Visual level measurement system application in the technological process automated control system of the recuperative furnace bath

A A Valke, D G Lobov, A G Shkaev, A A Shkaev, D B Ponomarev
Omsk State Technical University 11, Mira, ave., Omsk, 644050, Russia

Abstract. The paper considers the melted material level determining problem in the recuperative furnace bath melter in technological process automated control system for the basalt mineral fiber production. To solve this problem, it is proposed to use a visual level measurement system based on the analysis and processing of the melt boundary image. A block diagram of the visual level measurement system developed by the authors is presented, and an algorithm for determining the melt level using a modified Sobel edge detection method is proposed.

Keywords: visual level measurement, melt level, automation.

1. Introduction
Currently, in the construction and industry heat and sound insulation materials based on mineral fiber (mineral wool) are widely used. The popularity of these materials is due to their high thermal-insulation properties, the ability to work at high temperatures (up to 700°C) and relatively low cost.

Blast furnace slags, natural rocks, as well as industrial waste (brickbat, keramzite and cement production emitted dust) can serve as raw materials for the mineral fiber production. At the same time, mineral wool obtained from basalt group rocks has the highest quality.

The mineral fiber production process includes raw material mixture (furnace charge) preparation operations, its melting, obtaining fiber from the melt, mineral wool subsidence, mineral wool carpet formation with subsequent processing, cutting into products of specified sizes and packaging.

2. Problem statement
For melting the raw material mixture in modern production bath regenerative and recuperative furnaces are mainly used. Recuperative bath furnaces contain a recuperator in which the heat from the hot exhaust gases is used to heat the air coming to the burner. Due to this recuperative furnaces are more efficient than regenerative furnaces.

The bath furnace consists of two parts: cooking and working (feeder). The preprepared charge is fed to the cooking pool using loaders through special loading windows in the furnace side walls. There are burner devices in the cooking part that provide the furnace charge melting, after which the resulting melt enters the feeder. There is a threshold between the cooking part and the feeder preventing unmelted raw material from entering the feeder. The melt from the feeder is issued for the subsequent mineral fiber forming operation.

One of the most important technological process parameters during the bath recuperative furnace operation is the melt level in the cooking part, which, in accordance with the regulations, must be maintained with an accuracy of ±20 mm. The melt level is maintained by the automatic control system by changing the loaders mode time.

The melt level direct control is a complex problem, since the known contact and non-contact methods for its determination [1,2] are hardly suitable due to the constant presence of foam on the melt surface (Fig. 1a) and clusters of unmelted raw materials (Fig. 1b).
For this reason, the melt level automatic control is usually based on indirect data representing the difference between the amount of raw material loaded and the melt output. It is also possible to work with the periodic actuation of loaders on time without any feedback.

These two control methods have a significant drawback: the accurate data lack on the melt level necessarily leads to errors in the automatic loader control system operation, which leads to either an overflow of the furnace with melt, or a decrease in the melt level below the minimum allowable value. Therefore, the melt level direct continuous measurement problem in the furnace cooking part is relevant.

3. Theory

Based on the analysis of the recuperative melting furnace loading nodes studies results [3], the authors proposed a method for measuring the melt level drawing on visual observation. The method is based on the fact that the furnace wall and melt light intensity almost always have different values. The successful using of video camera for temperature measuring [4] and mineral wool quality control [5] is known.

The melt height is determined by the difference in the furnace wall light intensity and the melt light intensity. In the course of research, it was found that a grayscale black-and-white image (256 grayscale) is more informative than a color image. Also, during the experiments it was found that hot air and gas flows inside the furnace make it difficult to determine the melt level in addition to foam and unmelted raw materials. They cause image instability, resulting in geometric distortions and blurring. In the course of performing field tests it was found that to improve the melt level determining quality pre-processing of the obtained video image is required. Image pre-processing consists of several stages.

At the first stage, the effect of geometric distortions and image blurring is reduced. To do this, the image is averaged frame-by-frame over time. The averaging time is selected depending on the process and can be set from 1 second to 5 minutes.

At the second stage, the image contrast increases.

Increasing the contrast made it possible to use the image brightness scale more fully. Obtained video images histograms analysis showed a low contrast of the recuperative furnace internal cavity image. Figure 2 shows a histogram of the recuperative furnace internal cavity image.

As one can see from the presented histogram, the most informative brightness image values are in the range from 80 to 160, so it was decided to use the brightness range from 80 to 160, which was stretched to the full scale (from 0 to 255). This made it possible to display the melt boundary more clearly on the screen.

The third stage is to increase the image transitions sharpness, which makes it even more possible highlight the melt level against the furnace wall background.
Since the melt level is always parallel to the horizon, it is possible to use the horizontal transitions sharpness, the so-called edge enhancement, to display it more clearly. In this case, the edge is a sharp change in the image brightness. The edge brightness is proportional to the change in brightness surrounding the edge in the image. There are several methods of edge enhancement: convolution, Laplace, shift and difference, and others [6,7]. By analyzing video images obtained during field tests, it was found that the best result is obtained when the edge is strengthened by the convolution method. In this case, the convolution core has the form shown in figure 3:

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-1 -1 -1 -1 -1
0 0 0 0 0
1 1 1 1 1
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**Figure 3.** The convolution core

Figure 4 shows the recuperative furnace internal cavity image after preprocessing.

The only area with the melt level is preprocessed instead of entire image to minimize the image preprocessing time. The melt level is determined using a modified Sobel edge detection method. The essence of this method is as follows [6]. Image area selected in size of 3x3 pixel is indicated in Figure 5:
Four lines can be drawn through the center point "e" of this area: Line 1: a-e-i, Line 2: b-e-h, Line 3: c-e-g, Line 4: d-e-f. Each of these lines divides the space adjacent to the point "e" into two three-point areas, and the absolute value of the difference between these two subdomains average values is calculated. The image element under consideration is assigned the largest value of the four absolute differences. This new element value is then compared to a specific threshold value. A modification of the Sobel algorithm is that the melt boundary is always horizontal, so it makes sense to determine the boundary only along the d-e-f line, and not consider the other lines. This allows to speed up the melt level calculation. In addition, it was proposed to use a 10x10 matrix to determine the melt boundary more correctly. Accordingly for each point located in the melt level vicinity a new value is calculated using the formula:

$$I_{x,y} = \frac{1}{10} \sum_{k=1}^{10} I_{x,y+k} - \frac{1}{10} \sum_{k=1}^{10} I_{x,y-k},$$

where $I_{x,y+k}$ is a brightness over the pixel $x,y$; $I_{x,y-k}$ is a brightness under the pixel $x,y$; $k$ is a whole number. The obtained value of the point $I_{x,y}$ is compared with a threshold value that is set in the configuration program, depending on furnace and technological process. If the point $I_{x,y}$ new value is greater than the threshold, then the corresponding element of the one-dimensional array $H$ is increased, which stores information about how many points $I_{x,y}$ of the corresponding row has a value greater than the threshold. After processing all points in the melt level vicinity, the largest element is searched in the array $H$, which determines the melt boundary position. The melt level is calculated based on the array $H$ maximum element index.

4. Experimental results
The block diagram of the visual level measurement system developed by authors is shown in Fig. 6. In addition, this system also allows visually controlling the processes occurring in the furnace internal cavity. Two specially designed high-resolution IP video cameras are used to record the melt level in the system. The presence of two video cameras allows to monitor the melt level in the presence of foam and unmelted raw materials on its surface more accurately. Video streams from IP cameras are sent via an Ethernet commutator to an industrial computer with specialized software developed by the authors. The software processes the received data, calculates the melt level and transmits this information to the automatic control system of the furnace charge loaders in the furnace via the RS485 interface.
The visual level measurement system block diagram

Figure 6. The visual level measurement system block diagram

The system software consists of three modules:
- the administration module;
- the melt height calculation module;
- module for working with archived data.

The administration module allows to enter new or delete existing system users and change their access level. When starting the administration module, it is necessary to enter the user name and password in the window that appears. If the user has "Administrator" access, the main module window is loaded. In this window there is the possibility to add a new user, delete a user, or change the user's access level. In total, the system has four access levels:
- Guest;
- Operator;
- Engineer;
- Administrator;

The "Guest" access level is set by default when the program starts and only allows viewing information about the melt height. When the software is idle, it also automatically switches to this access level from any other level.

The "Operator" access level allows not only viewing information about the melt height, but also correcting the melt height in case of a failure in the melt level determining. To do this it is necessary to select the "Melt level" menu item and specify the current level on the image. After that, the program begins to determine the melt level based on the newly received information.

The "Engineer" access level allows to configure the system to determine the melt level in addition to the above actions.

The "Administrator" access level allows to perform all the listed actions, as well as enter new or delete existing users of the system and change their access level.

Figure 7 shows the main window of the administration module.
The melt height calculation module is the main software module. This module performs the following functions:
• calculating the melt height;
• basic software settings;
• data archivation.

The main window of the melt height calculation module, software for the visual level measurement system, is shown in figure 8.

The window for this module displays the image obtained by the video camera (1), the current date and time (2,3), the current melt height (4), change trend of the melt height in time (5).
The system configuration is made in the window "Setting", the input to which is carried out in the menu item "Setting". This menu is active only if you log into the program with the "Engineer" or "Administrator" access.

The window "Setting" is shown in figure 9. The "Melt level" tab sets various fixed points or areas on the visualized image of the furnace internal cavity. They allow to determine the melt level more accurately. The "Configuration" tab allows to perform general system configuration. For example, it is possible to specify the path to save data, or select the port to connect to the loader management system. The "Add. Settings" tab sets parameters for image preprocessing and melt level determining. These parameters include the contrast threshold, minimum brightness, maximum brightness and filter order.

Figure 9. The "Setting" window

The module for working with archived data displays the trend of changes in the melt level and the furnace internal cavity image the period under present observation. Archived data can be accessed over the network. Figure 10 shows the archive module window.

Figure 10. The archive module window
Conclusions

The visual level measurement system developed by the authors makes it possible to determine the melt level with an accuracy of ±2 mm. The level measurement system has been tested and implemented as part of the automatic control system for the recuperative furnace bath loaders at TECHNONICOL Corporation (Chelyabinsk) - one of the enterprises producing mineral wool products.

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