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The role of digitalization in improving energy efficiency in steel smelting in Uzbekistan

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Abstract. This article analyzes the potential of improving energy efficiency in electric arc furnaces (EAFs) through Digitalization, specifically using Fuzzy logic-based control systems. By optimizing key parameters such as arc length, electrode movement, and arc resistance, digital control systems can significantly reduce energy consumption and CO_2 emissions. The research results indicate that digitalization can reduce energy consumption by up to 15%, bringing SEPC values closer to global standards and contributing to sustainability. In calculating CO_2 emissions during the steel melting process, digital technologies help reduce emissions generated from natural gas and electricity usage. This study demonstrates that Digitalization is crucial for Uzbekistan's steel smelting industry, enabling alignment with international energy efficiency standards and enhancing environmental sustainability.

INTRODUCTION

In today's world, achieving energy efficiency is a pressing issue not only globally but also in Uzbekistan. Specifically, in 2016, the total electrical power consumption was 45.7 billion kWh, whereas the analysis for 2023 indicates that this figure has reached 66.1 billion kWh, marking an increase of approximately 44.6% compared to 2016. A significant portion of this consumption is attributed to industrial enterprises, which currently account for 52% of the annual total electrical power consumption. Metallurgical enterprises represent a crucial segment of industrial enterprises, and as of 2023, the annual electricity consumption of the metallurgy industry in Uzbekistan averaged 10% of the total, amounting to 7 billion kWh. Moreover, nearly 20% of the total electricity consumption is directed towards steel and rolling production, while 50% is consumed in the production of pig iron. Additionally, there are 1271 metallurgical enterprises in the country, making them one of the major electrical power consumers in the industrial enterprises. This underscores the critical importance of improving energy efficiency in metallurgy [8-12].

TABLE 1. Comparison of energy intensity for producing 1ton of ferrous metal in the metallurgical industry.

Product name	Avarage SEPC in Uzbekistan (2023)	Foreign countries indicators
Coke	32,3	19,8
Pig iron	334,9	280,8
Steel smelting	68,7	50,8
Iron (EAF)	302,5	150,3
Rolling	17,6	8,5

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As seen from table 1, the SEPC in Uzbekistan's metallurgical industry are 1.5 to 2 times higher compared to foreign countries. For example, the SEPC for melting 1 ton of steel in the Republic's electric arc furnaces (EAF) averages between 500 and 540 kWh. To contrast, the global average SEPC for melting 1 ton of steel is between 379 and 420 kWh. Analysis of the data shows that the SEPC in Uzbekistan is 47% higher than the permissible value [1-4].

EXPERIMENTAL RESEARCH

The fact that the SEPC exceeds the allowable value indicates that there is excessive electrical power consumption, amounting to an additional 10% of the Republic's total electrical energy usage. To tackle these challenges, Digitalization offers significant potential. Digitalization technologies can optimize operations, reduce electrical power consumption, and can enhance productivity. In the context of electric arc furnaces (EAFs) used for steel melting in metallurgy, the process of melting metal is directly linked to the electrodes. Adjusting the arc between the electrodes and the metal can significantly reduce electrical power consumption. In EAFs, the movement of electrodes and the control of the arc are traditionally managed using conventional control systems. By introducing Digitalization for arc regulation, substantial reductions in electrical power consumption can be achieved. Currently, in the country's EAFs, the distance between the electrodes and the metal is controlled using traditional electric hydraulic power regulators. However, *these types of regulators have several drawbacks*, such as [13-16]:

- *Excessive electrical power consumption*
- *Increased electrode consumption*
- *Electrodes breakage and failure*
- *Increased product cost*

By using Digitalization in the control systems of metallurgical plants in Uzbekistan, the SEPC can be aligned with the best global standards. Currently, various Digitalization technologies are being used globally in the metallurgy industry to achieve energy efficiency by controlling the movement of electrodes and the arc conditions. Some examples of these applications and their effectiveness are illustrated in fig.1. Digitalization-based control systems in EAFs represent an important technological advancement with the potential to transform the metallurgy industries. Compared to traditional control systems, Digitalization can offers numerous advantages, as well as some disadvantages, which are presented in SWOT analyze in Fig. 2 below.

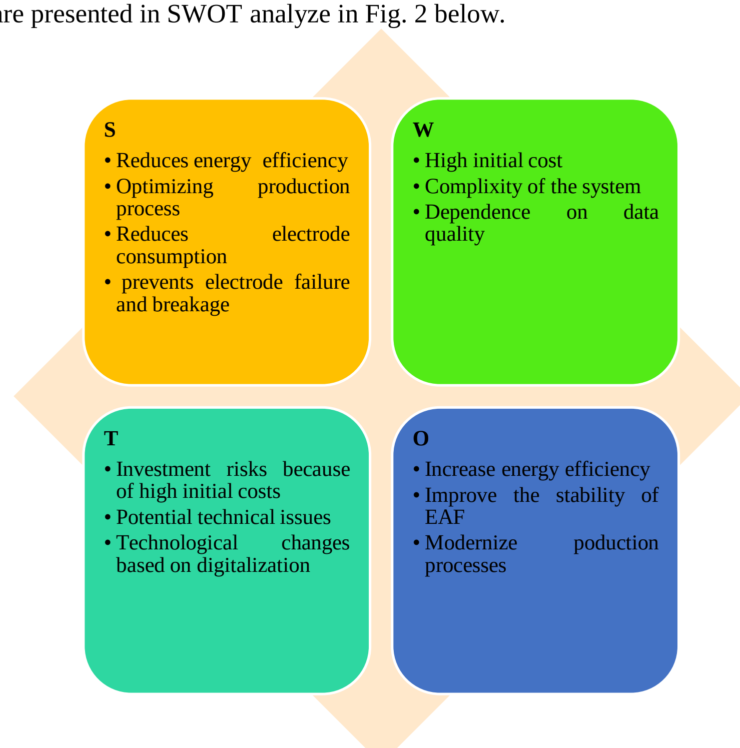


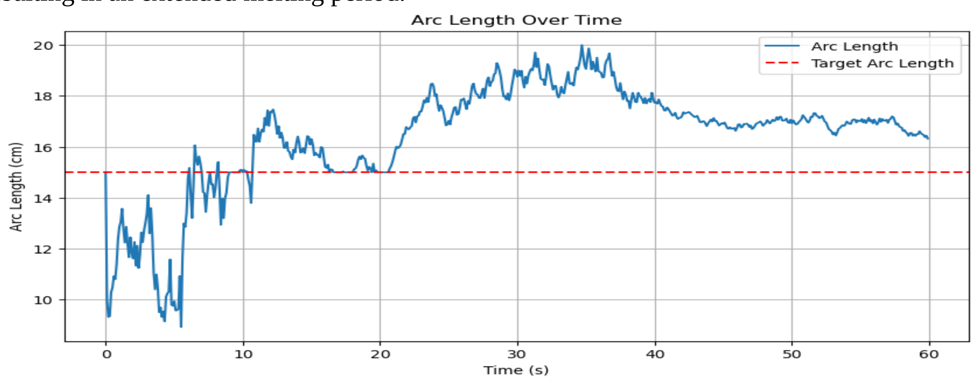
FIGURE 1. The SWOT analysis of Digitalization-based control systems in EAF

Accomplishment of Digitalization-based control systems**.** Based on the analysis provided in the SWOT analysis, it is evident that the shortcomings of traditional control systems mentioned at the beginning of the article are effectively addressed by Digitalization-based control systems. Integrating Digitalization technologies into EAF controlling systems can lead to improve energy efficiency. Digitalization algoritms can optimize operations by analyzing data and making improvements to electrode positions and arc conditions. But, issues related to high initial costs, data dependency, and system complexity need to resolve. So that integrating Digitalization-based control systems into EAF control systems can lead to significant improvements in overall process stability [5-7].

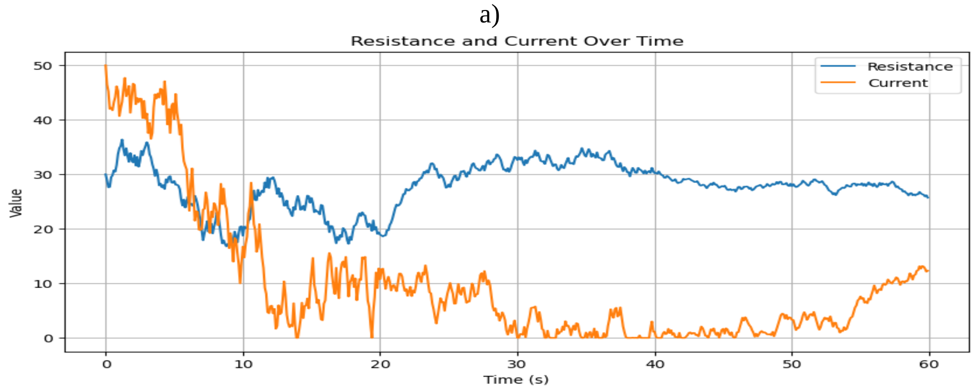
RESEARCH RESULTS

Traditionally, obtaining electric arc characteristics and ensuring the stability of alternating current is very complex, leading to problems and shortcomings when using conventional regulators. We will explore integrating the process of controlling electric arc length with Digitalization systems using fuzzy logic.

In the first case, Fig. 2.a) presents the graphs of electric arc length variations over a duration of 1 minute. It shows significant changes in arc length at the onset of arc formation. Fig. 2.b) displays the characteristics of resistance and current over time. This figure illustrates that as the arc length increases, the resistance increases and the current decreases, resulting in an extended melting period.



a)



b)

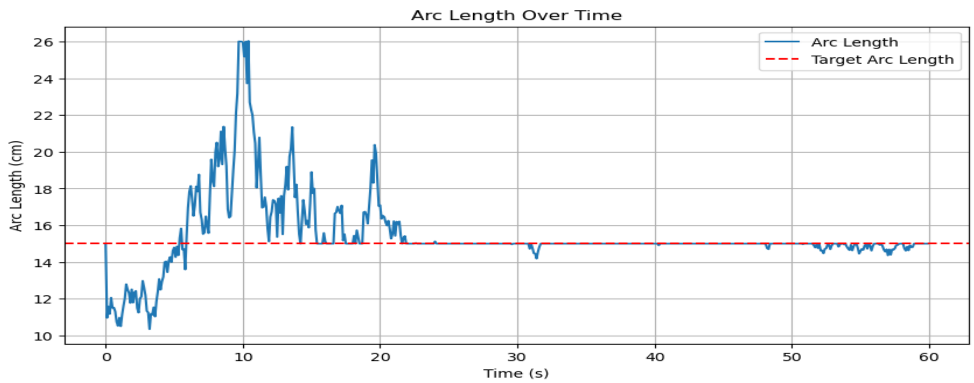
FIGURE 2. a) Arc length over time, b) resistance and current over time

In figs.2.a and 2.b, the graphs are shown that at the beginning of the arc, due to the instability of the arc, there is a slight complexity in controlling it with fuzzy logic. The fuzzy logic control system was applied considering the input variables of resistance and current. The arc length was designated as the output variable. After 10 seconds, a reduced variation in arc length was observed. The gradual change in resistance and the stabilization of the current indicate the effective impact of implementing the fuzzy logic system.

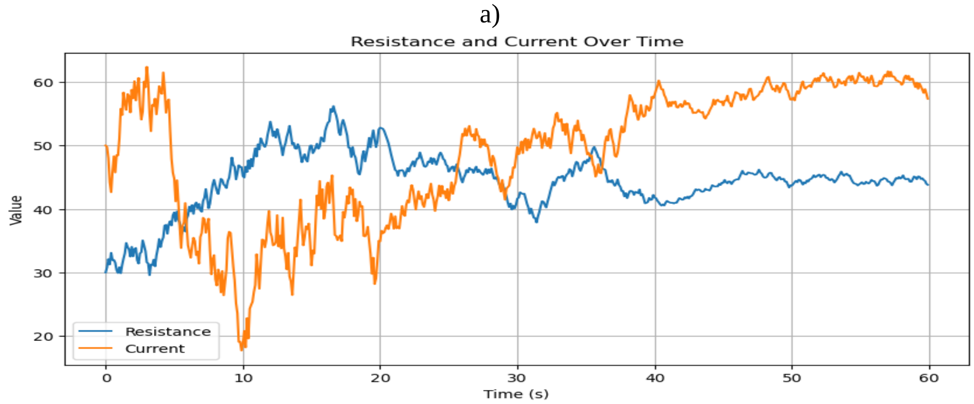
Fig.3. a) and b) present the graphs of resistance and current variations over time, adjusted using the fuzzy logic control system. The purpose of these graphs is to demonstrate how the fuzzy logic control system manages the dynamics of arc length, resistance, and current values over time. These graphs illustrate that by adjusting arc length, current, and resistance values through the fuzzy logic control system, it is possible to reduce melting time and energy

consumption, thereby enhancing energy efficiency. These graphs show that the fuzzy logic control system effectively manages the electrical parameters of current and resistance, as well as arc length. This analysis highlights the impact of the system on operational and energy efficiency and also demonstrates the creation of optimal operating conditions by preventing electrode breakage.

This control process is directly related to evaluating environmental indicators, particularly CO_2 emissions. CO_2 emissions are largely dependent on energy consumption and the type of fuel used. Through the digitalization process, significant reductions in CO_2 emissions can be achieved by improving energy efficiency. The amount of CO_2 emissions varies depending on several factors, such as the type of fuel used in power plants, for instance, natural gas. If natural gas is used, factors like its molar mass, the efficiency of the power plant (ECE), temperature and pressure, and the mixing of oxygen with natural gas must be considered.



a)



b)

FIGURE 3. a) Arc length over time, b) resistance and current over time with Fuzzy logic

For example, since natural gas (methane) is the primary fuel used in our country's power plants, its molar mass must be calculated. The main composition of natural gas follows the reaction equation ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$), where 1 mol of CH_4 produces 1 mol of CO_2. The molar mass of methane (CH_4) is calculated as follows:

$$CH_4 = 12 + 4 \times 1 = 16g/mol$$

The molar mass of CO_2 is: $CO_2 = 12 + 2 \times 16 = 44g/mol$. Thus, 16 g of methane combustion produces 44 g of CO_2 . Since there is a 1:1 molar ratio between methane and CO_2, 1 m³ of methane combustion results in 44.81 mol of CO_2. Therefore, for 1 m³ of methane, the CO_2 emissions are: $CO_2 = 44{,}81\ mol\ \times 44g/mol = 1{,}98\ kg$

In steel melting furnaces, aside from electricity consumption, natural gas and oxygen are also used to accelerate the steel melting process. For example, in a 30-ton electric steel melting furnace, approximately 200 m³ of natural gas and 650 m³ of oxygen are used for heating. The combustion of natural gas results in significant amounts of CO_2, contributing to the increase in industrial emissions. Based on the aforementioned values, where 1 m³ of natural gas combustion produces an average of 1.98 kg of CO_2, the natural gas used to melt 30 tons of steel results in 394 kg of CO_2 emissions. Although oxygen itself does not produce CO_2 during combustion, its use accelerates the burning of natural gas, thereby increasing emissions [9, 15].

The use of electricity in steel melting furnaces has significant implications for CO_2 emissions. The share of CO_2 emissions varies depending on the specific energy consumption (SEPC) of electricity used in the process. Therefore, analyzing CO_2 emissions at power plants and comparing them with SEPC values is essential. This analysis helps identify measures to reduce SEPC in steel melting processes. In an ideal scenario, when natural gas is used as fuel in thermal power plants with an estimated efficiency (FIK) of 55%, approximately 0,5 kg of CO_2 is emitted for every 1 kWh of electricity produced. According to the data presented earlier, with an average SEPC of 520 kWh in the steel melting process, the corresponding CO_2 emissions amount to approximately 260 kg. Based on the analysis, the total CO_2 emissions per ton of steel in the steel melting process can be calculated as follows:

$$CO_2 = CO_{2gas} + CO_{2elec} = 394\ kg + 260\ kg = 654\ kg$$

Reducing this value can be achieved by improving the control of electrode movement using the latest digital software, which will help reduce the SEPC for the product. By applying fuzzy logic as presented in Figures 5a and 5b, it is possible to create a flexible process for controlling electrode movement in complex systems by adjusting arc current and resistance. Fuzzy logic dynamically adjusts the control parameters based on the non-linear characteristics of arc current and resistance, helping to maintain optimal operating conditions. Ultimately, this enables a reduction in SEPC and energy consumption. Fig. 4 below presents this process over a span of several years.

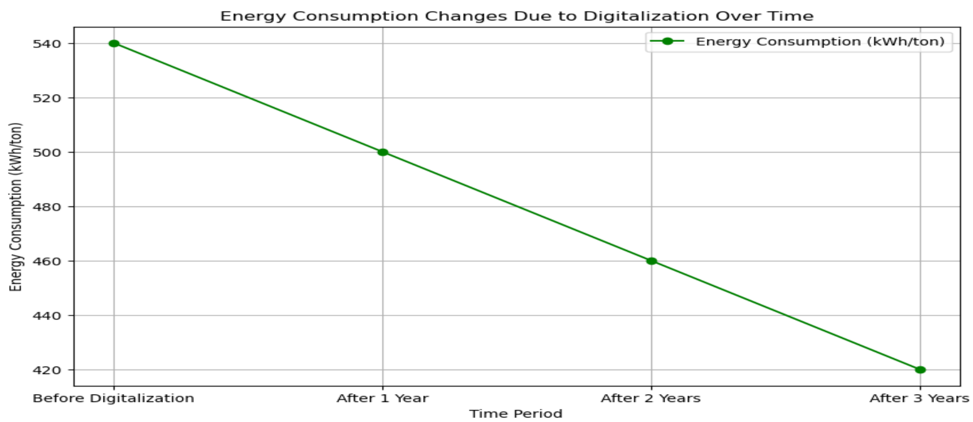


FIGURE 4. SEPC predictions for steel melting furnaces over the years

As seen in the three-year forecast graph, digitalization allows SEPC values in steel melting technology to approach normative levels. By reducing SEPC, it is possible to model how CO_2 emissions will change over time in steel melting technology. Fig. 5 illustrates the estimated changes in CO_2 emissions based on the implementation of digitalized processes.

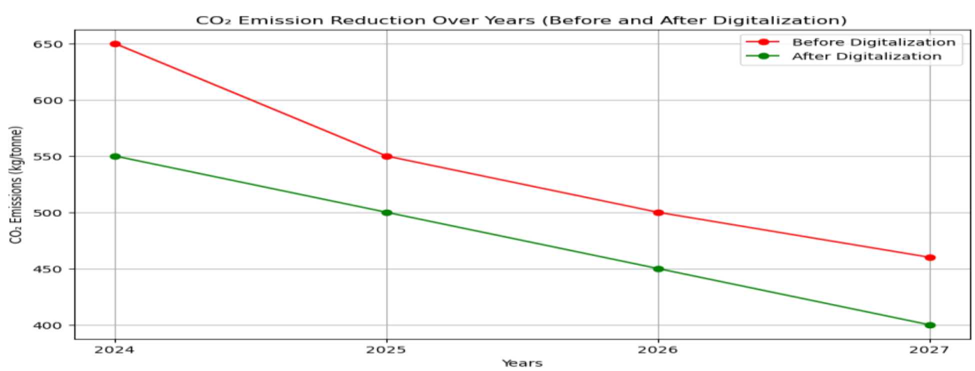


FIGURE 5. Comparative CO_2 emissions in steel melting furnaces.

As illustrated in Fig. 5, the application of digital technologies in managing multi-stage steel melting furnaces enables a substantial reduction in (SEPC) over the 4 years. The graph shows that, before the implementation of digitalization, CO_2 emissions remain significantly higher, reflecting the inefficiencies in the steel melting processes. But, after digitalization, the CO_2 emissions exhibit a marked downward trend, indicating that digital control systems play a vital role in optimizing energy use, reducing waste, and lowering overall emissions.

CONCLUSIONS

This article analyzes the key indicators of energy efficiency in EAF including the specific energy consumption per unit of product and environmental indicators, specifically the amount of CO_2 emissions. Additionally, the process of controlling electrode movement in EAFs through digitalization is examined, utilizing fuzzy logic based on arc current and resistance. The study also discusses the differences between fuzzy logic-based control of technological processes and traditional control systems. Furthermore, the article provides forecasts on improving energy efficiency, optimizing production processes, and ensuring stability in technological processes through the implementation of digitalization. It is highlighted that the introduction of digitalization technologies will result in reduced energy consumption, better electrode movement regulation, and a decrease in CO_2 emissions.

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