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ORIGINAL RESEARCH ARTICLE

Design and performance evaluation of inverted downdraft biomass gasifier cook stove for improving the kitchen environment of rural area

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ABSTRACT

The use of biomass is becoming increasingly important as an alternative energy resource for developing countries. In India, various Chula or biomass Gasifier stoves are utilized in various restaurants, including kitchens and roadside tea stands. These Chula or existing biomass Gasifier stoves have higher smoke emissions as well as lower thermal efficiency. Therefore, sustainable design and performance evaluation of biomass Gasifier cookstoves are required. IDBG cookstove has an inner diameter, outer diameter, and height of 19 cm, 21.5 cm, and 45 cm used for experimentation. Wooden blocks, Charcoal, and Animal dung were used as feedstocks with three repetitions of experimentations. The present case study illustrated the design and analysis of an inverted downdraft Biomass gasifier (IDBG) cook stove. It was tested in climate conditions of A D Patel Institute of Technology, Anand, Gujarat, India. Animal Dung found outstanding performance compared to other feedstocks, such as wooden blocks and Charcoal, with a thermal efficiency of 11-20% from the experiments. It has also been found that smoke emission of up to 20 to 40% is reduced using the IDBG cookstove. The current research has concluded that the IDBG cookstove reduced smoke emissions and improved thermal efficiency.

Keywords: energy; cookstove; efficiency; smoke emission; environment; gasifier

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Nomenclature

IDGB	Inverted Downdraft Biomass Gasifier	Q	Energy required
GHG	Greenhouse gas	HVF	Heating value of biomass
CO	Carbon monoxide	CV	Calorific value
LUD	Lit Updraft	η_g	Gasifier stove efficiency
IDD	Inverted Downdraft	D	Diameter of cylinder-type reactor
PM	Particulate matter	SGR	Specific gasification rate
FCR	Fuel Consumption rate	H	Height of cylindrical reactor
MJ	Mega Joule	t	Operating period
KET	Kitchen effective test	ρ	Bulk density
NGO	Non-Government Organization	T_{he}	Outer Temperature
CO_2	Carbon dioxide	Ti	Inner Temperature
M_f	Mass of 1 kg of rice	M_f	Mass of fuel
E_E	Specific Energy	M_w	Mass of water

1. Introduction

Energy is critical to a country's technological, industrial, social, and economic development. Conventional energy sources are primarily used in the domestic sector, particularly for cooking in the kitchen of rural areas, which is done with traditional stoves. About two-thirds of the population in developing nations use biomass fuel (wood, dung, and fibre wastes) for domestic cooking and heating[1]. For basic cooking and heating, more than 50% of the world uses solid biomass or coal fuels[2-4]. Consumption of such fuels needs more attention due to their effect on causing damage to three different sizes[5]. Combustion of rock-solid fuels causes pollution that harms health and contributes significantly to the worldwide population[6,7]. One of the reasons for excessive biomass consumption is poor conversion of biomass to energy. As a result, traditional cookstoves (particularly the 3-stone stove) consume more biomass, causing rapid forest degradation[8]. Furthermore, these inefficient stoves emit some hazardous particulates that contribute to indoor air pollution, posing a health risk to users[9]. Research into better energy-saving technology is ongoing in developing nations, resulting in a wide range of improved cook stoves for use by rustic houses[10]. Thermal efficiency can reduce fuel needs by 10–14% compared to a standard 3-stone cook stove. Earlier, a cook stove was launched on the market, filled with various checks to confirm that it was efficient and exceeded the international requirement. These tests offer consistent information about cookstove performance, allowing stoves to perform more effectively[10]. Modern stoves will benefit many who depend on low-cost, widely existing biomass fuels[11]. A Kitchen Effectiveness Test (KET) was conducted in Africa to evaluate the Esperanza stove's wood-saving performance over three stone stoves[12]. The Esperanza stove saves 60% of wood fuel compared to 3-stone stoves. The Esperanza stove uses 65 % more energy and 24.7 MJ per person than the 3-stone stove. Indoor pollution induced by inefficient solid biomass burning accounts for approximately two million premature deaths worldwide[13]. At the regional level, biomass cook stoves with poor combustion are causing environmental harm, putting people's health at risk, and contributing to climate change[3,14]. Most rural Indian households depend on biomass for cooking and heating purposes[15]. Wood, crop wastes, and cow dung are used as the primary energy source in rural areas, accounting for 85.7 percent of households compared to 23.2 percent of urban households[16]. Inverted Downdraft (IDD) gasifiers' thermal efficiency is higher than cross draft and updraft gasifiers with rice husks, producing the least tar and smoke[17]. Inverted Downdraft (IDD) or Top Lit Updraft (T-LUD) gasifiers function better with rice husks than cross-draft, bottom-lit downdraft, and updraft reactors[20,21]. Anderson and Reed[22] state that the inverted downdraft gasifier produces the least tar and smoke. Firewood is the most used fuel for cooking in Indian households, accounting for 49 %, followed by LPG/PNG, which accounts for 28.5 %. In the cookstove's performance evaluation, the cookstove's efficiency was estimated to be 20.76% for wood chips, 16.85% for coconut shells, 15.85% for palm kernel shells, and 10.54%[18,19].

The above literature shows that the cookstove is considered an essential device for cooking in the kitchen environment and has many drawbacks. This research aims to design, construct, and test an inverted downdraft gasifier cook stove for higher thermal efficiency and lower gas emissions using wood, Charcoal, and animal dung as feedstocks. Modern cook stoves provide cooking with clean energy. Additionally, it aids in lowering the health risks associated with the survival of women and children when using outdated biomass and cook stoves. There are several benefits to having efficient gasifier cook stoves that use easily accessible solid fuel, including reducing greenhouse gas (GHG) emissions. This current research work has conducted experiments at A D Patel Institute of Technology, Anand, Gujarat on cookstoves. The main aim of this research is to investigate the performance of the cookstove with Animal dung, blocks and Charcoal in terms of thermal efficiency and emission reduction.

2. Working principle of IDBG cookstove

In IDBG, cookstove sequence processes from top to bottom are drying, pyrolysis, oxidation, and reduction and are entirely driven by natural convection heat transfer. The air supply governs the rate of gas production and heating to the gasifier. The stove can be started and operated without exhaust fans if there is adequate internal ventilation and it does not emit a burning wood odour.

The IDBG stove's primary function is cooking for multiple people at once. The fuel ignition takes place at the top of the stove. After the air-fuel mixture is burned, pyrolysis produces heat at the top layer. Air drawn from the bottom of the stove ignites the gases. The flame pyrolysis zone, also known as the burning zone, constantly moves downward. Primary air is drained from the bottom of the stove during combustion. Air carries away volatiles as it passes through burning firewood and leaves Charcoal behind.

The top zone of a Gasifier is where the low-grade energy flue gases arrive after travelling through the Charcoal. Due to the chimney effect, heated gases move upward; therefore, no fan or blower is required for air delivery. Under typical working conditions, the top layer contains Charcoal, the middle layer is the flame pyrolysis zone, and the bottom layer has unburned fuel. This setup is the exact opposite of a standard down draught Gasifier. The reason is that air is fed from the air control zone at the system's bottom, and the gases are released from the upper part of the IDBG stove. IDBG is also known as a reverse-down draft gasifier. The middle-upper end of shells has some holes for supplying the secondary air for combustion. The gas wick towards the top of the shell helps create more drafts and evenly distributes the flame around the cooking pot. A lever at the bottom of the stove controls the initial air supply to the fuel bed, which controls the rate of fuel combustion. In order to reduce heat loss and the risk of burn injury, red clay was used to insulate both sides of the stove.

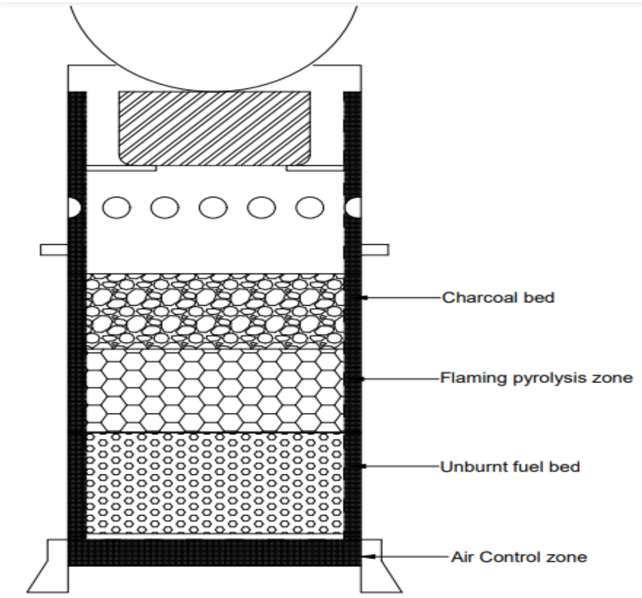

Figure 1. Inverted downdraft biomass gasifier cookstove.

3. Design of cook stove

The inverted downdraft biomass gasifier (IDBG) cook stove was developed at A D Patel Institute of Technology, New Vallabh Vidya Nagar, Gujarat. The following methods for designing the IDBG cook stove are available in the literature[20-23]. The following are the different parameters used in the design of the current cookstove.

3.1. Energy required (Q)

Here, data has been taken based on the rural house requirement. It assumes that one kilogram of rice is required daily for rural house people. The energy needed to cook one kilogram of rice (M_f) in fifteen minutes (t) is determined by considering the specific energy (E_E) of rice for cooking 1700 kJ/kg[24] below the formula.

$$\boldsymbol{Q} = \frac{M_f \times E_E}{t} \quad \textbf{(Eq.1)}$$

3.2. Fuel consumption rate (FCR)

The quantity of feedstock biomass required per hour in the cook stove provides the required energy. Fuel Consumption rate means the amount of energy required for cooking (Q in kJ/h), the heating value of biomass (HVF), and the efficiency of the gasifier.

$$\boldsymbol{FCR} = \frac{Q}{\eta_s \times CV} \quad \textbf{(Eq.2)}$$

Using wood-based products with an average heating value (CV) of about 17000 kJ/kg as a design basis and assuming a gasifier stove efficiency (η_g) of 24 percent[24], based on that, the fuel consumption rate is estimated.

3.3. Diameter of cylinder type reactor (D)

The cross-sectional area of the cylinder-type reactor in which wood and Charcoal are burned. In order to calculate the gasification rate, the fuel consumption rate (FCR) is used. The FCR is 2.00 kg/hr., which translates to an effective equivalence ratio (ER) of 0.3, and the specific gasification rate (SGR) for wood pieces is 75 kg/m^2 h, which translates to a producer gas to a wood ratio (PGWR) of 2.39. The following formula has been used to determine the reactor diameter of a gasifier.

$$D = \left[\frac{1.27\ FCR}{SGR}\right]^{\frac{1}{2}} \quad \textbf{(Eq.3)}$$

3.4. Height of cylindrical reactor (H)

The height of the Cylindrical reactor (H) determines how long the stove can run on a single load of fuel. Here, T is the reactor's operating period and is considered 3 hours. ρ is the bulk density, estimated to be 450kg/m^3[24]. The reactor height can be estimated using the Reactor volume as 0.0132 m^3, with the biomass consumption of the cook stove being 1 kg/hr[24].

$$H = \frac{SGR \times T}{\rho} \quad \textbf{(Eq.4)}$$

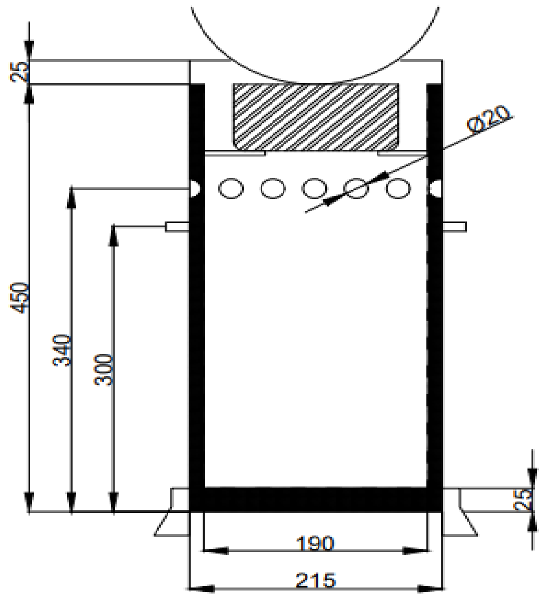

Figure 2. Design of inverted downdraft biomass gasifier cookstove.

4. Result and discussion

A CREO model of an IDGB cook stove was constructed using the major parameter as the basis for the model. The IDBG stove, which was designed, can calculate the thermal efficiency and emission level of rural kitchens. The thermal efficiency of IDBG cookstoves is a measurement of the system's thermal performance. During experimental work on IDGB cook stove using flue gases after combustion of 1 kg of feed stoke and find out the CO, Thermal efficiency, Specific fuel consumption at A D Patel Institute of Technology, V V Nagar, Anand, Gujarat, India.

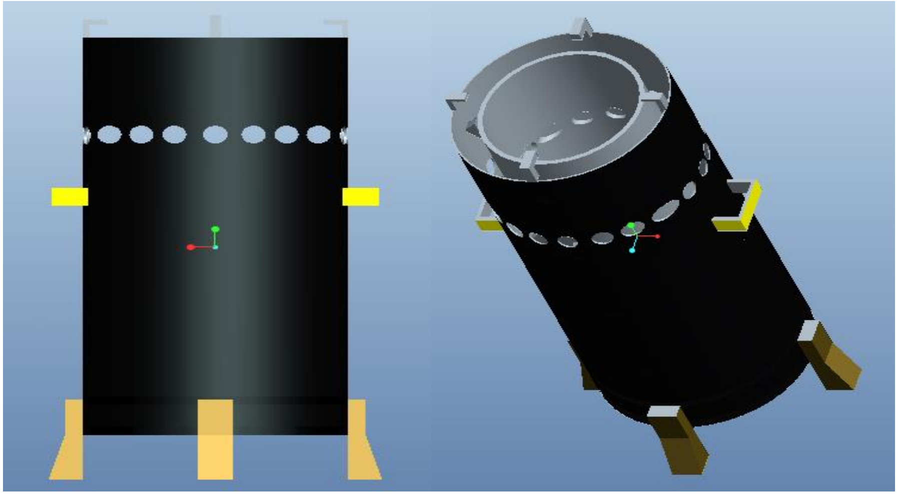

Figure 3. Model of IDBG cookstove.

In India, the average amount of heat energy essential to boil food for a family of five members is 6800 kJ/hr[24]. The essential reactor-based internal diameter and height designs were 0.19 m and 0.45 m, respectively. The Fuel consumption rate (FCR) is 0.78 kg/hr. Based on that, the model of the IDBG cookstove is fabricated and assembled, as shown in **Figure 4**.

Figure 4. Developed model of IDBG cookstove.

Figure 5. Flame of burning biomass and experimental work on IDBG cookstove.

The wooden block, Charcoal, and animal dung were used in the experiment as feedstock. A weighting machine has been used in current work to measure the feedstock mass. Nickel-Chromium-based K-type thermocouples were used to measure the Temperature of the water. The maximum Temperature is around 1,090 ^{0}C, and the accuracy of a K-type thermocouple is ± 1.5^{0}C or ± 0.75%. K-type thermocouples are low-cost, precise, consistent, and have an extensive temperature range. IDBG cook stove using wood, Charcoal, and animal dung as fuel reached 800°C during the hottest hour of fire, while the normal flame temperature ranged from 550°C to 680°C. No fan or blower for air supply in this IDBG design since hot gases rise higher due to the chimney effect. During the experimentations, the ambient Temperature ranged from 30 to 35 °C. Three repetitions of the tests were carried out, and the average experimental data are shown in **Table 1**.

Table 1. Experimental result.

Feedstock	Outer Temp. (T_{he}) °C	Inner Temp. (T_i) °C	Mass of Fuel (M_f) kg	Mass of Water (M_w) kg before	Mass of Water (M_w) kg After	Time to fuel burn Min.
Wood	68	130	1	3.75	3.3398	24.5
Charcoal	74	150	0.75	3.75	3.032	32
Animal dung	81	188	0.8	3.75	3.7	15.50

4.1. Fuel Consumption Rate (FCR)

(1) For wood :

$$\text{FCR} = \frac{fule\ mass}{time\ to\ burn} = \frac{1}{0.41} = 2.448 \text{ kg/h} \quad \textbf{(Eq.5)}$$

(2) For Charcoal :

$$\text{FCR} = \frac{0.75}{0.53} = 1.406 \text{ kg/h} \quad \textbf{(Eq.6)}$$

(3) For Animal dung:

$$\text{FCR} = \frac{0.8}{0.258} = 3.1 \text{ kg/h} \quad \textbf{(Eq.7)}$$

4.2. Efficiency

$$\eta = \frac{M_{wi} \times C_{pw} \times (T_e - T_i) + (M_w \times H_{1)}}{m_f \times H_f} \quad \textbf{(Eq.8)}$$

M_{wi} = In Vessel Mass of Water for Cooking Purpose

C_{pw} = Water’s Specific heat, kJ/kg °C

M_w = Water mass which is evaporated, kg

M_f = Fuel mass for combustion

T_e = Temperature of evaporated water, °C

T_i = Temperature of water at Inlet, °C

H_l = At 100°C and 105 Pa - Latent heat of evaporation, kJ/kg

H_f = Fuel's Calorific value, kJ/k

(1) For wood:

$$\eta = \frac{3.75 \times 4.181 \times (100-30) + 0.352 \times 2256.9}{1 \times 17000} = 11.37\%$$

(2) For Charcoal:

$$\eta = \frac{3.75 \times 4.181 \times (100-30) + 0.7 \times 2256.9}{0.75 \times 33000} = 11.17\%$$

(3) For Animal dung:

$$\eta = \frac{3.75 \times 4.181 \times (100-30) + 0.05 \times 2256.9}{8000 \times 0.8} = 19.25\%$$

For different feedstocks, the fuel consumption rate and the thermal efficiency obtained are shown in **Table 2** below.

Table 2. Results of the Feedstocks, required time, Fuel consumption rate, and thermal efficiency for various feedstocks.

Feedstocks	Required Time in (h)	Fuel Consumption Rate (FCR) kg/h of biomass	Thermal Efficacy η (%)
Wood	0.41	2.448	11.37
Charcoal	0.53	1.406	11.17
Animal dung	0.258	3.1	19.25

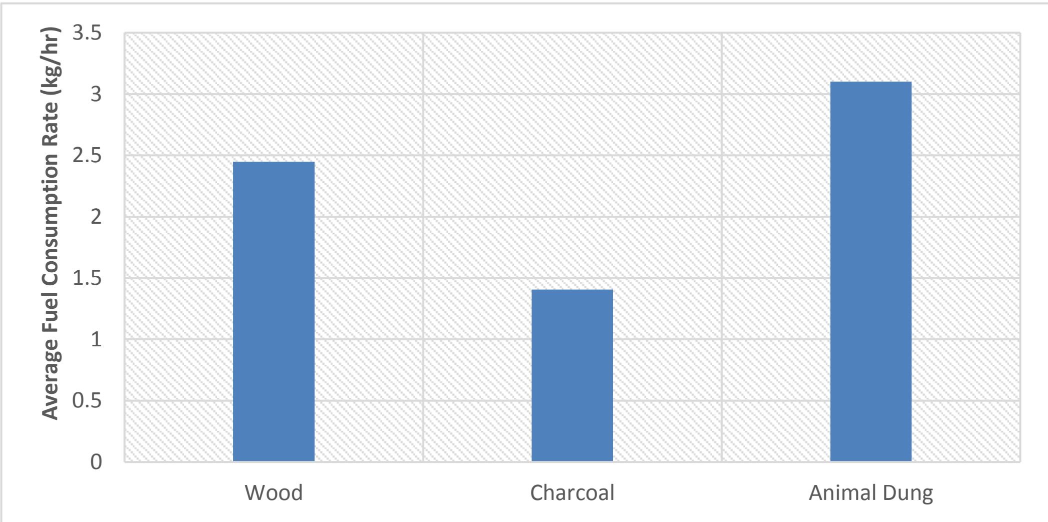

Figure 6. Average fuel consumption rate with various fuels in IDBG cookstove.

The IDBG cookstove has an average meal fuel consumption of 80–90% lower in terms of kg/h compared to traditional Chula stoves and existing gasifiers that burn wood[23]. **Figure 6** illustrates the findings of the experimental study on the IDBG cookstove and shows that animal dung has a higher fuel consumption rate. Due to its lower calorific value, animal dung consumes fuel 80–90% more than Charcoal and 25–35% higher than wood. Additionally, compared to wood and Charcoal, animal excrement contains a higher percentage of moisture. **Figure 7** displays the fuel consumption rate using wood, Charcoal, and animal dung. Animal dung burns faster than wood or Charcoal, reducing cooking time by 35 to 47%.

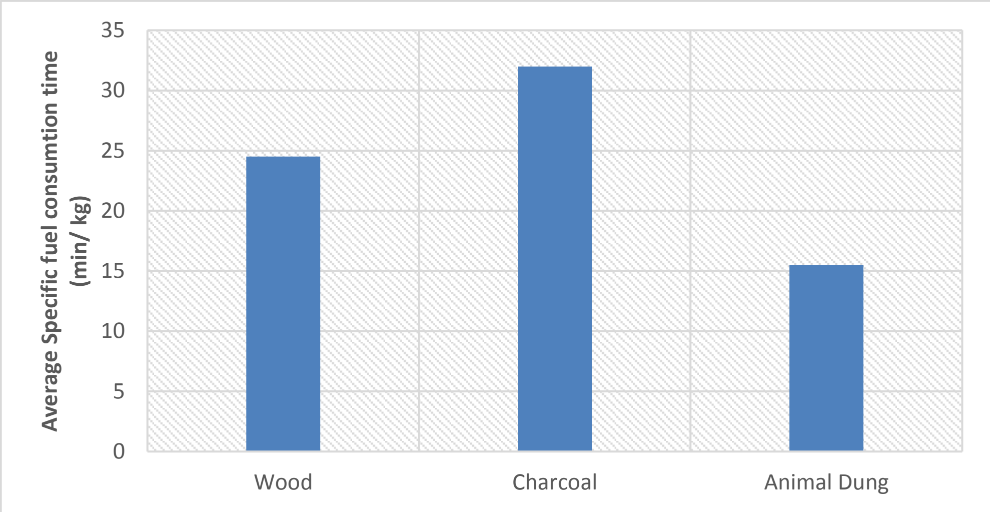

Figure 7. Average specific fuel consumption time (min/kg).

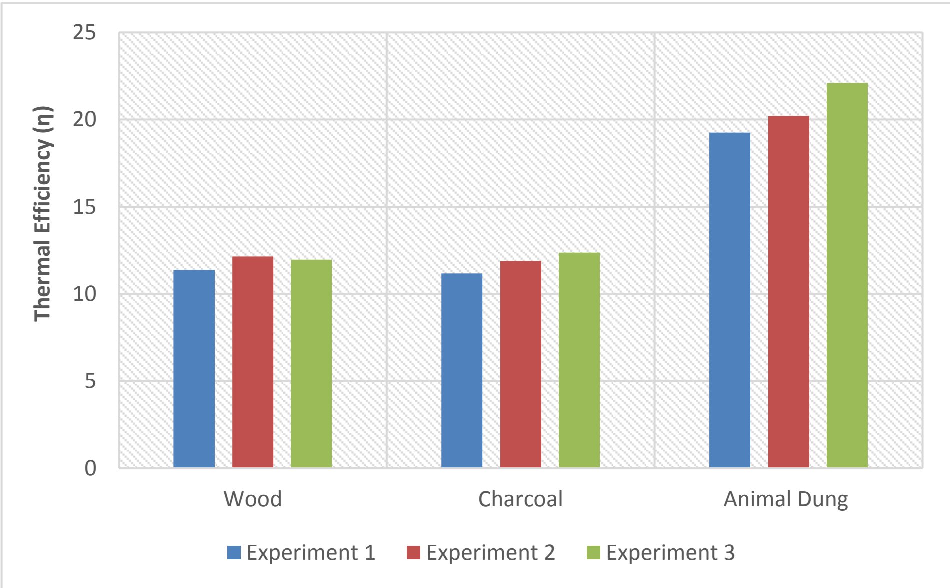

Figure 8. Thermal efficiency of IDBG cookstove with various fuel.

The regular thermal efficiency of the IDBG cookstove was near 2.5 to 2.7 %, which is more than the traditional Chula and existing gasifier[23]. **Figure 8** shows the higher efficiency of the IDBG cookstove with animal dung as a fuel due to the design approach of the IDBG cookstoves compared with 3- the traditional stone Chula. The thermal efficiency of a cookstove with animal dung is 38-49 % higher than wood and Charcoal. A different study found that using mango-chopped wood, maize cobs, and sawdust briquettes with a similar gasifier model. It has been found the cook stove's thermal efficiency was 36–39 %t, 29.59 percent, and 38.68 %, respectively[24,25].

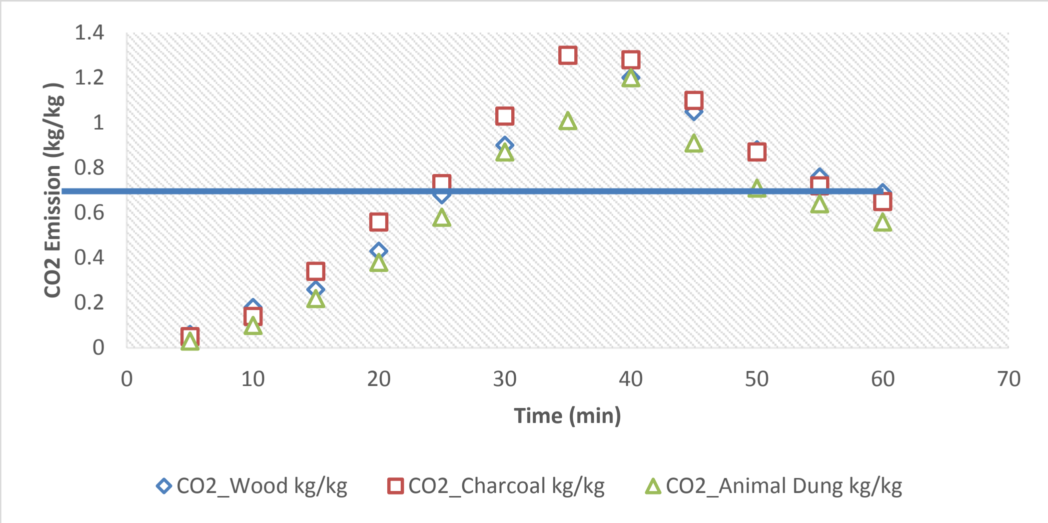

Figure 9. CO_2 emission from IDBG cookstove.

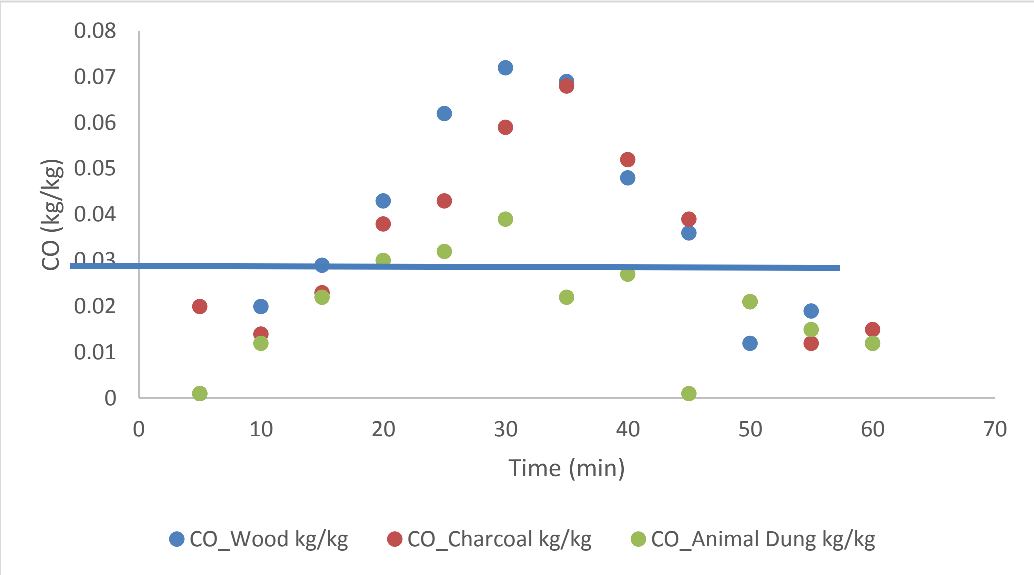

Figure 10. CO emission from IDBG cookstove.

The emissions of CO and CO_2 were measured at a five-minute interval for an hour during experimentations. The average result of CO_2 emission with wood, Charcoal, and animal dung is shown in Figure 10. It has been found the average CO_2 value of wood, Charcoal, and animal dung is 0.699 kg/kg, 0.73 kg/kg, and 0.60 kg/kg, respectively. The average result of CO emission with wood, Charcoal, and animal dung is shown in Figure 10. It has been found that the average CO emission value of wood, Charcoal, and animal dung is 0.0416 kg/kg, 0.0377 kg/kg, and 0.0234 kg/kg, respectively. Some researchers[21,22,23] have also done experimental work on a similar IDGB cook stove with wood and animal dung. The results of CO are in the range of 0.069±15 and 0.04±10, respectively. The CO_2 emission with wood and animal dung as feedstock has also been found to be 1.35±42 and 1.046 ±10. Figures 10 and 11 show a straight horizontal line indicating the average CO_2 and CO emission during experimental work with different feedstock in the cookstove. The average CO_2 is 0.676 kg/kg, and the average CO is 0.0293 kg/kg. Respectively. The experimental results show that the developed IDBG cookstove reduces the emission level, which helps improve the kitchen environment in rural areas.

5. Conclusion

Current research shows the design and performance analysis of the IDBG cook stove for reducing emissions in rural kitchens. The IDGB cookstove design is different from conventional stoves. It is a cylinder-shaped shell made of a mild steel sheet of 2 mm thickness. The shell's inner diameter, outer diameter, and height are 19cm, 21.5 cm, and 45 cm, respectively. A 12.5 mm thick layer of fire clay is applied as an insulator to the shell's inside surface to reduce heat losses and considerably increase fuel combustion. The experimental work was carried out at the A D Patel Institute of Technology, New V V Nagar, Gujarat, for combustion purposes. During the experiment work, it has been found the thermal efficiency and CO and CO_2 emission levels with different feedstock like wood, Charcoal, and Animal Dung. From the present research work, the following points are concluded:

- Due to the lower calorific value and percentage of moisture, the fuel consumption rate (FCR) of Animal dung is 80-90% higher than Charcoal and 25-35 % higher than wood.
- The thermal efficiency of the cook stove is between 11 and 22 % with different feedstock. Thermal efficiency of IDGB cook stove is found between 19-22% with Animal dung. Compare the thermal efficiency of cookstoves with wood, and Charcoal is 38-49% less than feedstock as animal dung.
- The emissions were measured using a portable Gas Chromatography analyzer for CO, CO_2, H_2, and NOx. Due to instrument errors, the emissions of PM and NOx could not be measured. Some readings indicate that NOx is lower than CO_2.
- The average CO_2 value of wood, Charcoal, and animal dung is 0.699 kg_s/kg_{feed}, 0.73 kg_{gas}/kg_{feed}, and 0.60 kg_{gas}/kg_{feed}, respectively. The average CO emission value of wood, Charcoal, and animal dung is 0.0416 kg_s/kg_{feed}, 0.0377 kg_{gas}/kg_{feed}, and 0.0234 kg_{gas}/kg_{feed}, respectively. Results from the experimental investigation showed lower levels of CO and CO_2 compared to those found in previous studies.
- Animal dung's average CO_2 and CO emission levels are 14-18 % lower than wood and charcoal feedstock in IDBG cookstove.
- It is also observed that 35-47% of cooking time can be saved with a 3- a stone cook stove with the same heat generation capacity.
- Using the IDBG cook stove is helpful to Rural Indian Women with substantially reduced fuel consumption, cooking time, and kitchen pollution.

Conflict of interest

The authors declare no conflict of interest.

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