



Performance Evaluation of a Biomass Cook Stove with Variation of Chimney Height and Air Intake System

Md. Tarek Ur Rahman Erin^{1✉}, Md. Mizanur Rahman², Rezwan us Saleheen²

¹ Textile Engineering College, Zorargonj, Mirsarai, Chattogram, Bangladesh

² Department of Mechatronics Engineering, World University of Bangladesh, Dhaka-1205, Bangladesh

Received June 22, 2021

Revised November 6, 2021

Accepted November 6, 2021

Published online: May 24, 2022

Keywords

Chimney height

Air intake

Thermal efficiency

Harmful emission

Abstract: Biomass cook stove is one of the conventional methods of cooking in rural households and industries. Typical stove designs presume inefficient combustion processes along with harmful emissions. Subsequently a more efficient design of biomass cook stove has been a foremost research interest for scientists during the last decades. The study focused on enhancing the combustion process altering the key parameters of a biomass cook stove i.e. height of the chimney and the air intake port opening. From the study, it is found that height of the chimney and the air intake port opening is very influential on the performance characteristics of the biomass cook stove. For estimating the comprehensive performance of the improved biomass stove water boiling test (WBT) was carried out for varied chimney heights (95 cm, 80 cm, 65 cm & 50 cm) & varied air intake port opening (40%, 60%, 80% & 100 %). At chimney height of 80 cm & fully air intake port opening, optimum thermal efficiency has been found to be 33.76%, 33.79%, respectively. The highest concentration of CO was identified around 23 ppm during the 40% opening of the air intake port and it minimized to 9 ppm as the air intake port opened fully. Both the values for CO₂/CO and indoor air quality were within acceptable limits.

© 2021 The authors. Published by Alwaha Scientific Publishing Services, ASPS. This is an open access article under the CC BY license.

1. Introduction

Energy implies an indispensable contribution to life and all living organisms. For a more equitable and sustainable world, energy is needed in all sectors of life (Permana et al. 2012). Household energy consumption is a distinct requirement among all the utilizations specially used for cooking (Sagouong & Tchien, 2018). Reducing the energy consumption in household applications has a remarkable influence on both society & environment. Even now in the countryside throughout the world, most people use biomass for preparing their daily meal (Modi et al. 2005). An estimation illustrates that about 2.6 billion

people will be depending on the usage of biomass energy by 2030. In many countries nearly 50% of household energy consumption and 95% indigent countries use biomass as energy source for their daily needs (Ezzati et al. 2002). Many developed countries show their interest in renewable energy sources rather than using fossil fuels for a cleaner & healthy environment but the real scenario is not so satisfying (Adane et al. 2021). Generally, Biomass stove is the implementation of the energy conversion from fuel to heat through the combustion process. Such a combustion process of biomass initiates heat and fire in the stove are useful for cooking purposes (Lombardi et al. 2017). Traditional stove design involves some several drawbacks

✉ Corresponding author. E-mail address: tarekerin@gmail.com

that are widely used by the locality. The thermal efficiency is an estimation of the energy savings capability of a stove which is influenced by the fuel burning operations. There are some other parameters i.e. temperature, airflow and turbulence. These have huge impact on the thermal efficiency of a biomass cook stove (Surjosatyo & Ani, 2011). Harmful releases like particulate matter (PM) and carbon monoxide (CO) are generated in the cooking process on a biomass cook stove. Besides, in imperfectly ventilated space there is a risk of initiating fires and contamination in the air quality. Such contamination in the air quality is extremely threatening, initiating risks of acute respiratory infections and lung cancer to those who spend time in cooking and wandering around them.

In order to fabricate a cook stove, expertise on parameters related to the cook stove is needed. Several demonstrations of enhanced biomass cook stoves improved the efficiencies nearly 12% to 35%. Several investigations suggest that the biomass cook stove's behaviour greatly depends on air passages. In this current work, following design criteria have been analyzed & considered to enhance the previous design of a biomass cook stove:

1. Upgradation of combustion process by ensuring the sufficient air presence in the combustion chamber.
2. Decrease the amount of air contamination by the modified design of biomass cook stove.

Thermal System and energy conservation sectors enhanced with several analytical and experimental studies during the last decade (Sagouong & Tchuen, 2018). Investigations were carried out in search of an optimum system to embrace the challenges for useful energy consumption, sustainable development or climate change. Wood-burning cook stove is one of the antiquated additions in energy management but even it requires some modification to cope up with the latest demand. Along with the economic and environmental considerations, another focal improvement required for the wood stove is the health factor (Probst et al. 2021). A mud stove named as the Kilakala having capacity of operating at a 30% reduced fuel rate was demonstrated by Sokoine University, Tanzania. Though it was made utilizing local materials it did not provide sufficient illumination (Crewe et al. 1990). The Kenya Ceramic Jiko (KCJ), developed an efficient urban stove project which is disseminated throughout Kenya (Varunkumar, 2012). Through the Eastern African region, nearly 25-40% useful heat is gained of the total heat

generated. It indicates that a huge development has been achieved in terms of waste heat utilization in biomass cook stoves.

The idea of chimney implementation in the cook stove was explained by Winiarski (Bryden et al. 2002). He suggested that by incorporating a chimney in the cook stove can enhance the combustion process as well as heat transfer efficiency (Wazir et al. 1980). Stone and Shelton illustration shows the features of gas emitted against different height of the chimney (Smith et al. 1993). Substantially all over the developed regions implies a ventilation system for almost every solid fuel combustion system operating from indoor domain to fetch combustion by-product (Smith et al. 1993).

Moreover, several researches were carried out prioritizing the design of a more efficient chimney along with a stove considering the environmental issues (Boy et al. 2002). The investigations suggested that the chimney has a huge impact on both cook stove performance & environment. A chimney can alter the performance of a cook stove considerably. The researchers also numerically analyzed the cook stove to evaluate the cook stove performance (Baldwin, 1987).

Makonese & Bradnum (2018) investigated on six designed variants of the biomass stove to reduce the fuel consumption and pollutant emissions. Their work suggested that better performance was shown by the larger hopper stoves regarding thermal & emission criterion. Their work also showed that stoves with large hoppers consumed more fuel resulting in higher fire power (Makonese & Bradnum 2018).

Among all the previous work, only variation in chimney height is reviewed to evaluate the cook stove performance. In this work, effects of both height of the chimney and the air intake port opening are studied on the performance of a biomass cook stove. Besides, air pollution generated by cook stoves is studied in this work. Hence for a more efficient stove design, the outcome of height of the chimney and the air intake port opening has been analyzed throughout the work.

Several variables that assist proper combustion with less impurities in air could theoretically be influenced by chimney height & opening of air intake port. The objective of this current work is to give clearer insight into the outcome of height of the chimney & opening of air intake port on the evaluation of biomass cook stove & flue

gas properties. The study also aimed to evaluate the biomass cook stove for energy and heat utilization, specific fuel consumption, burning rate and emission performance.

2. Methodology

An economic biomass cook stove heated by wood is to be developed precisely designed for the rural communities of the developing world. The design emphasizes on improving emissions & thermal efficiency. The output of the cook stove largely depends on the chimney height & air intake port opening. In this work, a relative analysis among different chimney heights and air intake ports were carried out in order to evaluate the cook stove performance. To overcome the flow of frictional obstacles, a chimney with a certain height needs to be employed. For a better combustion process, excess air is required to acquire an adequate amount of oxygen (Karekezi, 1991). However excess air will generate unnecessary heat that escapes through the chimney. Besides, the contamination of air can be lessened by utilizing chimneys (Varunkumar, 2012). This investigation focused on determination of optimum height of the chimneys along with the air opening port of the biomass cook stove.

For varied height of the chimney and air intake port opening investigation was carried out by water boiling test (WBT) to evaluate stove performance. It is actually a laboratory-based test to estimate the fuel efficiency and the amount of emissions generated while cooking. For selecting proper design of the cook stoves, WBT is conducted for cook stove operating states comprising of high power and low power phase. High power consists of cold start and hot start while low power is called simmer.

- Cold start: In this phase, the test begins with the stove at room temperature and water temperature elevates to saturation temperature i.e. 100°C.
- Hot start stage: This stage follows immediately after the first test while water temperature elevates to saturation temperature i.e. 100°C from room temperature.
- Simmering phase: The third phase follows immediately from the second phase. In this stage, the amount of fuel required is measured while maintaining the water temperature just below the saturation point.

Several features of the stove's performance can be evaluated by all these phases of tests. Nevertheless,

only thermal efficiency of the stove can't specify the overview of stove performance. Researchers may perceive different outputs in the context of their stove program i.e. thermal efficiency, burning rate; and specific fuel consumption.

For improving the fuel economy & emission control, fuel analysis plays an essential role. Parameters that are commonly investigated through flue gas analysis include:

- Oxygen (O₂)
- Carbon Monoxide (CO)
- Exhaust gas temperature
- Draft

Some techniques are prescribed by the American Society for Testing to assess the wood's moisture content. Oven-dry test is carried out to assess the wood's moisture content in this work (Zambrano et al. 2019).

2.1. Design Analysis

The stove (Figure 1) is circular in section and generally comprises of a combustion chamber and chimney. The stove integrates combustion chamber of L-shaped and vertical internal chimney. At the base, an opening port for supplying fuel wood & air is attached. Whereas four refractory rings are incorporated to assist various sizes of pot.

Mild steel is used to construct the chimney which is assembled at the upper portion of the stove to move out flue gas and other by-products of combustion. Draft is created by chimney through which combustion gases accelerate & move upward.



Fig. 1. Construction of Biomass Cook Stove.

Table 1: Structural details of biomass cook stove.

Combustion chamber Height	40 cm
Combustion chamber Radius	10 cm
Mild steel casing radius	20 cm
Height of stove base	40 cm
Radius of chimney	3.5 cm
Height of chimney	95 cm

Data found on the basis of mass analysis of typical fuel wood (Tran & White, 1992) & from the study (Parker et al. 1969) it is found that for evaluating chimney diameter following relation is used: $a_c \leq 10A_{air}$,

In this study, the Initial diameter of the chimney is 7 cm. Structural details of biomass cook stove are listed below (Table 1).

3. Result Analysis

Performance analysis for the biomass cook stove is obtained including the comparison among various values of chimney heights and opening at the base of the biomass cook stove. Performance data of biomass cook stove can be obtained using mathematical Equations (See Table 2).

3.1. Flue Gas Properties

For attaining optimal combustion, flue gas analysis is performed by inserting a probe into the flue of the chimney. In order to minimize the contaminations of flue gas i.e. carbon monoxide (CO), carbon dioxide (CO₂), oxygen (O₂), and particulate matter, flue gas analysis of a biomass cook stove is mandatory.

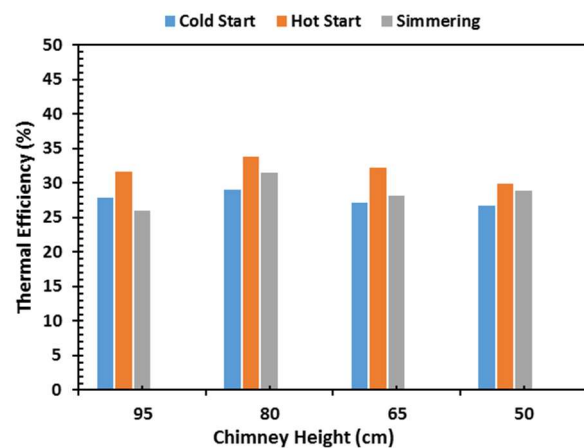
The outcome of height of the chimney and the air intake port opening have been analyzed throughout this work by governing the water boiling test (WBT). Analyzing test results, the effect of these parameters are disclosures through graphical representation.

Table 2: Mathematical equations for obtaining performance data of biomass cook stove.

i. Thermal efficiency, h_c	$h = \frac{4.186(T_2 - T_1)(P_1 - P) + 2260.W_p}{f_d \cdot LHV}$
ii. Burning rate, r_b	$r_b = \frac{f_d}{\Delta t}$
iii. Specific fuel consumption, SC	$SC = \frac{f_d}{W_r}$

i. Thermal efficiency is a key parameter to evaluate the performance of a biomass cook stove. Figure 2 illustrates the analysis of the biomass cook stove's thermal efficiency with respect to cold start, hot start and simmer phase for variation in height of the chimney. As the height of the chimney minimizes (from 95 cm–50 cm), thermal efficiency of the biomass cook stove minimizes (from 33.76%–29.19%) except for the chimney height of 80 cm. As the chimney height minimizes, natural draft produced by the chimney minimizes. For maximum chimney height (95 cm) due to high natural draft air the generated heat can't be utilized and the amount of fuel consumption increases. 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 occurs (Darlami et al. 2019). From the experimental results, it is found that the optimum thermal efficiency obtained is 33.76% for chimney height of 80 cm. Furthermore, from figure 5, it is seen that as the air intake port opening increases (40%–100%), thermal efficiency of the biomass cooking stove increases (28%–33.79%) due to increased presence of air for more opening of air intake port.

ii. Figure 3 provides an overview of biomass cook stove's burning rate of for individual heights of the chimney. In general, the burning rate is approximately taken as the mass loss rate of fuel. Burning rate completely depends on the complete combustion. As with increased levels of air presence, air fuel mixture is so uniform in the combustion chamber which tends to create more complete combustion. From the test result, it is seen that as the chimney height minimizes, burning rate also minimizes. It is found that the burning rate is between 10.23 grams/min and 12.16 grams/min. Here, lowest burning rate (10.23 grams/min) is

**Fig. 2.** Thermal efficiency of biomass cook stove.

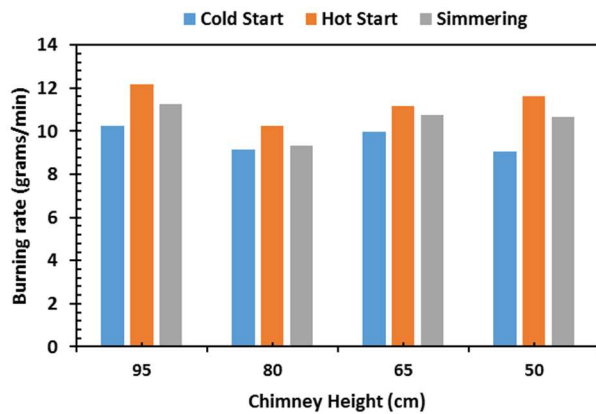


Fig. 3. Burning rate of biomass cook stove.

found for 80 cm chimney height where maximum thermal efficiency (33.76%) is obtained. Figure 5 illustrates the burning rate for the air intake port opening. It is seen that as the air level increases, the biomass cooking stove's burning rate slightly increases. For fully air intake port opening (100%), burning rate becomes 10.9 grams/min.

iii. Specific fuel consumption is the amount of burning wood required to evaporate the water. Figure 4 illustrates the overview of specific fuel consumption for varied height of the chimney. From the test result, it is found that with the increase in chimney height Specific fuel consumption

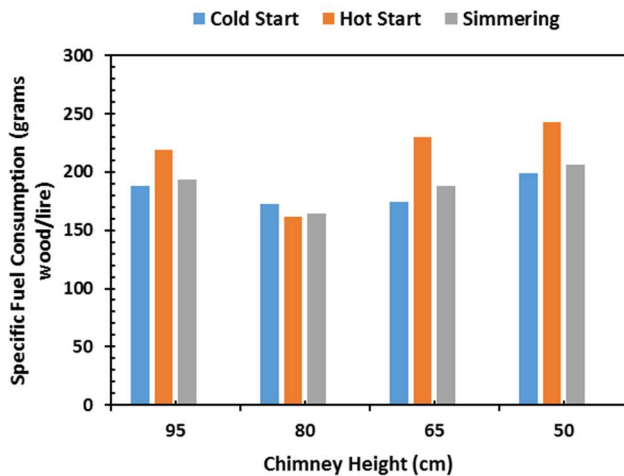


Fig. 4. Specific fuel consumption of biomass cook stove.

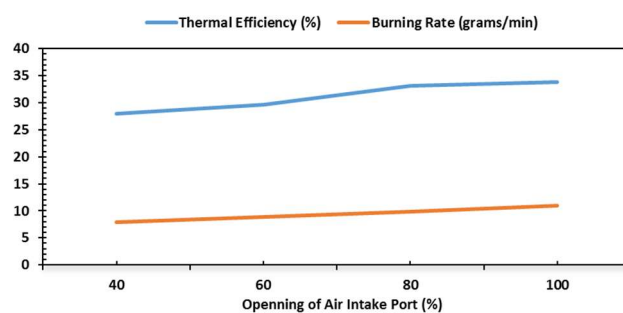


Fig. 5. Thermal efficiency & burning rate vs opening of air intake port.

reduces. For 80 cm chimney height, specific fuel consumption is minimum (161.97 grams' wood/ litre). It is because as the cook stove becomes more thermally efficient against the varied height of the chimney, the amount of specific fuel consumption minimizes.

iv. The general relationship between the concentration of CO in the flue gas with the height of the chimney & air intake port opening is represented in Figures 6 and 7, respectively. Thermal efficiency has a great impact on flue gas properties. Fuel consumption minimizes as the thermal efficiency of the biomass cook stove rises which leads to less time and less exposure to CO emission. incomplete combustion generates higher particulates and carbon emissions which are hazardous to health. From the test results, it is found that the maximum CO level is 23 ppm for 40% opening of the air intake port which tends to lessen (9 ppm) for fully open air intake port. It is because with the increased air presence in the combustion chamber, the generation of CO molecules minimizes abruptly. The reason behind this is excess presence of O_2 atoms which contribute to the formation of CO_2 from CO.

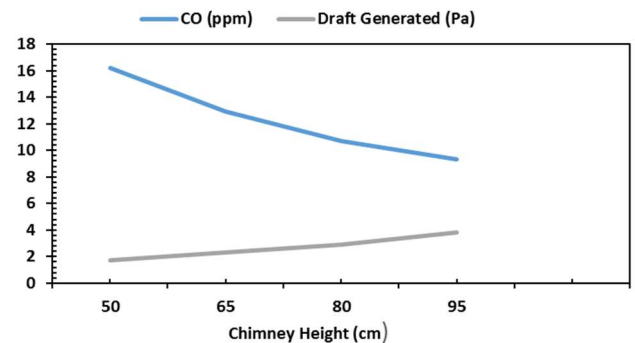


Fig. 6. CO (ppm) of flue gas & draft generated (pa) vs height of the chimney.

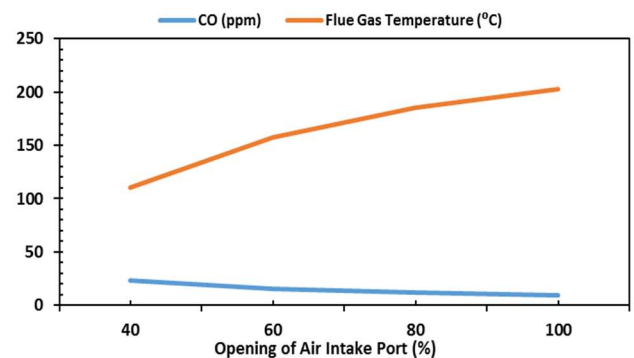


Fig. 7. Flue gas temperature (°C) & CO (ppm) vs air intake port opening.

4. Conclusion and Future Work

A biomass cook stove is fabricated and investigated for thermal and emissions performance analysis employing the standard water boiling test (WBT) & flue gas analyzer. The consequences of the WBT studied and their graphical representation illustrates that height of the chimney and air intake port have an underlying impact on the thermal efficiency which again, has considerable impact on CO emission in the cold start, hot start and simmering phase. The biomass cook stove with higher height of the chimney & air intake port opening exhibit better performance regarding thermal and emissions variables. At chimney height of 80 cm & fully air intake port opening, optimum thermal efficiency has been found to be 33.76% and 33.79%, respectively. Furthermore, specific fuel consumption rates become lower (87.4 grams' wood/ liter) in chimney heights of 80 cm giving increased thermal efficiency. Fuel consumption minimizes as the thermal efficiency of the biomass cook stove rises which leads to less time and less exposure to CO emission. At chimney height of 95 cm & fully air intake port opening, CO emission has been found to be 9.3 ppm and 9 ppm, respectively which are within acceptable limits.

In forthcoming Parameters i.e. combustion chamber, diameter of the chimney, mass flow rate and fuel properties which have a significant effect on the evaluation of biomass cook stove should be analyzed. Thereby, additional research work should be implemented regarding biomass cook stove performance analysis considering following observations:

- i. With proper installation, thermal efficiency of biomass cook stove can be enhanced. Insulation will minimize the rate of heat loss in the combustion chamber wall by conduction.
- ii. Electrical cogeneration can be incorporated into the stove design for better implementation of newer technology to ease our lives.

Nomenclature

T_1	Water temperature at start of test, °C
T_2	Water temperature at end of test, °C
Δt	Time duration of the test, min
P_1	Mass of pot of water before test, kg
P	Mass of pot, kg

W_v	Water vaporized, kg
f_d	Equivalent dry wood consumed, kg
LHV	Lower Heating Value of wood, J/kg
W_r	Effective mass of water boiled, kg
a	Cross-sectional area of the combustion chamber.

Disclosures

Free Access to this article is sponsored by SARL ALPHA CRISTO INDUSTRIAL.

References

- Adane, M.M., G.D. Alene, S.T. Mereta, K.L. Wanyonyi (2021) Effect of improved cookstove intervention on childhood acute lower respiratory infection in Northwest Ethiopia: a cluster-randomized controlled trial. BMC Pediatrics, BMC Pediatrics, volume 21, Article number: 4.
- Baldwin, S.F., (1987) Biomass stoves: engineering design, development, and dissemination. Volunteers in Technical Assistance, USA, pp. 287.
- Boy E., Bruce N., and Delgado H. (2002) Birthweight and exposure to kitchen wood smoke during pregnancy. Environ Health Perspect, 110 : 109–114.
- Brewer, J.P., A. Eldridge, P.C. Luter (2007) Chimney Fires: Causes, Effects & Evaluation. Chimney Fire Education and Research Task Force, Chimney Safety Institute of America 46168(317).
- Bryden, M., D. Still, P. Scott, G. Hoffa, D. Ogle, R. Bailis, K. Goyer (2002) Design Principles for Wood Burning Cook Stoves: Aprovecho Research Center.
- Crewe, E., (1990) Morogoro fuel wood stove project, Women Training Center, Christian Council of Tanzania, Review and Recommendations, Intermediate Technology Development Group (ITDG), Rugby, UK.
- Darlami, H.B., B.B. Ale, G.R. Pokharel (2019) Experimental Analysis of Thermal Efficiency of Mud Improved Cookstove With Variation of Different Parameters and Economic Analysis, Journal of the Institute of Engineering, Vol 15 (No. 3) : 385-392.
- Ezzati, M., D.M. Kammen (2002) The health impacts of exposure to indoor air pollution from solid fuels in developing countries: Knowledge, gaps, and data needs. Environ Health Perspect. 110(11):1057–68.
- Kammen, D.M., F. Kammen, B. (1992) Energy, food preparation and health in Africa: The roles of technology, education, and resource management. African Technology Forum 6(1): 11-14.

- Karekezi, S. (1991) The role of a stoves information network in addressing the indoor air pollution - an African perspective." Indoor Air Pollution from Biomass Fuel, Working Papers from a WHO Consultation, pp. 89-104.
- Lombardi, F., F. Riva, G. Bonamini, J. Barbieri, E. Colombo (2017) Laboratory protocols for testing of Improved Cooking Stoves (ICSs): a review of state-of-the-art and further developments. Biomass Bioenergy 98:321–335.
- Makonese, T., C.M. Bradnum (2018) Design and performance evaluation of wood-burning cookstoves for low-income households in South Africa, Journal of Energy in Southern Africa, Vol 29 No 4.
- Modi, V., S. McDade, D. Lallement, J. Saghir (2005) Energy Services for the Millennium Development Goals. New York: Energy Sector Management Assistance Programme, UNDP.
- Parker, J.D.; Boggs, J.H.; and Blick, E.F. (1969) Introduction to fluid mechanics and heat transfer. Reading, Mass., Addison-Wesley Pub. Co.
- Permana, A.D., A. Sugiyono, M.S. Boedoyo, M.A.M. Oktaufik (2012) Indonesia Energy Outlook.
- Probst, B., L. Westermann, L.D. Anadon, A. Kontoleon (2021) Leveraging private investment to expand renewable power generation: Evidence on financial additionality and productivity gains from Uganda", World Development Volume 140, 105347.
- Sagouong, J.M., G. Tchien (2018) Mathematical modelling of traditional stoves using the Thermal Network Approach. International Journal of Engineering Trends and Technology (IJETT) V58(1), 1-9.
- Smith, K.R., G. Shuhua, H. Kun (1993) One hundred million improved cookstoves in China: how was it done? World Dev 21(6):941–961.
- Surjosatyo, A., F.N. Ani (2011) Study of Enhancing the Swirl Burner Performance On a Small Scale Biomass Gasification", Int J Eng Technol, 11 04 p21–38.
- Tran, H.C.; and White, R.H. (1992) Burning rate of solid wood measured in a heat release rate calorimeter, Fire & Materials. 16(4): 197-206.
- Varunkumar, S., (2012) Packed bed gasification–combustion in biomass based domestic stove and combustion systems (Ph.D. thesis), Bangalore: Indian Institute of Science.
- Wazir, S., (1981) Evaluation of Chulas. Master of Technology Thesis in Mechanical Engineering, Indian Institute of Technology, Bombay, India.
- Zambrano, M. V., B. Dutta, D. G. Mercer, H. L. MacLean, M. F. Touchie (2019) Assessment of moisture content measurement methods of dried food products in small-scale operations in developing countries: A review. Trends in Food Science & Technology, Volume 88, 484-496.