Fabrication and Performance Analysis of a Biomass Cook Stove

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Abstract— improving the thermal as well as emissions performance of biomass cook stoves has been of interest to researchers for a long time. Despite there being a vast literature on the subject, several technical issues remain unresolved with a variety of data and opinions being presented. This project is concerned with the development of a new class of single fan high efficiency, low emission stoves, named biomass gasifier stoves that promise constant power that can be controlled using any solid biomass fuel in the form of pellets. These stoves use battery-run fan based air supply for gasification (primary air) and for combustion (secondary air). Design with the correct secondary air flow ensures near stoichiometric combustion that allows attainment of peak combustion temperatures with accompanying high water boiling efficiencies (up to 35 % for vessels of practical relevance) and very low emissions (of carbon monoxide, particulate matter and oxides of nitrogen). The use of high density agro-residue based pellets ensures operational duration of about an hour or more at power output of 1.5 kW (18 g/min). The principles involved, the optimization aspects of the design are outlined. The dependence of efficiency and emissions on the design parameters are described. The field imperatives that drive the choice of the rechargeable battery source and the fan are brought out. The process development, testing and internal qualification tasks were undertaken at RCOEM Nagpur. This technology was initially developed as a business by BP, India (earlier) and subsequently taken on by FEPL. At this time, over four hundred thousand stoves have been sold in four states in India. The implications of such developments to the domestic cooking scenario of India are briefly brought out.

Key words: Biomass Pellets, Gasification, Secondary Air, Fire Power, Thermal Efficiency, Emissions, Etc

I. INTRODUCTION

Cooking food using fire was invented 1 million years ago. During those earlier ages, cooking was presumably done over an open-fire with fuel arranged in a pyramid configuration. This system had a major drawback of dispersion of flames and heat during wind conditions. A major step towards the evolution of other cook stoves was after the invention of pots in various shapes and sizes. This in turn led way to create shielded-fires in order to balance the pot over the fire. Subsequently, the shielded-fire was changed to a U-shaped mud or mud/stone enclosure with an opening in the front for fuel feeding and combustion air entry. In order to conserve heat from the hot flue gases and to enhance cooking productivity, additional pot holes were later added. These pot-hole enclosures were connected by a tunnel. All the above mentioned innovations in the cook stove design were made mainly by the users in light of their own experiences. These innovations did increase the efficiency of the stoves to some extent, however the health hazards persisted. It is also alarming that ever year 1.3 million people die worldwide due to the exposure of harmful gasses from Bio-mass cook stoves. With low efficiency and poor indoor air quality, many people had switched over to fossil fuels like LPG, kerosene. The threat in using fossil fuel is its high cost and low reliability. On a long run and for a sustainable path forward, biomass is seen as potential fuel however the cook stoves requires huge improvements in terms of efficiency and low emission.

In the recent years, the technical challenges in the development of clean, efficient and also user-friendly cook stoves has received greater attention from the researchers leading to a new generation of cook stove designs, most of them using the gasification route with forced air supply as the fundamental design feature and many adopting thermoelectric generators for driving the air supply fans. These developments also have their own challenges. Design of cook stoves has slowly grown from being primarily an art with trial and error approach into a more scientific exercise, with clear identification of generic principles and mathematical modeling including the use of advanced tools like the finite element analysis and CFD simulation. Even testing of stoves is being recognized as an area which requires a sound scientific understanding for its effective use Government of India through National Biomass Cook stove Program, promoted manufactures and buyers to go for improved cook stoves. Ministry of Natural and Renewable, India approves the biomass cook stoves by testing them. The researches happened and currently we have few good biomass cook stoves available in market. This research paper tries to understand the performance and suitability of newly designed biomass cook stove for domestic purpose.

II. FUEL SPECIFICATION

Biomass is one of the most utilized renewable resources worldwide. Its importance for the energy and chemical industries is expected to increase to enable the transition from fossil fuels to renewable, so as to meet various climate goals and to create a more sustainable society in the long term. Compared with the concentrated highly energy-dense fossil fuel resources, biomass is widely spread geographically and in its original form has a low energy density owing to its high moisture content, low bulk density, and high oxygen content. Furthermore, biomass is very heterogeneous in nature and its properties vary within plant species and even within the same plant. Studies on the biomass diversity of physical property and chemical composition have been widely reported in the open literatures. The biomass diversity makes it difficult to characterize biomass and to define representative properties that can be used to describe the conversion behavior in, for example, a biomass boiler for heat and power production or a gasifier for gas production.

Fig 3.1: Biomass Pellet as Fuel

In contrast to coal, most of the chemical energy in biomass is stored in the volatiles rather than in the char. Nevertheless, the chemical energy stored in the char is significant. Thus, the process of char conversion in a boiler or gasifier plays an important role in plant design. For this reason, extensive efforts have been made to generate representative kinetic data and reaction models for various types of biomasses. Di Blasi et al. summarized different reaction models and showed that the kinetics varied by several orders of magnitude. Dall'Ora et al. studied the influence of pyrolysis conditions on char reactivity and morphology. Adánez et al. extrapolated the kinetics obtained at low temperatures to conditions at high temperatures by a combined method. Wornat et al. pointed out that the heterogeneity from particle to particle, in char properties, particle shape, and combustion reactivity, is an overwhelming feather of biomass char. Related work performed within our research group has shown that the properties of the ash vary significantly, even from pellet to pellet in a single batch of straw pellets. Thus, it is reasonable to assume that char kinetics is also particle-specific and even varies according to the location within a single particle. However, to authors' best knowledge, studies on

Diameter	6 – 10 mm
Length	10 – 30 mm
Net Calorific Value	15043 KJ/Kg
Bulk Density	800 Kg/m3

Table 1: Fuel specification

Contents	%	Contents	%
Carbon	45.5	Moisture	8.74
Hydrogen	6.59	Ash	2.16
Nitrogen	0.87	Volatile Matter	68.47
Sulfur	0.27	Fixed Carbon	21.23
Oxygen	44.61	HHV	17.15 MJ/Kg

Table 2: Ultimate and Proximate Analysis

The biomass diversity of char reaction kinetics are rare. These raise two questions related to engineering calculations. The first question is how to choose a conversion model and related kinetic data to predict conversion rates in an industrial reactor. The second question is how to obtain appropriate kinetic data and determine in an efficient way its variability in a batch of biomass.

III. THEORETICAL DESIGN

A. *Design of Cook stove*

The design of cook stove was based on the principle of the forced draft gasifier. The present design carried out on the basis of energy required for an average size family. One man required energy for cooking was 26.78 MJ/(day/person) *[Ojolo S. J. et al. 2012]*. Assuming 5 people in the family, then the energy required for this family is approximately 5.6 MJ per hour. The following table shows the assumption made in the design of the cook stove.

Assumptions were made for the design

Sr. No.	Specification	Parameter
1	Gasification efficiency (%)	35
2	Calorific value of feed stock (KJ)	15043
3	Specific gasification rate (kg/hr-m^3)	80
4	Biomass density (kg/m^3)	800
5	Equivalence ratio	0.3
6	Air velocity (m/s)	0.2-0.3
7	Air density (kg/m^3)	1.225

Table 4.1: Parameters to be assumed while designing cook stove

B. *Energy Input, FCR*

The theoretical fuel consumption was calculated by following formula:

$$\text{FCR} = \frac{Qg}{\text{HVf X } \xi g}$$

C. *Dimension of reactor*

The diameter of the combustion chamber was taken as 0.14 m. [Indian Institute of sciences, Bangalore]. The height of the combustion chamber was calculated by following formula:

$$\text{H} = \frac{\text{SGR X T}}{\rho}$$

D. *Stoichiometric air requirement for combustion*

Preliminary investigations such as proximate analysis were carried out to compute the theoretical airflow ratio.

Based on elemental and proximate analysis, amount of theoretical air required for combustion of 1kg of fuels was calculated by using following formula,

Amount of air required theoretically for the combustion of 1 kg of fuel

$$= \left[\frac{32}{12} \times C + 8\,H - O + S\right] \times \frac{100}{23}$$

E. *Amount of Air Needed for Gasification, AFR*

The theoretical amount of air needed for Gasification was calculated by following formula:

$$\text{AFR} = \frac{\varepsilon \times \text{FCR} \times \text{SA}}{\rho a}$$

F. *Area for primary air requirement, A*

The area for primary opening was calculated by following formula

$$\text{A} = \frac{\text{AFR}}{\text{v}}$$

G. *Capacity of combustion chamber*

Effective fueling height of combustion chamber

H = Length of c.c. + Gap between grate and c.c. −Distance of Secondary air holes from top of c.c.

The capacity of combustor chamber was calculated by following formula

Capacity of combustion chamber = πr^2H × Bulk density

H. Burning test

The burning test was determined by BIS standard. To carried this test the combustion chamber fill with test fuel in honey-comb fashion up to third-forth of the height of the cook stove in the pattern recommended.

To ignite the fire 10–15 ml of kerosene oil has been sprinkled on the fuel pellets from the top of the cook stove and fire. The weight of the cook stoves along with fuel was measured before igniting the fire and again it was done an hour of burning the pellet fuel as per the procedure given in BIS standard. To calculate the burning capacity of the cook stove, the following equation was used:

Burning capacity rating = (M1 – M2) kg/hr

Heat input per hour = (M1 – M2) × CV kJ/hr

I. Power Output Rating

The power output rating of cook stove is a measure of total useful energy produced during one hour by the fuel. It shall be calculated as follows:

Power output rating, Po = F × CV × η / 360000 kW

J. Combustion Zone Rate

The CZR rate calculated by following formula,

$$CZR = \frac{Length\ of\ reactor(m)}{total\ operating\ time(hr)}$$

IV. STOVE DESCRIPTION

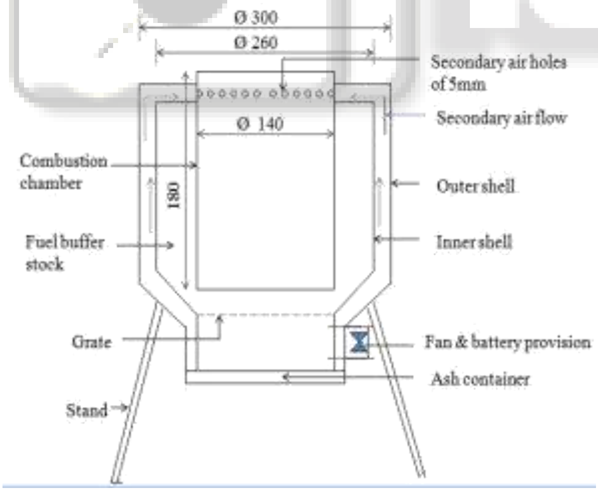

Fig. 4.1: Schematic view of biomass cook stove

Forced draft stoves tested in the study works on the principle of biomass gasification. The combustion of gaseous fuel is clean when compared to solid fuels like fuel wood. With the air input gaseous fuel forms a uniform combustible mixture and provides clean combustion results in higher efficiency. The device that enables conversion of solid fuel to gaseous fuel by a thermo-chemical conversion process is known as gasifier. This process involves sub-stoichiometric high temperature oxidation and reduction reactions between the solid fuel and an oxidant. These high temperature combustible gases are burnt at the top of the combustion chamber with additional air (secondary air) supply. An important factor of this mode of operation is maintaining a fixed ratio between the amounts of combustible gases produced and the primary air supplied for gasification. The fuel consumption increases with the increase in primary air supply. This results in an Increase of the power output. Therefore the heat input of the cook stove is directly proportional to the supply of the primary air. The gas produced from biomass is called as producer gas, which consists of combustible gases like carbon monoxide, hydrogen, methane, and some higher hydrocarbons.

These gases are burnt to carbon dioxide and H2O using the secondary air which is supplied at the top of the combustion chamber. The flame temperature of the gasifier stove is in the range of 1000 C - 1100 C. The flame temperature of the conventional stove is in the range of 700 C - 800 C. The higher the flame temperature will result into the increased heat transfer rate, thus making the gasifier stoves work at higher efficiency than the traditional stoves.

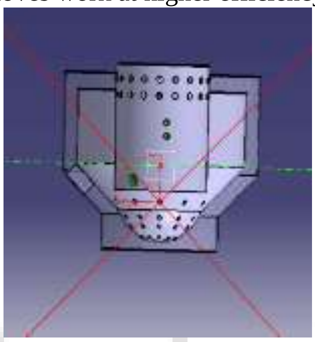

Fig. 4.2: Cookstove assembly Fig-4.3:Fabricated cookstove

V. METHODS FOR PERFORMANCE ANALYSIS OF A COOKSTOVE

A. Test methods Used for testing of cookstove

Water Boiling Test (WBT): Modified version of the well-known Water Boiling Test (WBT) is a rough simulation of the cooking process that is intended to help stove designers understand how well energy is transferred from the fuel to the cooking pot.

The WBT developed consists of three phases that immediately follow each other.

1) In the first phase, the cold-start high-power test, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood or other fuel1 to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test.
2) The second phase, the hot-start high-power test, follows immediately after the first test while stove is still hot. Again, the tester uses a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot.
3) The third phase follows immediately from the second. Here, the tester determines the amount of fuel required to simmer a measured amount of water at just below boiling for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

The outputs are:

- time to boil;
- burning rate;
- specific fuel consumption;
- firepower
- turn-down ratio; and
- thermal efficiency

VI. CALCULATIONS

To get accurate results, number of test has to be repeated and the average of all the tests will yield best results for cook stove experimentation. In this Project three tests were taken. Sample brief calculations need to be done to get performance of biomass cook stove and they are as follows,

- fuel consumed, moist (grams),

$$fm = fci - fcf \quad \ldots (1)$$

- Net change in char during test phase (grams)

$$\Delta c = cc - k \quad \ldots (2)$$

- Water vaporized (grams)

$$w_v = Pci - Pcf \quad \ldots (3)$$

- Water remaining at end of test (grams)

$$w_r = Pcf - P \quad \ldots (4)$$

- Burning rate (grams/min)

$$r_b = \frac{fcd}{tcf - tci} \quad \ldots (5)$$

- Specific fuel consumption (gm/lit of water)

$$SC = \frac{fcd}{Pcf - P} \quad \ldots (6)$$

- Thermal efficiency

$$\eta = \frac{4.2 \times (Pci - P) \times (Tcf - Tci) + 2260 \times (Wcv)}{fcd \times LHV} \quad (7)$$

- Firepower (W)

$$FP = \frac{fcm \times LHV}{60 \times (tci - tcf)} \quad \ldots (8)$$

VII. RESULTS AND DISCUSSION

The improved biomass cook stove was designed, fabricated and its performance evaluation was done using Water Boiling Test using 3 litter of water and 1Kg of fuel under conditions similar to household kitchen. Compacted and sized type of biomass pellets is used as fuel to evaluate its performance. Observations and respective calculations for burning rate, fire power, thermal efficiency and power output were done and emissions from cook stove were recorded by emission sensor through fume hood. Following are various factors considered and discussed as per this cook stove is concerned.

A. Fuel consumption rate

Fig. 4 shows the fuel consumption rate of biomass cook stoves during cold start and hot start phases (g/min). Tests were taken for 1 Kg of fuel and its consumption were recorded after every 5 min. The graph shows, hot start phase is faster than cold start phase for consumption of 1 Kg of fuel. Very crucial factor for fuel consumption rate in case of solid biomass is the amount of gasification and combustion air we supply in cook stove. The results indicate that the fuel used in cold start phase has a higher burning rate than in hot start phase. This is due to the condition of combustion chamber and controlled supply of primary and secondary air into the combustion chamber using the fan.

The average fuel burning rate during high power cold start was 15.38 g /min while during high power hot start test it was 18.32 g/min. Average time to complete test are 56 min and 64 min for high power cold start and high power hot start phase respectively. This shows energy release is higher during hot start phase than cold start phase. The results should be nearly same in order to have uniform energy release during operation.

B. Water Temperature

Fig 6.2 shows, the behavior of water temperature with cooking time. Gain in water temperature mainly depends on amount of heat loss from the cook stove. This is one of criteria for performance of cook stove and its thermal efficiency. When heat losses are more, slow response of cook stove to gain in temperature and hence thermal efficiency. This cook stove shows relatively slow response in cold start than in hot start. The average time to boil water (100C) is 29 min in cold start and 22 min in hot start phase. The slope of later is more than former phase in behavior. Ways of heat loss are same in both the cases except heat loss to body surface of cook stove in case of cold start and the reason for slowness in it.

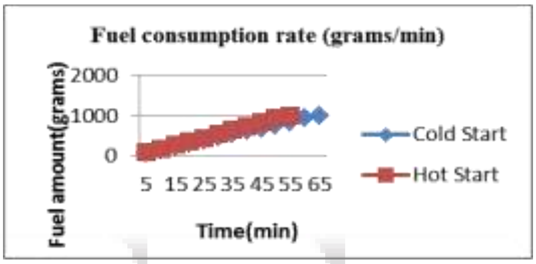

Fig 6.1: Graph between Fuel amount and time duration

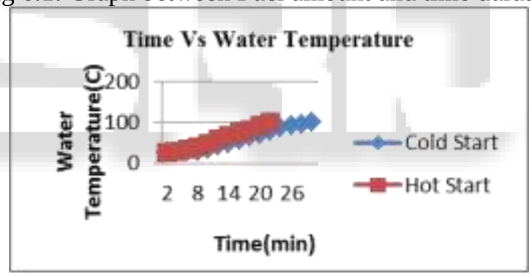

Fig 6.2: Graph between water temperature and time duration

C. Effect of pot diameter on thermal efficiency

Fig. 6.3 Shows, effects of various standard pot diameters on thermal efficiency of biomass cook stove. Graph shows similar effects in both phases as per variation in thermal efficiency is concerned. The slope is more in case of cold start indicates appreciable rise in efficiency with pot size than hot start, but overall performance in hot start is better than other. Pot size of 280 mm shows good results for both the phases and can be recommended as standard pot for this cook stove. Above 280 mm, results shows slight rise in efficiency which can be considered if cooking requirement is more.

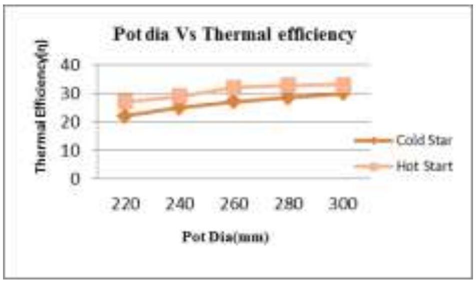

Fig-6.3: Graph between pot diameter and thermal efficiency

D. Thermal efficiency and Fire power

This section shows the actual relationship between energy produced in combustion chamber and energy utilized in cooking food. It is not necessary that when fire power is more, efficiency will rise subsequently. It is much more depends on surrounding conditions, flame velocity and condition of secondary air. Approximate range of fire power yield best results for particular cook stove rather than more fire power like if 3 stone open fire stove. The controlled energy output will save fuel consumption and energy waste during operation. For controlled fire power, controlled fuel burning rate needs to provide by setting the speed of fan at required output.

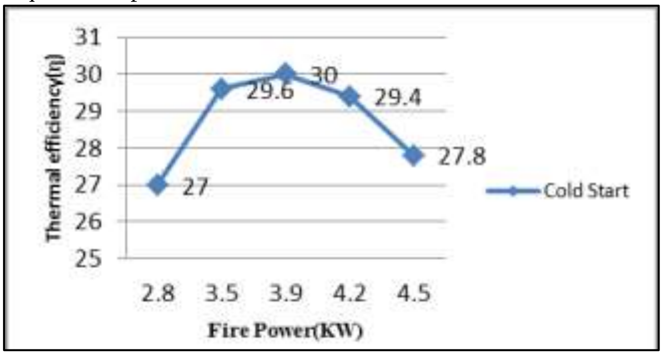

Fig-6.4.1: Graph between Fire power and Thermal efficiency for cold start

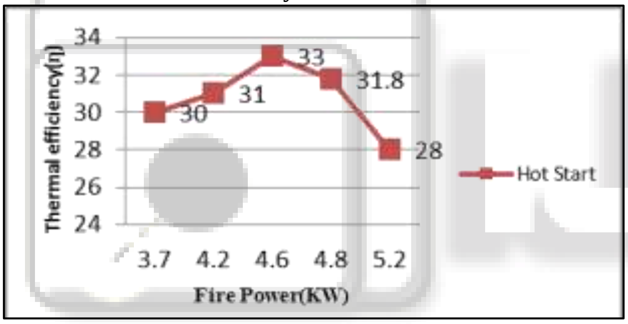

Fig-6.4.2: Graph between Fire power and Thermal efficiency for hot start

Fig-6.4. shows relation between thermal efficiency and Fire power for two different phases, in which performance curves are drooping in nature. It increases up to certain fire power and then starts decline rapidly. It means higher fire power is not desirable in above certain limit of best performance and this limit is approximately 3.9 KW for cold start and 4.6 KW for hot start phase. Thermal efficiency above these fire power ranges as excess energy is released than required for cook stove which needs to be controlled one.

E. Emission from cook stove

The emission behavior of cook stove is never uniform; it changes continuously over the span of cook stove performance. An emission fluctuates rapidly as it depends upon amount of secondary air supplied for combustion of hot gases from gasification process. These are measures of impact on health and environmental effect and must be within limits set by MNRE, India. As per this stove is considered, CO emission are < 5 gm/ MJ and TPM are < 150 gm/MJ and within acceptable range set by MNRE, India.

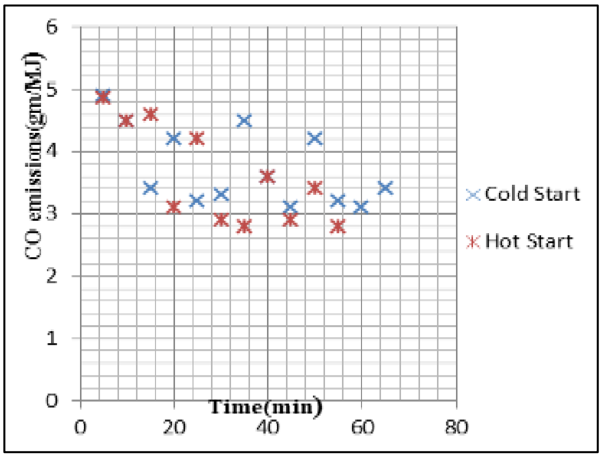

Fig 6.6: Graph between CO emissions and time duration

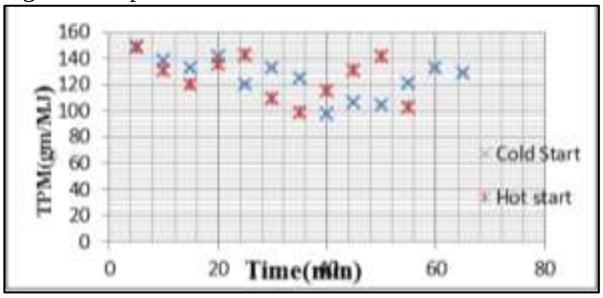

Fig-6.7: Graph between TPM emissions and time duration

VIII. CONCLUSION

Some of conclusions from experimentation and calculations can be drawn as follows;

1) This study deals with the performance of biomass cook stove using mixed biomass pellets shows that the results obtained from this stove satisfies limiting measures of MNRE (Ministry of New and Renewable Energy).
2) Thermal efficiency of biomass cook stove is a function of fuel burning rate, amount of primary and secondary air, draft between top and bottom of combustion chamber. Biomass cook stove regarding this project has a thermal efficiency of ~33% which is good as per MNRE but more work needed on the same as the model is newer one.
3) The stove while operating takes little time to get warm and hence need more time to boil water in cold start compared to hot start. Once water boils (approximately 22 min), further operation of cook stove has approximately similar operation through.
4) At the start of the test, amount of emission is more. As operation proceeds level of emission goes on decreasing. Amount of CO_2 emission is 4.87 mg / MJ per day and Total Particulate Matter is about 148 gm / MJ-day which are bellow acceptance limit set by MNRE, India.
5) The fuel burning rate of cook stove is about 15 -18 grams / min for better operation, which is controlled by regulating speed of fan/blower.
6) Body temperature of cook stove is about 80C > 60C, is little more than limiting value by MNRE, India.
7) Fuel buffer stock helps in heat loss to surrounding by taking stove wall temperature for gasification of fuel which is utilized in combustion. It increases the

capacity of cook stove operation / recharge interval. Because of buffer stock, overall weight of cook stove increases little.

8) Now we can conclude that this stove has most of operating parameters within range set by MNRE, India. Hence this stove can be another option for domestic cooking purposes and large scale model can be option for community appliances.

IX. FUTURE SCOPE

Additional studies are suggested to further examine the role and function of improved cook stoves; regional studies testing effectiveness of improved cook stoves on different food types and different solid biomass fuel types; longitudinal studies of improved cook stove use on the environment and human health; Promotion of improved cook stove projects in conjunction with micro-lending to reduce poverty; improved cook stove use and the rebound effect; improved cook stove use as a measure to reduce carbon monoxide emissions and ultimately mitigate climate change; and improved cook stoves as a form of carbon trading. Results shows stove need future work on type of material used in its manufacturing; thermal efficiency can be increased by reducing the heat loss to the surrounding with the help of quality insulation.

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