Fiber-optical method of pyrometric measurement of melts temperature

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Abstract. There is a scientific problem of non-contact measurement of the temperature of metal melts now. The problem is related to the need to achieve the specified measurement errors in conditions of uncertainty of the blackness coefficients of the radiating surfaces. The aim of this work is to substantiate the new method of measurement in which the influence of the blackness coefficient is eliminated. The task consisted in calculating the design and material of special crucible placed in the molten metal, which is an emitter in the form of blackbody (BB). The methods are based on the classical concepts of thermal radiation and calculations based on the Planck function. To solve the problem, the geometry of the crucible was calculated on the basis of the Goofy method which forms the emitter of a blackbody at the immersed in the melt. The paper describes the pyrometric device based on fiber optic pyrometer for temperature measurement of melts, which implements the proposed method of measurement using a special crucible. The emitter is formed by the melt in this crucible, the temperature within which is measured by means of fiber optic pyrometer. Based on the results of experimental studies, the radiation coefficient $\varepsilon > 0.999$, which confirms the theoretical and computational justification is given in the article.

1. Introduction

There are most technological processes are driven by temperature in modern metallurgical industry. Increased the importance of accurate temperature measurements in the most sought after processes for the smelting of iron, steel, non-ferrous metals. For solving problems of temperature measurements of melts at different times have proposed various kinds of methods. For example, direct pyrometric measurement of the radiation exposed surface of the melt, the method of the sighting tube, the method being blown pipe, dip of the contact of the thermocouples in the melt. At present, there are two methods for solving this problem most widespread: contact and pyrometric methods.

In the factory practice, in general, the method of contact measurements is used with the use of one-time thermoelectric transient transducers for short-term immersion. The advantage of the contact method measurements is sufficient accuracy, and the disadvantages are one-time use of measuring instruments and their greater inertness [1, 2]. An example of a wide application of contact measurements in industrial thermometry for measuring the temperature of melts is a thermocouple with replaceable measuring inserts. Such converters are widely used in our country and abroad in platinum and tungsten-rhenium thermocouples for measuring the temperature of metal melts [3, 4, 5]. The converters consist of two parts: a body (rod) and a replaceable thermocouple measuring package of one-time use.

The advantages of the pyrometric method of temperature measurement include non-contactness and high speed of measurement, and the disadvantages are a high error associated primarily with the uncertainties of the blackness coefficients [6, 7]. A large number of publications [2, 13] have been
devoted to solutions to reducing the uncertainties associated with the uncertainties in the blackness coefficients in pyrometric measurements.

2. Problem definition
It should be noted that the processes of high-speed heating have become widespread in recent years in metallurgy and problems have arisen to automatically maintain the preset metal temperatures [5], when the control of the quality of heating is of great importance for increasing productivity and reducing specific fuel consumption. In this regard, the use of contact means, and especially one-time, for automated management of heating processes is difficult. The use of pyrometers for the solution of these tasks in the conditions of operation of the furnaces is faced with the difficulty of considering the influence of the following factors: the presence of the absorbing gas medium, the uncertainty degrees of blackness melts (unknown dependence on temperature, slag, mill scale), the effect of multipath radiation. There is a pyrometer for measuring the temperature of the melt in this work, where these factors are overcome by forming in the melt of the emitter in the form of a model of a blackbody and application of a fiber-optical pyrometer is offered. In this pyrometer the detuning from the effects of acquisitions gases, accompanying the processes of smelting, is due to the use of fiber. The elimination of the uncertainties associated with the unknown ratio of black will occur due to the formation of the measuring surface in the form of emitter type of model a blackbody. In such a pyrometer, the temperature of the melt is measured by recording the radiation of this cavity. For this, it is necessary to immerse the hollow body in the form of a crucible in a melt and to visor a fiber optic pyrometer (similar to that used in replaceable thermocouples) to its bottom [8]. As material of a crucible it is necessary to apply the brand of glasses with high melting point and the greatest transparency in the spectral sensitivity of the fiber optic pyrometer, then the melt, forming a radiating cavity after placement of the crucible and will be a radiator type of model a blackbody.

3. Theory
For meaningful calculations of the emitter was chosen the cylindrical shape of a blackbody, as this form cavities suitable for practical manufacture. For such a model have been carried out below the calculations of geometrical parameters of the emitter in the form of a blackbody model. The calculations were performed based on methods described in [9].

![Diagram of a blackbody cavity](image)

**Figure 1. Sketch of the blackbody cavity.**
L – cylinder length, r – cylinder radius.

The calculation was carried out according to the formula Guffe (1):

\[
\epsilon' = \frac{\epsilon[1+(1-\epsilon)[\frac{\sigma}{S} - \frac{S}{S_0}]]}{\epsilon(1-\frac{\sigma}{S}) + \frac{\sigma}{S}}
\]  

Then, when the emissivity of the material of the crucible \(\epsilon = 0.9\) (glass type KI) and the ratio \(\frac{L}{r} = 10\) estimated relative emissivity of a cavity is equal to \(\epsilon' = 0.999\), where \(\epsilon\) – is the emissivity of the cavity walls; \(\sigma\) – is square holes in the cavity; \(S\) – is total surface area of the cavity; \(S_0\) is the distance between the plane of the holes and the farthest point of the cavity.
With diaphragm to ensure more isothermal cavity emitter design will be like (Fig. 2).

Figure 2. Diaphragm cylindrical cavity.

\[ d_0 \] – is the diameter of the aperture, \( d \) – is the diameter of the cylinder.

Emissivity of the crucible material \( \varepsilon = 0.9 \) and the relation \( \frac{d_0}{d} = 0.1 \), and preservation conditions \( \frac{L}{r} = 10 \), the settlement coefficient of radiation will be \( \varepsilon' > 0.999 \).

Simplified formula for diaphragm cylindrical cavity

\[ \varepsilon' = 1 - \frac{\rho \cdot r_d^2}{(r_d^2/r)^2} \]

(2)

where, \( r_d \) – diaphragm opening radius; \( \rho \) – cavity wall material reflection coefficient, the settlement coefficient of radiation will be \( \varepsilon' > 0.999 \).

By results of calculations the following geometrical sizes of a design of a radiating crucible have been received: \( L = 100 \text{ mm}; r = 10 \text{ mm}; d_0 = 2 \text{ mm} \).

Quartz glass brand KI was chosen as the material for the manufacture of the cavity of a blackbody on the basis of its spectral characteristics, which is shown in Fig. 3 [10].

Figure 3. Spectral characteristic of glass brand KI.
Calculations carried out using the above Planck function (3) [10, 12, 13] have shown that about 90% of the radiation lies in the region of 200-3000 nanometers at melting temperatures in the range 1100-2500. It allows to claim that losses on absorption in crucible walls will be less than 10% of glass KI brand. These losses exceed (35-40) % for brands of other glasses, for example, KV-2, KV-1 brands.

\[
\tau(\lambda) := \left( \frac{\hbar c}{e^{\frac{kT_1}{\lambda}} - 1} \right)^{-1} \frac{2\pi \cdot \hbar c^2}{\lambda^5} \tag{3}
\]

where, \( r(\lambda) \) is the spectral density of irradiance; \( C \) – light speed; \( \lambda \) – wavelength; \( T_1 \) is the temperature in Kelvin; \( h \) – Planck constant; \( k \) – Boltzmann constant.

According to the calculations’ results, changes in the spectral densities of the energy luminosities of surfaces were obtained at temperatures of 1100 °C and 2500 °C, shown in Fig.4.

As a fiber optic, the pyrometer type PD-10-02 is proposed to be used, serially produced by JSC “SPE” Etalon”.

It should be noted that in the proposed measurement method, crucibles can be used in the pyrometer design from any materials whose melting point exceeds the range of measured temperatures (for example, silicon carbide). Then a radiating cavity is formed by the molten metal, and isothermal surface of the crucible is heated to a temperature of molten metal. In this case, the measurement time constant will increase until the time of thermodynamic equilibrium establishment between the crucible and the molten metal.

**Figure 4.** The dependence of irradiance of the wavelength at the temperature 1100°C and 2500°C.

1 – dependence at a temperature 2500°C, 2 – dependence at a temperature of 1100°C.
3. Experimental results
The measuring device realizing the offered method has been installed in trial operation of the Omsk enterprise JSC “Omsktransmash” on furnaces for isothermal training of the cutting tool in the environment of fusion chlorine - barium salt.
As a result of experimental observations after the room of a crucible in the furnace and vising on the bottom of a fiber-optical pyrometer increase of indications of a pyrometer was observed too long (within 30 minutes). The initial emissivity of the material at the steady state value of indications of the thermometer did not match the calculated value of $\varepsilon' > 0.999$ and was 0.85. During the hour of operation, the readings of the pyrometer rose by 30 degrees, which corresponded to the radiation coefficient $\varepsilon' > 0.999$. At shutdown of the furnace the regular thermocouple has been rechecked in the quick-response tubular furnace with using PPO converter 2 categories.
EMF (electromotive force) of the working thermocouple at a temperature of 1100 degrees corresponded to the nominal statistical characteristics according to GOST (governmental standard).

The operating characteristics of the furnace are given in Table 1.

The operating characteristics of the furnace are given in Table 1.

| Characteristic                          | Interpretation                                                                 |
|----------------------------------------|-------------------------------------------------------------------------------|
| Type                                   | Furnace hardening tool (FHT)                                                  |
| Bathtub sizes                          | Bath diameter 500 mm, depth 1000 mm                                           |
| Environment hardening                  | Chlorine-barium salt                                                          |
| Heating type                           | Electric arc                                                                  |
| Denomination                          | Furnace for isothermal annealing of the cutting tool                           |
| Type standard tools of measurement for the control and temperature regulation | Potentiometer recording KSP-3 with a class of accuracy 0,5 together with corner cover of own manufacture. |
| Operating temperature                  | 1240°C.                                                                       |

Conclusions
Such pyrometers can be used to measure the temperatures of different melts in the range of 1100-2500 °C instead of the currently widely used expensive platinum-rhodium and tungsten-ferric thermocouples type TPR-2085 and TBP 2085. The advantage of the presented tools temperature measuring of melts in front of the variety of thermometers available on the market today, is the detuning of the measurement results from the acquisitions of gas environments, uncertainties associated with unknown coefficients blackness melts, influences of the rereflected radiations

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