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Experimental Analysis of Thermal Efficiency of Mud Improved Cookstove With Variation of Different Parameters and Economic Analysis

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Abstract:
Most of the rural people of Nepal use fuelwood for cooking and space heating in residential sector. Government of Nepal has announced to make Nepal as a smokeless country by replacing traditional cookstoves. Two pot mud improved cookstove is one of the most promoted cookstoves in the context of Nepal. There is a need to study the effects of different parameters on mud improved cookstove for its better performance. The objective of this work is to study the effect of variation of different parameters on two pot mud ICS and identify parameters for its better performance. Power test of cookstove, specially focusing on thermal efficiency, has been performed by changing different parameters. Effect of varying fuel feeding rate, chimney height, opening area of air fuel inlet, inlet area of interconnecting tunnel, combustion chamber height, grate height and insulating material on thermal efficiency have been studied individually. Then cookstove has been developed by different best combinations such as a) geometrical parameters b) use of grate and insulations in best geometrical parameters and formation of channel on the opening. Thermal efficiency of modified cookstove increased from 18% to 25.6%; i.e. the increment of 7.60%. Economic analysis of different thermal efficiencies cookstove has been performed.

Keywords: Firepower, Efficiency, Grate, Combustion Chamber Height, Chimney, Insulation, Net Benefit

1 Introduction

Biomass is one of the widely available renewable energy resources which is using for cooking and space heating for long time. In the context of Nepal,60.9% people are using fuelwood cooking purpose [1]. Use of improved cookstove by improving thermal efficiency and combustion performance can reduce adverse effects on human health, reduce energy consumption and contribute to environmental aspects [2]. About 16 million hector of forests is being consumed as cooking fuel annually throughout the world. Fuelwood consumption and subsequent environmental pollution can be reduced by improving the thermal efficiency of cookstove and through optimum use of biomass fuel [3]. Till date around 1.3 million improved cookstove (ICS) has been disseminated and still about 2 million people are using traditional cookstove. According to Biomass Strategy 2017, it has been planned to make “Indoor Air Pollution free Nepal” by 2022 through the promotion of clean cooking technologies in all households and promote modern clean energy in all the households using solid biomass by 2030 [4].

Research work should be done to develop high performance cookstove in terms of thermal efficiency and emission parameters. From the literature review, the following parameters have been identified as vital for cookstove performance:

Thermal efficiency is highly influenced by fuel feeding rate and has maximum value at a certain range [5,6,7].

Chimney should be made with optimum combination of height and diameter of chimney [8]. Chimney controls the mass flow rate of incoming air [9]. Variation of chimney height affects the performance of cookstove [10].

If the height of the combustion chamber is less than the flame height, the flame will touch the cold pot which will result in quenching of flame, incomplete combustion of fuel, deposition of soot at the bottom of the pot and increase in the emission of pollutants [11]. On the other hand, if combustion chamber’s height is too high, there is possibility of less heat transfer to the pot due to quenching of the flame.

A side opening in the stove has the purpose of air and fuel inlet. Fuel burning rate, temperature of combustion chamber and air supply is controlled by side opening.

There is also loss of heat through radiation and convection by opening. Thus, a side opening has a profound influence on the efficiency of the cookstove [12].

Shape and size of the interconnecting tunnel affects the draft of air flow, turbulence of flue gases and combustion process of the cookstove. Diverging and converging tunnels have more resistance to flow of flue gases and flame. It also creates more turbulence on the flue gases. On the other hand, tunnels with small diameter creates more pressure drop [8]. Purpose of modification of pathway to second pot is to increase the efficiency of heat transfer to second pot, swirling of incoming air and flue gases. Swirling in incoming air increases the turbulence of air in combustion chamber resulting in increase of thermal efficiency [7].

Use of insulation layer in the combustion chamber reduces the heat transfer to walls of cookstove. This results in high combustion chamber temperature which increases combustion efficiency and ultimately thermal efficiency [13].

Use of the grate increases the thermal efficiency of cookstove. The primary air coming from below the grate is heated from the char and ash. Grate also aids in proper burning of char [7]. Thermal efficiency of cookstove can be improved by 3% to 5% by using grate [14].

Seconary air ensure proper and complete combustion of fuel. It increases thermal efficiency and improves quality of emission parameters [15].

Fuel burning rate, temperature of combustion chamber and air supply is controlled by side opening. There is also loss of heat through radiation and convection by opening.

2 Materials and Methods

2.1 Fabrication of cookstove

Two pot raised mud ICS of size 82×40×28cm has been fabricated by using solid bricks, supporting structure parts and additives which is promoted by Alternative Energy Promotion Center (AEPC) Mud used for the fabrication of brick was composed up of 5/8 fraction clay or local mud, 2/8 fraction rice husk or saw dust and 1/8 fraction cow or buffalo dung parts by volume. Rectangular shaped bricks have been fabricated for wall of cookstove and square shape bricks for chimney by using moulds.

2.2 Experimental analysis

For the analysis of cookstove parameters, experiment has been performed at Stove Lab of Pulchowk Campus, Institute of Engineering, Tribhuvan University, Lalitpur, Nepal. Power test was done for the evaluation of thermal efficiency.

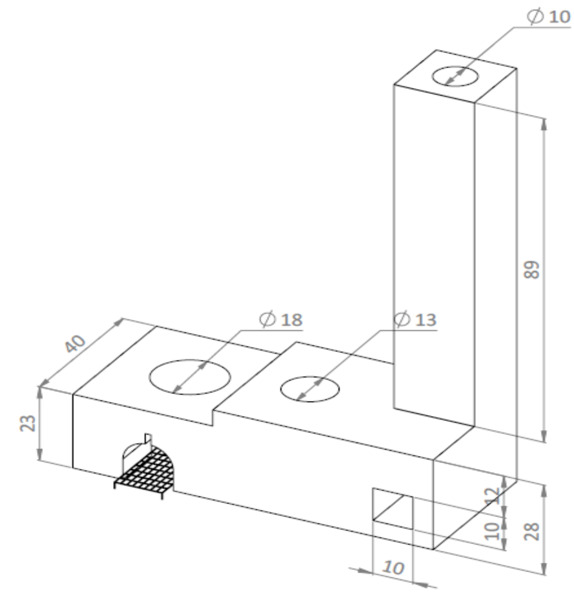

Figure 1: Schematic drawing cookstove

Thermal efficiency of cookstove has been calculated by using "Power Test". Maintaining constant power during Water Boiling Test (WBT) is difficult and power variation results in data with high standard deviation and variance. The stove power varies according to the person supplying fuelwood to cookstove and for the same person, it depends on the steadiness of fuelwood feeding. To remedy this problem, power test was devised. While most of the procedures are similar to cold start of WBT, some aspects are considered differently. First of all, the test has been conducted for one hour and secondly, constant fuel feeding rate has been maintained. The amount of wood to be supplied is divided in different batches of equal weight and is fed to stove at constant time intervals. All other protocols for testing were of Water Boiling Test 4.2.3. version [16]. For the calculation of thermal efficiency of cookstove, excel sheet provided by Global Alliance for Clean Cookstove has been used.

2.3 Economic analysis

Economic analysis of the cookstove has been done for the sustainability of the project. Cost benefit analysis and marginal adaptation cost has been calculated for single cookstove.

3 Results and Discussions

3.1 Thermal efficiency at different firepower

Input fuel feeding rate has been varied considering fire power range from 3.3 kW to 6.6 kW to find the optimum feeding rate as shown in Figure 2.

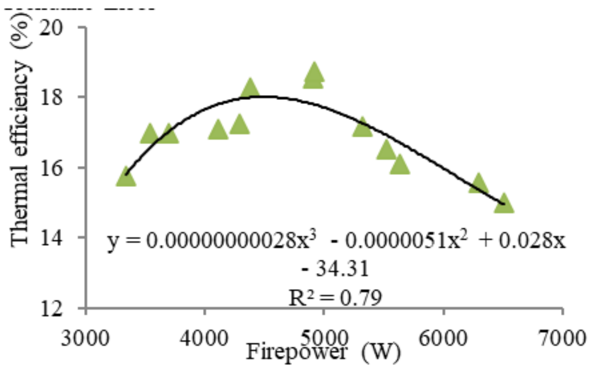

Figure 2: Thermal efficiency of cookstove at different firepower

As the fuel feeding rate increases, the efficiency first increases, reaches maximum value, and then decreases. The reason for low efficiency at lower fuel feeding rate is due to quenching of flame because of high excess air ratio. For higher fuel feeding rate, there is lack of air for complete combustion because of which the efficiency decreases. The shape of the graph is inverted bowl shape which is in accordance with the literature [7,17]. From polynomial equation of the graph, its maximum value has been found at value 4.5 kW and corresponding thermal efficiency 18%. Feeding rate for further experiments has been maintained as per optimum firepower.

3.2 Thermal efficiency at different chimney height

Chimney height of the cookstove has been varied from 81cm to 132cm with fixed chimney hole diameter of 10cm. The nature of thermal efficiency vs. chimney height has been found concave downward as shown in Figure 3.

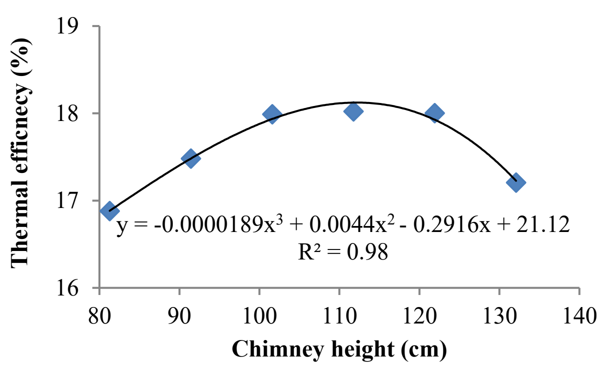

Figure 3: Thermal efficiency of cookstove at different chimney height

The graph for chimney height vs. firepower has been found as bell shape. For shorter chimney height, the draft created due to stack effect is less which results in lower suction of air. For higher chimney height, leading to higher excess air, higher losses of heat through flue gas. The polynomial equation gives optimum efficiency 18.16% at chimney height 113cm.

3.3 Thermal efficiency at different opening area of air fuel inlet

Size of opening inflences the air flow entering into the combustion chamber and convetion and radiation heat losses. Social factor such as size of fuelwood used also influence the size of the opening [18]. Thermal efficiency of cookstove has been obtained by varying the area of opening from 110cm^2 to 170cm^2 as shown in Figure 4.

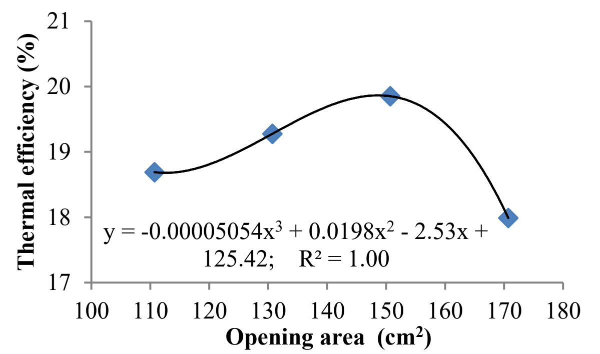

Figure 4: Thermal efficiency of cookstove at different opening

Nature of the graph has been found concave downwards. The maximum efficiency of 19.85% is obtained at opening area of 148cm^2. The cause of low thermal efficiency at smaller opening is due to more space occupied by fuelwood and less space available for incoming air which results in insufficient air for complete combustion. At larger opening, supply of excess air causes quenching of flame and at the same time more convection and radiation heat losses through openings. From design aspect, minimum opening area of combustion chamber should maintain with the capacity to accommodate at highest firepower [19]. Considering social viability [18] and design aspect, 148 cm^2 area is suitable for optimum performance.

3.4 Thermal efficiency at different size of entry area of inter connecting tunnel

Thermal efficiency test has been performed by varying entry area for the interconnecting tunnel from 139cm^2 to 14cm^2. Rectangular wall has been raised from bottom of the entry hole to reduce area.

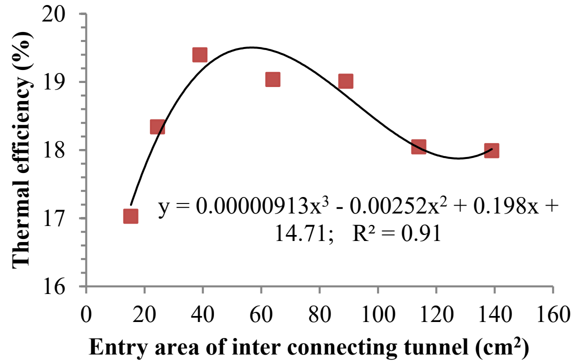

Figure 5: Thermal efficiency of cookstove at different entry area of inter connecting tunnel

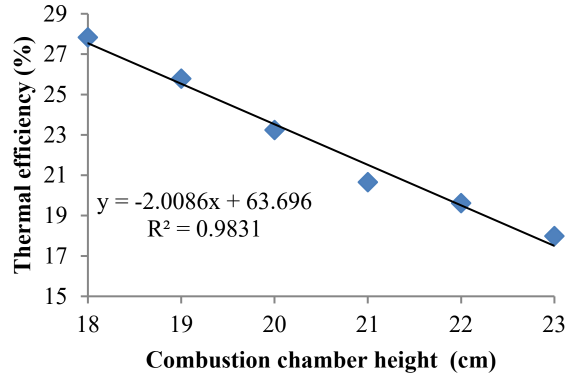

Figure 6: Thermal efficiency of cookstove at different combustion chamber height

As area of interconnecting tunnel decreases, turbulence of air entering the second combustion chamber increases and overall contact time of flue gas increases. Further, reduction of entry area of interconnecting tunnel, results in lack of the area for flow of flue gas. Because of this, insufficient air enters the combustion chamber leading to incomplete combustion and decreased thermal efficiency.

3.5 Thermal efficiency at different combustion chamber height

Thermal efficiency test of cookstove has been performed by varying combustion chamber height from 18cm to 23cm as shown in Figure 6. Result shows that there is linear relationship between thermal efficiency and combustion chamber height. As the combustion chamber height decreases, thermal efficiency increases. This is because the flame directly comes in contact with the pot, transferring more heat to the pot and increasing the thermal efficiency. But the combustion chamber height can be reduced up to a certain limit only. Below the limit, the combustion is incomplete and high soot deposits are formed on the bottom of the pot. Higher combustion chamber height causes quenching of flame and results in decrease of thermal efficiency [11].

By using Herwijn empirical formulae, height of the flame for the stove without grate has been found 19.98cm in which thermal efficiency has been found 21.93% [20]. In this condition, combustion process was found normal and there was no exess soot formation on the pot. For the 18cm height combustion chamber, i.e. 2cm less than flame height, thermal efficiency has been found 27.83%. This is due to shorter distance between bed of combustion chamber and bottom of the pot, shape factor increases and pot receives more heat at high temperature and thermal efficiency increases. But this leads to increased deposition of soot on the pot, incomplete combustion and increased emission of pollutants. So, combustion chamber height of the cookstove should be equal to flame height.

3.6 Thermal efficiency with the use of grate

Use of grate increases the thermal efficiency of the cookstove [21]. Thermal efficiency of cookstove by using grate of height of 1cm, 2cm and 3cm have been found 20.61%, 21.69% and 22.70% respectively as shown Figure 7. This shows that thermal efficiency has been increased by 2.62% (from 18 to 20.61%) by using grate of height 1cm. Similarly, thermal efficiency increased by 1.08% and 1.01% by increasing subsequent each 1cm grate height respectively. Use of grate supplies primary air from bed which carries heat from combusted ash and results in improvement of combustion quality. Preheating of incoming air improves quality of combustion and improves thermal efficiency [22].

Grate height has not been increased more than 3cm due to size of opening area, size of the fuelwood used and social factor. Here, thermal efficiency has been increased from 17.85% to 22.69%, i.e. with net increase of 4.84% with the use of 3cm grate but for 3 cm grate height, the fuelwood has to be cut into small pieces and considering social aspects 3cm grate is not a viable option. It has been found that thermal efficiency has been increased by 3.83% with the use of 2cm grate. Socially, technically and geometrically, grate height has been fixed 2cm.

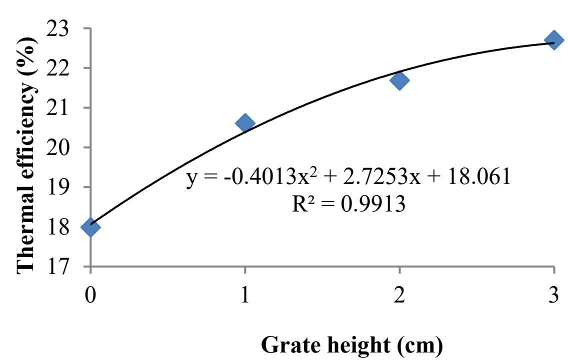

Figure 7: Thermal efficiency of cookstove at different grate height

3.7 Thermal efficiency with the use of insulation

Inner layer of the combustion chamber has been coated by insulating material and effect on efficiency has been observed. Composition of insulating material were Ash 5/12, Saw dust 3/12, Talcum powder 1/12, fire clay 1/12 and Bulk clay 2/12 parts by volume. The main reason for use of this material for insulation is consideration of social aspects. This stove is a nationwide disseminated cookstove and the insulation material should also be locally manufacturable.

Thermal efficiency of cookstove with insulating layer increased from 18% to 20.21%, i.e. 2.21% increase in thermal efficiency as shown in Figure 8. This is due to decrease in conductivity which results in less heat transfer to the wall. Also, the temperature of flame increases and ultimately, thermal efficiency increases [23].

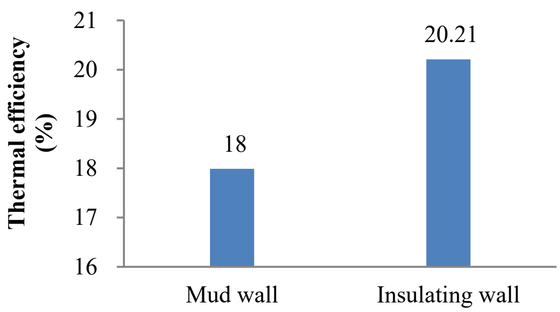

Figure 8: Thermal efficiency of cookstove with use insulating material

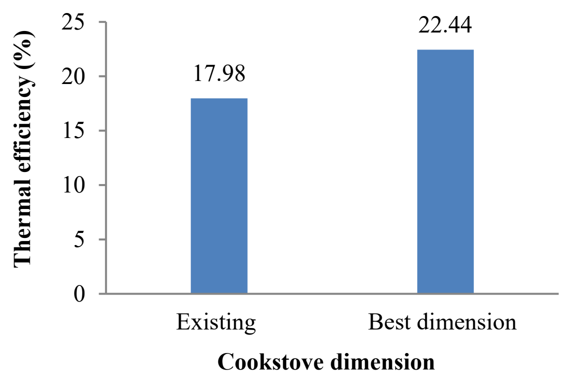

Figure 9: Thermal efficiency comparison at different dimension

3.8 Thermal efficiency at best condition

Similarly, best dimension such as chimney height, air fuel inlet opening, entry area of interconnecting tunnel and combustion chamber height have been found 112.88cm, 148cm^2, 56.95cm^2 and 20cm respectively. Thermal efficiency of cookstove at overall optimum dimensions have been found at 22.45%. This value is 0.51% more than individual optimum value at combustion chamber height of 20cm. So, experimental results show that combustion chamber height is most sensitive parameter for the thermal efficiency. Thermal efficiency of the cookstove at different parametric condition has been shown in Figure 9.

3.9 Thermal efficiency with the use of grate and insulation

For the optimum dimension, with the use of 2 cm grate, thermal efficiency has been increased from 22.45% to 23.86%; i.e., net increase of 1.41%.

Thermal efficiency of cookstove with the use of insulation on the inner layer of combustion chamber at optimum dimension has been found 23.63% which is 1.19% more than in case with use of existing.

Furthermore, using 2cm grate on the cookstove fabricated in optimum dimension with insulation in the inner layer of combustion chamber, thermal efficiency has been found 24.70% which is 1.07% higher than the case of without use of grate.

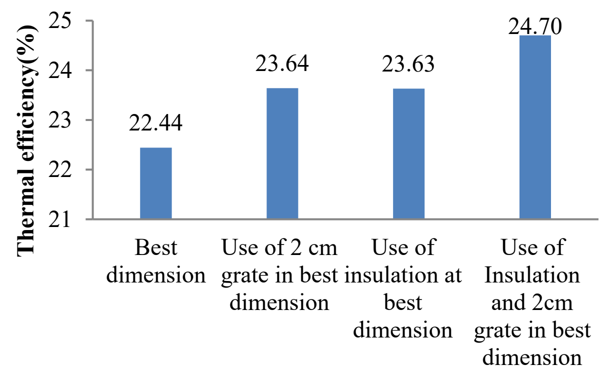

Figure 10: Thermal efficiency with the use of insulation and grate

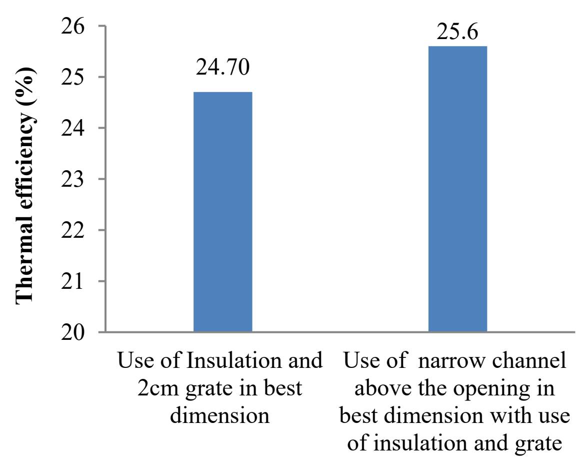

Figure 11: Thermal efficiency of cookstove with formation of narrow channel

3.10 Thermal efficiency with formation of narrow channel

Air has been supplied by making rectangular slot of 4cm width and 3.5cm above the air fuel inlet. Figure 11 shows thermal efficiency of cookstove has been increased by 0.9% with formation of narrow channel for the best dimension cookstove with use of insulation and 2cm grate.

4 Economic analysis

Economic analysis has been done for the single cookstove. In economic analysis, Net benefit analysis and marginal abatement cost analysis has been performed. Benefit analysis has been used for decision making for the installation of Improved Cook Stove. Costs includes installation costs (sum of trained technician costs, material cost, the costs of grates and chimneys) as shown in Table 1.

Table 1: Input parameters for economic analysis

Particular	Cost of cookstove (NPR)	
	Initial	Yearly maintenance
TCS	1,000	100
Existing ICS	3,490	250
Best dimension	3,490	250
With use of grate at best dimension	3,790	250
With use of insulation, grate and formation of narrow channel in best dimension	4,090	450

Marginal abatement cost of cookstove has been performed to identify the cost require for per unit reduction of tCO_2 eq. Input parameters for economic analysis shown in Table 2.

Net benefit analysis shows that benefit increases from NPR 16,569 to 23,619 with increase of thermal efficiency from 17.99% to 25.60% which is shown in Figure 12.

Marginal adaptation cost of cookstove has been found lowest NPR 556/ tCO_2eq for 22.4% thermal efficiency cookstove and highest 735/ tCO_2eq for 17.99% shown in Figure 13. Cost of existing ICS (17.99% thermal efficiency) and best dimension cookstove (22.40% thermal efficiency) are same just differences in dimension of cookstove.

From net benefit cost analysis and marginal abatement cost analysis as shown in Figure 12 and Figure 13, cookstove should be made at best dimension (22.4% thermal efficiency) cookstove in which thermal efficiency is 4.5% higher than existing cookstove. While comparing existing and best dimension cookstove, net benefit increases by NPR 5,378 and marginal abatement cost decreases by NPR 179/tCO_2eq **[24]** respectively.

Table 2: Input parameters for economic analysis

Parameters	Value	Reference
Lifetime of a cookstove	3 years	AEPC
Fuelwood consumption	3.066 ton/year	[24]
Efficiency –Traditional cookstove (TCS)	10%	Methodology AMS-II G
Efficiency of cookstove a. Existing ICS b. Best dimension c. With use of grate at best dimension d. With use of insulation, grate and formation of narrow channel in best dimension	 17.9% 22.4% 23.6% 25.6%	Experimental analysis
Market price of carbon	\$5/tCO_2eq	AEPC
Dollar exchange rate	1\$=NPR 117	October 8, 2018
Efficiency derating factor (ICS (%))	10	Assumption
Emission factor of fuelwood	1.224tCO_2 eq/ tonne	[25]
Discount rate	6%	Assumption
Cost of fuel for hill area	NPR 4700/ tonne	[26]

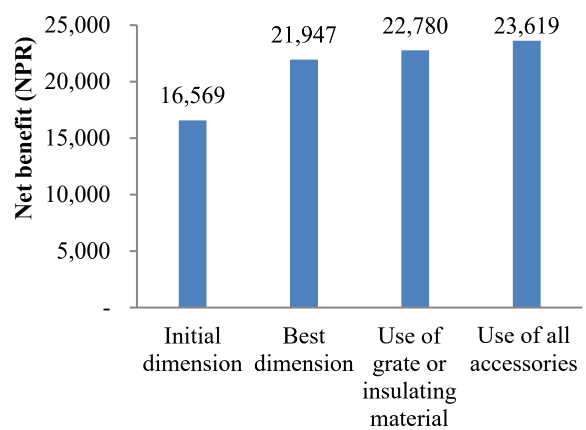

Figure 12: Net benefit of different efficiencies cookstove

5 Conclusions

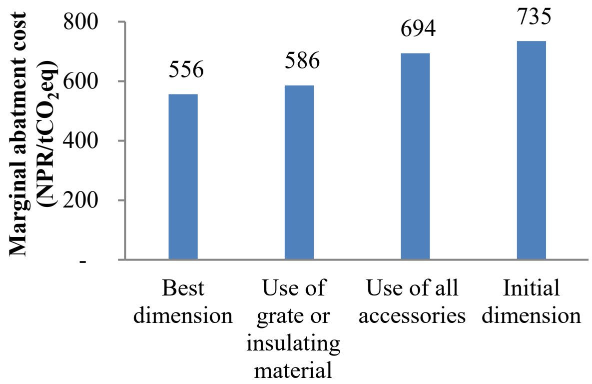

Figure 13: Marginal adaptation cost of different efficiencies cookstove

Following are the conclusion from the study

- Thermal efficiency has been found to be 18% at optimum firepower of 4.45 kW, i.e., 1.2kg/h feeding rate for the existing cook stove.
- At best dimension of air fuel inlet opening of 148cm^2, combustion chamber height of 20cm, entry area of interconnecting tunnel 56.95cm^2 and chimney height of 113cm, thermal efficiency has been found to be 19.45%, 21.93%, 19.46%, 18.16% respectively.
- Thermal efficiency of cookstove at best possible dimension has been found 22.44% and 25.6% for the use of grate, insulating material and narrow channel; i.e., 7.60% increment from existing design.
- Net benefit has been increased from NPR 16,569 to 23,619 with comparison to traditional cookstove with increased thermal efficiency from 17.99% to 25.60%.
- Marginal abatement cost of cookstove has been found lowest NPR 556 tCO_2eq for best dimension cookstove and highest for 735 tCO_2eq for initial dimension cookstove.

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