Improving Combustion Technology for Cooking Activities for Pollutant Emission Reduction and Carbon Neutrality

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Abstract: Inefficient residential solid fuel combustion contributes significantly to ambient and indoor air pollutants. It consumes large quantities of fuel and produces harmful effects on health. Improvements in residential biomass cooking stoves have great potential for energy savings and emission reduction. This study presents an advanced biomass gasifier cooking stove to overcome the disadvantages of high-pollutant emissions from widely used stoves in China. The most innovative features of the stove are (1) negative pressure produced by a jet fan located at the junction of the chimney, and (2) combustion and carbonization processes taking place in the same chamber. Compared with a traditional chimney stove, the advanced biomass gasifier cooking stove presented higher TE (thermal efficiency) and comprehensively lower pollutant emissions when raw crop straws, crop straw briquettes, and pellets were burned in it. Approximately 40% CO₂ and 90% of PM₂.₅ (the aerodynamic diameter was less than or equal to 2.5 µm) EFs (emission factors) were eliminated, and TE drastically tripled. Furthermore, biomass briquette/pellet was identified as more suitable than raw biomass as a fuel to be burned in the new stove, especially because the raw biomass displayed an increase in the EFs of As, Se, and Pb when burned in the new stove. The advancement in biomass cooking stove technology is a practical approach to reducing the emissions of CO₂, PM₂.₅, and other hazardous pollutants.

Keywords: stove technology; CO₂ emissions; biomass combustion

1. Introduction

Solid fuels are still used in traditional stoves or open fires for cooking or heating by approximately 3 billion people around the world [1,2]. There is strong evidence showing that residential emissions contribute greatly to air pollution [3]. About 5.4% of global GHG (greenhouse gas) emissions come directly from household combustion [4]. In China, rapid economic development has been accompanied by a continuous increase in CO₂ emissions [5]. At present, China is the most important emitter of GHGs, accounting for about 30% of the world’s total anthropogenic carbon emissions [5,6]. In China, household consumption takes up 40% of total GHG emissions [7]. In September 2020, general secretary Xi Jinping declared to the world at the seventy-fifth United Nations General Assembly that China would strive to achieve their peak in CO₂ emissions before 2030 and to achieve carbon neutralization by 2060. The CO₂ emissions caused by residential coal combustion was estimated to be about 5.0% in China [3]. The development of low-carbon cooking is important in carbon reduction. Two activities play key roles in the reduction in GHGs in the atmosphere: the reduction in anthropogenic emissions of CO₂ and the creation or promotion of carbon sinks in the biosphere. Residential emission reduction can be achieved by decreasing coal consumption and by developing combustion technology. As a renewable and CO₂-neutral energy source, biomass is said to be widely adopted for fossil energy saving and CO₂ reduction all over the world [8–10], providing about 10% of the global...
energy supply [9]. Its easy accessibility and low cost also contribute to its widespread utilization, especially in developing countries. In China, biomass fuels (e.g., crop residues and firewood) are still widely used in traditional agricultural areas and poor remote rural areas despite the promotion of clean energy in the past decade in China [11,12]. The GHG mitigation potential of China’s bioenergy would be 1653–5860 Mt CO$_2$ by 2050 [10]. At present, however, a large amount of biomass is directly burned without using advanced combustion technology [13]. In some less-developed provinces in China, three-stone stoves and unvented stoves (without chimneys) are still the most popular biomass cooking stoves, accounting for 76% and 67% in Guizhou and Yunnan’s total stoves, respectively [14,15]. When burning in inefficient stoves, raw biomass not only releases excessive CO$_2$ per unit energy but also discharges various harmful gases and particles [3], such as PM$_{2.5}$, CO, and other toxic compounds. Extended exposure to contamination poses a serious health hazard, particularly for women and children who spend much time indoors [16–18]. In addition, it endangers the outdoor ambient air beyond the household [19,20], resulting in severe haze pollution, decreased visibility, and acid rain, etc. [21,22]. Therefore, energy conservation and emission reduction are necessary for the sustainable utilization of biomass.

Refined fuel and stoves will most likely serve as practical solutions to the above issues [3,23,24]. First, compressing raw biomass into pellets or briquettes is an effective way to reduce pollutant emissions because they generate far lower EFs than the corresponding raw (or unprocessed) materials [25–28]. When crop straw was burned in pellet form, most of the air-pollutant emissions dropped by over 80% [29]. Similar results were discovered in woody materials [30,31]. In addition, pellets are convenient for storage and transport due to their significantly larger densities. Second, improvements in combustion efficiency of household stoves is the other major method of reducing pollutant emissions from domestic biomass burning [3,24]. In recent decades, stove types have been continuously upgraded [32–35]. The innovations mainly lie in structural changes and functional accessories [33,36,37]. For instance, the rocket stove with a “rocket elbow” structure emitted a flame like an inverted rocket when biomass burned in it [38], achieving a reduction of 75% in CO emission and 46% PM (particulate matter) emission compared with the three-stone open fire [39]. In addition, the design of the down-draft stove was based on reverse combustion technology with the flame located below the fuel. It achieved a significant reduction of 79% in PM$_{2.5}$ emission [40]. Notably, quite a number of programs have been undertaken in mainland China to develop household stove technologies since the early 1980s [41–43]. Highly efficient biomass stoves have been effectively promoted. The most popular models include hand-made brick cooking stoves without grate and chimney (before 1980s), an advanced stove with a chimney for the smoke exhaust (during 1980s), and a biomass gasification stove (in the late 1990s) [42]. Until recently, gasifier cooking stoves, which features a secondary air supply from the top in addition to the primary air supply from the bottom, have been introduced to further improve TEs and to decrease pollutant emissions [44,45]. However, the major weakness lies in the fact that they fail to meet the national indoor air-quality standard (GB/T18883-2002), in part because of the wide variety of fuels and stove combinations used by households [43]. Because the gasification furnace is directly connected to the stove, gasifier cooking stoves have problems such as unsafe use, and excessive tar deposal and waste water [46] and therefore are not widely used. Additionally, the advanced stove with a chimney for smoke exhaust, which was the most popular model in the 1980s, has still been widely used over the past few decades [47]. To sum up, biomass gasifiers need innovation for better performance in safety, convenience, applicability, and emission reduction capacity.

Considering the goals of carbon neutrality and pollutant reduction, this study introduces an advanced gasifier cooking stove with convenient and safe operation for biomass burning. It is characterized by both combustion and carbonization processes happening in the same chamber due to the positive effect of newly increased negative pressure. Combustion properties of the stove are thoroughly investigated in comparison with a widely used chimney stove in present rural China. Three crop straws, three biomass briquettes, and one
pellet are measured, taking the TEs and EFs of CO\textsubscript{2}, PM\textsubscript{2.5}, NO\textsubscript{x}, SO\textsubscript{2}, and toxic elements as the target parameters. The mechanism of pollutant reduction and TE development of the advanced biomass gasifier cooking stove are also investigated.

2. Materials and Methods

2.1. Solid Fuel Samples

The residues of corn, rice, and wheat dominate the energy potential of China’s crop residues, occupying 74.7% of the total potential [10], and wood is widely used as household fuel in Chinese rural areas [48]. Therefore, this study chose the three common crop straws and one sawdust (details in Table 1) from Xuzhou of Jiangsu province in China for comparative experiments, and raw, briquette, and pellet were the measured combustion forms. The briquettes of the three crop straws were made using the following process: molding pressure of 25 MPa, particle size of 1 mm, ellipse shape (3 cm diameter and 2 cm height), and 10% clay (bonding agent). The pellet used was purchased from the market. In order to avoid the influence of moisture on the test results, all samples were dried in an oven at 105 °C for 16 h until constant mass was achieved [49].

| Raw Material     | Industrial Analysis (%) | Elemental Analysis (%) | Q\textsubscript{net,ar} (MJ/kg) |
|------------------|--------------------------|------------------------|-------------------------------|
|                  | M\textsubscript{ar} \textsuperscript{1} | A\textsubscript{d} \textsuperscript{2} | V\textsubscript{daf} \textsuperscript{3} | FC\textsubscript{d} \textsuperscript{2} | C\textsubscript{daf} \textsuperscript{3} | H\textsubscript{daf} \textsuperscript{3} | O\textsubscript{daf} \textsuperscript{3} | N\textsubscript{daf} \textsuperscript{3} | S\textsubscript{t,d} \textsuperscript{2} |
| Wheat straw      | 5.68                     | 8.97                   | 74.04                         | 81.33                         | 16.99                         | 49.76                         | 7.17                         | 42.00                         | 0.71                         | 0.33                         | 14.90                         |
| Rice straw       | 6.36                     | 10.38                  | 74.31                         | 82.95                         | 15.31                         | 49.18                         | 7.40                         | 42.30                         | 0.81                         | 0.28                         | 13.42                         |
| Maize straw      | 5.44                     | 5.03                   | 80.58                         | 84.85                         | 14.39                         | 48.66                         | 7.08                         | 42.86                         | 1.00                         | 0.37                         | 15.04                         |
| Sawdust          | 9.3                      | 2.93                   | 77.47                         | 79.81                         | 19.6                          | 53.04                         | 6.91                         | 39.33                         | 0.70                         | 0.02                         | 16.37                         |

\textsuperscript{1} M\textsubscript{ar} and Q\textsubscript{net,ar} denote the received moisture content and net calorific value, respectively. \textsuperscript{2} A\textsubscript{d}, V\textsubscript{daf}, FC\textsubscript{d}, and S\textsubscript{t,d} indicate the dry ash, volatile matter, fixed carbon, and total sulfur contents, respectively. \textsuperscript{3} V\textsubscript{daf}, C\textsubscript{daf}, H\textsubscript{daf}, O\textsubscript{daf}, and N\textsubscript{daf} indicate the dry and ash free volatile matter, carbon, hydrogen, oxygen, and nitrogen contents, respectively.

2.2. Tested Stove and Combustion Technologies

A typical domestic cooking stove in Chinese families, which was once called “advanced” chimney stove, was selected for the combustion experiments. The internal structures and mechanisms of the advanced biomass gasifier cooking stove and the chimney cooking stove for tests are shown in Figure 1. The corresponding stoves for the experiment are presented in Figure S1. The advanced biomass gasifier cooking stove was a top-loading, batch-fed stove. Compared with the previous gasifier [37], its internal space was roughly divided into two chambers: gas channel and fuel chamber, instead of gasification chamber and combustion chamber. The processes of combustion and carbonization were carried out in the same chamber. The biggest difference from previous gasifiers [37] was a booster fan (40 W jet fan) installed at the junction of the two chimney sections. It accelerated the flue smoke discharge and raised the negative pressure in the stove, resulting in faster forced secondary air. The booster fan operated continuously, which made up for the decreased combustion effect caused by the intermittent operation [32]. Devolatilization of the lower part of the combustion chamber was aggravated by negative pressure, and then, volatile matter was sent to the top of the combustion chamber to combust. The design of a secondary air passage outside the combustion chamber enabled the second air flow to be preheated by the stove wall before being mixed with the volatile matter. The ash at the upper part was beneficial to the pollutant reduction and promoted the burnout degree [50]. There was no need for catalyst addition [51].
The measurement method for TEs adopted in our research has been reported in previous publications [23,26]. CO, NO$_x$, SO$_2$ (Thermo Scientific; 43i, and 42i for CO, NO$_x$, and SO$_2$, respectively; Thermo Fisher Scientific Inc, Waltham, MA, USA), and CO$_2$ (GC-0012; Gas Sensing Solutions Ltd., Cumbernauld, Scotland) were tested using online gas analyzers. PM was sampled by a PM$_{2.5}$ cyclone (16.7 L/min, URG-2000-30 EH, URG Corp., Chapel Hill, NC, USA), a PM$_{1.0}$ cyclone (16.7 L/min, URG-2000-30EHB, URG Inc.), and a TSP sampler (homemade). The concentrations of gases were measured at room temperature and atmospheric pressure. The particle samples were weighted with a microbalance with a resolution of 10 $\mu$g to determine the mass, and then, the toxic elements of As, Se and Pb were analyzed using an energy dispersive X-ray fluorescence (XRF) spectrometer (NAS100, Nayur Technology Co., Ltd., Beijing, China) for the PM$_{2.5}$ samples. A kettle with 2.0 kg of room temperature water was employed to test the TEs each time. A second kettle with the same amount of room temperature water replaced the previous one when the water temperature reached 90 °C in case water vapor ran into the flue piper [23,26]. The kettles were exactly the same, and the initial water temperature was kept constant every time. Each test was repeated three times to maintain accuracy of the experiment.

2.4. Analysis Methods

The mass-based $EF_m$ of TSP, PM$_{2.5}$, and PM$_{1.0}$ were calculated using Equation (1).

$$EF_m = M_f \times F / M_c$$

(1)

where $M_f$ is the particle mass collected, $M_c$ represents the dry mass of solid fuel (0.2 kg for raw biomass, 0.6 kg for biomass briquettes and saw-dust pellets), and $F$ stands for the ratio of total flow rate in the dilution tunnel to the sampling flow rate.

The $EF_m$ of As, Se, and Pb were obtained with the following equation (Equation (2)).

$$EF_m = C \times 52.8 \times F / M_c$$

(2)

where $C$ is the mean concentration of As, Se, or Pb in the tested PM$_{2.5}$ quartz filter with the sampling area of 52.8 cm$^2$.

The $EF_m$ of NO$_x$ and SO$_2$ were determined with Equation (3).

$$EF_m = \frac{Q_f \rho_s}{M_c} \int_{\text{start time}}^{\text{extinction time}} C_s \, dt$$

(3)

where $C_s$ (ppm) is the measured concentration of CO, CO$_2$, NO$_x$, or SO$_2$; $\rho_s$ is the species density; and $Q_f$ is the gas flow rate in the tunnel.

Figure 1. Schematic diagram of the stove used in the experiment: (a) advanced biomass gasifier stove and (b) traditional chimney stove.
The TE was derived from the increased temperature (ΔT) of the water in the kettle. It can be expressed as Equation (4).

\[ TE = M_w C_w \Delta T / M_c Q_c \] (4)

where \( M_w \) stands for water mass in the kettle, \( C_w \) is the specific heat capacity of water, and \( Q_c \) is the net calorific value as received.

The delivered energy-based \( EF_t \) was obtained as Equation (5).

\[ EF_t = EF_m / (TE \times Q_c) \] (5)

\( MCE \) (modified combustion efficiency) was determined using Equation (6).

\[ MCE = \Delta CO_2 / (\Delta CO_2 + \Delta CO) \] (6)

where \( \Delta CO_2 \) and \( \Delta CO \) are the fire-integrated excess molar mixing ratios of \( CO_2 \) and \( CO \), respectively, and refer to the EFs of the overall combustion processes of \( CO_2 \) and \( CO \).

\( \eta_{br} \) (burnout ratio) was calculated as Equation (7).

\[ \eta_{br} = (1 - A_{bot}) / (1 - A_d) \times 100\% \] (7)

where \( A_{bot} \) is the ratio of bottom ash mass to the fuel mass in a combustion cycle and \( A_d \) represents ash on a dry basis obtained by proximate analysis.

3. Results
3.1. \( CO_2 \) Emmisions, MCE, and TE

Figure 2 presents the \( CO_2 \) EFs, MCE, and TE of all tested samples burned in both the advanced biomass gasifier cooking stove and the chimney stove. For the advanced biomass gasifier cooking stove, the delivered energy-based \( CO_2 \) EFs performed the reduction result, while an opposite trend was observed in MCE and TE. When the samples were combusted in the chimney stove, the \( CO_2 \) EFs were 1.76–1.99 g/kJ for raw crop straws and 0.96–1.3 g/kJ for biomass briquettes/pellets, respectively. In the advanced biomass gasifier cooking stove, the values were reduced by 34.7–45.5% and 32.8–61.0%. The TEs were 1.97–2.29% for the chimney stove, and the values were 4.55–6.53% when raw crop straws were burned in the advanced biomass gasifier cooking stove. The trend was more obvious when biomass briquettes/pellets were under study, curving a development from 3.83–4.60% to 10.14–13.66%. Improvements of 14.7–16.1% and 6.2–10.9% were presented in terms of MCE for raw crop straw and biomass briquettes/pellets, respectively, as well.
from raw biomass, biomass briquettes, and pellets compared with the chimney cooking stove.

Figure 2. (a) TEs, (b) CO$_2$ EFs, and (c) MCE for raw crop straws, biomass briquettes, and pellets burned in the advanced biomass gasifier cooking stove and the chimney cooking stove.

3.2. Emissions of PM, NO$_x$, SO$_2$, and Three Toxic Elements

The PM$_{2.5}$ EFs of raw crop straws, biomass briquettes, and saw-dust pellets combusted in the advanced biomass gasifier cooking stove and the chimney cooking stove are listed in Figure 3 (detailed EF information of PM$_{2.5}$, TSP, and PM$_{1.0}$ is listed in Table S1). For the chimney cooking stove, the PM$_{2.5}$ EFs were $256.7 \pm 11.2$ mg/kJ, $235.8 \pm 3.7$ mg/kJ, and $109.72 \pm 7.0$ mg/kJ for raw maize straws, wheat straws, and rice straws, respectively. When they were burned in the advanced biomass gasifier cooking stove, the values dropped sharply to $14.58 \pm 3.06$ mg/kJ, $14.67 \pm 3.89$ mg/kJ, and $13.68 \pm 6.43$ mg/kJ, which means as much as $94.3 \pm 1.2\%$, $93.8 \pm 1.7\%$, and $88.7 \pm 4.9\%$ of PM$_{2.5}$ were eliminated. When the biomass briquettes and pellets were tested, they were $28.0 \pm 2.81$ mg/kJ, $37.0 \pm 4.33$ mg/kJ, $58.57 \pm 4.48$ mg/kJ, and $20.46 \pm 3.54$ mg/kJ for maize straw briquettes, wheat straw briquettes, rice straw briquettes, and saw-dust pellets in the chimney cooking stove, and then, the values shrank to $3.17 \pm 1.33$ mg/kJ, $3.51 \pm 0.43$ mg/kJ, $3.63 \pm 0.64$ mg/kJ, and $3.24 \pm 0.28$ mg/kJ in the advanced biomass gasifier cooking stove. The reduction rate was as high as $88.7 \pm 4.9\%$, $90.5 \pm 1.6\%$, $93.8 \pm 1.2\%$, and $84.2 \pm 3.1\%$, respectively. This indicates that the advanced biomass gasifier cooking stove can effectively reduce PM$_{2.5}$ emission from raw biomass, biomass briquettes, and pellets compared with the chimney cooking stove.
Figure 3. PM$_{2.5}$ EFs for raw crop straw, biomass briquettes, and pellets burned in the advanced biomass gasifier cooking stove and the chimney cooking stove.

Figure 4 details the NO$_2$ and SO$_2$ EFs from raw crop straws, biomass briquettes, and pellets burned in the advanced biomass gasifier cooking stove and the chimney cooking stove. The NO$_x$ EFs were 9.47 ± 1.72 mg/kJ, 7.86 ± 3.91 mg/kJ, and 5.01 ± 3.03 mg/kJ for the three raw crop straws in the chimney cooking stove, and the values slumped to 2.93 ± 0.15 mg/kJ, 2.36 ± 0.26 mg/kJ, and 2.48 ± 0.3 mg/kJ when combustion occurred in the advanced biomass gasifier cooking stove. The decreasing trend was also presented by the SO$_2$ EFs, which diminished from 1.68 ± 0.06 mg/kJ, 2.6 ± 0.95 mg/kJ, and 1.43 ± 0.23 mg/kJ to 0.24 ± 0.02 mg/kJ, 0.6 ± 0.06 mg/kJ, and 0.42 ± 0.05 mg/kJ, respectively. Based on the above data, it can be concluded that the advanced biomass gasifier cooking stove can achieve effective reduction in NO$_x$ (by 50.5–70.7%) and SO$_2$ (by 70.6–85.7%) from raw crop straw burning. However, the opposite trend manifested itself for both NO$_x$ and SO$_2$ when biomass briquettes and pellets were studied. This indicates that the advanced biomass gasifier cooking stoves can possibly release more NO$_x$ and SO$_2$ from the biomass briquettes or pellets burning.

Figure 5 shows the toxic elements EFs from raw crop straws, biomass briquettes, and pellets burned in the advance biomass gasifier cooking stove and the chimney cooking stove. For biomass briquettes and pellets in the chimney cooking stove, the EFs of As, Se, and Pb reached 0.53–8.48 ug/kJ, 0.27–0.5 ug/kJ, and 4.22–16.87 ug/kJ, while the values fell to 0.22–2 ug/kJ, 0.08–0.3 ug/kJ, and 0.94–4.72 ug/kJ in the advanced biomass gasifier cooking stove. Another significant decline was discovered ($p = 0.050$), namely 55.4–92.8%, 37.5–70.4%, and 72–94.1%.

However, a negative effect was also noticeable: raw crop straws released more toxic elements in the advanced biomass gasifier cooking stove. Raw straw therefore was not the ideal fuel for this stove when a reduction in toxic element emissions was set as the aim.
Figure 3. PM2.5 EFs for raw crop straw, biomass briquettes, and pellets burned in the advanced biomass gasifier cooking stove and the chimney cooking stove.

Figure 4. (a) NO\textsubscript{2} EFs and (b) SO\textsubscript{2} EFs for raw crop straws, biomass briquettes, and pellets burned in the advanced biomass gasifier cooking stove and the chimney cooking stove.

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4. Discussion

Due to its unique air-supply design of the negative-pressure system, the advanced biomass gasifier cooking stove effectively improved the TEs from the residential combustion, and the pollutants emissions decreased as well: about 40% in CO\(_2\) and about 90% in PM\(_{2.5}\). The biomass briquette/pellet performed better in the stove regarding TE and pollutant emissions. Under the action of the negative-pressure system, three aspects could account for these improvements: the three-stage combustion in the same chamber, top, ash and heat transfer.

First, the mode of three-stage combustion in the same chamber induced by negative pressure contributed to sufficient combustion with more energy release, and it ultimately resulted in the TE increase. The advanced gasifier cooking stove was characterized by the processing of combustion and carbonization in the same chamber, dividing the combustion process into three stages. The first stage was devolatilization. As the biomass was ignited from the upper part after being loaded into the combustion chamber, volatile matter was rapidly discharged due to the combined action of the top high temperature and the increased negative pressure. The second stage was volatile matter combustion. The volatile matter was sent into the upper combustion region caused by the enlarged negative
pressure as well and then burned with the secondary air provided. The third stage was the combustion of biomass coke located in the lower part of the combustion chamber. It was induced by sufficient air under the action of negative pressure, solving the problem of difficult utilization of biomass coke in rural areas. Sufficient combustion converted more carbon elements in biomass into CO$_2$, which was proved by the $\eta_{br}$ of bottom ash (ranged from 99.5–99.7%). The experimental results of higher EFs of SO$_2$ and NO$_x$ from biomass briquette/pellet burned in the advanced biomass gasifier cooking stove offered strong evidence that the fuel’s combustion was sufficient (see Figure 4), indicating that more sulfur and nitrogen elements in the biomass briquette/pellet were oxidized by sufficient oxygen. In addition, this conclusion was supported by the development trend in the MCE as well. Contributing to the advantage of biomass combustion form, briquettes/pellets showed more efficient combustion effect than raw biomass. The three-stage combustion mode broke through the limitation of insufficient air supply compared with the chimney cooking stove, in which combustion occurred mainly with insufficient air. The decrease in EFs of SO$_2$ and NO$_x$ for raw biomass burned in the advanced biomass gasifier cooking straw was mainly due to the increase in TE. An opposite trend was discovered with the biomass briquettes and pellets, which was related to the thermal diffusion speed. Biomass briquettes/pellets had lower devolatilation speed due to its high density, which led to uniform thermal diffusion. The combustion was carried out more thoroughly.

Second, the upper ash generated by biomass combustion slowed down the flow of volatile matter from the lower chamber to the upper chamber and enhanced the combustion with sufficient oxygen provided in time. Therefore, the upper ash layer, together with the effect of three-stage combustion mode, was responsible for the PM reduction in which the precursor organic components were decreased with the complete combustion [22,25].

Third, the high temperature region was elevated from the top of fuel due to the increased negative pressure, which enhanced TE and pollutants emissions. The rise in the high temperature region from the chamber of the furnace enabled the fuel to provide more sufficient heat to the kettle, thus improving the TE. The heat in the combustion chamber was moved away from the fuel in time. Consequently, the gasification of toxic elements of As, Se, and Pb was inhibited for biomass briquettes and pellet burning, resulting in the slump of toxic elements emission as well (see Figure 5). However, the burning of raw biomass displayed a significant increase in the EFs of As, Se, and Pb for the advanced biomass gasifier cooking stove, which was related to its raw combustion form. More toxic elements from raw biomass were released owing to the rapid and thorough combustion and concentrated thermal release.

5. Conclusions

To reduce pollutant emission of CO$_2$ and other pollutants by improving household cooking stove, we introduced an advanced biomass gasifier cooking stove and conducted a comparatively experimental investigation to identify its combustion property compared with the previous “advanced” chimney stove. The major findings include the following: (1) Both raw and molded biomass presented developed TEs, namely from 1.97–2.29% to 4.55–6.53% and from 3.83–4.60% to 10.14–13.66%. Approximately 40% CO$_2$ and 90% of PM$_{2.5}$ EFs were reduced. The biomass briquette/pellet performed much better with the stove in terms of TEs and pollutants emissions. (2) Biomass briquettes/pellets was more suitable for use in the advanced biomass gasifier cooking stove. (3) The stove is safe and easy to operate without the trouble of biomass coke.

Based on the above findings, the advanced biomass gasifier cooking stove can be regarded as a viable substitute for the traditional biomass and coal stoves. Its environmental benefits are evaluated as follows. The biomass used for cooking in China is approximately 17.2 Mt, producing 6.88 Mt CO$_2$ and 0.33 Mt PM$_{2.5}$ [25,51]. There will be dramatic reductions of 2.76 Mt in CO$_2$ and 0.29 Mt in PM$_{2.5}$, if the advanced gasifier stove can be comprehensively adopted in household activities throughout the nation. About 0.17 billion households live in Chinese remote rural areas, which are rich in biomass resources. They
will benefit from the advanced biomass gasifier cooking stove [52]. It can be summarized that the marked superiority of the advanced biomass gasifier cooking stove is substantially beneficial to pollutant reduction and energy utilization. It will play an important role in improving rural indoor air quality and bringing about possible health benefits. It is therefore a practical and promising approach for CO$_2$ reduction from household activities and is a sustainable path to realize carbon neutralization and carbon emission reduction by biomass utilization.

**Supplementary Materials:** The following are available online at https://www.mdpi.com/article/10.3390/atmos13040561/s1, Table S1: TSP, PM2.5, and PM1.0 EFs of tested samples in this study, Figure S1: Photos of the tested residential cooking stove: (a) the advanced gasifier cooking stove and (b) the traditional chimney stove.

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