COMPUTATIONAL MODELLING OF FLOW FIELD IN BOILER BEFORE AND AFTER UREA INJECTION UNDER DIFFERENT CONDITIONS

by

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In order to achieve ultra-low NO_x emissions, the effects of total excess air coefficient, air coefficient in main combustion zone, blended-coal combustion, and ammonia-nitrogen molar ratio on a 330 MW coal-fired boiler combustion were studied by numerical simulation. The results show that the velocity field and temperature field in the furnace have synergy, the better the synergy is, the faster the temperature rises, and the more NO_x it generates. Compared before and after urea spraying, the NO_x concentration decreased with the decrease of the total excess air coefficient, the optimum total excess air coefficient is about 1.15, and the denitrification rate is as high as 76.2%. The smaller the air coefficient in the main combustion zone is, the smaller the NO_x concentration is. The optimum air coefficient in the main combustion zone is about 0.92, and the denitrification rate is 85%. After urea injection, the denitrification rate of high volatile coal combustion is higher than that of low volatile coal combustion, and the reasonable blending mode of coal can reduce NO_x emissions. The larger the ammonia-nitrogen molar ratio is, the lower the NO_x concentration is. When the ammonia-nitrogen molar ratio is greater than 2, the amount of ammonia escape at the flue outlet exceeds the standard. When the ammonia-nitrogen molar ratio is less than 1, the NO_x concentration at the flue outlet is greater than that before urea injection. The optimal ammonia-nitrogen molar ratio is about 2.

Key words: *low nitrogen combustion, blended coal combustion, urea injection in main combustion zoneexcess air coefficient, numerical simulation*

Introduction

With the improvement of environment protection requirements, the emission standards of NO_x in coal-fired power plants are becoming more and more stringent [1]. At present the deep NO_x emission reduction technologies of coal-fired power plants include flue gas circulation, reburning technology, air staging, low nitrogen burners, selective catalytic reduction and selective non-catalytic reduction (SNCR). The combination of air staging and low nitrogen burners is the most simple and effective denitrification method, but the denitrification efficiency is only 40~60%. The SNCR is also a simple and effective denitrification technology in the process of combustion of the boiler, but the temperature window of reduction reaction is narrow [2].

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Many scholars have expanded the SNCR technology to high temperature region. Yao *et al*. [3] investigated and analyzed the current situation of ammonia injection denitrification technology and ammonia pollution in coal-fired power plants in China. Fan *et al*. [4] experimentally studied the effect of ammonia solution and its metal additive solution (Fe_2O_3, Fe_3O_4, CuO, Cu_2O, MnO, *etc*.) on NO emission from coal-fired boiler at high temperature. The results show that only under the condition of no oxygen or trace oxygen, the injection of ammonia can reduce NO in the process of pulverized coal combustion. Masato *et al*. [5] successfully carried out ammonia-coal co-combustion test on a 1.2 MW pulverized coal boiler. Tsukada *et al*. [6] studied the effect of OH radical in fuel-NO_x formation during co-combustion of ammonia with hydrogen, methane, coal, and biomass. The results show in staged combustion, if the concentration of OH free radical in the fuel-rich area is too low, the decomposition of ammonia will be inhibited and the amount of NO_x will increase, while the amount of NO_x produced by coal-ammonia mixed combustion is lower than that of methane-ammonia at the same equivalence ratio. Further studies [7] show that in the temperature interval of 900-1600 °C, H radical can significantly promote the decomposition of N_2O, and OH radical can promote the reduction of NO. The O radical decomposed by CO/O_2 promoted the conversion of N_2O to NO, as well as NH_3 to NO.

Numerical simulation technology has also made great progress in coal combustion and SNCR technology. Carlo *et al*. [8] introduced the application of SNCR in industry and its development in numerical simulation technology. Wang *et al*. [9] carried out a numerical simulation study on the combustion characteristics and NO_x emission law of a 350 MW supercritical cogeneration tangential boiler. The process of combustion in a grate boiler and the process of nitrogen NO_x reduction using the SNCR method is shown, and the operation of the supersonic nozzles that are used in the patented furnace jet boiler system is presented [10]. Sakiko *et al*. [11] studied the effect of ammonia-coal co-combustion on NO emissions from coal-fired boiler. The results show that compared with conventional coal combustion conditions, injecting ammonia into the flame zone can reduce NO_x emissions by 30%, while spraying ammonia can enrich NO in the flame zone. Norbert *et al*. [12] used numerical simulation technology to study the combustion flow characteristics in the SNCR technology of a coal fired grate boiler, and predicted the NO_x emissions. Zhang *et al*. [13] also carried out a similar study in high temperature zone of cement precalciner. Guo *et al*. [14] pointed out that reducing the angle between the velocity field and temperature gradient is an effective method to enhance heat transfer. Zeng *et al*. [15] applied the multi-field synergy theory to analyze the flow and heat transfer characteristics in the advanced vortex combustion. In many industrial fields, the field synergy theory has also been verified and popularized [16, 17], but there are few studies on the heat transfer characteristics of boiler combustion from the point of view of the synergy of temperature field and velocity field.

Combined with the field synergy theory, a 330 MW tangential coal-fired boiler is studied by numerical simulation. Through the analysis before and after urea injection in the main combustion zone, the effects of different total excess air coefficient, different air coefficient in main combustion zone, blended-coal combustion and ammonia-nitrogen molar ratio on furnace combustion characteristics and NO_x emissions were studied.

Boiler structure

As shown in fig. 1, in a 330 MW subcritical boiler, rich-lean separation direct current burners and concentric reverse tangential combustion technology are used to organize combustion in the horizontal direction. The offset angle of the primary air clockwise is 40.5°, and the offset angle of the secondary air counterclockwise is 45°. In the vertical direction, the burners

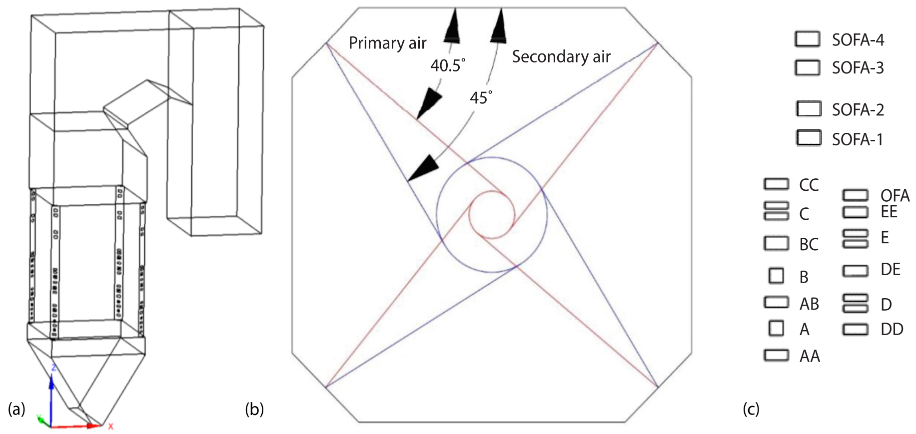

Figure 1. Boiler structure; (a) boiler body, (b) the horizontal nozzles cross-section, and (c) nozzle lay-out

are arranged in the four corners of the furnace, and layered from bottom to top. A, B, C, D, and E are primary air nozzles. For A and B, the coal in the inner is rich and the outer is lean, For C, D and E, the coal in the lower part is rich and the upper is lean and there are seven nozzles of secondary air, which are arranged alternately with primary air. A layer of over-fire air (OFA) nozzles and four layers of separated over-fire air (SOFA) nozzles are arranged in the upper part of the main combustion zone. The urea solution concentration is 10%, which is injected into the furnace together with the secondary air of the AA layer. High volatile coal (HV-coal) and low volatile coal (LV-coal) are selected for combustion. The coal property analysis is shown in tab. 1.

Table 1. Ultimate and proximate analyses of coal

Coal type	Proximate analysis [%]				Ultimate analysis [%]					Low heating value $Q_{net,ar}$ [MJkg^{-1}]
	M_{ar}	A_{ar}	V_{ar}	FC_{ar}	C_{ar}	H_{ar}	O_{ar}	N_{ar}	S_{ar}	
HV-coal	18	9.63	27.96	44.41	60.96	4.08	4.67	1.39	1.27	21.33
LV-coal	44	23	14.45	18.54	22.77	1.45	7.12	0.61	1.05	9.24

Mathematical model and calculation method

Mathematical model

The expression of synergy angle:

$$\beta = \arccos\frac{|U\nabla T|}{|U||\nabla T|} = \arccos\left|\frac{u\dfrac{\partial T}{\partial x}+v\dfrac{\partial T}{\partial y}+w\dfrac{\partial T}{\partial z}}{\sqrt{u^2+v^2+w^2}\sqrt{\left(\dfrac{\partial T}{\partial x}\right)^2+\left(\dfrac{\partial T}{\partial y}\right)^2+\left(\dfrac{\partial T}{\partial z}\right)^2}}\right| \tag{1}$$

where β is defined as the synergy angle, which is the angle between the velocity vector and the temperature gradient in boiler combustion.

The boiler furnace includes heat and mass transfer processes such as pulverized coal combustion, NO_x formation, urea denitrification and so on. The Euler-Lagrangian method is used to calculate the gas-solid two-phase flow, in which the Reynolds average Navier-Stokes equation is used to solve the gas phase, and the discrete particle phase includes coal particles and urea droplets. The gas-solid phase interaction force is coupled in a two-way coupling method. The SIMPLE algorithm is selected to couple the calculation of pressure and velocity. The convection term is the second-order central difference, and the diffusion term is the second-order upwind difference. The standard κ-ε model is used to calculate the gas turbulent flow, and the standard wall function is used to deal with the boundary-layer grid.

The gas phase turbulent combustion is calculated by the finite reaction rate-eddy dissipation model, in which urea is decomposed by Step 2 reaction mechanism, the reduction of NO_x by urea is Step 7 reaction mechanism [18], char combustion is Step 4 surface particle combustion [19], the volatile combustion of pulverized coal is Step 8 decomposition combustion [20]. The decomposition of volatile matter is: Vol $\rightarrow a$CO + bH_2S + cCH_4 + dH_2O + eH_2 + fN_2. The molar coefficients (that is, a, b, c, d, e, f) of volatiles pyrolysis into CO, H_2S, CH_4, H_2O, H_2, and N_2 (products of volatile nitrogen) vary with different types of coal, which can be calculated based on the conservation of heat and element mass before and after coal combustion. The volatile decomposition model is a two-equation parallel reaction model, where two rates that dominate over different temperature ranges are weighted to yield the final devolatilization rate. The char combustion is the dynamic-diffusion controlled reaction rate model. The radiative heat transfer is calculated by P1 method. More details about these models can be found in [21-23].

In the combustion of pulverized coal boiler, the production of rapid NO_x is so small that it can be neglected, the main sources of NO_x are thermal NO_x and fuel NO_x. Thermal NO_x follows the extended Zedovich mechanism, and the partial equilibrium of [O] and [OH] was selected to predict the relative O atom and OH concentrations in consideration of the influence of the radical concentration in the turbulent flames [24]. In the fuel NO_x model, volatile N can be converted into intermediates HNC and NH_3, while char N can be either converted directly into NO or first to intermediates (HNC or NH_3) and then partially to NO. In the process of combustion, NH_3 produced by lignite is about 10 times that of HNC, while bituminous coal produces more HNC intermediates [25]. The use of HNC/NH_3 = 9/1 for bituminous coal is more consistent with the experimental results of NO_x generation [26]. In this paper, bituminous coal with high volatile is used, so HNC/NH_3 = 9/1 is adopted and the path of Char N-to-NO with high NO_x production is selected as the fuel NO_x model [27].

Meshing and boundary conditions

The boiler is divided into four parts, cold ash bucket zone, burners zone, upper part of furnace zone and vertical flue zone, and it is meshed by high quality hexahedral grid. After the independence test, the total number of grids is 1.7 million. In order to reduce the pseudo diffusion in the calculation process, the direction of the grid line is consistent with the direction of fluid-flow, and the burners zone is divided into a radial grid. Because of the large physical gradient near the burner nozzles, the local grid refinement is carried out in this region.

Boundary condition is shown in tab. 2. The primary air is put into the burner nozzles A, B, C and D, and the burner nozzle E is shut down. The secondary air nozzles, OFA nozzles, SOFA nozzles are all open. The total excess air coefficient is 1.15. the total air volume is 313.1 m^3/s, the total coal mass is 41.94 kg/s, and the rich-lean ratio of the pulverized coal is 6:4. The design condition is taken as the standard condition, another simulation cases are based on the standard condition, as shown in tab. 3. The urea solution mass of the four nozzles in AA layer is distributed equally, the jet deflection angle is 45° and the jet velocity is 25 m/s. The required urea solution capacity is calculated according to the NO_x concentration at the outlet of the boiler flue, and the amount of urea sprayed is calculated according to the normalized stoichiometric ratio (NSR):

$$NSR = 2\frac{\left[\mathrm{CO}\left(\mathrm{NH}_2\right)_2\right]}{\left[\mathrm{NO}\right]} \tag{2}$$

Table 2. Boundary conditions

Project name	Air velocity [ms^{-1}]	Air temperature [K]	Ratio of air [%]
Primary air	26	368	20
Secondary air	47.7	628	50
OFA	28.6	628	10
SOFA	20.2	628	20

Table 3. Other cases

Boiler load	α	φ	HV-coal:LV-coal	NSR	Relationship
100%	1.10\1.15\1.20\1.25	0.92	1:0	0	The control group
100%	1.10\1.15\1.20\1.25	0.92	1:0	2	
100%	1.15	1.15\1.10\1.04\0.98\0.92\0.86\0.80\0.75	1:0	0	The control group
100%	1.15	1.15\1.10\1.04\0.98\0.92\0.86\0.80\0.75	1:0	2	
100%	1.15	0.92	1:0\0.7:0.3\0.3:0.7\0:1	0	The control group
100%	1.15	0.92	1:0\0.7:0.3\0.3:0.7\0:1	2	
100%	1.15	0.92	1:0	0.6-3.0	–

Results and discussion

The oxygen volume fraction and NO_x concentration at the outlet of boiler flue in references [28] are compared with the simulated values in this paper, and the results are shown in tab. 4. The error rate of O_2 volume fraction and NO_x concentration is less than 5%. It can be seen from tab. 4 that the numerical values in this paper can reasonably reflect the combustion characteristics and NO_x emissions characteristics in the boiler furnace.

Table 4. Validation of simulated results

Project name	Test value [28]	Simulation value	Error rate [%]
Oxygen volume fraction [%]	3.60	3.75	4.1
NO_x emissions [mgNm^{-3}]	345	350	1.4

Field synergy and its impact on NO_x emissions

Figure 2 is the temperature field and velocity flow field. The velocity streamline is distributed in a ring, and along the direction of the velocity streamline, the temperature distribution is also a ring. Figure 3 is the synergy angle distribution and velocity flow field. The air-flow is injected from the four corners of the furnace, the synergy angle is smaller along the flow direction of the air-flow, while the synergy angle is larger at the tail of the air-flow, about 80°, and the synergy angle also shows a similar ring distribution as a whole. Because in the direction of the air-flow, the stiffness of the air-flow is large, the direction of the temperature gradient is more consistent with the direction of the velocity vector, the synergy angle is smaller. At the tail of the air-flow, the stiffness of the air-flow weakens, the turbulent kinetic energy increases, the velocity vector changes rapidly, the synergy angle becomes larger, and the synergy between the velocity field and the temperature field becomes worse.

In the velocity flow field, the primary air carries pulverized coal into the furnace from the four corners of the boiler. Along the direction of air-flow, pulverized coal is distributed in a tangential circle while it is pyrolyzed, volatilized and burned. In the direction of velocity streamline, the heat transfer is the fastest and the temperature rise is the fastest. In the vertical direction of the velocity streamline, the heat transfer is the slowest and the temperature rise is the slowest. Therefore, an annular temperature distribution is formed along the annular velocity streamline.

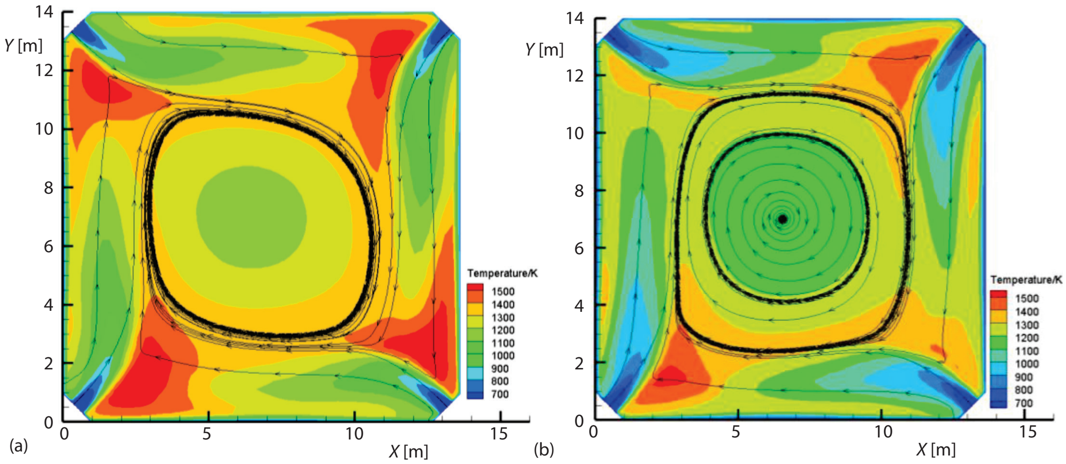

Figure 2. Temperature distribution; (a) before spraying urea and (b) after spraying urea

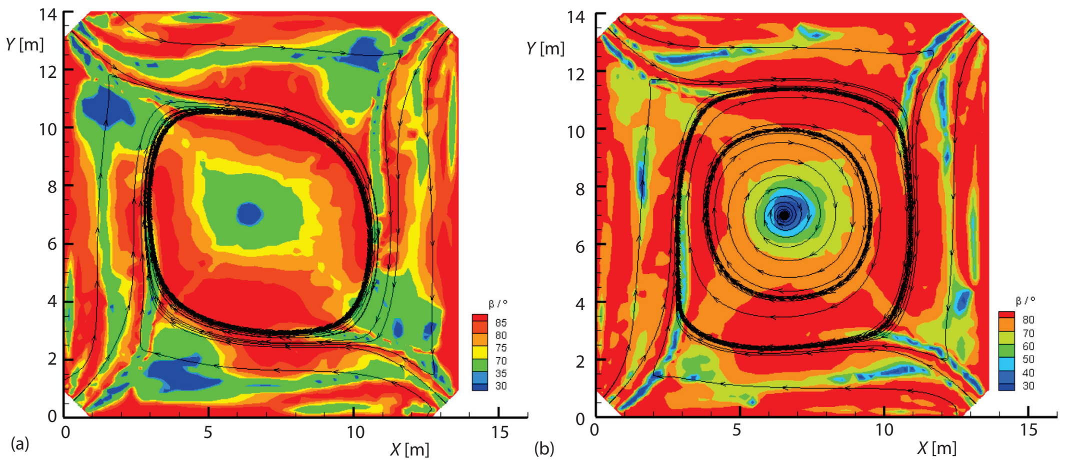

Figure 3. Synergy angle distribution; (a) before spraying urea and (b) after spraying urea

Figure 4 is the volatile content distribution. Near the air-flow nozzles of the boiler, the volatile shows an obvious rich-lean distribution, and it is more uniform in the center of the furnace. Combined with the temperature distribution in fig. 2, the rich-lean separation burners can separate the volatile of pulverized coal into two levels, and the high concentration of volatile releases more heat in the area with smaller synergy angle, resulting in a local high temperature zone. Figure 5 is the NO_x concentration distribution. Before spraying urea, the NO_x concentration shows a circular distribution with the velocity streamline, and its concentration is higher in the four furnace walls and in the center of the furnace. After spraying urea, the NO_x concentration as a whole is lower than that before spraying urea, and it is even lower in the center of the furnace. Because the heat flow transfers fastest along the velocity streamline, forming a ring-shaped local high temperature zone, thermal NO_x is more generated in the high temperature region. The tangential velocity momentum is not only conducive to the reduction of NO_x by urea, but also allows the generated NO_x to rotate and centrifuge to concentrate near the furnace walls.

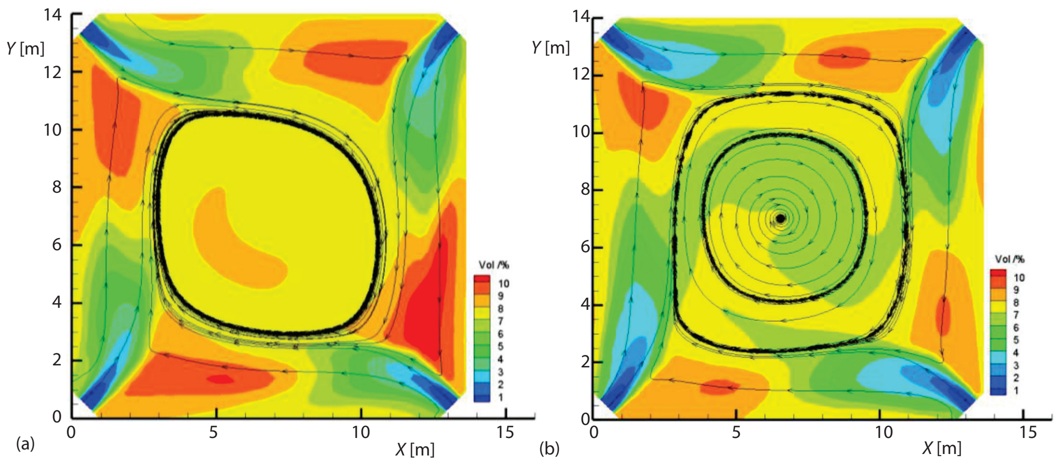

Figure 4. Volatile distribution; (a) before spraying urea and (b) after spraying urea

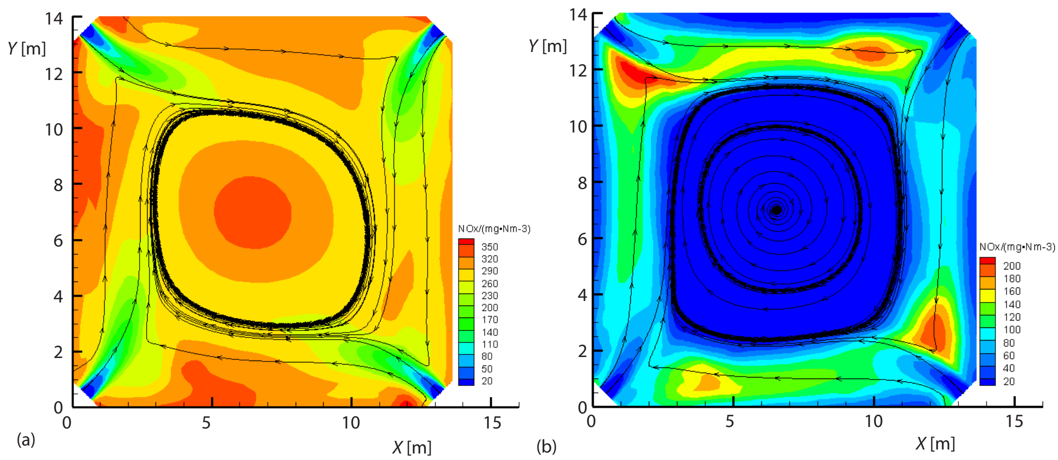

Figure 5. The NO_x concentration distribution; (a) before spraying urea and (b) after spraying urea

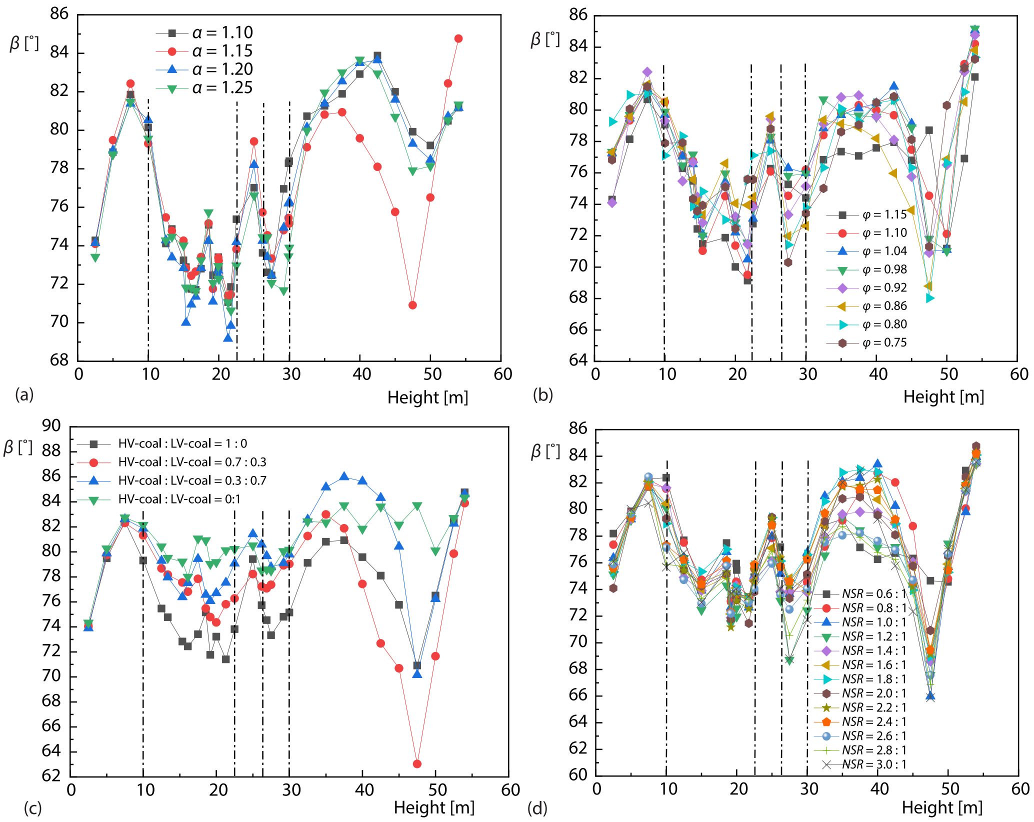

Figure 6. Effect of different parameters on the synergy angle; (a) effect of different total excess air coefficients on synergy angle, (b) effect of different air coefficients in main combustion zone on synergy angle, (c) effect of different coal blending ratios on synergy angle, and (d) effect of different ammonia-nitrogen molar ratios on synergy angle

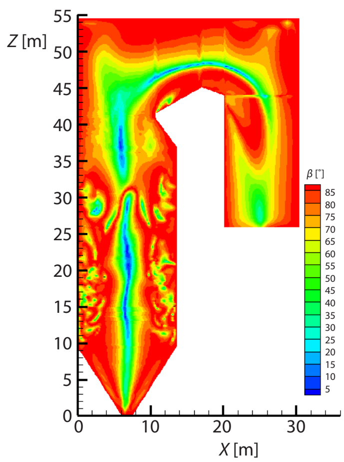

Figure 7. Synergy angle distribution in symmetry axis section of the boiler

Figure 6 shows the effect of different parameters on the β after spraying urea in the furnace. Figure 7 shows the β distribution on the section of the symmetry axis of the furnace under the standard condition. In fig. 6, along the furnace height direction, different parameters have similar effects on the β. Within the height range of 10-15 m, the β decreases rapidly from about 82° to about 70°. The reason is that with the continuous injection of pulverized coal, primary air and secondary air, a stable and consistent temperature field and velocity field are gradually formed in the lower part of the furnace. In the range of 15-30 m, the β fluctuates up and down, because a large amount of OFA and SOFA are fed in, making the flow, combustion, heat and mass transfer in the furnace extremely uneven, which results in poor synergy between temperature field and velocity field. Starting from 30 m, the β as a whole increases first, then decreases, and finally increases. Combined with the fig. 7, it is the upper part of the furnace from 30 m, and the turbulent kinetic energy carried by the lower incoming flow is further released in this region, which makes the synergy of temperature and velocity worse, so the β becomes larger. At the height of 40 m, the cross-section of the furnace suddenly shrinks, the velocity of flue gas slows down, and the high temperature flue gas diffuses along the horizontal flue of the furnace top to the vertical flue. Therefore, the smaller the β is at the horizontal flue, the synergy of temperature field and velocity field is better.

Effect of total excess air coefficient on NO_x emissions

Figure 8 shows the effect of different total excess air coefficients, α, on NO_x concentration along the furnace height before and after urea injection. Before spraying urea, in the cold ash bucket zone (0-10 m), the NO_x concentration is high and tends to decrease, because the air-flow in this zone was not circulating. In the height range of 12-30 m, the NO_x concentration slowly increased by about 50 mgN/m^3, then increased to maximum, and finally decreased slightly. Because the effect of air staging is obvious in the main combustion zone (10-22 m), the formation of NO_x is restrained, so the increase of NO_x concentration becomes slow. In the reduction zone (22-26 m) and burnout zone (26-30 m), there are some physical and chemical processes, such as the formation and reduction of NO_x, the secondary burnout of unburned coal, the dilution of NO_x concentration.

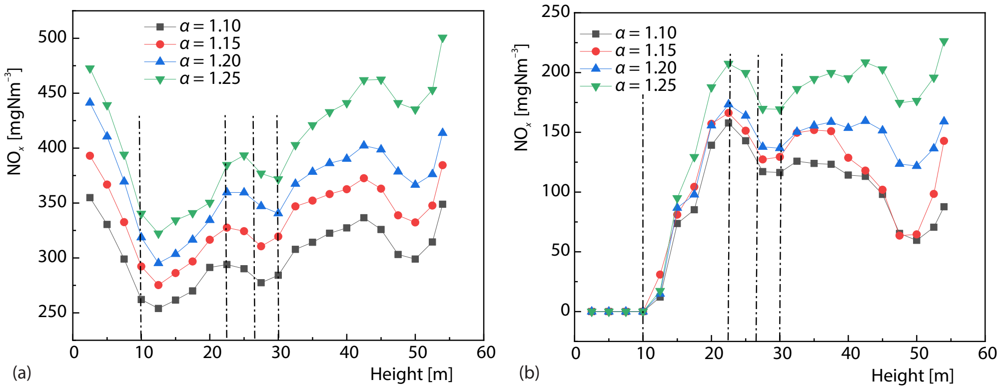

Figure 8. Effect of different total excess air coefficients on NO_x emissions; (a) before spraying urea and (b) after spraying urea

The dilute urea solution is injected into the furnace from AA layer four nozzles (z = 12.7 m) with the secondary air. In fig. 8, after spraying urea, the NO_x concentration in the cold ash bucket zone is almost zero, and the NO_x concentration in the main combustion zone increases rapidly, while in the reduction zone and burnout zone, the NO_x concentration decreases obviously. The reason is that the urea solution is injected into the lower part of the furnace, and the droplets are broken, atomized, evaporated, sublimated and decomposed into NH_3 and HNCO [29], which promotes the reduction of NO_x at the bottom of the furnace. In the main combustion zone, due to the delivery of oxygen, the reduction rate of urea to NO_x is weakened to some extent, so the concentration of NO_x increases rapidly. At the same time, in the reduction zone, the residence time of urea in the furnace is prolonged, which is beneficial to the full mixing of NO_x and urea. A sufficient amount of SOFA also dilutes the concentration of NO_x in the burnout zone. At the height of 50 m, the NO_x concentration suddenly increases. The reason is the enrichment of NO_x at the horizontal flue on the top of the boiler. In short, compared with no spraying urea, the NO_x concentration in the whole furnace after spraying urea decreases greatly, from above 250 mg/Nm^3 to below 200 mg/Nm^3.

Figure 9 is the NO_x concentration before and after urea injection, the denitrification rate, and the amount of ammonia escape at the flue outlet under different total excess air coefficients. In fig. 9, before and after urea injection, the larger the total excess air coefficient is, the higher the NO_x concentration at the outlet of the flue is. Compared with before spraying urea, the NO_x concentration of each working condition decreased by about 250 mg/Nm^3 after spraying urea. The highest denitrification rate after spraying urea can reach 76.2%, and the amount of ammonia escape is less than 0.4 mg/Nm^3. In a word, the total excess air coefficient and urea injection in the main combustion zone can affect the formation and emission of NO_x, and the optimum total excess air coefficient is about 1.15.

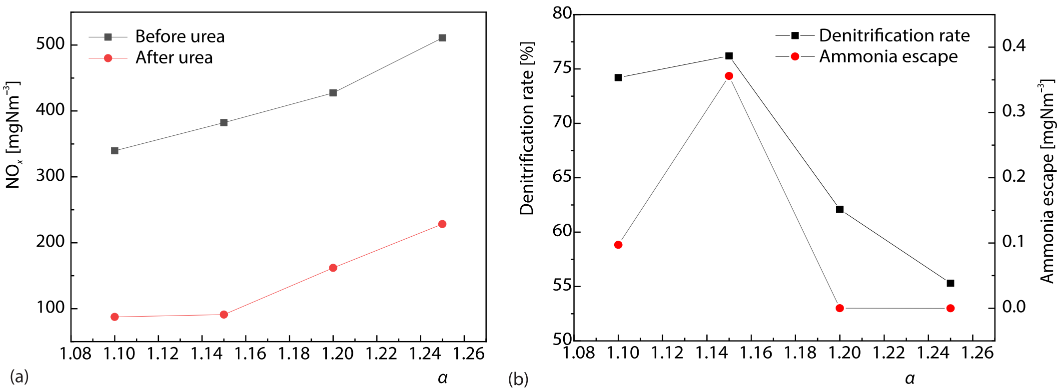

Figure 9. Denitrification index under different total excess air coefficients; (a) the NO_x concentration and (b) denitrification rate and ammonia escape

Effect of air coefficient in the main combustion zone on NO_x emissions

The air coefficient, φ, of the main combustion zone in the furnace is very important for the staging combustion and the reduction of NO_x by urea. It can be adjusted indirectly by changing the ratio of SOFA. Figure 10 shows along the furnace height, the effect of different air coefficients of main combustion zone on NO_x concentration before and after urea injection. In the height range of 10-22 m, the increase rate of NO_x concentration after urea spraying is greater than that before urea spraying. In the height range of 22-30 m, the NO_x concentration increases slightly for some cases before spraying urea, while for most cases, the NO_x concentration decreases slightly after spraying urea. At the height of 30 m and above, the NO_x concentration before urea spraying shows a gradually increasing trend, while the NO_x concentration after urea spraying shows a constant or decreasing trend. The difference between the two stems from whether the urea solution is injected into the lower part of the furnace. The smaller the air coefficient in the main combustion zone is, the smaller the NO_x concentration is, and the rate of decrease in NO_x concentration is also gradually slowing down. After spraying urea, when $\varphi \leq 0.92$, the NO_x concentration is less than 150 mg/Nm^3, and the NO_x concentration does not change much with the decrease of φ. The optimum air coefficient of the main combustion zone is about 0.92.

Figure 11 shows the NO_x concentration at the flue outlet, the denitrification rate and the amount of ammonia escape with different air coefficients in the main combustion zone. Before and after urea injection, reducing the air coefficient in the main combustion zone can effectively reduce the NO_x emissions at the outlet of the flue, with a decrease of about 200 mg/Nm^3. At the same time, compared with before spraying urea, the denitrification rate of the boiler after spraying urea is ≥45%, and the smaller the φ value is, the higher the denitrification rate is. Because reducing the air coefficient in the main combustion zone not only deepens the degree of air staging and inhibit the formation of NO_x, but also creates a *high temperature and low oxygen* atmosphere, which is beneficial to the reduction of NO_x by urea.

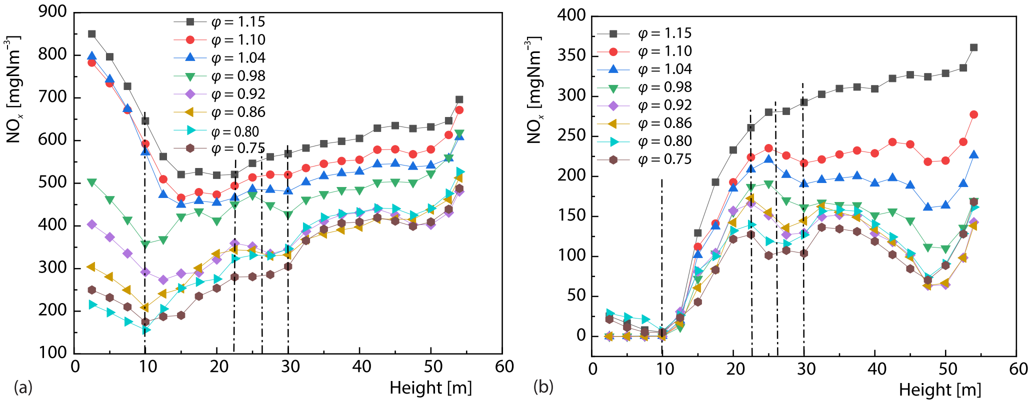

Figure 10. Effect of different air coefficients in main combustion zone on NO_x emissions; (a) before spraying urea and (b) after spraying urea

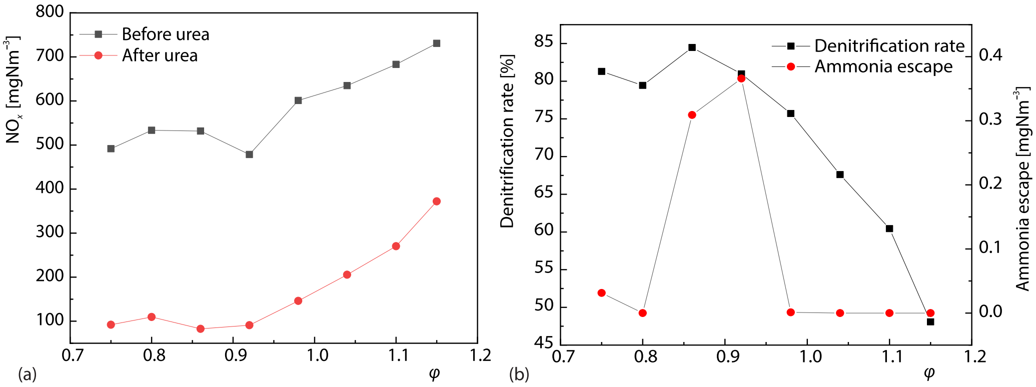

Figure 11. Denitrification index under different air coefficients in main combustion zone; (a) the NO_x concentration and (b) denitrification rate and ammonia escape

Effect of blended coal combustion on NO_x emissions

Figure 12 shows the variation curve of NO_x concentration along the furnace height before and after urea injection in blended coal combustion. Before spraying urea, the low volatile coal and the high volatile coal are burned separately, and their NO_x concentration changes differently. The NO_x concentration of low volatile coal decreases gradually and tends to remain unchanged after the height of 30 m, while the NO_x concentration of high volatile coal increased gradually from the height of 10 m. This is due to the fact that the low volatile coal has high water content and low carbon content, and the moisture evaporates ahead of time in combustion, which accelerates the cracking, crushing and burning of coal structure, so NO_x is generated centrally in the main combustion zone, while the combustion process of high volatile coal is exactly the opposite. The variation of NO_x concentration of blended coal combustion is similar to that of high volatile coal, but different blending proportions also affect the NO_x concentration. When the ratio of high volatile coal to low volatile coal is 0.7: 0.3, the NO_x concentration is lower than that of high volatile coal, when the ratio of high volatile coal to low volatile coal is 0.3: 0.7, the opposite is true. The reason is that the blending of high volatile coal has inhibition and promotion effect on the combustion of blended coal and the formation of NO_x [30]. When the proportion of high volatile coal in the blended coal is high, the high volatile coal will precipitate a large amount of volatile content and consume the oxygen share in the furnace in advance, resulting in the *air robbed phenomenon*, which makes the low volatile coal burning insufficient oxygen, hindering burnout of blended coal, NO_x production is also suppressed. When the proportion of high volatile coal in the blended coal is low, the high volatile coal is burned beforehand, which raises the local temperature at the initial stage of combustion, promotes the ignition and burning of low volatile coal, and produces a higher amount of NO_x.

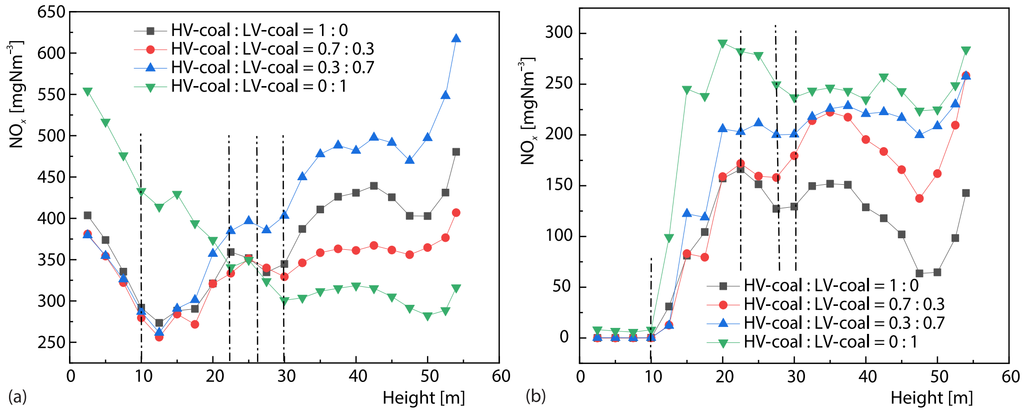

Figure 12. Effect of blended coal combustion on NO_x emissions; (a) before spraying urea and (b) after spraying urea

After urea is sprayed into the furnace, the overall NO_x concentration in the furnace is less than 300 mg/Nm^3, and the NO_x concentration is the lowest of the high volatile coal, while the NO_x concentration of the low volatile coal is the highest, and the NO_x concentration of the blended coal is between the two. Because the reduction of NO_x by urea changes the burning law of single coal, NO_x is gradually generated along the height of the furnace when high volatile coal is burned, and NO_x is concentratedly generated in the main combustion zone when low

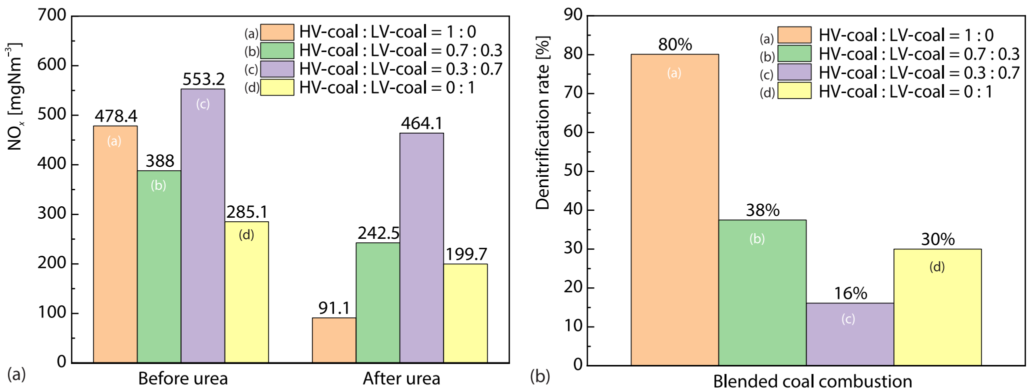

Figure 13. Denitrification index on blended coal combustion; (a) the NO_x concentration and (b) denitrification rate

volatile coal is burned. Due to the difference of NO_x formation region between the two kinds of coal, the mixing degree of urea to NO_x of high volatile coal combustion is better than that of low volatile coal combustion. In blended coal combustion, when the proportion of high volatile coal is large, the NO_x concentration is also lower, but higher than that of high volatile coal, which may be caused by the comprehensive effect of *air robbed phenomenon* and urea on NO_x.

Figure 13 is the NO_x concentration value of the flue outlet before and after urea injection, the denitrification rate after spraying urea. The denitrification effect is best when burning high volatile coal alone, and NO_x concentration is reduced from 478.4-91.1 mg/Nm^3. The blending ratio of different coal types also has a great influence on the denitrification rate after spraying urea, so attention should be paid to the method of coal blending.

Effect of ammonia-nitrogen molar ratio on NO_x emissions

Figure 14(a) shows the effect of different ammonia-nitrogen molar ratios on NO_x concentration along the furnace height after urea injection. Figure 14(b) shows the NO_x emissions and ammonia escape at the flue outlet with different NSR. In fig.14(a), along the furnace height, the NO_x concentration increases most rapidly in the main combustion zone, then decreases slightly in the reduction zone, and finally almost unchanged in burnout zone. The larger the NSR is, the smaller the NO_x concentration in the furnace is. Combined with fig. 14(b), when NSR > 2, the NO_x concentration at the flue outlet is stable below 50 mg/Nm^3, but the amount of ammonia escape also suddenly increases to >8 mg /Nm^3. When NSR < 1, the NO_x concentration at the flue outlet is ≥350 mg/Nm^3, which is higher than that before spraying urea. The reason is that when NSR is less than 1, the dosage of urea in the furnace is not enough, and the decomposed NH_3 and HNCO may be oxidized into NO_x. When NSR is greater than 2, there is a large ammonia escape at the flue outlet, which is easy to cause alkaline corrosion, and the optimum ammonia-nitrogen molar ratio is about 2:1.

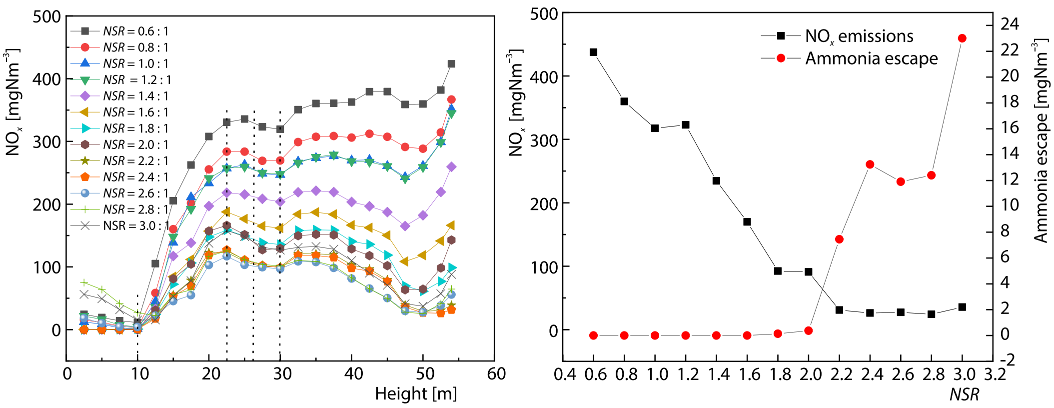

Figure 14. Effect of different ammonia-nitrogen molar ratios on NO_x emissions; (a) the NO_x concentration in height direction of boiler and (b) the NO_x concentration and ammonia escape at flue outlet

Conclusions

In this paper, the combustion flow in the furnace of a tangential boiler is numerically simulated, and the NO_x emission law of the boiler is analyzed from four aspects, total excess air coefficient, air coefficient in main combustion zone, blended coal combustion and ammonia-nitrogen molar ratio. The conclusions are as folows.

- The better the synergy between the velocity field and the temperature field in the boiler furnace, the faster the temperature rises and the greater the amount of NO_x generated is.
- Spraying urea in the main combustion zone can effectively reduce the overall NO_x concentration in the furnace, and its denitrification rate is up to 80%.
- Before and after spraying urea, the greater the total excess air coefficient is, the greater the NO_x concentration is. High temperature and low oxygen in the main combustion zone is the necessary condition for denitrification by urea injection. Reasonable blending ratio of blended-coal can reduce NO_x emissions. The higher ammonia-nitrogen molar ratio is, the smaller the NO_x concentration is, and the best molar ratio of ammonia-nitrogen is about 2:1.

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Nomenclature

T – temperature, [K]
U – velocity vector, [ms^{-1}]
u, v, w – velocity component, [ms^{-1}]

Greek symbols

α – total excess air coefficient, [–]
β – the synergy angle, [°]
φ – air coefficient of the main combustion zone, [–]

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