

**136 МЕТАЛУРГІЯ**

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**DEVELOPMENT OF THE SERVICE FOR CALCULATING  
THE MATERIAL AND THERMAL BALANCE OF STEEL SMELTING**

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The literature review highlights innovative approaches to modeling: the use of kinetic equations, computational fluid dynamics (CFD) and machine learning algorithms (XGBoost, Random Forest) to predict carbon and oxygen content. Special attention is paid to adapting models to new environmental technologies, in particular the use of hydrogen and scrap metal processing, the share of which in the charge can reach 40%. The experience of world leaders (Danieli Corus, Kutner) and domestic scientific schools (NMetAU) in creating decision support systems, such as the «Technologist-Operator Advisor», is separately considered. The own development of the Department of Metallurgical Technologies of DUET and «Metinvest Polytechnics» is presented – a universal service for calculating smelting balances. The software product is built on the basis of a modern technology stack (HTML, CSS, JavaScript) using the Node.js platform for the server part. This choice of tools provides cross-platform compatibility, easy integration with existing industrial systems, and the possibility of remote access, which is critically important for training engineers in conditions of pandemic restrictions. The service is implemented in two modes: «light» (for educational purposes) and "industrial" (with full consideration of all elements of the charge). The program allows you to quickly enter data on the composition of pig iron, scrap, ferroalloys and receive final balance tables with an error of no more than 0.1-0.5%. The authors provide examples of the program code and the system interface, demonstrating the mechanisms for checking the chemical composition of the charge and generating final reports.

**Keywords:** Basic Oxygen Furnace (BOF); material and heat balance; automation of metallurgy; web service; chemical composition prediction; digitalization of production; mathematical modeling; Node.js.

**Statement of the problem**

The modern BOF process is characterized by a high level of automation. The use of powerful computing systems allows steelmakers to significantly simplify a number of technological operations: carry out an accurate calculation of the shrinkable metal charge, slag-forming and additives in the smelting process, to predict the chemical composition of the metal on heaps and after deoxidation, and much more.

The steelmaking process is controlled by a distributor operator, whose main role until recently was reduced to the analysis of computer data, which are assembled by a system of sensors and measuring instruments and further technological decision, based on the received data. In recent years, the development of digital technologies has reached

a level at which the capabilities of modern software have become so extensive that they have allowed them to be introduced into the management processes of complex, multifactor technologies.

The development of an online system for calculating material and thermal balances is a critical task for modern basic oxygen furnace (BOF) steelmaking. Modern research focuses on integrating kinetic models, computational fluid dynamics (CFD), and data-driven approaches to enhance the accuracy of real-time process control.

**Analysis of the latest achievements  
on the identified problem**

The core of any converter control system lies in the precision of its material and heat balance equations. Recent

studies emphasize the need to adapt these balances to new technologies, such as bottom-blown  $O_2$ - $CO_2$ - $CaO$  processes, where researchers have established high utilization ratios for injected materials (e.g., 91.35% for lime powder) [1]. Similarly, the transition to greener steelmaking through direct reduction plants (DRP) requires comprehensive mass conservation principles and enthalpy-based heat balance calculations to evaluate the impact of hydrogen injection [2]. The inclusion of specific technological factors, such as the presence of a slag "skull" on the lining, significantly alters the thermal regime and requires additional heat balance articles to account for the physical heat and slag-forming components introduced by the skull [3].

Scrap metal serves as a primary coolant to balance excess heat in the BOF. Advanced numerical models now consider scrap blending by simultaneously analyzing steel quality, production cost, and energy use [4]. Research indicates that the density and proportion of scrap (up to 40% of the charge) drastically change the dynamics of bath temperature and carbon oxidation [5]. To maintain a rational melting process, models must account for the changing reactive surface area of scrap as it melts, often using fourth-degree polynomials for better accuracy [5].

A significant challenge in online systems is the transient nature of carbon removal. Kinetic equations have been developed to describe carbon removal in real-time, even in small converters working with cupola furnaces [6]. Modern approaches integrate machine learning (e.g., XGBoost, Random Forest) with theoretical kinetic models to predict tapping carbon and oxygen levels, improving prediction accuracy by over 6% through cyclic iteration algorithms [7]. Furthermore, coupling CFD with thermodynamic databases allows for the investigation of high-temperature reactions at the bubble-melt interface, providing insights into saturation times and pressure effects [8].

The efficiency of mass exchange and slag formation is deeply tied to the blowing mode. The use of two-tier lances has been shown to improve the heat balance and accelerate slag formation by optimizing the afterburning of  $CO$  to  $CO_2$  [9]. Hydrodynamic factors, such as the ratio of the reaction zone length to the bath depth, are used to characterize mixing intensity and its subsequent effect on desulfurization and dephosphorization [10]. Optimal control strategies, including Model Predictive Control (MPC), are employed to stabilize  $CO_2$  levels and minimize production costs while adhering to the boundary conditions of the steelmaking process [11].

Physical properties of slag, particularly viscosity, govern the splashing process used for lining protection [12]. Modern 3D models using the Volume of Fluid (VOF) method allow for quantitative analysis of droplet behavior and liquid film formation [13]. These models help determine optimal oxygen lance heights and flow rates to balance slag splashing effectiveness with safety and cost [13]. Additionally, out-of-furnace refining technologies for pig iron are being evaluated through adapted balance models to determine their impact on specific lime consumption and liquid iron yield [14].

In recent years, significant progress has been observed in steelmaking processes in the implementation of automated control systems for the oxygen-converter process. Metallurgical technology is an area of extremely specific processes, where the relationships between different factors can appear themselves with different strengths in conditions, differing only in hundredths of different indicators. Nevertheless, the high level of development of science allowed researchers to get a complete understanding of the chemical processes taking place in the converter bath, and the use of modern computing power has opened the way for a comprehensive study of the relationships between thousands of factors affecting steelmaking technology.

In 2014, the conference «Modern technologies of steelmaking production» was held at the PJSC «ArcelorMittal Kryvyi Rih». Representatives of the world's leading metallurgical companies spoke at the conference (Heraeus Electro-Nite, Danieli Corus, Siemens VAI Metals Technologies, Steel Work, Kuttner GmbH), largest metallurgical enterprises (Dneprovsky metallurgical plant, Energostal, PJSC «ArcelorMittal Kryvyi Rih») and scientific institutions of Ukraine (Z.I. Nekrasov Institute of Ferrous Metallurgy, National Metallurgical Academy of Ukraine, Kriviy Rih Metallurgical Institute). It is noteworthy that almost all the speeches were devoted to increasing the degree of automation and computerization of production.

Thus, Danieli Corus employees presented a universal model of the oxygen-converter shop (fig. 1), which allows engineers and technicians to carry out long-term planning for the development of the workshop, simulate logistics, calculate the potential for expanding production capacity, lay out the sequence of technological operations and much more [15].

Danieli Corus and Kuttner [16, 17] presented new solutions in the field of technological process control, which make it possible to reduce the duration of steel smelting by measuring the temperature of the melt and its chemical composition. As a result, technologists hit into the range of specified characteristics and there is no need for additional corrective measures.

The Department of Steel Metallurgy of the National Metallurgical Academy of Ukraine has developed a comprehensive program for forecasting the results of converter smelting "Advisor to the Technologist-Operator" (fig. 2), which is based on modern theoretical concepts of the pattern of converter processes and practical data on the operation of converters [18].

The program allows you to set the main parameters of technology by predicting the results of melting, based on controlled, conditionally controlled and uncontrolled process parameters. Thus, the program works as an assistant for the technologist, allowing him to quickly calculate consumables, determine the economic efficiency of certain solutions, and most importantly, to carry out calculations exclusively «by chemistry», thanks to which the technologist gets rid of the need to coordinate various process

parameters, which are highly dependent on the conditions of a particular production.

calculations of the material and thermal balance of converter smelting.

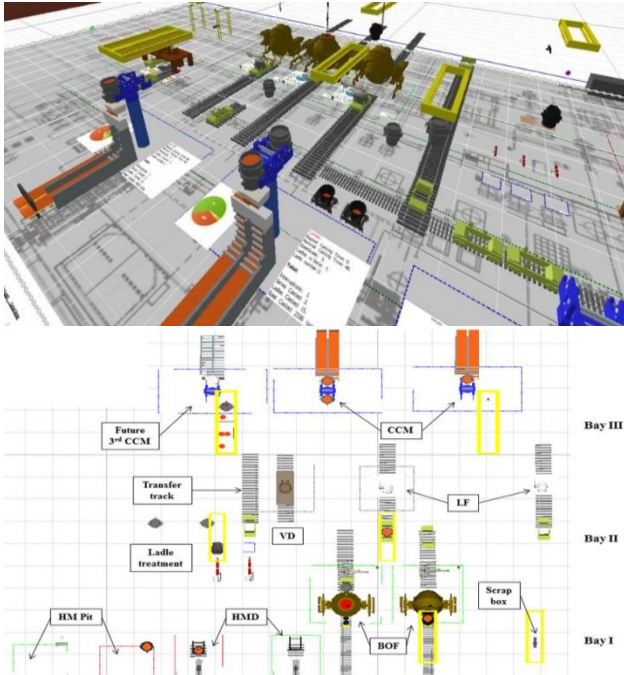


Fig. 1 – BOF model from Danieli Corus

Хімічний склад чугуна, температура чугуна і лома		Шихтовка плавки	
Содержание углерода, %	4,30	Садка конвертера, т	66,00
Содержание кремния, %	0,60	Расход чугуна, т	54,000
Содержание марганца, %	0,50	Расход металлолома, т	12,000
Содержание фосфора, %	0,085	Расход кремнистого лома, т	0,000
Содержание серы, %	0,030	Расход скрапа, т	0,000
Температура чугуна, °C	1300	Расход твердого чугуна, т	0,000
Температура лома, °C	20	Расход ЖСБ, т	0,000
		Расход извести, т	3,700
		Расход магнезитового флюса, т	0,306
		Расход плавикового шлата, т	0,207
		Расход известняка, т	0,000
		Расход дополнительного материала, т	0,000
		Расход рудного материала, т	0,000
		Расход теплоносителя, т	0,000
		Расход кислорода, м³	3153

Fig. 2 – Application interface «Technologist-operator advisor»

It should be noted, that the presence in the shop not of one, but several information systems, which would "lead" the process in parallel is not a disadvantage, but an advantage. This is due to the fact that each specific software is often based on different principles, and combining their results with recommendatory patterns for the technologist allows you to get a powerful synergistic effect, that has a positive effect on all production chains.

Nevertheless, the literary analysis and study of the proposals of the leading enterprises serving metallurgical plants, shows that at the moment there are not so many solutions on the software market, which would be based on

**Purpose and task statement**

The aim of the article is to substantiate and develop a service for automated calculation of material and heat balances of oxygen-converter smelting, which allows to increase the accuracy of predicting the chemical composition of the metal and optimize the consumption of charge materials. The presented work seeks to combine modern theoretical models of metallurgical processes with IT technologies (Node.js, JavaScript) to create a universal tool that provides remote access to calculations for both operational management of real production and for training qualified engineering personnel.

**Summary of the main material**

Material and heat balance of smelting is one of the most effective mechanisms for controlling the steel smelting process. With its help, technologists can make high-precision calculations of the entire converter process, from the blending to the predicted chemical composition of the steel after deoxidation.

In this regard, at the Department of Metallurgical Technologies of State University of Economics and Metallurgy Polytechnic work has begun on the creation of a service for calculating the material and heat balance, which can be easily connected to any software or hardware products from the outside.

The use of the web interface (fig. 3) was due to two reasons: 1) the developed program must have open opportunities for interaction with industrial enterprises, which is extremely easy to achieve precisely in the format of a web service; 2) the developed product is planned to be used in the process of training process engineers in the field of metallurgical technologies, and in the context of the pandemic situation that has formed in the world in 2020, the creation of training services that can be accessed remotely from anywhere in the world is an extremely urgent task.

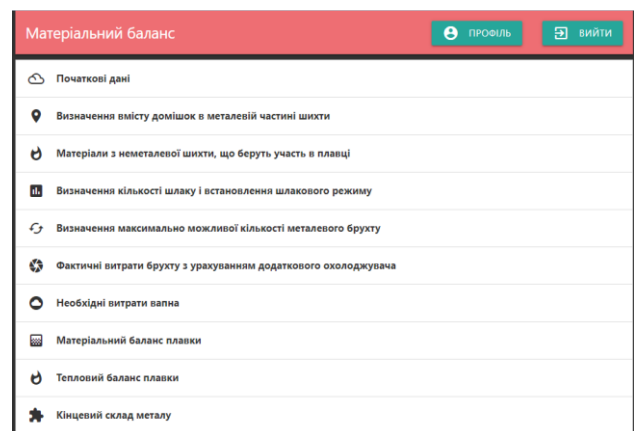


Fig. 3 – Service interface «Material and thermal balance of converter smelting»

When creating the program, the basic principles of web development were used, that is HTML (HyperText Markup Language – «hypertext markup language»), CSS (Cascading Style Sheets – cascading style sheets), JavaScript – multiparadigm programming language. As known, any client part (frontend) developed with language JavaScript. The main architectural features of the language: dynamic typing, weak typing, automatic memory management, prototype programming, functions as first class objects. Java Script is an object-oriented programming language, but it uses prototyping in the language. In addition, JavaScript has several advantages: functions as first-class objects, objects as lists, anonymous functions, closures, auto-casting, auto-garbage collection, and so on, which gives the language additional flexibility.

The application also uses an authorization system and a database, which makes it possible to store the data of an individual client. For the server side, the Node.js software platform is used.

Node.js adds the ability for JavaScript to interact with Input/Output devices through its API (written in C++), connect other external libraries written in different languages, providing calls to them from JavaScript-code. Node.js is used primarily on the server, serving as a web server.

A summary check of the chemical composition of elements is presented as an example code (fig. 4).

```
// liquidIron values
let iron_form = document.getElementById('ironResultForm'),
    ironResult = document.getElementById('iron_result')
carbon_value = iron_form.elements.liquidCarbon.value,
silicon_value = iron_form.elements.liquidSilicon.value,
manganese_value = iron_form.elements.liquidManganese.value,
sulfur_value = iron_form.elements.liquidSulfur.value,
phosphorus_value = iron_form.elements.liquidPhosphorus.value,
iron_value = iron_form.elements.liquidIron.value;
// trash values
let trash_form = document.getElementById('trashResultForm'),
    trashResult = document.getElementById('trash_result')
carbon_value = trash_form.elements.trashCarbon.value,
silicon_value = trash_form.elements.trashSilicon.value,
manganese_value = trash_form.elements.trashManganese.value,
sulfur_value = trash_form.elements.trashSulfur.value,
phosphorus_value = trash_form.elements.trashPhosphorus.value,
iron_value = trash_form.elements.trashIron.value;
// FeSi 65% values
let ferrum_form = document.getElementById('ferrumSiResultForm'),
    ferrumResult = document.getElementById('ferrum_result')
ferrum_value = ferrum_form.elements.ferrumSiliCarbon.value,
ferrum_value = ferrum_form.elements.ferrumSiliSilicon.value,
ferrum_value = ferrum_form.elements.ferrumSiliManganese.value,
ferrum_value = ferrum_form.elements.ferrumSiliSulfur.value,
ferrum_value = ferrum_form.elements.ferrumSiliPhosphorus.value,
ferrum = ferrum_form.elements.ferrumSiliIron.value;
// FeSiMn values
let ferrumSiMn_form = document.getElementById('ferrumSiMnResultForm'),
    ferrumSiMnResult = document.getElementById('ferrumSiMn_result')
ferrumSiMn_value = ferrumSiMn_form.elements.ferrumSiMnCarbon.value,
ferrumSiMn_value = ferrumSiMn_form.elements.ferrumSiMnSilicon.value,
ferrumSiMn_value = ferrumSiMn_form.elements.ferrumSiMnManganese.value,
```

```
ferrumSiMn_value = ferrumSiMn_form.elements.ferrumSiMnSulfur.value,
ferrumSiMn_value = ferrumSiMn_form.elements.ferrumSiMnPhosphorus.value,
ferrumSiMn = ferrumSiMn_form.elements.ferrumSiMnIron.value;
// function that returns the result of changes in the table
let ElementsChanged = (selector, resultContainer) => {
    const fields = document.querySelectorAll(selector)
    const values = {}
    let sum = 0
    fields.forEach(field => {
        const {name, value} = field
        values[name] = value
        sum += +value
    })
    resultContainer.innerHTML = sum.toFixed(2)
}
// select all selectors will change
let iron_form_inputs = document.querySelectorAll('.iron-form-inputs') // liquid iron
let trash_form_inputs = document.querySelectorAll('.trash-form-inputs') // trash
let ferrum_form_inputs = document.querySelectorAll('.ferrumSi-form-inputs') // FeSi 65%
let ferrumSiMn_form_inputs = document.querySelectorAll('.ferrumSiMn-form-inputs') // FeSiMn
// cycles for take inputs values
// ----- start -----
for (let i = 0; i < iron_form_inputs.length; i++) {
    iron_form_inputs[i].addEventListener("keyup", () => {ElementsChanged('.iron-form-inputs', ironResult)})
}
for (let i = 0; i < trash_form_inputs.length; i++) {
    trash_form_inputs[i].addEventListener("keyup", () => {ElementsChanged('.trash-form-inputs', trashResult)})
}
for (let i = 0; i < ferrum_form_inputs.length; i++) {
    ferrum_form_inputs[i].addEventListener("keyup", () => {ElementsChanged('.ferrumSi-form-inputs', ferrumResult)})
}
for (let i = 0; i < ferrumSiMn_form_inputs.length; i++) {
    ferrumSiMn_form_inputs[i].addEventListener("keyup", () => {ElementsChanged('.ferrumSiMn-form-inputs', ferrumSiMnResult)})
}
// ----- end -----
// call functions in the start app
ElementsChanged('.iron-form-inputs', ironResult)
ElementsChanged('.trash-form-inputs', trashResult)
ElementsChanged('.ferrumSi-form-inputs', ferrumResult)
ElementsChanged('.ferrumSiMn-form-inputs', ferrumSiMnResult)
```

**Таблиця 1 - Хімічний склад металевої шихти, %**

Найменування	C	Si	Mn	S	P	Fe	Усього
Чапуна рідики	3.6	0.950	0.7	0.045	0.100	94.605	100.00
Бруки	0.2	0.160	0.420	0.030	0.040	99.150	100.00
FeSi 65%	0	0	0	0	0	0	0.00
FeSiMn	2.5	17	65	0.03	0.1	15.370	100.00
Горюча сира	0.17-0.22	1-1.5	1-1.5	0.035	0.04	-	-

Fig. 4 – Checking the chemical composition of the charge

It should be noted that the program operates in two modes: lightweight and industrial. The lightweight version is more focused on the learning process of students and allows you to calculate the material and heat balance for the main chemical elements, and the industrial one takes into account all the chemical elements that can be found in the charge materials of oxygen-converter smelting.

When you click on each individual menu item shown in Fig. 3, the accountable interface is opened, where the technologist either sets certain indicators, or sees the results of the calculations.

The main summary tables of the calculation are the tables of material (fig. 5) and heat (fig. 6) balances, as well as the final composition of the metal (fig. 7).

**Таблиця 11 – Матеріальний баланс плавки**

Задано	Кіль-сть, кг	Отримано	Кіль-сть, кг
Чавун	77.51	Метал	90.42
Брухт	22.49	Шлак	13.654
Вално	7.721	Викиди металу	2
Оксидиші	0.3	Корольки в шлаку	0.41
Плавильний шлаг	0.25	Втрата з пилком	0.389
Футеріака	0.3	CO	5.35
Дугги	5.898	CO2	2.102
Разом	114.469	H2O	0.081
		SO2	0.004
		N2	0.047
		Разом	114.457

Нев'язка, % 0.01

Fig. 5 – Material balance of smelting

Прихід	кДж	%	Витрати	кДж	%
Фізичне тепло чавуну	91392.595	49.038	Фізичне тепло чавуну	126118.8	49.038
Фізичне тепло мінерального шлаку	772.584	0.415	Фізичне тепло шлаку	27407.410	14.706
Хімічне тепло окислення домішок	66656.401	35.765	Фізичне тепло газів, що відходить	13198.493	7.082
Тепло окислення заліза	10397.821	5.579	Розкладання оксиду заліза	5528.946	2.967
Тепло шлакоутворення	8666.5	4.65	Випаровування вологи	428.148	0.23
Тепло допалювання CO	8485.128	4.553	Розкладання карбонату	1122.336	0.602
Всього	186371.029		Тепло заліза, що виносіться газами	411.764	0.221
Разом	100		Тепло виводів	2802.64	1.504
			Теплові втрати	7454.841	4
			Всього	186371.029	100

Нев'язка, % 0

Fig. 6 – Heat balance of smelting

**Кінцевий склад металу**

Елемент	Вміст, %
[C]rot	0.122
[Si]rot	0.068
[Mn]rot	0.369
[S]rot	0.025
[P]rot	0.031

Fig. 7 – Final metal composition

An important element of the calculation, which indicates its accuracy, is the residual indicator. For the industrial version, the indicator of the discrepancy of the material-heat balance should not exceed 0.1%, for the educational version - no more than 0.5%.

At the moment, the application is hosted on the local server of the State University of Economics and Technology and is undergoing the last stages of testing. The actual tasks for improving the service is to launch a separate server to store user-defined calculation results, introduction of the possibility of graphical comparison of heats with different charge materials, functions for creating graphs to study the influence of various factors on melting parameters, adding the main languages of the European Union.

## Conclusions

The article analyzes the latest software and hardware solutions for the modern oxygen-converter process, shows examples of their implementation and practical benefits from their use in real industrial conditions.

The development of the Department of Metallurgical Technologies together with colleagues from other universities is presented. The created web service for calculating the material and thermal balance of oxygen-converter smelting represents a new solution for the industry. The popular programming language used during development, as well as the ability to connect industrial systems to the service to obtain the results of parallel calculations, make it a convenient solution for metallurgical enterprises.

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## РОЗРОБКА СЕРВІСУ ДЛЯ РОЗРАХУНКУ МАТЕРІАЛЬНОГО ТА ТЕПЛОВОГО БАЛАНСУ ВИПЛАВКИ СТАЛІ

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У статті проведено комплексний аналіз сучасного стану автоматизації киснево-конвертерного процесу (BOF). Відзначається, що сучасна металургія характеризується переходом від простого збору даних сенсорами до впровадження складних програмних комплексів, здатних керувати багатофакторними технологіями в режимі реального часу. Дослідження підкреслює, що точність розрахунку матеріальних та теплових балансів є фундаментом для прогнозування хімічного складу металу, оптимізації витрат енергії та зменшення собівартості продукції. В огляді літератури висвітлено інноваційні підходи до моделювання: використання кінетичних рівнянь, обчислювальної гідродинаміки (CFD) та алгоритмів машинного навчання (XGBoost, Random Forest) для передбачення вмісту вуглецю та кисню. Особлива увага приділяється адаптації моделей до нових екологічних технологій, зокрема використання водню та переробки металобрухту, частка якого в шихті може сягати 40 %. Окремо розглянуто досвід світових лідерів (Danieli Corus, Kuttner) та вітчизняних наукових шкіл (НМетАУ) у створенні систем підтримки прийняття рішень, таких як «Порадник технолога-оператора». Представлена власна розробка кафедри металургійних технологій ДУЕТ та «Метінвест Політехніки» – універсальний сервісу для розрахунку балансів плавки. Програмний продукт побудований на базі сучасного стеку технологій (HTML, CSS, JavaScript) із використанням платформи Node.js для серверної частини. Такий вибір інструментарію забезпечує кросплатформність, легку інтеграцію з наявними промисловими системами та можливість дистанційного доступу, що є критично важливим для навчання інженерів в умовах пандемічних обмежень. Сервіс реалізовано у двох режимах: «полегшеному» (для освітніх цілей) та «промислому» (з повним урахуванням усіх елементів шихти). Програма дозволяє оперативно вводити дані про склад чавуну, брухту, феросплавів та отримувати фінальні таблиці балансів із похибкою не більше 0,1-0,5 %. Автори наводять приклади програмного коду та інтерфейсу системи, демонструючи механізми перевірки хімічного складу шихти та формування підсумкових звітів. У висновках окреслено перспективи розвитку проєкту, що включають запуск окремих серверів для зберігання клієнтських даних, впровадження інструментів графічного аналізу впливу різних факторів на плавку та локалізацію інтерфейсу мовами ЄС. Робота має високу практичну цінність як для виробничого сектору, так і для цифровізації профільної вищої освіти.

**Ключові слова:** киснево-конвертерний процес; матеріальний та тепловий баланс; автоматизація металургії; вебсервіс; прогнозування хімічного складу; цифровізація виробництва; математичне моделювання; Node.js.

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