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Numerical simulation study of the influencing factors related to the blending of biomass syngas with coal

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ABSTRACT

Co-firing of biomass syngas with pulverized coal under oxygen-rich combustion conditions is an advanced technology that facilitates the utilization of biomass energy and reduces greenhouse gas emissions. Numerical studies were conducted to investigate the characteristics of co-firing of biomass syngas with coal. The effect of biomass syngas injection position on the boiler combustion process when the total heat input to the boiler is stable. The simulation results show that the biomass syngas injection location also has an important effect on the co-combustion characteristics and NO_x emissions. NO emissions were lowest when biomass syngas was injected at the bottom of the re-combustion zone. This study can provide a reference for the operation and optimal design of biomass syngas co-combustion boilers.

Keywords: biomass syngas, co-firing, oxy-fuel combustion, injection position, numerical simulation

1. INTRODUCTION

Global warming driven by emissions of greenhouse gases causes a series of problems. Rising temperatures contribute to the retreat of glaciers, permafrost, and sea ice. Increasing atmospheric energy and rates of evaporation brings about more intense storms and weather extremes. Growing atmospheric CO_2 concentrations have also led to ocean acidification that threatens the stability of ecosystem [1-2].Since CO_2 accounts for 76% of total greenhouse gas emission [3],reducing CO_2 emissions, especially from combustion of fossil fuels, has become a top priority.

Expanding the use of renewable energy is an effective method to reduce CO_2 emissions. Biomass is considered as one of the most promising energy sources due to its renewable and CO_2-neutral characteristics[4-6]. However, the high water content and low energy density of biomass have limited its huge-scale application in biomass-fired power plants, which have a lower thermal efficiency than coal-fired power plants [7]. Biomass co-firing with coal provides an efficient way to make full use of biomass resources, which could not only reduce emissions of CO_2 and NOx but also mitigate the environmental problem associated with biomass waste disposal [8].

In this study, a numerical investigation is performed to simulate the co-firing of biomass syngas and coal in a 660 MWe tower boiler. The influences of oxy-fuel condition, different biomass syngas and syngas injection position have been discussed in detail. A refined WSGG model is implemented to modify the model of gas radiation under oxy-fuel conditions. To predict the NOx emission in these conditions, models of HCN oxidation and NO-char reaction are modified to substitute the default models usually applied by the user-defined functions (UDFs) in CFD codes. The findings are beneficial for a better understanding of biomass syngas with coal co-firing under oxy-fuel conditions.

2. METHODOLOGY

2.1 Furnace and burner configuration

Fig 1 shows the schematic configuration of the case-study 660 MWe tangentially fired tower-type boiler. The boiler dimensions are: 18.15 m (depth), 18.15 m (width), and 97.50 m (height). The furnace could be divided into four parts, including hopper, burner zone, reburn zone, and upper furnace area. The boiler consists of coal nozzles injecting pulverized coal and primary air (PA), surrounding air nozzles, secondary air nozzles (SA), and deflected secondary air nozzles (DSA) to form tangential firing. The PA burners are divided into four levels in the burner zone, which are surrounded by several SA and DSA nozzles. In addition, six levels of separated over fire air (SOFA) nozzles are equipped over the burners. The injection direction of SA and SOFA are also shown in Fig 1, with the deflected secondary air (direction 2) deviating

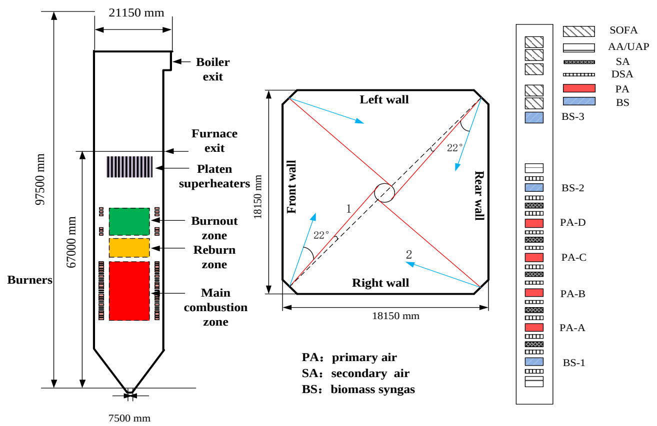

Fig. 1: Schematic of the boiler

from the direction of primary air (direction 1) by 22°. The arrangement and position of these burners are based on the design data provided by the manufacturer. Three layers of biomass syngas nozzles BS-1, BS-2 and BS-3 are set up to study the effect of injection position on co-firing characteristics.

2.2 Fuel Properties and cases Conditions

Biomass syngas is injected through the nozzle of the burner to replace the use of coal. Three different sets of grid systems were selected for grid independence testing. The total number of cells in the systems were 1565078, 1880167, and 2241660. 1880167 cells were used in the simulation area. Biomasses wood, rice straw, and palm were gasified using air as the gasification agent. The composition of the obtained syngas and the properties of coal are shown in Table 1 and Table 2, respectively.

Table 1: The Composition of the Biomass Syngas

Types	LHV ($KJ\cdot m^{-3}$)	Composition (%)				
		H_2	CO	CH_4	CO_2	N_2
Woody	5300	17.8	20.3	1.7	8.3	51.9

Table 2: Coal Properties

Proximate analysis (wt %)	V_{ar}	A_{ar}	FC_{ar}	M_{ar}	
	22.86	28.25	36.99	11.9	
Ultimate analysis (wt %)	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}
	47.4	3.24	7.21	0.8	1.2

2.3 Computational Modeling

The standard k-ε model was applied to describe the gas-phase turbulence. The radiation heat transfer was calculated by the P-1 model. Char combustion processes of coal were simulated by a diffusion/kinetics model. A two-competing-rates model was chosen to describe the devolatilization process of the coal.

Due to the introduction of the biomass syngas, the combustion processes of the blended fuel were different from the coal fired only. A gas phase combustion mechanisms is implemented into the CFD code to simulate the co-firing of biomass syngas and coal. The reaction equations can be written as follows:

$$CH_4 + 0.5O_2 = CO + 2H_2 \quad (1)$$

$$CH_4 + H_2O = CO + 3H_2 \quad (2)$$

$$CO + H_2O = CO_2 + H_2 \quad (3)$$

$$H_2 + 0.5O_2 = H_2O \quad (4)$$

3. RESULTS AND DISCUSSION

3.1 Validation of the CFD Model

The numerical calculation for the coal fired case was first conducted with the purpose of validating the CFD model. The outlet temperature of the furnace obtained by numerical simulation is 1430 K, which is 4.6% lower than the given calculated temperature. This is acceptable for practical engineering. For oxy-fuel condition, the selected models had been widely applied in the previous oxy-firing investigations [9-10]. These results confirm that the selected CFD model is suitable for the present work.

3.2 Effect of biomass syngas injection position

The detailed simulation conditions are listed in Table 3. The excess air ratio at the furnace outlet is 1.15. the gas temperatures of PA and biomass syngas are 349 K and 300 K, respectively, while the temperature of SOFA is 625 K. The share of syngas refired fuel is between 10% and 20%, calculated as the share of total energy supplied to the boiler. Each case considered in this study is named in the form of A2-0.24Y. A2 stands for biomass syngas and 0.24 for co-firing ratio. y stands for injection position. For example, in the case of A2-0.24M, the co-combustion share is 24% and the injection position is BS-2.

Table. 3 Cases considered in this study

Case	Co-firing ratio	Atmosphere	O_2 fraction	Injection position
A2-0.24L	20	O_2/CO_2	24%	BS-1 nozzles
A2-0.24M	20	O_2/CO_2	24%	BS-2 nozzles
A2-0.24U	20	O_2/CO_2	24%	BS-3 nozzles

The variation of biomass syngas injection position, which has an impact on the combustion process, is investigated. For different biomass synthesis gas injection positions, the relationship between temperature and furnace height is shown in Fig 2.

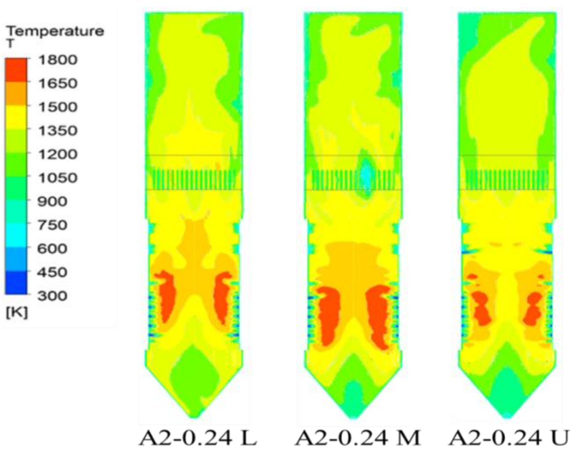

Fig. 2 The temperature profile for various injection positions

The positions of biomass syngas injection also have an effect on O_2 distribution in the furnace. As shown in Fig 3, the O_2 fraction drops sharply near the area of the biomass syngas injected, which is caused by the quick reaction between the biomass syngas and oxygen. In case A2-0.24L, the O_2 fraction at the bottom of the boiler is the lowest. The lowest O_2 fraction of case A2-0.24M appears near the BS-2 burner, while the lowest oxygen concentration of case A2-0.24U appears near BS-3 burner.

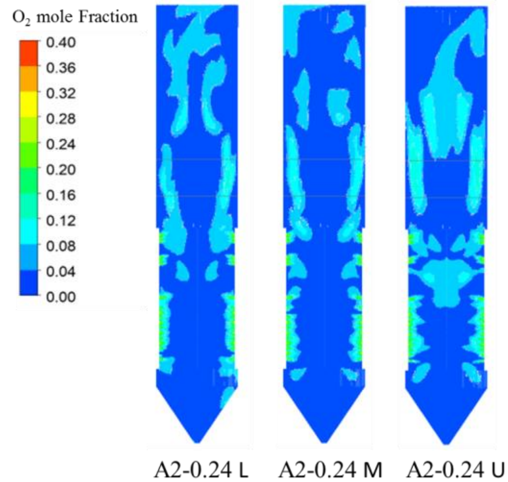

Fig.3 The O_2 distribution for various injection positions injection positions.

Fig 4 depicts the impacts of biomass syngas injection positions on the NO emission. It is obvious that low NO concentration region corresponds to biomass syngas injection position. Near the syngas injection nozzle, a reducing atmosphere is formed, which could reduce the formation of NO. Thus, the lowest NO concentration position is BS-1, BS-2 and BS-3 nozzle (Fig 1) in A2-0.24L, A2-0.24M and A2-0.24U case respectively.

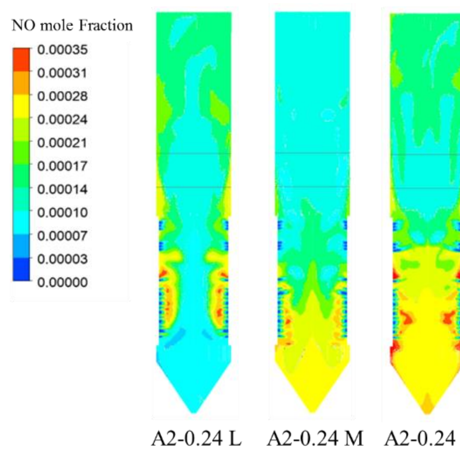

Fig.4 The NO profile for various injection positions

The NO concentration along the furnace height for these cases is displayed in Fig 5. The NO concentration rises sharply in main combustion zone for all the cases. Then the NO concentration decreases above main combustion zone. The reduction of NO concentration in A2-0.24L case is smaller than that in A2-0.24M. Finally, the NO concentration in the furnace outlet under A2-0.24M case is the lowest, while the NO concentration in A2-0.24L case is the highest. Compared to A2-0.24L case (syngas injection through the BS-1 nozzles), more NO is reduced to N_2 by gaseous N species and char above the main combustion zone, since a strong reducing atmosphere is formed there.

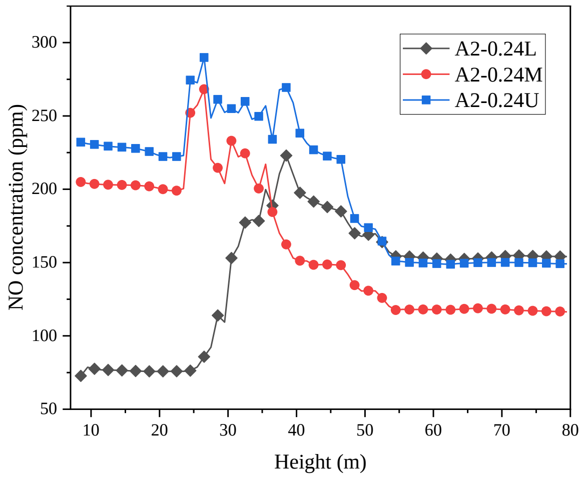

Fig.5 The NO distribution along the furnace height for various injection positions.

Therefore, the NO concentration in A2-0.24M and A2-0.24U cases are lower than that in A2-0.24L case. The NO emission is reduced by 22.5% when the biomass syngas injection position moves from the BS-1 nozzles to the BS-2 nozzles. Moreover, the temperature is also a key parameter in the process of syngas reburning. Higher temperature leads to a higher NO emission in burnout zone. Thus, the discrepancy of NO emission between A2-0.24M and A2-0.24U case could be understood. The results show that BS-2 is the optimal biomass syngas injection position (A2-0.24M case) in the present study, producing the lowest NOx concentration at the furnace outlet, Fig 4 and 5.

4. CONCLUSION

In this study, computational fluid dynamics (CFD) modeling was performed to simulate the co-combustion performance of biomass syngas and coal in a 660 MW tower boiler. The location of the biomass syngas injection was considered. The following conclusions were obtained:

The biomass syngas injection position is a key factor for co-combustion characteristics. The syngas is burned at a relatively higher rate, which leads to the low O_2 distribution near the syngas injection nozzle. NO emission is reduced up to 22.5% when the injection position moves from the BS-1 nozzle to the BS-2 nozzle, under the same co-firing ratio. To maximize the reducing effect of biomass syngas, the syngas should be injected to the reburn zone of the boiler.

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