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Effect of sodium carboxymethyl cellulose addition on particulate matter emissions during biomass pellet combustion

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HIGHLIGHTS

- Effect of CMC addition on PM emissions during biomass combustion was investigated.
- CMC combustion emits large amount of PM due to the formation of NaOH and Na_2CO_3.
- The influence of CMC is linked to the content and chemical composition of fuel ash.
- Mixing of rice husk or Si-rich minerals with biomass can reduce PM emission issues.

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ABSTRACT

Sodium carboxymethyl cellulose (CMC) can be used as a cost-effective and environmentally friendly binder in the pelletizing process for production of biomass pellets with good quality. However, the effect of its addition on the emission of particulate matters (PM) during the combustion process, are still not clear. In this study, four typical biomass fuels, cotton stalk, cornstalk, camphorwood and rice husk, were used to investigate the effect of the addition of 5 wt% CMC in the biomass pellets on PM emissions during the combustion process. In the case of pure CMC combustion, a large amount of PM mainly with $PM_{2.5}$ were generated, which was associated to the evaporation and condensation of NaOH and Na_2CO_3. The PM_{10} emission from the combustion of the four biomass fuels varied from 9.72 mg/Nm^3 to 23.12 mg/Nm^3 with mainly PM_1. The addition of 5 wt% CMC in cotton stalk, corn stalk and camphorwood significantly increased the PM emissions due to the evaporation and subsequent condensation of Na-containing species, e.g. NaCl, Na_2SO_4, NaOH and Na_2CO_3. For rice husk, the addition of CMC hardly affected PM_1 emission due to the dominated SiO_2 component in rice husk ash, which reacted with the Na-containing species from the combustion of CMC and facilitated the formation of coarse ash particles and the reduction of PM_1 emission. Although the addition of CMC in biomass fuels can greatly enhance the pellets qualities, its addition increases the PM emissions to varying degree. Therefore, in the industrial application of CMC to biomass densification, countermeasures such as mixing of high Si-containing rice husk or SiO_2-rich minerals with biomass fuels should be taken to alleviate the PM issues resulting from the introduction of CMC.

1. Introduction

As a renewable resource, biomass has the advantages of abundance in reserve, carbon-neutral and wide distribution [1,2]. Its utilization can effectively mitigate the energy crisis of fossil fuels and the environmental pollutions. However, biomass generally has the characteristics of high moisture content, low energy and bulk density [3,4]. Meanwhile, its distribution is strongly dependent on the seasonal and geographical conditions [5]. These issues greatly restrict the large scale utilization of biomass.

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In the past decades, some pre-treatment methods such as densification, torrefaction, etc., have been studied [6–8] in order to overcome the above-mentioned problems associated to biomass resource. Densification is one of the most simple and effective ways which can greatly increase the bulk and energy density of biomass [9]. The densified products also exhibit a uniform performance with desirable handling properties and reduced transportation cost, which is advantageous for large scale utilization [10]. In the densification process, biomass is normally first preheated to activate natural binders in biomass material, such as lignin, protein and water soluble carbohydrates, and to promote the deformation of thermoplastic particles [11]. These activated natural binders are then squeezed out of the matrix cells and form glassy coating on the surface of the pellet [12,13]. This glassy coating acts as solid bridges which bind the particles together, ensuring an acceptable pellet quality. However, the preheating process consumes large amounts of energy and therefore is not cost-effective. Additionally, agricultural biomass generally does not have an adequate amount of natural binders and the lignin is bound to the lignocellulosic matrix of biomass which is hard to be activated during the palletization process [14]. Therefore, a variety of binders, including both organic (e.g. starchy additives, cellulose, lignin) and inorganic (e.g. Calcium/sodium hydroxide, bentonite), have been used to improve the physical properties of the pellet as well as to reduce the energy consumption in the densification process [15]. Sodium carboxymethyl cellulose (hereafter referred to as CMC), as a cost-effective and environmentally friendly binder, has been widely used in the food, medicines, common chemicals, and construction sectors [9,16]. The recent utilization in the production of biomass pellets [9] and char/carbon materials [17] has gained increasing attention. Si et al. [9] investigated the effects of the addition of CMC in three agricultural biomasses on the qualities of the pellets. They reported that the addition of CMC could facilitate the formation of strong bond between CMC and biomass solid particles. The energy consumption was considerably reduced and the qualities of the resultant pellets including relaxed density, compressive strength and durability were enhanced [9]. Therefore, the utilization of CMC in the densification of biomass fuels seems to be appealing from the view of increasing the pellets quality.

In the present energy market for the production of heat and power, pellet combustion has been very popular in many countries, and is one of the most advanced and robust biomass utilization technologies [18]. During the combustion process, volatile and char in the fuel are firstly reacted with oxygen to produce CO_2-rich flue gas and release heat. As the consumption of the fuel, volatile inorganic species such as alkali compounds are prone to releasing to gas phase and form the so called PM_{10} (fine particles with a diameter less than 10 µm) [19]. The emitted particulate matter is a major reason of atmospheric pollution, particularly in China, and poses a hazard to human health. It has been confirmed that long term exposure to particulate matters increase the risk of asthma attacks, cardiopulmonary and lung cancer [20,21]. Therefore, research on PM emissions during biomass pellets combustion has received increasing attention. Roy and Corscadden [22] investigated the PM emission behavior from biomass briquettes combustion in a domestic stove. The results indicated that PM emissions vary significantly from 30–47 mg/Nm^3 to 300–800 mg/Nm^3 for different types of wood. Combustion tests of peat, wood and agro-pellets showed that dust emissions from citrus shell, wheat straw and sunflower husk pellets were significantly higher than that from wood and peat combustion [23]. Garcia-Maraver et al. [24] found the PM emissions from the combustion of five types biomass pellets in a domestic boiler were dominated by $PM_{2.5}$. Meanwhile, the fuel ash composition and the amount of K and Na in the ash had a great influence on the PM emissions [24,25]. In the combustion tests of 11 woody biomass pellets, 2 straw biomass pellets, 2 peat pellets and the mixed pellets, Lamberg et al. [26] found that the PM_1 emission was closely related to the K and (K + Na + Cl) content in the fuel and the (K + Na)·(2Cl/S) molar ratio of the fuel. It is clear that alkali metals K and Na play an important role in the PM formation. Carboxymethyl cellulose is a cellulose derivative with carboxymethyl groups (sbndCH2sbndCOOH). It often presents in the form of sodium carboxymethyl cellulose with Na organically bonds to the char matrix. The introduction of Na is inevitable when CMC is used as a binder in the densification of biomass. Therefore, it can be anticipated that the addition of CMC will affect PM emission to a certain degree. However, research on the effect of the addition of CMC in biomass pellets on PM emission is hardly found. An intensive study is needed before the industrial application of CMC in the biomass pellets production.

In this study, four biomass materials, including a woody and three agricultural feedstocks, were employed to elucidate the effect of the addition of CMC on PM emissions. The results of this study can provide a scientific guidance for the industrial application of CMC as an additive in biomass densification.

2. Experimental section

2.1. Fuels

The feedstocks used in the experimental test were three agricultural residues, cotton stalk (CS), corn stalk (CSK) and rice husk (RH), and a woody biomass camphorwood (CW). The agricultural residues are abundant in the central area of China and have a great potential to replace coal for heat and electricity generation [27,28]. Camphorwood is widely distributed in southeast China and has been used as a biofuel for heat production. The detailed information of the biomass fuels have been described in previous work [27]. The proximate analysis, ultimate analysis and heating value of the fuel were measured using a SDTGA-2000 industrial analyzer (Las Navas, Spain), EL-2-type elemental analyzer (Vario, Germany), and automatic calorimeter (model 6300, Parr Instrument Company, Moline, IL, U.S.A.), respectively. The ash chemical composition of the fuel was measured by a X-ray fluorescence spectrometer (XRF, EAGLE III, EDAX Inc. USA). The measured fuel properties are shown in Tables 1 and 2, respectively.

The as received fuels were milled and sieved to get a particle size of less than 200 µm and then dried overnight at 105 °C. The particle size was selected to avoid rapid springback of the pellet produced from raw biomass [29]. The fuels were then mixed homogeneously with 5 wt% CMC in an electric stirrer (DJ1C-40) and the resultant samples were marked as CS/CMC, CSK/CMC, CW/CMC, RH/CMC, respectively. Finally, 15 wt% deionized water was added in the samples and stirred for half an hour to ensure complete mixing. Then the samples were pelletized using a universal material testing machine (CMT5205, MTS, China). The pelletization was carried out at a pressure of 120 MPa under room temperature and was held for 180 s to get a pellet with a diameter of 6 mm and length of 2–3 mm. The resultant pellets have a particle density of 870–1060 kg/m^3 for raw fuels and 1030–1150 kg/m^3 for fuels with CMC. The detailed description about the instrument and

Table 1
Proximate, ultimate analysis and heating value of the fuels.

	Cotton stalk	Corn stalk	Camphorwood	Rice husk
LHV, MJ/kg db[a]	15.97	13.49	17.56	11.66
Proximate analysis (wt% db[a])				
Volatile matter	78.80	76.20	84.59	68.09
Fixed carbon	15.97	19.64	13.80	15.71
Ash	5.24	4.16	1.61	16.2
Ultimate analysis (wt% db[a])				
C	47.12	48.59	50.69	49.04
H	6.25	6.28	6.35	6.53
N	0.57	1.31	0.25	0.36
S	0.20	0.18	0.15	0.16
O, by difference	40.63	39.47	40.95	27.71

[a] db = dry basis.