FABRICATION AND PERFORMANCE EVALUATION OF IMPROVED FORCED DRAFT STOVE

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***ABSTRACT**: In many non-industrial and developing countries, a substantial portion of the population lacks access to modern energy services. Whereas electricity and natural gas availability are erratic, affecting cooking practices. Liquefied petroleum gas (LPG), an option, remains cost-prohibitive and limited. Escalating fossil fuel prices underscores the need for alternative cooking solutions This study contributes by focusing on sustainable cooking solutions by analyzing the two prevalent improved stoves such as natural draft and forced draft. Whereas, natural draft stoves operate at 10-20% thermal efficiency, while forced draft stoves offer 40-43%. Building on the advantages of forced draft stoves, this study designs and develops an efficient stove for various fuels, comparing it to an improved natural draft stove. This analysis offers insights into the efficiency and cost-effectiveness of the forced draft stove. Focus on thermal efficiency, and fuel consumption highlights benefits, demonstrating improved performance and reduced environmental impact. The study aids decision-makers and stakeholders seeking energy-efficient, eco-friendly cooking solutions. Addressing fabrication, design, and material limitations, this research advances affordable stove technologies, positively impacting household energy use and indoor air quality.*

Keywords: Forced Draft Stove, Natural Draft Stove, Stove Efficiency, Fuel Consumption, Indoor Air Pollution

INTRODUCTION

A major chunk of the world's population resides in non-industrial and developing countries that lack ingress to advanced and modern energy services for socio-economic development [1]**.** Moreover, A significant proportion of households from such countries, lack access to electricity and natural gas supply. Thus, those who rely on electricity and natural gas for cooking experience episodic supply. Although Liquified petroleum gas (LPG) is considered a viable option for cooking, Yet, due to its high cost and access to limited areas, is not cost-effective and inaccessible to impoverished populace. In addition, the skyrocketing prices of fossil fuels and the fuel crisis have highlighted the need to produce suitable alternatives to electricity, natural gas, and various other fossil fuels for household cooking [2].In developing countries, non-governmental organizations have made significant efforts to promote and adopt improved stove technologies in households. This study will contribute to the ongoing efforts to promote sustainable and efficient cooking solutions in developing countries.

As of now, there are two kinds of improved biomass stoves, i.e., forced draft and natural draft, that are commercially available in developing nations. [3]The natural draft stoves combust fuel by intaking oxygen (Inflow air) from the environment through a supply route for air in a stove, whereas in the forced draft stove, oxygen (inflow air) for combustion is supplied by installing a blower/fan in the stove [4]**.**

Most of the natural draft stoves operate at 10-20 % thermal efficiency. Whereas the thermal efficiency range of forced draft is between 40-43% [5]. Given the notable advantages associated with forced draft stoves, the objective of this study was to design and create a forced draft stove capable of efficiently burning various types of fuel while ensuring optimal performance. This stove was developed with the goal of maximizing its efficiency. The primary aim was to evaluate and compare the performance of the developed forced draft stove with an improved natural draft stove, which served as a benchmark. Through this comparative analysis, the study sought to offer valuable insights into the efficiency and cost-effectiveness of the newly developed stove when contrasted with an improved natural draft stove. The study's emphasis on key factors such as thermal efficiency, emissions, and fuel consumption aimed to shed light on the advantages and merits of the advanced forced draft stove. This included showcasing improved performance and a reduced environmental footprint. By assessing and comparing these crucial aspects, the study aimed to contribute to the body of knowledge surrounding stove technology and offer practical information for decision-makers, users, and stakeholders interested in adopting energy-efficient and environmentally friendly cooking solutions. By addressing the limitations in stove fabrication, design, and material selection, this study will advance the development of effective and affordable stove technologies that can positively impact household energy consumption and indoor air quality.

LITERATURE REVIEW

Cooking constitutes around 70-60% of the total energy used in the rural sector and 80-90% of domestic thermal energy need is met through dung briquettes, crop residues, and wood [6]**.**

Biomass with its widely spread geographical distribution has the highest annual production rate among all renewable energy resources, and because of that biomass is considered to be the most viable alternative to fossil fuel [7]. As per [8]**,** 2.5 billion people across the globe use charcoal and wood for cooking. Most of these people who rely on wood and coal for cooking reside in developing nations [9]. In addition to this, a humongous portion of these people employ open fire or traditional stoves for cooking. Due to poor design, material, and air regulation, they have very high indoor and outdoor air pollution and low thermal efficiency [10]**.** Conversely, the increased biomass utilization by inefficient technologies has enhanced forest degradation with loss of environmental services (e.g., watershed protection) and biodiversity [11]**.** Moreover, such stoves enhance the risk of accidental fires. Furthermore, exposure to emissions from these may lead to various eye and lung diseases, premature deliveries, and deaths [4].

According to [12], Wood/Biomass requires special conditions for complete combustion, and because of that it is quite difficult to combust wood/Biomass in traditional stoves. As a result, frequent usage of improperly designed stoves, as well as traditional stoves, results in IAP (Indoor Air Pollution). Hence, such stoves cause severe impacts on user health [1]. Especially, Women and children are especially affected by indoor pollution as compared to men because they spend more time in the home near the fire or kitchen. For instance, according to [13]. About 2 million deaths in developing countries of children and women annually are associated with IAP. More precisely to (Formaldehyde and benzene) volatiles and CO (Carbon Monoxide) exposure in stove smoke [14]

According to [3] the forced draft technique reduces the emissions level by 90% and fuel consumption by 40%. Moreover, the introduction of a chimney in stoves significantly reduces indoor air pollution within the house/Kitchen.

As per [3], the improvement in the design of the stoves can reduce the concentration of CO (Carbon Monoxide) by 98-99% and Particulate Matter (PM2.5) by 71-84% in the exiting gaseous stream. However, modern and improved stoves have pre-installed chimneys. Which reduces the exposure to indoor air pollution by shifting the pollution to the outdoor environment [15]. Therefore, instead of transferring the pollution issue to outside the house, it is essential to reduce and bring under control the pollution emitted from stoves by opting for techniques & technology that completely combust the fuel inside the combustion chamber. According to [3], stoves with chimney reduces indoor air pollution but they take 74 % more time and 61 % more fuel than traditional stoves.

The application of improved biomass stoves not only shields the user from Indoor and outdoor pollution but also from the risk of diseases associated with the usage of traditional stoves, at the same time providing maximum thermal efficiency while safeguarding the environment by negating the constituents instrumental for climate change. Moreover, the installation of improved stoves helps in fighting poverty and safeguards the natural as well as social environment of a country. Hence, the implementation of such stoves plays a key role in environmental sustainability. According to [16], the successful implementation of improved stoves in developing countries can significantly remove GHG (greenhouse Gasses) from the environment. Moreover, such an initiative can save 17% of premature deaths, bronchitis, eye infections, heart diseases, and respiratory diseases while saving 55.5 million years of healthy life on Earth that otherwise would have been lost due to exposure to air pollution.

The type of material used for stove construction plays a key role in determining the efficiency of a stove because various types of materials are used for distinctive stove designs. Hence, they have different thermal efficiencies. For instance, stones and bricks are used for the construction of three-stone or traditional stoves but A significant portion of thermal energy produced by biomass combustion is consumed by these stove fabrication materials [17]. Hence, the thermal efficiency of the stove is inversely proportional to the material energy consumption. The material that consumes more energy has less thermal efficiency. Because instead of transferring heat to the pot for cooking, most of the combustion energy is consumed by the material. Especially during the cold-start high-power phase [18]. Stoves are manufactured using various types of materials. For instance, there are metal stoves fabricated only using metals. Then there are stoves produced using both clay and metal combinations. Similarly, few stoves are designed using vermiculate material whereas few portable forced draft stoves are constructed using metal and insulation material for better thermal efficiency [4]. Hence, it is equally important to select the right kind of materials having low thermal mass and high insulation properties for high thermal efficiency.

Table 1: Thermal Characteristics of Different Materials

Materials	Thermal Conductivity	Density	Specific Heat
Mild Steel	80	7870	447
Stainless steel	14.9	7900	447
Vermiculate	0.07	960	91
Ceramic Wool	0.09	85	1070
Bricks	0.3	1285	1000
Clay	0.65	2400	2400

However, the efficiency of these stoves can be improved if certain operating parameters are regulated. For instance, effective maximum heat/temperature is generated only when the fuel is completely combusted, which occurs only when the flow of oxygen (Inflow air) is equal to the theoretical oxygen. If the input oxygen (inflow air) is less than the required theoretical oxygen, then fuel combusts incompletely and releases more particulate matter and carbon monoxide in exiting gaseous emission thus less heat is generated. Similarly, if the input air (Inflow air) is greater than the required theoretical oxygen, the heat is lost with the exhaust emissions. As a result, the actual temperature of the combustion is less than the theoretical temperature [19]. However, excessive inflow air is preferred as it reduces the concentration of particulate matter and carbon monoxide in the exhaust stream [20].

MATERIALS & METHOD

Forced Draft Stove

The fabrication of the module involved the use of several materials, including mild steel, and mixed galvanized iron. These materials were selected for their specific properties and suitability for stove construction. Additionally, Clay was utilized for insulation purposes in the stove. These materials were chosen to provide effective insulation, helping to retain heat and improve the stove's overall efficiency. The design specifications of the fabricated forced draft stove are given in Figure 1.

The fabricated forced draft stove comprises of two cooking plates: a primary plate and a secondary plate. The primary plate is strategically situated directly above the combustion chamber, featuring a 6.5-inch aperture tailored for cookware accommodation. Correspondingly, the secondary plate is interconnected with the combustion chamber via a 2-inch conduit, analogous in its structure with a 6.5-inch hole for cookware placement. The integration of cookware atop the primary plate serves a dual purpose: it acts as a thermal barrier and confines emissions from escaping to the environment.

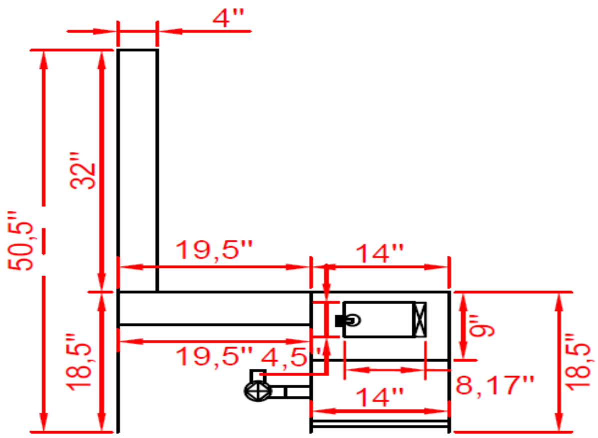

Figure 1: Fabricated Forced Draft Stove Design

This arrangement facilitates efficient heat transfer, where the convective energy of flames is directly transferred to the cookware, optimizing cooking dynamics. Emissions emanating from the combustion chamber traverse a sequential trajectory, first interacting with the primary plate's cookware, followed by impinging on the culinary apparatus situated on the secondary plate. The exhaust gases then find their exit through the chimney at the extremity of the secondary plate. Concurrently, the plates are endowed with protective covers, mitigating heat dissipation during inactive phases. A blower assembly is discretely positioned beneath the primary plate, operating on a 12-volt system with a 0.5A current draw. This orchestrated airflow bolsters combustion efficiency by regulating oxygen supply. The apparatus spans dimensions of approximately 33.5 inches in length, and 50.5 inches in height, and bears a structural composition of robust mild steel, conferring a mass of 12 kilograms. This refined architectural rendition substantiates elevated culinary efficacy, exhaust governance, and an ergonomic orientation, thus offering a comprehensive culinary solution.

Natural Draft Stove

To establish a comparison with forced draft stoves, an improved version of natural draft stoves was chosen.

The design specification of the improved natural draft stove used during the study is given in Figure 2. The design was similar to the forced draft stove. It also consists of two plates, a primary and a secondary plate. The combustion chamber was also below the primary plate and the secondary plate was connected to the combustion chamber via a pipe from where the hot emissions rose and moved toward the chimney which was located at the extremity of the secondary plate. However, the key difference between both the stoves was their burning principle.

Thermal Efficiency

The Water Boiling Test (WBT) and Simmering test are crucial for evaluating the thermal efficiency and performance of wood stoves. The WBT serves as an initial assessment and allows for a comparison of different stove designs in performing similar tasks outlined in the International Standard on testing the efficiency of wood-burning stoves, prepared by Volunteers in Technical Assistance (VITA), USA. In this study, the WBT consisting of high-phase, low-phase, and Simmering was conducted on a forced draft stove and natural draft stove using different fuels, and the acquired test data was compared.

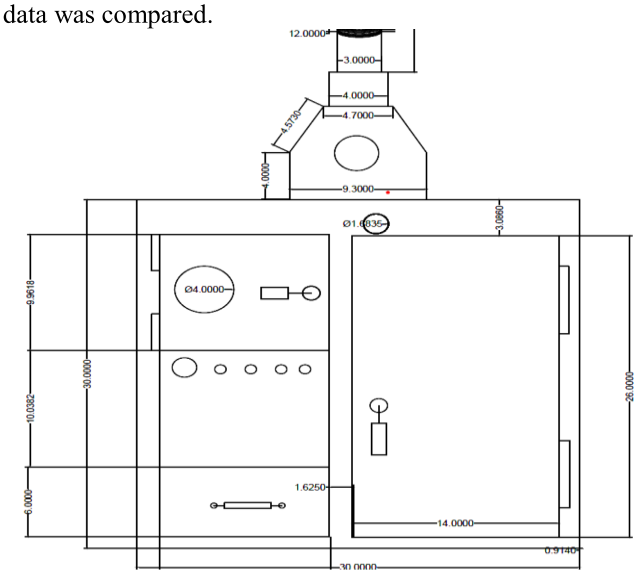

Figure 2: Improved Natural Draft Stove

The efficiency was computed using two equations, where high-phase efficiency is the energy required to raise the temperature of the water, whereas low-phase energy is needed to evaporate the water. Efficiency can be expressed by following the equation for the hi-power phase and low-power phase. The test result data of high-phase and low-phase are depicted in Table 2.

Where M_{wi} and M_{wf} are the initial and final mass of water in (mL), T_i and T_f are the initial and final temperature in (Ċ), M_{ev} is the mass of evaporated water in (mL), W_c is the heat capacity of water in (J/g /Ċ), M_{ci} and M_{cf} is initial and final mass of fuel in (g), H_c is Heating content (J/g) and H_w heat of vaporization of water (j/g) and W_{hat} is latent heat of water. Whereas the calorific value for coal, wood, and briquettes/pallets was 16980 (J/g), 24632 (J/g) and 18080 (J/g) respectively.

RESULT & DISCUSSION

Thermal Efficiency (High-Phase)

Thermal efficiency was computed using high and low-efficiency equations discussed above. The results highlight the significantly higher efficiency of the forced draft stove than the natural draft stove. when operating on coal, the thermal efficiency of the forced draft stove was measured at 57.7%, while the natural draft stove achieved an efficiency of 25.5%, marking a substantial 32.2% difference in favor of the forced draft stove. Similarly, when operating on wood in the High Phase, the forced draft stove achieved a thermal efficiency of 47.4%, whereas the natural draft stove achieved 28.8%, representing an 18.6% difference.

Table 2: Thermal Efficiency Outcome Of Natural And Forced Draft Stoves on Different Fuels.

Stove Type	Fuel Type	Hi-Phase Efficiency (%)	Low-Phase Efficiency (%)
Natural Stove	Wood	28.8	6.3
	Coal	25.5	9.5
	Briquttes/Pallets	49.6	33.6
Forced Draft Stove	Wood	47.4	38.5
	Coal	57.7	43.8
	Briquttes/Pallets	68.8	58.3

Whereas on low phase, Forced Draft stove exhibits higher efficiency compared to natural draft stove. As shown in Table 2, when operating in the low phase with coal, the Forced Draft stove achieved a thermal efficiency of 43.8%, while the natural draft stove only reached 9.5%, resulting in a substantial 34.3% difference in favor of the forced draft stove.

Figure 3: Forced Draft Stove with Amplified Flames Inside Secondary Plate Chamber.

Similarly, when operating with wood in the low phase, the Forced Draft stove achieved a thermal efficiency of 38.5%, while the natural draft stove managed only 6.3% efficiency. Furthermore, in the efficiency of burning dung briquettes, the Forced Draft stove exhibited an efficiency of 58.3%, whereas the natural draft stove achieved only 33.6% efficiency. These findings clearly indicate that the Forced Draft stove demonstrates higher efficiency in burning all three types of fuel compared to the natural draft stove.

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Fuel Consumption

The forced draft stove exhibited remarkable fuel efficiency by consuming less fuel if compared with the natural draft stove. The results of fuel consumption are depicted in Figure 4. Upon analyzing the results, a distinct disparity between the two stoves becomes apparent.

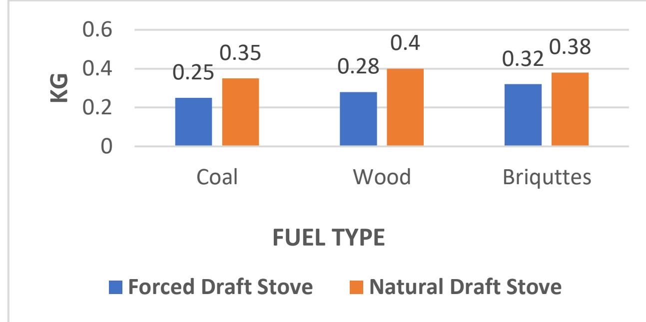

Figure 4: Fuel consumed by stoves to boil water.

The forced draft stove only consumed 250g of coal to boil 1 liter of water. In contrast, the natural draft stove required an additional 100g, resulting in a total fuel consumption of 350g for the same task. Similarly, when considering wood as the fuel source, the forced draft stove consumed 280g, while the natural draft stove consumed 400g, resulting in an extra 120g of fuel usage. Finally, in terms of briquette fuel, the forced draft stove utilized 600g, whereas the natural draft stove burned 800g to achieve the desired outcome. Based on these findings, it can be concluded that the forced draft stove saves approximately 300-400g of fuel per day and a substantial 12 kg of fuel per month in comparison to the natural draft stove. These results clearly demonstrate the superior fuel efficiency of the forced draft stove, making it a more economical and environmentally friendly choice.

Time Required For Boiling The Water

The water boiling test was conducted for boiling 1 liter of water on forced draft stoves and natural draft stoves on 3 types of fuel. The time to boil the water was from fuel ignition to when the water boil occurred. In all the tests, the forced draft stove showed remarkable ability in boiling the water by consuming the shortest span of time. The results of the test are depicted in Table 3.

Table 3: Time Required To Boil Water 1 liter water

Stove Type	Fuel Type	Plate 1 (Minutes)	Plate 2 (Minutes)
Natural Stove	Wood	19	Failed to achieve the boiling point
	Coal	22	
	Briquettes/Pallets	23	
Forced Draft Stove	Wood	6	10
	Coal	9	13
	Briquettes/Pallets	8	12

The forced draft consumed the shortest time on wood to boil water, i.e., forced draft stove plate 1 achieved boiling in 6 min and consumed 10 min on plate 2 whereas natural draft stove consumed 19 minutes on plate 1 and failed to achieve boiling point on plate 2.

Figure 5: Water Boiling Test on Natural Draft Stove

On average forced draft took 7 minutes on plate 1 and 11 min on plate 2. In contrast, the natural draft stove took 21 min on average on plate 1 to do the same task whereas it failed to achieve boiling temperature on plate 2.

Figure 6: Water Boiling Test on Forced Draft Stove

Therefore, Considering the regular meals, breakfast, lunch, and dinner, the forced draft stove can save on an average of 14-20 min cooking time per day and 7-10 hours per month in contrast to the natural draft stove.

Water Evaporation Test (Simmering)

Thermal efficiency is indeed a valuable indicator when evaluating stoves, as it considers the work done in heating and evaporating water relative to the energy consumed by burning fuel. To measure thermal efficiency, a defined quantity of 1000 ml water was heated for a specific duration of 60 minutes using 1 kg of fuel. The water was then allowed to evaporate by removing the cooking pan lid, and the change in water quantity due to evaporation is calculated. The results of the water evaporation test are shown in table 4.

Table 4: Water Evaporation test results

Stove Type	Fuel Type	Plate 1 Water Evaporated (ml)	Plate 2 Water Evaporated (ml)
Natural Stove	Wood	725	50
	Coal	280	60
	Briquettes/Pallets	305	140
Forced Draft stove	Wood	690	485
	Coal	590	305
	Briquttes/Pallets	505	365

Where a greater change in water quantity indicates higher heat transfer efficiency of the stove. On plate 1, when operating with coal, the forced draft stove evaporated 590ml of water, while the natural draft stove evaporated 220ml. Similarly, when using wood, the forced draft stove evaporated 690ml of water, whereas the natural draft stove evaporated 275ml. Finally, when utilizing briquettes, the forced draft stove evaporated 505ml of water, while evaporated 305ml.

In addition, on plate 2, The results reveal that the forced draft stove evaporated 305ml of water when using coal, 485ml on wood, and 365ml on briquettes. In comparison, the natural draft stove on plate 2 evaporated 60ml of water on coal, 50ml on wood, and 140ml on briquettes. Hence, the forced draft stove showed remarkable efficiency of heat transfer to the cooking pan than the natural draft stove.

Emissions Reduction Efficiency

The concentration of waste emissions from the stake of the forced draft stove and the natural draft stove was measured by inserting the flue gas analyzer at the exit of the chimney. The results are shown in table 5.

The average CO_2 emissions from the forced draft stove on wood were 65% lower than that of the natural draft stove. In addition, the natural draft stove emitted 43.2% more CO2 on coal and 21.4% more on briquettes in comparison to the forced draft stove.

Table 5: Air emissions from the stake of the stove during testing/cooking

	Natural Draft Stove			Forced Draft Stove		
Parameter	**Wood**	**Coal**	**Briquettes**	**Wood**	**Coal**	**Briquettes**
CO_2 Max (Ppm)	20.7	18.4	9.4	10.1	13.4	7.1
CO_2 Avg (Ppm)	3.26	6.01	1.4	1.12	3.41	1.1
CO Avg (Ppm)	86.7	78.4	69.7	7.9	5.4	5.1
NO (Ppm)	10	38	20	7	22	11
HC (µg/M^3)	173	106	59	56	62	47

Moreover, the forced draft stove outperformed the natural draft stove by reducing CO concentrations by 90.8% on wood, 93.1% on coal, and 92.6% on briquettes. The improved performance in terms of reducing CO can be attributed to the superior oxygen-to-fuel ratio. Nevertheless, the forced draft stove exhibited excellent performance in reducing HC concentrations in the waste air stream, The Natural draft stove had HC concentrations 67.6 % higher on wood, 41.5 % higher on coal, and 20.33 % higher than the advanced forced draft stove.

Furthermore, the NO emissions were 30% higher on wood, 42.1% higher on coal, and 45 % higher on briquettes for natural draft stoves than the forced draft stoves. Consequently, the forced draft stove displayed superior efficiency in reducing pollutant concentrations in the chimney's smoke.

CONCLUSION

The forced draft stove showed superior performance over the natural draft stove. Therefore, this study concludes that stoves with forced draft mechanism exhibited higher efficiency than natural draft stoves. The forced draft stove outperformed the natural draft stove in terms of thermal efficiency, fuel efficiency, and emissions efficiency. The forced draft stove achieved a maximum thermal efficiency of 68.8% in the high phase and 43% in the low phase, while the natural draft stove achieved 49% in the high phase and 33% in the low phase. Moreover, during water boiling tests, the forced draft stove showed a significant reduction in boiling time, leading to less cooking time required to prepare food. Additionally, the forced draft stove resulted in significant reductions in waste emissions, particularly carbon monoxide, hydrocarbons, and nitrous oxide when compared to the natural draft stove. Furthermore, the forced draft stove consumed less fuel than the natural draft. In conclusion, the development of the forced draft stove addresses the need for improved wood stoves by utilizing a forced draft mechanism, offering high thermal efficiency, reduced cooking time, lower emissions, and decreased fuel consumption compared to improved natural draft stoves.

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