the theory and practice of fuel combustion in glass furnaces**

Glass production procedures are intricate, time-consuming, and energy-intensive [14]. This is especially true for big furnaces with multi-channel burners, which produce glass with a high energy intensity [15].

A block diagram of the production sequence of operations in the glass industry is shown in Fig. 1. Glass production consists of six stages: preparation of raw materials (1.1), its melting (1.2) and transformation of molten glass into a specific form on specialized machines (1.3), firing of the resulting product (1.4), product quality control (1.5) and packaging of the finished quality product (1.6).

It is essential to apply new innovative control methods to these processes to further reduce energy consumption.

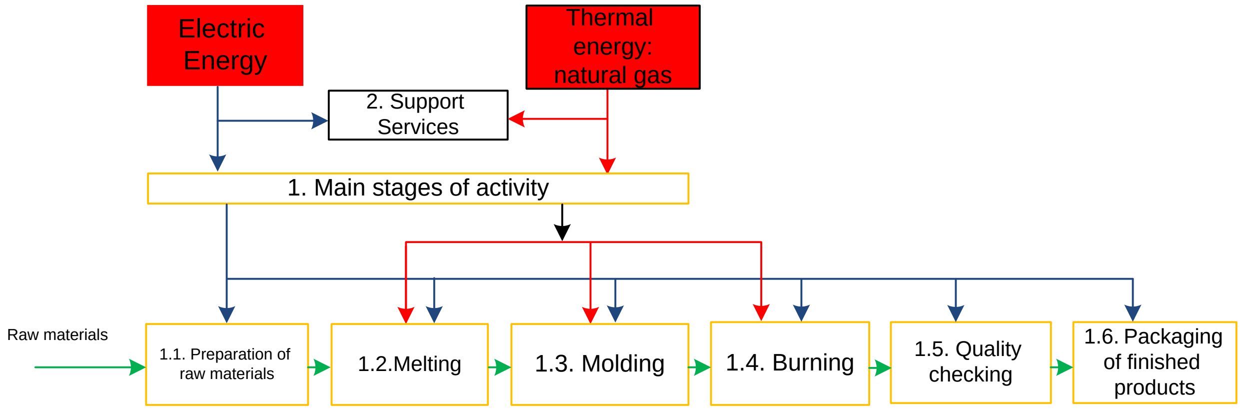


*Fig. 1.* ***Block diagram of the glass production process*****.**

The effectiveness of managing fuel combustion in glass furnaces, which is determined by the automatic maintenance of a reasonable balance between energy resources and the supply of consumed raw materials, controlled by the average shift productivity of a technological complex or device, and ensuring the required quality of the finished product, has a significant impact on the technical and economic production indicators worldwide [16]. The management of energy- and resource-intensive technological techniques of burning fuel in gas-burning furnaces with minimal resource and energy costs while assuring high quality of the completed product is one such pressing need for production automation [17].

A typical glass furnace operating system should have two main subsystems: learning based on fuzzy rules and multi-objective optimization based, for instance, on genetic algorithms. In order to enhance the appropriate algorithms and create an error detection system that ensures the optimization of the product life cycle, these algorithms are used in glass melting furnaces, a schematic diagram of which is shown in Fig. 2.

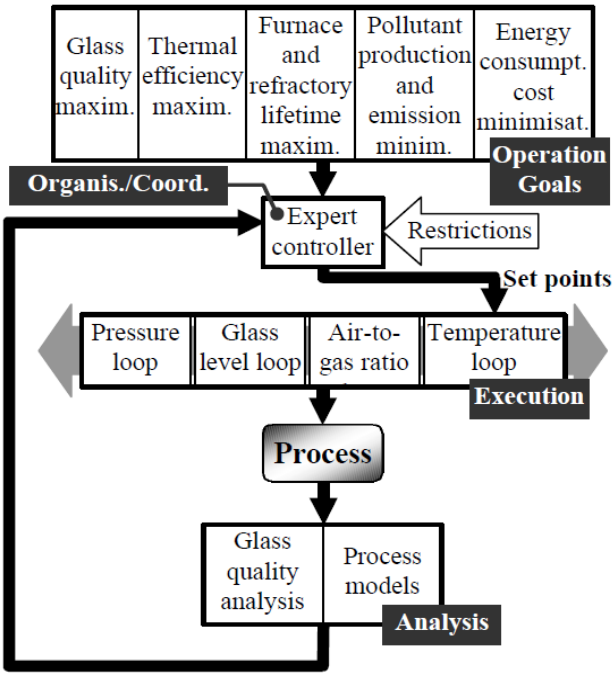


*Fig. 2.* ***Hierarchical architecture of a glass furnace operating system.***

Modern gas chamber furnaces manage the temperature at reference locations (using thermocouples), which sends a signal to the controller of the automatic control system (ACS), to assure the temperature regime of fuel combustion. In order to alter the fuel consumption (for gas furnaces) or the electricity consumption (for electric furnaces), the measured temperature is compared to the preset value.

Gas furnace fuel usage rises during the product's heating phase, then falls or stays the same until the end of the temperature holding phase. A particular temperature is reached before air is introduced (through the combustion unit) to cool the firebox.

The processes of heat transfer from hot gases to the furnace grate and brickwork by radiation and convection, as well as radiation heat exchange across surfaces at various temperatures, all take place in chamber furnaces. Tri- and polyatomic gases absorb and reflect heat rays from fuel combustion, and the reflected rays then fall on a non-fluid medium. A non-flowing media, on the other hand, reflects some of the radiant energy that strikes it back into the fluid medium while absorbing some of it. A variation of the so-called conjugate heat transfer is what happens when these processes are combined.

The few scientific papers [18–19] on gas combustion plants that have been published over the past two decades mostly focus on ensuring the potential of energy efficiency and enhancing product quality. Research and development are focused on enhancing the materials utilised, technological features of the furnace design, techniques and means of monitoring control, diagnosis measurement, and control of the fuel combustion process, according to a review of patent and scientific literature.

The best technologies currently available for the manufacture of glass products were analysed in the studies [18–20] under review. Additionally, methods for maximising heat transfer processes in low, medium-, and high-temperature units were identified. The combination of numerical simulation and real measurements leads to improved energy efficiency of furnaces. The publications reviewed focus on methods for reducing $CO_2$, $NO_x$ and $SO_2$ emissions. The issues of optimizing the topology, modes and boundary conditions of the operation of a combustion furnace are studied, and new rack designs in a chamber furnace are discussed in order to increase the efficiency of the process under study.

The majority of the most well-known [20–21] mathematical models of technological procedures and units for gaseous fuel combustion have been created recently. Based on these, numerical modelling was done, some modes' parameters were examined, their efficacy was determined, and suggestions for improvement were made. Transport processes were studied using the CFD code Fluent and ANSYS CFX, with the help of which it became possible comprehensively more fully and simulate the processes occurring.

Regarding works on this topic [16–22], they only take into account particulars of this process and the accompanying solution to a particular engineering problem. This does not address modelling heat transfer in individual furnace elements. A tiny number of publications, some of which are articles covering particular elements of a heating system as a whole, are dedicated to the study of non-stationary conjugate heat transfer. Numerical research on turbulent diffusion fires examines how radiative heat transport affects the absorption coefficient. The wall thermal load related to conjugate heat transport was anticipated using CFD code simulations.

The literature study also includes articles [11–24] on diffusion, high-temperature combustion, and modelling of turbulence and combustion processes in industrial thermal installations. The large number of published publications demonstrates the value placed on understanding the combustion process, especially diffusion and high-temperature combustion. The use of numerical methods for simulating combustion in laboratory conditions and in a real combustion chamber made it possible to analyze reactive and non-reacting turbulent vortex flows. The development of combustion technology and especially modern vortex burners is assessed, and the influence of the vortex intensity of a turbulent flame during diffusion combustion with the formation of soot is studied. Modern turbulence models used in CFD are presented (mainly using the standard k-ε model), along with a description of a new three-stage methane-air reaction mechanism, and an SST (Menter) turbulence model is developed to clarify the peripheral interactions between the media involved.

Publications [23-25], related to the improvement of the combustion process in the combustion chambers of furnaces, are aimed at increasing the efficiency of combustion systems through the use of swirling vortex flows, as well as reducing fuel consumption.

A significant part of published articles [21-29] are devoted to the issues of programming environments, CFX, CFD, verification and validation in CFD. A number of studies in the field of industrial heating engineering have been published in this direction using modern computer environments (codes) Fluent, Ansys CFX, FDS, Flotran and others. Due to the quick advancement of these software programmes and the rise in processing capacity of common computers, it is now possible to apply 3D modelling of objects and processes. The CFD verification and validation processes are described in general. [25] The investigation of the major numerical errors made during computations, when examining the environment, and when validating the data acquired are all recommended methods to be used in the study and change of these operations while developing commercial software.

The findings of a study on the energy usage and effectiveness of melting furnaces in the glass industries of many nations are presented in paper [26]. About 150 furnaces' individual energy requirements were calculated, and the results were corrected for direct energy efficiency comparison. The technological advancements and furnace designs that use the least amount of energy have been recognized. However, only data on the smelting furnace's energy consumption was compared in this study without accounting for fuel or electricity. Tableware and other industries' data were also gathered however the findings are not included in this work.

Significant development was observed in the mathematical modelling of flow and heat transfer phenomena in glass furnaces between 1996 and 2002. The paper [27] describes developments in the fundamental scientific and practical aspects of modeling, including model formulation and modeling techniques, modeling glass quality and post-processing environmental emissions, and measuring the thermodynamic and transport properties of a modeling solution, integrating model-based knowledge.

The problems of mathematical modelling of the melting of raw materials in glass furnaces are addressed by Petr Schill and Miroslav Trochta [28]. The three-dimensional model of periodic melting, which includes the swelling of shale during melting, the release of gases, and the evaporation of water, is described in this paper.

An open method for modeling heat exchange processes in regenerators is described in [29]. The construction model's dependability was initially assessed by contrasting it with experimental and/or analytical data gathered using Euclidean geometry techniques. At the second step, the findings of a thorough investigation of the object were presented with a sizable experimental setup that faithfully mimics the behaviour of a regenerator in an industrial glass furnace.

Qingyu Yang, Xianghua Uao, Ren Shi [30] proposed a DCS (Distributed Control System) complex for large glass melting furnaces [30]. They presented a method for designing the structure of a system and its reliability. In addition, OPC (OLE for Process Control) technology has been introduced for DCS (Distributed Control System) and MIS (Management Information System). DCS (Distributed Control System) management is aimed at comprehensive control of product management and quality.

At the furnace exit, both recorded and unmeasured temperature data were modelled in [31]. The flue gas temperature in the furnace was primarily used to develop the model. If the mathematical model of this work incorporated the remaining melted furnace characteristics, the physicochemical changes occurring in the furnace would be more accurately depicted.

Laurent Pilon and etc. [32] analyzed the loading speed of the charge, the melting temperature, the depth of loading the charge into the liquid, heat losses on the furnace wall, the thickness of the glass melt and gas bubbles under the molten glass in glass melting furnaces, and found that as a result of the study, heat losses in the furnace have a significant influence on the flow of glass melt.

The work [33] describes the structure of fuzzy logic controllers for a glass melting furnace and presents a new type of fuzzy PID control system, provides the characteristics of a fuzzy PID control system in comparison with a conventional PID control system, and also reflects the use of a fuzzy PID control system for temperature control in a glass melting furnace. It is shown that the furnace temperature Ts is regulated by a PID controller, as part of the structure of the intelligent control system shown in Fig. 3.

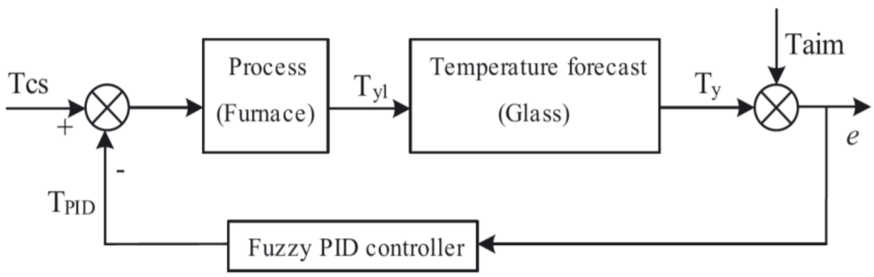


*Fig. 3.* ***Intelligent glass furnace control system.***

The work of Vishal Sardeshpandeva and etc. [34] presents a model-based approach for benchmarking energy-intensive industrial processes in glass furnaces. A simulation model of the facility was developed using empirical equations based on mass and energy balance, heat loss equations for different zones of the furnace. Experimental results from commercial glass furnaces support the hypothesis. You can determine a furnace of this type's energy characteristics using the simulation model.

The growth of the glass sector is dependent on the creation of new melting technologies and the automatic management of those technologies in order to conserve energy and safeguard the environment. For melting glass raw materials in flight, in-flight melting technology has been developed, and numerous studies have been done on how different heating sources affect the melting behavior of particles [35]. According to the findings, samples that have been exposed to plasma exhibit the fastest rates of boiling, molten glass flow, and disintegration. The glass's flow response is significantly influenced by its viscosity.

Simulation is widely used in the glass industry and is described in detail in "Modeling and Control of a Combined Heat and Power System" [36]. The furnace temperature needs to be maintained and controlled in order to manufacture high-quality glass. Therefore, the usage of mixed control systems is given a lot of thought. It is desirable to utilize the extra heat produced indirectly while melting the glass because hot smoke emissions have a detrimental impact on the quality of the glass melt. As a result, it is suggested in this study to use a rotary regenerator to transmit waste heat from a gas turbine to the inlet air of a furnace for melting glass. The gas turbine exhaust gases are delivered from the turbogenerator, which is running at full power, to a revolving regenerator, where they are heated and then transferred to the air entering the glass furnace. A PID controller is suggested in this paper.

As was already discussed, there are a lot of factors to take into account if you want to get a more fusing glass. When glass is melting, data on the energy consumed is given to a device that compares the actual value with the desired one. If there is a discrepancy, an error is handled, and the real value is adjusted to the desired one. The control equation determines how the equipment reacts to an error signal. The proportional-integral-derivative (PID) algorithm is the most commonly used controller. The general equation for a PID controller is as follows:

$$G_C = \frac{K_D s^2 + K_P s + K_I}{s} \quad (1)$$

Here: $K_D$ – differential part, $K_P$ – proportional part, $K_I$ – integral part. The process response curve is the information used to tune the PID controller. The phase characteristic of the furnace is used to determine the settings of the PID controller. Table 1 shows the PID controller settings obtained using the process response curve method. Figure 4 shows a melting furnace with a PID controller.

Table 1

**Adjusted PID settings**

| Algorithm type | $K_D$ | $K_P$ | $K_I$ |
|---|---|---|---|
| PID | 0.066 | 0.001 | 0.046 |

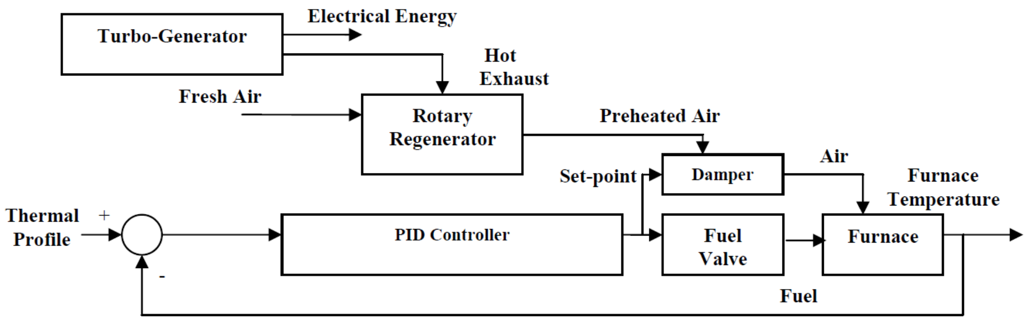


*Fig. 4.* ***Management system structure.***

The use of fuzzy PID controllers instead of the classical PID controller [33] allows us to reduce the time for evaluating parameter settings and ensure the quality of process control.

It is currently possible to use a unified approach to obtain dynamic models of furnaces as automatic control objects by using equivalent circuits for connecting regulated circuits [38] to obtain a structural model of a glass melting furnace. This method is based on systematic interpretation and comparison of processes occurring in the system with dynamic equivalent circuits of similar components.

The development of a transition model [39] that takes into account the operational stages of the melting, refining, cooling, and glass production process is still useful today for designing furnaces with energy efficiency and good performance characteristics. Using such a model, a thorough investigation of the energy balance revealed that over 70% of the energy supplied during the daily cycle is discharged as flue gases.

Since the purifying process uses the most energy, it is this step that determines the overall energy demand. The estimated energy efficiency varies between 13% and 16%. The side-flame combustion configuration ensures the same heat transfer characteristics to the glass as the conventional configuration while allowing the gas velocity and temperature to be reduced close to the glass being melted and the furnace walls. This is demonstrated by steady-state simulations of the combustor and glass vessel.

Eric Meisenberg [40] demonstrated the benefits of using FlammaTec burners in a glass melting furnace and proved that improved control of flame shape and reduction of excess oxygen in the furnace lead to improved energy efficiency.

This is mostly caused by the decreased wall surface and improved torch coverage of the glass. The refractory wall must not, however, be permitted to become too hot. The problem of mathematical modelling of the study item was not addressed in the work [41].

The work [42] considers the issues of intellectual studies in monitoring systems for diagnostics, control and control of a glass melting furnace based on the use of neural networks of counter-propagation of errors, capable of performing online measurements of specific gravity based on the air pressure at the furnace inlet, the differential pressure of the gas mixture and the pressure drop of the gas-air mixtures. Integrating these three functions as input to neural networks allows for the creation of excellent online specific gravity estimation resources. It is shown that with online measurements of specific gravity during control and management, an average error of a minimum error of 0,08% and a maximum error of 4,43% was achieved. The development of an intelligent system ensures specific gravity is predicted before it exceeds specified limits. Corrective actions can be taken early before the process gets out of control. The diagnostic actions enabled by this intelligent system can prevent unwanted catastrophic shutdowns of glass production furnaces.

The capabilities of standard genetic algorithms (SGA) for optimizing discrete parameters of the PID controller of a multi-parameter glass melting furnace are presented [43]. Control-oriented models of each multivariable furnace are used to optimize discrete controls based on glass temperature and excess oxygen content, as well as individually adjustable SGA thresholds.

The development of production technology based on granular glass ceramics, thermal insulation material and cullet modified with slightly soluble and inorganic additives is given in [44]. The effect of the fundamental physical characteristics of the slag components on the hole formation process, the identification of the critical variables impacting the stability of the glass melt foaming process, and the creation of an automatic slag fire control system are all given special consideration.

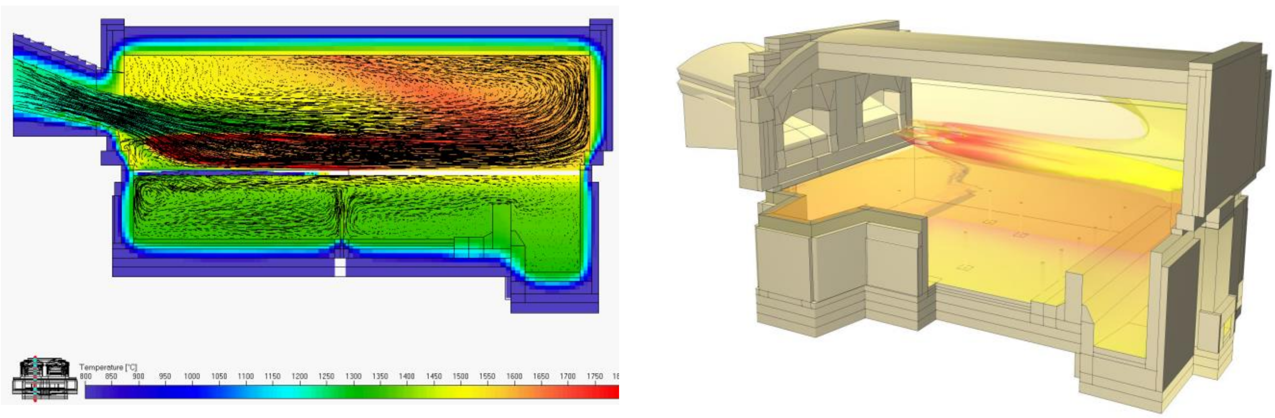


*Fig. 5.* ***Temperature in glass furnace.***

In his research, Eric Meisenberg [45] put up a strategy for creating and managing an intelligent system to raise the general effectiveness of a glass melting furnace. Additionally, he suggested approaches for maximizing output power while the research object was in use and examined the effect of burner and barrier placement on energy efficiency. The best placement of barriers inside the furnace enhances melting quality and prevents incomplete melting of molding machines, according to his analysis.

Monitoring the process in the furnace (Fig. 5.) using modern sensors and analysis of automatic control, and studying the quality of the final product covers in detail in [45]. The work [46] presents the implementation of a system for automatically calculating the corresponding descriptors of the glass melting process from an image of the glass surface using modern technical vision cameras (Fig. 6). The aim of the system is the automatic analysis of process status in real time and provision of batch information. The created system was developed in Matlab and implemented keeping in mind industrial requirements.

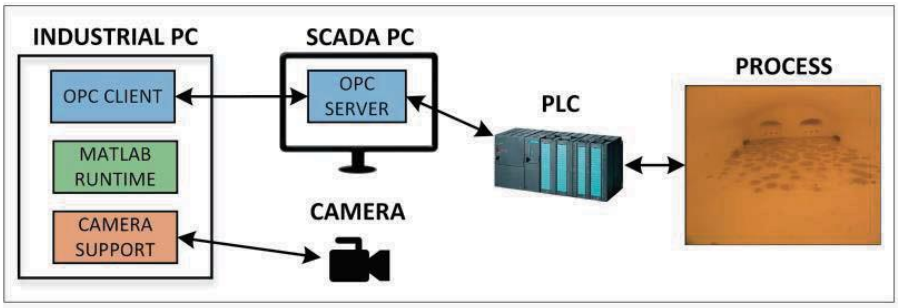


*Fig. 6.* ***Diagram of a glass production control system with a technical vision module.***

More recently, Eric Muissenberg and Robert Boddy [47] proposed adding a proprietary software package to the Model Predictive Control (MPC) toolkit for monitoring batch coating in a melting furnace. Imaging is linked to melt control to improve furnace stability and glass quality, and the developed expert system (ES) uses high-resolution cameras with near-infrared capabilities for automatic batch analysis and intelligent software to interpret glass coatings. For a deeper level of control to enhance furnace stability and glass quality, batch coating is modelled along with other process variables with various inputs and outputs.

Glass furnace heat analysis reveals its impact on the trajectory of development. Generalized equations for the furnace's heat balance at the edges of the glass channels were put out in [48]. Studying the impact of specific heat consumption of melting 1 kg of glass while accounting for the generalized heat balance's proportion of consumable materials. Calculation of the flow direction in a glass melting furnace under various conditions of energy distribution in the melting space [49] serves to improve energy efficiency. The aim is achieving higher melting rates and reducing heat loss. From the simulation results, it follows that the melting rate increases and heat loss decreases. It has been determined that infrared radiation coatings have a high spectral emission of infrared radiation at high temperatures, which can be employed in glass melting furnaces to efficiently reduce the energy required to melt glass and maintain the necessary temperature. The surface of the molten glass inside the furnace and the outer surface of the top and side walls of the furnace have a significant effect on enhancing radiation heat transfer and increasing the thermal efficiency of the furnace.

The work [50] describes in detail what the concept of "Industry 4.0" means for the glass industry, in particular, it shows how to solve complex problems of the melting process. The possibility of using advanced control concepts, cyber-physical systems, the Internet and cloud control systems is shown. In particular, Glass Service System 4.0 proposed a system control method known as Model Predictive Control (MPC). This requires new tools (such as using existing cameras and other smart sensors to detect what is happening in the smelter) [51].

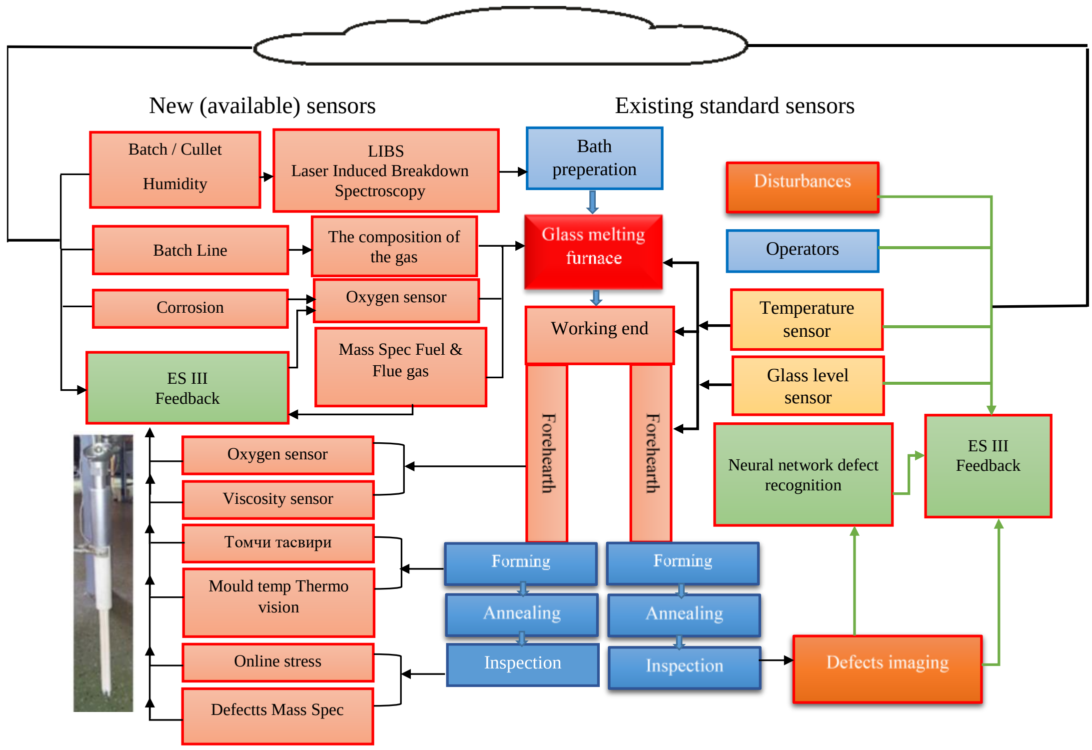


*Fig. 7.* ***Modern, new and existing sensors.***

The «Industry 4.0» concept includes many sensors, as shown in Figure 7, such as the moisture content of the glass that is fed into the glass melting furnace; monitoring and control of the calorific value of natural gas, oxygen number, CO, NO2 and SO2 sensors, glass color and quality control sensors. Computers have the computing capability necessary to comprehensively analyze all the input data, and all of these sensors simultaneously collects and analyze complicated data.

«Industry 4.0» [52] is the next level of control and management of glass production, implying the creation of an optimal strategy for responding to demand and power quality using a hybrid method based on integrated control using a simple algorithm characterized by high computing power, which ensures successful results of thermal stability in glass melting furnaces [53]. If electrodes are installed in a glass melting furnace with a capacity of 500–600 tons per day, the combustion zone and the glass vessel are integrated in big furnaces, and three-dimensional models are produced [54]. These organized models help to speed up melting and increase the lifespan of the glass melting furnace.

Glass makers may more precisely predict the extent of refractory coating, repair and design life based on actual wear rates by using a thorough laser mapping setup across the whole furnace wall including wall thickness and contour data [55].

Optimization of highly efficient thermal insulation structures of refractory furnaces is based on a computational experiment and the application of a phenomenological heuristic evolutionary approach [56-57] using the optimal variant of the thermal balance of a furnace operating with glass. This optimization method allows you to extend the service life of the furnace side walls with minimal heat loss to the environment.

The RC-SLW mathematical model has been reliably used to accurately calculate radiative transfer in engineering applications [58–59]. For integrated heat transfer calculations, a table of model parameters (weights and related absorption coefficients) is required to maintain the model's price affordable. Analysis of the temperature fields of the glass mass in various areas of the furnace and its walls is made feasible by the simulation findings [60]. By maintaining the temperature regime at designated areas in the furnace, it is possible to produce glass melt that complies with the provided technological regulations.

Fig. 8 shows the level of automation in the glass industry today.

**Conclusion**

The presentation chart reflects the state and level of automation in the glass industry today.

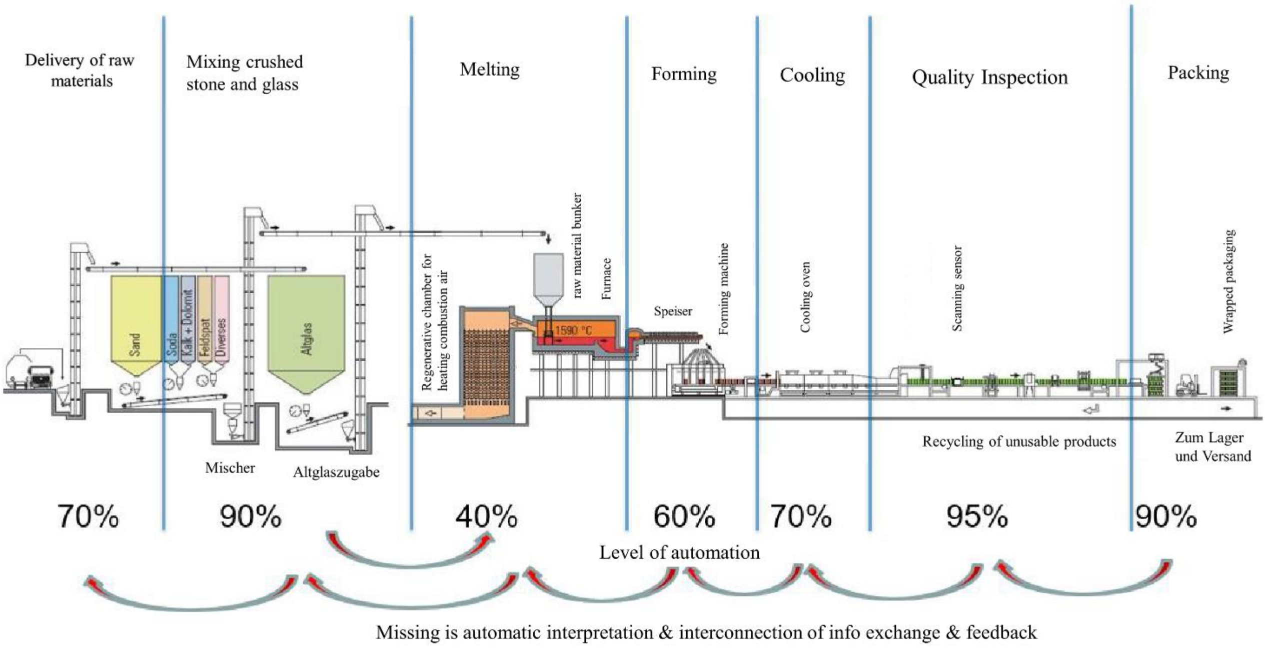


*Fig.8. **Degree of automation in the glass industry.***

The results of the analysis of publications and scientific developments contained in the Scopus database and relating to the period 2014-2022 on scientific works of scientists from the USA, Germany, Italy, China, Russia, Uzbekistan and other countries are shown in Fig. 9.

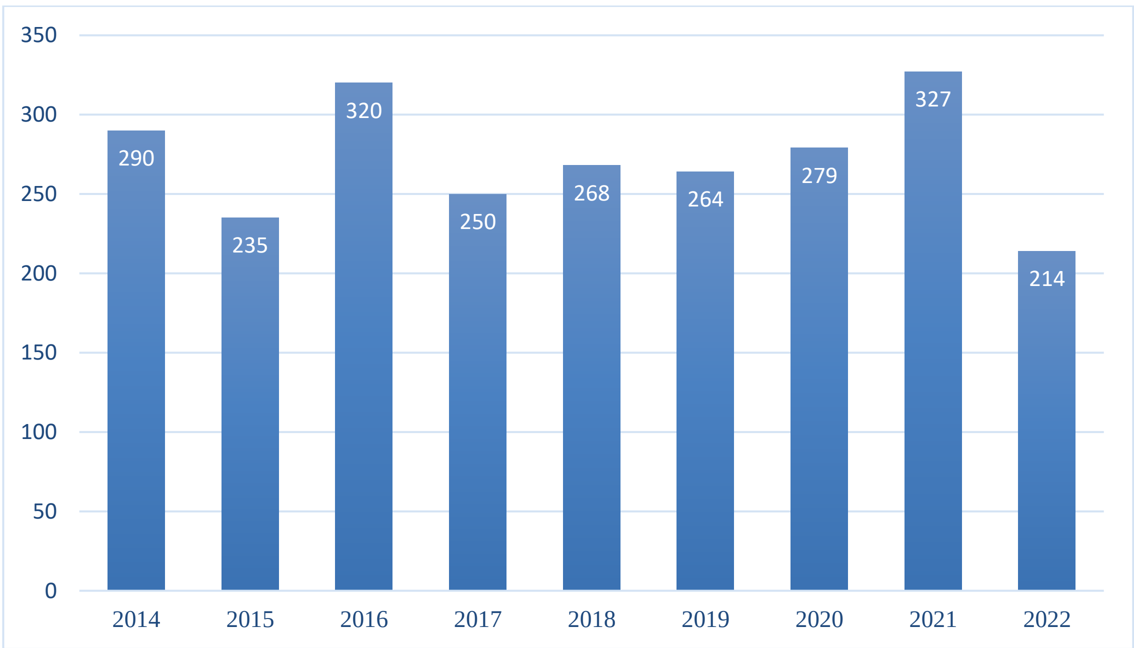


*Fig.9. **Diagram of scientific developments related to the glass industry recorded in the Scopus database between 2014 and 2022.***

The results of studying scientific research works on the glass industry in the Web of Science database are reflected in Fig.10.

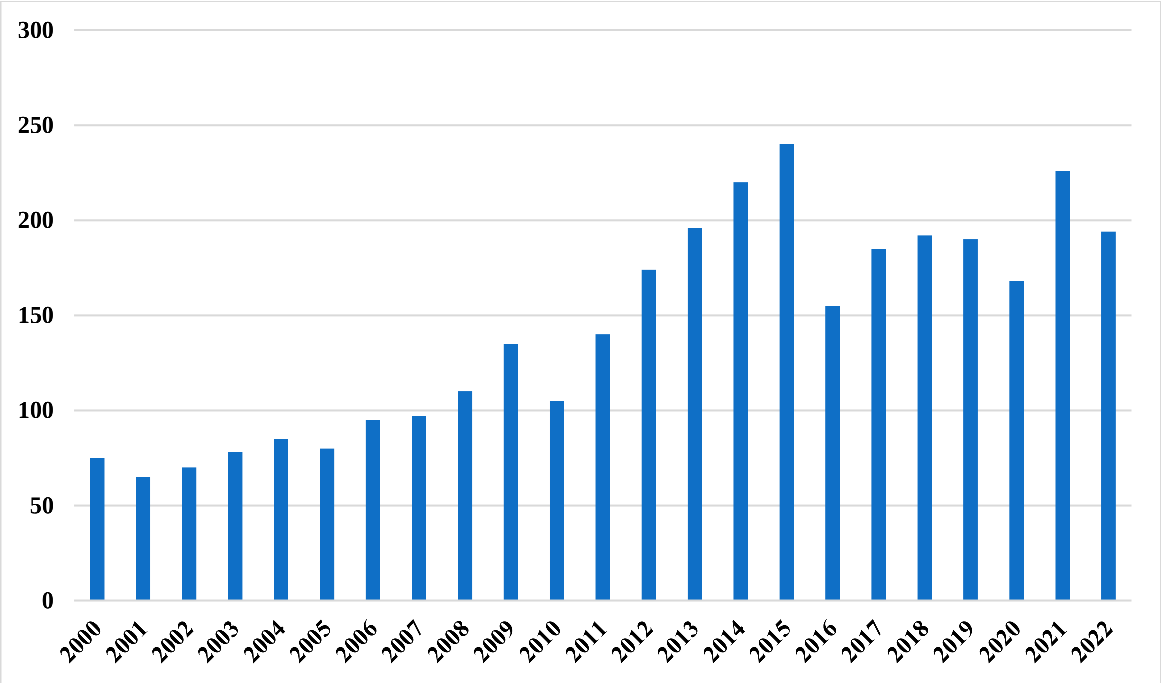


*Fig. 10.* ***Scientific developments related to the glass industry in the Web of Science database for the period 2000-2022.***

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