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CONTINUOUS LIGHT-GUIDE CONTROL OF MELTS TEMPERATURE IN INDUCTION FURNACES

Abstract. *The article is devoted to the question of the most effective for the full use of the induction furnaces technological flexibility continuous temperature control. The aim of the work is to create a light-guide technology for continuous temperature control of the processes of induction melting, treatment and pouring of liquid metal in metallurgy of machine building. The investigations of crucible and channel, melting, holding and pouring induction furnaces from the standpoint of light-guide thermometry have been developed. Materials, designs, as well as technologies of manufacturing, mounting and safe operation of the light-guide and auxiliary devices have also been investigated. Using the results of complex studies, the base light-guide thermometry system, general and particular methods of the light-guide temperature measurements have been developed. On the base of the Huygens construction, as well as the laws of geometric and crystal optics, techniques for calculation of the optical characteristics of the light-guide and focusing devices, as well as schemes of their optical joint have been developed. These techniques increase the metrological characteristics of the light-guide thermometry. Standard construction of the secondary part of thermometry system requires classical pyrometry methods application. These methods are acceptable for continuously operated metallurgical aggregates, where stable emissivity of the light-guide operating end takes place. The secondary part of thermometry system has been modernized in order to widen application field of light-guide thermometry on periodically operated metallurgical aggregates where emissivity of light-guide immersion end randomly changes. Modernized secondary part is purposed for spectral (multicolor) pyrometry methods realization. These methods minimize influence of the instability of emissivity of light-guide immersion end on methodical errors of temperature measurements. Research and industrial exploitation, at domestic and foreign enterprises, have shown obvious metrological advantages of the light-guide thermometry technology in comparison with known solutions. Implementation of the light-guide thermometry systems on induction furnaces has high technical-economic efficiency, including by reduction the spoilage of metal products and resource costs for production.*

Keywords: induction furnace, continuous temperature control, light-guide thermometry, amorphous, poly- and single-crystalline materials, measurement error, Huygens construction, technical-economic efficiency.

1. Introduction

Nowadays the problem of redundant, technically unjustified electrical and heat energy consumption in the course of melting, treatment and pouring processes is very topical for metallurgy [1]. So, for example, for steel making plants which use arc and induction melting furnaces, real energy consumption exceeds theoretically calculated values on 35–100 %. Additionally, the losses due to the imperfection of treatment and pouring processes take place. As a result of these losses the value of electrical energy per unit of ready production exceeds calculated value in 3–6 times. So, it is very important to reduce energy consumption for metallurgy in general.

By the authors opinion, the most efficient way of energy consumption decreasing in metallurgy is continuous measurement of melts temperature directly in metallurgical furnaces and aggregates with following optimal its regulation in the course of technological/production process – i.e., continuous temperature control. Imperfection and, especially, lack of the temperature control are impermissible for modern enterprises. Due to this fact the number of defect metal products increases, probability of emergency situations sharply increases, energy costs exceed calculated ones in several times, resource of metallurgical aggregates lining decrease. Correspondingly, continuous temperature and especially high-temperature control allow avoiding mentioned problems and due to this has high efficiency and fast payback. For example, continuous temperature control on one tundish of TATA Steel Company (department in Netherlands, 2017) provides economy 2.36 million EUR per [2].

Nowadays from 1 to 2 billion USD have been spent in the world for development of continuous temperature control of converter process. Nevertheless, this problem has not yet been solved. In converter production periodical temperature measurements with thermoelectric immersion transducers are being still used. Mentioned high expenses on development of continuous temperature control confirm its high technical-economic efficiency on converters, actuality and complexity of this problem. Proposed light-guide thermometry together with modern ceramic materials, including nanomaterials, ensure serious preconditions for solving this worldwide problem [2].

Cupolas of various types, arc and induction crucible/channel melting, holding and pouring furnaces are used for obtaining, treatment and pouring of liquid metal. Induction furnaces differ from cupolas and arc furnaces by high technological flexibility which allows to:

- load metal charge and subcharge materials with different volumes at necessary sequence and temperature;
- the melt being overheated to determined temperatures;
- perform the melt treatment, including slag and thermal-time, as well as add modifying and doping components;
- pour the metal with necessary volumes and at determined temperatures;
- achieve high homogeneity of alloys structure due to the continuous stirring of the melt under electromagnetic field [3].

High technological flexibility provides typical for modern metallurgy of machine building implementation of induction technologies. So, in the world, beginning from 1960-s, induction melting equipment began to replace cupola furnaces. This process intensified in the middle of 1970-s, when tiristor control of induction furnaces were implemented. For example, in China in 2016 the part of cast iron melted in cupolas consisted about 35 % and decreasing continued [4]. In USA, beginning from 2010, the number of operating cupolas decreased in 2 times, at the same time the number of induction furnaces increased in 2.5 times. Remarkable is the fact, that among the world amount of induction furnaces more than 80 % belong to middle-frequency furnaces and can be used for any alloys obtaining, including cast iron [5, 6]. Induction crucible furnaces of industry frequency (50 Hz) consist overwhelming majority of them.

The purpose of this work is to develop the light-guide technology of continuous temperature control of induction melting, treatment and pouring of liquid metal in metallurgy of machine building with following estimation of the metrological characteristics of this technology under industrial conditions.

2. Materials and methods

Induction furnaces are complicated objects for temperature measurements. For example, in [7] the question of melt temperature measurement by thermoelectric transducers is considered. But operating induction furnace is characterized by high level of electromagnetic disturbances on thermoelectric measurement circles with all following consequences. These consequences restrict application of such decision even for periodical measurements. Therefore indirect, on energy consumption, methods of continuous melts temperature measurements for induction pouring and holding furnaces have been proposed by a number of specialists [8–12]. They are based on temperature estimation by solving, for necessary time points, equation of thermal balance for the furnace. For this purpose, consumed electrical power, as well as heat flow to be lost by the furnace are being measured simultaneously. For example, in work [8] for liquid steel temperature estimation they have proposed to measure the temperature of cooling water near the outer wall of the furnace. Such methods require complicated multiple-factor models of heat exchange between the furnace and environment medium to be built. They operate correctly only when conditions for which they had been built are strongly met. Due to the complexity of taking into consideration of a large number of factors which influence on induction melting and treatment processes, such indirect methods for temperature estimation were not widely implemented in metallurgy. L.F. Zhukov in [13] proved that energy consumption strictly depends on random complicatedly controlled conditions of industrial application of induction technologies, including:

- slagging, metallization and deterioration of lining;
- feeding-discharge and temperature regimes of furnace filling by liquid metal;
- relation of masses between sump and feeding charge/subcharge materials;
- thermal-time, modifying and doping treatment of melt;
- temperatures of melt overheating and discharging;
- furnace power.

In general influence of more than 10 factors has been studied under industrial conditions, on the furnaces of ICHT type with capacity 2.5; 6.0 and 10 t. It has been proved that energy consumption for the same overheating temperature differs on 45 % under different conditions. This value determines methodical error of indirect temperature measurement. In principle, such indirect temperature control is possible only for the stage of melt overheating, using temperature corrections on the base of periodical temperature measurements by thermoelectric transducer. At the same time the furnace should be turn off in order to exclude impact of alternative electromagnetic field on results of temperature measurements. However, at the same time, the most resource and energy consumptive stage of furnace filling by liquid metal remains without temperature measurements and control.

For passing through and quasi-passing through metallurgical aggregates, including cupolas and arc furnaces, contactless optical thermometry has no alternative. Construction and operating regimes of induction furnaces exclude traditional optical contact of pyrometer through the accompanying gaseous media. From the part of hearth and side walls melt is covered by furnace construction elements. From the top side melt is covered by layer consisting of feeding metal charge, subcharge materials and slag [14]. Therefore, induction furnaces refer to metallurgical aggregates of closed type from optical thermometry position. Such type of aggregates excludes continuous contactless control of liquid metal temperature with the help of pyrometers, sighted on melt mirror via accompanying gaseous medium (Fig. 1, a).

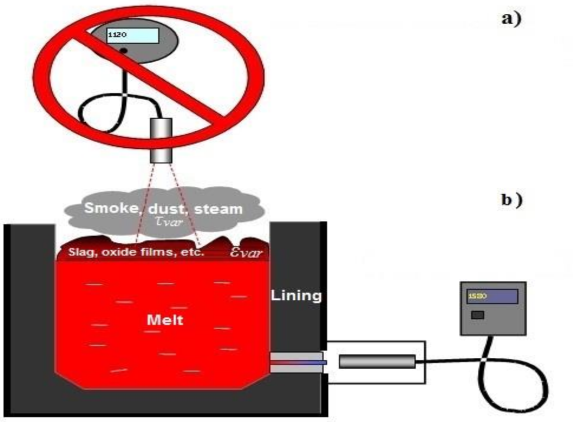

Fig. 1. Potentially possible realization schemes of continuous contactless (a) and light-guide (b) temperature control of metal melt in induction crucible furnace

Analysis of construction and operating conditions of induction crucible furnaces indicates necessity of the light-guide thermometry technologies use (Fig. 1, b). Under industrial conditions significant methodical errors of contactless temperature control exclude it application. Even though it is possible to direct the pyrometer on the melt after slag removing (before metal discharging), errors of such ineffective temperature measurement (Fig. 1, a) under random influence of oxide films, turbulence of the melt, which cause emissivity (ε_{var}) of melts surface instability, as well as under influence of melting products, which cause transparency of accompanying intermediate medium (τ_{var}) instability for classical optical pyrometry reach unacceptable 8 % and more. In this case the most effective continuous temperature control necessary for optimal resource and energy saving control of processes of furnace filling by liquid metal, as well as treatment and pouring, is excluded.

The complex theoretical and experimental studies of metallurgical equipment from positions of the light-guide thermometry under conditions of obtaining, treatment and pouring of liquid metal have been performed for technical realization of light-guide temperature measurements. In particular, it has been investigated [13]:

- constructions and operating regimes of the induction furnaces;
- deterioration, metallization, slagging and temperature fields of the lining;
- operating regimes of light-guide units and optimal zones of their mounting;
- materials, constructions, technologies of production, mounting and cooling regimes of the light-guide units and lining.

Experimental studies of materials, constructions, technologies of production and mounting of measurement accessories, auxiliary, light-guide and focus units, primary pyrometric transducers and schemes of their optical joint have been performed. The general and particular, for main types of metallurgical aggregates, methods of light-guide thermometry have been developed. The measurement principle of these methods is based on light-guide generation and transmission through the lining of metallurgical aggregate electromagnetic heat radiation, thermometric parameters of which are unambiguously coherent with the temperature of controlled melt.

3. Results and discussion

On the base of carried out complex of theoretical and experimental studies several modifications of the light-guide systems for continuous control, registration and indication of melts temperature in metallurgical aggregates, including induction crucible and channel melting, holding and pouring furnaces, have been developed. Functional scheme of the basic light-guide thermometry system is showed on Fig. 2.

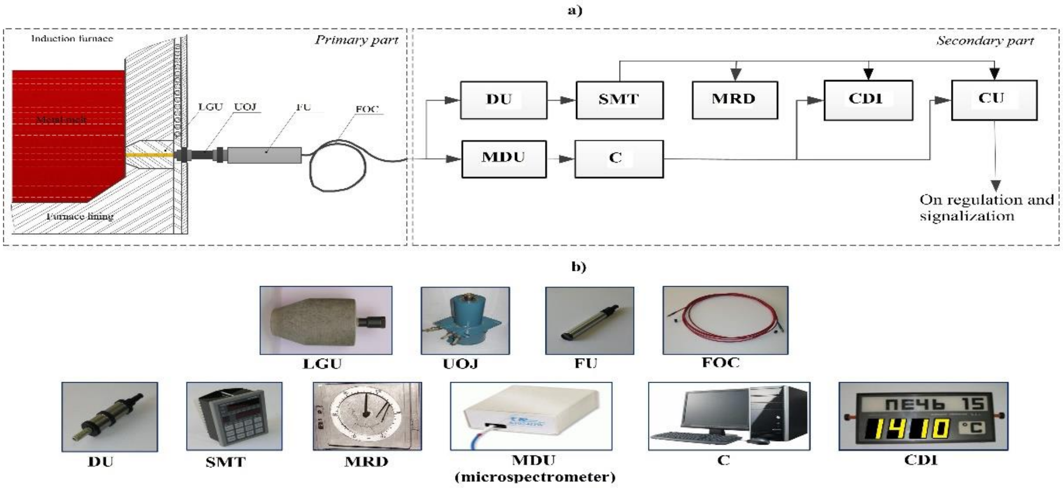

Fig. 2. Functional scheme (a) and elements (b) of the basic light-guide thermometry system

The light-guide thermometry system consists of primary individual and secondary universal electronic parts. The primary part, being adopted to the conditions of metallurgical aggregates, consists of light-guide unit (LGU), unit of optical joint (UOJ), focus unit (FU) and fiber-optical cable (FOC). The secondary part consists of detecting unit (DU), secondary measurement transducer (SMT), measuring-recording device (MRD), carry-out digital indicator (CDI) and control unit (CU).

LGU provides stable generation and transmission through the lining of metallurgical aggregate electromagnetic heat radiation, thermometric parameters of which are unambiguously coherent with the temperature of controlled melt. Construction of the LGU is showed on Fig. 3.

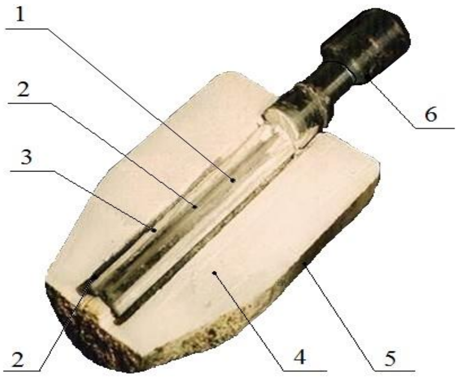

Fig. 3. Construction of the LGU

LGU is the most responsible element which determines metrological characteristics, exploitation reliability and safety of thermometry system. The materials and construction of the LGU have to meet very strong requirements, as much as they work under harsh conditions of long-term mechanical, temperature and chemical influence of the lining and melting products. The main element of the LGU is the light-guide (1), which is the rod made of amorphous or single-crystalline SiO_2, Al_2O_3 and BeO. The light-guide is reinforced by load-bearing construction. For example, this construction is made of fused ceramics based on ZrO_2, Al_2O_3 and SiO_2, combined with the lining and controlled melt. Additionally, the light-guide has to have stable transmissivity of electromagnetic heat radiation of the melt, in operating spectral range of primary pyrometric transducers, during all campaign of the lining at technological temperatures of metallurgical equipment.

It should be noted that in contact with the metal melt, the immersion end of the light-guide is covered with a film [13]. It was experimentally established that after several hours of operation of the light-guide in a pacific metal bath, the thickness of the film reaches 150–300 μm. With intense electromagnetic stirring of the melt, the thickness of the film does not exceed the thickness of the boundary layer which borders to the immersion end of the light-guide. For a stirring speed of the melt 1–4 m/s, the thickness is from 3 to 21 mm. When examining the film that formed after 2 hours of work, it was established that the film consists of a mixture of α-quartz and α-cristobalite, and the concentration of α-quartz prevails. Furthermore, the film consists of $Al_2O_3 \cdot SiO_2$, FeO and $\gamma\text{-}Fe_2O_3 \cdot H_2O$. After 14 and 1080 hours of light-guide operation phase composition of the film did not change, but modifications of α-quartz and α-cristobalite redistributed. The main modification became α-cristobalite. It has been established by calculation and experimental way that normal spectral emissivity of the mentioned film in spectral range 0.8–1.8 μm and at temperature of light-guide immersion end 1600 °C consists of 0.8–0.9 [13]. Influence of the emissivity, as well as losses of radiation by light-guide material (scattering, absorption and Fresnel reflection from outer end) are accounted when calibration of the measurement system is performed on the object for the methodical error of temperature measurement to be excluded.

The light-guide is placed on the ceramic pipe (3) axis. Circular gap between light-guide and load-bearing pipe is compacted by reinforcement material (2). For example, this material is developed on the base of spheroidal Al_2O_3, AlN or BN with application of ceramic nanotechnologies. The nano-size inclusions should improve the mechanical and heat-resistant properties of the LGU. The described light-guide assemblage is placed on the axis of force block (4) with non-stick coating (5). Circular gap between load-bearing pipe and force block is also compacted by reinforcement material (2). Light-guide bushing (6) is mounted on the outer end of load-bearing pipe and purposed for mechanical joint of the UOJ, by thermal-blocking thread, with light-guide (1). The LGU is being installed in aggregate lining, by immersion end in contact with the melt. It is purposed for operation during all lining campaign (from 1 month to 2.5 years). Mounting zone should the most fully meet requirements of the light-guide thermometry [13].

UOJ provides optical joint between FU and LGU, as well as their hermetic sealing, mechanical protection and cooling. Engineering techniques to calculate the schemes of optical joint of optical-electronic transducers of radiation (placed in DU) with straight immersion isotropic and anisotropic light-guides with straight faces have been developed for the next conditions [15]:

- at $d_{\mathrm{e.h.}} > d_{\mathrm{e.p}}$ and $n_{21}=1$

$$d_{\mathrm{lg}} > D_{\mathrm{f.v.}} = 2\cdot L_{\mathrm{i.e.\text{-}e.p}}\cdot\left(1-\frac{d_{\mathrm{e.p}}}{d_{\mathrm{e.h}}}\right)\cdot \mathrm{tg}(\omega) - d_{\mathrm{e.p}}, \tag{1}$$

- at $d_{\mathrm{e.h.}} > d_{\mathrm{e.p}}$, $n_{21}>1$ and $n_{21}<1$

$$d_{\mathrm{lg}} > D_{\mathrm{f.v}} = 2\cdot\left(1+\frac{d_{\mathrm{e.p}}}{d_{\mathrm{e.h}}}\right)\cdot\left[\left(L_{\mathrm{i.e.\text{-}e.p}} - L_{\mathrm{lg}}\cdot\left(1-\frac{1}{\sqrt{n_{21}^2\cdot(n_{21}^2+1)\cdot\left(1+\frac{d_{\mathrm{e.p}}}{d_{\mathrm{e.h}}}\right)^2\cdot \mathrm{tg}^2(\omega)}}\right)\right]\cdot \mathrm{tg}(\omega) - d_{\mathrm{e.p}}, \tag{2}$$

- an anisotropic light-guide is made of single-axis crystal, optical axis of which doesn't coincide with the geometrical axis of a rod

$$d_{\mathrm{lg}} > D_{\mathrm{f.v}} + L_{\mathrm{o.r\text{-}n.r}}. \tag{3}$$

At the same time, to exclude limitation of the radiant flux by the side surface of the outer part of the light-guide the next condition should be met

$$d_{\mathrm{lg}} > 2\cdot(L_{\mathrm{i.e\text{-}e.p}} - L_{\mathrm{lg}})\cdot\left(1-\frac{d_{\mathrm{e.p}}}{d_{\mathrm{e.h}}}\right)\cdot \mathrm{tg}(\omega) + d_{\mathrm{e.p.}}. \tag{4}$$

The second term in right part of the expression (3) have been determined on the basis of Huygens construction, as well as laws of geometrical optics and crystal optics

$$L_{\mathrm{o.r\text{-}n.r}} = L_{\mathrm{lg}}\,\frac{(n_{\mathrm{n.r}}^2 - n_{\mathrm{o.r}}^2)\mathrm{tg}(\alpha)}{n_{\mathrm{o.r}}^2\mathrm{tg}^2(\alpha) + n_{\mathrm{n.r}}^2}. \tag{5}$$

In formulas (1–5) the following symbols are agreed: d_{lg} – diameter of the light-guide, m; $D_{\mathrm{f.v}}$ – diameter of the field of vision, m; $L_{\mathrm{i.e\text{-}e.p}}$ – distance from immersion end of the light-guide to the entrance pupil, m; $d_{\mathrm{e.h}}$ – diameter of entrance hatch of the transducer, m; $d_{\mathrm{e.p}}$ – diameter of entrance pupil of the transducer, m; ω – the half of the angle of transducer field of vision, °; L_{lg} – length of the light-guide, m; $L_{\mathrm{o.r\text{-}n.r}}$ – length between ordinary and non-ordinary rays, which come out from the light-guide, m; α – angle between optical and geometrical axes of crystal, °; n_{21} – coefficient of light-guide material refraction relatively to the intermediate medium; $n_{\mathrm{o.r}}$ – coefficient of ordinary ray refraction; $n_{\mathrm{n.r}}$ – coefficient of non-ordinary ray refraction.

Proposed calculation techniques provide technical realization of optical joint between primary pyrometric transducers and straight immersion light-guides, which have straight faces. Such optical joint increases metrological characteristics of light-guide thermometry due to exclusion of transducers field of vision limitation, vignetting of radiant flux and influence of background radiation from side surface of the light-guide. Mentioned factors cause significant methodical component in measurement error of light-guide temperature measurements on working with sump and, even more, with full discharge induction crucible melting furnaces. Due to this component temperature measurement error of induction melting exceeds in 2 and more times an error of light-guide temperature control with using of proposed techniques of optical joint (≥26 °C at confidence level 0.95).

FU collects heat radiation, transmitted by LGU from depth of metallurgical aggregate, and directs it into the FOC, which transmits radiation on DU. DU is photonic transducer of radiation, which is also called sandwich-detector. It is sensitive for radiation in 2 spectral ranges in visible and near infrared bands of spectrum. SMT performs analog to digital conversion, processes obtained primary pyrometric information in accordance with algorithms of classical pyrometry methods and calculates sought temperature of the melt. Information about the current value of liquid metal temperature is being brought out on CDI, MRD and CU for indication, registration, regulation/signalization, respectively.

Standard construction of the secondary part of thermometry system is purposed only for classical one- or two-color pyrometry methods application [13]. For continuously operated aggregates, which are permanently filled by liquid metal, classical methods are rather acceptable, because of the emissivity of the immersion end of light-guide remains stable during all period of aggregate operation. Usually, the aggregate period of continuous operation is determined by operation term (campaign) of it lining. Cyclic heat changes, which cause unexpected changes of film thickness on the light-guide immersion end take place in periodically operated aggregates, including operating with full discharge (tapping) induction furnaces. Respectively, the emissivity of immersion end, which determines methodical error of temperature measurement, unexpectedly changes too. In order to widen application field of the light-guide thermometry technology on periodically operated aggregates, the secondary part of thermometry system has been modernized. This modernization allows realizing the methods of spectral (multicolor) radiation pyrometry. They minimize influence of emissivity instability of the light-guide immersion end on methodical error of temperature measurement by the way of multicolor (3 or more waves) algorithms of primary pyrometric information processing. At the same time, it is not necessary to calibrate measurement system by the thermoelectric transducer. Modernization of secondary part of the system means that DU and SMT have been replaced on multicolor detecting unit (MDU) – microspectrometer and computer (C), respectively (Fig. 2). As an MDU the microspectrometer S2000 (Ocean Insight Inc., USA) have been applied. This device allows registering the brightness of radiation on 2048 wavelength in spectral range 0.5–1.1 μm.

In the course of industry exploitation metrological characteristics of the light-guide thermometry on the base of methods of classical radiation pyrometry have been investigated. It has been proved that, in contrast to existing technical solutions, the light-guide thermometry technologies, for the first time in world practice, provide continuous temperature control of melts, including high-temperature ones, directly in metallurgical aggregates. These aggregates include operating continuously or with sump, crucible and channel, melting, holding and pouring induction furnaces. The limit errors of temperature measurements in mentioned furnaces are respectively 12.8; 9.8 and 8.6 °C, at confidence level 0.95. Technical realization of the light-guide temperature control for induction furnaces is shown on Fig. 4.

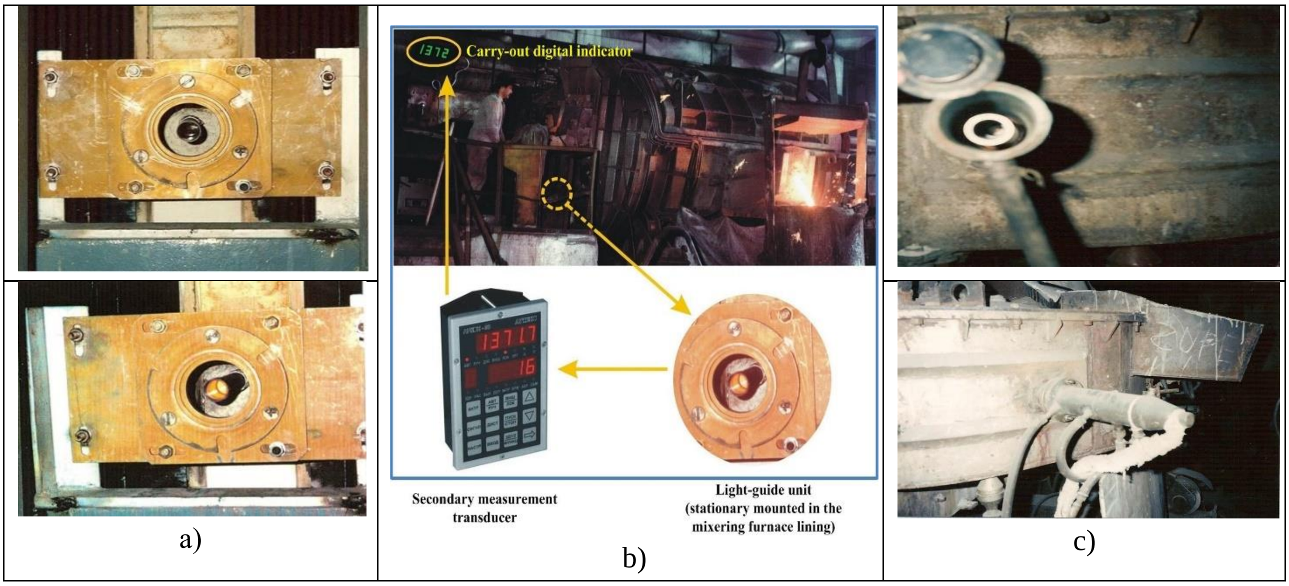

Fig. 4. Continuous light-guide control of liquid metal temperature in induction melting (a), holding (b) and pouring (c) furnaces

To investigate metrological characteristics of the light-guide thermometry under conditions of metallurgical enterprises the technique of comparative measurements has been used. This technique has been developed by the highest metrological organization – VNIIM named after D.I. Mendeleev with L.F. Zhukov participation [13]. Comparative measurements have been performed by the light-guide thermometry system under consideration and reference short-time immersion thermoelectric thermometer of TPR-2075 type with nominal static characteristic (NSC) of B-type.

Comparative tender tests of the light-guide technology (Ukraine) and the technology with blowing tuyere (Germany) have been carried out on foreign enterprise (MIRDC, Taiwan). Much higher metrological characteristics and exploitation advantages of the light-guide technology have been proved as a result of these tests. For example, on induction crucible steel-melting furnace limit measurement error reached respectively 3.5 and 65.0 °C, within the temperature range 1400–1750 °C, at confidence level 0.95.

At present day the light-guide thermometry technology has also been adopted for heating furnaces (Fig. 5).

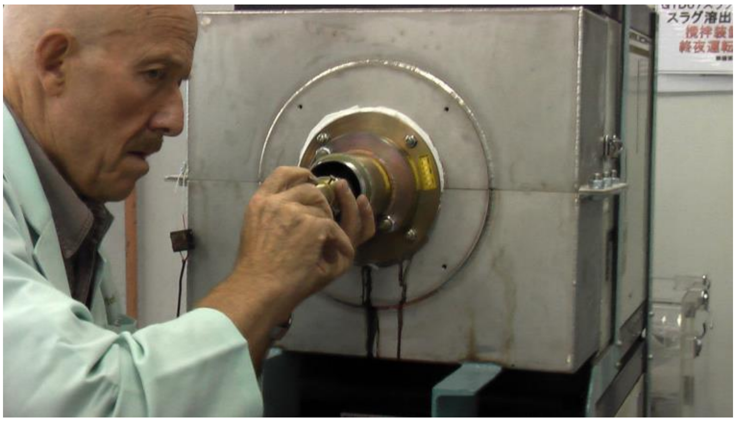

Fig. 5. Mounting of the light-guide thermometry system on heating furnace (Nippon Steel and Sumitomo Metal Corporation – Japan, Kimitsu, 14.07.2011)

Long-term tests of the light-guide technology have confirmed its efficiency and prospectivity for continuous precision high-temperature control on heating furnaces under industrial conditions. For comparative periodical short-time temperature measurements in heating furnace reference thermoelectric thermometer of TPP type with NSC of S-type has been applied. During tests deviations of readings between the light-guide system and reference thermoelectric thermometer have not been observed. Here we should note that in continuous operation regime under test conditions drift of the NSC of such type thermoelectric thermometer reaches 1 % during 24 hours [13].

Operation under industrial conditions at domestic and foreign enterprises has shown that the light-guide thermometric technology:

- provides continuous temperature control directly in metallurgical aggregates of a closed type during all stages of obtaining, treatment and pouring of liquid metal;
- is promising for application on converters, blast, arc, heating furnaces, as well as glass-melting and coke furnaces; on sets for continuous casting; as well as for continuous temperature control of high temperature part of Thermal Power Plants boiler units;
- does not complicate the operation of heat engineering and metallurgical equipment, including feeding charge materials, slag removing, liquid metal tapping, etc.;
- compared to contactless optical thermometry, the technology increases the accuracy of measurements due to the redistribution of radiation over the spectrum, elimination of the optical characteristics instability influence of controlled surface and intermediate medium and the increase in the degree of correlation between thermometric parameters of the radiation, formed and transmitted by the light-guide with measured temperature.

Continuous temperature control of metal melts directly in furnaces stimulates investigations and resource-, including energysaving, optimization of continuous and sump processes of obtaining, treatment and pouring of liquid metal. For example, investigations on industrial induction furnaces have shown that implementation of developed on the base of continuous light-guide temperature measurements technological algorithms of control, including implemented in Production Control System of induction melting, provide high technical-economic characteristics (Table 1) [16].

Table 1. Technical-economic characteristics of the continuous light-guide temperature measurements and technological processes control on its base

Developments names	Objects	Technical-economic characteristics				
		Spoilage reduction «due to the temperature», %	Waste reduction, %	Lining resource increase, %	Decrease in the consumption of electric power, %	Melting productivity increase
Light-guide thermometry technologies	Induction melting, holding and pouring furnaces	20–60	20–30	20–90	10–30	-
Technological algorithms of control		20–40	–	30–50	20–40	20–30

Algorithms of control, based on the continuous light-guide temperature measurements provide maximum level of mentioned technical-economic indices on metallurgical enterprises of machine-building metallurgy with large-scale production of castings on the base of mono-, duplex- and triplex processes of obtaining, treatment and pouring of liquid metal.

4. Conclusions

Thus, it has been determined, that full use of induction furnaces technological flexibility can be realized only on the base of continuous measurement and regulation of melts temperature.

Disadvantages of indirect (by energy consumption) methods of temperature measurements in induction furnaces have been shown. In particular, it has been proved that energy consumption, for the same overheating temperature, differs on 45 % in dependence on different combinations of factors which influence on conditions of melting. Respectively, such dispersion of energy consumption transforms into the error of indirect temperature measurement.

The necessity of the use of light-guide thermometry technology for continuous temperature control of melts in metallurgical aggregates of closed type, which include induction furnaces, is proved. For technical realization of light-guide temperature control complex investigations of induction crucible and channel, melting, holding and pouring furnaces have been carried out from position of light-guide thermometry. Experimental studies of materials, constructions, technologies of production and mounting of measurement accessories, auxiliary, light-guide and focusing units have been performed.

On the base of performed investigations and developments, as well as modern amorphous, poly- and single-crystalline materials, optoelectronic and computer technologies the base light-guide thermometry system has been created. The measurement principle is based on light-guide generation and transmission through the lining of metallurgical aggregate electromagnetic heat radiation, thermometric parameters of which are unambiguously coherent with the temperature of controlled melt.

On the basis of Huygens construction, as well as laws of geometrical optics and crystal optics the techniques for calculation of optical characteristics of light-guide and focusing units, as well as schemes of their optical joint have been developed. These developments increase metrological characteristics of the light-guide thermometry. In order to widen application field of light-guide thermometry on periodically operated metallurgical aggregates (where emissivity of light-guide immersion end randomly changes) the secondary part of thermometry system has been modernized on the base of microspectrometer and computer. Such modernization allows realizing the methods of spectral (multicolor) pyrometry, which minimize the emissivity instability influence of light-guide immersion end on methodical error of temperature measurement.

Investigations under industrial conditions have shown that light-guide thermometry technology (using the classical radiation pyrometry methods), for the first time in world practice, provides continuous temperature control of melts within the range 1200–1750 °C, during lining life duration (up to 2.5 years) in induction crucible and channel, melting, holding and pouring furnaces with limit errors respectively 12.8; 9.8

and 8.6 °C, at confidence level 0.95. As a result of comparative tender tests, it has been determined that measurement errors of the light-guide and blowing tuyere thermometry technologies do not exceed respectively 3.5 and 65.0 °C within the temperature range 1400–1750 °C. During tests on heating furnaces the readings deviations between the light-guide system and reference thermoelectric thermometer have not been established.

Tests and operation of the light-guide thermometry technology under industrial conditions confirm it high technical-economic indices, including due to the spoilage of metal products and resource expenses reduction, in particular energy expenses, for its obtaining.

References

1. Peaslee, K., Richards, V., & Smith, J. (2012). Melting Efficiency Improvement. Final Technical Report. *Missouri University of Science and Technology*, 42 p. URL: https://www.osti.gov/servlets/purl/1051407 (Last accessed: 11.09.2023).
2. Zrazhevskiy, A.D., Nogovitsyn, A.V., & Derbenev, D.V. (2017). VII The 7-th Conference of Ukrainian Steelmakers (review of reports). *Metal and Casting of Ukraine*, 11-12(294-295), 53–59 [in Russian].
3. Pachkolin, Yu., Bondarenko, A., & Levchenko, S. (2018). Practical application of mathematical models of electro-thermo-mechanical processes in industrial induction furnaces with the aim of increasing their energy efficiency. *Technology audit and production reserves*, 5, 1(43), 28–33 [in Ukrainian]. https://doi.org/10.15587/2312-8372.2018.146484
4. Development and application status of cast iron melting furnace at home and abroad. *ZHY Casting*. URL: https://www.zhycasting.com/development-and-application-status-of-cast-iron-melting-furnace-at-home-and-abroad/ (Last accessed: 16.07.2023).
5. Gandhewar, V.R., Bansod, S.V., & Borade, A.B. (2011). Induction furnace – a review. *International Journal of Engineering and Technology*, 3, 277–284.
6. Kulkarni, U., & Wali, U. (2020, July 2–4). Power efficiency tracking of induction furnaces. *In Proceedings of the 2020 IEEE International Conference on Electronics, Computing and Communication Technologies.* India, Bangalore, 1–4.
7. Smalcerz, A., & Przylucki, R. (2013). Impact of electromagnetic field upon temperature measurement of induction heated charges. *International Journal of Thermophysics*, 34, 667–679. https://doi.org/10.1007/s10765-013-1423-1
8. Kisel'gof, Ye.S. (1985). The algorithms of melts continuous temperature control during melting in induction crucible furnace. *Automatic systems of technological processes control*, 103–106 [in Russian].
9. Kuvaldin, A., Pogrebisskiy, M., & Fedin, M. (2008). Control system of the induction crucible mixer with indirect estimation of the temperature. *Przegląd Elektrotechniczny*, 84(11), 149–153. URL: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BPOB-0014-0015 (Last accessed: 12.09.2023).
10. Pansuwan, A., Smerpitak, K., & Ukakimaparn, P. (2009, March 18–20). Temperature estimation of liquid steel in induction furnace. *Proceedings of the International MultiConference of Engineers and Computer Scientists*. Hong Kong, II. URL: https://www.iaeng.org/publication/IMECS2009/IMECS2009_pp1326-1330.pdf (Last accessed: 29.04.2023).
11. Adetunji, O., Ojo, S., Oyetunji, A., & Itua, N. (2021). Melting Time Prediction Model for Induction Furnace Melting Using Specific Thermal Consumption from Material Charge Approach. *Journal of Minerals and Materials Characterization and Engineering*, 9, 61–74. https://doi.org/10.4236/jmmce.2021.91005
12. Barba Rossa, G., Sauvage, E., & Brun, P. (2017). Indirect method of measuring glass temperature in a Cold Crucible Induction Melter. *In Processing of XVIII International UIE – Congress on Electrotechnologies for Material Processing*. URL: https://cea.hal.science/cea-02434032/document (Last accessed: 12.09.2023).
13. Zhukov, L.F. (1992). Investigation and development of methods and means of temperature control and resource-saving technological processes of liquid cast-iron production in foundry engineering. [Dr. Sci. (Engin.)]. Kyiv: Institute of Foundry Problems of Academy of Sciences of Ukraine, 505 p. [in Russian].
14. Luzgin, V.I., Petrov, A.V., Rachkov, S.A., & Yakushev, K.V. (2006). Induction medium-frequency melting complexes with furnaces with a capacity of 1-16 tons for foundry production. *Metal and Casting of Ukraine*, 5(69), 34–39 [in Russian].
15. Zhukov, L.F. (2001). Optical joint of optoelectronic radiation converters with immersion light guides and calculation of their characteristics. *Journal of Engineering Physics and Thermophysics*, 74(5), 123–126 [in Russian].
16. Zhukov, L.F., Bogdan, A.V., Goncharov, A.L., & Smirnov, M.I. (2010). Temperature control of metallurgical processes, equipment and materials. *Bulletin of the Donbas State Machine-Building Academy*, 3(20), 99–106 [in Russian].

БЕЗПЕРЕРВНИЙ СВІТЛОВОДНИЙ КОНТРОЛЬ ТЕМПЕРАТУРИ РОЗПЛАВІВ В ІНДУКЦІЙНИХ ПЕЧАХ

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Анотація. *Статтю присвячено питанню безперервного контролю температури розплавів, який є найбільш ефективним для повного використання технологічної гнучкості індукційних печей. Мета роботи полягає в розробці технології світловодної термометрії для безперервного термоконтролю процесів індукційної плавки, обробки й розливання металу в металургії машинобудування. Виконано дослідження тигельних й канальних, плавильних, міксерних й розливних індукційних печей з позицій світловодної термометрії, а також вивчено матеріали, конструкції, технології виготовлення, монтажу й безпечної експлуатації світловодних й допоміжних пристроїв. З використанням результатів комплексних досліджень розроблено базову світловодну термометричну систему, а також загальний та часткові методи світловодного вимірювання температури. На основі побудови Гюйгенса, а також законів геометричної оптики й кристалооптики отримано методики розрахунків оптичних характеристик світловодних й фокусуючих пристроїв, а також схеми їх оптичного зчленування, які підвищують метрологічні характеристики світловодної термометрії. Стандартне виконання вторинної частини системи обумовлює використання методів класичної пірометрії випромінення. Ці методи є прийнятними для безперервно працюючих металургійних агрегатів, в яких випромінювальна здатність імерсійного торця світловода залишається сталою. З метою розширення області застосування світловодної термометрії на металургійні агрегати з періодичним режимом роботи, у яких випромінювальна здатність імерсійного торця світловода випадково змінюється, модернізовано вторинну частину термометричної системи. При цьому використовуються методи спектральної пірометрії випромінення, які мінімізують вплив нестабільності випромінювальної здатності імерсійного торця світловода на методичну похибку вимірювання температури. Дослідження в ході промислової експлуатації на вітчизняних й закордонних підприємствах показали явні метрологічні переваги світловодної технології порівняно з іншими відомими рішеннями. Впровадження світловодних термометричних систем на індукційних печах характеризується високою техніко-економічною ефективністю, в тому числі за рахунок зниження браку металопродукції й ресурсозатрат на її виробництво.*

Ключові слова: індукційна піч, безперервний термоконтроль, світловодна термометрична технологія, аморфні, полі- й монокристалічні матеріали, побудова Гюйгенса, похибка вимірювань, техніко-економічна ефективність.

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