Renewable and Sustainable Energy Reviews 70 (2017) 656–665

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A comprehensive review of technical aspects of biomass cookstoves

Mohammadreza Sedighi[a,*], Hesamoddin Salarian[b]

[a] Young Researchers and Elite Club, Karaj Branch, Islamic Azad University, Karaj, Iran
[b] Department of Mechanical Engineering, Islamic Azad University Nour Branch, Nour, Iran

A R T I C L E I N F O

Keywords:
Biomass
Cookstove
Cookware
Gasification
CFD
Efficiency
Emissions

A B S T R A C T

Interest in reducing household energy consumption and indoor air pollutants has increased. Simple devices such as cookstoves are important items in the reduction of the amount of domestic energy consumed in developing countries. This paper summarizes the literature available on biomass cookstoves used in villages of underdeveloped countries to determine their holistic performance, including efficiency and emissions. This is a detailed discussion on gasification, biomass fuel characteristics and heat output control of cookstoves. It reviews cookstove design, performance considerations, materials and geometric parameters along with the impact of supplementary tools on efficiency and emissions. Mathematical modeling and simulations are included and evaluation criteria consisting of testing protocols and performance parameters are compared. An efficiently designed pot can reduce domestic energy consumption, although its impact has been overlooked. Literature concerning the effects of materials and geometrical variables versus heat transfer efficiency of cookware is also discussed. The review addresses the gaps in the literature to pave the way for future research.

1. Introduction

Global attention has focused on mitigation of environmental issues by increasing energy efficiency and reducing carbon emissions. Fossil fuels are finite resources which must be managed. A decrease in fossil fuel consumption can be achieved by improving the efficiency of its use and finding renewable sources of energy and green alternatives. The contribution of household energy consumption to total energy consumed in developing countries is over 30% [1]. Cooking accounts for about 90% of domestic energy consumption in these countries. A majority of rural households use biomass fuels to meet their heating and cooking needs [2] with firewood constituting about 95% of fuel consumed for cooking in villages [3]. Each year about 16 million ha of forests are consumed as cooking fuel [4].

Approximately one-third of the world population does not have clean cooking facilities and this number is predicted to remain unchanged through 2030 [5,6]. The burning of biomass fuels releases indoor air pollutants and high amounts of hazardous smoke containing CO, NOx, SO, and particulate matter (PM) which have been proven detrimental to human health; these harmful emissions are responsible for three million deaths per year globally [7].

The three-stone fire is the simplest and the most common cookstove throughout history [8]. The first biomass cookstoves were introduced by Chulha [9] in the 1940s. Raju later developed multi-pot mud cookstoves for domestic use in the countryside [10]. Interest in improving cookstoves was fueled by energy shortages and global attention towards environmental issues during the 1970s. Winiarski enhanced the thermal efficiency of cookstove by introducing the rocket stove [11].

"The top-lit up-draft (TLUD)" stove was developed by Reed in 1985 [12]. The TLUD operates as a match when held vertically so that the upward flow of air from the flame supplies the primary air below the flame and secondary air within the flame [13]. This interesting design yields fewer harmful emissions than traditional stoves or the rocket stove [14]. Medwell et al. compared the TLUD to a three-stone fire and found that it decreased harmful emissions to almost an eighth of the three-stone fire [15] through gasification in which gaseous fuel is generated from solid fuel and burns separately. Another benefit is the ability to produce charcoal which can be used either for cooking or applied as a soil amendment after conversion to biochar [13].

The present paper has the following goals: to determine (i) how to produce the most energy from fuel with the fewest harmful emissions and (ii) how to transfer the most heat to the pot. This review addresses gaps in the literature and reviews pertinent research publications as well as the latest developments pertaining to biomass cookstove design, development and testing.

2. Direct and Indirect combustion

In direct combustion the solid fuel is directly burned to release its

* Corresponding author.
E-mail address: mr.sedighi67@gmail.com (M. Sedighi).

http://dx.doi.org/10.1016/j.rser.2016.11.175
Received 17 February 2015; Received in revised form 6 October 2016; Accepted 12 November 2016

chemical energy content. An example of this is the rocket stove [11], which is amongst the most efficient stoves with the lowest emissions [6]. In indirect-combustion, as in a gasifier stove, combustion takes place in two stages. The combustible gases are first produced from biomass fuel and burn by mixing with air in the presence of a natural or forced draft. This increases efficiency up to 35% and decreases emissions about 90% in comparison with a three-stone fire [16]. It also offers a 77% reduction in emissions compared with mud stoves [17].

2.1. Gasification

Gasifiers have been categorized into four groups: (1) feed gas, which includes air, oxygen and steam (CO_2) agents; (2) heat source, classified as direct gasifiers in which partial combustion of solid fuel supplies the required heat and indirect gasifiers in which an external source provides the needed energy; (3) gasifier pressure, either atmospheric or pressurized; (4) reactor design including fixed bed (the most easy-to-construct), fluidized bed (a more complex design), and the uncommon entrained flow [18]. Characteristic parameters of the performance of the biomass gasifier are synthesis gas composition and gasification efficiency [19]. The precise components of gas release from biomass as assessed by operating temperature and pressure, type of fuel, gasification reactor design, moisture fuel-content and gasification agents are too complicated to predict [20].

2.1.1. Gasification agents

Air/oxygen, steam or a mixture of these are generally used as gasifying agents. Steam produces more H_2 and can increase the heating value to 10–15 MJ/Nm^3. O_2 gasification agent provides 3–6 MJ/Nm^3 of heating value [19,21]. Lucas et al. [22] demonstrated that increasing the molar fraction of steam in an air-steam gasification agent from 0% to 83% increases H_2 formation from 13% to 29%. Garcia [23] reported that tar, char and CH_4 can be converted to H_2 and CO if CO_2 is used with Ni/Al as a catalyst and will yield more H_2 and CO.

Gasification using steam is an endothermic process. The heat required must be provided either through partial biomass oxidation using air or oxygen as a feed gas or by external sources by preheating the steam feed or transferring the heat through the external surfaces of the gasifier reactor body. A combination of steam (or CO_2) and oxygen (or O_2) is recommended as the gasifying agent to produce the heat required for gasification [22].

Lucas et al. [22] demonstrated the effect of preheated feed gas on gasification. The lower heating value of synthesis gas increased from 6.9 to 8.7 MJ/Nm^3 when the temperature of preheated feed gas increased from 350 to 830 °C. If the gasifying medium is preheated to a high temperature, less tar and char is produced and more syngas is released [24,25].

2.1.2. Gasifier-biomass ratio

Abuadala et al. [26] studied the hydrogen produced through gasification of sawdust using energy and exergy analysis. They showed that increasing the fuel decreased CO and H_2 production and H_2 production increased as the steam increased. CO decreased as the steam increased. Abuadala et al. used a low steam-biomass ratio of 0.15 to 0.51, resulting in a 51% to 63% hydrogen concentration [26]. Steam–biomass ratio was studied by Herguido et al. [27], who measured gas products at different gasification temperatures. H_2 production was reported to be 38% to 56%. Although the components of syngas change as the operating temperature and type of fuel consumed changed, they demonstrated that when temperature increased to 780 °C, the gas products become independent from the type of fuel [27].

Ptasinski [28] used exergy analysis to evaluate biomass gasification in the presence of air and steam gasifiers. He reported that exergy efficiency, the ratio of the exergy of gas and char as products to the exergy of biomass and air/steam as reactants, reaches a maximum of about 80% for air gasifier at the equivalence ratio of 0.26 kg/kg and about 87% for steam gasifier at the 1.3 kg/kg equivalence ratio. The carbon boundary is an optimal point at which a sufficient amount of gasifier does not produce carbon and hence attains complete combustion [29]. Efficiency at the carbon boundary point was 80.5% and the efficiency of slow pyrolysis with no extra air supply was 76.8% [30].

2.2. Biomass fuel characteristics

2.2.1. Fuel types

Ptasinki [28] evaluated the energy and exergy efficiency of grass, vegetable oil, manure, treated and untreated wood, straw, sludge and coal as biofuel. The energy efficiency was calculated using the lower heating value and exergy efficiency was tested for chemical exergy alone and combined chemical and physical exergy. Energy (or exergy) efficiency is determined by the energy (or exergy) of the combustible gases produced to the energy (or exergy) of the solid fuel. The energy efficiency for coal, treated and untreated wood, vegetable oil, grass and straw was similar, but sludge and manure had significantly lower efficiencies. The vegetable oil and coal had higher chemical and physical exergies in comparison with other biomass fuels. The chemical exergy of coal and vegetable oil was about 75% and for the others were 70–72% [28].

Wood is a preferable and superior solid fuel, but when wood is not accessible other biomass fuels can be used [31]. Arora et al. [32] reported that different fuel types produce different ranges of CO and PM emissions. Mustard stalks increased the CO to 45% and PM to 70% over firewood and kerosene, respectively. They studied the effect of fuel feeding interval on CO emissions. A fuel feeding interval of 15 min increased the CO concentrations up to 60% over a fuel feeding interval of 7 min as a result of smoldering [32].

2.2.2. Fuel sizes

The size of the fuel particles effects the heat released and the average temperature of particles. The heating value of combustible gases decreases when the fuel size increases. The gasification of small particles increases the amount of gases produced and the heating value of the producer gas. The use of fuel powder decreases gasification efficiency. Consequently, there is an optimal particle size to boost gasification [33]. Baldwin [34] explained that thick chips require a forced draft. The particle size influences the burn rate and emission production depending on the diameter of the reactor (D) [13]. The D/5 fuel size increases thermal efficiency over the other sizes [35].

2.2.3. Fuel moisture

Fuel moisture influences cookstove performance. MacCarty [36] studied the effect of fuel moisture content on efficiency of rocket stoves and found that efficiency increased from 33.9% to 36.6% when the moisture content increased from 0% to 30%. Yuntenwi et al. [37] demonstrated that the influence of wood fuel water content on combustion efficiency and emission is dependent on cookstove type. They tested a traditional open fire, a Chinese rocket stove and a skirt stove. The test examined moisture contents of 5–30%. The moisture content partially affected emissions either constructively or adversely.

The time required to bring water to a boil depends on the moisture content. Increasing the moisture content increases the boiling time and the amount of fuel consumed. The results show that there is an optimum moisture level at which the fuel shows improved functioning. Wet fuel increases fuel consumption, pollutants and cooking time. Certain amounts of moisture decrease emissions over dry fuel [37]. Fig. 1 compares the amount of fuel consumed in the three stoves.

2.3. Heat output control

There is a poor control of heat output in gasifiers. Kshirsagar [6]