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Performance Study of an Advanced Micro-gasifier Stove with Coconut Shell

D. Sakthivadivel [1*], P. Ganesh Kumar [2], V. S. Vigneswaran [2], M. Meikandan [3], S. Iniyan [2]

[1] *School of Mechanical Engineering (SMEC), Vellore Institute of Technology (VIT) University*, Vellore, Tamil Nadu, INDIA
[2] *Institute for Energy Studies, Department of Mechanical Engineering, CEG campus, Anna University*, Chennai, INDIA
[3] *Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Avadi*, Chennai, INDIA

*__Corresponding Author:__ sakthi2energy@gmail.com

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ABSTRACT

In this paper, an attempt has been made to study ACS IES-15 micro-gasifier stove tested with Coconut shell. The testing procedure followed to evaluate the performance of the stove is as per the standard protocol WBT 4.2.3, and the results are analysed in terms of thermal efficiency, firepower, specific fuel consumption, turndown ratio and specific energy consumption. It was found that the thermal efficiency of fixed bed advanced micro-gasifier cook stove ACS IES-15 is 36.7±0.4%. Experiments have also been accomplished to provide data to investigate the performance parameters of the new stove. Prominently the turndown ratio was found to be 3.3 shows better control on the combustion of new stove. Economic analysis of the stove reveals better pay back period for coconut shell.

Keywords: micro-gasifier stove, coconut shell, thermal efficiency, fire power, turndown ratio

INTRODUCTION

Biomass is one of the predominant renewable energy re-sources existing all over the world. It plays a vital role in meeting the energy demand of developing countries. Biomass from agricultural waste and woody constituents are widely used as feed stock for energy (Vamsee et al., 2012). Almost 3 billion people (nearly 40%) of the world's population depends on the traditional use of biomass for cooking and about half of these people live in developing countries like India, Brazil and Africa. Burning of biomass releases heat as well as significant amount of emissions in terms of particulate matter (PM) and carbon dioxide (CO_2) with incomplete combustion sometimes leading to carbon monoxide (CO) emissions. Arbex et al. (2017) described that these biomass emissions create a substantial health risk and also have a significant impact on climate change. Due to incomplete combustion of biomass fuels resulting in emission of toxic smoke, reduced combustion efficiency and poor heat transfer rate (Jessica, 2016). Thus the biomass traditional cook stoves operate at significantly lower thermal efficiency (~16%) articulates Raman et al. (2014) and emit high order pollutants than LPG and Kerosene based stoves described by Mukunda et al. (1988). Roth articulates that advanced cook stove (ACS) is the most viable option to replace the traditional cook stoves which have lower thermal efficiency and incomplete combustion (Raman et al., 2013a, 2013b; Roth, 2011). The advanced biomass forced draft cookstoves well advanced due to its increased in heat transfer rate as well as higher combustion efficiency (Jessica 2016). Eventually, fuel savings can be accomplished by ACS stove compared with ICS and TCS stoves in terms of efficiency and specific fuel consumption as indicted by Seemin Rubab and Kandpal (1996); Balakumar et al. 2015.

Table 1. Design parameters of ACS IES-15 stove

Design Parameter	Unit	Value
Heat required for cooking the food (Q_{fd})	kJ	1557
Efficiency of the cook stove (Raman et al. 2013a)	%	36
Total heat energy required from the fuel (Q_f)	kJ	4325
Total heat energy needed (Q_n)	kJ/hr	7208
Density of the fuel (ϱ)	kg/m^3	200
Calorific value of the fuel	MJ/kg	20
Fuel consumption rate (FCR)	kg/hr	0.36
Size of combustion chamber (V_{cc})	cm^3	1502
Diameter and Height of the combustion chamber	cm	D_{cc}=11.27; H_{cc} = 15.06

Commercial version of Oorja cook stove was designed by Mukunda et al. (2010) with an efficiency of about 50% and, followed by Varun kumar (2012) has conducted a detailed analysis on Oorja stove by maintaining constant air fuel ratio for varying air flow rates. Jan Alders (2007) and M/s Philips has developed a forced draft cook stove and some experiments were also been reported by Raman et al. (2013a).

In this paper a novel advanced micro-gasifer cook stove (called ACS IES-15) is proposed with an optimum tilted secondary air injection of 45º into the combustion chamber (Sakthivadivel and Iniyan, 2017; Sakthivadivel et al., 2017, 2019). In this study a new approach is introduced in order to achieve the higher fuel burning rate, higher fire power and low specific fuel consumption. The thermal efficiency, specific fuel consumption, fire power and turn-down ratio of newly developed ACS IES-15 cook stove are presented in detail. Furthermore the economic analysis of ACS IES-15 stove is elaborated.

DESIGN AND EXPERIMENTAL SETUP

Biomass gasification is the conversion of solid biomass fuel into combustible gasses like CO, H_2, and CH_4 by thermochemical conversion with presence of limited oxygen and hydrocarbon in the fuel (Claus et al. 2000). The fabrication of ACS IES-15 stove using low-cost materials is as per the theoretical design presented in **Table 1** (Panwar and Rathore, 2008; Sakthivadivel and Iniyan, 2018a, 2108b, 2019).

Specific Fuel Consumption (SFC)

Total amount of fuel required to perform the cooking process of boiling water in WBT 4.2.3 test is called specific fuel consumption. This can be represented in a simplified equation given by Raman et al. (2013a) as follows:

$$SFC = \{\frac{[75/(Tboil - Tstart)] \times [Massmw \times (1 - MC) - Massfwe] - 1.5 \times Masschar}{Masswaterremaining}\} \quad (1)$$

where, Mass of fuel wood used to vaporise the water can be written using the following equation:

$$Massfwe = \{\frac{[Massmw \times MC \times 4.186 \times (Tboil - Troom)] + 2257}{NCVfuel}\} \quad (2)$$

Specific fuel consumption (kg) is the amount of fuel required to boil (or simmer) 1kg of water. Factor of 75 is the standard temperature increase from starting temperature to local boiling temperature.

Thermal Efficiency

Thermal efficiency is an amount of the heat liberated by the fuel and subsequently transferred to the water in cooking vessel. The rest of the energy is wasted into the atmosphere (Lizette et al., 2018; WBT, 2014). The formula used to calculate the thermal efficiency is given in equation 3 as follows:

$$\eta th = \{\frac{[4.186 \times (Pwi - Pwf) \times (Twf - Twi)] + (2257 \times Wv)}{fwd \times NCVfuel}\} \quad (3)$$

Characterisation of the fuel

The developed ACS IES-15 stove is tested at Institute for Energy Studies (IES), Anna University, Chennai, Tamil Nadu. Also, the performance test is conducted using coconut shell as fuel. Coconut shell is taken as a fuel for this study because it delivers higher fire power (W) than any other biomass solid fuels. The local name of Coconut shell sold in the fuel wood market is 'Kottankuchi or Thotti or Serattai' in the state. Cost of coconut shell is approximately ₹5000 per ton (Raman et al., 2013a). The proximate and ultimate analysis of the coconut shell fuel used in this experiment is presented in **Table 2**. Based on the selection of the species for combustion, the

Table 2. Physical and thermal properties of Coconut shell fuel

Characteristics	[a]Coconut shell	Standard
Size (cm^3)	7.5× 4.1 × 0.2	--
Bulk Density (kg m^3)	610±20	--
GCV (MJ/kg)	17.37±1.2	ASTM E711 - 87
Moisture content (%)	10±0.01	ASTM E871 - 82
Volatile Matter (%)	72.05±0.85	ASTM E872 - 82
Ash content (%)	0.59	ASTM D1102 - 84
Fixed Carbon (%)	17.34	By difference
Carbon (%)	45.84±0.01	ASTM E777 - 08
Hydrogen (%)	5.51±0.02	ASTM E777 - 08
Nitrogen (%)	0.36±0.03	ASTM E778 - 08
Oxygen (%)	47.58±0.06	By difference
Sulphur (%)	--	--

[a]The mean value ± standard deviation for three determinations

proximate and ultimate analysis of the fuel was carried out in terms of the following procedure specified by ASTM standards (Refer **Table 2**).

The proximate analysis was carried out using muffle furnace and weighing balance while the ultimate analysis was achieved through an organic elemental analyser (Thermo Scientific Flash, 2000). The oxygen content was established by difference method as proposed by ASTM standard. The calorific value was estimated by igniting 1 g pelletized sample in an oxygen bomb calorimeter under adiabatic conditions. The results shown in **Table 2** are attained by conducting the experiment in the laboratory on dry basis.

The secondary air inlet in the combustion chamber is tilted to an angle of 45º to ensure better turbulence during volatile combustion and even during char burning mode (Sakthivadivel et al., 2017; Sakthivadivel and Iniyan, 2018a, 2018b).

EQUIPMENTS AND IN ACS IES-15 STOVE

Combustion Chamber

The secondary air injection profile is modified as per the design in the newly developed combustion chamber (Sakthivadivel et al., 2017). The material used for fabricating the combustion chamber is carbon steel. The carbon steel sheet of thickness 2 mm is bent into circular shape and two ends are joined together by welding. Similarly, the inner cylinder is also settled and both cylinders are arranged concentrically, they are joined using another strip of metal by welding. Also, cylindrical combustion chamber is placed 10 cm from the base of the combustion chamber to hold the fuel. The primary and secondary air inlets of diameter 0.3 and 0.4 cm respectively are drilled in the combustion chamber.

The thermal lining material is prepared with a mixture of vermiculite matter (93%), glass wool (2%) and cement (5%) by weight and the composite insulation is filled in the gap between the two layers of the combustion chamber. The thermal conductivity of this mixture is determined to be about 0.0472 W/m.K (Sakthivadivel and Iniyan, 2018a) by conducting thermal conductivity test as directed by BIS standard IS 9489 (BIS 2015). Care is taken to make sure that there are no obstructions due to the thermal lining material in the primary and secondary air path. Subsequently, the insulated combustion chamber is ready to be made into the stove body. The head of the stove is removed and the combustion chamber is placed inside to complete the arrangement of the ACS IES-15 stove. **Figure 1** shows the schematic view of the combustion chamber and experimental setup.

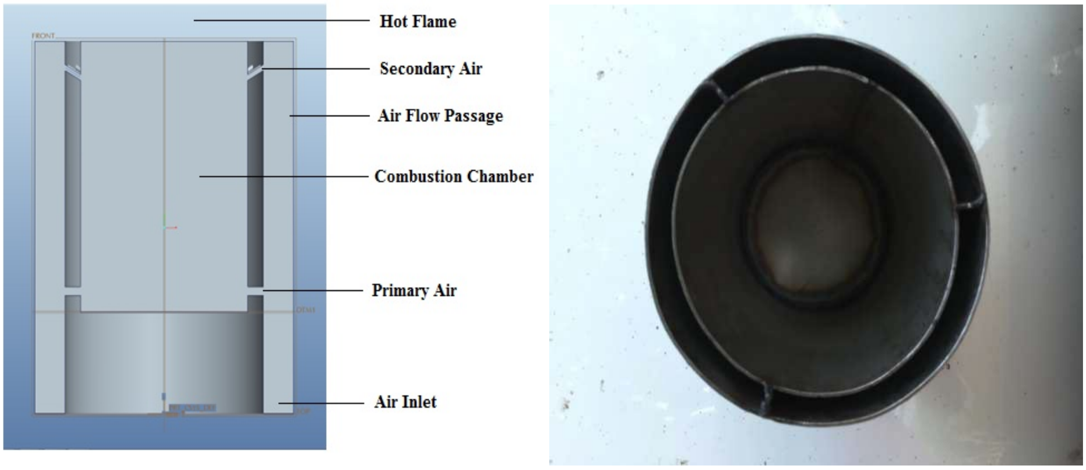

Figure 1. Model of (a) Schematic view of the experimental setup (b) combustion chamber

Table 3. Performance of ACS IES-15 stove with Coconut shell fuel

Phase	Fuel Burning Rate (g/min)	Efficiency (%)	Fire Power (W)	Specific Fuel Consumption (g/L)	Turn Down Ratio (TDR)
Cold	23.9	34±1	7349	65	
Hot	28.7	35±1	8804	66.5	**3.3**
Simmer	7	41±1.5	2217	83.6	

RESULTS AND DISCUSSION

Once the gasifier stove is ignited by spreading kerosene on the top of the fuel bed, the gasification and combustion begins and flame front propagates continuously into the bed by supplying of the heat released from the volatile gas reactions and char oxidation. The whole process comprises of sub-stoichiometric high-temperature oxidation and reduction reactions between the solid biomass fuel and an air (oxidant). These high-temperature combustible producer gasses are burnt at the top of the fuel bed with excess air (secondary air) supply.

The performance parameters and the thermal efficiency are calculated using WBT 4.2.3 standard protocol. A mercury column thermometer was used to measure the water temperature. A digital weight balance was used to measure the amount of water and wood spent during the water boiling experiment. The accuracy of the digital weight balance equipment used in the experiments is 5 g. All the values related to the performance parameters of the cook stoves like fuel burning rate, fire-power, specific fuel consumption, specific energy consumption and turndown ratio for three different testing methodologies called cold start, hot start and simmering are projected in **Table 3**.

Fuel Burning Rate

The observations made from **Table 3** that fuel burning rate (FBR) during the high-power phases are comparatively higher than simmering phase. Although the FBR during the low power phase is less when compared to the high-power phases, the duration of the simmering phase is much longer than the high-power phases. Therefore the total energy consumed during the simmering phase is much higher than the high-power phases.

Table 3 shows that there is a considerable variation in the burning rate during cold start and hot start but in simmering phase, it is almost constant for all replicated tests. The reason is due to the regulated air supply into the combustion chamber for better combustion as discussed by Raman et al. (2013a). Varunkumar (2012) established that FBR increases with decrease in the ratio of combustion to gasification flow rates. In order to maintain the stoichiometric condition, the primary air was increased without changing the total flow when the transition to char mode. A significant parameter of this mode of operation is preserving a fraction between the amounts of combustible producer gasses and the primary air supplied for gasification. Here, an attempt is made to achieve stoichiometric condition without changing the air flow rates. Hence, the proper supply of secondary air leads to the higher burning rate and firepower as shown in **Table 3**. Therefore, the average fuel burning rate of using coconut shell as fuel for ACS stove is about 19.8 g/min. The burning rate of the fuel differs with the calorific value of fuel used and the way of air injected into the combustion chamber.

Thermal Efficiency of the Stoves

When coconut shell is used as a combustible fuel, the thermal efficiency of the ACS stove is found to be about 36.7±0.4% after conducting three replicated tests. The temperature of the water is continuously monitored using thermometer during all the three phases of WBT test. It can be noticed that the time taken to boil 5 Liters of water is 13 min for ACS stove during cold start condition. However, during the hot start, ACS stove takes about 11 min to boil 5 Liters of water. Eventually, the temperature of the water is maintained between 95-97 ºC for 45 min during the simmering phase for ACS stove as suggested by WBT 4.2.3.

Specific Fuel Consumption

Specific fuel consumption ACS IES-15 cook stove during high power (cold start and hot start) and low power (simmer) are shown in **Table 3**. The average SFC of ACS IES-15 cook stove was 71.7 g/L. During cold start and hot start the cook stoves consumed the same amount of fuel unlike simmering phase. During cold and hot start more than 75% of the combustion chamber is loaded. The inner hot surface of combustion chamber with uniform air-fuel mixing due to turbulence causes better fuel burning rate and firepower provides low SFC. Since the combustion chamber is half loaded in simmer phase the 45° air injection and the inner surface of hot combustion chamber provide better SFC (Sakthivadivel and Iniyan, 2017). Meanwhile, this leads to the increase in specific fuel consumption and higher efficiency and low fire power.

Firepower

The firepower of the cook stove increases with increase in calorific value of the fuel. This increase in fire-power is due to an increase in the fuel burning rate of the fuel, as a result, there is an increase in temperature inside the combustion chamber. The flame temperature of an advanced micro-gasifier stove is ranges between 800–1000 °C. Whereas the flame temperature of the conventional cook stove is in the range of 700–800 °C (L'Orange, Volckens, and De-Foort, 2012). Hence, if the flame temperature of the stove increases the heat transfer rate increases, results in higher efficiency of advanced micro-gasifiers stove is achieved than the improved and traditional stoves.

In this study, coconut shell is taken as the fuel since it has higher order of calorific value than all other biomass solid fuels available in the market. While burning of coconut shell delivers more firepower in TERI SPT-0610 cook stove than Philips and Oorja plus stoves as discussed by Raman et al. (2013a,b). From **Table 3**, it is evident that the ACS IES-15 cook stove delivers more firepower in high power and low power phases. As a result, the average thermal efficiency of ACS stove is higher than prescribed limit of MNRE (more than 35%) also compared with TERI SPT-0610 (Raman et al. 2013a). Meanwhile, there is a significant improvement in efficiency at low as well as high power test of ACS stove (Refer **Table 3**).

During simmering phase, the temperature of the water should be maintained between 95-97 °C. So the fuel feeding is limited to half feeding and only about 50% of the combustion chamber (by volume) is filled with fuel. Due to 45° of the secondary air supply in ACS IES-15 stove, easy mixing of air and producer gas is achieved on the top of the fuel bed. The proper supply of air and producer gas forms a uniform combustible mixture that provides clean combustion with high efficiency (Sakthivadivel and Iniyan, 2017).

Turndown Ratio

The turndown ratio is a measure which controls the fuel saving during real cooking conditions. Raman, Ram and Ruchi Gupta (2014) reports that the higher value of TDR specifies a higher ratio of high power to low power, and could indicate a greater range of power control in the stove. The period of the simmering phase is nearly four times more than the duration of the hot-start phase. Hence, the ACS IES-15 stove having a high thermal efficiency (36.7±1%) and high TDR (3.3). However, the value of TDR only reveals the power control of the cook stove.

Specific Energy Consumption

The specific energy consumption of the developed cook stove was evaluated by observing the amount of fuel consumed during the three phases of WBT 4.2.3. It is witnessed from the **Figure 2** that high specific fuel consumption is found during simmering phase due to constant energy supply needed to maintain the temperature of the water between 95- 97 °C. The total energy consumed during the high power phases are very low when compared to the low power phase can be literally seen from the **Figure 2**. The reason is that the constant power is delivered during the simmer phase for four time's longer duration than cold start and hot start.

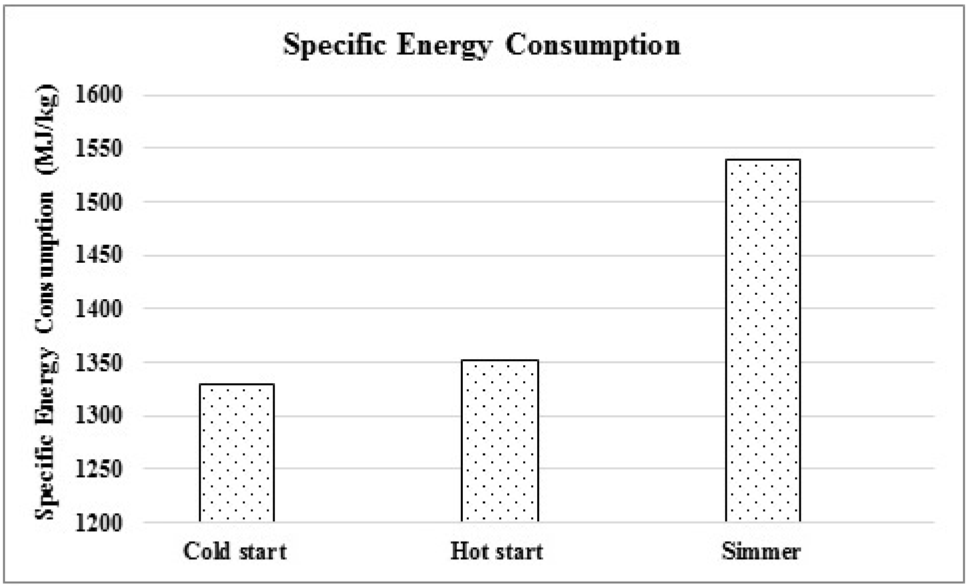

Figure 2. The specific energy consumption of the developed cook stove

Table 4. Economics of the stove

Parameter		Unit	Quantity
Investment cost of ACS stove		$	70
Investment cost of TCS stove		$	6.2
Cost of coconut shell (Raman et al. 2013a)		$/kg	0.08
Fuel required for four members of a family	ACS stove	kg/month	70
	TCS stove	kg/month	260
Simple Payback Period		months	4

ECONOMICS

Economic analysis is one of the major considerations when it is essential to compare the different cooking options. The economic analysis used in this section is based on the data obtained during the real cooking conditions and some data like fuel price are taken from the previous studies of different authors are cited below. In this study, we used to project the simple payback period (SPP) alone for the microeconomic analysis. The main objective of computing SPP is to predict the time period required for the reoccurrence on an investment cost to repay the cumulative sum of actual outlay. The higher level of profitability can be expected, if SPP is shorter. The following equation (4) is used to calculate the SPP:

$$SPP = \frac{(C_{acs} - C_{tcs})}{S_t} \tag{4}$$

CONCLUSION

This study illustrates the performance of a newly developed ACS IES-15 stove is analysed based on the thermal efficiency, firepower, specific fuel consumption, turndown ratio and specific energy consumption. The following are the important deliberations attained from the study are

- The thermal efficiency of the ACS IES-15 stove is 36.7±0.4% with a simple payback period of 4 months.
- The ACS IES-15 has more firepower during cold start, hot start than simmer phase for coconut shell fuel.
- The specific fuel consumption of simmering phase is very high than that of cold start and hot start due to the constant energy supply required to maintain the suggested temperature.

Therefore it has better robustness, low cost, and meets the needs of domestic energy requirement.

Nomenclature

Q_n	Energy needed (MJ h^{-1})
T	Duty hour
GCV	Gross calorific value (MJ kg^{-1})
NCV	Net calorific value (MJ kg^{-1})
FCR	Fuel consumption rate (kg h^{-1})
ηg	Gasification efficiency
Dcc	Reactor diameter (cm)
Hcc	Reactor height (cm)
SGR	Specific gasification rate (kg m^{-2} h^{-1})
ϱ_{wood}	Wood density (kg m^{-3})
$Mass_{char}$	Mass of the remaining charcoal after conducting
$Mass_{fwe}$	Mass of the fuel wood used to evaporate water
$Mass_{mw}$	Mass of the moist wood
$Mass_{water}$	Remaining mass of water remaining in the pot at the end of the test
$M_{water, i}$	Initial mass of water with pot (grams)
$M_{water, f}$	Final mass of water with pot (grams)
MC	Mass fraction of moisture content of the fuel on wet basis
T_{boil}	The local boiling temperature of water (°C)
T_{room}	The air temperature in the room (°C)
T_{Start}	Starting temperature of the water (°C)
T_{wi}	Water temperature before test (°C)
T_{wf}	Water temperature after test (°C)
W_v	Mass of water vaporized (grams)
C_{acs}	Investment cost of an ACS (₹)
C_{tcs}	Investment cost of a TCS (₹)
S_t	Saving in spending for fuel wood during period t (₹ /month)

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