



PERGAMON

Biomass and Bioenergy 23 (2002) 387–395

**BIOMASS &
BIOENERGY**

www.elsevier.com/locate/biombioe

Effects of selected parameters on performance and emission of biomass-fired cookstoves

S.C. Bhattacharya*, D.O. Albina, Aung Myint Khaing

*Energy Program, School of Environment, Resources, and Development, Asian Institute of Technology,
P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand*

Received 1 March 2002; received in revised form 26 April 2002; accepted 6 May 2002

Abstract

The effects of different parameters on performance and emissions of three biomass-fired stoves have been investigated. The parameters considered were moisture content of fuel, size of fuel, size of pot and method of ignition, while the selected stoves were an improved Indian stove, a Vietnamese traditional stove and an improved stove developed by the Royal Thai Forestry Department. It was found that increase in fuel moisture content resulted in decrease in stove efficiency, increase in the emission factor of CO and decrease in the emission factor of NO_x; a slight decrease in CO₂ emission factor was also observed, while emission of CH₄ was not significantly effected. The fuel size did not show any significant influence on the efficiency of the stove, however, it showed significant influence on the emission of CO for the size range investigated. The size of pan did not affect the efficiency of the stoves tested. Two methods of stove ignition—conventional bottom ignition and top ignition—were investigated. In general, emission of CO and NO_x was significantly less in case of top ignition in comparison with conventional bottom ignition. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Biomass stoves; Emission factor; Biomass combustion; Traditional cooking stoves; Improved cooking stoves; Stove efficiency; Moisture content; Fuel size; Pot size; Top ignition; Top-burning stove; Indian “Harsha” stove; RTFD stove; Vietnamese traditional stove

1. Introduction

Biomass is normally the main source of energy in the domestic sector of developing countries [1]. Even though traditional small-scale combustion of biomass degrades air quality and is thermally inefficient, the high price of cleaner substitutes and their unavailability in many locations make rapid shifts away from the use of the traditional fuels unlikely. Thus, biomass

fuels are likely to continue to meet the cooking energy needs of a majority of people in the poorer countries [2].

In order to overcome the two major drawbacks of traditional stoves, namely low efficiency and indoor air pollution, a large number of improved biomass fired stoves have been deployed in different countries. However, besides improvements in design, it is also important to understand how operation of stoves influences its performance in terms of efficiency and emission of pollutants; no serious work on this appears to have been reported in the open literature. This paper presents the results of a study on the effect of a number of parameters on the performance of three selected

* Corresponding author: Tel.: +66-2-524-5403; fax: +66-2-524-5439.

E-mail address: bhattacha@ait.ac.th (S.C. Bhattacharya).

stoves; no attempts were made to measure either the particulate or tar production of these stoves although it is recognized that particulate emission presents the most serious environmental/health problem created by stoves.

2. Experimental procedure

2.1. Stoves

The biomass stoves used in this study are an improved charcoal stove developed by the Royal Thai and Forestry Department (RTFD), the “Harsha” an improved Indian wood-fired stove and a Vietnamese traditional stove.

2.1.1. RTFD improved charcoal stove

The stove is a modified version of the RTFD charcoal bucket stove [3]. The stove is made of cement plaster with a top outside diameter of 30 cm and the height is 26 cm. The stove weights approximately 12 kg. The special design features include a conical rim, slanted pot rests that can accommodate various sizes of pots from 16–32 cm in diameter. The grate is 4 cm thick with 15 mm-diameter equally distributed holes. The stove can use charcoal and woodchips as fuel. Fig. 1 shows photographs and dimensions of the RTFD improved charcoal stove.

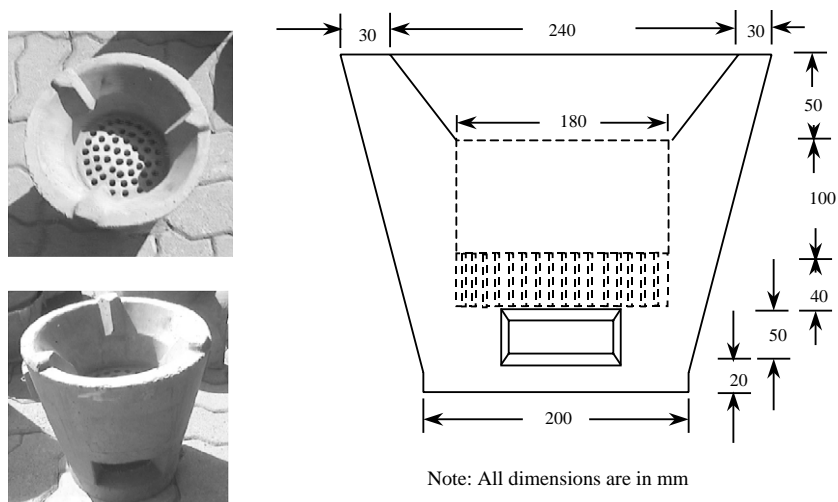


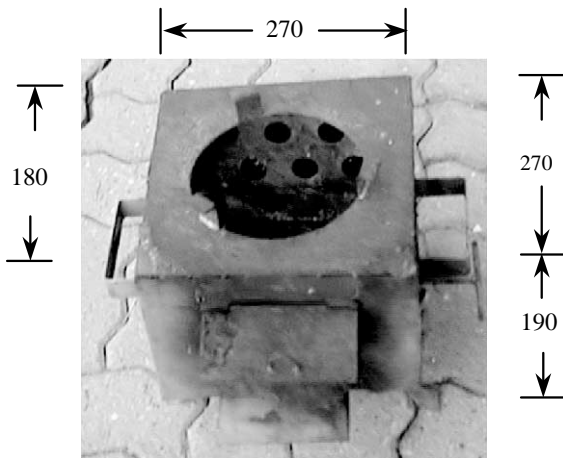
Fig. 1. The RTFD improved charcoal stove.

2.1.2. Indian “Harsha” stove

The Harsha is a portable, metallic, single pot stove without chimney and was designed for multi-fuel operation. Besides fuelwood, the Harsha can be used with dung cakes and a variety of agri-residues or with various combinations. The model, with a corrugated grate design with scraper (for periodical ash removal), can be manufactured by small shops having facilities for welding, cutting and punching sheet metal up to a thickness of 3 mm. This stove is gaining popularity and a number of manufacturers are making it. The stove is equipped with a well-designed fixed metallic grate with a movable ash-removing rake which can move along the space in between the grates. The stove is rectangular in shape with a metallic base with secondary air holes surrounding the combustion chamber. It has an 18-cm diameter pothole. The stove can burn wood, charcoal or coal as fuel and refueling can be done through an opening on one side of the stove. The stove is 27 cm long and 27 cm wide and 20 cm high. Fig. 2 shows a photograph of the Indian “Harsha” stove.

2.1.3. Vietnamese traditional stove

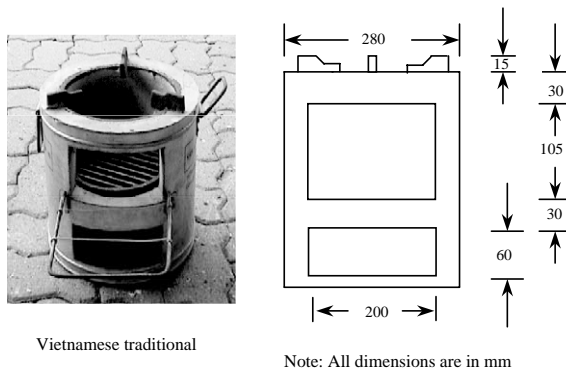
The stove from Vietnam is made of cement plaster and cylindrical in shape with a top outside diameter of 28 cm. It weighs 12 kg and can accommodate one pot of diameter 18–32 cm. It can burn wood, charcoal or coal. It has a metallic grate and refueling can be easily



Indian "Harsha" Cookstove

Note: All dimensions are in mm

Fig. 2. The Indian "Harsha" stove.



Vietnamese traditional

Note: All dimensions are in mm

Fig. 3. The Vietnamese traditional stove.

done through the opening provided at the side of the stove. Fig. 3 shows the photograph and dimensions of the Vietnamese traditional stove.

2.2. Efficiency test

Efficiency is defined as the ratio of the energy entering the pot to the energy content of the fuel consumed. The energy entering the pot produces two measurable effects: raising the temperature of the water to boil-

ing point and evaporating water. In this experiment, the water temperature was measured using a digital thermocouple.

Efficiency was determined by carrying the standard water boiling test (WBT). In the standard WBT, a known quantity of water is heated on the stove. The quantity of water evaporated after complete burning of fuel is determined to calculate the efficiency by using the following formula:

$$n = \frac{m_{w,i}C_{pw}(T_e - T_i) + m_{i, \text{evap}}H_l}{m_f H_f},$$

where $m_{w,i}$ is the mass of water initially in cooking vessel, kg; C_{pw} the specific heat of water, $\text{kJ kg}^{-1} \text{K}^{-1}$; $m_{w, \text{evap}}$ the mass of water evaporated, kg; m_f the mass of fuel burned, kg; T_e the temperature of boiling water, K; T_i the initial temperature of water in pot, K; H_l the latent heat of vaporization of water at 373 K, kJ kg^{-1} ; and H_f the calorific value of fuel, kJ kg^{-1} (higher heating value).

2.3. Emission test

In this study, the hood method was used for testing emission from biomass-fired stoves. The stove to be tested was placed under an extraction hood through which the flue gas was sucked by using a suction blower. Since high extraction rate may influence the combustion characteristics of the stove, extraction was chosen to be strong enough to avoid flue gas to escape from the bottom of the hood but not strong enough to have any effect on the combustion flame. The hood is provided with a probe for NO_x and hydrocarbon measurements. The sample gas passes through the probe into a heated sample line and then enters a pre-filter. The outlet from the pre-filter is connected to a Y-shaped heated line which is used to pass the sample gas to two separate heated analyzers; the Signal Model 4000 VM NO_x analyzer and the Signal Model 3000M hydrocarbon analyzer. Due to the equipment limitations N_2O was not measured in this study. A separate port is provided in the top portion of the flue gas enclosure for the sample gas collection for the BINOS CO and CO_2 analyzers. Readings shown by the gas analyzers are noted at regular time intervals until the readings of the gas analyzer drop to near ambient levels. More details regarding emission tests are given in Bhattacharya et al. (2002).

Table 1
Ultimate and proximate analysis of fuel used

	Wood	Charcoal
% ultimate		
Carbon	51.2	71.5
Hydrogen	7.31	3.39
Oxygen	39.03	22.17
% proximate		
Moisture	9.42	4.73
Volatile	72.65	20.71
Fixed carbon	17.40	72.68
Ash content	0.53	1.88
Higher heating value (dry basis), MJ kg ⁻¹	18.99	28.0

2.4. Burn rate

As it is difficult to determine the exact time when the fuel load of a stove is totally consumed, in this study the burn rate was determined by burning a known amount of fuel in a test and measuring the time for 90% of the fuel to be consumed. It was done by putting the stove on a weighing scale and the time was noted when 10% of the initial fuel weight was left.

2.5. Fuel

Wood and charcoal were used as fuel in this study. Charcoal (*mangrove*) was obtained from the local market while wood chips were cut from pine tree logs (*Casuarina equisetifolia*) and dried for days. The ultimate and proximate analysis of wood and charcoal are given in Table 1.

3. Results and discussion

3.1. Effects of moisture content

The effects of moisture content of wood on efficiency and emission of the stoves were investigated. In this study, the different levels of moisture content of the fuel were obtained by adding calculated quantities of water to the sundried fuel and leaving it in a sealed container for many days. Moisture content of the fuel was measured prior to testing.

To establish the effects of moisture content on the performance and emission of the stoves, each stove was tested a number of times (3) for each level of moisture content of the fuel. Table 2 shows the efficiencies and emission factors of pollutants of the biomass-fired stoves at different fuel moisture content.

The results showed that the efficiencies of all the three stoves decreased with increase in fuel moisture content. The decrease in efficiency is probably due to the fact that at higher moisture content of the fuel, a higher fraction of the heat released from combustion of the dry biomass is used for evaporating the moisture content; higher moisture content also reduces the flame temperature and thus, the rate of heat transfer to the pot. With increase in fuel moisture content from approximately 10–25%, the efficiencies of the improved Indian stove, the traditional Vietnamese stove, and the RTFD stove reduced from 26.1% to 19.7%, from 17.5% to 14.0% and from 17.1% to 9.1%, respectively. Among the three stoves tested, the RTFD stove was the most affected, and its efficiency reduced by 43% compared with the 24% reduction for the Indian stove and 20% reduction for the Vietnamese traditional stove as moisture content of fuel was increased. The significant reduction in efficiency of the RTFD stove appears to be due to the fact that it was a charcoal-fired stove, for which radiation is probably a more important mode of heat transfer to the pot compared to stoves fired by uncarbonized biomass. It may be noted that the rate of heat transfer by radiation depends on the fourth power of absolute temperature, and gets significantly affected by any temperature drop—in this case because of increase in fuel moisture content.

The emissions of CO, CO₂ and CH₄ were also investigated at different moisture content. As shown in Table 2, with increase in moisture content, all the three stoves showed an increase in the emission factor of CO and decrease in the emission factor of NO_x; a slight decrease in CO₂ emission factor was also observed, while emission of CH₄ was not significantly effected. The increase in CO emission factor appears to be due to lowering of gas phase reaction (oxidation) rates at reduced temperatures caused by higher moisture content, while the decrease in CO₂ emission factor is due to the fact that dry biomass per kg of the fuel is less at higher values of moisture

Table 2

Efficiencies and emission factors of stoves for different levels of moisture content of fuel^a

	Efficiency ^b (%)		Emission factor ^c (g kg ⁻¹)				
	Moisture content		CO	CO ₂	TNMOC	CH ₄	NO _x
Indian "Harsha" stove	9.78	26.1	40.1	1597.2	5.21	12.01	0.195
	12.1	25.2	45.7	1583.7	5.71	11.92	0.172
	14.9	25.3	56.4	1587.5	5.92	11.87	0.170
	21.3	20.1	72.1	1564.3	4.8	10.25	0.102
	24.5	19.7	78.2	1565.5	4.7	9.75	0.102
Vietnamese traditional	9.5	17.5	38.6	1608.7	12.01	7.82	0.073
	11.7	17.6	39.2	1597.8	11.92	7.98	0.062
	14.5	17.2	42.1	1568.2	11.87	8.05	0.061
	21.0	14.3	53.2	1555.7	6.8	8.07	0.052
	24.5	14.0	55.2	1547.2	6.8	7.98	0.051
RTFD improved stove	9.8	17.1	19.7	1605.3	10.84	10.83	0.113
	11.5	14.9	25.4	1597.2	10.97	11.21	0.105
	14.7	14.7	28.9	1590.9	10.71	12.95	0.091
	21.0	10.1	55.4	1582.1	9.32	10.11	0.087
	24.5	9.7	55.8	1572.1	8.88	9.78	0.082

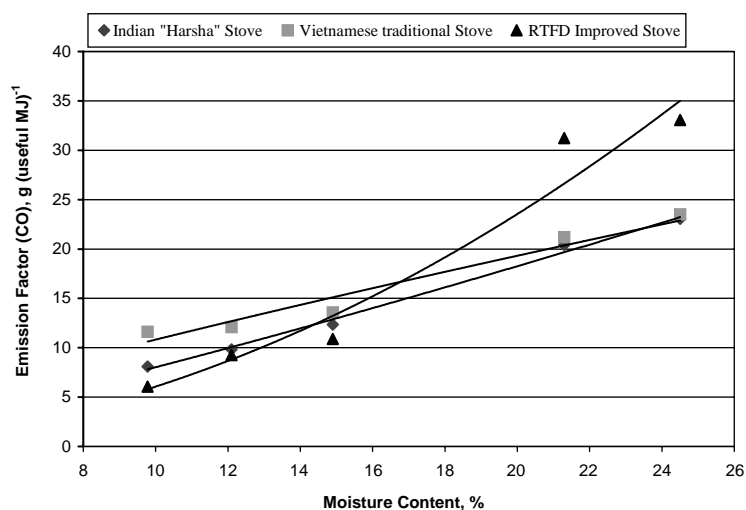
^aEfficiency testing for RTFD improved stove used charcoal as fuel.^bAverage for three test runs.^cAverage for three test runs; 50 × 50 × 50 mm³ size wood chips.

Fig. 4. Emission factor and efficiency of stoves at different wood moisture content (curve fitted).

content. The lower value of the emission factor of NO_x is due to lower flame temperature at higher moisture content. Since the efficiency of the stoves decreased with increase in moisture content, change in emission of the different gases per unit of useful energy deliv-

ered to the pot was greater compared with changed in emission per kg of fuel. This is illustrated in Fig. 4, which shows the variation of the emission factor of CO per useful MJ against moisture content of the fuel.

Table 3
Efficiency and emission factors of the stoves for different wood sizes of fuel

	Size of wood block ^a (mm)	Efficiency ^b (%)	Burn rate (kg h ⁻¹)	Emission factor ^b (g kg ⁻¹)				
				CO	CO ₂	CH ₄	TNMOC	NO _x
Indian "Harsha" stove	50 × 50 × 200	26.8	1.55	42.4	1595.2	11.9	6.1	0.175
	50 × 50 × 50	26.7	1.65	42.1	1597.7	12.1	6.0	0.195
	25 × 25 × 50	26.2	2.11	37.1	1601.2	12.1	6.0	0.210
Vietnamese traditional stove	50 × 50 × 200	17.9	1.33	38.1	1585.2	8.2	7.1	0.063
	50 × 50 × 50	17.2	1.57	38.2	1595.2	7.9	7.0	0.092
	25 × 25 × 50	17.2	1.85	36.5	1603.2	8.0	6.9	0.101
RTFD improved stove	50 × 50 × 200	17.8	1.24	25.9	1590.9	10.1	10.2	0.112
	50 × 50 × 50	17.8	1.55	25.9	1597.2	10.1	9.8	0.115
	25 × 25 × 50	17.1	1.74	23.7	1605.3	10.5	9.9	0.213

^aAt 10% moisture content.

^bAverage for three tests runs.

3.2. Effects of fuel size

The effects of the size of wood fuel on efficiency and emission of the stoves was investigated. Three sizes of wood blocks were used to fire for each stove with moisture content, type of ignition and other parameters held constant. Table 3 shows the efficiency and emissions of the stoves for different sizes of wood blocks.

As can be seen from Table 3, the fuel size had no significant influence on the efficiency of the stove. On the other hand, the table showed a strong influence of the size of fuel on the burn rate of the stove. It was observed that burn rate (kg h⁻¹) increased as the size of fuel decreased. Burn rate can be regarded as comparable to firepower (kW), which was defined by Tremeer et al. as the ratio of the energy content of the fuel consumed during a test to the duration of the test [4]. It has been reported that with increasing firepower, generally stove efficiency tends to reduce, as more energy is lost to the surroundings rather than transferred to the pot [4]. However, all the three stoves tested in this study showed no significant changes in efficiency as burn rates changed with fuel size.

The size of wood blocks seems to influence the emission of CO for the range investigated. The CO emission factor was found to reduce as the fuel size was reduced. The decreasing trend of emission

factor of CO can be attributed to intensification of the combustion process, as indicated by increased burn rate, when fuel sizes are reduced; the resulting rise in temperature level inside the stove promotes complete combustion so that less amounts of products of incomplete combustion are produced. The different sizes of fuel did not show any significant influence on the emissions of CO₂, CH₄ and TNMOC while there was a slight increase in NO_x emission as fuel sizes were reduced; the increase in NO_x emission can be attributed to the intensification of the combustion process for lower fuel sizes. Fig. 5 shows the influence of the different sizes of wood fuel on emission of the stoves tested.

3.3. Effects of pot size

The effects of the different pot sizes on the efficiency of the stoves were investigated with parameters such as moisture content, fuel size and method of ignition held constant during the test. The size of the pot did not influence the efficiency of the stoves tested. As shown in Table 4, the efficiency values remained nearly unaffected when the size of the pot was varied. Although the larger pots have more heat absorbing surface at the bottom and the sidewall, this seems to be offset by the greater heat loss by the larger pot than the smaller ones due to a larger surface exposed to the surroundings.

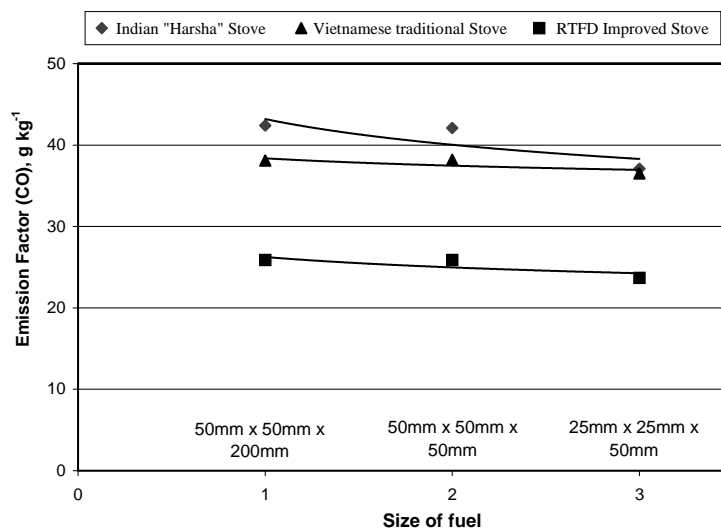


Fig. 5. Emission factor at different sizes of wood fuel (curve fitted).

Table 4

Test result of the effect of pot size on efficiency and time to boil

	Pot sizes (cm)	Efficiency ^a (%)	Time to boil (min)
Indian "Harsha" stove	26.0	26.8	15.5
	32.0	26.9	14.0
	36.0	26.5	14.0
Vietnamese traditional stove	26.0	17.8	18.5
	32.0	17.9	16.5
	36.0	17.2	16.0
RTFD improved stove	26.0	18.0	19.0
	32.0	18.0	17.5
	36.0	17.8	17.5

^a Average for 3 tests; at 10% moisture content and $50 \times 50 \times 50 \text{ mm}^3$ size wood chips.

3.4. The effects of the method of ignition and batch size

Two methods of stove ignition were compared in this study; these were conventional ignition from the bottom of the fuel bed and ignition at the top. To standardize the methods of ignition, kindling pieces of wood dipped into kerosene (50 g) were used for both top and bottom ignition. Table 5 shows the emission and efficiency of the three stoves tested for the two methods of ignition. The different methods of ignition did not affect the efficiency of the stoves tested. In gen-

eral, emission of CO and NO_x was significantly less in case of top ignition in comparison with conventional bottom ignition. Also, top ignition appeared to burn the wood fuel with much less smoke compared to burning with bottom ignition, particularly during start-up. This is reflected in Fig. 6, which shows the profile of the concentration of CO and CO₂ for top ignition and bottom ignition in the Vietnamese stove tested.

The effects of the amount of fuel loaded or batch size were also investigated in the study. Table 6 shows the efficiency and emission of the Indian "Harsha" stove at different batch sizes.

Table 5

Test results of the effects of method of ignition on the efficiency and emissions of the stoves^a

	Method of ignition	Efficiency ^b (%)	Emission factor ^b (g kg ⁻¹)				
			CO	CO ₂	CH ₄	TNMOC	NO _x
Indian “Harsha” stove	Top ignition	24.7	41.7	1593.4	10.7	4.9	0.099
	Bottom ignition	25.3	52.4	1587.5	11.8	5.2	0.182
Vietnamese traditional stove	Top ignition	16.8	27.2	1601.1	7.6	6.9	0.058
	Bottom ignition	17.2	43.5	1588	8.0	7.1	0.073
RTFD improved stove	Top ignition	14.7	19.3	1595.1	9.2	10.4	0.097
	Bottom ignition	14.7	28.7	1591.9	12.1	10.8	0.113

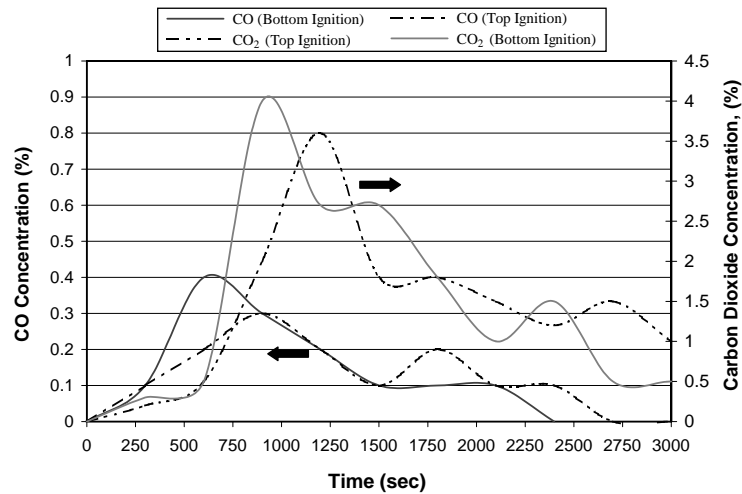
^aAt 10% moisture content; 25 × 25 × 50 mm³ size wood chips as fuel.^bAverage for 3 tests.Fig. 6. Concentration of CO and CO₂ for the Vietnamese traditional stove during top and bottom ignition at 90% weight of fuel consumed.

Table 6

Efficiency and emission factors at different wood batch size using the Indian “Harsha” stove

	Batch size ^a (kg)	Burn rate (kg h ⁻¹)	Efficiency ^b (%)	Emission factor ^b (g kg ⁻¹)			
				CO	CO ₂	CH ₄	NO _x
Top ignition	1	1.33	25.0	42.6	1599.2	11.57	0.115
	1.5	1.5	24.8	40.3	1603.2	12.7	0.192
	2.0	1.71	24.7	36.1	1612.7	12.9	0.200
Bottom ignition	1	1.50	25.4	42.9	1601.3	12.12	0.105
	1.5	1.63	25.3	52.4	1613.2	12.9	0.211
	2.0	2.0	25.3	49.1	1625.8	12.9	0.211

^aAt 10% moisture content; 25 × 25 × 50 mm³ size wood chips as fuel.^bAverage for 3 tests.

The efficiency of the Indian “Harsha” stove did not significantly change with increasing fuel load or batch size at either top or bottom ignition. In general, burn rate was found to increase with increase in batch size. Also, top ignition resulted in slightly lower burn rate in all cases. The NO_x emission factor slightly increased as batch size was increased; changes in emissions of the other gases with change in batch was not significant.

4. Concluding remarks

The effects of different parameters on performance and emissions of three biomass-fired stoves have been investigated. Parameters such as moisture content of fuel, size of fuel, size of pot and method of ignition were examined using an improved Indian stove, a Vietnamese traditional stove and an improved stove developed by RTFD.

In general, efficiency of the stoves decreased with increase in moisture content of fuel. Increase in moisture content of the fuel also resulted in increase in the emission factor of CO and decrease in the emission factor of NO_x ; a slight decrease in CO_2 emission factor was also observed, while emission of CH_4 was not significantly affected.

Fuel size did not show any significant influence on the stove efficiency. At lower fuel size, the emission of CO was found to decrease slightly, while that of NO_x increased slightly.

The size of pan did not affect the efficiency of the stoves tested.

Two methods of stove ignition—conventional bottom ignition and top ignition—were investigated. In

general, emission of CO and NO_x was significantly less in case of top ignition in comparison with conventional bottom ignition. Also, top ignition appeared to burn the wood fuel with much less smoke compared to burning with bottom ignition, particularly during start-up.

In general, burn rate was found to increase with increase in fuel batch size. The NO_x emission factor slightly increased as batch size was increased; changes in emissions of the other gases and stove efficiency with change in batch size was not significant.

Acknowledgements

The authors thank the Swedish International Development and Cooperation Agency (Sida) for the support provided for this work under the Asian Regional Research Program in Energy, Environment and Climate (ARRPEEC).

References

- [1] Ndiema CKW, Mpendazoe FM, Williams A. Emission of pollutants from biomass stove. *Energy Conversion Management* 1998;39(13):1357–67.
- [2] Ahuja DR, Joeshi V, Smith KR, Venkataraman C. Thermal performance and emission characteristics of unvented biomass-burning cookstoves: a proposed standard method for evaluation. *Biomass* 1987;12:247–70.
- [3] Stewart B. 1987. Improved wood waste and charcoal burning stoves. A practitioners manual. Intermediate Technology Publications, London.
- [4] Ballard-Tremeer G, Jawurek HH. Comparison of five rural wood-burning cooking devices: efficiencies and emissions. *Biomass and Bioenergy* 1996;11(5):419–30.