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Review

Application of Biomass Smoldering for Rural Building Heating in China: Strengths and Challenges

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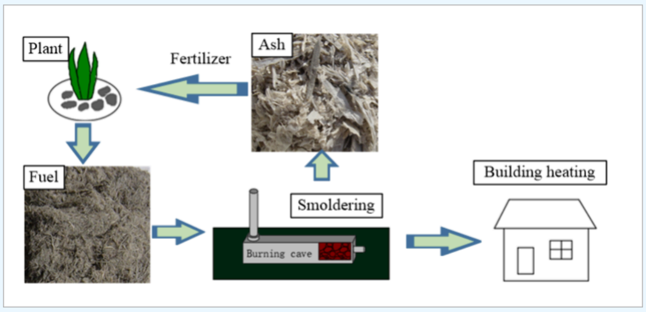
ABSTRACT: Biomass smoldering for rural building heating could be a potential choice for bioenergy utilization in China to reduce the pollution caused by agroresidues open burning and to satisfy the increased demand of rural building heating. Its strengths include low pretreatment, transportation, and storage fees of fuel; ease of operation; good fertilizer characteristics of ash; use of latent heat of water vapor; pollution reduction; reduction of pests, weeds, and plant diseases on the farm; etc. However, controls of the burn rate and the gas emission are two challenges of the application, and related solutions of these challenges are discussed.



1. INTRODUCTION

Field burning of agroresidues after harvest is conducted worldwide at present.[1−3] In China, with increasing crop yields, increasing quality of life, and the possibility of using other energy sources, open burning of crop residues has been occurring frequently in grain-producing regions—especially the rural urban fringe zone—although the government has enacted many regulations to prohibit field burning since 1990.[4] In Spain, the most frequent technique used to eliminate cereal waste is field burning.[5] In the USA, many farmers in the Inland Pacific Northwest region burn crop residues in the field after harvest, and public smoke exposure has led to legal and regulatory pressure to curtail such burning.[6]

Field burning causes not only air pollution but also is a waste of renewable energy.[7] Generally speaking, field burning of agroresidues emits very heavy smoke, which includes particles, organic and inorganic aerosols, incomplete combustion gas, etc. These emissions pollute the air and have caused several serious highway and air transportation accidents in China. What is more, by field burning, the only storable form of solar energy is wasted.

At the same time, building heating demand has grown fast in China. Heating is necessary for more than two-thirds of the China area in winter, and rural building heating constitutes 25% of total building energy consumption in China.[8] It is recorded that building energy use has increased by 40% from 1990 to 2009.[9] The rural building heating demand is expected to increase faster because of the poor current heating systems in rural areas, the income growth of farmers, the pursuit of more comfortable living environments, the expectation of more appropriate conditions for growing of plants and raising animals, and the fast increase (35% in 2010[9]) of the building floor-space.

In rural areas of northern China, coal burning is always the main heating method. However, this leads to severe air pollution. In recent years, some policies on clean burning have been introduced to control pollution. For example, loose coal is no longer allowed to be burned in most rural areas, and the proportion of clean energy heating in total heating should be increased to 50% in 2019 and 70% in 2021.[10] This is one big challenge to rural building heating. Agroresidues as clean energy can offer considerable prospects for replacing loose coal, and its application can meet the needs of rural heating.

As an improved type from traditional heating method, burning caves are increasingly used in rural building heating in China due to a better heating effect than Kang and mini stoves, ease of operation, free fuels from agro and forest wastes, and simple structure.[11] In 2012, there are 200,000 burning caves in use in north China. The most prominent feature of this utilization is that biomass fuels are smoldered in a chamber.[12]

In this paper, advantages and challenges of utilization of biomass smoldering for rural building heating are analyzed. Part 1 introduces the current utilization of biomass smoldering in China. Part 2 describes the advantages of the application of biomass smoldering for rural building heating in China. Part 3

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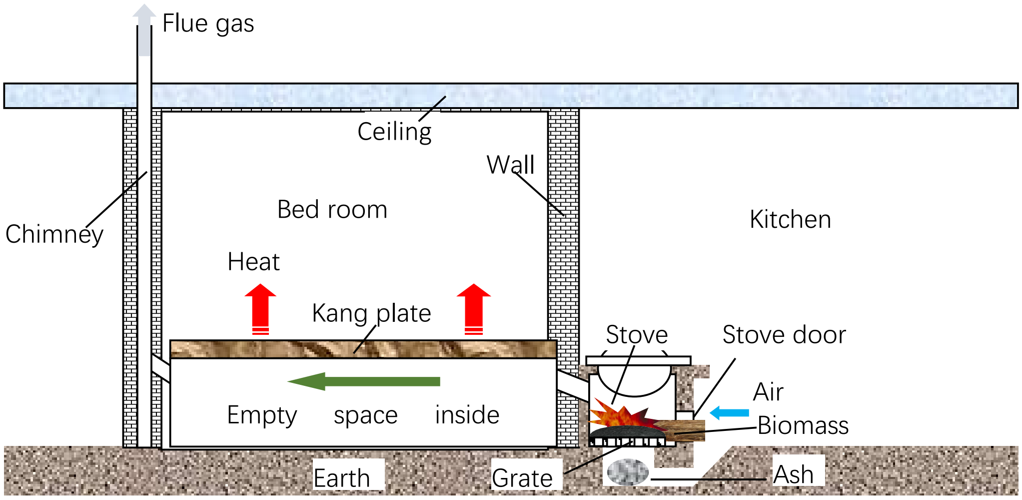

Figure 1. Schematic of a typical Kang.

discusses its challenges and related solutions. Finally in part 4, conclusions are summarized.

2. UTILIZATION OF BIOMASS SMOLDERING IN CHINA

Smoldering is a slow, low-temperature, flameless form of combustion.[13−15] It is a method of biomass utilization in China,[11] a hazard in many kinds of fire, and a novel technology concept under development.[16]

2.1. Wei Kang.[8,17] Utilization of biomass smoldering for heating has a long history in China. Wei Kang[8,18,19] is a typical example. A large scale field survey in 2006 showed that Kangs were found in nearly 85% of rural homes in northern China where it is mostly cold and dry in winter with 6−9 months of heating season, and as well as in Shandong and Henan Provinces.[5] The schematic of a Kang (includes a stove) is shown in Figure 1. Kang is used for cooking, sleeping, and domestic heating. During cooking, agroresidues or fire wood is burned in the stove, and the flue gas flows through the empty space below the top surface of the Kang and then goes out through the chimney. Heat is emitted to the room and absorbed by the clay of the Kang and the wall. After the extinguishing of the fire, the Kang will continue releasing the stored heat for a considerable time.

Wei Kang is necessary on cold days. It refers to the following process: a relatively large amount of fuel (∼ several kilograms) is filled together into the stove after cooking. And then the stove door is closed. The biomass keeps smoldering in the stove for several hours with the help of air leaked in through the gap between the stove and the stove door. This will keep the Kang warm for much longer time without the necessary of refilling fuel.

2.2. Hand/Foot/Chair Stove and Similar Applications. Another example is hand/foot/chair stove as shown in Figure 2. The stove probably appeared in the Sui Dynasty. The brass ones (Figure 2a) were often used in rich families, whereas the pottery ones and chair stove (Figure 2b) with bamboo/wood frames were often used in poor families. The small stove was often used to warm hands, feet, and body in cold days. Currently, the pottery stove is sometimes seen in rural area in China. Fuels are char from tree branches by carbonization, rice husks, incompletely combusted agrostalks from stoves, etc.

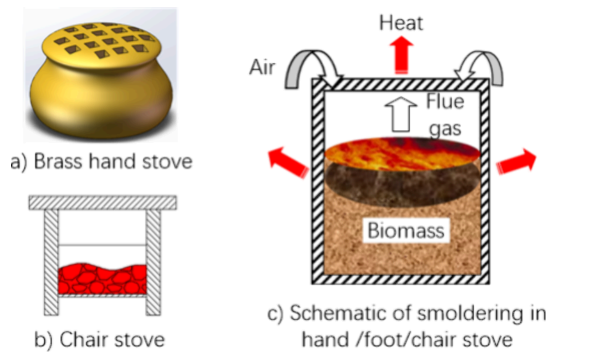

Figure 2. (a−c) Photos of hand/foot/chair stove and its schematic.

The schematic of the smoldering process in this small stove is shown in Figure 2c. The air diffuses into the fuel bed from the top of the stove, the flue gas flows up, and the smoldering propagates downward. The heat is transferred out through the side walls, the cover of the vessel, as well as with the flue gas. The process is very slow and keeps the shell of the vessel warm for several hours. The mechanism of the process has been investigated by He[20−23] both theoretically and experimentally.

A similar application also includes barbecue, which is applied worldwide. In China, other examples for preparing foods using biomass smoldering are shown in Figure 3. Figure 3a is an apparatus for cooking soup. The temperature in big pottery is about 180 °C, and the soup in small potteries is kept in the pottery for about 5−8 h. Figure 3b is a process for smoldering meat. Fresh pine branches are put on the top of smoldering old branches to bring some flavor to the meat and to form an anticorrosive layer. Temperature on the surface of the meat is

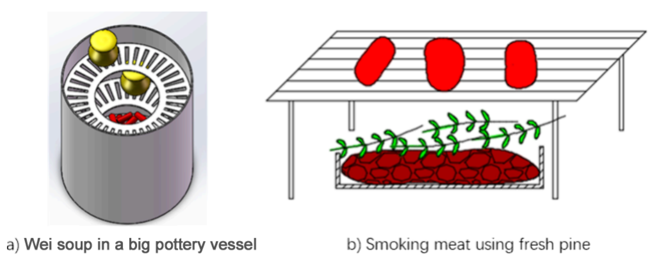

Figure 3. (a, b) Application of char smoldering in food cooking.

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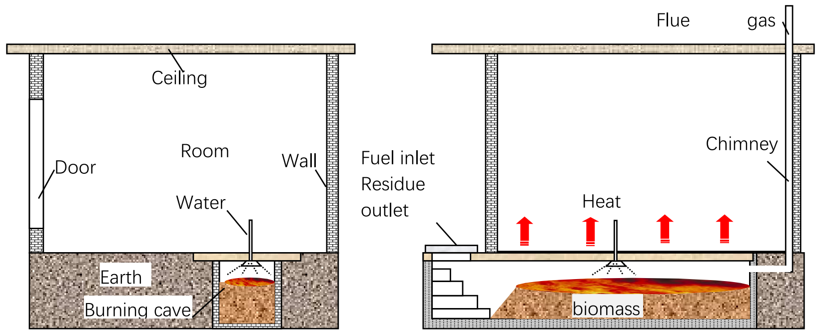

Figure 4. Schematic of a burning cave used for building heating in rural China.

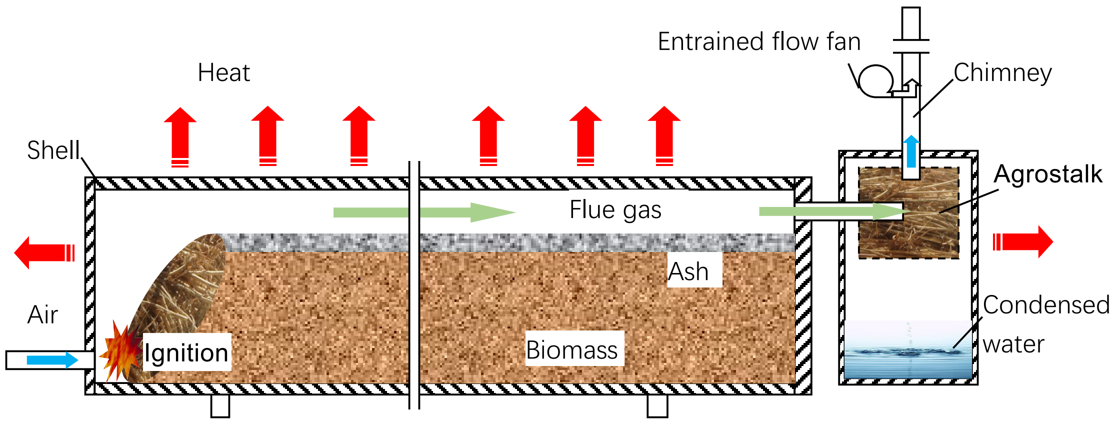

Figure 5. Schematic of a smoldering chamber.

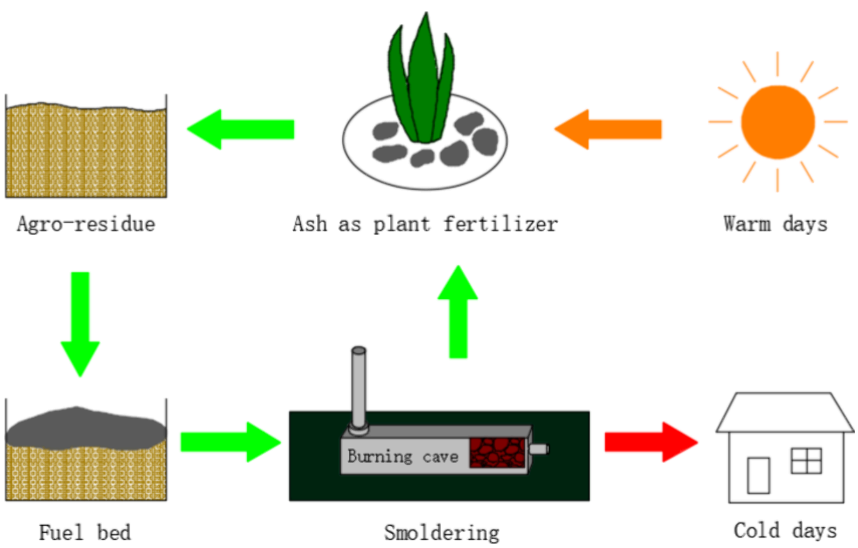

Figure 6. Mass and energy cycle of agroresidues in smoldering utilization.

controlled to be between 45 and 55 °C, and the pretreated meat (salted) is smoked for several or more than a dozen days.

2.3. Burning Caves. Burning caves[11] appeared in rural China in recent years, and its schematic is shown in Figure 4. Fuel is smoldered in a pit. The pit is rectangle or cylinder and is located below the building. The fuel inlet and the residue outlet can be located outside of the building to keep the rooms clean. Biomass is piled in the cave before the heating season. It is ignited in autumn, and smoldering is maintained for a long time (several weeks or the whole heating season). Air is leaked into the cave from the unsealed fuel inlet (or a separate air inlet tube), and flue gas goes out through the chimney. A water spray is often necessary for avoiding fire on the fuel bed. According to Chinese standard of DB 23T 316-2003 and our field survey,[24] the depth and the width of a burning cave are 1.6−2 m and 1.3−2 m, separately. And the length is flexible. Moisture content of fuel is around 40−50% in wet basis. To make the fuel loading frequency once a year, the floor area of the cave should be about 1/6 of the floor area of the building in Shandong Province in China.

2.4. Burning Chamber. A burning chamber is an optimization form of a burning cave. Sometimes it is referred

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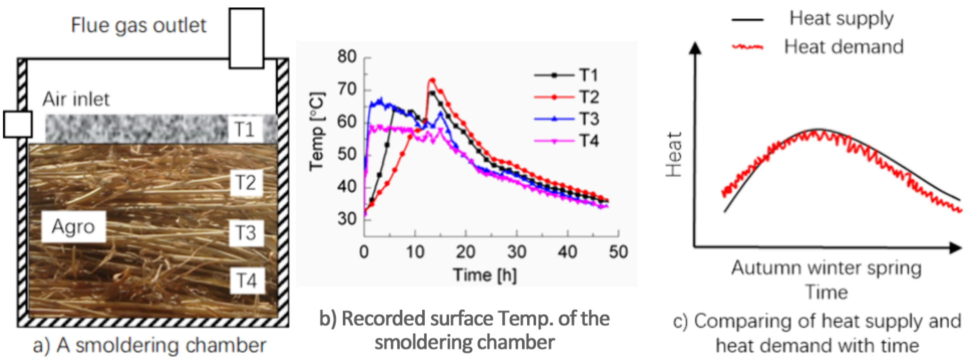

Figure 7. (a−c) Heat emission characteristics of a smoldering chamber and heat demand of a building in the heating season.

as a smoldering stove[25,26] (see also the authors' patent in Chinese: ZL 2005 20087539.1). The schematic of it is shown in Figure 5. It is characterized by a metal shell (can be made of 1 mm stainless steel), well arranged fuel bed (using ash above the fuel to avoid fire and to filter flue gas; see the authors' patent in Chinese: 201410128306), and no concrete construction in the earth (for heating of a greenhouse or a large-scale animal farm, it will not affect future utilization of earth when the building is dismantled).

It is flexible and portable. The metal surface of the chamber averages the surface temperature and enhances the heat transfer from the chamber to the environment.[27] The chamber is well sealed, and leakage of flue gas into the room is avoided. A gas cleaning and water vapor condensing instrument are added to the system, and the flexibility of the apparatus makes it possible for accurate control of the burning rate and emission.

3. STRENGTHS

Agroresidues have many more difficulties in energy utilization than other types of biomass (forest residues, wood chips, biomanufacturing waste, solid municipal waste, etc.). There are several reasons for this. The first one is that the agroresidues are seasonal products. Most of them are harvested within several days or weeks. The second one is its decentralized distribution. For example, the harvested yield of corn stover is around 0.5[28] to 0.9[29] kg/m^2. The third one is the low bulk density of the fuel. The loose piled bulk density of dry corn stover is only 20−40 kg/m^3.[29] For the chopped stalks, the loose filled bulk density is around 67.5 kg/m^3 for switchgrass, 36.1 kg/m^3 for wheat straw, and 52.1 kg/m^3 for corn stover.[30] Even for bales, the bulk density is only around 100−200 kg/m^3.[31] Due to the seasonal feature, the decentralized distribution and the low bulk density of agroresidues, the collection, transportation, and storage fees of centralized, all-around-year utilization are considerably high.[31−33]

Smoldering application for rural building heating can overcome most of the difficulties faced by other utilization. The mass and energy cycle of agroresidues in smoldering utilization are shown in Figure 6. After collection and little pretreatment of fuel, the fuel is loaded in the chamber and smoldered. Heat is emitted to the space indoors in cold days. After smoldering, ash is returned to field to help the growth of plants. And the new generation of biomass absorbs solar energy in warm days. There are many strengths of this application as follows.

3.1. Low Pretreatment, Transportation, and Storage Fees of Fuel. Agroresidues are the best smoldering fuels due to their high specific surface area,[34,35] high insulation properties, high oxygen content, and high gas penetration possibility. The specific leaf area of wheat straw is about 160−200 cm^2 per gram of dry mass.[36] The thermal conductivity of wood fibers is 0.042 W/(mK),[37] and the effective heat conduction coefficient of the fuel bed and the ash bed are even smaller. The oxygen content of biomass is around 40−50%.[38] For porous forest fuels, good permeability was found by Ernstson.[39]

At harvesting season, almost all agrostalks and grass—wet or dry, fresh or decayed, clean or dirty—sustain smoldering. Moisture content (% wet basis) of corn-residues at harvest is 55, 47, 82 for cob, husk, stalk and leaves, respectively, and the field dried of them are 19, 24, 33. In most burning caves, the moisture content of the fuel is around 40−50%. Frandsen[40] found that the moisture content limit and the inorganic to organic ratio limit to sustain smoldering is 93−103% (dry basis) and 4.3, respectively. In summary, very little pretreatment of fuel and storage requirement are necessary for smoldering.

The heating season normally begins at the harvesting season, and the heat demand of a rural building is characterized by decentralized distribution, seasonal, low heating load per unit floor-space. The rural building includes rural residential building, greenhouse, agricultural product processing factory, animal farm (e.g., hennery, hogpen, cattle farm), and etc. They are normally less than 5 km far away from the owner's farm in China, and most of them are single or double story buildings. Local decentralized seasonal energy options have the potential to sustain livelihoods in rural areas.[41] The quasi-on-site-on-time smoldering utilization saves the trouble of long-distance collection and transportation of the fuels. And the agrostalks can be stored outdoors near the building, and rigid fire prevention measures are not necessary.

3.2. Ease of Operation. One of the prominent features of smoldering is its slowness. Experiments[21] showed that 3.6 kg pressed grass (moisture content 8.1%) and wheat straw (moisture content 10.2%) smoldered in a chamber (33 cm × 46 cm × 45 cm, shown in Figure 7a for more than 10 and 6.5 h, respectively. The temperature at the surface of the chamber was kept above 50 °C for more than 12 h (one of the recorded temperature histories is shown in Figure 7b). Smoldering of biomass powder is slower. About 1.2 kg corn stalk powder smoldered in an open cylinder vessel (Φ22 cm × 26 cm) for more than 25 h.

The slowness and the development characteristics of process make a good match of heat demand with heat supply possible. Heat emission of the smoldering chamber to the building can

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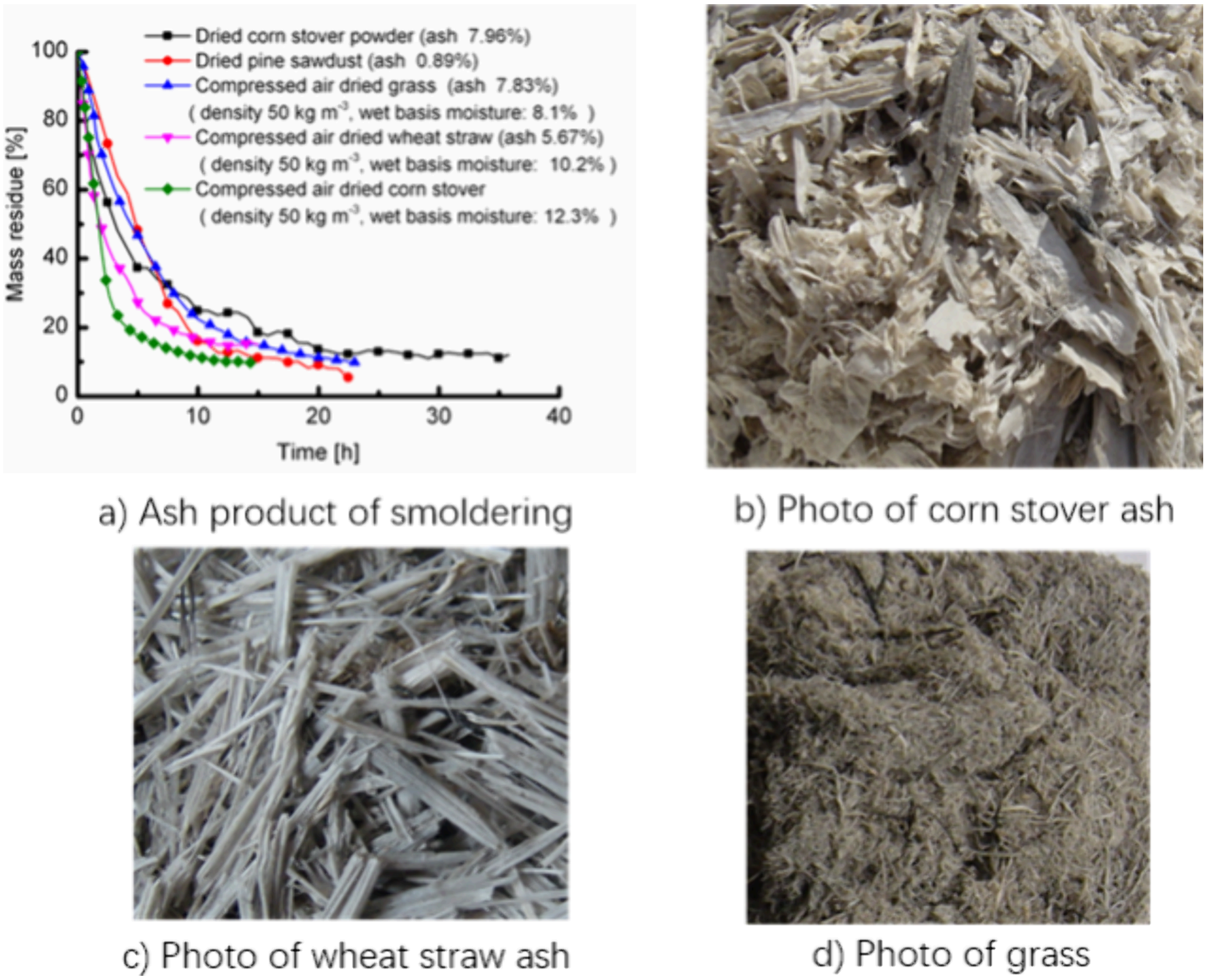

Figure 8. (a–d) Ash production of smoldering and ash photos. Adapted from ref 26. Copyright 2007 ETA Florence Renewable Energies.

be illustrated from Figure 7b. This feature of a low heat emission rate satisfies the low heating load demand of rural buildinga and of some drying processes of agricultural products. When a smoldering system is well designed and controlled, and the frequency of refilling fuels is 1 during the heating period, and the heat supply of smoldering is demonstrated as the black line in Figure 7c. At the same time, to keep a room at a comfortable temperature, the heat demand in a heating season of a year increases at the beginning and decreases at the end as demonstrated by the red line in Figure 7c. The good match of the heat supply and the heat demand makes regulation and operation of the process simple.

In spite of the simplicity in regulation and operation, almost no maintenance is necessary during the smoldering process. If the fuel inlet/outlet is located out of the building (as it usually is), the indoor environment is not affected. And no additional maintenance is necessary. The ash removal frequency is normally once a year, and it takes one man about tens of minutes or several hours. The fuel loading frequency of the burning chamber can be designed to be once a year, once a month, or once a week. It takes one man about several hours. What is more, there is no water supply system for the heating, and the troubles of possible frost crack of pipes are avoided.

3.3. Good Fertilizer Characteristics of Ash. The ash content of agrostalks is generally between 4% and 12% (d.b.),[42] much higher than the ash content of wood. During smoldering, more mass than pure ash is left in the residues as shown in Figure 8,[21,26] and considerable carbonates are included in the ash.

Biomass ash from domestic stoves has always been the traditional fertilizer in China,[43−46] and similar utilization of biomass ash is also seen in other countries.[47] Returning them to the farm is an environmentally friendly behavior. They contain all the elements the plants got from the earth during growing. Since the maximum temperature inside the fuel bed during smoldering is mostly less than 700 °C,[20,21,48] lower than the deformed temperature of most of the ash,[49,50] most gradients in the ash are not melted or fouled as they are in most combustion technologies.[50−54] Lots of nutrients in smoldering ash are water-soluble and can be digested in earth quickly. Photos of agrostalks' ash after smoldering are shown in Figure 8. The original shapes of the plants are kept very well, and the ash is very soft and can be crushed into powder by finger touch. Almost all of the smoldering ash disperses into water immediately except some carbonates particles, which are good soil amendments.

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3.4. Advantage in Pollution Reduction. Release of inorganics during biomass combustion, especially agroresidues, leads to deposit/fouling/sintering.[55−57] He[58] found that relative reduction of deposit/fouling is about 60% when the temperature of solid-combustion is <600 °C. It is well-known that a lot of slags are produced during high temperature combustion of biomass. This is one challenge in affording enough land filling sites every year because these slags often need to be landfilled. However, there are no big slags during biomass smoldering combustion, and ash can be returned to the farm as fertilizer. It is recorded[59] that about 0.95 million tons of solid waste can be reduced every year in China via smoldering combustion.

The concentrations of SO_x and NO_x in flue gas are significantly controlled[60−62] during biomass combustion nowadays. The release of S and N increases with the increase of temperature.[63,64] It is found that release of S is 70% at 906 °C and 100% at 1234 °C during smoldering combustion of corn stover.[65] This indicates that 30% SO_x can be reduced. It is reported that the release of N is 50% at 350 °C and is 93% at 1000 °C during smoldering combustion of sewage sludge,[66] which indicates that 40% NO_x can be reduced.

3.5. Use of Latent Heat of Water Vapor in Flue Gas. Due to the high moisture content of fuel in smoldering and the considerable amount of hydrogen content in biomass fuel, there is considerable water vapor in flue gas. A considerable amount of water vapor in the flue gas can be condensed in the gas treatment instrument (seen in Figure 5) because the temperature of the flue gas in the chimney is normally less than 60 °C. Thus, the latent heat of the water vapor can be utilized to heat the building, and it will significantly increase the heat efficiency of the utilization. For example, if the moisture content, hydrogen content, and the high heating value of the fuel is 25%, 6%, and 18 MJ/kg on dry basis, the theoretical increase of heat efficiency can reach 10%. It was found that the theoretical heat efficiency of smoldering of agrostalk is more than 60% based on the high heating value[42] without taking condensing of water vapor into account. This is much higher than the heat efficiency of some of other current technologies[67] utilized in rural areas.

3.6. Reduction of Pests, Weeds, and Plant Disease. As in many other thermal chemical applications of biomass, during smoldering of biomass, lots of weed seeds and pest eggs can be collected and eliminated. It is also recorded that biomass ash and its water solution can eliminate pathogens, nematodes, bacteria, and maggots on the farm.[68] This will reduce the amount of pesticide used in the farm, and it is an environmentally friendly technology.

4. CHALLENGES AND RELATED SOLUTION

4.1. Control of the Burn Rate. The control of the burn rate is of great importance in application for getting the appropriate temperature inside building. Normally, there are two methods[69,70] for the control. One is to adjust the moisture content of the fuel by adding water. This is often done before the smoldering process. The other is to regulate the air flow rate into the chamber. This is operated by using a valve or a fan during the smoldering process. However, the correlation of the burning rate with moisture content and air flow rate for the design of smoldering chamber is scarce.

The effects of moisture content on smoldering have been investigated by some researchers. Frandsen[40] found that peat moss sustained smoldering up to a range of 93−103% moisture in its natural state of 3.7% inorganic content. Yermán[71] investigated the effect of high moisture content of organic wastes on the destruction rates during smoldering combustion. It is found that the robust smoldering condition can only be achieved under the certain conditions when fuels have a high moisture content. Sun[69] et al. investigated the influences of fuel moisture content on the component of flue gas component. They showed that the effects of moisture differ significantly at different stages of smoldering (such as ignition stage, accumulation stag, developing stage, etc.). He et al.[21] investigated the effects of moisture content on the natural downward smoldering of biomass powder. Experiments showed that propagation velocity of the drying front is significantly affected by the moisture content, while the propagation velocity of the char oxidation velocity is almost not affected. De Souza Costa developed a mathematical model for analyzing a smoldering log and concluded that the propagation velocity of smoldering decreased with the increase of moisture content.[72]

As to the air flow rate, Palmer[73] investigated the effects of air velocity on the smoldering rate of cork dust and grass dust in an open area. He found that the smoldering velocity increased significantly (0.6−2 mm/s) with the increase of air velocity (from 0.4 to 10 m/s) above it when smoldering and air flow are in the same direction. Wang et al.[74] investigated the horizontally forced forward smoldering combustion of foam. It was found that increasing the air flow rate over the foam's surface not only enhanced the mass transfer of oxygen to smoldering reaction zone but also increased the heat loss to the surroundings. The maximum smoldering propagation rate was observed at a medium flow rate of air. Yermán et al.[71] performed a set of smoldering experiments and found that the air velocity is 300 times higher than the propagation of the smoldering under robust self-sustaining condition. Zhang et al.[75] investigated the effects of the airflow rate on sewage sludge smoldering combustion via an experimental study and modeling analysis. They found that minimum/maximum airflow rates are 0.3/8 cm/s. More investigation is necessary for qualification of this effect.

In fact, many factors affect the burn rate of smoldering of piled fuel. Ma et al.[76] investigated smoldering combustion of food-processing sludge in laboratory- and pilot-scale devices. They found that the pilot-scale device presents a higher smoldering velocity than that of laboratory-scale devices. Erland et al.[15] performed an experiment of smoldering in thin layers of pyrolysis oil and found that the smoldering propagation velocity increases with the increase of fuel temperature. Fernandez-Anez[35] studied the behavior of smoldering combustion during periodic refilling of fuels and calculated the ratio of combustion rates using the Arrhenius equation. He et al.[21,23] found that ash content dominates this burn rate and other important factors are species, bulk density, shrinkage of fuel bed, void size, etc. Further theoretical and experimental investigations on the mechanism of the control are necessary, and standards of the fuel should be set for the commercial development of smoldering technology.

4.2. Control of Pollutant Emissions and the Problem of CO. Traditional smoldering and open burning of biomass are characterized by their heavy smoke.[77] The smoke consists of a number of components which are same as those from combustion: CO_2, CO, CH_4, NOVOC (non-methane volatile organic components), PAH (polycyclic aromatic hydrocarbons), particles (char and carbonaceous soot, and aqueous aerosols), NO_x, NH_3, SO_x, heavy metal, O_3, HCl, PCDD/PSDF (dioxins and furans).[38,78] However, there are more large molecular hydrocarbons (tars) from smoldering than those from combustion of biomass. All these large molecular hydrocarbons are air pollutants,[5,79,80] and some of them lead to a bad smell and an increase of PM_{10} in the air. In contrast, the amount of ash particles in the flue gas from smoldering is much less than that from combustion due to the low velocity of gas inside the fuel bed, which make the entrained flow of ash with flue gas impossible.

A traditional way to reduce air pollutants in smoldering is carbonization of the original biomass to char. It is not economic for agroresidues because high energy consuming[31,32,81] little pretreatment of fuel (grinding, compaction) is necessary. What is more, considerable air pollutants appear in the carbonization process.

Another way we found[21,26] to reduce air pollutants in smoldering is by adding a layer of biomass ash on the fuel bed. Ash acts as filtration material, catalyst, and reactant. By good design, tars can be reduced to satisfy the requirement of emissions. Agrostalks themselves are a good filtration material, and they can be put into the gas cleaning instrument to filter gas. The filtration agrostalks can be changed regularly, and the used material can be put directly into the chamber as a smoldering fuel.

Emission of CO is another big problem of smoldering. The theoretical mole ratio of CO to CO_2 in the temperature scope of 400−800 °C (the normal char oxidation temperature of smoldering) is 0.04−7.5 calculated using eq 1.[82] It is very high at a high temperature. However, our experiments[20,21] showed that the ratio of CO/CO_2 is around 0.1−0.15, and the maximum value is less than 0.4 during smoldering of chars and several types of biomasses, even though this value shows that the degree of the incomplete combustion of smoldering is much higher than that of combustion. Compared with the mole ratio of CH_4/CO_2 in the composting process (0.01−0.04)[83] and anaerobic digestion (1−3),[84,85] the mole ratio of CO/CO_2 falls in between them. The reduction of CO in flue gas of smoldering is a hard one due to the following reasons. The first one is that the smoldering process is air limited. The second is that the current catalyst of CO oxidation is too expensive for this economic utilization.

$$CO/CO_2 = 2512e^{-6240/T} \quad (1)$$

5. CONCLUSION

Advantages and challenges of utilization of biomass smoldering for rural building heating in China has been analyzed. Its strengths include (1) collection, transportation, and treatment fee of fuel is low compared with other biomass utilization/treatment technologies because of the almost on-site-on-time utilization and the good smoldering characteristics of almost all biomass; (2) the operation of the process is easy because of the slowness of the process, the good match of the heat demand and heat supply, and the low requirement of the apparatus for maintenance; (3) good fertilizer characteristics of ash because of low ash forming temperature during smoldering; (4) the use of latent heat of water vapor because of the low temperature of the flue gas; (5) reduction of pests, weeds, and plant diseases because of eliminating pest eggs, weed seeds in smoldering, and disinfection function of biomass ash in the field.

There are two challenges of the process: (1) Accurate control of the burning rate: the burning rate of smoldering in a chamber is dominated by the ash content, moisture content, density of the fuel, and air flow rate in the chamber. Further investigation and standards are necessary for the control; (2) emission of particles and aerosols in flue gas: these emissions can be significantly reduced by filtration, reaction, and catalysis using ash and original biomass. Further investigation is also necessary.

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Notes

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