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Original Article

Thermal Performance Enhancement of a Bloomery Shaft Furnace via Waste Heat Recovery and Airflow Control

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Abstract - *This research investigated the effect of controlling the air flow rate into the reactor chamber of a bloomery shaft furnace with an air preheater using a spiral coiled tube recuperative heat exchanger. The aim is to enhance thermal efficiency and reduce fuel consumption during iron smelting processes at the community-industrial scale. Operation control was achieved with the help of a Variable Frequency Drive (VFD) to adjust blower speed and a butterfly valve to regulate airflow to the combustion chamber. The experimental results and the Analysis of Variance, Response Surface Methodology (RSM), setting VFD to work at 50 Hz with the butterfly valve open, are recommended to achieve better combustion performance during the preheating period. During thermal decay, the setting of the VFD frequency at 10 Hz with the butterfly valve open increases thermal retention time in the furnace. These results also suggest that the system can be further developed for small-scale industrial applications using modern heat-recovery and combustion-control technologies.*

Keywords - *Bloomery shaft furnace, Recuperative heat exchanger, Waste heat recovery, Response surface.*

1. Introduction

Bloomery iron smelting is the oldest iron smelting procedure in existence, dating to the Middle Bronze Age [1]. These furnaces worked at low temperatures to reduce a spongy mass of iron called bloom [1, 2]. The bloom was then hammered after being taken out of the furnace to increase its mechanical strength. The slag fragment after smelting operation included iron oxide species such as wustite (FeO), fayalite (Fe_2SiO_4), and a number of non-crystalline silicontes. The most commonly used raw material was limonitic ore often pre-roasted to render it in the form of ferric oxide (Fe_2O_3) and magnetite (Fe_3O_4) before charging with charcoal, which enhanced the reduction efficiency [3].

In recent years, the bloomery shaft furnace has been an advanced iron smelting technology that evolved from simpler bowl-shaped bloomery furnaces. The shaft design incorporates a vertical structure that significantly improves airflow management and temperature regulation [4]. These enhancements contribute to increased reduction efficiency and elevate the quality of the iron bloom. The evolution from traditional bloomery furnaces to shaft furnaces represents a significant development in metallurgical practices, as the shaft design enhances airflow control and temperature regulation. This advancement laid the foundation for later innovations [5]. Ancient iron ore deposits in northern Thailand, such as Nam Pi iron found in Uttaradit province, are considered significant sources of iron in the country [6]. The ores found in these areas are primarily composed of hematite (Fe_2O_3) and magnetite (Fe_3O_4). Hematite, as a very abundant ferric oxide, is an excellent source of iron that may be used in the production of steels and other iron products. On the other hand, magnetite itself occurs in mixed valences of iron to enhance reduction reactivity during the important smelting process. Two of these ores are enriched in goethite and lepidocrocite, minerals that have been used for millennia as sources of iron for extraction through traditional bloomery processes and small-scale smelting methods typical of artisanal local production. Nowadays, the utilization of these ancient iron ores is essentially for conservation purposes, serving as raw materials for community-level production. Consequently, small-scale iron producers in local industries often employ the Direct Reduced Iron (DRI) process, which is well-suited to local production contexts in terms of both technical feasibility and operational cost.

Bloomery furnaces and heat exchangers demonstrate the advancement of technology and applications across both traditional and modern industrial systems. In iron smelting using bloomery furnaces, heavy reduction (HR) techniques have been applied in conjunction with continuous casting to improve product quality. Numerical simulations indicate that optimizing HR parameters can significantly reduce carbon segregation and prevent internal cracking [7]. In contrast, heat exchangers play a vital role in modern thermal systems. Studies have shown that counter-flow heat exchangers outperform parallel-flow configurations in efficiency and offer considerable economic savings in thermal applications [8, 9].

Furthermore, the design of plate heat exchangers in binary flashing cycles requires geometric optimization to maximize thermal-hydraulic performance and minimize pressure drops [10]. Kurşun et al. [11] represent the three-tube heat exchanger (TTHX) system and found that the geometry of the inner and middle tubes significantly affected the melting rate of the phase change material (PCM), thus enhancing natural convection and reducing charging time.

Additionally, the integration of thermoelectric conversion technology for waste heat recovery shows that sustainable energy solutions, where optimized thermoelectric modules can efficiently convert waste heat into electrical power [12]. Research indicates that optimizing airflow and temperature profiles within the furnace can improve thermochemical states, particularly when utilizing hydrogen-rich gases, which lower temperature levels and pressure drops in the packed bed. Additionally, the implementation of rotary sinter coolers demonstrates substantial waste heat recovery potential, with findings showing that adjustments in particle size and porosity can lead to significant reductions in outlet temperatures and pressure losses [13]. These studies collectively highlight advances in heat transfer technologies. Each of these approaches plays a vital role in enhancing energy efficiency and promoting sustainability within modern industrial operations.

Although waste-heat recovery and airflow control technologies are known to improve efficiency in modern industrial metallurgy, their application to bloomery shaft furnaces has not yet been well studied in peer-reviewed literature. An overview of the literature shows that most studies focus on large continuous processes. The smaller batch-operated bloomery systems, however, receive much less coverage. This gap is important because bloomery-based techniques still play a role in traditional iron production and in the preservation of cultural heritage in many regions. Therefore, further research on thermal performance improvement for bloomery furnaces is still needed.

As mentioned previously, this research investigated the effect of controlling the air flow rate into the reactor chamber of a bloomery shaft furnace with an air preheater to increase smelting efficiency and reduce fuel consumption for the community. The literature review is described in Section 2. In Section 3, the schematic and methods of the improved bloomery shaft furnace system and recuperative heat exchanger are presented. Section 4 reveals and discusses the ideal results. Section 5 concludes the outline of this investigation.

2. Literature Review

2.1. Bloomery Shaft Furnace

The bloomery shaft furnace was a critical instrument for the production of iron in the past, and it significantly influenced the development of the metallurgical industry. In this type of furnace, iron blooms are produced. The following are exposed masses of slag and iron. The transformation occurs by heating a mixture of iron ore and charcoal in the furnace, establishing a reducing atmosphere that facilitates the conversion process. The quality and efficiency of the resultant iron are contingent upon various elements, including the furnace's physical construction, the characteristics and preparation of the raw materials, and the operator's proficiency [1].

2.2. Identification of Typical Waste Heat Sources in the Iron and Steel Industry

In the iron and steel industry, waste heat is a giant source of renewable energy. The steelmaking process is divided into two main approaches: the primary process (Blast Furnace - Basic Oxygen Furnace; BF-BOF) using iron ore as the raw material and the secondary process (Electric Arc Furnace; EAF) using scrap iron as the main raw material. High temperatures during these processes result in waste heat sources at various stages of production. Waste heat can be classified into three levels according to the temperature level: high heat (more than 500 °C) from sources such as high-temperature furnace gases and molten metal; medium heat (200-500 °C) from blast furnace gases and sintering processes; and low heat (below 200 °C) from waste steam and cooling water.

Waste-heat sources in the steel industry are classified by the production process, and they include those for coking, sintering or pelletizing, ironmaking, steelmaking, and rolling. In these procedures, ironmaking is a major generator of waste heat, and steelmaking and sintering are secondary generators. Recuperative heat exchange is a bridge to transport the waste heat, which can significantly improve energy efficiency and reduce production cost and greenhouse gas emissions for industry.

2.3. Waste Heat Recovery Technologies in Metallurgical Applications

Waste heat recovery technologies for all systems used by the metallurgical industry. As such, they can be grouped into a few categories based on their heat transfer processes and operating properties:

2.3.1. Recuperators

Recuperator is a gas-to-gas regenerative heat exchanger in which gas flows on one side of the material and air on the other, providing for direct transfer of heat energy between two streams across solid material [14, 15]. This apparatus has the potential to contribute greatly to energy saving for high-temperature industrial furnaces. A similar heat recovery device used in an austenitizing furnace achieved fuel savings. Modern recuperators often use high-temperature metals or alloys, as well as ceramic matrix composites, to improve long-term performance in harsh thermal and chemical environments [16].

2.3.2. Regenerative Systems

A regenerative system is a cyclic heat-exchange technology that uses burners and a thermal storage medium, such as refractory bricks or a ceramic matrix, to store and release heat to the incoming combustion air. This is the highest air-preheat temperature to have been used in this system, and it improves combustion efficiency. It is widely used in glass, steel, and aluminum melting furnaces, which require high operating temperatures [17].

2.3.3. Flue Gas Recirculation (FGR)

FGR is an energy-efficient method to feed a part of the exhaust gas into the combustion. It also serves to trap heat in the system and adjust the oxygen content present in the combustion region.

This phenomenon recovers more than 50% of the exhaust energy and helps in controlling the flame temperature for reducing NOx [18]. Recirculation ratio and oxygen level must be carefully controlled for stable combustion conditions with reduced formation of carbon monoxide.

3. Materials and Methods

3.1. Improved the Bloomery Shaft Furnace System

The improved bloomery shaft furnace is divided into five layers. Each layer can be disassembled and separated. The bloomery shaft furnace is cylindrical in shape. The first layer serves as the base to support the bloomery shaft furnace and acts as a flow channel for slag. The second layer of the bloomery shaft furnace serves as a reactor layer for burning fuel with iron ore and features a wind belt to introduce air into the bloomery shaft furnace. The third layer is used as a layer for burning fuel to create carbon monoxide gas, which reacts with iron. The fourth layer packs coal into the bloomery shaft furnace. The fifth layer is a heat exchanger set used to preheat air before entering the bloomery shaft furnace, as shown in Figure 1.

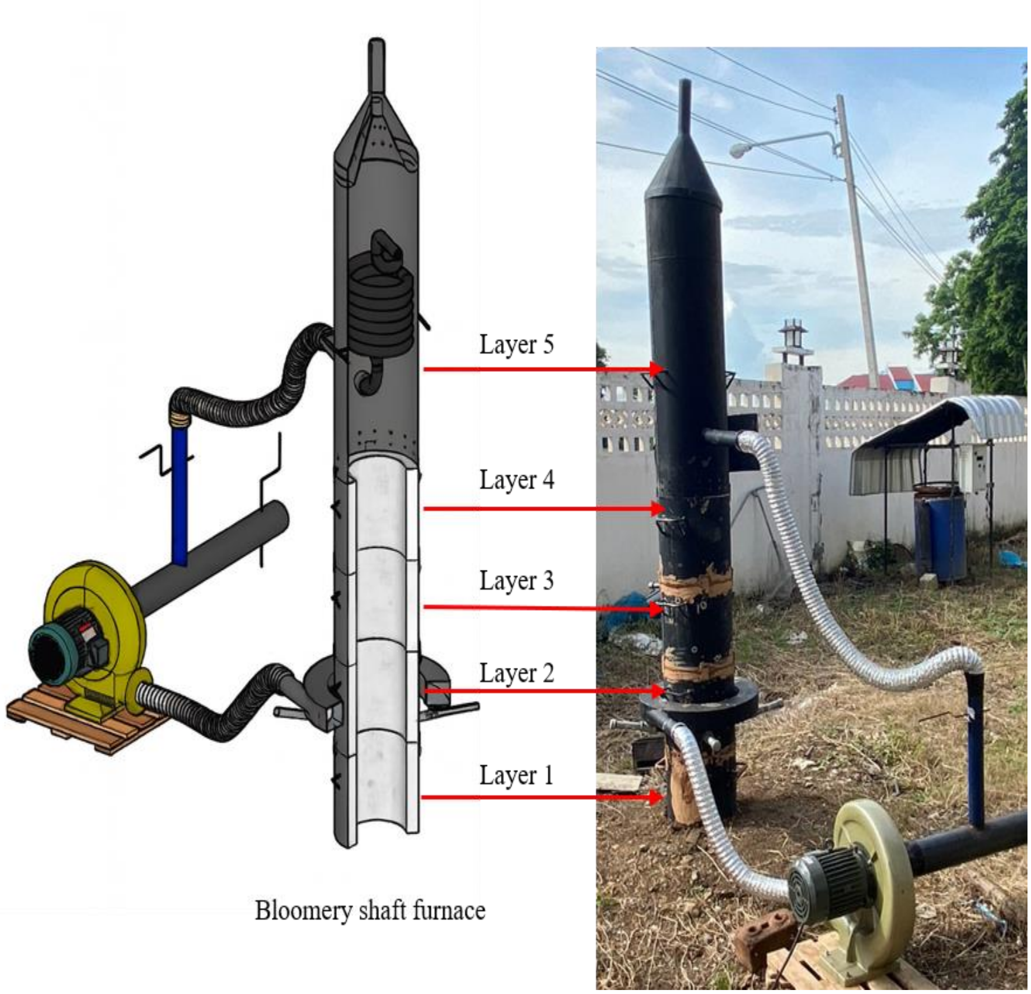

Fig. 1 Bloomery shaft furnace

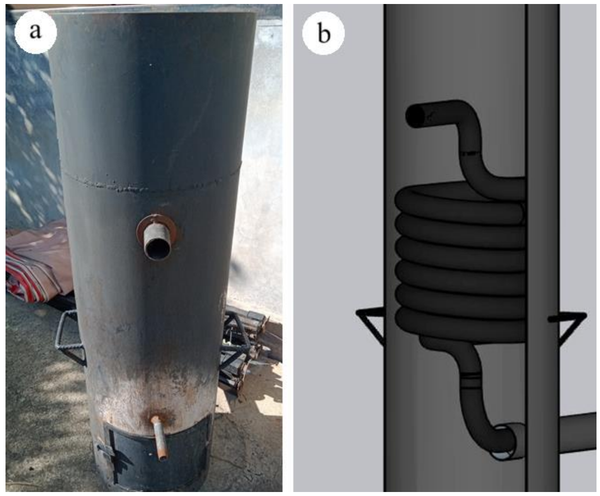

Fig. 2 Recuperative heat exchanger (a) The fifth layer of the bloomery shaft furnace, and (b) Recuperator spiral coiled tubes.

3.2. Recuperative Heat Exchanger Design

The recuperative heat exchanger is installed on the fifth layer of the bloomery shaft furnace. The outer shell is made of a 2 mm-thick rolled steel sheet, 350 mm in diameter and 1,200 mm high, as shown in Figure 2 (a). The design of the recuperator uses spiral coiled tubes by bending steel pipes with a diameter of 250 mm, as shown in Figure 2 (b), which is a small air preheater and requires little installation space. The recuperator operates on the principle of cold air flowing from outside through a curved and sloping pipe, which creates centrifugal force; this force generates a secondary flow that enhances heat transfer capacity, allowing for the circulation of hot air in the system and increasing the temperature of the hot air to ensure efficient combustion inside the reactor of the iron ore furnace.

3.3. Bloomery Shaft Furnace Control System

The operational control of the bloomery shaft furnace used a Variable Frequency Drive (VFD) to regulate the blower speed. The maximum rotational speed is 2,950 Revolutions Per Minute (RPM) and an airflow capacity of up to 26 Cubic Meters Per Minute (CMM), which is suitable for maintaining the temperature inside the reactor chamber as desired. This operation control system enhances energy efficiency and thermal stability, both of which are crucial for producing high-quality iron in bloomery operations.

Figure 3 shows the experimental setup of the bloomery shaft furnace system. A blower is used to supply air to the reactor chamber. The regulated air then passes through a butterfly valve that dictates open–close positions and the amount of air flow into the reactor chamber. A thermocouple Type-R is inserted into the reactor to have an online measurement for its internal temperature. The temperature data are sent to a temperature controller and a data-recording program on a computer for further analysis of the furnace's thermal performance. Red arrows represent the hot gases of combustion being recirculated into the system as a means to reuse waste heat. This is a great benefit for the overall thermal efficiency of the furnace. The combination of these components allows accurate control of airflow and temperature, making the system suitable for studying the effects of airflow on combustion performance and heat transfer inside the Bloomery Shaft Furnace.

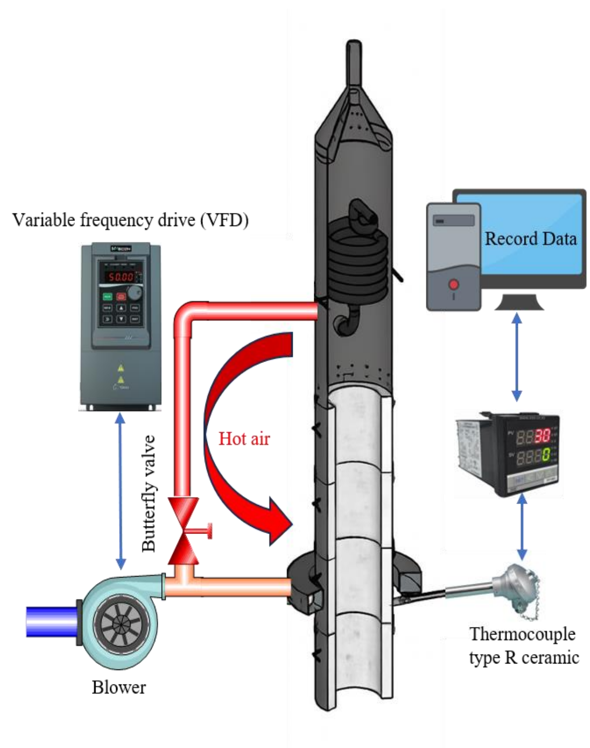

Fig. 3 Bloomery shaft furnace control system

The temperature control inside the bloomery shaft furnace is carried out by using a Type R thermocouple temperature sensor connected to the automatic control system. Suppose the temperature measured in the reactor chamber is lower than the set value. In that case, the control system will order the blower to operate at the appropriate speed to increase the air supply into the combustion process in the reactor layer of the furnace, which will increase the amount of oxygen sufficient to maintain the appropriate temperature for smelting. This control principle illustrates the practical application of frequency control technology in adjusting the efficiency of combustion systems in metallurgy.

3.4. Design of an Airflow Regulation System for the Bloomery Shaft Furnace

In order to effectively control the air supply into the reactor layer of the bloomery shaft furnace. This research aims to design the air inlet system into two channels: the first channel is a channel for normal temperature air from outside to enter the furnace, with a diameter of 10 cm, and the second channel is a channel for hot air from the recuperator, with a diameter of 5 cm.

Both air channels are equipped with butterfly valve plates inside the pipe to meet the requirement of controlling the direction and volume of air entering the reactor chamber. This design enables precise control of the airflow rate into the furnace, which directly affects the combustion conditions and the temperature inside the furnace, resulting in a stable and highly efficient smelting process.

4. Results and Discussion

The performance evaluation of the Bloomery Shaft furnace was carried out in two periods: the heating period and the thermal decay period inside the system. During the testing, the butterfly valve position and air flow rate were adjusted by a Variable Frequency Drive (VFD) at 10, 30, and 50 Hz.

These parameters directly affected the ability of the system. To identify the most suitable operating conditions, an Analysis of Variance (ANOVA) was applied to determine the optimal levels of both factors for improving the fuel efficiency of the bloomery furnace system.

4.1. Analysis of Waste Heat Recovery Systems' Efficiency During Preheating

The burning time was estimated by measuring the time required for 1.5 kg of eucalyptus charcoal to burn entirely in each experiment. Timing commenced at the moment the fuel was introduced into the combustion chamber and concluded when the fuel was entirely consumed, indicating the end of the combustion process.

Table 1 shows the Eucalyptus charcoal 1.5 kg combustion time as a function of different VDF velocities and valve openings during the preheating phase of the bloomery shaft furnace. Results clearly reveal that higher VDF speed leads to a considerable reduction in combustion time. The charcoal burning rate was significantly elevated as the VDF speed rose from 10 to 50 Hz. In addition, the open-valve situation is always associated with shorter combustion times than the closed valve at each frequency level. This fact highlights the need for higher airflow rates to enhance heat transfer and improve fuel combustion efficiency.

A normality assumption of the statistical model was tested using a probability plot of residuals. The remaining dots stick to the reference line, and the p-value is 0.672. It means the residuals are normally distributed. Therefore, the ANOVA model is appropriate for analyzing the experimental data, as shown in Figure 4.

Table 1. Combustion time of 1.5 kg of eucalyptus charcoal during the preheating period of the bloomery shaft furnace

VDF speed (Hz)	Valve status	Combustion time (sec)		
		No.1	No.2	No.3
10	Open	353	342	359
10	Close	405	391	376
30	Open	110	120	118
30	Close	166	183	175
50	Open	113	109	110
50	Close	180	170	173

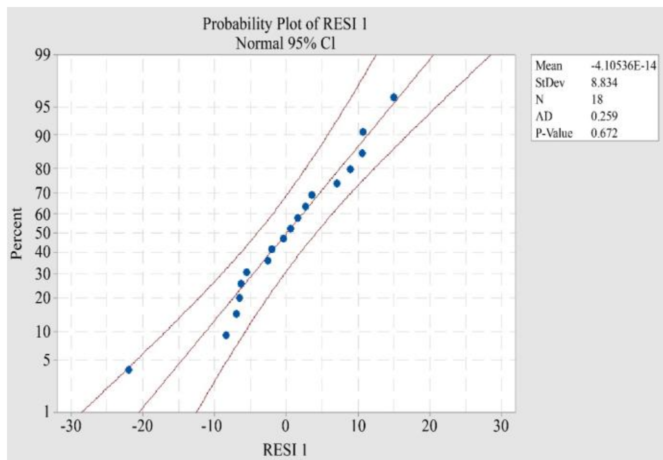

Fig. 4 Probability plot of residuals during preheating

The Analysis of Variance (ANOVA) in Table 2 shows that both factors, the VDF speed and the valve status, have a significant effect on the fuel combustion time during the preheating period. The VDF speed gives a high F-value of 1088.38 with a p-value of 0.000, which is below the 0.05 significance level.

This result showed that the VDF speed influences the combustion rate inside the bloomery shaft furnace. Similarly, the valve condition appears to have an F-value of 137.89 with a p-value of 0.000, whose opening or closing has a significant effect on the flow rate at which air is entering the reactor.

When the valve is open, the result shows faster and more efficient combustion than when the valve is closed for the preheating period.

Table 2. Analysis of Variance (ANOVA) of fuel combustion time during the preheating period

Source	DF	Adj SS	Adj MS	F	P
VDF Speed Valve Status	2 1	206291 13068	103146 13068	1088.38 137.89	0.000
Error	14	1327	95		
Lack-of-Fit Pure Error	2 12	495 831	248 69	3.58	0.061
Total	17	220686			

The analysis of mean separation for fuel combustion time during the preheating period of the bloomery shaft furnace was conducted using Fisher's Least Significant Difference (LSD) method at a 0.05 level of statistical significance. The results showed that the mean combustion times were 371, 145.33, and 142.50 seconds, respectively. However, the variable frequencies of 30 Hz and 50 Hz did not differ significantly, as presented in Table 3.

Table 3. Grouping fuel combustion time during the preheating period with the LSD method and a 95% confidence level

VDF Speed (Hz)	N	Mean	Grouping
10	6	371.00	A
30	6	145.33	B
50	6	142.50	B

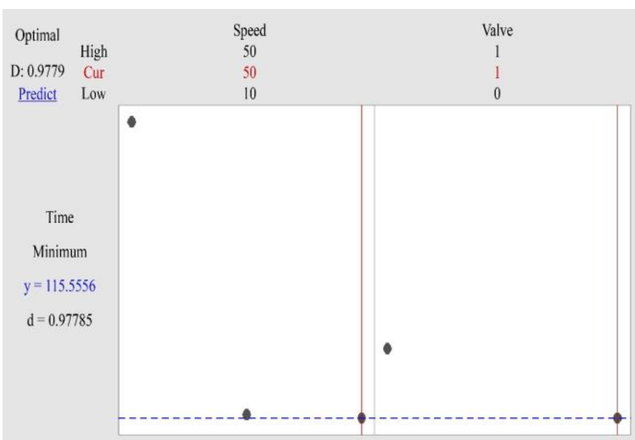

Fig. 5 Response optimization analysis during preheating

Figure 5 shows the response optimization analysis used to determine the best operating conditions for reducing the fuel combustion time during the preheating period of the Bloomery Shaft Furnace. The analysis indicates that the optimal conditions are a VDF speed of 50 Hz and an open butterfly valve (Valve = 1). Under these settings, the minimum predicted combustion time is about 115.56 seconds, with a desirability value of 0.9779, which is considered very high and reflects an excellent level of optimization. These results agree with the ANOVA and LSD analyses.

4.2. Analysis of Waste Heat Recovery Systems' Efficiency During Thermal Decay

Measuring the thermal decay period supports evaluating the furnace's ability to retain heat after combustion. It also helps identify the system's heat-loss rate and supports the design or improvement of waste-heat recovery systems to make them more efficient. The analysis of the waste-heat recovery performance during the thermal decay period evaluates the furnace's ability to retain heat after the combustion process has ended. This evaluation is based on measuring the rate at which the internal temperature decreases. The observation begins when the fuel is almost completely burned and continues until the temperature inside the furnace drops to 600°C, as shown in Table 4.

The data in Table 4 show that the combustion time during the thermal decay period clearly decreases when the VDF speed is increased and when the valve is in the open position. This indicates that even during the cooling stage of the furnace, the airflow rate still influences the combustion efficiency of the remaining fuel. In the probability plot shown in Figure 6.

Table 4. Combustion time of 1.5 kg of eucalyptus charcoal during the thermal decay period of the bloomery shaft furnace

VDF speed (Hz)	Valve status	Combustion time (sec)		
		No.1	No.2	No.3
10	Open	856	856	851
10	Close	753	740	760
30	Open	654	663	676
30	Close	564	581	567
50	Open	431	449	463
50	Close	366	384	386

Table 5. Analysis of Variance (ANOVA) of fuel combustion time during thermal decay

Source	DF	Adj SS	Adj MS	F	P
VDF Speed Valve Status	2 1	448638 36992	224319 36992	1132.24 186.72	0.000
Error	14	2774	198		
Lack-of-Fit Pure Error	2 12	1240 1533	620 128	4.85	0.029
Total	17	488404			

The data points lie close to the reference line, and the p-value of 0.644 is much higher than 0.05. The residuals are a normal distribution, and the model used in the analysis is statistically appropriate and reliable. These results confirm that VDF speed and valve status truly affect the combustion time during the thermal decay period and that the relationship is not caused by abnormal or inconsistent data.

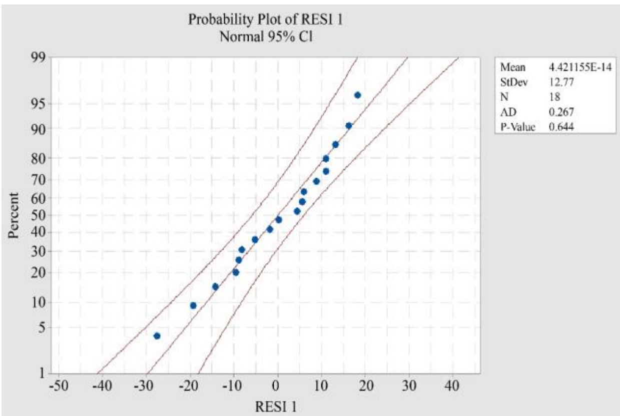

Fig. 6 Probability plot of residuals during thermal decay

The Analysis of Variance (ANOVA) in Table 5 shows that the VDF speed and the valve status have a significant effect on the combustion time during the thermal decay period of the Bloomery Shaft Furnace. The VDF speed is a high F-value of 1132.24 with a p-value of 0.000, which is far below the 0.05 significance level. This indicates that changes in VDF speed strongly influence the airflow rate and cause significant changes in combustion time during thermal decay. Similarly, the valve status shows an F-value of 186.72 with a p-value of 0.000, meaning that opening or closing the butterfly valve clearly affects the amount of air passing through the furnace during heat loss and has a strong impact on the remaining fuel's combustion time.

Table 6. Grouping waste heat recovery systems during thermal decay with the LSD method and 95% confidence

VDF Speed (Hz)	N	Mean	Grouping
10	6	799.667	A
30	6	617.50	B
50	6	413.167	C

As shown in Table 6, the VDF speed has a marked and significant effect on the combustion time during thermal decay. The LSD method divides the combustion times into three different groups. With the increase of VDF speed, the average combustion time has a downward tendency that implies increasing the airflow rate will bring an improvement in both more efficient and quicker combustion of the remaining fuel. The best conditions for increasing the temperature decay time of the Bloomery Shaft Furnace occur when the VDF speed is set to the lowest level (10 Hz) and the butterfly valve is open. These settings set the model to predict the maximum decay time of about 845 seconds, with a high desirability value of 0.9776. These conditions reduce heat loss by slowing the airflow into the furnace, allowing the system to retain heat for a longer period. This result confirms that controlling the airflow rate plays an important role in improving heat retention during the temperature decay phase, as shown in Figure 7.

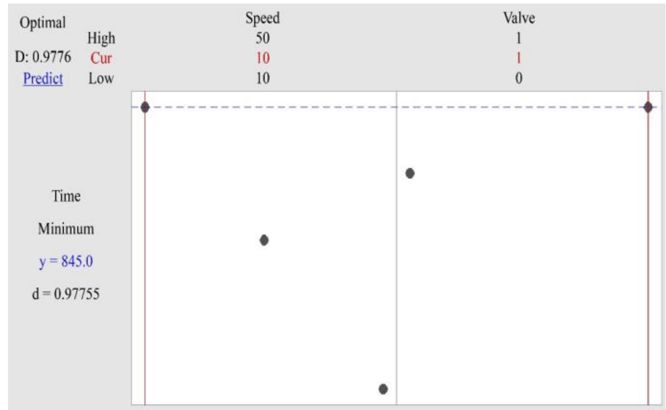

Fig. 7 Response optimization analysis during temperature decay

The results of this study are consistent with relevant research in several respects, including the concept of optimizing the smelting process through the use of advanced thermal techniques and control systems. The design of a Bloomery Shaft Furnace equipped with a spiral coiled tubular heat exchanger system can reduce heat loss and improve energy efficiency, which is consistent with the research of Yang et al. [7]. Similarly, Brown et al. [9] and Kurşun et al. [11] designed a heat exchanger that enhances energy transfer efficiency in systems that emphasize energy storage and heat transfer time. Furthermore, the combination of a Variable Frequency Drive (VFD) to regulate the blower speed and a butterfly valve in this research demonstrates the application of intelligent control concepts to improve system efficiency, aligning with international trends in thermal system optimization research. Therefore, this research is consistent with current academic concepts and can be further developed for industrial research and development.

5. Conclusion

This study shows that controlling airflow via a waste-heat recovery system can significantly improve the thermal performance of the Bloomery Shaft Furnace. The furnace was enhanced by integrating a spiral coiled-tube recuperative heat exchanger with an air-control system that includes a Variable Frequency Drive (VFD) and a butterfly valve. This combination allows more accurate adjustment of airflow and improves overall combustion conditions. The best performance was obtained at 50 Hz VFD and full open of the butterfly valve during the preheating period. In contrast, during the thermal decay period, the most suitable condition for retaining heat was a VFD frequency of 10 Hz with the valve open, which reduced convective heat loss and kept the internal temperature stable for a longer time. The improved

Bloomery Shaft Furnace design increases energy efficiency and supports more sustainable iron production at the community-industrial scale. These results also suggest that the system can be further developed for small-scale industrial applications using modern heat-recovery and combustion-control technologies. Furthermore, it could lead to communities producing higher-quality steel at lower production costs.

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