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Development of an Open Hearth Furnace with a Mechanical Blower and Mechanized Bellow

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Abstract: *This study focuses on the development of a hearth furnace with a mechanical blower and mechanized bellow intended to replace traditional open-hearth furnaces with restricted operational efficiency. The bellow system utilizes a crank-slider mechanism powered by an electric motor to generate a continuous airflow, thereby optimizing combustion within the furnace. The total force acting on the crank-slider was 22.22 N, and the calculated stoichiometric air required for complete combustion of the charcoal was 26.80* m^3/hr. *The maximum temperature recorded during performance evaluation was 110 5℃ for the blower with energy consumption of 940.8 kJ and 923.9 ℃ for the bellow with energy consumption of 24.4 kJ. The air speed achieved by the bellow was 3.5 m/s each time the bellow compresses, with reduced pulsating interval and enhanced combustion of the charcoal. Compared to manual operation, the furnace reduced human exposure to heat, eliminated operational fatigue, and improved the overall efficiency and safety of the furnace operation. The results demonstrate that integrating a mechanical blower and a mechanized bellow into open-hearth furnace systems is a viable method to boost production rates and occupational safety in small-scale foundry operations.*

Keywords: *Mechanical Blower, Mechanized Bellow, Hearth-furnace, Charcoal, Airspeed.*

1. INTRODUCTION

The open-hearth furnace is historically significant in metallurgical processes and remains a vital tool in small-scale foundry operations. Furnaces are widely use in the industry for the calcilnation of clay minerials and stell manufacturing [1], [2]. Furnaces rely heavily on effective combustion to achieve the high temperatures required for metal melting and heat treatment processes, and this combustion efficiency is largely dependent on a steady and adequate supply of air, which serves as a crucial component of the combustion triangle — fuel, heat, and oxygen [3] [4]. Generally, hearths have mechanical blowers attached to help in the combustion of fuel. Although these blowers are efficient in air supply, they are expensive and cannot be used in rural areas where there is no electricity [5].

Traditionally, manually operated bellows have been employed to provide the necessary airflow to support combustion in open-hearth furnaces. Bellows are devices that furnish a strong blast of air and are typically composed of two rigid boards connected with flexible leather sides. They enclose an airtight cavity that can be expanded and contracted by operating the handles. These manually operated bellows, however, present significant challenges that include uneven airflow, operator fatigue, low combustion efficiency, and increased operator health risks dueto heat exposure. These limitations have hindered the capacity of small-scale foundries to achieve consistent and high-temperature combustion that is required for metalworking [5] [6].

Over time, several types of bellows have been developed and improved upon across different cultures and historical periods. These include primitive pot bellows, animal-hide bellows, hand-cranked rotary bellows, water bellows, double-acting piston bellows, and double-lung accordion bellows [5]. Each of these bellows varies in airflow capacities and ease of operation. Despite these advancements, modern modifications for small-scale open-hearth furnace operations are limited. The use of electric forge blowers is being adopted in more industrial settings for their ability to supply continuous airflow [7]. Many small workshops still rely on manual systems due to cost and availability, and this has restricted operational efficiency [8].

To address these challenges, this study presents the development of a hearth furnace with a mechanical blower and a mechanized bellow driven by a crank-slider mechanism. The crank-slider mechanism was chosen for its ability to convert rotary motion into reciprocating motion, facilitating efficient air compression and delivery to the furnace. Similar mechanical solutions have been explored in other engineering applications, such as multi-hacksaw cutting machines, where the crank-slider mechanism has been used to automate cutting processes and reduce human effort [9]. By applying this principle to furnace air supply, the mechanized bellow aims to: provide a steady and controlled airflow to ensure efficient combustion, eliminate the physical strain and health hazards associated with manual operation. The addition of mechanized bellow therefore offers an intelligent approach to overcoming the limitations of traditional air-supply systems in open-hearth furnaces and challenges faced by small metallurgy workshops.

2. THEORETICAL ANALYSIS AND METHODOLOGY

2.1 Selection of Mechanical Blower

The specification of the blower used was selected by calculating the amount of air required to achieve complete combustion of 1kg of charcoal. To achieve this, proximate and ultimate analyses of the charcoal used were carried out using the appropriate methods in Table 1, and the results are presented in Table 2. The volume of oxygen to achieve complete combustion of one kilogram was calculated using Equation 1, and the volumetric flow rate was calculated using Equation 2 [10]. The calculated volume of air was 26.80 m^3/hr.

Table 1: Standard methods employed for proximate and ultimate analysis

Property	Standard Methods
Moisture Content (MC)	ASTM D2016-25
Volatile Matter (VM)	ASTM E872
Ash Content (AC)	ASTM D1102
Fixed Carbon (FC = 100 -VM-AC-MC)	By difference
Carbon, Hydrogen, and Nitrogen	ASTMD 5373
Sulphur	ASTMD4239-11
Oxygen (N% +C%+S%+H%-100	By difference

Table 2: Proximate and ultimate analysis of the charcoal

Proximate Analysis (%)	Ultimate analysis (%)
Fixed Carbon: 75.03	Sulphur: 3.1
Moisture Content: 7.24	Nitrogen Content: 1.4
Volatile matter: 11.32	Hydrogen Content: 4.1
Ash content: 11.4	Oxygen Content: 2.1
	Carbon: 70.66
	Energy Content: 3416 (Kcals/kg)

$$Q_a = \frac{22.41}{21}\left(\frac{C}{12} + \frac{H}{4} + \frac{S-O}{32}\right)(m^3\ O_2/kg\ fuel) \quad (1)$$

$$\dot{Q}_a = M \times Q_a\ (m^3/h) \quad (2)$$

Where Q_a is the volume of oxygen required, C is the amount of Carbon, H is the amount of hydrogen, S is the amount of sulphur, O is the amount of oxygen, M is the fuel mass flow rate, and $\dot{Q}_a$ is the oxygen flow rate. A centrifugal fan with an induction motor (3Hp, single phase, 50 Hz, AC voltage 230/240 V) was selected. The fan can produce a range of 25 to 80 m^3/hr. This capacity is higher than the calculated stoichiometric air.

2.2 Design of Crank-Slider Mechanism for the Bellow

The mechanized system was designed using a crank-slider mechanism, which transforms the rotary motion from an electric motor into linear reciprocating motion to effectively operate the bellow. The crank-slider mechanism achieves the reciprocating linear motion needed to compress and expand the bellow. The mechanism consists of a flywheel, connecting rod, and sliding guideways. The flywheel is attached to the electric motor and transmits motion to the connecting rod, which in turn drives the bellow lid. Key design parameters were derived from kinematic and force analysis.

2.3 Kinematic and Force Analysis

A 200 mm stroke length of the bellow was measured, as shown in Figure 1(a), to determine the extent of airflow per cycle. The crank radius and connecting rod length were computed using trigonometric relationships as illustrated in Figure 1(b).

The kinematic arrangement in Figure 1(a) is defined in Equation 3:

$$A = \pi D \qquad \text{(Where D is 70 mm)} \quad (3)$$

The trigonometric arrangement in Figure 1(b) is defined in Equation 4:

$$C^2 = A^2 + B^2 - 2AB\cos\theta \quad (4)$$

Where A = 220mm and B = 35mm, and Ɵ = 45°; C = 203.801mm. The force analysis considered various acting forces, including force due to the weight of air inside the bellow (Ff), force due to the weight of the bellow lid (Fb), force due to the weight of connecting rod (Fc), and force of inertia during discharge of air (Fa).

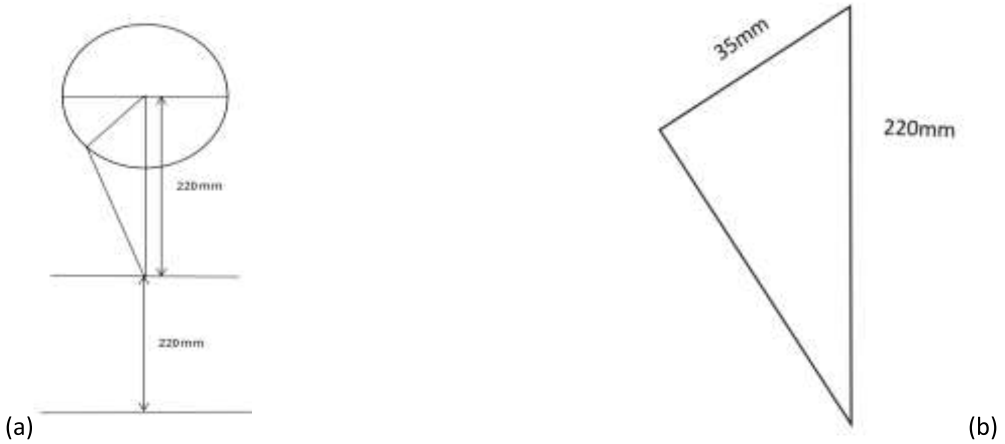


Figure 1: (a) Kinematic (b) Trigonometric arrangement

These forces were calculated using Equations 5, 8, 10, 11, 12, and 13.

The total force acting on the system (FT) was computed as:

$$F_T = \left(F_f + F_b + F_c\right) - F_a \tag{5}$$

The Torque (T) and power (P) required to drive the mechanism were calculated using Equations 6 and 7:

$$T = F_T \times R \tag{6}$$

$$P = \omega \times T \tag{7}$$

Where R is the crank radius and ω is the angular velocity. The summarized computed values are presented in Table 2. Because F_b and F_c are acting due to the force of inertia, the force of inertia (F_a) is evaluated.

$$F_a = M_a a_a \tag{8}$$

$$a_a = -\frac{\omega^2 S}{2} \tag{9}$$

$$F_b = \left(\frac{h \times b}{2}\right)\rho_b g t \tag{10}$$

$$F_c = (l \times b)\rho_c g t \tag{11}$$

$$F_f = \left(\frac{l \times b \times h}{3}\right)\rho_f g \tag{12}$$

$$F_a = M_a a_a = \pi(R^2 - r^2) l \times \rho_f \tag{13}$$

After substituting Equation (9)

$$F_a = (\pi(R^2 - r^2) l \times \rho_f) \times -\frac{\omega^2 S}{2} \tag{14}$$

Recalling from Equation 5,

$$F_T = \left(F_f + F_b + F_c\right) - F_a$$

After substituting Equations 10, 11,12,14, we have Equation 15

$$F_T = \left(\frac{l \times b \times h}{3}\right)\rho_f g + \left(\frac{h \times b}{2}\right)\rho_b g t + (l \times b)\rho_c g t - \left[(\pi(R^2 - r^2) l \times \rho_f) \times -\frac{\omega^2 S}{2}\right] \tag{15}$$

The angular velocity is defined in Equation 16

$$\omega = \frac{2\pi N}{60} \quad \text{(N is 50 rpm)} \tag{16}$$

Where Ma is the mass of air, aa is the acceleration of air from bellow, S is the Length of bellow stroke, $(\frac{h.b}{2})$ is the area of a triangle, t is the thickness, ρ_b is the density of the bellow lid (wood), g = acceleration due to gravity, (l x b) is the area of the connecting rod, $\left(\frac{l \times b \times h}{3}\right)$ is the volume of a pyramid, ρ_f = density of fluid (air), $\pi(R^2 - r^2)l$ is the volume of a hollow cylinder. The results of these calculations are presented in Table 3.

Table 3: Calculated forces, torque, and power requirements

S/N	Parameter	Symbol	Value (Unit)
1	Force due to the weight of the bellow lid (wood)	Fb	17.29 N
2	Force due to the weight of the connecting rod (mild steel)	Fc	4.85 N
3	Force due to the weight of compressed air inside the bellow	F_f	0.0876 N
4	Force released from the system due to air discharge	Fa	0.00441 N
5	Total force acting on the system	FT	22.22 N
6	Crank radius	R	0.1 m
7	The torque required to drive the system	T	2.22 Nm
8	Angular velocity (from motor)	ω	5.24 rad/s
9	Power requirement	P	11.63 W
10	Airflow capacity achieved	-	0.11 m^3/s

2.4 Design Considerations for the Mechanized Bellow

To ensure effective operation in small-scale foundry environments, the following factors were considered in the design and development of the mechanized bellow for the open-hearth furnace: material availability and affordability, strength and machinability of materials, ease of operation and assembly, and power requirements.

2.4.1 Material selection

The material selection was driven by economic and functional considerations such as affordability, local availability, and durability. The major components and materials used are listed in Table 4, and the materials used were sourced locally in Ilara-Mokin town, Ondo state, Nigeria.

Table 4: List of materials and specifications

S/N	Component	Material Used	Dimensions (mm)
1	Base Frame	Mild Steel (Angle bar)	40 × 40 × 3
2	Bellow Lid (Cover)	Wood	470 × 250 × 20
3	Connecting Rod	Mild Steel (Flat bar)	420 × 50 × 3
4	Flywheel	Mild Steel (Circular)	Radius: 35
5	Crank Arm	Mild Steel (Flat bar)	Radius: 35
6	Bellow Body (Flexible part)	Treated Leather	Diameter: 220
7	Electric Motor	Standard Electric Motor	12 V, 50 RPM
8	Fasteners (Bolts and Nuts)	Steel	M10 (standard size)
9	Nozzle diameter	Mild Steel Pipe	Diameter: 20

2.4.2 Modeling of the hearth furnace

The complete assembly was modeled using Autodesk Inventor Pro (2019), which provided 2D and 3D views for visualization and analysis. The isometric view and part lists of the mechanized hearth furnace are shown in Figures 2 and 3, respectively.

2.4.3 Fabrication of the mechanized bellow

Accurate measurements were made using standard steel rulers and marking tools to define cut lines and joint points. The Machining phase included cutting and drilling. Steel components were cut according to design dimensions using cutting machines. Holes were drilled at specified locations for bolt connections and assembly alignments. Welding was used for permanent joints, including the motor mount and frame structure. For moving parts such as the connecting rod and flywheel, bolts and nuts were used to allow flexibility in motion and alignment corrections. After fabrication, all steel components were cleaned and painted to prevent corrosion. Sharp edges were filed, and moving parts were lubricated to minimize friction and wear.

2.4.4 Fabrication and installation of the hearth furnace

The body of the hearth furnace was fabricated using mild steel, while angle iron was used for the frame support. The fabricated components were assembled into a complete unit. The mechanical blower and mechanized bellow were mounted appropriately. The electric motor is positioned and aligned to ensure efficient transfer of rotary motion to the flywheel. The air duct was securely connected to the bellow and to the furnace to ensure direct airflow into the combustion chamber, and the crank-slider mechanism aligned with the bellow. The developed mechanized open-hearth furnace is shown in Figure 4.

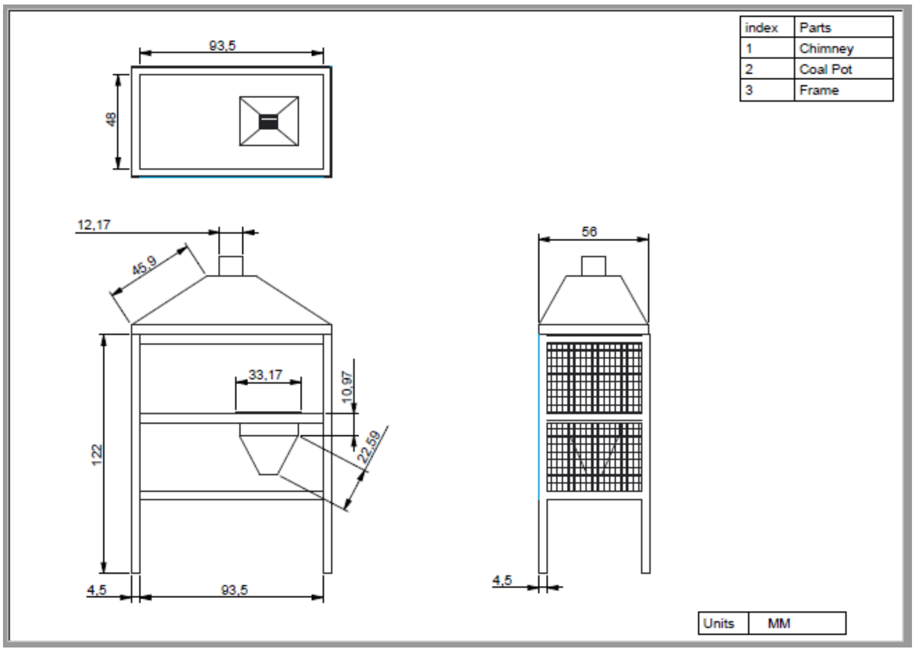
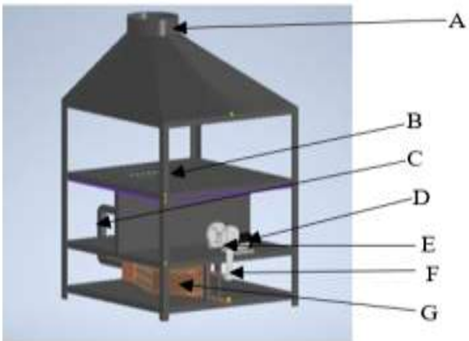


Figure 2: Isometric view of the mechanized hearth furnace



A	Chimney
B	Charcoal Basin
C	Air Duct
D	Electric Motor
E	Flywheel
F	Connecting Rod
G	Bellow

Figure 3: Part lists of the mechanized hearth furnace


Figure 4: Developed mechanized open-hearth furnace

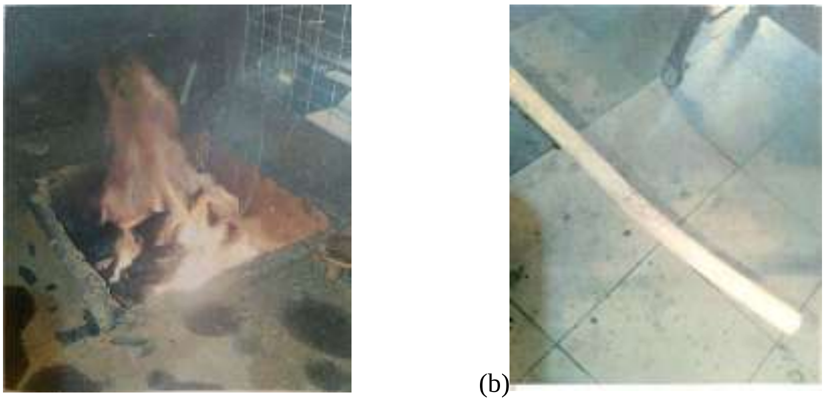
2.4.5 Performance testing

Performance evaluation was carried out by operating the hearth furnace, using the mechanical blower and the bellow air supply medium, to observe the effect of airflow rate on the combustion of charcoal. Combustion efficiency was assessed by the ability to ignite and sustain the burning of charcoal. The operational safety and ease were also monitored to ensure that the system requires minimal human intervention. The charcoal was ignited manually by using nylon and kerosene. After the ignition occurred, air was first supplied using the blower. At the end of the first experiment, the ash and leftover charcoal were evacuated. New charcoal was put in the charcoal basin, and the same method of ignition was followed. The electric motor that turns the crank-slider was connected to a 12V, 50-watt solar panel. As the bellow goes up and down, air was being supplied to the ignited charcoal, and the temperatures at different horizontal planes were determined. To check the performance of the furnace in metal working operations, a 12 mm low-carbon steel was heated in the hearth furnace while using the mechanical blower.

3. RESULT AND DISCUSSION

3.1 Performance of the Heart Furnace using the Mechanical Blower

The blower was operated at a speed of 4.5 m/s continuously above the calculated stoichiometric air. Charcoal of mass 0.5 kg was poured into the charcoal basin and ignited. After 5 minutes, the charcoal started becoming red-hot at a temperature of 616℃. Then another 1 kg was poured into the basin. After 7 minutes, the whole 1.5 kg was completely hot, and the temperature was 1105℃. The heat of the charcoal progressed quite fast from the bottom to the top of the basin, and it rose significantly. The colour progressed from dull red to bright red and to orange-yellow. Due to the progression of heat, three temperatures (465, 616, and 1105℃) were recorded. Conventional hot-forging temperatures for low-carbon steel ranged between 1000 and 1200 ℃ [11]. Therefore, the produced hearth furnace will perform effectively for metalworking operations. Ambient temperature and exposure of the basin to open air would have influenced the temperature recorded. The burning process is shown in Figure 5(a), and the heated low-carbon steel is shown in Figure 5(b). The electrical energy consumed by the blower within 7 minutes for the furnace to reach 1105℃ was 940.8 kJ, and the thermal efficiency was



(a) (b)

Figure 5: (a) Hearth furnace during operation, (b) Heated low-carbon steel of 2mm diameter

3.2 Performance of the Heart Furnace using the Mechanized Bellow

When the bellow was compressed, air was pushed out, and when expanded, air was drawn, hence a pulsating or intermittent air flow due to a momentary pulse before the next compression. The bellow delivered an air velocity of approximately 3.5 m/s per compression, which is within the range of conventional manually operated fireplace bellows (between 3-5 m/s). The adopted crank mechanism approach provided more stable air delivery and reduced fluctuation in temperature. The speed produced is sufficient for sustaining combustion and enabling the burning of hard fuels such as coal and coke. Table 5 presents the results of the performance evaluation of the hearth furnace at two different locations at an interval of 2 minutes with a crank slider motor of 50 rpm and an ambient temperature of 34.7 ℃, while Figure 6 is the plot of temperature against time at two different horizontal points. As time increased, charcoal got hotter with an orange fire colour and expanded as time progressed. At 30 minutes, the charcoal basin was 75% red, and the temperatures recorded at the two different points were 915.1 and 923.9 ℃. The result also shows that there was no significant difference in temperature between the two points, and this implies that quasi-static temperatures are attainable at horizontal positions. The crank-slider mechanized bellow was successfully implemented, assembled, and installed on the open-hearth furnace. The electrical energy consumed by the electric motor to drive the bellow for 30 minutes was 24.4 kJ. Upon testing the mechanized bellow under operational conditions, the system demonstrated better air supply, confirming its suitability for small-scale furnace applications.

Table 5: Temperature recorded at two different points and time intervals

Time (min)	Temp. @ point 1	Temp. @ point 2
0	34.7	34.7
2	91.8	95.8
4	148.6	149.7
6	207.5	210.4
8	260.7	267.3
10	301.8	299.1
12	362.7	365.5
14	410.5	411.2
16	468.9	463.5
18	530.9	537.2
20	610.8	616.4
22	670.3	689.7
24	730.5	745.9
26	790.8	785.7
28	854.6	865.3
30	915.1	923.9

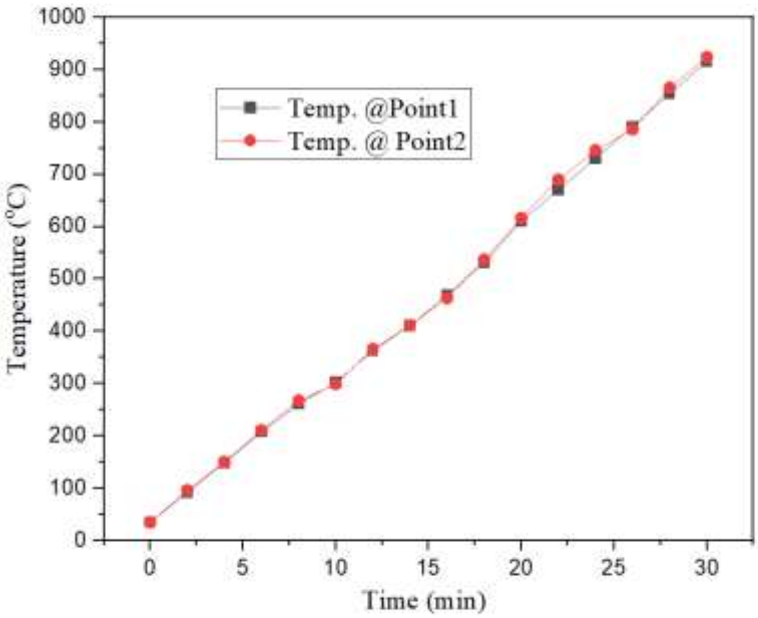


Figure 6: Plot of temperature against time at different points

3.3 Comparison of the Mechanical Blower and the Mechanized Bellow

The blower performed better than the mechanized bellow, as it produced a higher temperature of 1105 ℃ within 7 minutes than the bellow, which produced a maximum temperature of 923.9 ℃ at 30 minutes. This could be attributed to the pulsating air supplied when using the mechanized bellow, which resulted in a longer time to reach a high temperature. During the use of the mechanical blower, no smoke was generated, while at the onset of using the mechanized bellow, a huge amount of smoke was experienced, which later reduced and stopped as the air circulation progressed. The smoke generated could be attributed to poor and delay in air circulation due to the pulsating behaviour of the mechanized bellow. The electrical energy consumed by the mechanical blower (940.8 kJ) was higher than the energy consumed by the electric motor (24.4 kJ). This implies that the use of bellow, driven by an electric motor, is cost-effective compared with a mechanical blower when operated at the same time.

4 CONCLUSION

The design process, fabrication, installation, and testing of the hearth furnace were successful. The furnace attained improved efficiency compared to the manually operated blower, leading to an increased production rate. Health issues like fatigue, repetitive strain injuries, and heat waves were eliminated as the two air sources required no human effort. Time savage, while working with the furnace was also achieved. The maximum temperatures (1105 ℃ and 923.9 ℃) produced when using the two air sources were within the forging temperature of a low carbon steel rod (12mm diameter). The maximum temperature reported falls within the required forging temperature range of low-carbon steel. The designed heart furnace could be used in local blacksmith shops without any health or electricity issues. Further work could be done to improve the amount of air delivered by the mechanized bellow by increasing the air volume.

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