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Performance Analysis of an Inverted Downdraft Biomass Gasifier Cookstove and its Impact on Rural Kitchen

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Abstract – The paper presents an experimental study on performance analysis of an inverted downdraft biomass gasifier (IDBG) cookstove at laboratory level to determine its thermal efficiency and emissions as per BIS standards. Further, the study was extended to the field test of the same model for cooking food in the kitchen to study its impact on the rural kitchen in comparison with the traditional chulha. The major performance indicators considered during the study were saving of fuel wood and cooking time under the normal cooking practices followed by the identified user family. The laboratory evaluation of the IDBG cook stove showed that the thermal efficiency varied between 36 to 39%, while the average CO/CO_2 ratio was below 0.04. Field test showed that IDBG cookstove managed about 47% savings in fuel wood and 51% savings in cooking time as compared to traditional chulha which was the result of better thermal efficiency and heat transfer. The IDBG cookstove showed good acceptance to the user with requirements of few modifications.

Keywords – *Emission, field test, kitchen, gasifier cookstove, traditional chulha.*

1. INTRODUCTION

In India, domestic sector is one of the largest consumers of primary energy (nearly 40% of total energy demand), while cooking alone consumes about 90 percent of the household energy [1]. Biomass is the primary energy supplier with the biggest share in the total national energy consumption in rural parts of developing countries for cooking, water heating, *etc.* [2]. More than 3 billion people in the world are dependent on solid-fuel such as fuelwood, charcoal or crop residues and agro-processing to meet their cooking energy needs [3], [4]. In rural areas of developing countries, traditional biomass fuels account for over 90% of household energy consumption [5] whereas in India, out of 225 million households, 160 million households uses biomass as a fuel [6]. Generally rural households use traditional biomass cookstoves which are associated with incomplete combustion, low efficiency, higher cooking times and inefficient use of fuel wood and heat compared to improved cookstoves [7]-[9]. These cookstoves pollute the kitchen with significant emission of pollutants such as CO, CO_2 and particulate matter [10], [11] which makes women and accompanying children suffer from acute lower respiratory infection [12], [13]. Besides this, cookstoves act as a key source of pollutant species which are precursors of climate-change [14].

Despite the facts regarding the health hazards, a large number of people still use open fires and traditional stoves for household cooking and heating. The alternative way to overcome these issues is to use improved cookstoves which has better fuel combustion and heat transfer with increased thermal efficiency and reduced emissions. The benefits of improved cookstoves include saving of fuels and cooking time, higher thermal efficiency, more complete combustion, reduction in safety hazards such as less exposure to heat resulting in a better work environment [15]. The improved cookstove technology could potentially help mitigate adverse human health, energy, and environmental consequences [16]. The cookstove based on biomass gasification or wood gas stove burns the fuel 2-3 times more efficiently than that of the traditional stoves and has the potential to replace LPG stoves since the combustion of the gaseous mixture of CO and H_2 can be complete, thus minimizing the emissions of products of incomplete combustion (PIC), which is a major problem with solid-fuel combustion [17]. The improved cookstove benefits significantly in conservation of the fuel wood, about 27–66% [18]. Traditional cookstoves, because of their very low efficiency, emit more than 10% of their carbon as PIC, comprising varying amounts of tar, in addition with 100–180 g of carbon monoxide and 7.7 g of particulate matter per kg of wood [19]. The gasifier stoves can reduce particulate matter substantially, averaging 90% improvement over the three-stone fire [20].

In rural India, most of the households are dependent on biomass like fuel wood, crop residues and cow dung cake as a primary source of energy for cooking and heating operations, which comprises of about 85.7% of households against the 23.2% of urban household [21]. The data from census 2001 and 2011 for India shows that, the total household increased from 192 million to 247 million during the period with the most significant increase in household opted for LPG/PNG as shown in Figure 1. Still the use of the firewood for cooking by households at the national level is highest at 49%, followed by LPG/PNG occupying a percentage share of 28.5% as shown in Figure 1.

Fuelwood consumption, in India, estimated at about 205 MT $year^{-1}$, is the leading energy source used, followed by cattle dung (107 MT $year^{-1}$) and agro-waste (57 MT $year^{-1}$) in 2003–2004 as depicted in Table 1,

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which shows that the household energy consumption derived from biomass like fuelwood, agro-waste and dung cake having a dominating share. The projected use of fuel wood, agro waste and dung for the year 2031-32 as shown in Table 1, revealed that it remains significant at 52% with the rest of the share contributed by fossil fuel-based energy carriers [22].

The pattern of household energy consumption is region specific, depends on the income of the household, availability of local resources, alternative fuels and price of fuels, *etc.* [23]. In India, the states with higher per capita income generally inclined to have convenient and cleaner fuels whereas rural India has traditionally been reliant on biomass based fuels as mentioned earlier. The rural and urban India shows a wide division in their current use of cooking fuels as shown in Table 2 [24].

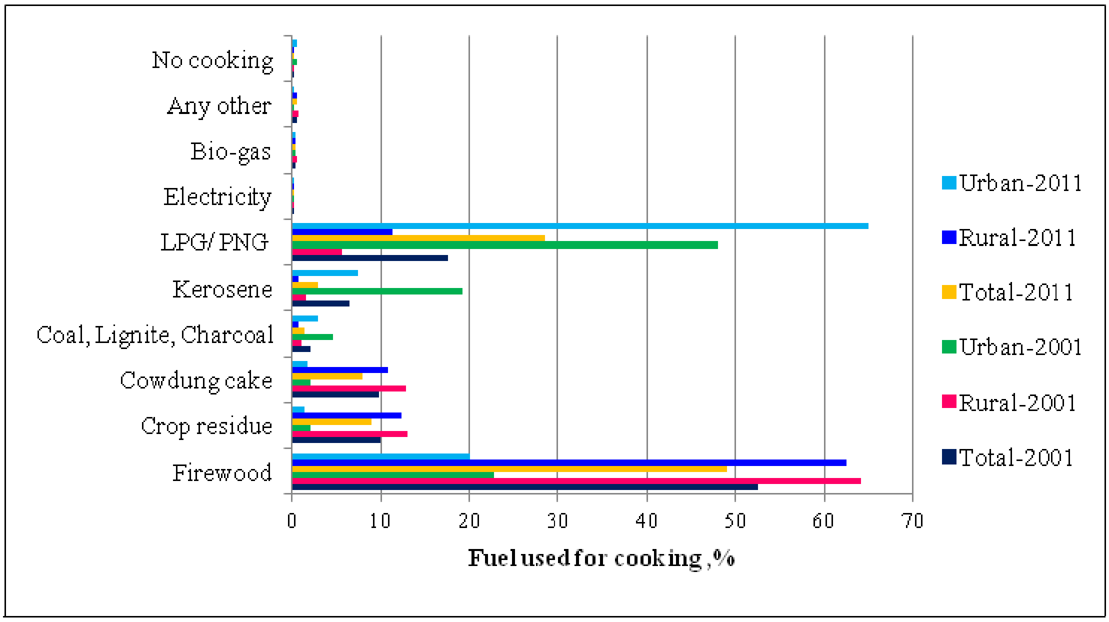


Fig. 1. Percentage share of households by type of fuel used for cooking, year 2001-2011- India. [Source 21].

Table 1. Energy consumption in household [Source 22].

Energy source	Consumption 2003-04, MTOE	% Consumption	Quantity Consumption	Projected 2031-32, MTOE	% Increment
Fuel wood	92.57	57.82	205.71 MT	106.39	37.44
Agro waste	17.12	10.69	57.1 MT	-	-
Dung cake	22.62	14.13	107.7 MT	40.47	14.24
Biogas	0.71	0.44	1.51 million m^3	-	-
Kerosene	10.69	6.68		15.12	5.32
Electricity	7.72	4.82		69.72	24.53
LPG	8.68	5.42		52.49	18.47
Total	160.11	100		284.19	

Table 2. Monthly per capita consumption of various fuels in India (1999-2000).

Fuel type	Urban	Rural
Fuel wood chips (kg)	6.45	17.4
Electricity (kW h)	22	6.35
Kerosene, l	0.68	0.61
LPG, kg	1.45	0.37

Looking at the significant share of the biomass based energy consumption in rural household, it is necessary to deploy high efficiency improved cookstove at a large and sustainable scale which could offer multiple benefits like reducing global greenhouse gas (GHG) emissions, reducing pressure on forests and woody biomass resources, reducing indoor air pollution associated with use of traditional stoves as well as saving the local population from their efforts undertaken for procurement of fuel-wood [25]. With the view of the above scenario, the study focuses on the development of the inverted downdraft biomass gasifier (IDBG) cookstove and measurement of the thermal efficiency as well as CO and CO_2 emissions at the laboratory level. Further extension of study involves deploying the IDBG cookstove in the rural kitchen for cooking and evaluates its impact in terms of saving of fuelwood and cooking time as compared to the traditional mud *chulha* during normal cooking practices.

Inverted Downdraft Biomass Gasifier Cookstove

The inverted downdraft biomass gasifier (IDBG) cook stove works on a micro-gasification principle that enables solid-fuel conversion into gaseous fuel. Early work on natural convection inverted gasifier cook stove was reported by La-Fontaine and Reed [26], Reed and Larson [27] and then subsequently on the forced draft gasifier cook stove by Mukunda [28]. In gasifier cook stove, the conversion process takes place in sub-stoichiometric condition at high temperature and the gaseous product generated moves upward. The stove operates using natural convection. The rate of gas production and heating is controlled by the primary air supply from the bottom. The term 'inverted downdraft' coined as the fuel feed is lit "on the top", and forms a layer of charcoal there; the flaming pyrolysis zone is below that, the unburned fuel is on the bottom of the pile; and primary air or pyrolytic gasification enters at the bottom and moves up, forming gas in the flaming pyrolysis zone.

2. MATERIAL AND METHODS

2.1. Design and Construction

Inverted downdraft biomass cookstove (IDBG) cookstove was designed, developed and fabricated at Sardar Patel Renewable Energy Research Institute (SPRERI), Vallabh Vidyanagar. The general method followed for designing the cookstove is adopted from the method given in published literature [15], [26], [27] [29].

a. Energy needed (Q): The amount of energy needed to cook a meal for a family of six members is estimated about Q=15. 8 MJ.

b. Fuel consumption rate (FCR): It is the amount of biomass fuel fed into the cookstove to supply the required energy. It can be determined using the given formula.

$$FCR = \frac{Q}{\eta \times C_v} \quad (1)$$

Where, C_v= heating value of wood (15.5 MJ kg^{-1}); η= gasifier stove efficiency (40%).

c. Diameter of Reactor: The reactor diameter is a function of the fuel consumption rate and the specific gasification rate. Specific gasification rate (SGR) is defined as the amount of fuel used per unit time per unit area of the reactor. The specific gasification rate (SGR) for wood pieces taken as 90 kg m^{-2} h^{-1}.

$$D = \sqrt{\frac{1.27 FCR}{SGR}} \quad (2)$$

***d. Height of Reactor*:** It is the height of the reactor which would determine the time for which the stove to be operated after loading fuel and it can be determined by using the equation.

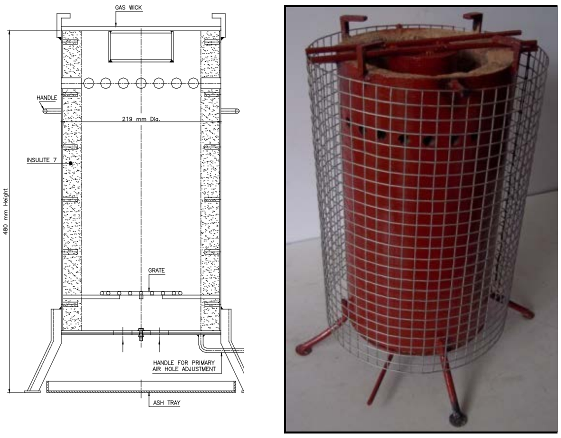
$$H = \frac{SGR \times t}{\rho_{fuel}} \quad (3)$$

Where, t= time the reactor will be required to operate assumed (1-1.5 hours) and ρ_{fuel} = bulk density of fuelwood (280 kg m^{-3}).

2.2 Description of IDBG cookstove

The designed cookstove was suitable for cooking a simple Indian meal for the family of five to six adults at a time. The biomass consumption of the cookstove could vary between 1-2 kg-h^{-1}. The effective diameter and the height of the reactor were 170 mm and 330 mm, respectively; while, total height of cookstove was 480 mm. The outer shell was made of 2 mm thick MS sheet. On the inner side of shell, 25 mm thick insulation of refractory cement (Insulyte-7) was provided to minimize heat losses, which helped in better heat transfer to cooking utensils. The cookstove operates on the principle of natural convection as it draws primary air for partial combustion from the four numbers of holes (25 mm dia.) provided at the bottom. The amount of primary air supply is controlled by the lever movement which adjusts the holes openings and subsequently controls the rate of gas generation and heating. Total 24 numbers of holes (15 mm dia.) were provided at the top part of the stove which works as 'burner' for supplying the secondary air for proper combustion of producer gas generated. The gas wick, provided at the upper end of the shell, helps in the development of additional draft and distributes the flame all around the cooking pan. The metal body of the cookstove is provided with galvanized iron mesh to protect the user from direct contact with the hot surface and burns during cooking. The schematic and fabricated unit of the cookstove is shown in Figure 2 (a, b).

The IDBG cook stove is primarily designed for operation in batch mode. The fuel is lit and ignited on top of the stove. Due to the heat of the burning fuel layer at the top, the layer just below the burning bed gets heated up and releases the pyrolysis gases. The gas burns using the air drawn from the bottom of the stove. The burning zone, called a flaming pyrolysis zone, continuously moves downward and utilizes the available unburnt fuel. During operation, primary air is drawn through an adjustable opening provided at the bottom of the stove. The air passes through the bed of burning wood pieces and carries the volatiles, leaving the charcoal. The resulting gas passes through the charcoal available in the upper zone and is reduced to a low-energy fuel gas. The hot gases rise upward under chimney effect. Therefore, in this design, a fan or blower is not required for the supply of air. Under normal operating conditions, the top layer contains charcoal; the intermediate layer is the flaming pyrolysis zone, and the bottom layer contains unburnt fuel. This arrangement is a reverse of the sequence generally found in typical down draft gasifier. Therefore, IDBG is sometimes also referred to as reverse down draft gasifier, where air is supplied from the bottom, and the gases come out from the top [28].



a b

Fig. 2. (a) Schematic and (b) fabricated model of IDBG cookstove.

2.3 Laboratory Testing of IDBG Cookstove

The basic performance criteria for cookstoves include thermal and emission performance. Thermal performance is expressed either as a thermal efficiency, i.e. the ratio of the amount of useful heat for cooking to the heat contained in the fuel or more simply as specific fuel consumption (kg of fuel burned per kg of food cooked), which, however, is situation/device specific [6]. Emission performance includes the emissions of pollutants per kg of fuel (or per unit of energy in the fuel, if one is comparing very different fuels) burned, typically for CO and PM. A key measure of combustion efficiency, or clean burning, is the CO/CO_2 ratio [6]. Thermal efficiency and CO/CO_2 ratio of the IDBG cookstove were tested in the institute laboratory according to the cookstove testing method given by the Bureau of Indian Standards (BIS) [31].

2.3.1 Thermal Efficiency

The thermal efficiency of the cook stove was determined using standard water boiling test (WBT) which uses a set amount of fuel, based on stove heat production rate and determining the amount of the thermal energy transferred to the pot. The stove is lit and pot of water is heated to just below water boiling point and replaced with fresh water until all fuel has been consumed. As per the BIS, the following instruments/ equipments were used during testing.

i) Measuring cylinder for water; ii) Platform balance; iii) Aluminium vessels with lids; iv) Wood fuel in proper size; v) Glass thermometer; vi) Portable hand held 'K' type thermo-couple(DTS-3508-ADI control); vii. Bomb calorimeter (Scientronics Instruments, New Delhi, India); viii) Diesel to ignite the stove; ix) Stopwatch.

The thermal efficiency is the ratio of heat utilized to the heat supplied and determines as given below [15], [32].

$$\eta_{thermal}\,(\%) = \frac{Heat\ utilized}{Heat\ produced} \times 100 \qquad (4)$$

$$Heat\ \ utilized = \begin{Bmatrix} (n-1)(W \times 0.896 + w \times 4.186)(f_2 - f_1) \\ + (W \times 0.896 + w \times 4.186)(f_3 - f_1) \end{Bmatrix}, kJ \qquad (5)$$

$$Heat\ \ produced = 4.186\left[\left(X \times c_1\right) + xdc_2/1000\right], kJ \qquad (6)$$

Where, η_{th} = thermal efficiency, %; w = mass of water in the vessel, kg; W = mass of vessel complete with lid and stirrer, kg; X = mass of fuel consumed, kg; c_1 = calorific value of wood, kcal kg^{-1}; x = volume of diesel consumed, ml; c_2 = calorific value of diesel, kcal kg^{-1}; d = density of diesel, gml^{-1}, f_1 = initial temperature of water, ^oC; f_2 = final temperature of water, ^oC; f_3 = final temperature of water in vessel at the completion of test, ^oC; and n = total number of vessels used.

2.3.2 Power Output Rating

The power output rating is a measure of total useful energy produced during one hour burning of fuel wood. It was determined by using equation given below [15].

$$Power\ output\ rating = \frac{FC \times \eta_{th}}{860 \times 100}, kW \qquad (7)$$

Where, F= quantity of fuel wood burnt, kg h^{-1}; C_v= higher calorific value, kcal kg^{-1}; η= thermal efficiency, %.

2.3.3 Emissions

The emission test was carried out using the emission hood method as prescribed by BIS [30]. The percentage concentrations of CO and CO_2 was measured with portable infrared sensors (Model ACE-9000X-CGA). The test for measurement of particulate matter (PM) emission could not be conducted and hence the results could not be given in the study.

2.4 Field Evaluation

The main objective of the field evaluation was to access the impact of use of IDBG cookstove in saving of fuel wood and cooking time as compared to *chulha* under the normal cooking conditions practiced in the rural kitchen. A user family was identified in a nearby village, Karamsad, Anand district of Gujarat State (India) which was consisted of four family members; two adults and two school going children. The family used traditional mud *chulha* for day to day cooking and other operations like heating water, tea making, boiling milk, *etc.* as family and did not had kerosene or LPG stove. The *chulha* was made of bricks with thick plaster of mud applied all over the surfaces. The front area was provided with half circular riser so that the charcoal should not scatter out. The *chulha* was kept outside of the home under the temporary shed which was also used for storing the wood sticks for cooking. The approximate dimensions of the *chulha* at the user site are shown in Figure 3.

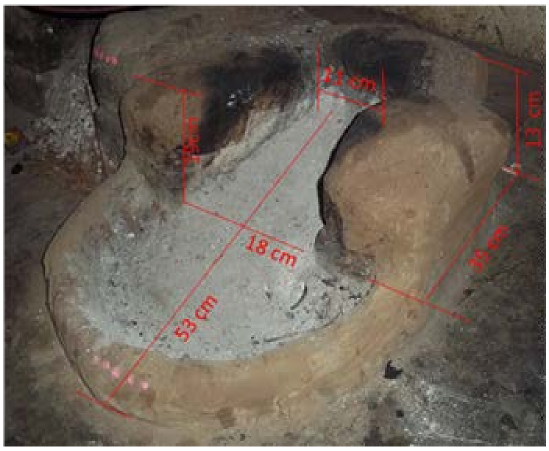


Fig. 3. Traditional mud *chulha* at user site.

Fig. 4. Mango cut wood for lab testing.

Fig. 5. Mixed wood for field testing.

Initially the thermal efficiency of the *chulha* was determined at site as per BIS standard using wood sticks available at the user home. The both types of the cookstoves were evaluated on the basis of the food cooked most often, the amount of food cooked, typical cooking duration and approximate amount of food consumed. A daily cooking practice was followed during evaluation. Two tests for each type of cookstove i.e for *chulha* and IDBG cookstove were carried out for cooking the food which included vegetables like potato (*solanum turosum*), cabbage (*brassica oleracea L*) and bottle guard (*lagenaria siceraria*), rice and *rotla*- a traditional Gujarati pearl millet bread. Generally for cooking rice and vegetables aluminium pan was used while for roasting *rotla*, a concave earthen pan was used. Same utensils were used throughout the experiment to eliminate the performance errors during testing. The fuel and time consumed during cooking meal of a family on a traditional mud *chulha* were considered as base fuel consumption to evaluate the same in IDBG cookstove.

2.5 Biomass Fuel

For laboratory testing of IDBG cookstove, mango wood (30 mm x 30 mm x 30 mm) was used as shown in Figure 4 and for field testing babul wood (length= 25 mm, Diameter= 25 mm-30 mm) was used as shown in Figure 5. The fuelwood used by family for day-to- day operations was mostly included sticks of local species like mango (*magnifera indica*), babul (*prosopis julifera*) and Nim (*azadirachta indica*) and same was used for evaluation of the *chulha*. The properties of the fuelwood used in testing are given in Table 3.

Table 3. Characteristics of biomass used for testing.

Parameters	Lab Test	Field Test	
	IDBG	IDBG	Mud *Chulha*
Wood used	Mango	Babul	Mixed
Moisture Content, (% wb)	6	12	14
Calorific Value, MJ kg^{-1}	16.30	15.68	15.56
Bulk Density, kg m^{-3}	284	267	-
Shape and Size	Cubes, 30 mm x 30 mm x 30 mm	Round, L= 25 mm, D= 25±10 mm	Sticks, small logs in varied sizes and thickness

3. RESULTS AND DISCUSSION

3.1 Laboratory Performance of IDBG Cookstove

Total five laboratory tests were conducted for determination of thermal efficiency. During testing, feeding of the fresh fuel lot was done at once depending on power output rating of the cookstove. The results showed that the thermal efficiency varied in between 36% to 39% while the average power output rating of the IDBG cookstove was determined as 2 kW. The higher thermal efficiency was achieved due to the better control of the combustion, more heat transfer rate to the vessel and minimum heat losses which is probably not happens in traditional *chulha* as it uses open fire and generally not ventilated. The controlled air submission gives better and efficient combustion during operation of the cookstove. At the same time, the thermal insulation provided on the inner side of the cookstove reduced the heat losses and transferred heat effectively to the vessel. The gas wick at the top of the cookstove helped in proper distribution of the flame around the vessel. Thus, better air control, thermal insulation and proper flame distribution helped in achieving better heat transfer to the vessel and therefore, the better efficiency. However, studies reported that laboratory measurements do not always reflect in attaining similar efficiencies in the field-based kitchen performance test (KPT) [28], [33]. The relationships between stove performances during controlled testing in the laboratory and during normal daily use are not well understood, so a prediction of stove performance in kitchens based on laboratory testing can be difficult [32], [34]-[36].

The emissions of CO and CO_2 were measured in two tests *i.e.* second and fourth tests. The measurements were taken continuously at a minute interval for an hour. The averaged results of CO, CO_2 and CO/CO_2 ratio are shown in Figure 6 and Figure 7 respectively, which showed that during most of the operation period, the CO/CO_2 ratio was below 0.04, which is well within the permissible value prescribed by MNRE [37]. The emission of particulate matter could not be measured due to limitation of the suitable measurement device and hence not reported. However; thermal efficiency of the same model of IDBG cookstove reported by other researchers using maize cobs and saw dust briquettes was 29.59% and 38.68%, respectively [38], and 31.10% for Jatropha shell [39]. Another study reported that CO and CO_2 emission were found in the range of 3-6 ppm and 22-26 ppm respectively for IDBG cookstove [39]. In India, reported data show that improved cookstoves reduces the average indoor air concentrations of carbon monoxide and $PM_{2.5}$ generally by 50% [40]; while the average PM emission factor for improved cookstoves with chimneys (4.5 g kg^{-1}) was almost 50% lower than that of traditional cookstoves (8.2 g kg^{-1}) [36]. In a gasifier stove, the generation and separation of combustible gases from fuel and its subsequent combustion take place to produce heat, which leads to the higher combustion efficiency and therefore, reduces the emission of incomplete combustible products. The study on natural-draft, top-lit up-draft (TLUD) semi-gasifier cookstoves also revealed that emissions and efficiency varied substantially with stove design and fuel type, and transient increases in CO emission correlated with refueling. The highest measured thermal efficiency was 42%. The lowest CO and PM emissions were 0.6 g MJ d^{-1} and 48 g MJ d^{-1} [41]. Table 4 shows the comparative emissions of the different cookstoves.

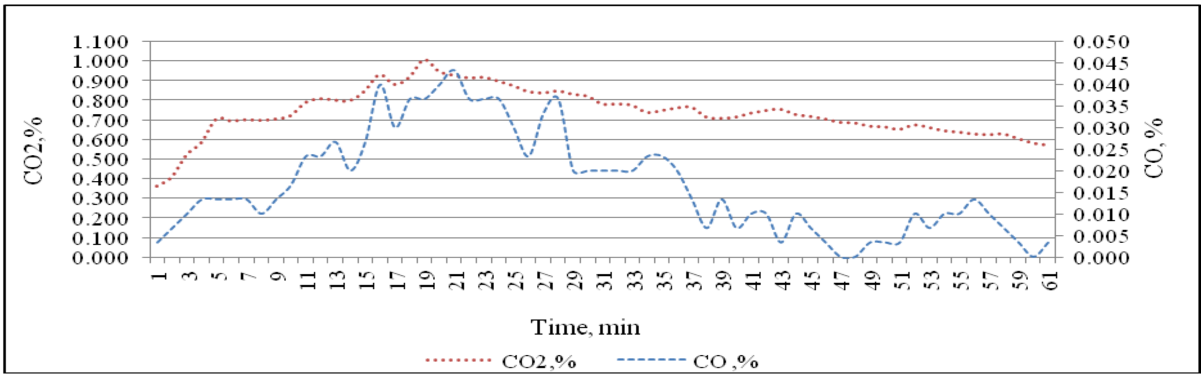


Fig. 6. CO and CO_2 emission from IDBG cookstove.

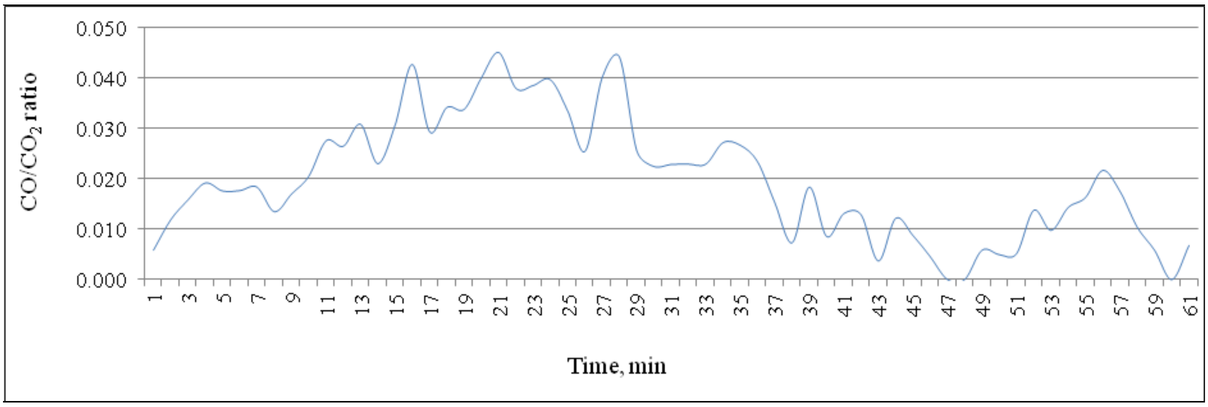


Fig. 7. CO/CO_2 ratio for IDBG cookstove.

Table 4. Comparative efficiency and emission from different cook stoves.

Type of stove	Efficiency, %	Emissions					
		CO, g/kg	CO_2, g/kg	CH_4, mg/kg	PM, mg/kg	BC, mg/kg
Traditional wood	13.8±2.2[42,43]	69±15[45,46,48]	1358±43[45,46,48]	5±4[45,46,48]	3.2±2[48,49]	0.6±0.15[49]
Traditional Crop/ Agri. Residue	11.8±3[42,43,44]	65.6[45,46]	1302[45,46]	7.6[45,46]	6.3±2.9[45,46, 48]	0.6±0.23[49]
Traditional Dung	11±2[42,43,44]	39.9[45,46]	1046[45,46]	4.5[45,46]	3.0±1.9[45,46,48]	0.12[49]
Traditional Coal	14.3[6]	275.1[45,46]	2411[45,46]	7.9[45,46]	17.9[50]	5.42[50]
Liquefied Petroleum Gas	57±4.8[44,45]	14.9[45,46]	3085[45,46]	0.05[45,46]	0.32[45,46,48]	0.01[49]
Pulverized fuel stove	37[47]	12[47]	-	-		

Table 5. Food item and quantity of food cooked during cooking performance test.

Test	Type of cook stove	Food items and quantity (g) cooked		
TC_1	Traditional *chulha*	Rice (355)	Potato (375)	Rotla (250)
TC_2	Traditional *chulha*	Rice (345)	Cabbage (415)	Rotla (255)
IC_1	IDBG[a]	Rice + pulses (615)	Potato+ cabbage (545)	Rotla (250)
IC_2	IDBG[b]	Rice (240)	Bottle guard (310)	Rotla (250)

TC-traditional *chulha*; IC-IDBG cook stove; a and b: Sequence of cooking; [a]Rice- vegetable-*rotla*; [b]Rotla-vegetable-rice; Values in bracket shows the quantity used during cooking.

3.2 Field Evaluation

The performance of the IDBG cookstove was evaluated and compared with the traditional *chulha* for saving in fuel wood use and cooking time. The food items and the quantity cooked during the testing period are depicted in Table 5. The effect of sequence of cooking food items had not studied, but mentioned, which happened in the second test of IDBG cookstove. The tests were conducted in the month of August of rainy season. The cooking operation with traditional *chulha* and IDBG cookstove is shown in Figure 8 and Figure 9, respectively.

The average thermal efficiency of the IDBG cookstove determined in laboratory was found 2.5 to 2.7 folds more than that of the traditional *chulha;* as determined at user site, for which it varied between 12-14.6% as shown in Figure 10. The average fuel consumption in IDBG cookstove was almost half of that traditional *chulha* as shown in Figure 11. The tests revealed that the use of IDBG cookstove resulted in 47% savings in fuel wood and 51% reduction in cooking time as shown in Figure 12. Specific fuel consumption in IDBG cookstove was 0.90 kg kg^{-1} food cooked as compared to 2.02 kg kg^{-1} food cooked for traditional *chulha*; nearly 50% less than that of the traditional mud *chulha* as shown in Figure 13. This value for IDBG cookstove included the quantity of the charcoal left after cooking was completed. If the charcoal left after cooking is recovered and used, specific fuel consumption for IDBG cookstove reduced to 0.66 kg kg^{-1} food cooked as shown in Figure 13. Though the specific fuel consumption, in case IDBG cookstove seems to be more than reported values [51], [52] for improved coostove, the reason being that the *rotla* is roasted on earthen pan, which has low heat conductivity as compared to the metal pan (mild steel or aluminium). Also the *rotla* was prepared by first baking on earthen pan, and then roasting directly on fire/charcoal heat which consumes more energy and time. There might be the effect of cooking under the open shed in rainy season, having a low ambient air temperature with high humidity. Roasting of *rotla* took more time (22 min- 28 min) for complete roasting as compared to rice (15 min -19 min) and vegetables (12 min -17 min).

The actual energy requirement for cooking depends on several factors, like fuel used, stove efficiency, dish ingredients, cooking utensils, cooking methods, *etc.* Moreover; the dishes cooked also varies to a large extent influenced by income levels, regional tastes and flavor and several cooking methods from boiling to the hot plate open baking. This non-uniformity makes the task of determining average cooking energy demand for an average household extremely complex. Several studies have employed various methods to estimate cooking energy demand in India [6], [44], [53]. Using current data on food consumption and household size, the estimated mean end use energy need of 11 MJ stove day^{-1} for cooking; the amount of biomass (wood and crop residues) used for all cooking was estimated at 4 kg day^{-1}, with an efficiency varying from 11% to 18% depending on the biomass type [53].

The maximum flame temperature in case of IDBG cookstove was attained to 751°C during the peak hour of combustion while the average flame temperature varied between 633°C to 651°C, measured with the help of portable hand held thermocouple (‘K’ type). The GI wire mesh provided around the outer surface of the cookstove helped in protecting from direct burns or contact as it maintained the temperature almost around 40°C to 52°C during cooking operation. The overall working environment was much improved compared to traditional *chulha*.

During operation of the gasifier cookstove, some energy is left over in the form of the char after cooking was completed. The average charcoal retained was about 292 g kg^{-1} wood used. The glowing charcoal retained in the cookstove after complete cooking of the food can be recovered or could be used for heating water, boiling milk in continuation. Other utilization may include as a fuel in a charcoal-burning stove or as a soil amendment [41]. In some cases, TLUD/charcoal cookstoves have been designed in which the fuel chamber can be removed to transform a semi-gasifier cookstove into a charcoal stove once the gasification process is complete [54], [55].

Fig. 8. Traditional mud chulha at user site.

Fig. 9. Cooking with IDBG cookstove.

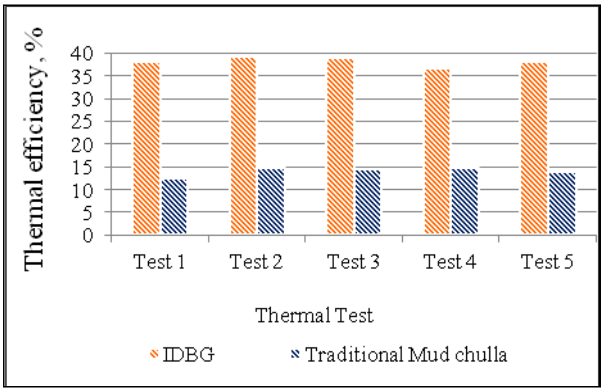


Fig. 10. Thermal efficiency of cookstove (5% error bar).

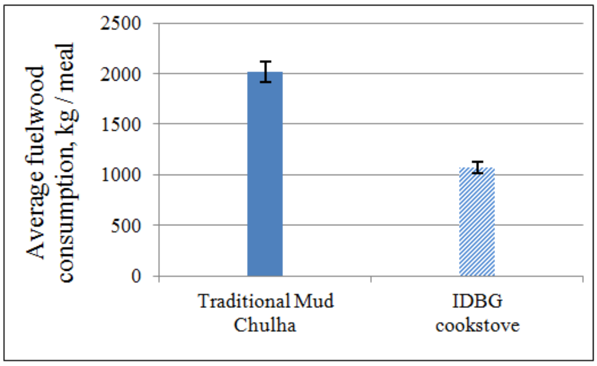


Fig. 11. Average fuel wood consumption, (5% error bar).

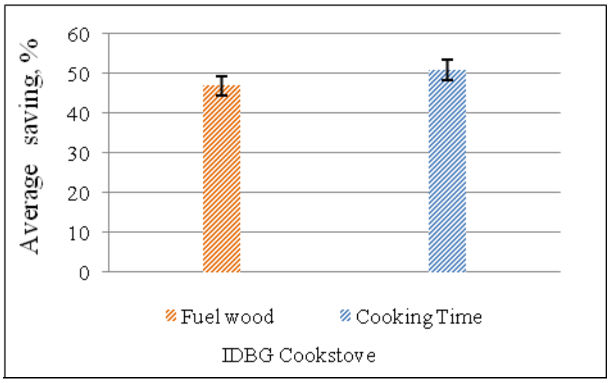


Fig. 12. Average saving of fuel wood and cooking time, (5% error bar).

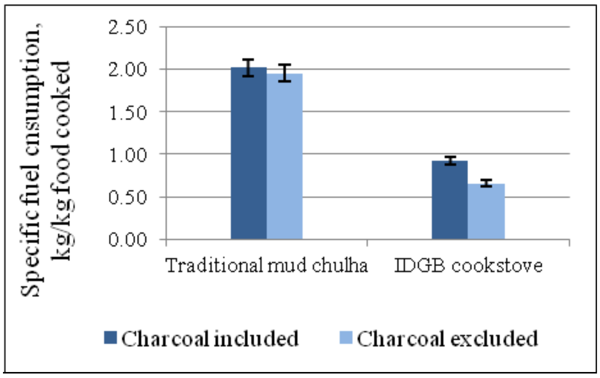


Fig. 13. Specific fuel consumption, (5% error bar).

3.3 User Response and Acceptability

The family used the IDBG cookstove for one month in peak rainy season, in the month of August –September for cooking food and other heating applications. According to the user the cookstove was easy to operate, benefited in wood saving as well as a reduction in cooking time and smoke. The residual heat was retained for extended time and was useful for keeping the food and water warm. However, the user reported that cooking with large-sized utensils was little inconvenient because of the height of the stove, which she managed using a small stool for seating while cooking. The user agreed that they managed to save fuel wood and completed cooking in a shorter time span but could not quantify the parameters. The kitchen environment was much improved than use of traditional *chulha*. During initial use of the cookstove i.e. for 3-4 meal preparation, the family had given ready cut wood pieces while for the rest of period family managed to cut the wood into the approximate size of pieces with the help of available sharp blade cutter.

4. CONCLUSION

The use of IDBG cook stove had significant impact in reducing fuel consumption, cooking time and kitchen pollution. The fuelwood consumption was reduced almost 50 percent using gasifier cookstove as compared to the traditional *chulha* and helped with conservation of the valuable fuelwood for the family. Though there are proven benefits of improved cookstove, making available the cut wood and cost of the cookstove plays an important role in end user acceptability.

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