Sustainable Environment Research 28 (2018) 438–443

Contents lists available at ScienceDirect

Sustainable Environment Research

journal homepage: www.journals.elsevier.com/sustainable-environment-research/

Original Research Article

Comparative evaluation of the performance of an improved biomass cook stove and the traditional stoves of Iran

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ARTICLE INFO

Article history:
Received 4 January 2018
Received in revised form
7 April 2018
Accepted 1 August 2018
Available online 6 October 2018

Keywords:
Biomass waste
Thermal efficiency
Firewood
Regression model

ABSTRACT

In international development programs on improvement of energy supply for cooking in remote regions, biomass gasifier cook stoves have a remarkable place. Fuel type and size play a key role on the performance of such stoves. The most abundant woody biomass waste in Iran is apple pruning waste (up to 1.32 Mt a year). This paper reports the result of evaluation of a top lit updraft biomass stove specifically modified to burn apple pruning waste. In addition, the improved biomass cooking stove (ICS) was technically compared with traditional cook stove (TCS) based on Water Boiling Test 4.2.3 and time to boil (TTB) instruction. Water and flame temperature variations were compared with a natural gas stove (GS), as the most common cooking device in Iran. The average TTB was 12, 13, and 20 min for the GS, ICS, and TCS, respectively. The comparison of regression equations indicated that the rate of increase in the flame and water temperature in the both ICS and GS were similar. In general, better thermal efficiency was observed in the ICS (about 35%) in comparison with the TCS (12.6%). The specific and the total fuel consumption in the ICS were 73 and 67% lower than that of the TCS, respectively.

1. Introduction

Among the various sources of renewable energy, biomass with high annual production rate and geographically widespread distribution throughout the world has a special place [1,2]. It is considered to be the most promising alternative for conventional fossil fuels and feedstocks [3,4]. Statistics shows that more than 2.5 billion of the world's population rely on wood and charcoal for cooking [1,5]. The majority of them are living in rural areas of developing countries [6,7]. A large portion of these individuals use open fires for cooking which corresponds to low thermal efficiency and high air pollution due to poor burning characteristic [1]. The indoor air pollution causes threats to health and even may lead to premature death [8]. Every year, about four million people die prematurely due to indoor air pollution from cooking [9]. It has been proven that the existing biomass cook stoves can be improved to reduce emission of toxic gasses and harmful particulates based on the principle of gasification [1]. It has been estimated that 570,000 unexpected losses of poor women and kids in India could be kept away from, if clean cook stove initiatives were set up [10]. Recently, Mamuye et al. suggested that the use of improved charcoal stoves (Merchaye and Lakech) in Ethiopia could help to mitigate climate change, deforestation, and household workload [11].

Emissions and efficiency of a biomass stove depend on various factors (e.g., stove type, lighting, fuel feeding practice, and combustion temperature) [12]. Among these factors, fuel type and size play a key role on the performance of a stove [13]. Therefore a unique design is required for a given biomass type. For instance, Raman et al. evaluated three types of forced draft stove by feeding with coconut shell [14]. Parmigiani et al. proposed a special stove design for using rice husk as the fuel [13]. Grimsby and Borgenvik examined the feasibility of using Jatropha fruit coats in a sawdust cook stove and resulted in different performance [15]. In a recent research, Njenga et al. compared the ease of use, energy consumption, fuel efficiency, and emissions of a small-scale gasifier cooking stove with a traditional three-stone stove and an improved “Hifadhi” in the rural area of Kenya. They concluded that fuel saving is a great advantage of gasifier stoves. In addition, the relatively faster cooking and less indoor air pollution are the other benefits of

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Peer review under responsibility of Chinese Institute of Environmental Engineering.

https://doi.org/10.1016/j.serj.2018.08.001

the improved stove [16]. In another research, Singh et al. reported that 41% fuel saving is possible by using improved stoves. It seems that researchers tried to modify an existing, or develop a new design in accordance with the availability of the biomass waste in their target region [17].

The most abundant woody biomass waste in Iran is apple pruning waste. A total area of 208,000 ha is under the cultivation of apple garden which corresponds to an annual wood waste of up to 1.32 Mt [18]. During the pruning season, the branches should be moved outside the garden and somehow be disposed of, eliminating the risk of pests' outbreak. This feedstock can be simply considered as free fuel, without negative effect on natural resources. The use of an improved biomass stoves fueled with apple wood could be a good alternative for traditional open fire stoves. Various stove designs could be tested for fueling with apple wood, however, the top lit updraft (TLUD) stove proposed by Anderson [19] has some technical and economic advantages over the other designs [5]. This stove was previously examined using wood chips, almond shell, and corncob [20] but in order to make it suitable for feeding with apple waste, the present researchers made some minor modifications on this stove and evaluated its performance by fueling with apple pruning waste. Therefore, the present paper aims to: (i) evaluate the modified TLUD stove as an improved cook stove (ICS) and compare it's time to boil (TTB) with a gas stove (GS) which is the most common device for cooking in Iran; (ii) assess the flame features and temperature via regression models during the tests; and (iii) evaluate the technical performance parameters and CO emission of the ICS fed with apple pruning waste and compare to the Iranian traditional three-wall cooking stove (TCS). The efficiency parameters including burning rate, specific fuel consumption, and thermal efficiency were also monitored.

2. Materials and methods

2.1. Stoves specifications

The TCS was made according to the most popular form of the biomass stove in Iran. It had three hard brick side walls of 230 mm height and an opening of 260 mm wide in front (Fig. 1c). A metal sheet was placed under the TCS to weight the remaining fuel and calculate the amount of consumed fuel at the end of each test. The ICS has two concentric metal cylinders with 0.6 mm thickness and two sets of primary and secondary air inlet holes. The details of the design are shown in Fig. 1a and b. Based on the latest experience with the various dimensions of the stoves, the authors have found that, having a gap of about 75 mm between the inner and the outer cylinders bottoms provides a better performance (Table 1).

2.2. Feedstock

Apple wood was collected from Khorasan Razavi province (Iran) during the pruning season. The woods were dried in oven at 40 °C for 72 h. Based on the pretests, it was found that the uniformity of fuel pieces strongly influences the performance of the ICS, i.e., large pieces of wood were not suitable for stove startup. Hence, the fuels were manually shredded to uniform pieces. The other fuel characteristics were determined in accordance with general standards (Table 2).

2.3. Test protocol

Water Boiling Test (WBT) version 4.2.3 [21] was applied in four replications. This procedure was frequently used by other researchers (e.g., [13,14,22–24]) and designed principally to evaluate cook stoves performance. It simulates the actual cooking process to help understanding the rate of energy transfer from the fuel to the cooking pot [24]. This protocol consists of three phases of cold start, hot start, and simmering. In all tests, the stove was fired at room temperature (23 ± 2 °C). In each run, 3 kg of water in a 5-L popular pot (Taban, Iran) without a lid, reached to the local boiling point (96.6 °C, for the test location, Mashhad).

2.4. Technical calculations

During each phases of WBT, the amount of water and evaporated water was measured. Fuel and remaining charcoal were weighed by separating the fuel at the end of the test. The temperatures and elapsed time were also recorded continuously. These measurements were used to evaluate the stove performance at low or high power phases [21]. Thermal efficiency (η) of a biomass cook stove indicates how well the stove can transfer the energy of the biofuel to the cooking pot. It is defined as the ratio of the energy received by the water to the total energy content of the used fuel [21,24] as Eq. (1).

Table 1
Geometric properties of the ICS (mm).

Main parts	Height	Cylinders diameter	Hole diameter	Hole distance
Outer cylinder	300	200	15	10
Inner cylinder	225	150	8[a] 5[b]	10 3

[a] Secondary air holes.
[b] Primary air holes.

(a) (b) (c)

Fig. 1. View of the ICS (a and b) and the TCS (c). A) The outer cylinder legs. B) The outer cylinder. C) The inner cylinder. D) The outer and inner cylinder coupling. E) Connector bolt to air control top door).

Table 2
Characteristics of the apple wood as biofuel and the methods of measurement.

Factor	B.D[a] (kg L^{-1})	M.C[b] (%)	V.M[c] (%)	Ash (%)	L.H.V[d] (MJ kg^{-1})	Size (mm)
Amount	0.19	5	94	4	17.5	length 53 diameter 17
Method	EN 15103:2009	EN 14774-3:2009	EN 15148:2009	EN 14775:2009	Based on the literature review[e]	EN 16127:2012

[a] Bulk Density.
[b] Moisture Content.
[c] Volatile Matter.
[d] Lower Heating Value.
[e] As described in Nakomcic-Smaragdakis et al. [32].

$$\eta = \frac{(m \cdot c \cdot \Delta\theta)_{H_2O} + (m \cdot h_v)_{H_2O(evap)}}{f_{ac}} = \frac{(m \cdot c \cdot \Delta\theta)_{H_2O} + (m \cdot h_v)_{H_2O(evap)}}{dryfuel_{equ} \cdot LHV_f - E_{moist} - char\ mass \cdot LHV_{char}} \tag{1}$$

where $(m \cdot c \cdot \Delta\theta)_{H_2O}$ is the energy received by water (J); $(m \cdot h_v)_{H_2O_{(evap)}}$ is the energy absorbed by water for evaporation (J); $dryfuel_{equ}$ is the mass of dry fuel used during the test (g); E_{moist} is the energy needed to evaporate the moisture content of the fuel (drying section) (J); *char mass* is the mass of charcoal remained at the end of the test (g). The parameter *c* is the specific heat of water (4.186 J g^{-1} K^{-1}), h_v is the heat of vaporization of water (2260 J g^{-1}), *m* is the mass in (g) and $\Delta\theta$ is the difference of local boiling point of water and the ambient temperature (73 °C). Also LHV_f is the lower heating value of the fuel (17.54 J g^{-1}) and LHV_{char} is the remaining charcoal lower heating value in J g^{-1}. It should be noted that f_{ac} is the actual mass of the consumed fuel during the test (Eqs. (2) and (3)), where $fuel\ mass_{wet}$ is the total mass of the fuel used in the test (g), *MC* is the moisture content of the fuel, T_b is the local boiling point (96.6 °C) and T_a is the ambient temperature at the beginning of the test (23 °C).

$$dryfuel_{equ} = fuel\ mass_{wet} \cdot (1 - MC) \tag{2}$$

$$E_{moist} = fuel\ mass_{wet} \cdot MC(4.186(T_b - T_a) + 2260) \tag{3}$$

Moreover, TTB was measured in minute along with the other performance indicators including Burning Rate (BR), Fire Power (FP), Specific Fuel Consumption (SFC), and Useful Fire Power (FP_U) through Eqs. (4)–(7).

$$BR = \frac{f_{ac}}{time\ to\ boil} \tag{4}$$

$$FP = \frac{f_{ac} \cdot LHV_f}{time\ to\ boil \times 60} \tag{5}$$

$$SFC = \frac{f_{ac}}{water_{re}} \tag{6}$$

$$FPU = FP \cdot \eta \tag{7}$$

where $water_{re}$ is the water remaining at the end of test (L).

The average of CO_{ave} concentration (ppm) was determined by Eq. (8) ([25]).

$$CO_{avg} = \frac{\sum_{i=1}^{t} CO_i}{t} \tag{8}$$

where CO_i is the CO level in any given second (ppm) and t is the duration of trial (s).

2.5. Test procedures and equipment

The ICS was mounted on a GF-6100 electronic balance with 0.01 g readability. The device was equipped with a bright vacuum fluorescent display, a RS-232 port with a built-in Super Hybrid Sensor (A&D, Japan). The weighing platform was connected to a computer equipped with “Rs-com” interface for real-time recording of the fuel consumption during the tests. In the TCS tests, a bundle of 3 kg fuel was prepared for each test. To calculate the mass of consumed fuel, the mass of remaining fuel at the end of the test was subtracted from the original 3 kg bundle. The fuel feeding intervals were determined based on the appearance of the flame. Whenever the flame had subsided, new stock of fuel was added. The fuel feeding was continued until the beginning of the water boiling. In order to investigate the effects of feeding on the performance of the ICS stove, one WBT continued beyond the cold start phase by adding three bundles of fuel (150, 100 and 50 g) to prolong the flaming for 60 min. WBT was also performed for the cold start phase using a GS as the control treatment. TTB and flame temperature variations were used to compare GS against the TCS and ICS stoves.

A “K” type thermocouple was used to measure the water temperature. An immersion thermocouple probe (“K” type HP-502A-M21, China) with 3 s response time was used for flame temperature measurement. A real time four-channel data logger (TM-947SD, Taiwan) was employed to record the temperatures data received from the thermocouples every 2 s.

Indoor air pollution measurements were also carried out to investigate the concentration of CO in the cooking environment. When using biomass stoves, most of the cooking procedures are done by an operator for gradual feeding of biomass and condition monitoring of the flame (especially in traditional stoves). It means that the operator is highly exposed to the harmful gasses emitted from the stove. Therefore, the emission measurement was done by locating the sensor in front of the stove (50 cm) at the height of 60–70 cm. The CO concentration was recorded every 10 s during the test.

3. Results and discussion

3.1. Performance results

The comparative results of the technical parameters are shown in Fig. 2. It can be seen that the BR of the two stoves are quite different, i.e., 18.7 g min^{-1} for the ICS and 42.4 g min^{-1}. The higher BR in the TCS implies the higher gas release from the wood. The average of the total consumed fuel was approximately 350 and 1065 g while the FP_U was 1.5 and 1.9 kW for the TCS and the ICS, respectively. η increased as FP decreased. The η of the ICS in the cold start phase was approximately 35%, while for the TCS it was only 12.6%. A more recent research also showed that even a small improvement on the three-stone stoves could enhance the η [26].

As can be seen in Fig. 2, the SFC for the ICS and the TCS was 88 and 327 g L^{-1}, respectively. In a latest attempt on the improvement

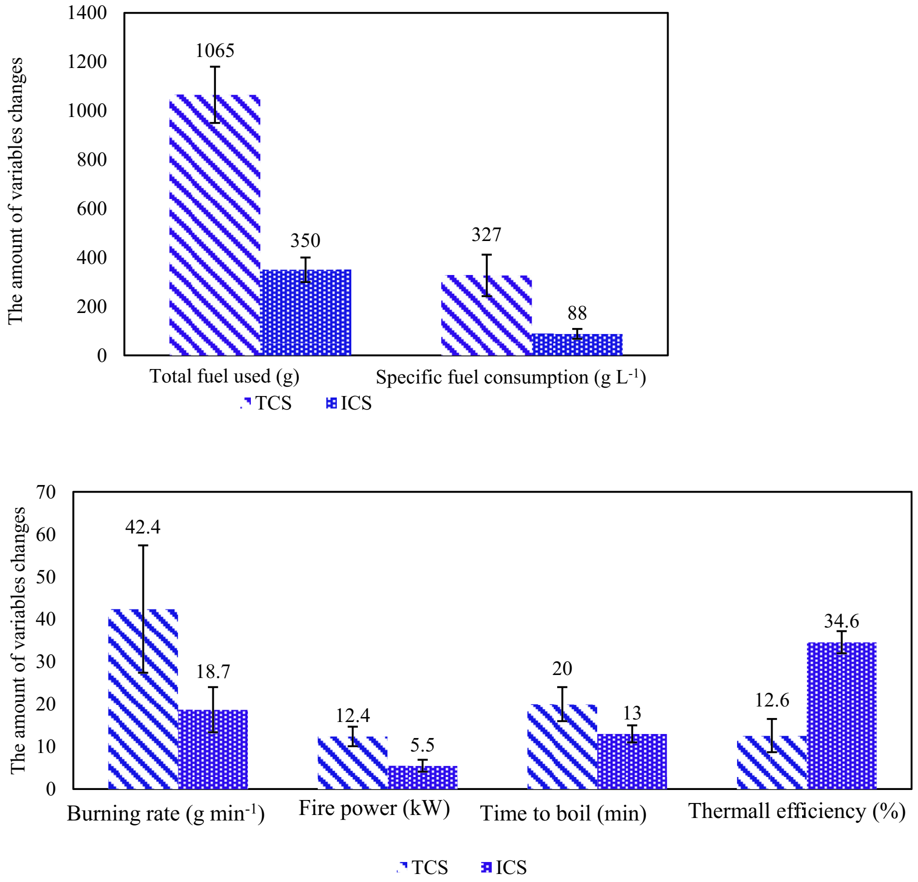

Fig. 2. Performance of WBT for the TCS and ICS. The results are shown in two separate charts, according to their scales.

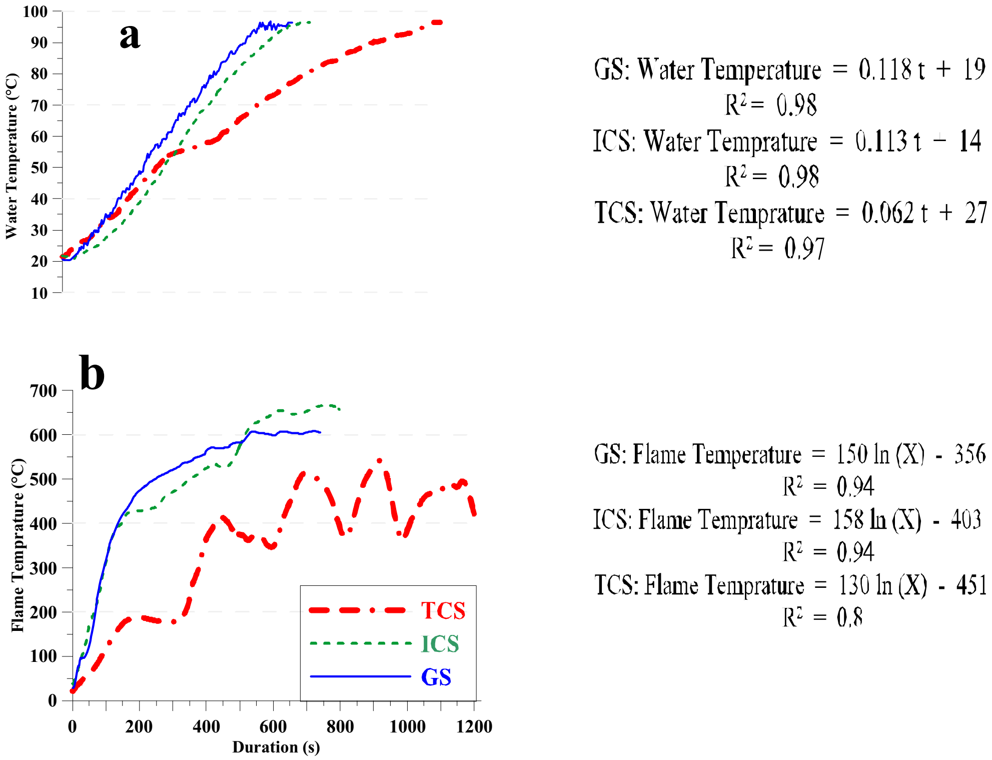

Fig. 3. Variations and regression equations the temperature of water (**a**) and flame (**b**). Unlike the uniform and similar pattern for GS and ICS, lots of tolerance happened in the case of the TCS.

of traditional stoves in rural Kenya, Ochieng et al. stated that the modification on the traditional three-stone stove substantially decreased the fuel consumption [27]. Many researchers tried to reduce the fuel consumption with promising outcomes [10,28,29]. The average of TTB for the TCS was 20 min while for the ICS was reduced to 13 min. In practice, cooking by TCS involved often cooling of the pot due to the blowing of the flame by the wind. At the same time, wind access to the core of the fire in TCS results in more oxygen availability for the woods. This leads to higher BR, more FP, more fuel consumption, and consequently lower TE. In the ICS, due to the controlled air flow, the precipitous consuming of fuel can be regulated. Moreover, preheating of the secondary air optimizes the combustion in the ICS. In the TCS, in contrast, the wind cools down the fire environment. In fact, though the ICS exhibited lower FP, but due to its higher TE, it could provide more favorable FP_U index. In addition, the controlled and uniform downward movement of the pyrolysis layer reduced the total fuel consumption and SFC index in the ICS [30].

3.2. Water temperature versus time

The experimental WBT cold start phase was also done for a GS as a control test. The data of the temperature variations were fitted in a simple regression model. The average TTB was 12, 13, and 20 min for the GS, ICS, and TCS, respectively. The comparison of the slopes of regression lines (0.11) indicated that the rising trend of water temperature in the ICS is almost the same as the GS. The slope of regression line measured for the TCS (0.06) was meaningfully different. This difference means a lower heat transfer to the water during the TCS operation, increasing the TTB index for the TCS Fig. 3a.

3.3. Flame temperature variations evaluation

Fig. 3b shows the flame temperature of each stove during the experiment. The best prediction of the flame temperature variations was demonstrated by logarithmic regression functions. The highest flame temperature was 608, 667, and 542 °C for the GS, the ICS, and the TCS, respectively. It can be seen that the flame temperature in both the GS and the ICS increased in a uniform and similar pattern, with much tolerance observed in the case of the TCS. The TCS is affected by wind blowing. It cools down the pyrolysis vapors and the flame surrounding. It also spreads out the flame. Moreover, due to the lower η, more often fueling is needed in this stove. New added fuel again means cooling down the fire.

3.4. Emission performance

Fig. 4a and b shows CO concentrations during the test for each stove separately (a for the ICS and b for the TCS). It can be seen that the CO emission from the TCS was significantly higher than that of

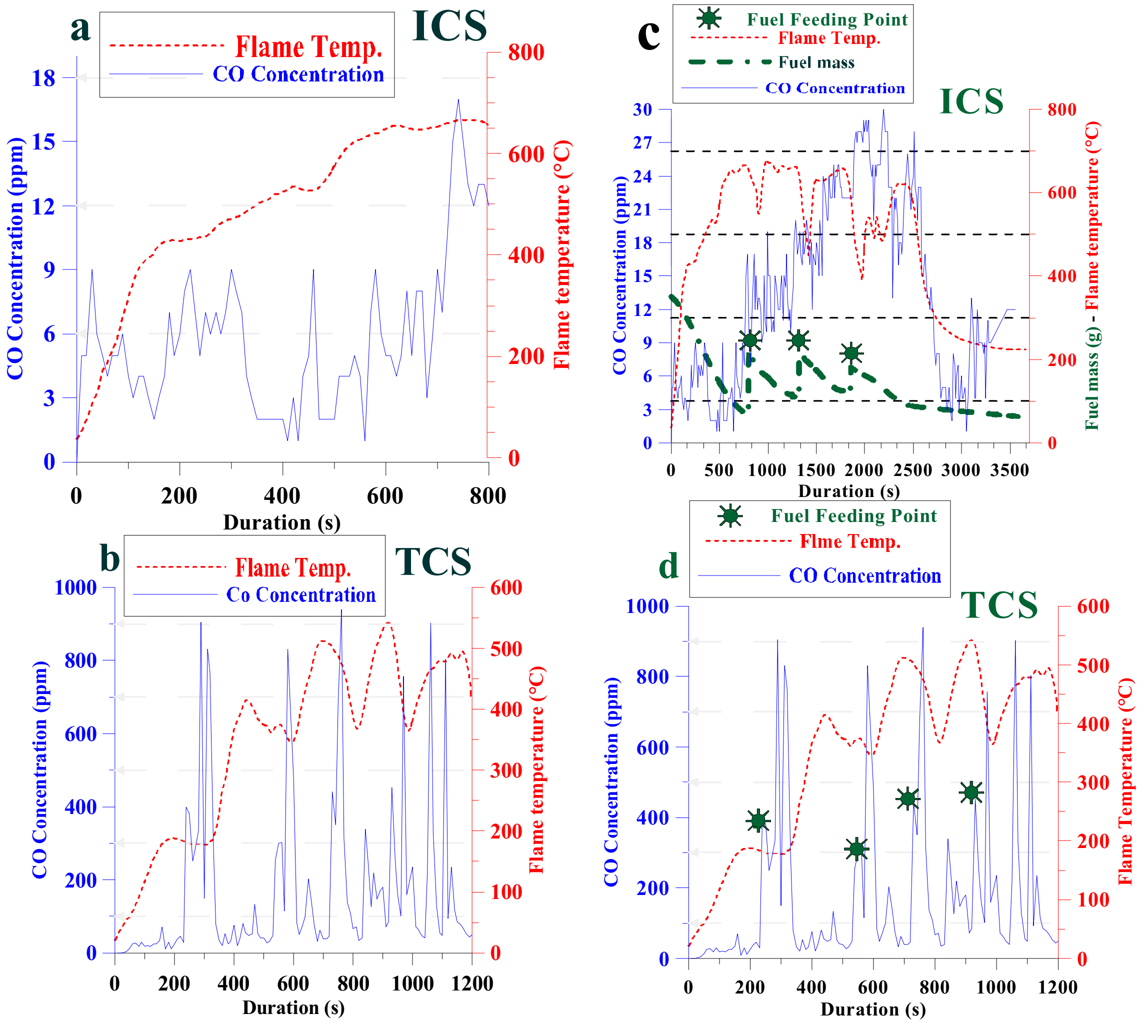

Fig. 4. CO concentration and flame temperature variation during the cold start test of the ICS (a) and the TCS (b) and total consumed fuel mass, CO concentration and flame temperature variations of the ICS (c) and the TCS (d).

the ICS. The maximum and the average amount of CO emission from the TCS was 940 and 172 ppm respectively. These values were 17 and 6 ppm for the ICS. Uncontrolled situations in the TCS is the main contributor for higher CO emission [31]. While by employing the primary and secondary air supply in micro-gasifiers, high combustion efficiency is guaranteed and low pollutant emission is provided [19].

Rapid increase in CO concentration in either curves of Fig. 4c and d corresponds to the moment of fueling the stoves. Tryner et al. also observed that adding solid fuel during the stove operation makes a sharp increase in CO emission [24]. In general, the results reveal that even though each stove has its exclusive behavior but, fuel feeding has two direct effects in both the stoves; decreasing the flame temperature, and at the same time, increasing CO emission. When the fuel was fed into the combustion chamber, a portion of heat was spent for fuel drying and volatilization which resulted in a sudden decrease in temperature.

4. Conclusions

The performance of a TLUD biomass stove fed with apple pruning waste was compared to that of gas stove and traditional biomass stove. Based on the regression models, there is a similar trend between the ICS and GS for water temperature. CO emission from ICS was in acceptable range however, refueling during the operation led to transient increases in CO emission. Therefore a gradual feeding is suggested. In the TCS, on the other hand, due to the lower efficiency, more often refueling leads to further increase in smoke emission. While the fire power for the TCS was only 27% more than that of the ICS, its fuel consumption was 1.3 times higher. Thermal efficiency of the ICS was found to be 35%. Generally, from practical point of view, ICS could be a good substitute for TCS for remote regions where there is no access to the natural gas or kerosene. Considering the higher efficiency of the ICS, this could substantially reduce the need for wood collection and therefore can be of impact in prevention of desertification.

Acknowledgements

This work was supported by the Ferdowsi University of Mashhad (grant number 39761). The authors would like to thank Mehdi Jahantigh for his valuable effort on setting up the test rig.

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