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A METHOD FOR MONITORING GLASS MELT SURFACE IN A GLASS FURNACE

Keywords: glass industry, glass smelting process, vision monitoring

Abstract: This article describes a method for vision monitoring of the glass surface inside a glass furnace with its main advantages and limitations. It presents the structure of a vision monitoring system developed by the authors with a dedicated vision head and the operator's stand. The elements of this monitoring system have been installed in a glass factory. The experimental research which has been conducted confirmed the proper functioning of the system. The registered images of the furnace interior are a foundation for further work on the development of a programme module for automated image analysis and selected parameter measurements of the process. The authors of the article have reviewed publications on the processing and analysis of glass furnace images. This monitoring system constitutes a very important source of information on the condition of the glass melt surface inside the furnace as a support for the operators in charge of the glass melting process.

Metoda monitorowania lustra szkła w piecu szklarskim

Słowa kluczowe: przemysł szklarski, proces wytopu szkła, lustro szkła, monitoring wizyjny

Streszczenie: W artykule zaprezentowano koncepcję wizyjnej metody monitorowania lustra szkła w piecu. Przedstawiono podstawowe możliwości i ograniczenia metody. Zaprezentowano strukturę wizyjnego systemu monitorowania z opracowaną przez autorów dedykowaną głowicą wizyjną i stanowiskiem operatora. Elementy systemu monitorowania zostały zainstalowane w hucie szkła. Przeprowadzone badania eksperymentalne potwierdziły poprawność działania systemu. Zarejestrowane obrazy wnętrza pieca są podstawą do planowanych dalszych prac związanych z opracowaniem modułu oprogramowania do automatycznej analizy obrazów i pomiaru wybranych parametrów procesu. Autorzy artykułu dokonali przeglądu literatury odnośnie do metod przetwarzania i analizy obrazów dla pieców szklarskich. Opracowywany system monitorowania stanowi bardzo istotne źródło informacji o stanie lustra szkła wewnątrz pieca, wspomagając operatorów kontrolujących proces wytopu szkła.

Introduction

The increase in demand for utility glass products and progress in manufacturing have contributed to the automation of the manufacture in the glass works, which, in turn, has influenced the introduction of large output, continuous operation furnaces [1, 2, 3, 4]. In automated manufacture plants, the daily requirement for raw glass material can be as large as several hundred tons [3]. The image of the inside of the melting tank provided by the camera mounted in the vision head in the upper part of the furnace is an supplemental source of information for the operator managing glass melting. Even though there have been a number of vision systems introduced in the glass industry, which serve as an optical inspection tool for the manufactured glass [5], at the stage of melting, the visual evaluation of glass surface in most of the installed systems is conducted by humans [6, 7]. If the temperature is set too low, the resulting product may be of inferior quality, causing considerable losses. If the maintained temperature is too high, it results in an increased energy consumption, which plays a substantial part in manufacturing costs [8] and in increased output of pollutant (mainly nitrogen oxides and greenhouse gases). The automated measurement of the process parameters based on the analysis of the glass surface images can ensure the repeatability and optimisation of melting process [6].

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The glass works Trend Glass has applied for and is the recipient of the system, while the Łukasiewicz Research Network – The Institute for Sustainable Technologies is carrying out the research and development work. Each specific module of the system (Fig. 1) carries out its assigned task consisting in monitoring different stages of the production process and product quality inspection, including the preparation of the tools for product forming, monitoring the melting process, and quality inspection of glass products.

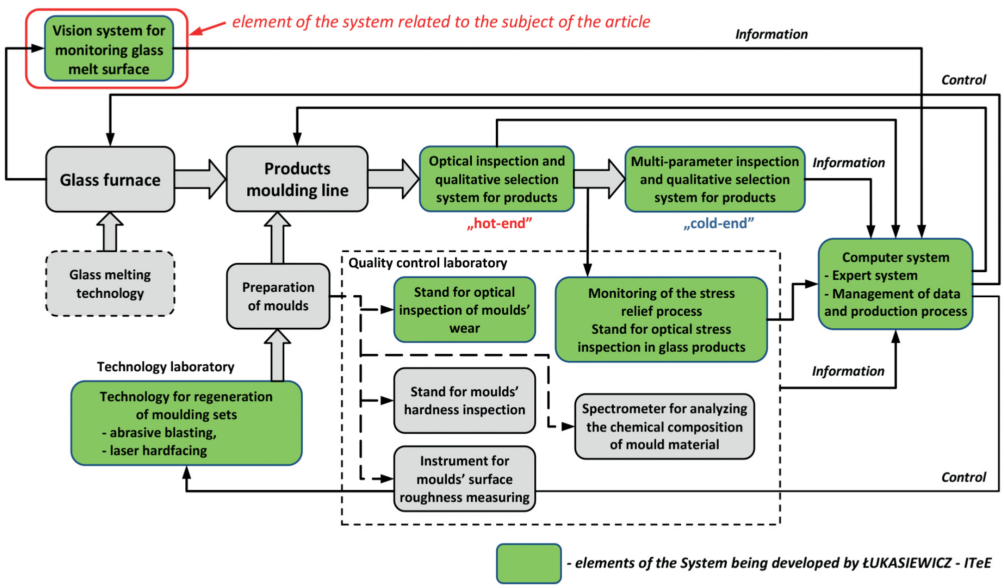


Fig. 1. An integrated, multifunctional system for increasing manufacturing effectiveness and product quality – general structure (developed by Łukasiewicz Research Network – The Institute for Sustainable Technologies ITeE)

This article focuses on the module which provides a vision monitoring system of the glass melt surface in the furnace.

1. The structure of a glass furnace

Tank furnaces work on a continuous shift basis where all the stages and processes of glass melting are taking place simultaneously in various parts of the tank. From one end, the tank is loaded with a mix of raw materials, i.e. glass melting set, which on contact with the hot flame melts. The molten glass filling the tank flows to the other end where it is transferred to the forming machine, and the decrease in the glass melt is filled as the other end the tank is charged with another batch of mix [2]. Glass furnaces can be fuelled by natural gas, generated gas, or heating oil. The burning of these fuels takes place using burners which create long flames touching the surface of the bath across a large area [4]. Depending on how the burners are situated, the furnaces are divided into side-port and end-port furnaces. In side-port furnaces (Fig. 2a) the burners are situated in the side walls perpendicularly to the glass flow in the bath. In end-port furnaces, the burners are placed in the back wall, and the flame from the burner curves into a U when firing (Fig. 2b).

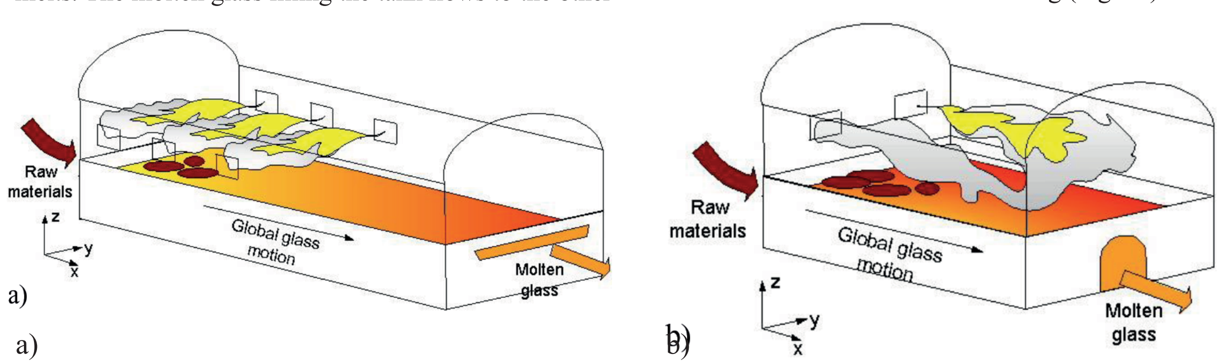


Fig. 2. Diagrams of glass furnaces with different flame paths [1]: a) a side-port furnace, b) an end-port furnace

Moreover, the furnaces are equipped with heat regenerator systems, which improve thermal efficiency for the glass melting process. In the regenerator chamber, the supplied air is pre-heated using the outgoing hot flue gas. Regenerators work cyclically. In the first cycle, hot flue gas is run through the chamber, and in the next cycle, the intake of air, going in the opposite direction, absorbs the heat accumulated in the chamber [4]. Figure 3 shows an example of a cross-section of an end-port regenerative glass furnace with a bath (melting tank).

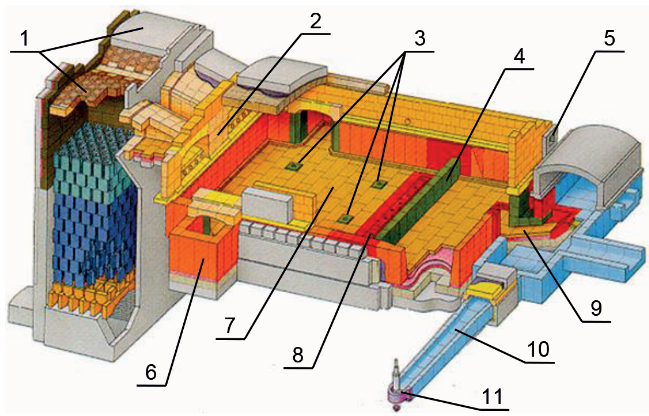
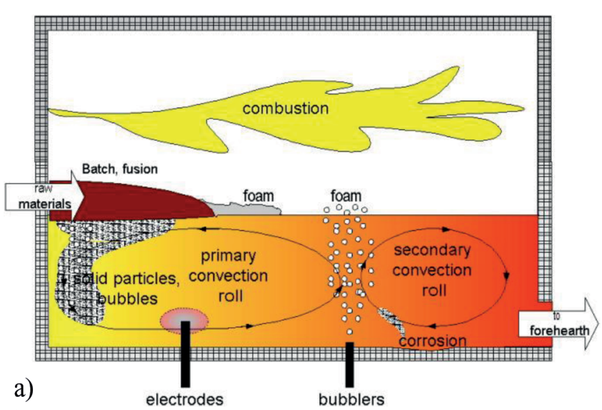


Fig. 3. A cross-section of a regenerative, end-port furnace [9]: 1 – regeneration chambers, 2 – burner wall, 3 – electrodes, 4 – weir, 5 – inspection viewer, 6 – doghouse, 7 – tank, 8 – bubblers, 9 – flow, 10 – distribution feeder, 11 – gob feed spout

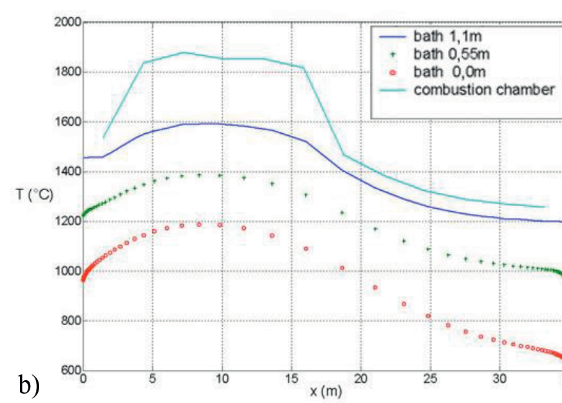
The cross-section of the furnace shows the typical elements, such as the doghouse where the new batches of glass material are supplied, the openings for electrodes which enable electric, supplementary heating, and the bubblers. Bubbling is a process of blowing compressed air into the glass bath through the vents placed in a row in front of the weir. Its purpose is to prevent the flow of unmolten particles into the fining zone. The molten glass flows through the channel to the feeders, and there to the gob spout, where it is fed to the machines which make glass products.

2. The glass melting process in the furnace

Figure 4a shows a diagram of the glass melting process in a tank furnace. The raw materials for glass production include quartz sand, cullet, soda (glass mix) [3] and are supplied at one end of the tank. These elements float on the surface of the molten glass, and as a result of firing, these elements melt and sink into the glass melt. The glass melt creates convection currents which allow the melt to mix. Additionally, the heating electrodes cause the creation of vertical convection currents. The weir and the bubblers create return currents and further equalise the temperature in the melt and extend the minimal path that the mass must travel before reaching the other side of the bath [1, 2].



a)



b)

Fig. 4. A presentation of glass melting process [1]: a) a diagram showing the process in the glass melt with the currents b) a temperature chart for different levels of the melt and in the flaming zone

Figures 4b show the chart for temperature distribution at different levels of the glass melt along the entire length of the bath and additionally at the flame level above the surface of the melt.

3. The concept of a vision monitoring method

A simplified model of a glass furnace bath is shown in Figure 5. In the front wall, from the working end, there is an opening for inserting the vision head. Due to extreme temperatures inside the furnace of 1,500°C, only an endoscope is inserted through the opening. It contains an internal system for image transmission and a water jacket cooling system. The forced circulation of the cooling medium and the cooling generator of sufficient power provide continuous monitoring the operation. Figure 5 shows sample images of the inside of an end-port glass furnace registered by a thermal imaging camera [11] and a visible light camera [12]. The images show the surface of the melted glass, the unmelted fragments of the glass mix floating on the surface, the back wall with burners, parts of the side walls, and the furnace roof. The application of a thermal imaging camera provides the measurements of the temperature distribution on the surface of the glass melt and the visible for the camera part of the internal furnace structure, while the application of the visible light camera provides images of the furnace interior with a greater resolution. The monitoring system with the visible light camera is cheaper than the one with the thermal imaging camera. The lower price is related to the the camera itself and to the image transmission system. It is important in the monitoring system that the lens in the vision head is wide-angle and includes as large an area of the furnace as possible.

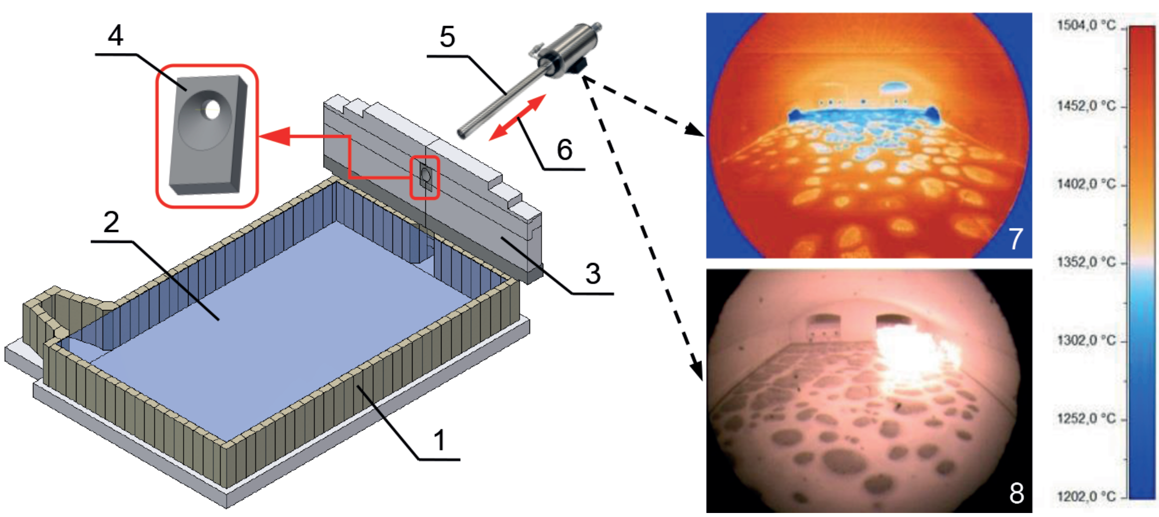


Fig. 5. A concept of vision monitoring system inside a glass furnace, originally developed based on [10, 11, 12]: 1 – a simplified model of glass melt tank, 2 – glass melt bath, 3 – furnace front wall, 4 – fitting with an opening for the vision head, 5 – an example of a vision head with a furnace endoscope [10], 6 – retraction system for the endoscope, 7 – the image of the furnace interior obtained from the thermal imaging camera with colour scale for temperature changes [11], 8 – the image of the furnace interior obtained from the visible light camera [12]

The system presented in Figure 5 is intended for continuous on-line inspection of the condition of the glass melt surface via a vision method. An important element of the system, which influences the operation safety, is the retraction system of the endoscope. If the temperature limit is exceeded, or water flow or air compression is decreased, the control system ensures an automatic retraction of the endoscope from the aperture in the furnace.

Table 1 presents basic capabilities and limitations of the vision monitoring method for the glass furnace interior. The surface of the glass melt can be used for the observation of level of the glass melt in the bath, the size and location of unmelted fragments of the glass mix, and whether the bubbling process is taking place properly. In addition to the observation of the glass melt surface, this method also enables the observation of the shape and location of the flame from the burners, the burner wall, and fragments of side walls and the roof.

Table 1. The main capabilities and limitations of the vision monitoring method for a glass furnace (based on authors' work)

Capabilities (advantages) of the method	Limitations (disadvantages) of the method
– A contact-free measurement method – The observation of the location and size of the glass mix batch – The observation of the shape and location of the flame issuing from the burners – The observation of the bubbling process – The measurement of the temperature distribution of the glass melt surface and the structure of the interior of the furnace (requires thermal imaging camera) – The observation of the melt glass level in the bath – The improvement in the stability of the glass melting process – The decrease in energy consumption and the nitrogen oxide and greenhouse gasses emissions	– A limited area of monitoring when only one camera is installed – A limited resolution of images in thermal imaging camera – A limited resolution of optics systems used in furnace endoscopes (including visible light as well as thermovision in infrared) – The effect of the flames from the burners on the measurements (the necessity to conduct some of the measurements during a reversal) – A limited precision of the measured temperature when using thermal imaging camera

4. The construction of the vision head

Figure 6 shows key construction elements of the vision head for monitoring the interior of a glass furnace as follows: protective casing with the camera placed inside, and the furnace endoscope in the form of a water jacket cooling system enclosing the optical tube for image transmission. The endoscope is inserted into the furnace, while the camera in its casing remains outside of the furnace.

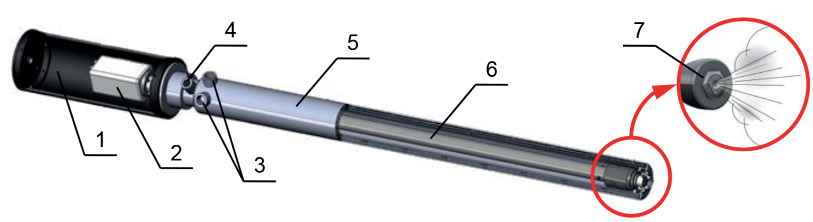
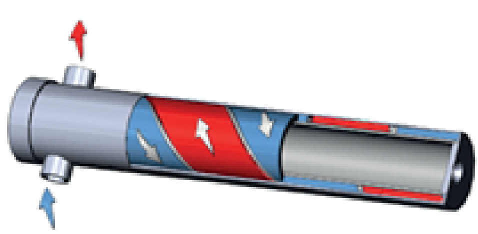


Fig. 6. An illustrative diagram of vision head structure [13]: 1 – protective casing of the camera, 2 – camera, 3 – water supply points, 4 – compressed air supply point, 5 – cooler with a water jacket, 6 – optical tube, 7 – air flow arount head lens

As a support for the cooling process, the water inside the cooler is additionally set into a swirling motion (Vortex effect) [13]. There are two basic structures of the coolers, i.e. with one or with two water jackets (Fig. 7). Using a double water jacket provides better protection and a more uniform temperature distribution on the surface of the cooler.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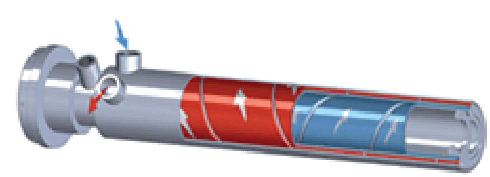

b)

Fig. 7. Basic constructions of water coolers used for monitoring high temperature processes [13]: a) with one water jacket, b) with a double jacket

The front lens, as the most forward element of the vision system, is most exposed to the temperature inside the furnace and thus exposed to thermal damage; therefore, in addition to closed system water cooling, the endoscope is equipped with open system air flow (Fig. 6). The compressed air cleans the lens and also cools it using the Venturi effect [13].

Inside the cooler with a water jacket, there is an image transmission system from the interior of the furnace. There are two main ways of image transmission. The first solution (Fig. 8a) applies an optical tube with an internal system of lenses, which cooperate with the camera placed in the outer protective casing. The second solution (Fig. 8b) uses a comprehensive vision system including a camera and a lens placed inside the cooler. In this case, the range of applications is limited to a small camera due to the small inside diameter of the cooler, and its distinguishing characteristic is a lack of external protective casing for the camera. This solution is used mainly for visible light cameras.

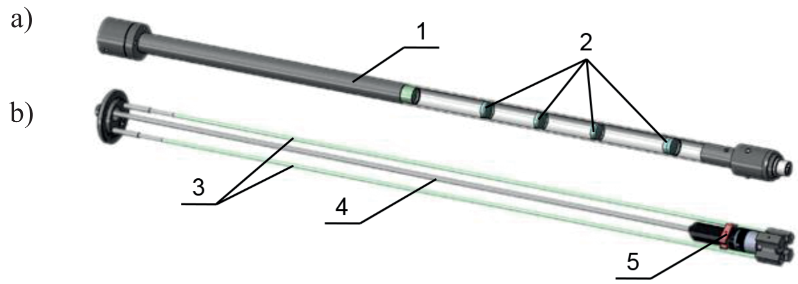


Fig. 8. Modes of transmission inside the the vision head [13]: a) optical tube with a system of lenses, b) comprehensive viewing system including the camera and the lens (1 – optical tube, 2 – lens system, 3 – mounting brackets, 4 – image transmission cable, 5 – vision system (camera + lens)

As a result of tests done on the demonstration vision heads (using thermal imaging and visible light cameras), a monitoring system of glass melt surface was selected using visible light colour camera, which also met the industry partner's requirements. The available systems with visible light camera (by SVA Industrie Fernseh) work with the monitor for viewing the interior of the furnace and an optional image recorder. The monitoring system for a glass furnace is shown in Figure 9. In the SVA design, the complete viewing system, including the camera and the lens, is placed inside the cooler [14].

a) b)

Fig. 9. A general view of the standard version of the monitoring system for glass melt surface using visible light camera [14]: a) vision head with the coupling system and with the endoscope retraction b) a control system for endoscope retraction with the media connection box

The standard solutions do not have the functionality required in the project related to the analysis of the recorded images and the transfer of the results to the IT system. The authors proposed a dedicated monitoring system for the glass melt surface adapted for industrial settings. The main differences in comparison with the available solutions include the use of a high resolution camera with the capability to transfer digital signal (Gigabit Ethernet) and an operator stand with a computer system, which analyses the images and sends the results to the primary IT system.

The elements selected for the vision system are a digital visible light camera and a wide angle pinhole lens. The selection of the pinhole lens was determined by the small diameter of the front lens (a few millimetres), and because it minimises the negative effect of heat on the optical elements of the lens. The C-mount type was selected, which is commonly used in industrial cameras. Among available small and compact cameras, the standard case size was selected of 29 mm by 29 mm. It is a size for a large selection of cameras available from different manufacturers including JAI, Basler, Flir, Allied Vision, and it will allow for easy selection of replacement parts. Mounting of these types of camera (a diagonal of ca. 41 mm) is possible inside a cooler with the inside diameter of 50 mm. The main specifications of the vision system of the camera and the lens are presented in Tables 2 and 3 below.

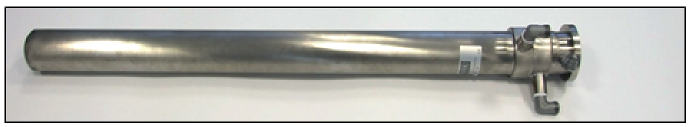
Table 2. Main parameters for the camera

Manufacturer	Allied Vision
Sensor resolution	1.9Mpx (1600x1200px)
Sensor type	CMOS, colour
Sensor size	1/1.8”
Interface	GigE PoE
Mounting type	C-mount
Working temperature	+5°C – +45°C

Table 3. Main parameters for the lens

Manufacturer	CBC (Computar)
Focal length	4 mm
View angle	76.3° (H), 61.6° (V)
Working with the sensor	1/2”
Aperture	F2.5 – F32C
Mounting type	C-mount
Working temperature	-20°C – +50°C

The cooler manufactured by SVA with a water jacket, 100 cm long, and an inside diameter of 50 mm is shown in Figure 10a. The photograph of the image transmission system, developed by the authors, which is placed inside the cooler, is shown in Figure 10b. The view of the whole head with the cooler and the vision system mounted inside is shown in Figure 10c.

a)

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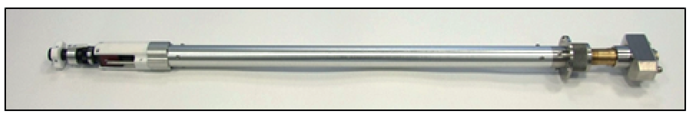
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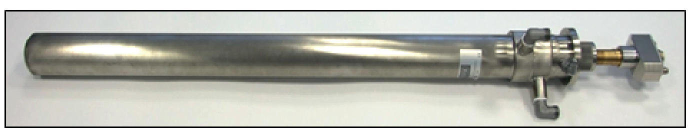


Fig. 10. The elements of the dedicated version of the vision head (authors' work): a) a cooler with a water jacket, b) the developed image transmission system, c) a vision system mounted in the cooler

A detailed view of the front and the back of the image transmission system is shown in Figure 11. The front part (Fig. 11a) has a vision system consisting of a visible light camera with a pinhole lens. At the end of the lens, there is a bracket which sets the location of the lens inside the cooler. Behind the bracket, there is a lens lock, which is to block any accidental change of settings. The photographs show one of the two Pt100 type temperature sensors placed on each side of the camera, which provide data for monitoring the temperature inside the cooler by the retraction system and by the operator's stand in the control room. The aluminium conduit contains cables which provide the transmission of the image from the camera, supply electricity, and the reading of the signals from the temperature sensors.


a)

b)

Fig. 11. A detailed view of the image transmission system (authors' work): a) a detailed view of the vision system, b) a detailed view of the electric connector module

Electric cables from the subcomponents of the vision system are connected to the connector module located at the back of the vision head (Fig. 11b). The photo also shows the flange, which enables the installation of the vision system inside the cooler.

5. The structure of the vision monitoring system

Figure 12 shows the general structure of the monitoring system for the glass melt surface inside a furnace with all of the necessary modifications. In the high temperature zone by the furnace, there is a dedicated vision head, which has a pneumatic system for emergency retraction of the endoscope from the furnace. Near the furnace, there is a control system for endoscope retraction and the media connection box. The system has an independent container with compressed air for emergency retraction of the vision head in case when there is a lack of compressed air in the system. In this area, there is also a cooling generator (chiller), which ensures the cooling of the vision head. The cooling agent is demineralised water. For the control room, the operator's stand was designed for conducting the observations of the inside of the furnace.

Figure 13 shows the vision head with the mounting system to the structure of the furnace and the head retraction using pneumatic actuator system.

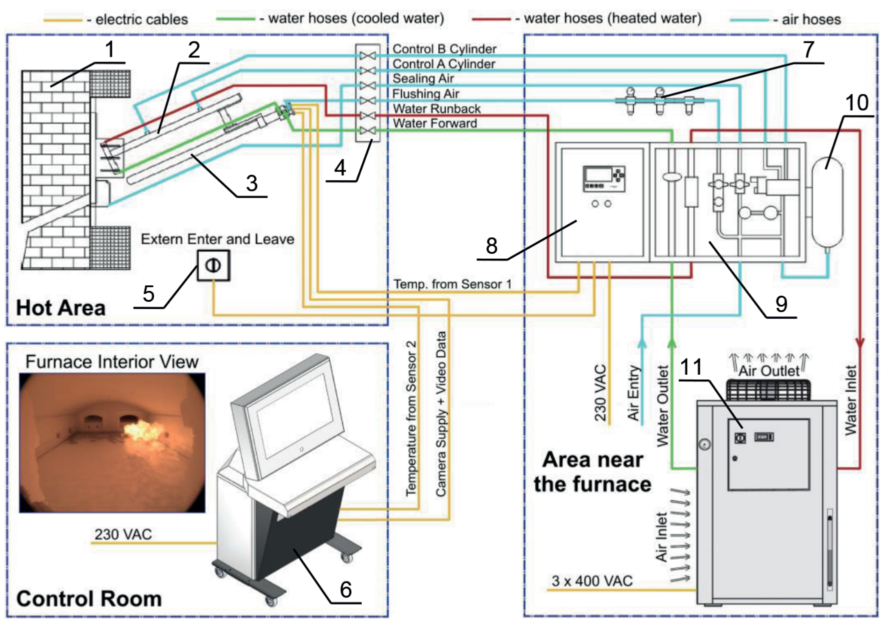
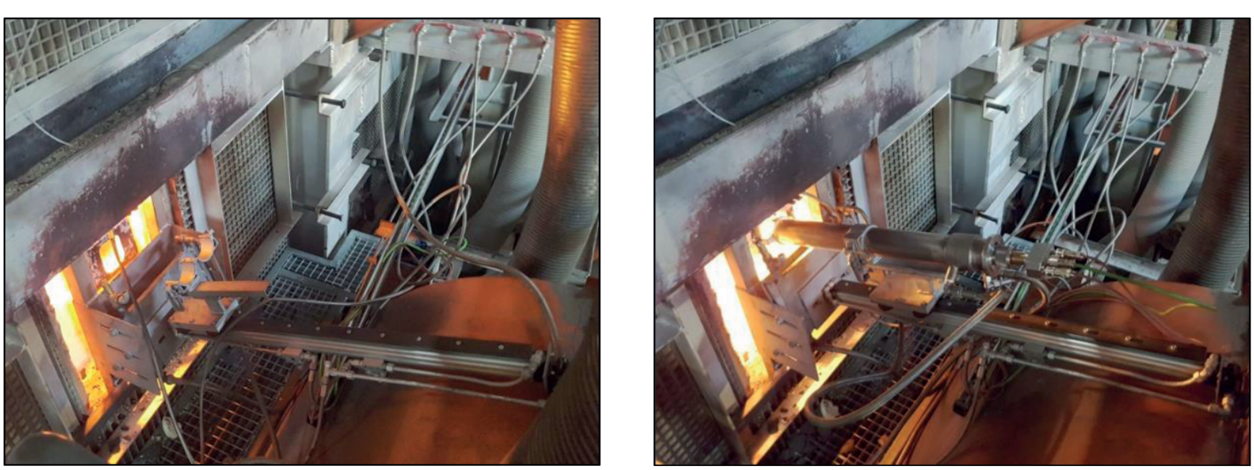


Fig. 12. The structure of the vision monitoring system of glass melt surface (authors' work based on [15]): 1 – furnace wall, 2 – the system for vision head retraction, 3 – vision head, 4 – terminal with valves, 5 – manual control of head retraction, 6 – operator's stand in the control room, 7 – air filter set, 8 – control system box for vision head retraction, 9 – media connection box, 10 – reserve air container, 11 – cooling generator (chiller)



a) b)

Fig. 13. Photographs of the mounting system of the vision head to the structure of the furnace with the the endoscope retraction system (installation location: high temperature zone – directly next to the glass furnace), (authors' work): a) dismounted vision head, b) vision head mounted in the clamp

Photographs of the remaining elements of the system, including the cooling generator and the control system of the head retraction with the media connection box, are presented in Figure 14. These elements were installed under the furnace's glass tank.

a)

b)

Fig. 14. Photographs of the remaining elements of the system for monitoring glass melt surface (location of installation: under the glass-melt tank (authors' work): a) cooling generator, b) control system box for the retraction of the vision head, with the media connection box and a set of air filters

The operator's stand for a glass melt surface monitoring system was developed and manufactured (Fig. 15). The dedicated industrial casing protects the following elements placed inside: an industrial computer, an LCD monitor, programmable PLC controller, and emergency UPS power supply. It protects those elements from the negative effects of external conditions including dust, dirt, or splashing. The stand is placed on wheels with a stop lock, so it can be placed wherever needed.

a)

b)

c)

Fig. 15. A view of the developed operator's stand for monitoring the surface of glass melt in a furnace (location: furnace control room), (authors' work): a) a photo with the keyboard retracted, b) a photo with the keyboard extended, c) screenshot of the operator's interface

The operator's stand is equipped with a pull-out shelf with a water and dust proof keyboard (Fig. 15b). The keyboard comes with a touchpad. After the operator sets the appropriate parameters, the shelf can be retracted (Fig. 15a). Using the developed software installed in the operator's stand (Fig. 15c), the monitor can display the images of the furnace interior and register video sequences on demand.

6. Experimental research

First, the images of the inside of the furnace were recorded using the developed vision head. After the effectiveness of the cooling system was ascertained and the endoscope was placed properly in relation to the opening in the fitting, several sequences of furnace images were registered. Sample images for different stages of furnace firing are shown in Figure 16. The registered images encompass a large portion of the glass melt surface, the back wall with burners, the doghouse, the furnace roof, and portions of the side walls. On the surface of the glass melt, there are unmelted fragments of the glass mix batch, shown as darker areas near the rear wall of the furnace with light areas of the flames from the burners. During this study, the bubblers were turned off, which is why the process is not visible in the images.


a)


b)


c)


d)

Fig. 16. A sample of registered images of the furnace interior (authors' work): a) initial testing and setting the correct placing of the vision head (the aperture in the fitting for vision head is visible), b) burners turned on, on the right, c) burners turned off during reversion, d) burners turned on, on the left

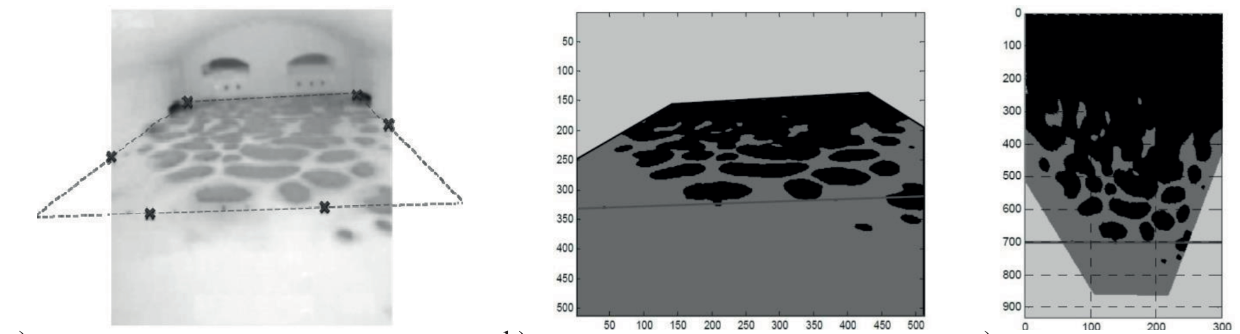
The testing confirmed the correct functioning of each the elements in the monitoring system, the effectiveness cooling of the vision head, the satisfactory quality of the registered imaged, the large field of view, and the correct placing of the vision head in the aperture.

7. The system's potential for further development

One of the functionality requirements of the monitoring system for glass melt surface is the transfer of the measurement information to the primary IT system. The data will be obtained based on the analysis of the registered images of the furnace interior by the vision head directed towards the surface of the glass melt. The planned analysis includes the calculation of the percentage of the glass mix content, the detection of the limits of the mix, the analysis of the bubbler system functioning, the measurement of the glass melt surface level (optional), the analysis of the shape, and the angle of the flames from the burners.

The authors have reviewed the publications related to the methods of image processing and analysis of glass furnaces [6, 7, 16], and their one common denominator is the necessity to take into account the point of view of the images. The camera is placed in the chamber of the furnace at an angle, so the image is a two dimensional, homographic transformation of the surface of the glass melt. By identifying the parameters of this transformation, we can conduct a reverse transformation and obtain the image of the glass melt surface as seen from above [6, 7]. Another common feature of the applied algorithms is conducting the segmentation of the glass melt image based on the image brightness. The purpose of this operation is to delimit areas with unmelted fragments of the mix in order to calculate the percentage of the glass melt surface coverage by glass mix and borders of the glass mix batch.

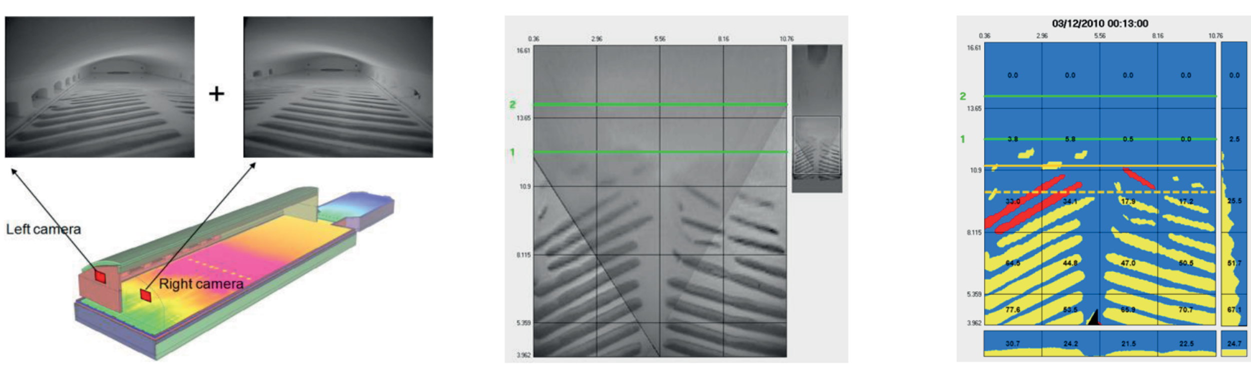
Sample stages of image processing based on [6] are shown in Figure 17. The resultant image (Fig. 17c) shows the surface of the glass melt surface in a projection form above. The black shows the glass mix, dark grey shows clear glass melt, and the light grey is the area beyond the field of view of the camera.



a) b) c)

Fig. 17. The stages of image processing for glass melt surface (one-camera system) [6]: a) the image obtained from the vision head with the glass melt surface marked and delimited by the bubblers, b) glass melt surface after the segmentation of the glass mix (the scale on the axes is in the camera pixels), c) the image after perspective processing showing the projection from above (the scale on the axes is in centimetres)

In order to limit the dead zones of the system, the single camera system can be replaced with two cameras placed on both sides of the front wall of the furnace (Fig. 18) [16].



a) b) c)

Fig. 18. The stages of image processing for glass melt surface (two-camera system) [16]: a) the image obtained from the left and the right camera, b) the image after perspective processing showing the projection from above (data from both cameras), c) the image after the segmentation of the glass mix

The literature analysis shows that the methods for processing and analysis of images of furnace interior relate to the glass melt surface and allow: the detection of glass mix limits, the determination of the percentage of glass mix coverage, the delineation of the asymmetry of the glass mix distribution, the control of the bubbling process, and others. The planned development of authors' software for automated analysis of the interior of the furnace, in addition to monitoring the glass melt surface, will include the analysis of the flame issued from the burners located above the surface of the glass melt.

Conclusions

The system which is being developed is intended for continuous on-line monitoring of the condition of the glass melt surface using the vision method. It constitutes a very important source of information for the operators in charge of the process of glass melting. Until now, the information on the process was based solely on the sensors (e.g., thermo-elements) placed in the selected areas of the furnace. Additionally, at set intervals, the operator would conduct visual inspection of the melting process by observing the interior of the furnace through the side inspection holes using special glasses with optical filters. The visual inspection carried out by humans in the proximity of the furnace is not safe and causes fatigue due to the high temperature, noise, and dust. The possibility of the remote monitoring of the glass melt surface will greatly improve working conditions for the operator. Moreover, so far, there has been no system for archiving the images of the furnace interior, e.g., in an atypical situations where the parameters are exceeded, or if there is an emergency situation; however, the periodic registration of the images can determine the range of fluctuation of the processes inside the furnace. The planned development of the software module for an automated analysis of the images of the furnace interior will offer the advantage of eliminating the human factor related to a lack of repeatability, fatigue, subjectivity, etc. In a majority of systems for monitoring the interior of the furnace, the evaluation of the condition of the glass melt surface is still done by a person. This system, at this stage of development, does not ensure an automation of the flame control process or the work of the doghouse directly based on the image analysis. This monitoring system plays the support role, increasing the operator's capabilities of real-time control of the process based on the condition of the glass melt surface inside the furnace.

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