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Development and performance evaluation of a clean-burning stove

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ABSTRACT

Many suburb and rural households in the world are still using small coal-fired stoves for cooking and heating, which traditionally has been associated with low-efficiency combustion devices and low-grade coal, and the consequent severe air pollution. Therefore, it is very urgent to develop and widely disseminate clean and efficient combustion technologies for household use. This paper reported the development and research of a novel clean coal technology which burns clean coal-biomass briquette in a novel clean-burning coal stove. In order to reduce the emission of nitrogen oxides and particulate matters, this stove is designed with a pyrolysis chamber and a combustion chamber. In order to improve the thermal efficiency, the secondary air ducks are arranged to recover the waste heat in the ash pit and use it to warm up the inlet secondary air; sulfur retention agent calcium oxide & magnesium oxide were added to reduce the emission of sulfur oxides; low-cost corn & wheat biomass was blended with coal to utilized agricultural waste, and reduce the cost and ash content of the briquette. The thermal efficiency and the pollutants emission of this new stove were compared with the conventional one-chamber stove. The results revealed that the thermal efficiency of the stove was improved to 68%, compared with the conventional stove of 50%, while the emissions of sulfur dioxide, nitrogen oxides and carbon monoxide were reduced significantly. The coal biomass-briquette was demonstrated to be excellent in sulfur dioxide retention compared with other types of local coal. In addition, a significant reduction in the indoor concentration of carbon monoxide and PM using coal biomass-briquette in the new stove was confirmed. Information from this study demonstrates the high thermal efficiency and environment-friendly feature of the newly designed coal stove and the coal biomass-briquette. This new clean coal technology has been successfully demonstrated in two counties of Shanxi Province in China, and has great potential for improving regional and indoor air quality.

1. Introduction

Even though coal will continue to be the dominant energy source for developing countries such as China and India in the near future, there have been serious concerns on its associated pollution issues (Hao et al., 2015). Therefore, clean coal technologies must be developed and widely adopted. In China, the majority of coal was consumed in the industrial sector (Chen and Xu, 2010). Clean coal technologies, such as using upgraded fuel (Andrić et al., 2014), changing combustion systems, implementing reliable emission control technologies have been successfully applied to retrofit power plant, medium-size coal-fired industrial furnaces and kilns due to strict environmental regulations (Fujii et al., 2013). However, as the second largest coal consumer, the residential sector in China has not gained enough attention until recently. This situation may be inevitably responsible for the recent air quality disasters in China, noted as the notorious heavy haze (Xu and Lin, 2015). For Shanxi province, the top producer and consumer of coal in China, the haze is much severe during the heating season compared to the non-heating season (Xu et al., 2014), which shows the intimate relationship between the residential coal utilization and the substantial air quality issues. In order to reduce the haze, many actions were taken, such as providing centralized heating for the city, and switching domestic stove to natural gas or liquefied petroleum gas (LPG) stoves (Li et al., 2015).

Nevertheless, due to the cost issue, dispersed household stoves will still maintain its significant role in rural households. Currently,

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considering the cost of daily heating and cooking, suburbanites in developing countries apparently prefer the cheaper inferior bulk coal (Ahmad and de Oliveira, 2015), which has higher ash and sulfur contents than the clean washed coal. Along with the cheap, inferior bulk coal, the use of low-efficiency conventional stoves results in incomplete combustion, associated with dense smoke. Meanwhile, lacking desulphurization and denitrification equipment resulted in the discharge of flue gas with high concentration of sulfur dioxide (SO_2) and nitrogen oxides (NOx). Due to stringent regulations, flue gas treatment devices and clean combustion technologies have been widely used in industrial boilers, but not for individual energy sources. It was found the emission of flue gases from individual sources can sometimes be more harmful for humans than generally believed (Wojdyga et al., 2014). As the largest consumer of coal worldwide, the development and adoption of clean coal technologies are of paramount importance to China, especially for the central region (Xu and Lin, 2015). In order to relieve the severe air pollution issue, this research was conducted to develop a clean dual-purpose burning stove and clean coal-biomass briquette to reduce air pollution caused by the household use of coal stove.

In the United State (US), Environmental Protection Agency (EPA)'s publication No.EPA-456/B-13-001 in 2013 reported that the Changeout Campaign to replace the non-EPA certified wood and coal stove has been conducted across the country. Approximately, 10 million wood stoves are currently in use in the United States, and 65 percent of them are aged, and inefficient conventional stoves. In a successful replacement and changeout program, consumers can receive financial incentives to replace the aged wood-burning appliances with the cleaner home heating devices. This strategy significantly reduced harmful pollution including particulate matter 2.5 ($PM_{2.5}$), carbon dioxide (CO_2), methane and air toxins. Even though similar subsidy programs were implemented in regions close to Beijing and some selected cities, this kind of program cannot be widely implemented in a short time in China due to economic and geographical concerns.

In developing countries, various clean combustion technologies can be utilized to mitigate adverse environmental impacts. The available technologies to reduce emissions include the removal of the source of pollutants (sulfur, nitrogen) from the coal prior to combustion or utilize a substitute clean fuel; adding inside-stove measures to avoid the generation of pollutants during combustion; removing pollutants from flue gases by “end-of-pipe” methods. J. Giuntoli et al., designed three pathways for domestic-heat production using forest logging residues with different combustion technologies. Their researches showed the supply-chain GHG savings of the three pathways analyzed ranged between 80% and 96% compared to a natural gas system (Giuntoli et al., 2015). Isobe et al. (2005), used the coal-biomass briquettes as the alternative fuel, and measured the indoor concentrations of SO_2 emitted from the combustion of either coal biomass-briquettes or low-grade coal in households in Nanchuan, China. Their experiments showed that SO_2 concentrations resulting from the use of coal–biomass briquettes were reduced significantly, comparing with those resulting from the use of low-grade coal. Some stoves used in China's rural and urban households employ stove blower, which blows abundant secondary air to enhance combustion, in order to reduce smoke and improve combustion efficiency. Although excessive air flow facilitates combustion, it cannot reduce and may even generate more nitrogen oxides. Meanwhile, sometimes the secondary air may be too forceful and reduce the combustion efficiency. Pemberton-Pigott et al. (2010), in South Africa, presented a bottom-lit, down-draft devices (BLDD) to substitute the conventional top-lit, up-draft (TLUD) braziers named ‘Mbaula’. The BLDD stove, with a wired grate and tangential secondary air injection design, can be ignited quickly and burn much cleaner than an ‘Mbaula’. This novel stove is cost efficient and can be made conveniently using simple tools and material, which suggest that significant improvements in the domestic stove are possible with low cost. As to the upgrade of coal-fired facilities, analysis shows energy-saving technologies and structure-adjustment measures are the most favored options in terms of cost-effectiveness, while end-of-pipe control measures are the least preferred (Mao et al., 2014).

In most modern power production and industrial combustion units, selective non catalytic reduction (SNCR) and selective catalytic reduction (SCR) is applied to remove NOx from the flue gas, however, it is impossible to implement them in the household stoves. Some prior research showed that coal pyrolysis can form some reducing gas, such as carbon monoxide (CO), hydrocarbon (C_mH_n, including methane and other carbon-hydrogen radical) and hydrogen (H_2) (Daood et al., 2013). Consequently, nitrogen oxides can be reduced to nitrogen (N_2) by these kinds of reducing gas (Smoot et al., 1998). Furthermore, literature (He et al., 2006) reported that char can reduce NOx emission to N_2. How to use these findings from fundamental research to reduce the pollution from the household stove is an important strategy and up to now, few papers have reported it.

This paper reported the development of a clean coal technology for domestic use. In this method, clean coal biomass-briquette is used in an innovative clean-burning household stove to achieve the best performance. The emissions of SO_2, NOx, $PM_{2.5}$ and other pollutants from both the clean-burning coal stove and a traditional stove, when firing five different types of feedstock, were monitored. The stove's emission reduction capacity and its adaptability to different types of coal were evaluated. The concentrations of the indoor pollutants were also monitored to reveal the health effect of the new clean coal technology. Information from this study can be used in the development and adaptation of air pollution reduction strategies to improve regional air quality.

2. Stove design and combustion experiments

The stove, properties of the coal and the briquette, as well as the experimental procedures, are described below.

2.1. The design of a clean-burning household stove

This research team developed a clean-burning, highly efficient dual-purpose stove for household cooking and heating. The schematic drawing of the stove is shown in Fig. 1. This stove is composed of the shell, the base, the fire door, furnace chamber, grate, fire flap, chimney, *etc*. The furnace chamber described here is divided by a hearth arch into two parts, the primary combustion chamber and the secondary combustion chamber. The two-chamber pyrolysis-combustion design (Fig. 1) is significantly different from the conventional coal-fired stove (Fig. 2) with only one combustion chamber. In this stove, several secondary air ducks (item (4) in Fig. 1) are arranged to introduce hot air around the ash in the grate area into the secondary combustion chamber. The hot air, serving as the secondary air, can enhance combustion. This design utilizes the waste heat carried by the hot air around the ash, and it significantly improved the thermal efficiency of this stove. Moreover, the opening of the secondary air ducts can be adjusted to facilitate the combustion. The chamber area and the flue gas channel are separated by a flipable plate (item (5) in Fig. 1), namely flue gas damper. When the plate is pulled down, the flue gas channel is blocked and the heat is concentrated for cooking; when cooking is finished and room heating is needed, the plate can be pulled up so that the flue gas from the combustion chamber can enter the flue gas channel to