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COMPARISON OF CRATER GEOMETRY DURING TOP BLOWING IN AN OXYGEN CONVERTER UNDER LOW- AND HIGH-TEMPERATURE MODELLING CONDITIONS

Introduction. *The oxygen converter process for liquid steel production requires continuous improvement to enhance process efficiency and steel quality.*

Problem Statement. *Most technological improvements have focused on the development of advanced top-lance designs. Their implementation requires physical modelling under both low-temperature (using low-melting-point liquids) and high-temperature (using molten iron-carbon alloys) conditions. Although low-temperature modelling is widely used because of its simplicity and lower cost, strict compliance with similarity criteria does not ensure the direct transferability of the results to industrial steelmaking. Therefore, reliable approaches for interpreting low-temperature modelling results under real process conditions are required.*

Purpose. *To establish the relationship between gas jet penetration into a liquid bath under low- and high-temperature modelling conditions using transparent-wall physical models.*

Materials and Methods. *Low-temperature modelling (air blowing into a water model) and high-temperature modelling (oxygen blowing into a molten steel bath) have been performed using the same single-nozzle top lance under comparable technological conditions on transparent-wall physical models. The geometric parameters of the interaction crater have been measured and analyzed.*

Results. *Significant differences in crater formation during gas-liquid interaction under low- and high-temperature conditions have been identified. Under identical blowing conditions, the crater wall inclination angle has been found to be 1.4–1.5 times smaller, the crater depth decreases up to 7 times,*

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and the crater diameter is reduced by up to 35% during high-temperature modelling. The experimentally obtained crater geometry has formed the basis for developing empirical equations describing the crater diameter and depth under high-temperature blowing conditions.

Conclusions. Empirical equations for predicting crater diameter and depth during gas jet interaction with a liquid bath under top-blowing conditions have been developed based on the results of physical modelling. The proposed equations account for the physical properties of the model liquids and gases. Their principal advantage has been demonstrated by enabling the prediction of crater geometry in industrial molten steel using data obtained from low-temperature physical modelling.

Keywords: top blowing, gas jet, crater, low-temperature modelling, high-temperature modelling, interpretation of results.

Modern fundamental metallurgical science aims to develop modelling theories, among which modelling of oxygen converter processes plays an important role as the only currently economically and technologically competitive process for the production of liquid steel [1]. Namely, the development and improvement of methods of low-temperature modelling (under conditions of blowing most often with air, as the most accessible gas, and with model media of liquids with low melting points) and high-temperature modelling (under conditions of blowing with oxygen or air of molten metals and their alloys, which are characterised by high melting points). An important task is to develop methods for analysing and interpreting modelling data, determining the relationship between the results of low-temperature and high-temperature modelling, which allow the results of low-temperature modelling to be interpreted for real-world conditions as well.

Both modelling approaches have been developed in parallel for several decades. Each has its own specific focus, determined by the physical capabilities of the modelling technique, as well as its inherent advantages. The first approach is low-temperature modelling, which, owing to the transparency of both the modelling liquid and the experimental unit, has enabled comprehensive investigations of the aerohydrodynamic interaction between gas jets discharged from various blowing devices and the surrounding liquid medium. Previous studies [2–13] have reported the characteristics of gas jet penetration into a liquid bath using water and air as modelling media at gas flow rates ranging, for example, from 0.0176 to 0.129 m³/min [2] and

from 0.005 to 0.07 m³/min [5, 6]. It should be noted that these flow rates are considerably lower than those used under industrial steelmaking conditions and have been selected primarily to facilitate visualisation and detailed observation of crater formation during gas jet penetration into the liquid bath. To investigate bath mixing under both top- and bottom-blowing conditions, various tracers, including dyes and KCl or NaCl salts, have been added to water as the principal modelling medium [4, 12]. In three-phase low-temperature modelling, petroleum jelly (Vaseline) [5] or various oils, including motor oil [9, 10], silicone oil [11], and vegetable oil [4, 8], have additionally been employed to simulate the slag phase. Studies investigating gas-liquid interaction using low-melting-point media other than water have remained limited, with Wood's alloy systems representing the most common alternative [2, 3].

The second approach is high-temperature modelling. It has primarily focused on investigating physicochemical interactions at the gas-metal-slag interfaces, including reaction mechanisms, kinetics, and interphase phenomena. Such studies are frequently limited to relatively small or even droplet-scale melt volumes [14, 15]. Investigations of the hydrodynamic behaviour of converter bath blowing under conditions of oxygen injection into sufficiently large volumes of molten iron or steel have remained scarce and, particularly in recent years, have become increasingly uncommon [16–18]. This trend has largely resulted from the considerable complexity and high cost associated with conducting such experiments, especially when trans-

parent-wall facilities are required to visualise the interaction zone between the gas jet and the molten bath [18]. Consequently, low-temperature physical modelling using water has become the principal experimental tool worldwide for investigating blowing processes and optimising oxygen converter steelmaking.

A distinctive feature of physical modelling of oxygen converter steelmaking is the reproduction of the gas-dynamic and hydrodynamic characteristics of gas jet interaction with a liquid bath within geometrically scaled laboratory models while preserving the geometric similarity between the prototype and the model. The reliability of such modelling depends on satisfying the relevant similarity criteria, which account for the combined influence of the governing physical forces acting during the process [19, 20]. The principal similarity criteria used in low-temperature modelling of oxygen converter blowing are modified Froude number accounting for the density difference between the interacting media and the Weber number describing the influence of liquid surface tension [19, 20]. Similarity between the modified Froude numbers for the model (subscript *m*) and the prototype (subscript *o*) is expressed as follows [19, 20]:

$$\frac{\rho_g \cdot u_g^2}{g \cdot d_m (\rho_l - \rho_g)} = \frac{\rho_{ox} \cdot u_{ox}^2}{g \cdot d_o (\rho_{st} - \rho_{ox})}, \quad (1)$$

where ρ_g , ρ_{ox} are the densities of the gas used for blowing on the model and oxygen used as the main blowing gas at the actual steel smelting unit, kg/m³; ρ_l , ρ_{st} are the densities of the liquid used as a liquid bath on the model and actual liquid steel, kg/m³; u_g and u_{ox} are the velocities of the gas flows supplied for blowing, m/min; d_m and d_o are the diameters of the holes (nozzles) for blowing on the model and at the actual unit, m.

The Weber criterion correspondingly takes the following form:

$$\frac{\sigma_{st}}{d_o \cdot \rho_{st} \cdot u_{ox}^2} = \frac{\sigma_l}{d_m \cdot \rho_l \cdot u_g^2}, \quad (2)$$

where σ_{st} and σ_l are the surface tension of molten steel and the liquid that imitates it in the model, N/m.

At the same time, the velocity of the blowing gas is related to the gas flow rate:

$$u = \frac{4Q}{\pi \cdot d^2}, \quad (3)$$

where Q is the gas flow rate, m³/min.

Accordingly, the ratio of blowing gas flows according to the modified Froude criterion and Weber criterion used in the model (index “*m*”) and object (index “*o*”) is:

$$\frac{Q_m}{Q_o} = \sqrt{\frac{\rho_{ox} \cdot d_m^5 (\rho_l - \rho_g)}{\rho_g \cdot d_o^5 (\rho_{st} - \rho_{ox})}}. \quad (4)$$

$$\frac{Q_m}{Q_o} = \sqrt{\frac{\rho_{st} \cdot \sigma_l}{\rho_l \cdot \sigma_{st}}}. \quad (5)$$

The impact of the temperature difference between the high-temperature and low-temperature models is taken into account in accordance with the methodology described in [21].

The blowing pressure depends on the flow rate in accordance with the equation [22]:

$$Q = \frac{P \cdot F + P_a \cdot f}{511 \rho_g}, \quad (6)$$

where P and P_a are the pressure of the blowing gas and atmospheric pressure, respectively, Pa; F is the area of the jet at the contact with the bath, m²; f is the cross-sectional area of the blowing nozzle, m².

Accordingly, the correlation between the results obtained from low-temperature and high-temperature modelling is determined primarily by the physical properties of the modelling media [19, 20, 23]. However, it is well established that compliance with the similarity criteria alone is insufficient to directly transfer the results of low-temperature modelling to a real industrial process. A clear understanding of the correspondence between the physical phenomena occurring under different temperature conditions and in different media is required, particularly for the key process in oxygen converter steelmaking — the interaction of a gas jet with the liquid bath during jet penetration.

Therefore, the present study aims to establish the relationship between the gas jet penetration proces-

ses occurring under low-temperature and high-temperature modelling conditions using experimental models equipped with transparent observation walls, which enable direct visualisation and quantitative assessment of the gas–liquid interaction zone.

The object of the study is the crater formed during top blowing as a result of gas jet penetration into the liquid bath. The geometry of this crater governs the subsequent gas–liquid interaction, including splashing behaviour, mass-transfer processes, and the probability of jet impingement on the converter lining. The comparison is performed for the initial stage of blowing, before ignition of the heat in the high-temperature model. After heat ignition, the gas–liquid interaction mechanism changes substantially because of oxidation reactions occurring in the molten metal, accompanied by the formation of gaseous reaction products and slag, which significantly alter the hydrodynamic conditions in the interaction zone.

The main physical parameters of the models are as follows.

Low-temperature model:

1) liquid simulating the liquid phase — water at a temperature of 25 °C;

- ◆ density of the model liquid — 1000 kg/m³;
- ◆ viscosity of the model liquid — 0.001 Pa·s;
- ◆ surface tension of the model fluid — 0.073 N/m;
- ◆ dynamic viscosity of the model fluid — 1.002 mPa·s;

2) blowing gas — compressed air blown into an environment with a temperature of 25 °C (considered to be a conditional diatomic gas);

- ◆ density of the blowing gas — 1.23 kg/m³;

High-temperature model:

1) liquid simulating the liquid phase — molten steel at a temperature of 1550 °C;

- ◆ density of the model liquid — 7000 kg/m³;
- ◆ viscosity of the model liquid — 0.005 Pa·s;
- ◆ surface tension of the model liquid — 1.4 N/m;
- ◆ dynamic viscosity of the model liquid — 5.5 mPa·s;

2) blowing gas — oxygen blown into the environment at a temperature of 1500 °C (diatomic gas);

- ◆ density of blowing gas — 1.43 kg/m³.

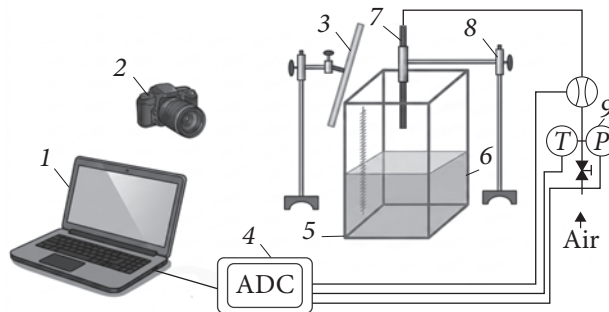


Fig. 1. Diagram of a low-temperature model with a transparent wall: 1 — personal computer for recording process indicators; 2 — device for photo and video recording; 3 — linear solid-state light source; 4 — ADC for collecting indicators measured during the experiment; 5 — transparent container with flat walls; 6 — water; 7 — model lance; 8 — tripod; 9 — blow gas parameter control units

To ensure the comparability of the results obtained from both modelling approaches, the same top-blowing lance equipped with a central cylindrical nozzle of 2.3×10^{-3} m in diameter is used in both cases. The lance is positioned at a working height corresponding to 40 nozzle diameters above the surface of the quiescent bath. A single-nozzle lance is selected because, under the conditions of high-temperature modelling with a transparent observation wall, accurate visualisation, recording, and quantitative evaluation of the interaction zone formed by multiple gas jets are considerably more difficult.

Low-temperature experiments are conducted using a 100 kg transparent vessel with flat walls to minimise optical distortion during image acquisition, thereby enabling accurate measurement of the crater width and depth formed by the interaction of the gas jet with the liquid bath. A schematic diagram of the experimental setup is presented in Fig. 1. The water model is blown with compressed air supplied by a compressor.

High-temperature studies are conducted using a 40 kg oxygen converter model equipped with a transparent quartz wall, as shown in Fig. 2. Blowing is performed with technical oxygen supplied from cylinders. The transparent observation wall is made of quartz glass measuring 120 mm in width and 10 mm in thickness.

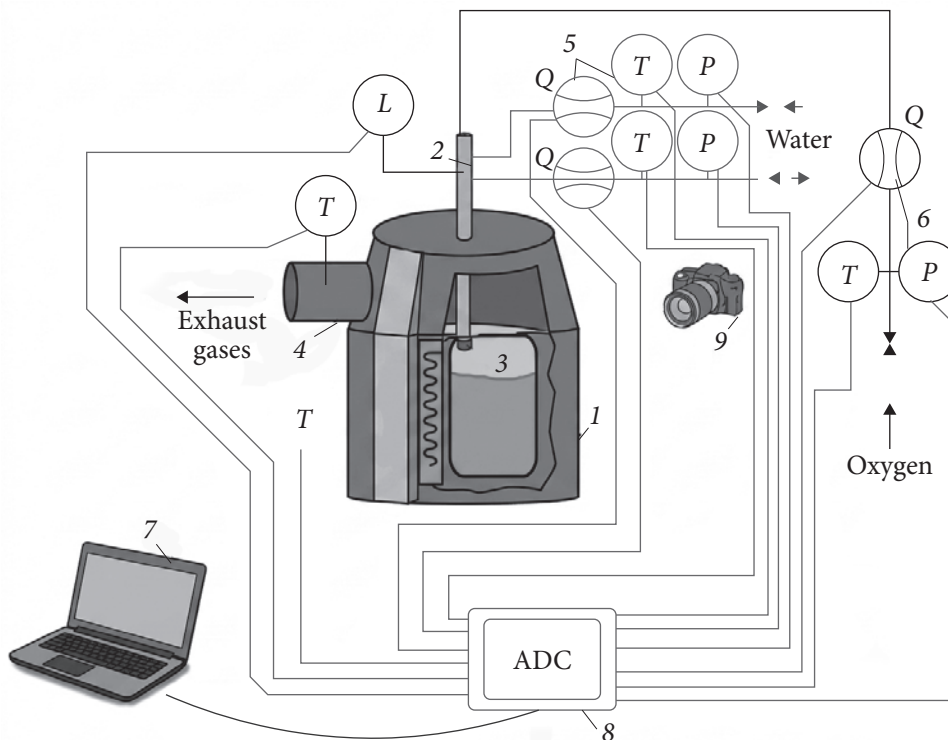


Fig. 2. Diagram of a high-temperature model with a transparent wall: 1 — high-temperature model with a transparent wall; 2 — model lance; 3 — molten steel; 4 — sleeve for forced removal of exhaust gases; 5 — system for supplying water to the lance; 6 — system for controlling blowing gas parameters; 7 — personal computer; 8 — ADC for collecting indicators measured during the experiment; 9 — device for photo and video recording

In accordance with the similarity criteria established between the industrial converter and the physical models, the gas flow rate in the low-temperature model is 0.00004 of the corresponding industrial value versus 0.0001 in the high-temperature model. Thus, the gas flow rate in high-temperature modelling is 2.5 times higher than that in low-temperature modelling. For both modelling approaches, the blowing gas pressure varies within the range of 100–400 kPa and is monitored using a digital pressure gauge. The blowing process is recorded using a CASIO EXILIM EX-F1 high-speed video camera. Under high-temperature conditions, the bath temperature is measured using a Type B platinum–rhodium thermocouple (Pt–30%Rh/Pt–6%Rh) with a measurement range of 600–1750 °C and an accuracy of $\pm 1\%$.

Representative images illustrating the comparative results of the low-temperature and high-temperature modelling are presented in Fig. 3 for gas blowing pressures ranging from 100 to 300 kPa. Visual comparison of the blowing process has shown that, under top-blowing conditions, a crater (a cavity formed by the impingement of the gas jet on the liquid bath) appears in the model liquid. Owing to the close proximity of the blowing lance to the transparent wall, the crater is clearly visible in both the low-temperature and high-temperature models. Above the crater, liquid splashing is observed as a result of the interaction between the gas jet and the free liquid surface.

A comparative analysis has revealed distinct differences in crater geometry between the two modelling approaches. In the high-temperature model,

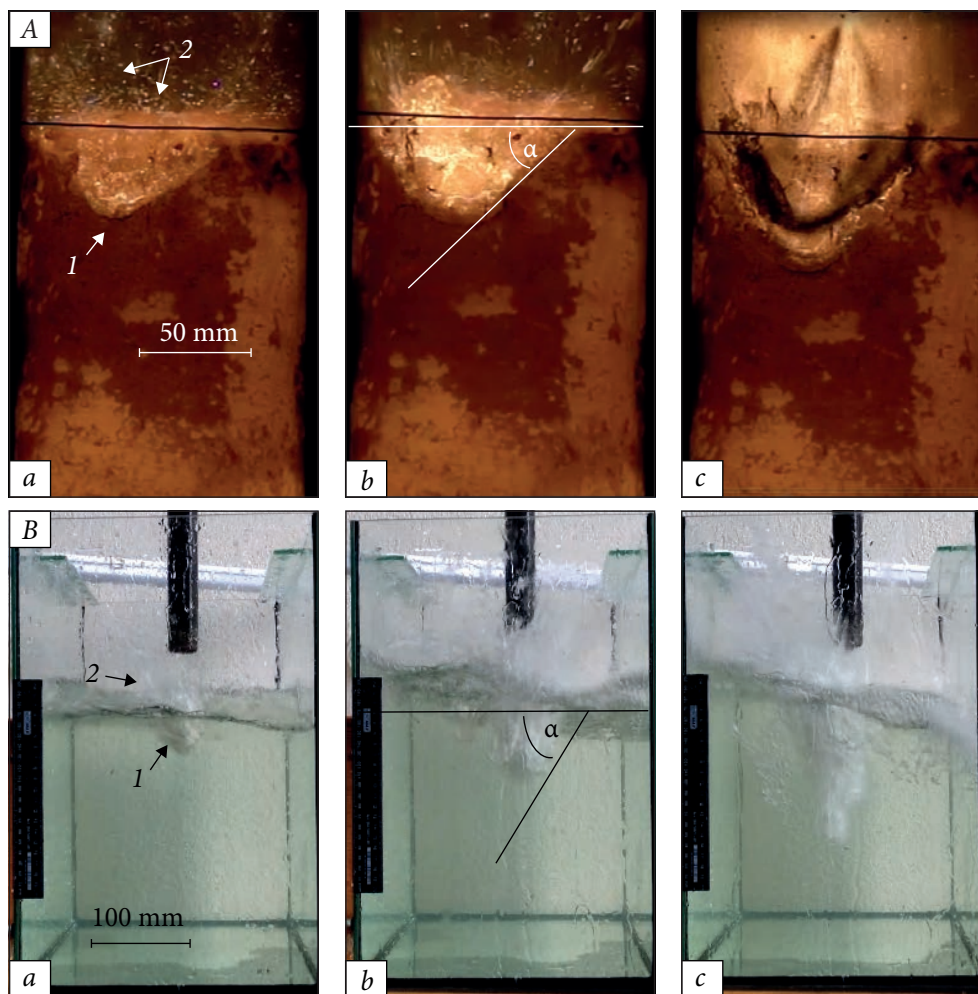


Fig. 3. Visual comparison of the hydrodynamic characteristics of the bath during blowing on a high-temperature (A) and low-temperature (B) model at a gas pressure of 100, 200 and 300 kPa (respectively in photos a—c): 1 — crater formed when a gas jet is immersed in a model liquid; 2 — splashes formed by the impact of a gas jet on the liquid surface; α — angle of inclination of the crater wall

the crater appeared smaller and exhibited a flatter profile, characterised by a lower angle of inclination of the crater walls relative to the horizontal plane. In contrast, the crater formed during low-temperature modelling is deeper, steeper, and more elongated, with a significantly greater wall inclination angle.

Analysis of the video recordings has shown that the angles of inclination of the crater walls relative to the horizontal plane at blowing pressures of 100, 200, and 300 kPa are 36°, 43°, and 48°,

respectively, for the high-temperature model, compared with 52°, 60°, and 73° for the low-temperature model. Thus, the crater wall inclination in the high-temperature model is 1.4—1.5 times smaller than that observed during low-temperature modelling. These differences are primarily attributed to the substantial variation in the physical properties of the modelling media, particularly the approximately sevenfold higher viscosity and nineteenfold higher surface tension of molten steel compared with water.

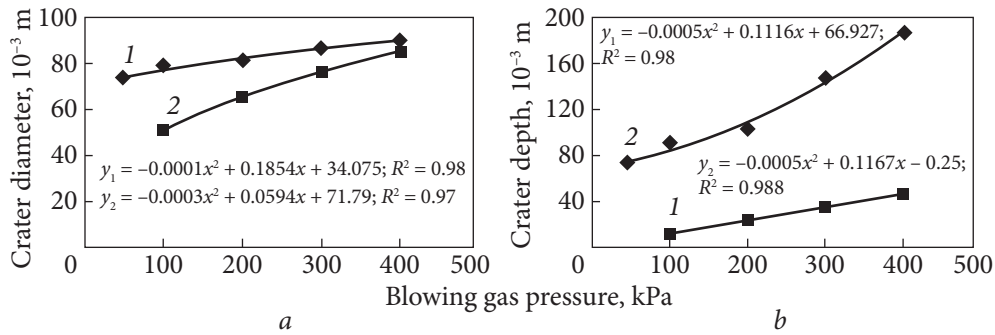


Fig. 4. Comparison of the parameters of the crater of immersion of a gas jet into a liquid bath (diameter (a) and depth (b)): 1 — high-temperature model; 2 — low-temperature model

Figure 4 shows the graphical results of the analysis of the data obtained on the video fixations of blowing (presented for the same pressure for better comparison). It has been found that the crater diameter according to the results of high-temperature modeling has smaller values by a relative value of 5–35% depending on the blowing gas pressure with a larger deviation at a lower gas pressure. As for the crater depth, according to the results of high-temperature modeling, its indicators are approximately 4–7 times smaller, respectively, for different blowing gas pressures with larger deviation values at lower gas pressures. This also corresponds to the visually drawn conclusions and the noted smaller angle of inclination of the crater walls under high-temperature modeling conditions. This is due to the above-mentioned differences in the physical characteristics of the model environments.

The obtained graphical results have indicated a tendency that, while maintaining the equality of blowing conditions, the hydrodynamic features of the interaction of the gas jet with the liquid bath are basically determined by the physical properties of the model liquids and gases used in the studies.

The obtained research results have been analyzed using the *Analysis Package* built into the *Microsoft Office Excel* in accordance with the statistical data processing methodology. As a result of the processing, the dependence of the crater diameter during the operation of the lance for blowing

metal melt (for the conditions of a single-nozzle lance placed at a height of 40 calibers) on the physical characteristics of the model environments, given the results of low-temperature modeling, has been obtained as follows:

$$D_c^H = D_c^L \cdot d \cdot (0.0198 \cdot \ln P - 0.0305) \times \left(\frac{\sigma_w}{\sigma_{st}} \right)^{0.209} \cdot \left(\frac{\eta_{st}}{\eta_w} \right)^{0.61} \cdot \left(\frac{\rho_{st}}{\rho_w} \right)^{0.526} \cdot \left(\frac{\rho_{ox}}{\rho_{air}} \right)^{0.961}, \quad (7)$$

where D_c^H and D_c^L are the crater diameter on high-temperature (“H”) and low-temperature (“L”) models, respectively, m; d is the nozzle diameter, mm; P is the gas pressure in front of the lance, kPa, σ is the surface tension of liquids (hereinafter, “w” is water for a low-temperature model, “st” is steel for a high-temperature model), mN/m; η is the dynamic viscosity of model liquids, Pa·s; ρ is the density of model liquids and model gases (“ox” is oxygen and “air” is air, respectively), kg/m³.

Also, according to the obtained data, by mathematical approximation using the *Solution Search* add-in of the *Microsoft Office Excel* environment, an equation relating the geometric dimensions of the crater during high-temperature modeling to the results of low-temperature modeling has been derived. The *Microsoft Office Excel Solver* tool uses the Generalized Reduced Gradient (GRG2) non-linear optimization program, and is based on the simplex method algorithm with variable constraints and the branch and bounds method to sol-

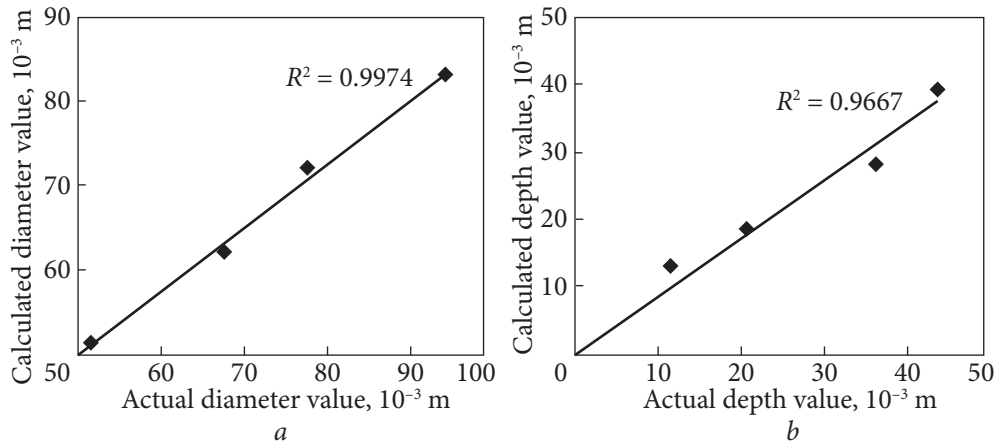


Fig. 5. Comparison of the results of using the derived formulas for determining the geometric parameters of the crater of the interaction of the gas jet with the liquid bath during the top blowing in the oxygen converter with the actual data of high-temperature studies: *a* — verification of the formula for the crater diameter; *b* — verification of the formula for the crater depth

ve linear and integral optimization problems. The resulting expression is:

$$\frac{D_c^H}{H_c^H} = \frac{D_c^L}{H_c^L} \left(\frac{\sigma_w}{\sigma_{st}} \right)^{0.209} \cdot \left(\frac{\eta_{st}}{\eta_w} \right)^{0.61} \times \left(\frac{\rho_{st}}{\rho_w} \right)^{0.526} \cdot \left(\frac{\rho_{ox}}{\rho_{air}} \right)^{0.961}, \quad (8)$$

where H_c^H and H_c^L are the crater depth on high-temperature (“H”) and low-temperature (“L”) models, respectively, m.

When deriving the equations, the following computational parameters have been adopted: a relative error of 1×10^{-6} , an allowable tolerance of 5%, and a convergence criterion of 1×10^{-4} . In the *Solver* add-in of *Microsoft Excel*, the relative error specifies the required solution accuracy by determining the acceptable correspondence between the value of the constrained cell and the specified target, lower bound, or upper bound. The relative error is defined as a decimal value ranging from 0 to 1. In the context of linearising experimental data using the *Microsoft Excel* environment, the allowable tolerance represents the maximum percentage by which the objective cell satisfying the integer constraint may deviate from the true optimal value while still being accepted as a valid solution.

In order to verify the obtained expressions, the actual data and the calculated data regarding the diameter and depth of the crater for the conditions of the high-temperature model have been compared (Fig. 5).

As shown in the figure, the calculated values have exhibited excellent agreement with the experimental data, confirming the high predictive accuracy of Eqs. (7) and (8). The developed equations for determining the geometric parameters of the crater formed by the interaction of a gas jet with the liquid bath during top blowing in an oxygen converter, derived from low-temperature modelling data, have demonstrated a high degree of agreement with the results of high-temperature modelling. The deviations between the predicted and measured values have amounted to only 0.3% for the crater diameter and 3.4% for the crater depth.

These results have confirmed that the proposed equations can reliably predict the crater geometry generated by an oxygen jet during top blowing using a single-nozzle lance positioned at a working height of 40 lance calibers above the bath surface, providing a level of accuracy sufficient for industrial applications. A distinctive advantage of the proposed approach is that it enables the prediction of gas–liquid interaction parameters under molten steel blo-

wing conditions using data obtained from low-temperature modelling with water as the modelling medium, which is substantially simpler and more cost-effective than high-temperature experiments.

Since modern oxygen converters are equipped predominantly with multi-nozzle lances, the next stage of this research focuses on extending the developed equations to account for the geometric characteristics and operating conditions of industrial multi-nozzle lance designs.

A comprehensive investigation of the hydrodynamic behaviour of the converter bath under both low- and high-temperature conditions has been carried out using a single-nozzle lance positioned at a height of 40 lance calibers above the quiescent bath level in transparent-wall physical models. The transparent-wall configuration has enabled direct visual observation and quantitative measurement of the crater formed during gas jet penetration into the liquid bath. The results have demonstra-

ted that the overall mechanism of gas–liquid interaction is similar under both modelling conditions; however, significant differences in crater geometry have been identified. Under high-temperature conditions, the crater wall inclination angle has been 1.4—1.5 times smaller, while both the crater diameter and depth have been reduced, reflecting differences in the thermophysical properties of molten steel and water.

Analysis of the experimental data has resulted in empirical equations for predicting the crater diameter and depth under high-temperature blowing conditions using low-temperature modelling data. Comparison of the calculated values with the experimentally measured crater parameters obtained during high-temperature modelling has confirmed the high accuracy of the proposed equations, demonstrating their suitability for both industrial applications and research in oxygen converter steelmaking.

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СПІВСТАВЛЕННЯ ГЕОМЕТРИЧНИХ ПАРАМЕТРІВ КРАТЕРУ У КИСНЕВОМУ КОНВЕРТЕРІ З ВЕРХНЬОЮ ПРОДУВКОЮ ПРИ НИЗЬКО- ТА ВИСОКОТЕМПЕРАТУРНОМУ МОДЕЛЮВАННІ

Вступ. Киснево-конвертерний спосіб отримання рідкої сталі потребує постійного вдосконалення.

Проблематика. Найбільша кількість поліпшень пов'язана з розробкою нових чи покращенням наявних конструкцій верхньої продувної фурми. Технологічні нововведення потребують дослідження на фізичних моделях, серед яких головними є низькотемпературна (з використанням рідин з низькою температурою плавлення) та високотемпературна (з використанням залізовуглецевого розплаву). Наразі перевагу надають низькотемпературній моделі. Однак, попри обов'язкове дотримання критеріїв подоби при моделюванні, отримані результати не можуть бути напряду інтерпретовані до реальних металевих розплавів. Це потребує пошуку закономірностей, які б сприяли в інтерпретації результатів.

Мета. Встановлення залежності між процесами занурення газового струменя у рідину, що відбуваються за умов низькотемпературного та високотемпературного моделювання, на моделі з прозорою стінкою.

Матеріали й методи. Низькотемпературне (на водній моделі з продувкою повітрям) та високотемпературне (з продувкою киснем сталевого розплаву) моделювання верхньої продувки крізь однакову односплову фурму при дотриманні подібних технологічних умов на моделях з прозорою стінкою.

Результати. Встановлено відмінності у формуванні кратеру взаємодії газового струменя з рідкою ванною при продувці рідкої сталі та води: менший у 1,4—1,5 рази кут нахилу стінки кратеру, менша на величину до 7 разів глибина та менший на величину до 35 % діаметр кратеру при однакових технологічних умовах продувки. Отримані дані щодо параметрів кратеру стали базисом для розроблених рівнянь залежності діаметру та глибини кратеру за умов продувки високотемпературної моделі.

Висновки. За результатами фізичного моделювання складено рівняння розрахунку параметрів кратеру (діаметр та глибини), утвореного при взаємодії газового струменя з рідкою ванною за умов верхньої продувки, які враховують фізичні особливості модельних рідин та газів. Особливістю рівнянь є використання результатів низькотемпературного моделювання для прогнозу параметрів кратеру на реальному сталевому розплаві.

Ключові слова: верхня продувка, газовий струмінь, кратер, низькотемпературне моделювання, високотемпературне моделювання, інтерпретація результатів.