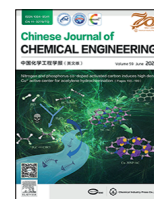




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Full Length Article

Optimization of decoupling combustion characteristics of coal briquettes and biomass pellets in household stoves

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ABSTRACT

Burning coal briquettes or biomass pellets in household decoupling stoves is of significance to the reduction of residential pollutant emissions such as NO and CO. In order to make full use of the superiority of decoupling combustion technology, the household stoves should be specially designed and optimized to adapt to fuel types and combustion characteristics. Using numerical simulation and experimental validation, this study quantitatively clarified that the reducibility of devolatilization char plays an important role in the suppression of NO emission in the decoupling combustion of coal, while the reducibility of pyrolysis gases has a dominant effect on the reduction of NO in the decoupling combustion of biomass. An optimal parameter combination of throat height and grate angle was obtained for the simultaneous suppression of NO and CO emissions in the household decoupling stove burning coal briquettes. Two types of decoupling stoves were developed to enable the clean combustion of biomass pellets. The A-type biomass stove with a multi-pass smoke tunnel shows a better comprehensive NO and CO reduction effectiveness than the B-type biomass stove consisting of a two-stage grate structure and an S-shaped pyrolysis chamber. The optimal structural parameters provided references for the design and manufacture of commercial decoupling coal and biomass stoves.

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1. Introduction

Residential emissions from household coal- and biomass-fired heating were considered to contribute much to ambient air pollution in China [1]. It was reported that about 71% of PM, 92% of SO₂, 72% of NO_x and 74% of CO can be attributed to the combustion of residential raw coal in northern China in 2013 [2]. The emissions of PM_{2.5}, SO₂ and NO_x from raw coal combustion still account for 29%, 11% and 2.2% of total pollutant emissions in 2022, respectively, though the raw coal takes up only 2.9% of total energy consumption of China [3]. Biomass is a renewable fuel, but its high-efficiency utilization is often challenged because of economic difficulties and combustion disadvantages [4,5]. Burning coal briquettes and/or biomass pellets has been proven to be a feasible and economical option for the reduction of residential pollution in China because combining fuel briquettes and improved stoves promotes combustion efficiency but reduces pollutant emissions

compared with the direct combustion of non-treated raw fuels [6–12].

As solid fuels are heated to a high temperature, NO_x can be formed from either light N-containing components such as HCN and NH₃ in pyrolysis gases or N-containing solid species in devolatilized fuel particles (char), in which large amounts of CO may also be produced due to incomplete combustion [13]. On the other hand, the conversion of HCN and NH₃ can also be controlled to form N₂ instead of NO_x in reducing atmosphere [14]. The formed NO_x can be reduced by the reducing gases and char particles [15,16]. Therefore, suppressing the conversion of fuel nitrogen to NO_x and utilizing the reducibility of volatiles and char as much as possible are the key to high-efficiency and low-emission combustion of solid fuels.

In traditional updraft or downdraft stoves, the pyrolysis and combustion processes occur in one hearth simultaneously, which leads to the possible incomplete combustion of volatile matter and char [17–20]. Many methods were adopted to increase the thermal efficiency but reduce the pollutant emissions of household stoves. Some researchers laid emphasis on using clean solid fuels [21,22], while others devoted themselves to improving stove

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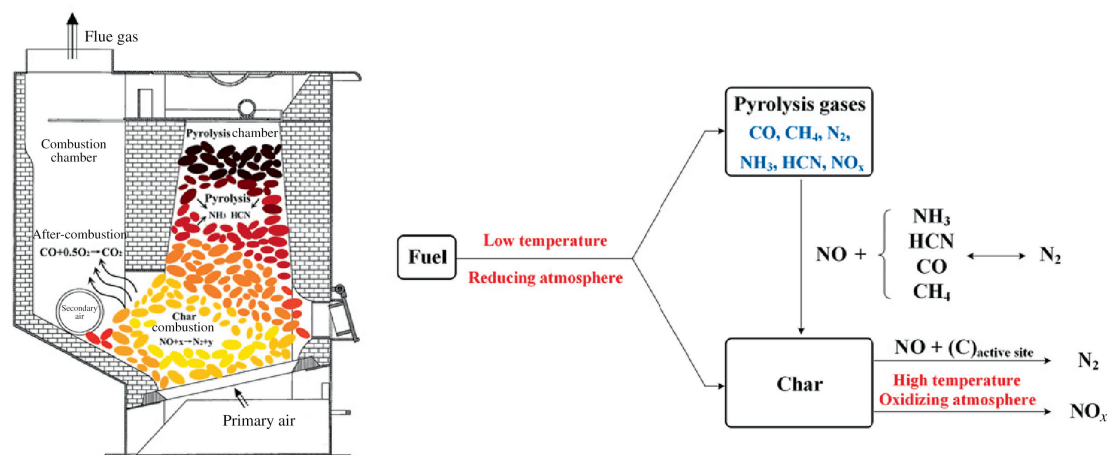


Fig. 1. Principle of household decoupling stoves.

design [17,20,23,24] and further the combination of fuel and stove [19,25,26]. In a decoupling stove, as shown in Fig. 1 [27], the hearth of stove is divided into a pyrolysis chamber and a combustion chamber as well as a bottom passage in between. Solid fuels are added from the top of pyrolysis chamber, while air is introduced from the bottom inclined grate and flue gas is exhausted from the top of combustion chamber. So, the combustion process is decoupled into the fuel pyrolysis process in low-temperature and reducing atmosphere and the combustion of volatiles and char in high-temperature and oxidizing atmosphere, which can facilitate the targeted regulation of combustion process to utilize the reducibility of pyrolysis products themselves, so as to increase thermal efficiency but lower NO_x emissions [16,27–30].

The char reactions are considered as the major contributor for the NO_x and CO emissions in coal combustion, while the conversion of volatile matter plays an important role for the clean combustion of biomass [16,31–33]. In the decoupling coal stoves, the above-mentioned mechanism can be enhanced by forming a gas flow circulation in the pyrolysis chamber to increase the possibilities for NO_x reduction and CO burnout [26,34,35]. In order to make full use of the superiority of decoupling combustion technology, it is necessary to optimize the stove structure and further the combination scheme of the pyrolysis and combustion processes according to the variation of fuel type [36,37].

In previous numerical simulation of grate-firing stoves, it is a common thing to consider only the homogeneous reactions in the gas phase for simplification [38,39], though the fuel bed can be simulated by using empirical models or discrete methods at the cost of large amounts of computation resources and time consumption [40–44]. In order to simulate accurately the decoupling combustion stoves, the fuel bed was included in the computational domain and taken as a porous zone subjected to the mass and energy balances in this study [45–47]. A decoupling coal stove was simulated in detail to optimize its structural parameters corresponding to bituminous briquettes further. Two decoupling biomass stoves were newly developed and numerically analyzed to adapt to the combustion characteristics of biomass pellets. Different dominant mechanisms for NO_x suppression in the decoupling coal and biomass stoves were clarified in the simulation, and experiments were performed to verify the effectiveness of the optimized decoupling stoves in lowering the NO_x and CO emissions. The optimal structural parameters provided references for the design and manufacture of commercial decoupling coal and biomass stoves.

2. Simulation and Experiments

2.1. Simulation method

The whole household stove with a similar characteristic structure to the prototype in Fig. 1 is taken as the computational domain. Because the design of household decoupling stove may vary with fuel types such as anthracite, bituminous coal and biomass, the detailed structures of decoupling coal and biomass stoves will be described in the following subsections, respectively. Coal briquettes or biomass pellets are packed in the pyrolysis chamber at the experimental porosity, and the fuel bed is ignited from the bottom of the pyrolysis chamber.

The simulation is implemented by ANSYS® FLUENT 17.2. The gas phase is treated as continuum, while the trajectories of fuel particles are simulated by the discrete phase model (DPM). The packing effect of fuel bed is considered by the porous media. The both phases are coupled by the exchange of the mass, momentum and energy between them. The RNG k -epsilon model is employed to describe the turbulence dynamics since it can provide overall superior prediction performance for various flow regimes [48]. The heat conduction, convection and radiation are considered in the simulation, where the basic physical properties of gas/solid mixtures are calculated by mass-weighted mixing law. Specially, the radiation heat transfer is calculated by the DO model [49,50]. The Finite rate/Eddy dissipation (FR/ED) model accounts for the turbulence-chemistry interaction in this study as the homogeneous combustion process is affected by chemical reaction rate as well as turbulence [51].

A single kinetic rate model is used to describe the pyrolysis processes of the coal or biomass fuel [52]. As the chemical reactions of fuel particles mainly take place in diffusion/chemical control zone, the kinetic/diffusion limited rate model is employed to describe the combustion and gasification of large particles of coal char or biomass char [53,54], that is,

$$-\frac{dm_c}{dt} = \pi d_c^2 \frac{\rho_c R T x_{O_2}}{M_{O_2}} R_T \quad (1)$$

with the total reaction rate R_T

$$R_T = \frac{1}{\frac{1}{R_{kin}} + \frac{1}{R_{diff}}} \quad (2)$$

where, d_c is char diameter; ρ_c is char density; R_{kin} is chemical reaction rate; R_{diff} is external diffusion rate.

Only NO from fuel nitrogen is mainly considered for simplification and comparison with the experiments since its content dominates the NO_x emissions from household stoves [55], which is calculated by using the post-processing module of Fluent after the combustion simulation as it is assumed to affect little the simulated stable flow field in the stoves. Structured hex meshes are adopted in this study, and the average length of the mesh is determined to be 6 mm according to mesh independent tests. The wall boundaries and the inlet/outlet conditions of the stoves were determined experimentally. The general settings of simulation are summarized in Table 1.

Main chemical reactions as well as corresponding kinetic equations involved in the simulation are listed in Table 2. The homogeneous reactions include the oxidation of CO, CH₄ and H₂. The heterogeneous reactions mainly consist of the fuel pyrolysis as well as the combustion and gasification of char with O₂, CO₂, H₂ and H₂O [58]. It is worth noting that the pyrolysis and combustion kinetics of bituminous briquettes as well as the pyrolysis kinetics of biomass pellets are determined experimentally because they may differ by orders of magnitude from the corresponding intrinsic kinetic parameters [59].

Considering the moisture content of as low as 1.98% in coal briquettes, the water evaporation process is neglected in the steady

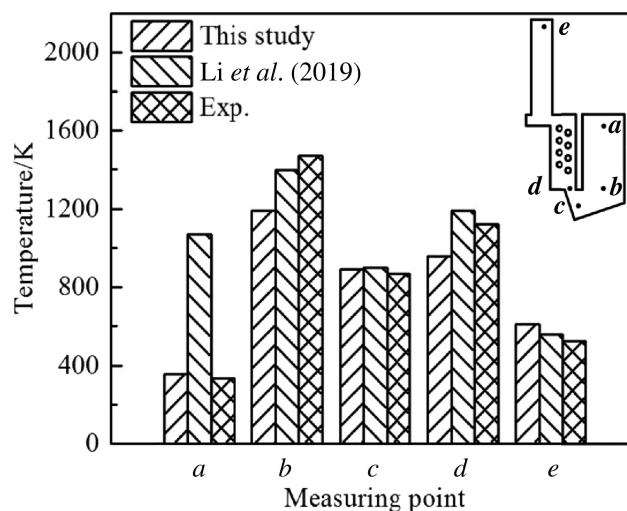


Fig. 2. Temperature distribution in the prototype of decoupling coal stove.

state simulation of coal combustion for simplification, which is however taken into account in the biomass combustion simulation by adopting the water evaporation model of Bryden *et al.* [60]. The two types of fuel particles are simplified as spheres with an equivalent diameter of about 33 mm and 11 mm, respectively. Correspondingly, the porosity of porous zone is set as 0.52 for the coal stove, while 0.46 for the biomass stoves.

Table 1
Simulation settings

Simulation	Setting
Space	3D
Time	Steady
Pressure-velocity coupling	SIMPLE
Spatial discretization	Second-order upwind
Radiation model	Discrete Ordinate
Turbulent model	RNG <i>k-ε</i>
Pyrolysis	Single-rate model
Homogeneous combustion	Finite rate/Eddy dissipation model
Heterogeneous combustion	Kinetic/diffusion limited rate model

Table 3
Pollutant emissions from the prototype of decoupling coal stove

	CO/mg·m ⁻³	NO/mg·m ⁻³
Exp.	584 ± 67	157 ± 13
This study	595	134
Li et al. (2019) [34]	628	166

Table 2
Main reactions and kinetic parameters.

Chemical reaction	Rate equation	Kinetic parameter	References
fuel → vol + char	$-\frac{dm_v}{dt} = m_v R_v$	$R_v = 700 \cdot e^{-\frac{8861}{T_s}} \text{ (coal)}$ $R_v = 11 \cdot e^{-\frac{6580}{T_s}} \text{ (biomass)}$	Experimentally determined
H ₂ + 0.5O ₂ → H ₂ O	$R_1 = k_1 c_{O_2} c_{H_2}$	$k_1 = 9.87 \times 10^8 \cdot e^{-\frac{3.7 \times 10^6}{T_g}}$	Gómez <i>et al.</i> , 2014 [47]
CO + H ₂ O $\xrightleftharpoons[R_3]{R_2}$ CO ₂ + H ₂	$R_2 = k_2 c_{CO} c_{H_2O}$ $R_3 = k_3 c_{CO_2} c_{H_2}$	$k_2 = 2.78 \cdot e^{-\frac{1.5 \times 10^6}{T_g}}$ $k_3 = 93690 \cdot e^{-\frac{5.6 \times 10^6}{T_g}}$	
CO + 0.5O ₂ → CO ₂	$R_4 = k_4 c_{CO} c_{O_2}^{0.25} c_{H_2O}^{0.5}$	$k_4 = 2.239 \times 10^{12} \cdot e^{-\frac{20447}{T_g}}$	Desroches-Ducarne <i>et al.</i> , 1988 [56]
CH ₄ + 1.5O ₂ → CO + 2H ₂ O	$R_5 = k_5 c_{O_2}^{0.8} c_{CH_4}^{0.7}$	$k_5 = 1.585 \times 10^{10} \cdot e^{-\frac{24157}{T_g}}$	
C + 2H ₂ → CH ₄	$R_6 = k_6 c_{H_2}$	$k_6 = 3.42 \times 10^{-3} \cdot T_s \cdot e^{-\frac{15600}{T_s}}$	Thunman <i>et al.</i> , 2002 [57]
C + H ₂ O → CO + H ₂	$R_7 = k_7 c_{H_2O}$	$k_7 = 3.42 \cdot T_s \cdot e^{-\frac{15600}{T_s}}$	
C + CO ₂ → 2CO	$R_8 = k_8 c_{CO_2}$	$k_8 = 3.42 \cdot T_s \cdot e^{-\frac{15600}{T_s}}$	
C + O ₂ → CO ₂	$R_9 = k_9 c_{O_2}$	$k_9 = 0.014 \cdot e^{-\frac{11779}{T_s}} \text{ (coal)}$ $k_9 = 1.715 \cdot T_s \cdot e^{-\frac{9000}{T_s}} \text{ (biomass)}$	Experimentally determined Thunman <i>et al.</i> , 2002 [57]

2.2. Numerical validation

In order to validate the simulation method based on the porous zone approach and the experimentally-determined reaction kinetics, the prototype of decoupling coal-fired heating stove was firstly simulated to compare with the results of Li *et al.* [34] since they ignored the packing effect of fuel particles. As shown in Fig. 2, the introduction of the porous zone hinders the movement of high-temperature flue gas stream from the bottom to the top of the pyrolysis chamber, and thus results in a much reasonable simulated temperature at the top of pyrolysis chamber (point *a*). Similarly, this obstructing effect provides much more chances for NO_x reduction and CO burnout. Thereby, as indicated in Table 3, the simulated NO and CO emissions are lower than the previous simulated results and in better agreement with the corresponding experimental values.

2.3. Experimental validation

The experiments were carried out to validate the optimized design of stoves. The proximate and ultimate analyses of coal briquettes and biomass pellets are given in Table 4. Lower calorific values of coal briquettes and biomass pellets are 25.59 MJ·kg⁻¹ and 18.38 MJ·kg⁻¹, respectively.

As shown in Fig. 3, the tested stove can be switched between coal and biomass stoves according to the experimental needs. The effective thermal load of the tested stove can be on-line monitored by detecting the flowrate of cooling water as well as its inlet and outlet temperature. Characteristic temperatures in the different zones of tested stove were measured by some thermocouples fixed at different measuring points. The outlet emissions including NO, CO and O₂ concentrations, *etc.* were online analyzed at the stable flaming state by using a gas analyzer (ABB AO2020). The flue gas sampling point is located at 1.5 m away from the bottom of the chimney of 6 m high. All measured pollutant emissions are corrected to the same dry oxygen basis of 9% (vol) for comparison.

Table 4
Proximate and ultimate analyses of coal briquettes and biomass pellets

Solid fuel	Proximate analysis (ar)/% (mass)				Ultimate analysis (daf)/% (mass)				
	M	V	FC	A	C	H	O	N	S
Coal briquette	1.98	31.66	48.34	18.02	81.83	5.35	10.68	1.63	0.51
Biomass pellet	7.04	82.96	7.42	2.58	51.00	7.03	41.33	0.62	0.02

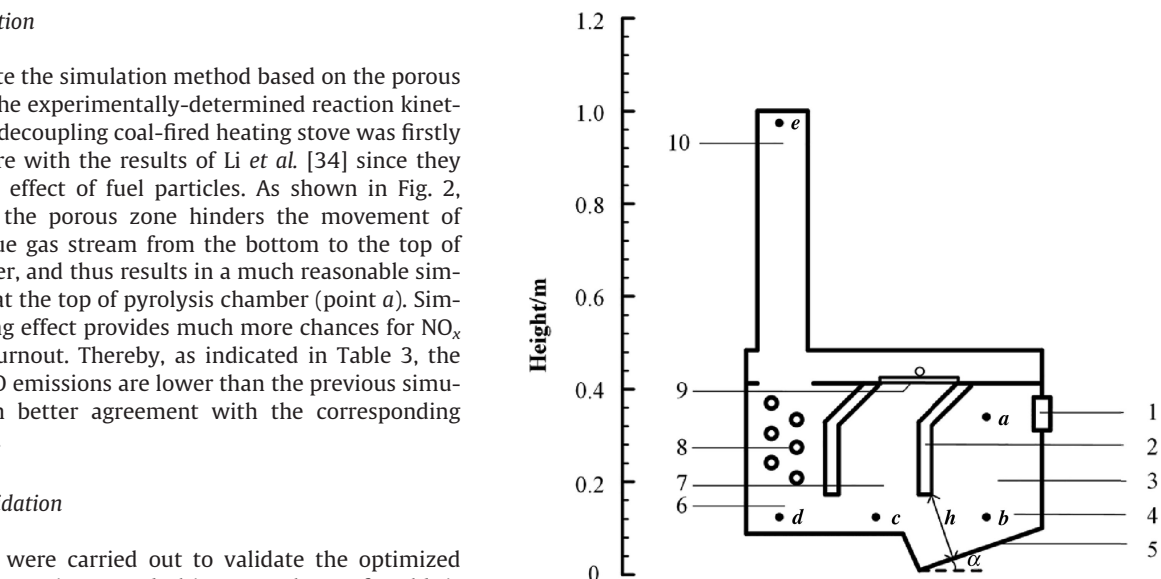


Fig. 4. Schematic diagram of decoupling coal stove: 1—Coal feeding; 2—Baffle; 3—Pyrolysis chamber; 4—Measuring point; 5—Grate; 6—Combustion chamber; 7—Cooking chamber; 8—Heat exchange tube; 9—Adjusting plate; 10—Stove outlet.

3. Results and Discussion

3.1. Optimization of household decoupling coal stoves

As shown in Fig. 4, based on the prototype of decoupling coal heating stove, a household coal-fired cooking and heating stove with a rated thermal power of 10 kW was developed by adding another hearth as the cooking chamber. The length, width and height of the household decoupling coal stove are about 0.68 m, 0.24 m and 1.00 m, respectively. Throat height (*h*) and grate angle

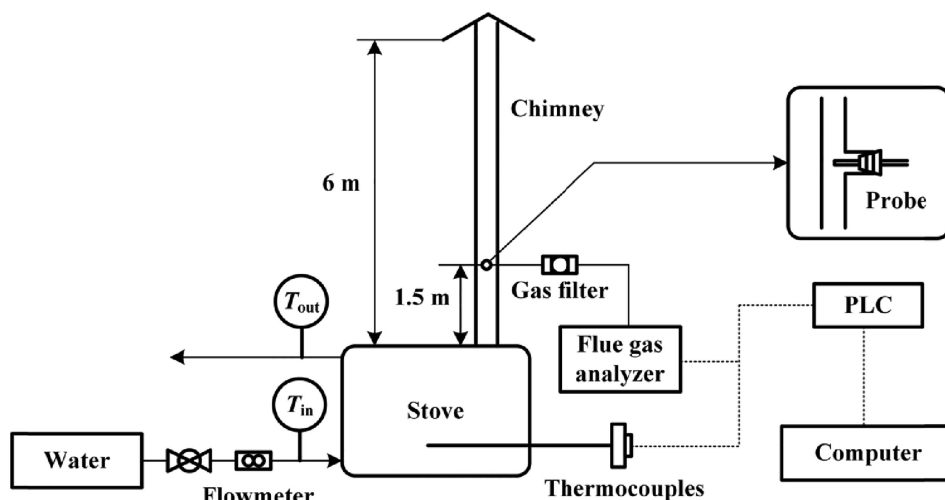


Fig. 3. Schematic diagram of the experimental system.

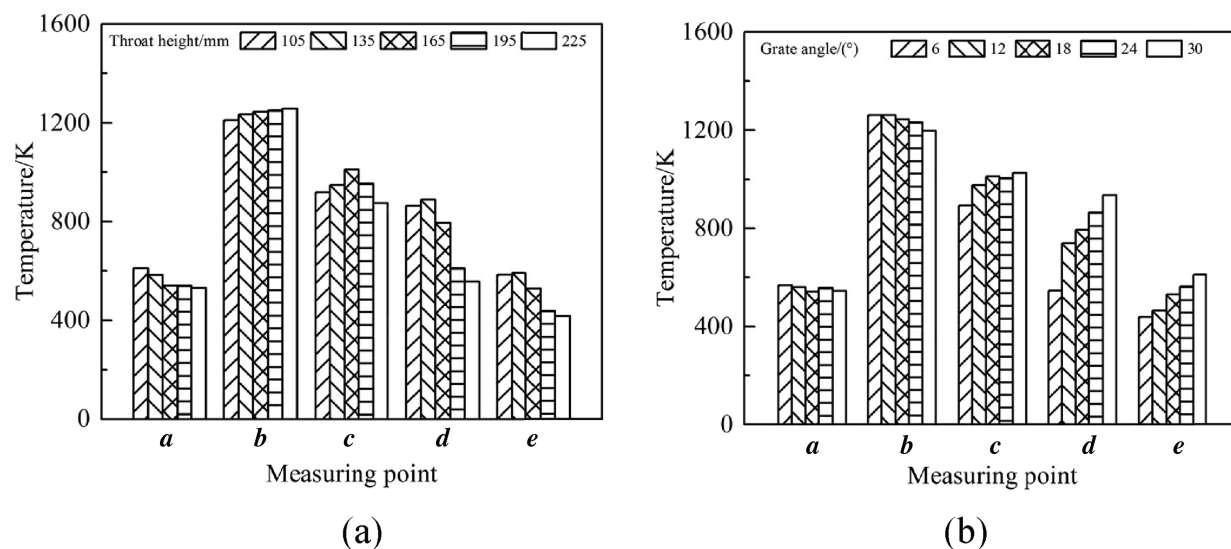


Fig. 5. Temperature variation with (a) throat height, and (b) grate angle at the different measuring points.

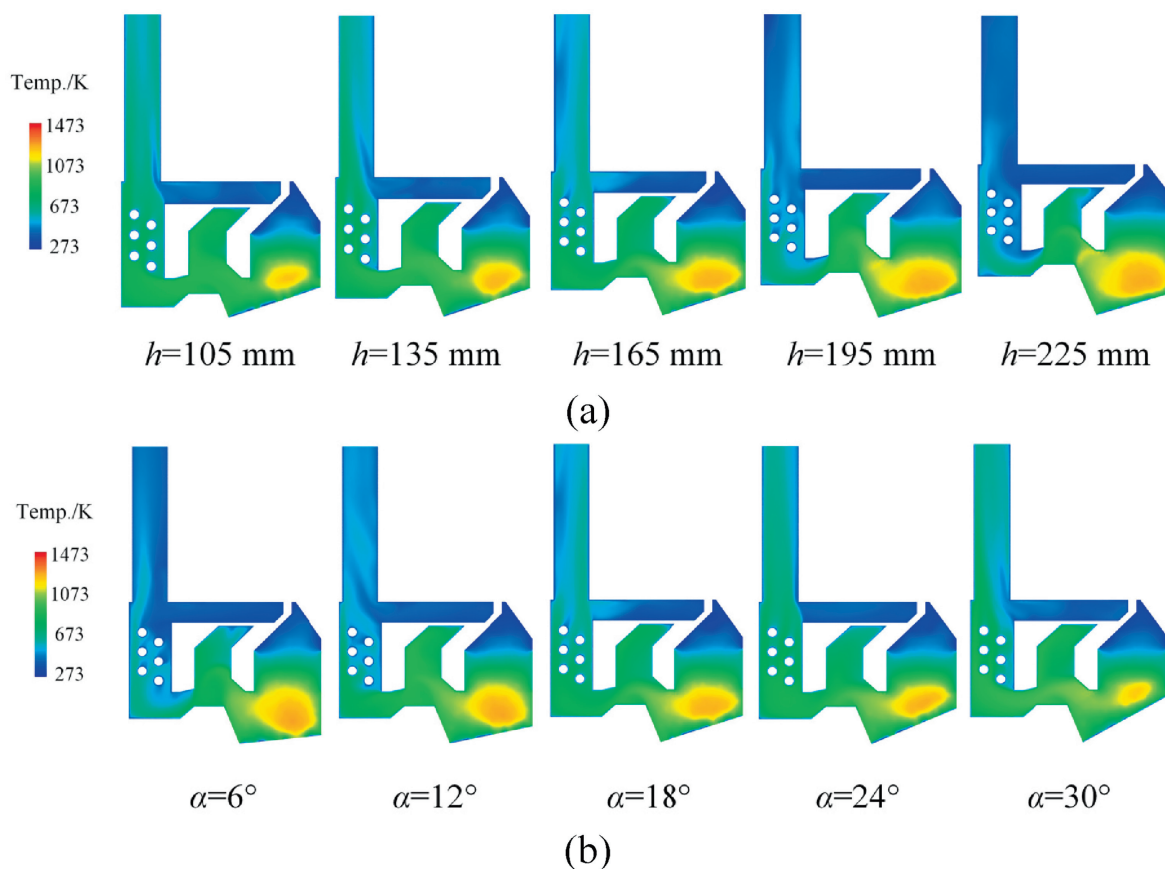


Fig. 6. Temperature profiles at the different (a) throat heights, and (b) grate angles.

(α) are the two key structural parameters of decoupling combustion stove because they both decide the pyrolysis and combustion atmospheres as well as the depth of char layer, which have significant effects on multiple pollutant emissions [26,27]. Considering the limits of thermal load and topological structure, the throat height and the grate angle are numerically optimized at the ranges of 105–225 mm and 6° – 30° , respectively. However, the cooking chamber is generally covered by an adjusting plate in the real-world combustion scenario of China, so this study is mainly

focused on the simulation of the heating mode rather than the cooking mode. Five measuring points of temperature from *a* to *e* are set to obtain the temperature distribution characteristics in the stove.

As illustrated in Fig. 5(a), the temperatures at the points *a*, *d* and *e* generally decrease with increasing throat height because the increase of effective depth of fuel bed hinders the flowing of inlet air into the combustion chamber and thus reduces the homogeneous combustion intensity at these points. Additionally, the inlet

air together with high-temperature flue gas produced at the pyrolysis chamber bottom can hardly flow to the pyrolysis chamber top. Contrarily, the temperature of the point *b*, representing the combustion state in the core char zone, increases with increasing throat height because both the heterogeneous and homogeneous combustion reactions become much stronger due to sufficient air supply at the zones. The temperature of point *c* is strongly related to the combustion of CO and other combustible components at the measuring point. On one hand, sufficient cold inlet air resulting from the thin effective fuel bed may cool the flue gas there and lead to the incomplete combustion of CO [61]. On the other hand, as shown in Fig. 6(a), the increases of temperature and area of char zone with increasing throat height may result in the release of very few CO to be combusted at the bottom passage. So, a maximum temperature can be observed at the point *c* during the variation of throat height.

The increase of grate angle was implemented by counterclockwise rotating the grate about the lowest point of the stove for its convenient manufacture, implying that the throat height decreases correspondingly. A great grate angle accompanied by a small throat height allows much more inlet air and combustible gases flowing into the combustion chamber, and leads to a contracting char combustion zone and a weakening combustion intensity at the pyrolysis chamber bottom, as indicated in Fig. 6(b). This actually indicates that much more CO and other combustible gases may be released from the pyrolysis chamber to be burnt in the combustion chamber. Therefore, as shown in Fig. 5(b), with the increase of grate angle the temperature clearly increases at the points *c* to *e*, but slightly decreases at the points *a* and *b*.

Fig. 7 shows the NO concentration profile in the middle cross-section of the stove under the different cases. In the coal stoves, NO mainly originates from the oxidization of volatile and char

nitrogen at the pyrolysis chamber top and bottom, respectively [62], while its reduction by char takes place in the bottom char zone. The suppression of volatile NO at the pyrolysis chamber top and the full utilization of the reducibility of char at the pyrolysis chamber bottom are the key to decreasing NO emission from the decoupling coal stove. As discussed before, great throat heights and grate angles are not in favor of the movement of inlet air up to the pyrolysis zone and enhance the reducing atmosphere in this region. Thereby, NO is mainly concentrated in the pyrolysis chamber bottom as well as the combustion chamber. The outlet NO emission seems to decrease with increasing throat height and grate angle. Moreover, in the pyrolysis chamber bottom region NO concentration profile takes on a clear circular shape at the suitable combination of throat height and grate angle. This distribution indicates the circulation flow of flue gas in the pyrolysis chamber and the reduction of NO by char.

In order to statistically analyze the evolution of NO in the decoupling coal stove, total NO reduction rates by coal char and pyrolysis gases (e.g., CO, NH₃, HCN) are calculated by summing the corresponding simulation values in the whole computational domain, respectively. As shown in Fig. 8, the total NO reduction rates by char and pyrolysis gases as well as their sum appear to firstly increase with increasing throat height, and then slightly decrease at the greatest throat height. This may be attributed to that the expansion of high-temperature char zone can provide much more time and space for the reduction of NO, but the circulation flow pattern of flue gas becomes unclear at the greatest throat height and thus significantly reduces the chance for the reduction of NO. However, these two reduction rates and their sum seem to gradually decrease with increasing grate angle but decreasing throat height because the high-temperature char zone contracts and the circulation flow of flue gas disappears gradually.

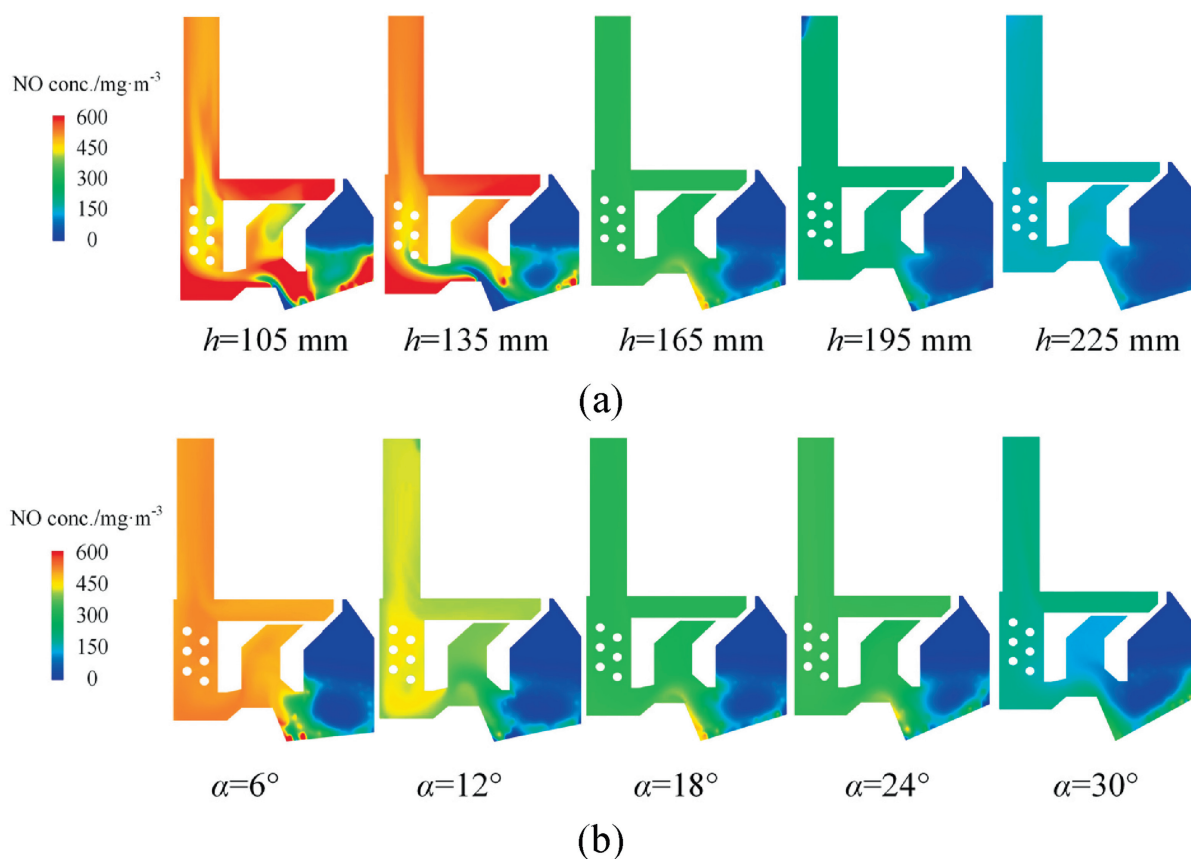


Fig. 7. NO concentration profiles at the different (a) throat heights, and (b) grate angles.

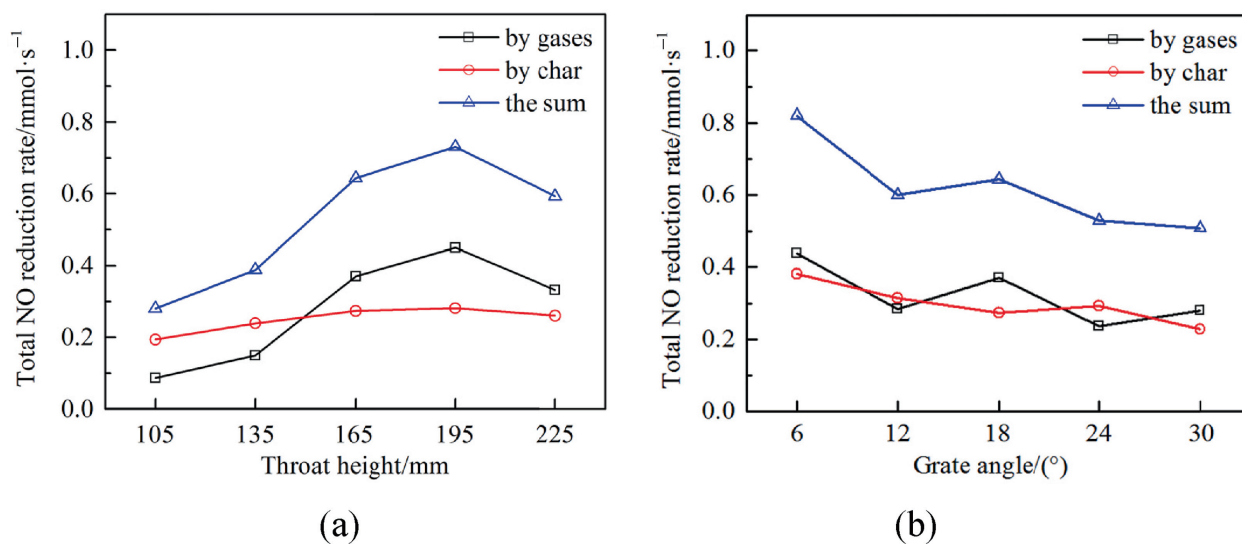


Fig. 8. Variation of total NO reduction rate in the whole coal stove with (a) throat height, and (b) grate angle.

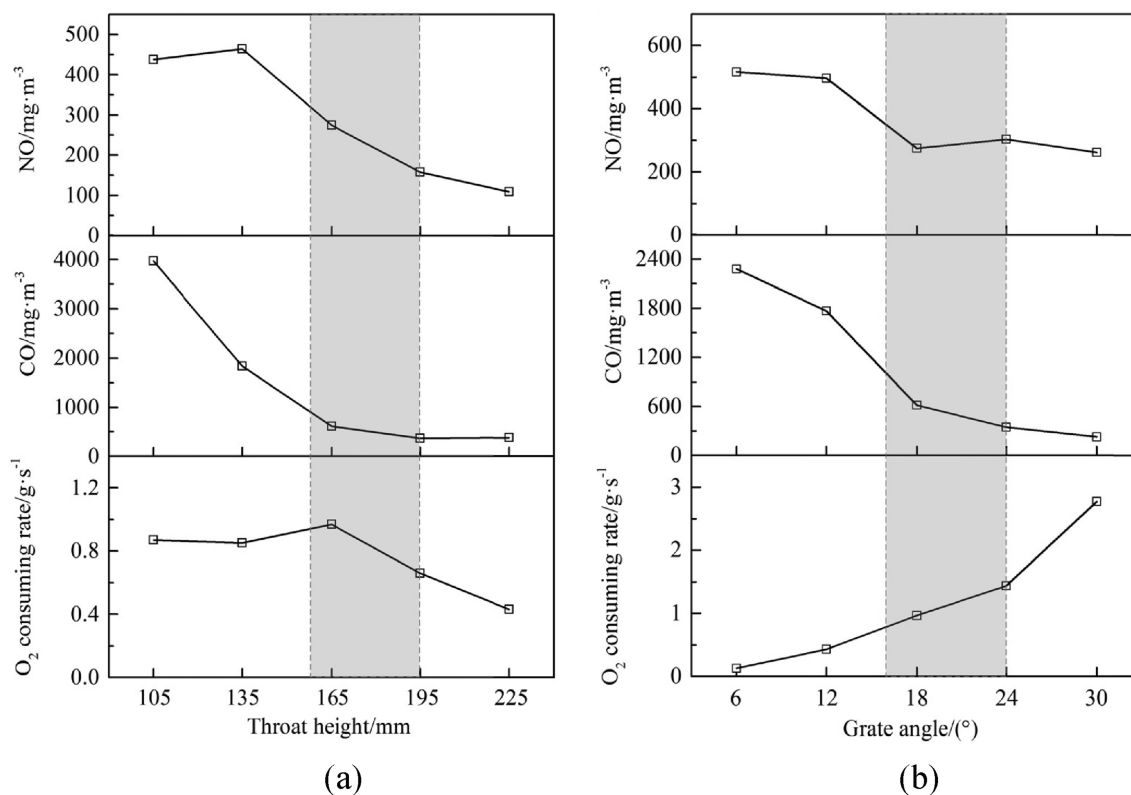


Fig. 9. Variations of outlet CO and NO emissions as well as total O_2 consumption rate with (a) throat height, and (b) grate angle.

It is worth noting that the total NO reduction rate by coal char is generally equivalent to that by pyrolysis gases in the decoupling coal stove because of the heterogeneous reducibility of char itself as well as its catalytic effect on the homogeneous reduction of NO_x [16,63,64].

Total NO production rate in the decoupling coal stove is actually dominated by the oxidation of char nitrogen, which may increase with increasing throat height because of the expanded char zone and increased char temperature, but decrease with increasing grate angle due to the contracted char zone and decreased char temperature (Fig. 6). However, the total NO reduction rate in the

whole stove significantly increases with increasing throat height but slightly decreases with increasing grate angle (Fig. 8). Therefore, as indicated in Fig. 9, the outlet NO emission decided by the difference between the total NO production and reduction rates gradually decreases with increasing throat height or grate angle, which consolidates the results shown in Fig. 7. The outlet CO emission is mainly decided by the degree of CO burnout in the decoupling coal stove. At a small throat height, most of inlet air tends to flow into the combustion chamber because of a thin effective fuel layer, which leads to a small high-temperature char zone as well as low temperature in the bottom passage, and further incom-

plete combustion of CO. This phenomenon can be sharply improved by increasing throat height at the given grate angle. However, the incomplete combustion of CO in the combustion chamber may become significant due to the decreased inlet air and temperature there at the great throat height of 225 mm, and thus results in a slight increase of outlet CO emission. Under this case, total O_2 consumption rate decreases clearly, which implies that the thermal load of stove is much lower than the rated thermal power. Therefore, as indicated by the shaded area in Fig. 9 (a), an optimal range of throat height can be determined as about 160–195 mm corresponding to the tested coal fuel. Similarly, a small grate angle of 6° leads to very less inlet air flowing into the bottom passage and the combustion chamber, and thus a high outlet CO emission. The significant increases of inlet air and temperature in the combustion chamber help to the burnout of CO though the high-temperature char zone contracts at the great grate angles and the small throat heights. However, the grate angle has a significant effect on the draft of inlet air in the decoupling combustion stove, which results in that the total O_2 consumption rate varies sharply with grate angle, that is, the thermal load of stove may deviate very much from its nominal value. Accordingly, as indicated by the shaded area in Fig. 9(b), an optimal range of grate angle is determined as about 16° – 24° based on comprehensive consideration of pollutant emissions and thermal power.

According to the optimal structural parameters, a newly-developed decoupling coal stove of 10 kW was produced and tested in the experimental system to validate the effectiveness of emission reduction. As shown in Table 5, the simulated results are in agreement with the experimental data in terms of outlet NO and CO emissions as well as temperature profile. Burning the tested bituminous briquettes in the decoupling coal stove, the

experimental values of average outlet NO and CO emissions can be as low as about $(205 \pm 21) \text{ mg} \cdot \text{m}^{-3}$ and $(691 \pm 200) \text{ mg} \cdot \text{m}^{-3}$, corresponding to the simulated values of $275 \text{ mg} \cdot \text{m}^{-3}$ and $614 \text{ mg} \cdot \text{m}^{-3}$, respectively.

3.2. Development of household decoupling biomass stoves

The decoupling combustion technology can also be utilized to design household biomass stoves to better take the advantage of simultaneous pollutant suppression. Suppressing the conversion of volatile nitrogen is thought to be the main NO_x reduction approach for biomass combustion [65–69]. The rapid release of volatile matter calls for the enhancement of volatile combustion and draft condition in the biomass stoves. Therefore, compared to decoupling coal stoves, smaller throat heights and larger grate angles are adopted to control the pyrolysis and combustion rates of biomass fuels in household decoupling stoves. According to the numerical optimization approach described in Section 3.1, two types of decoupling biomass stoves of 10 kW were designed to make full use of the superiority of decoupling combustion technology to reduce NO_x and CO emissions simultaneously.

As shown in Fig. 10(a), an A-type decoupling biomass stove has a similar structure to the decoupling coal stove, in which the throat height and the grate angle were numerically determined as 105 mm and 40° , respectively. In addition, the smoke tunnel is specially designed as a multi-pass structure to extend the residence time of gas and enable the burnout of combustible gases. The length, width and height of the A-type decoupling biomass stove are about 0.60 m, 0.24 m and 0.75 m, respectively. Fig. 10(b) shows a B-type decoupling biomass stove, which consists of a two-stage grate structure and an S-shaped pyrolysis chamber. The bottom

Table 5
Pollutant emissions and temperature profile in the decoupling coal stove

	Emission/ $\text{mg} \cdot \text{m}^{-3}$		Temperature/K				
	NO	CO	a	b	c	d	e
Exp.	205 ± 21	691 ± 200	552 ± 17	1299 ± 14	975 ± 25	737 ± 11	533 ± 8
Sim.	275	614	541	1170	1010	794	530

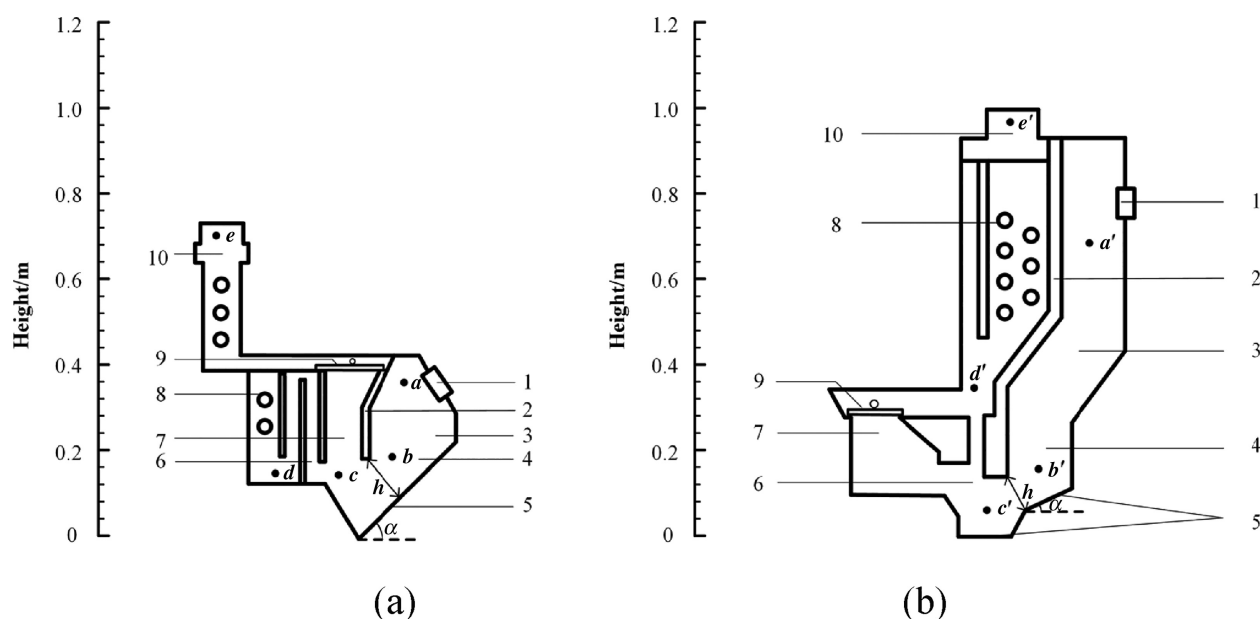


Fig. 10. Schematic diagrams of decoupling biomass stoves: (a) A-type; (b) B-type. 1—Coal feeding; 2—Baffle; 3—Pyrolysis chamber; 4—Measuring point; 5—Grate; 6—Combustion chamber; 7—Cooking chamber; 8—Heat exchange tube; 9—Adjusting plate; 10—Stove outlet.

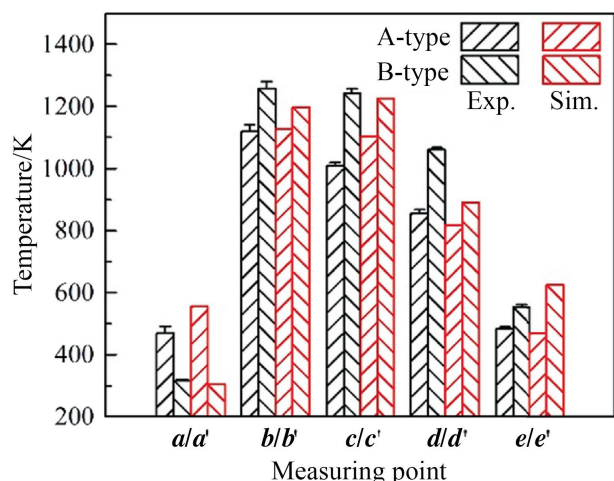


Fig. 11. Simulated and experimental temperature distributions in the two decoupling biomass stoves.

horizontal grate is designed to hold biomass char to form a possible stable char layer and introduce the secondary air, while the upper inclined grate with the throat height of 85 mm and the grate angle of 25° allows the introduction of primary air. The length, width and height of the B-type decoupling biomass stove are about 0.68 m,

0.24 m and 1.00 m, respectively. In this subsection, the emphasis will be laid on comparing the performance of the two decoupling biomass stoves and clarifying their mechanisms for NO_x and CO suppression.

As indicated in Fig. 10, the points *a* (*a'*), *b* (*b'*), *c* (*c'*), *d* (*d'*) and *e* (*e'*) represent the characteristic zones including the pyrolysis tops, the char zones, the throat zones, the combustion chambers and the outlets of the two decoupling biomass stoves, respectively. Fig. 11 shows the experimental and simulated temperature profiles in the heating modes of the two stoves. It can be seen that the simulated results are qualitatively coincident with the experimental data. The temperature at the point *a'* in the B-type stove is lower than that at the point *a* in the A-type stove because the high S-shaped pyrolysis gas chamber hinders the flow of inlet air and high-temperature flue gas to the pyrolysis chamber top, which also implies the stronger reducibility in the pyrolysis chamber of B-type stove. Correspondingly, the temperatures at the points *b'*, *c'*, *d'* and *e'* in the B-type stove are generally higher than those at the points *b*, *c*, *d* and *e* in the A-type stove, respectively. These phenomena are reasonable because much inlet air is introduced into the char zone and the combustion chamber in the B-type stove, and further enhances the heterogeneous and homogeneous combustion reactions there.

As shown in Fig. 12(a), the temperature distribution in the A-type biomass stove features a high-temperature zone in the throat and combustion chamber areas because the homogeneous combustion of volatile matter dominates the biomass combustion pro-

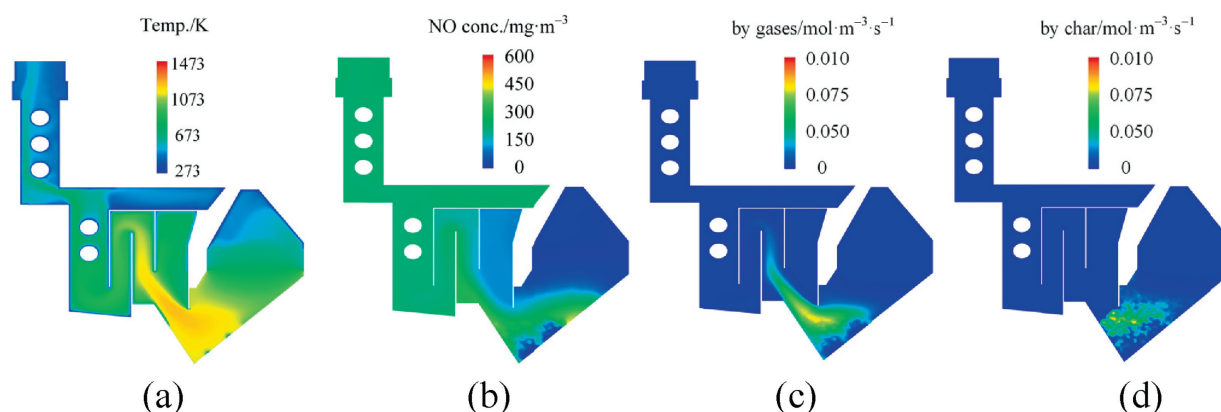


Fig. 12. Simulated distributions of (a) temperature; (b) NO concentration; (c) NO reduction rate by pyrolysis gases; (d) NO reduction rate by biomass char in the A-type decoupling biomass stove.

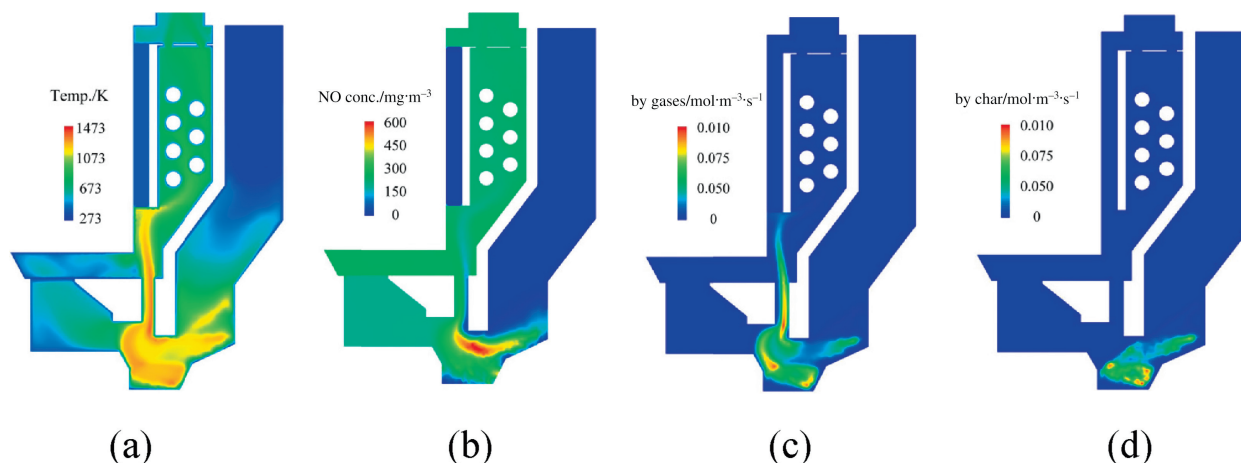


Fig. 13. Simulated distributions of (a) temperature; (b) NO concentration; (c) NO reduction rate by pyrolysis gases; (d) NO reduction rate by biomass char in the B-type decoupling biomass stove.

Table 6

Simulated and experimental outlet NO and CO emissions of decoupling biomass stoves

Biomass stove	NO/mg·m ⁻³		CO/mg·m ⁻³	
	Exp.	Sim.	Exp.	Sim.
A-type	250 ± 10	243	1099 ± 846	858
B-type	304 ± 20	311	728 ± 700	788

cess [33,70]. However, as indicated in Fig. 6, the highest temperature zone is generally located at the char combustion region at the pyrolysis chamber bottom in the coal stove since the char combustion plays a dominant role in the coal combustion. Therefore, as shown in Fig. 12(b), most of NO is formed in the throat and combustion chamber of the A-type stove. Moreover, unlike the NO concentration distribution in the coal stove (Fig. 7), the high NO concentration area extends into the bottom of pyrolysis chamber in the A-type stove due to the lack of char reducibility resulting from the disappearance of stable biomass char layer and gas circulation flow. Correspondingly, as shown in Fig. 12(c) and (d), the NO reduction by pyrolysis gases mainly happens in the high-temperature zone, while the NO reduction by biomass char generally occurs at the bottom of pyrolysis chamber.

Comparing Figs. 13(a) and 12(a), it can be found that the average and highest temperatures in the throat and combustion chamber of the B-type stove are higher than those in the A-type stove, which is consistent with the results indicated in Fig. 11. This leads to higher NO concentrations in those regions of the B-type stove (Fig. 13(b)), though the NO reduction rates by pyrolysis gases and biomass char become higher too (Fig. 13(c) and (d)). In the A-type stove, the total NO reduction rates by pyrolysis gases and biomass char in the whole computational domain are 0.000361 mol·m⁻³·s⁻¹ and 0.000113 mol·m⁻³·s⁻¹, respectively. Nevertheless, in the B-type stove these two values become 0.000516 mol·m⁻³·s⁻¹ and 0.000184 mol·m⁻³·s⁻¹, respectively. Although the specially-designed two-stage grate structure in the B-type stove favors the enhancement of NO reduction by biomass char, much more NO is still produced in B-type stove because of the increased temperature in the throat and combustion chamber areas. Moreover, in the both decoupling biomass stoves the total NO reduction rate by pyrolysis gases is always higher than that by biomass char, which is different from the situation in the coal stove and indicates the significance of pyrolysis gases on the NO reduction in the biomass stove [71–73].

Table 6 shows that the simulated NO and CO emissions are in agreement with the experimental results in the both biomass stoves. As discussed before, the outlet NO emission of the A-type stove is lower than that of the B-type stove, while the variation trend of the outlet CO emission is contrary to that of the outlet NO emission. This implies that the key factors of low-NO_x and -CO emissions in the biomass stoves lie in the suppression of the conversion of volatile nitrogen to NO_x in the biomass pyrolysis process and the formation of NO_x in the volatile combustion process. This can be implemented by properly decreasing temperature but increasing residence time of gas in the combustion chamber.

4. Conclusions

The decoupling combustion technology has been proven to enable the simultaneous suppression of NO_x and CO emissions from household coal stoves, which however calls for optimizing the stove structure according to fuel type to make full use of its superiority. For the design of decoupling coal stoves, the combination of throat height and grate angle should be optimized to take full advantage of the reducibility of coal char, which is equivalent to that of pyrolysis gases in the combustion of coal briquettes.

However, much attention should be paid to the optimization of the structure of combustion chamber as well as the introduction of secondary air to fully utilize the higher reducibility of biomass volatiles than that of biomass char in the combustion of biomass pellets.

By using numerical simulation and experimental validation, this study obtained an optimal parameter combination of throat height (160–195 mm) and grate angle (16°–24°) for the household decoupling coal stove. The NO and CO emissions from the decoupling coal stove burning a kind of commercial coal briquettes can be as low as 205 mg·m⁻³ and 691 mg·m⁻³ (9% O₂ basis), respectively. According to the combustion characteristics of biomass pellets, two types of decoupling biomass stoves were specially designed to better utilize the decoupling combustion principle. Burning a kind of commercial biomass pellets, a so-called A-type decoupling biomass stove with the similar structure to the decoupling coal stove was verified to allow the NO and CO emissions as low as 250 mg·m⁻³ and 1099 mg·m⁻³ (9% O₂ basis), respectively.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] J. Liu, D.L. Mauzerall, Q. Chen, Q. Zhang, Y. Song, W. Peng, Z. Klimont, X.H. Qiu, S.Q. Zhang, M. Hu, W.L. Lin, K.R. Smith, T. Zhu, Air pollutant emissions from Chinese households: A major and underappreciated ambient pollution source, *Proc. Natl. Acad. Sci. USA* 113 (28) (2016) 7756–7761.
- [2] G.R. Zhi, Y.Y. Zhang, J.Z. Sun, M.M. Cheng, H.Y. Dang, S.J. Liu, J.C. Yang, Y.Z. Zhang, Z.G. Xue, S.Y. Li, F. Meng, Village energy survey reveals missing rural raw coal in Northern China: Significance in science and policy, *Environ. Pollut.* 223 (2017) 705–712.
- [3] X. Liu, X.Y. Zhang, R.E. Zhang, X.D. Yang, M. Shan, Y.Q. Liu, Report on Chinese urban scattered coal management, Energy Foundation, Tsinghua University Research Center of Building Energy Efficiency, Beijing, 2022.
- [4] J. Werther, M. Saenger, E.U. Hartge, T. Ogada, Z. Siagi, Combustion of agricultural residues, *Prog. Energy Combust. Sci.* 26 (1) (2000) 1–27.
- [5] Z.H. Luo, L. Zhang, G. Li, W. Du, Y.C. Chen, H.F. Cheng, S. Tao, G.F. Shen, Evaluating co-emissions into indoor and outdoor air of EC, OC, and BC from in-home biomass burning, *Atmos. Res.* 248 (2021) 105247.
- [6] G.R. Zhi, C.H. Peng, Y.J. Chen, D.Y. Liu, G.Y. Sheng, J.M. Fu, Deployment of coal briquettes and improved stoves: Possibly an option for both environment and climate, *Environ. Sci. Technol.* 43 (15) (2009) 5586–5591.
- [7] G. Shen, S. Tao, S. Wei, Y. Zhang, R. Wang, B. Wang, W. Li, H. Shen, Y. Huang, Y. Chen, H. Chen, Y. Yang, W. Wang, W. Wei, X. Wang, W. Liu, X. Wang, S.L. Masse Simonich, Reductions in emissions of carbonaceous particulate matter and polycyclic aromatic hydrocarbons from combustion of biomass pellets in comparison with raw fuel burning, *Environ. Sci. Technol.* 46 (11) (2012) 6409–6416.
- [8] Y.J. Chen, C.G. Tian, Y.L. Feng, G.R. Zhi, J. Li, G. Zhang, Measurements of emission factors of PM_{2.5}, OC, EC, and BC for household stoves of coal combustion in China, *Atmos. Environ.* 109 (2015) 190–196.
- [9] Y. Wang, Y. Xu, Y.J. Chen, C.G. Tian, Y.L. Feng, T. Chen, J. Li, G. Zhang, Influence of different types of coals and stoves on the emissions of parent and oxygenated PAHs from residential coal combustion in China, *Environ. Pollut.* 212 (2016) 1–8.
- [10] K. He, Z.X. Shen, B. Zhang, J. Sun, H.J. Zou, M. Zhou, Z. Zhang, H.M. Xu, S.S.H. Ho, J.J. Cao, Emission profiles of volatile organic compounds from various geological maturity coal and its clean coal briquetting in China, *Atmos. Res.* 274 (2022) 106200.
- [11] L.J. Chen, L. Xing, L.J. Han, Renewable energy from agro-residues in China: solid biofuels and biomass briquetting technology, *Renew. Sustain. Energy Rev.* 13 (9) (2009) 2689–2695.
- [12] G.F. Shen, M. Xue, Comparison of carbon monoxide and particulate matter emissions from residential burnings of pelletized biofuels and traditional solid fuels, *Energy Fuels* 28 (6) (2014) 3933–3939.

- [13] H. Watanabe, J.I. Yamamoto, K. Okazaki, NO_x formation and reduction mechanisms in staged O₂/CO₂ combustion, *Combust. Flame* 158 (7) (2011) 1255–1263.
- [14] M.J. Aho, J.P. Hämäläinen, J.L. Tummaavuori, Importance of solid fuel properties to nitrogen oxide formation through HCN and NH₃ in small particle combustion, *Combust. Flame* 95 (1–2) (1993) 22–30.
- [15] E.G. Garijo, A. Degn Jensen, P. Glarborg, Kinetic study of NO reduction over biomass char under dynamic conditions, *Energy Fuels* 17 (6) (2003) 1429–1436.
- [16] J.D. He, W.L. Song, S.Q. Gao, L. Dong, M. Barz, J.H. Li, W.G. Lin, Experimental study of the reduction mechanisms of NO emission in decoupling combustion of coal, *Fuel Process. Technol.* 87 (9) (2006) 803–810.
- [17] B. Tohniyaz, N. Zhao, P. Mperejekumana, Y.G. Zhou, D.Y. Chen, G. Li, G.F. Molelekwa, A.M.I. Zayan, R.J. Dong, Evaluation of PAHs, PM_{2.5} and gaseous emissions from solid fuel direct-fired and cross-draft stoves, *Int. J. Environ. Anal. Chem.* 102 (6) (2022) 1318–1331.
- [18] M. Kuang, Z.Q. Li, Review of gas/particle flow, coal combustion, and NO_x emission characteristics within down-fired boilers, *Energy* 69 (2014) 144–178.
- [19] M. Šyc, J. Horák, F. Hopan, K. Krpec, T. Tomšej, T. Ocelka, V. Pekárek, Effect of fuels and domestic heating appliance types on emission factors of selected organic pollutants, *Environ. Sci. Technol.* 45 (21) (2011) 9427–9434.
- [20] Q. Li, J.K. Jiang, J. Qi, J.G. Deng, D.S. Yang, J.J. Wu, L. Duan, J.M. Hao, Improving the energy efficiency of stoves to reduce pollutant emissions from household solid fuel combustion in China, *Environ. Sci. Technol. Lett.* 3 (10) (2016) 369–374.
- [21] Y.F. Liu, Y. Zhang, C. Li, Y. Bai, D.M. Zhang, C.Y. Xue, G.Q. Liu, Air pollutant emissions and mitigation potential through the adoption of semi-coke coals and improved heating stoves: field evaluation of a pilot intervention program in rural China, *Environ. Pollut.* 240 (2018) 661–669.
- [22] J. Qi, Q. Li, J.J. Wu, J.K. Jiang, Z.Y. Miao, D.S. Li, Biocoal briquettes combusted in a household cooking stove: Improved thermal efficiencies and reduced pollutant emissions, *Environ. Sci. Technol.* 51 (3) (2017) 1886–1892.
- [23] J. Wang, H.H. Lou, F.L. Yang, F.Q. Cheng, Development and performance evaluation of a clean-burning stove, *J. Clean. Prod.* 134 (2016) 447–455.
- [24] B. Rashidian, Y.M. Al-Abdeli, D. Patiño, F.G. Guzzoni, G.H. Yeoh, Effect of freeboard deflectors in the fixed bed combustion of biomass, *Appl. Therm. Eng.* 103 (2016) 543–552.
- [25] G.F. Shen, Changes from traditional solid fuels to clean household energies – Opportunities in emission reduction of primary PM_{2.5} from residential cookstoves in China, *Biomass Bioenergy* 86 (2016) 28–35.
- [26] B. Liang, H.L. Bai, D.R. Bai, X.H. Liu, Emissions of non-methane hydrocarbons and typical volatile organic compounds from various grate-firing coal furnaces, *Atmos. Pollut. Res.* 13 (4) (2022) 101380.
- [27] X.H. Liu, J. Han, N. Zhang, J.J. Wang, Status of decentralized civil heating technology in China, *Bull. Chin. Acad. Sci.* 34 (4) (2019) 401–408.
- [28] J.H. Li, G.W. Xu, L.D. Yang, M. Kwauk, J.G. Zhang, Y.L. Guo, Z.Y. Zhou, A method of coal-fired smokeless combustion for NO_x suppression as well as its application in household stoves, CN Pat., 95102081.1 (1995).
- [29] J.H. Li, Y.R. Bai, W.L. Song, NO_x-suppressed smokeless coal combustion technique, In: Proceedings of International Symposium on Clean Coal Technology, Xiamen, China (1997).
- [30] J.H. Li, W.L. Song, Y.R. Bai, Y.N. Xu, G.W. Xu, J.G. Zhang, M.S. Guo, NO_x-suppressed smokeless coal combustion and furnaces, *Bull. Chin. Acad. Sci.* 15 (4) (2001) 206.
- [31] L. Dong, S.Q. Gao, W.L. Song, G.W. Xu, Experimental study of NO reduction over biomass char, *Fuel Process. Technol.* 88 (7) (2007) 707–715.
- [32] P. Glarborg, A.D. Jensen, J.E. Johnsson, Fuel nitrogen conversion in solid fuel fired systems, *Prog. Energy Combust. Sci.* 29 (2) (2003) 89–113.
- [33] A. Williams, J.M. Jones, L. Ma, M. Pourkashanian, Pollutants from the combustion of solid biomass fuels, *Prog. Energy Combust. Sci.* 38 (2) (2012) 113–137.
- [34] H.L. Li, J. Han, N. Zhang, X.H. Liu, J.D. He, W. Du, Effects of high-temperature char layer and pyrolysis gas on NO_x reduction in a typical decoupling combustion coal-fired stove, *J. Therm. Sci.* 28 (1) (2019) 40–50.
- [35] J. Han, X.H. Liu, J.D. He, Experimental study on the combustion of typical coal fuels in household decoupling stoves, *Chin. J. Process Eng.* 20 (6) (2020) 728–736.
- [36] Y. Zhou, D.W. Huang, J.L. Lang, T. Zi, D.S. Chen, Y.Y. Zhang, S.Y. Li, Y.F. Jiao, S.Y. Cheng, Improved estimation of rural residential coal emissions considering coal-stove combinations and combustion modes, *Environ. Pollut.* 272 (2021) 115558.
- [37] N.N. Jin, L. Guo, X.H. Liu, Machine learning-aided optimization of coal decoupling combustion for lowering NO and CO emissions simultaneously, *Comput. Chem. Eng.* 162 (2022) 107822.
- [38] Z. Husain, S.S. Tiwari, A.B. Pandit, J.B. Joshi, Computational fluid dynamics study of biomass cook stove—part 1: hydrodynamics and homogeneous combustion, *Ind. Eng. Chem. Res.* 59 (9) (2020) 4161–4176.
- [39] A. Kaundal, S. Powar, A. Dhar, Numerical investigation of the effect of air supply on cook stove performance, *Inhal. Toxicol.* (2021) 1–11.
- [40] T. Klason, X.S. Bai, Computational study of the combustion process and NO formation in a small-scale wood pellet furnace, *Fuel* 86 (10–11) (2007) 1465–1474.
- [41] A. Shiehnejadhesar, R. Scharler, R. Mehrabian, I. Obernberger, Development and validation of CFD models for gas phase reactions in biomass grate furnaces considering gas streak formation above the packed bed, *Fuel Process. Technol.* 139 (2015) 142–158.
- [42] B. Peters, Measurements and application of a discrete particle model (DPM) to simulate combustion of a packed bed of individual fuel particles, *Combust. Flame* 131 (1–2) (2002) 132–146.
- [43] E. Simsek, B. Brosch, S. Wirtz, V. Scherer, F. Krüll, Numerical simulation of grate firing systems using a coupled CFD/discrete element method (DEM), *Powder Technol.* 193 (3) (2009) 266–273.
- [44] A.H. Mahmoudi, M. Markovic, B. Peters, G. Brem, An experimental and numerical study of wood combustion in a fixed bed using Euler-Lagrange approach, *XDEM, Fuel* 150 (2015) 573–582.
- [45] J. Porteiro, J. Collazo, D. Patiño, E. Granada, J.C. Moran Gonzalez, J.L. Míguez, Numerical modeling of a biomass pellet domestic boiler, *Energy Fuels* 23 (2) (2009) 1067–1075.
- [46] J. Collazo, J. Porteiro, J.L. Míguez, E. Granada, M.A. Gómez, Numerical simulation of a small-scale biomass boiler, *Energy Convers. Manag.* 64 (2012) 87–96.
- [47] M.A. Gómez, J. Porteiro, D. Patiño, J.L. Míguez, CFD modelling of thermal conversion and packed bed compaction in biomass combustion, *Fuel* 117 (2014) 716–732.
- [48] V. Yakhot, S.A. Orszag, Renormalization-group analysis of turbulence, *Phys. Rev. Lett.* 57 (14) (1986) 1722–1724.
- [49] E.H. Chui, G.D. Raithby, Computation of radiant heat transfer on a nonorthogonal mesh using the finite-volume method, *Numer. Heat Transf. B Fundam.* 23 (3) (1993) 269–288.
- [50] G.D. Raithby, E.H. Chui, A finite-volume method for predicting a radiant heat transfer in enclosures with participating media, *J. Heat Transf.* 112 (2) (1990) 415–423.
- [51] B.F. Magnussen, B.H. Hjertager, On mathematical modeling of turbulent combustion with special emphasis on soot formation and combustion, *Symp. Int. Combust.* 16 (1) (1977) 719–729.
- [52] S. Badzioch, P.G.W. Hawksley, Kinetics of thermal decomposition of pulverized coal particles, *Ind. Eng. Chem. Proc. Des. Dev.* 9 (4) (1970) 521–530.
- [53] C.S. Wang, G.F. Berry, K.C. Chang, A.M. Wolsky, Combustion of pulverized coal using waste carbon dioxide and oxygen, *Combust. Flame* 72 (3) (1988) 301–310.
- [54] E.S. Hecht, C.R. Shaddix, J.S. Lighty, Analysis of the errors associated with typical pulverized coal char combustion modeling assumptions for oxy-fuel combustion, *Combust. Flame* 160 (8) (2013) 1499–1509.
- [55] P. Burchill, L.S. Welch, Variation of nitrogen content and functionality with rank for some UK bituminous coals, *Fuel* 68 (1) (1989) 100–104.
- [56] E. Desroches-Ducarne, J.C. Dolignier, E. Marty, G. Martin, L. Delfosse, Modelling of gaseous pollutants emissions in circulating fluidized bed combustion of municipal refuse, *Fuel* 77 (13) (1998) 1399–1410.
- [57] H. Thunman, B. Leckner, F. Niklasson, F. Johnsson, Combustion of wood particles—A particle model for eulerian calculations, *Combust. Flame* 129 (1–2) (2002) 30–46.
- [58] P.R. Solomon, M.A. Serio, E.M. Suuberg, Coal pyrolysis: Experiments, kinetic rates and mechanisms, *Prog. Energy Combust. Sci.* 18 (2) (1992) 133–220.
- [59] J.J. Wang, S.W. Hu, X.H. Liu, Kinetic modelling and experimental validation of single large particle combustion of coal char, *Chem. Eng. J.* 450 (2022) 138227.
- [60] K.M. Bryden, K.W. Ragland, C.J. Rutland, Modeling thermally thick pyrolysis of wood, *Biomass Bioenergy* 22 (1) (2002) 41–53.
- [61] L.S. Johansson, B. Leckner, L. Gustavsson, D. Cooper, C. Tullin, A. Potter, Emission characteristics of modern and old-type residential boilers fired with wood logs and wood pellets, *Atmos. Environ.* 38 (25) (2004) 4183–4195.
- [62] J.A. Miller, C.T. Bowman, Mechanism and modeling of nitrogen chemistry in combustion, *Prog. Energy Combust. Sci.* 15 (4) (1989) 287–338.
- [63] A. Tomita, Suppression of nitrogen oxides emission by carbonaceous reductants, *Fuel Process. Technol.* 71 (1–3) (2001) 53–70.
- [64] H.L. Du, M. Zhang, Y.L. Zhang, Y.H. Luo, Characteristics of NO reduction by char layer in fixed-bed coal combustion, *Energy Sources A Recovery Util. Environ. Eff.* 39 (10) (2017) 963–970.
- [65] P.G. Kristensen, P. Glarborg, K. Dam-Johansen, Nitrogen chemistry during burnout in fuel-staged combustion, *Combust. Flame* 107 (3) (1996) 211–222.
- [66] E. Vilas, U. Skifter, A. Degn Jensen, C. López, J. Maier, P. Glarborg, Experimental and modeling study of biomass reburning, *Energy Fuels* 18 (5) (2004) 1442–1450.
- [67] J. Ballester, R. Ichaso, A. Pina, M.A. González, S. Jiménez, Experimental evaluation and detailed characterisation of biomass reburning, *Biomass Bioenergy* 32 (10) (2008) 959–970.
- [68] S. Munir, W. Nimmo, B.M. Gibbs, The effect of air staged, co-combustion of pulverised coal and biomass blends on NO_x emissions and combustion efficiency, *Fuel* 90 (1) (2011) 126–135.
- [69] X.D. Yang, Z.Y. Luo, X.R. Liu, C.J. Yu, Y.A. Li, Y.C. Ma, Experimental and numerical investigation of the combustion characteristics and NO emission behaviour during the co-combustion of biomass and coal, *Fuel* 287 (2021) 119383.
- [70] C.G. Yin, L.A. Rosendahl, S.K. Kær, Grate-firing of biomass for heat and power production, *Prog. Energy Combust. Sci.* 34 (6) (2008) 725–754.
- [71] B. Leckner, M. Karlsson, Gaseous emissions from circulating fluidized bed combustion of wood, *Biomass Bioenergy* 4 (5) (1993) 379–389.
- [72] H. Zhou, A.D. Jensen, P. Glarborg, A. Kavaliuskas, Formation and reduction of nitric oxide in fixed-bed combustion of straw, *Fuel* 85 (5–6) (2006) 705–716.
- [73] Y. Shu, H.C. Wang, J.W. Zhu, G. Tian, J.Y. Huang, F. Zhang, An experimental study of heterogeneous NO reduction by biomass reburning, *Fuel Process. Technol.* 132 (2015) 111–117.