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Effect of Gas Recycle Rate on Net Plant Efficiency of A SPOC Power Plant

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ABSTRACT

Oxy-combustion technology is a promising near-zero carbon emission technology, however, its low efficiency and low economy limit its wide application to some extent. In this paper, a new thermal power system is proposed, which is a staged, pressurized oxy-combustion (SPOC) coupled with sCO_2 *cycle coal-fired power generation system. The system was constructed and simulated by Aspen Plus v12, and the influence of flue gas recycle (FGR) ratio on system efficiency was studied. The research shows that: in the range of 10% - 55.53%, the net efficiency of the system gradually decreases with the increase of the recycle ratio. When the recycle rate is 50%, the efficiency decreases by 3.5% compared with the condition without gas recycle. However, the relationship between the net efficiency and the recycle ratio is not linear. The net efficiency is greatly lost when recycle ratio is higher than 27.8%, and less than 27.8%, the net efficiency loss is less than 1 percentage point.*

Keywords: Staged, Pressurized Oxy-Combustion; supercritical CO_2 cycle, Simulation; flue gas recycle

1. INTRODUCTION

Reducing CO_2 emissions is a key point in the design of new coal-fired power plants. The technologies of carbon capture and storage in coal-fired power plants include pre-combustion capture, post-combustion capture and oxy-combustion [1,2]. Oxy-combustion is one of the most promising near-zero carbon emission technologies which can effectively reduce the power consumption of CO_2 separation and capture. However, atmospheric oxy-combustion technology increases the power consumption of oxygen production and CO_2 compression, resulting in low net efficiency of the atmospheric oxy-combustion. Thermal Energy Corporation proposed the concept of pressurized oxy-combustion (POC), which improves the efficiency of the oxy-combustion. On this basis, Gopan et al [3,4] proposed a novel POC technology, reducing the compression power consumption of FGR by reducing the FGR ratio and further improve the net efficiency.

Improving energy conversion efficiency can also reduce carbon emission. In recent years, a new technology has been proposed to replace the steam Rankine cycle through the coal-fired boiler with sCO_2 cycle, which can greatly improve the net efficiency of the coal-fired plant [5,6].

In order to improve the efficiency of oxy-combustion technology, a novel thermal system is proposed in this paper, which replaces the steam cycle of SPOC system with sCO_2 cycle.

2. System layout

The advantages of SPOC system include: (1) Higher operating pressure can realize the recovery of the latent heat of steam in the flue gas, remove almost all SO_X and most of NO_X and other pollutants in the flue gas, and reduce the size of the equipment; (2) The smallest FGR almost eliminates the pumping power consumption and cost associated with the FGR, increasing the efficiency and economy.;(3) Maximize radiant heat transfer, improve efficiency and minimize heat transfer surfaces, thereby reducing costs. (4) Staged and modular design theoretically improves operational flexibility.

Based on the first generation of SPOC, Gopan et al. designed a new arrangement with some modifications. In the first generation of SPOC system, O_2 only passes into the first stage boiler, and the flue gas circulation is low. The new arrangement will pass O_2 into all levels of boilers and increase the amount of flue gas circulation. Although this improvement resulted in a slight loss of efficiency to some extent, it significantly reduced process complexity.

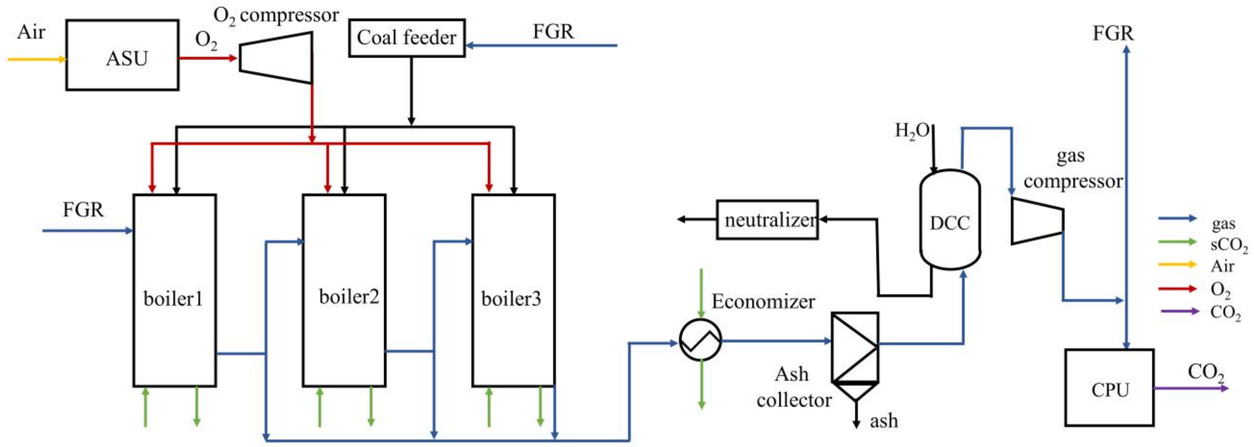

Fig.1 Flow diagram of SPOC coupled with sCO_2 cycle system

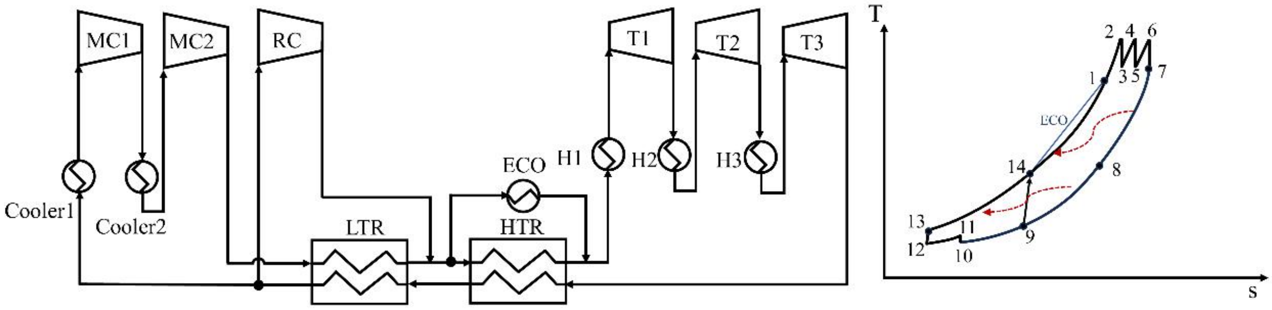

Fig.2 sCO_2 cycle arrangement

Fig.1 shows the simplified process flow diagram. In this process, FGR is required only in first stage to control the O_2 concentration near the furnace wall, and the O_2 concentration in the furnace wall in other stage will be controlled by combustion products from the previous stage. The phased oxygen supply provides additional control over the amount of O_2 at each stage and its inlet concentration. The advantages of this arrangement can be obtained from the characteristics of the second-generation SPOC arrangement: the expansion is increased, and the scale reorganization of the power plant can be realized by adding a new boiler on the basis of the original boiler. In the system, three-tower Air Separation Unit (ASU) based on cryogenic method is adopted. CO_2 compression and purification (CPU) use double flash tank type. Direct contact condenser (DCC) is used for desulfurization and denitration.

The cycle process is shown in Fig. 2: sCO_2 enters heater 1 (H1) at point 1 to absorb heat, after which the obtained working fluid 2 enters Turbine1 (T1) to do work, and then enters heater 2 and 3 (H2, H3) to absorb heat in processes 3-4 and 5-6 respectively, and enters turbines 2 and 3 (T2, T3) to do work in processes 4-5 and 6-7. After the fluid 7 is released from the turbine outlet, it enters the High Temperature Recuperator (HTR) and the working medium on the cold side of the Recuperator for heat transfer to point 8, where the point 8 fluid enters the Low Temperature Recuperator (HTR), After the LTR, part of the fluid is compressed by the Re-compressor (RC) and then combined with s CO_2 on the cold side of the LTR to enter the high temperature regenerator, and the other part of the fluid is cooled by Cooler1 (cooler 1) to point 10. After compression by the Main Compressor 1 (MC1), cooling by the cooler 2, and compression by the main compressor 2, point 13 is obtained, and then into the low temperature regenerator. Part of the flow at point 14 goes into the Economizer (ECO) for heating and then into the heater, and part goes into the high temperature regenerator for heating and then into the heater 1.

3. Parameter Settings and model method

3.1 Parameter Settings

In the second-generation arrangement, the gas volume of each boiler entering the next stage is controllable, and part of the flue gas from the upper furnace outlet directly enters the next stage, while part of the flue gas directly enters the economizer, so that the smoke volume can be controlled. Fig. 3 shows the O_2 concentration in the furnace when all the flue gas produced by the combustion of boiler enters the next stage. When the FGR ratio is 40%, the O_2 concentration of the third-stage boiler is too low and cannot be burned normally. When the circulating flue gas volume is 50%, the oxygen concentration in the flue gas at the second and third stages is as low as 12%, which is obviously unacceptable. Excessive flue gas intake into the boiler may cause a series of problems, affect the efficiency of the boiler operation, and reduce the thermal efficiency. First of all, excessive flue gas will carry too much heat discharge, resulting in increased flue gas heat loss of the boiler, reducing the thermal efficiency of the boiler. Secondly, too much gas volume will make the airflow speed in the furnace too high, so that the mixture of fuel and air is uneven, resulting in incomplete combustion, combustion deterioration, and further reducing the efficiency of the boiler. In addition to the impact on efficiency, incomplete combustion also increases emissions of pollutants such as carbon monoxide. At the same time, excessive flue gas will also increase the load of desulfurization and denitrification equipment, if it exceeds the processing capacity of the equipment, it will lead to excessive emissions of sulfur dioxide, nitrogen oxides and other pollutants, causing pollution to the environment. Therefore, controlling the proportion of flue gas entering the lower furnace is the key to realize the new layout.

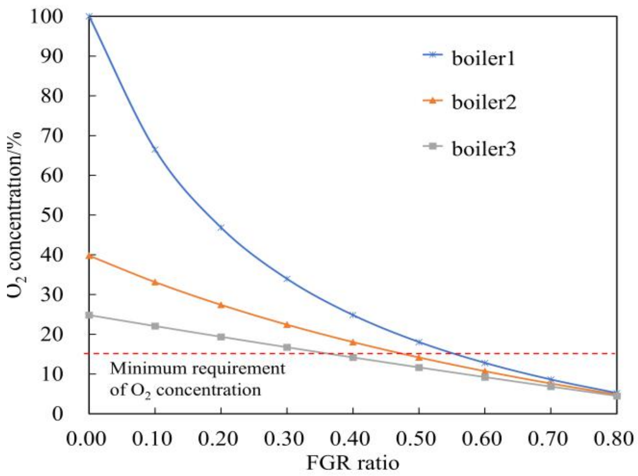

Fig.3 Effect of FGR ratio on O_2 concentration in boiler

FGR ratio needs to be adjusted during simulation to achieve a controllable total smoke volume. When the O_2 concentration is less than 15%, the pulverized coal cannot normally ignite and is difficult to continue burning, which requires the proportion of circulating flue gas must be kept below 50%, otherwise when the pulverized coal is sent at 1:1:1 and does not pass the additional input of oxygen, the pulverized coal cannot maintain stable combustion in any first-stage boiler. The following conditions are observed when setting parameters:

1) The oxygen concentration of each stage boiler should be kept above 15% to maintain normal combustion;
2) The O_2 concentration of each stage is greater than 102.5t/h to ensure the full combustion of pulverized coal. The oxygen distribution ratio is α1, α2, α3, where α1 is greater than 1/3, α1+α2 is greater than 2/3, α1+α2+α3=1;
3) When the proportion of the first stage oxygen quantity α1 is greater than 1/3, the proportion of flue gas entering the lower furnace will be 100%, that is, to ensure that excess oxygen enters the next stage furnace for combustion, to avoid oxygen waste, the parameter is introduced - the proportion of flue gas directly into the economizer β. Similarly, when α1+ α2 is greater than 2/3, β2=0;
4) Try to ensure that the smoke volume in each stage of the furnace is the same with different parameters, and at least 307.5t/h, a reasonable smoke volume is to ensure that the furnace is not subject to too little smoke and heat exchange deterioration, while ensuring roughly the same combustion condition. The system parameter setting and working condition setting are set in Table 1 and Table2.

Table 1 system parameter setting

parameter	values
Coal mass flow/(t/h)	157.5
Coal distribution ratio	1:1:1
Total O_2 flow /(t/h)	307.5
O_2 concentration	95%
FGR ratio λ	0%~60%

Table2 Working condition setting

λ	$α_1$	$α_2$	$α_3$	$β_1$	$β_2$
0	1	0	0	0	0
0.1	0.832	0.000	0.168	0.000	0.000
0.2	0.622	0.045	0.333	0.000	0.270
0.3	0.352	0.315	0.333	0.000	0.390
0.4	0.333	0.333	0.333	0.444	0.250
0.5	0.333	0.333	0.333	0.584	0.249
0.6	0.401	0.422	0.177	-	-
0.7	0.625	0.375	0.000	-	-
0.8	1.000	0.000	0.000	-	-

According to the working condition setting, when the ratio of circulating flue gas λ is 60%, 70%, 80%, the O_2 concentration in the third, second and first stage furnace cannot meet the requirements; It is calculated that when λ is 55.53%, the oxygen concentration of each furnace stage can be achieved above 15% by adjusting β.

3.2 model method

Physical property method selection: PR-BM method (PENG-ROB) was used to simulate flue gas flow; The REFPROP method is used to simulate the sCO2 loop part. ELECTRNL method is used to simulate DCC. The PR-BM method is commonly used to simulate cryogenic engineering, including ASU and CPU.

In the combustion subsystem, the boiler is realized by the combination of RYield and Rgibbs modules. The distillation column of ASU subsystem is simulated by Radfrac module. DCC flash tank was simulated by Flash2. Flash tank in CPU was simulated with Flash2. The rotating device is implemented by Compr; The cooling equipment is realized by heater, and multi-stream fluid heat transfer is realized by MHeatx module. The shunt and Mixer processes are realized by Fsplit and Mixer modules respectively. The throttling and pressure drop processes are simulated by the Valve module.

4 Result

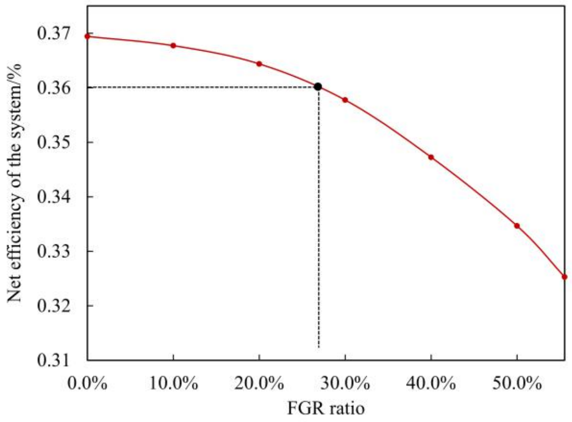

Fig.4 Effect of FGR ratio on net efficiency of the system

The ASU and CPU power combustion are calculated when the net efficiency is calculated. The net efficiency of the system when the FGR ratio ranges from 10%-55.53% is shown in Fig.4. The net efficiency decreases with the increase of the FGR ratio. When the recycle rate is 50%, the efficiency decreases by 3.5% compared with the condition without gas recycle. However, the relationship between the net efficiency and the recycle ratio is not linear. The net efficiency is greatly lost when recycle ratio is higher than 27.8%, and less than 27.8%, the net efficiency loss is less than 1%.

Fig. 5shows the heat absorption of the cycle from the boiler and economizer under different cycle ratios, and Fig. 6 shows the net cycle work output and gas compression power consumption under different cycle ratios to analyze the reason why the net efficiency increases. It can be seen from Fig. 5, with the increase of λ, the total heat input to the cycle gradually decreases, in which the heat transfer between the boiler and the cycle decreases, and the heat transfer between the economizer and the cycle increases. Because DCC is a direct contact hot cooling tower, the flue gas temperature from the outlet of DCC is reduced to about 25 ° C, and after compression to 1.6MPa, the temperature rises to about 40 ° C into the furnace, so the return flue gas will reduce the average temperature of the flue gas entering the furnace. The increase in the proportion of return flue gas pushes a large amount of sensible heat energy downstream of the process to a lower temperature area, that is, the heat is transferred from the furnace to the economizer and lower temperature heat transfer components. Therefore, in the recirculation process, the heat transfer of the boiler part decreases with the increase of λ, and the heat transfer of the economizer part increases due to the increase in the smoke volume. The increase of unused heat carried away by the flue gas after the economizer results in the decrease of the total heat. Figure (b) shows the relationship between λ and the change of cycle output work cycle and gas compression work consumption. Based on the analysis of Figure (a), λ increases the heat absorption of the cycle working medium at low temperature, and the average heat absorption temperature decreases, thus reducing the cycle efficiency, and then superimposed the influence of the decrease of total cycle heat absorption, and the final system net efficiency decreases with the increase of λ. Gas recirculation also increases the power consumption of circulating gas compression.

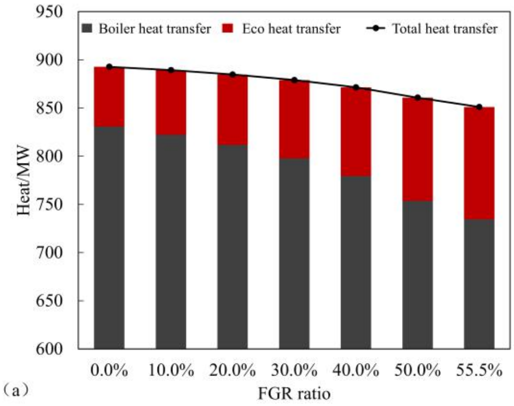

Fig.5 Effect of FGR ratio on heat transfer

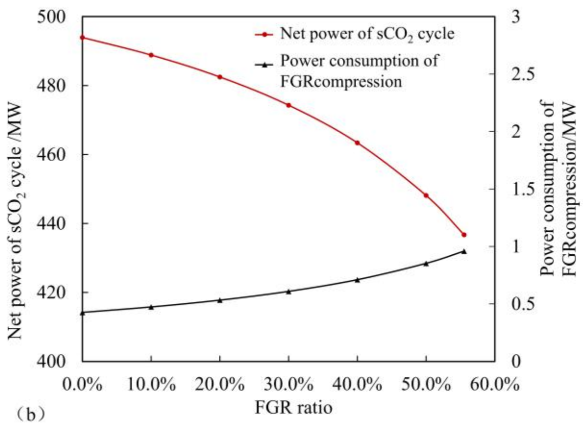

Fig.6 Effect of FGR ratio on power consumption

5. conclusion

The net efficiency decreases with the increase of the FGR ratio. When the recycle rate is 50%, the efficiency decreases by 3.5% compared with the condition without gas recycle. However, the relationship between the net efficiency and the recycle ratio is not linear. The net efficiency is greatly lost when recycle ratio is higher than 27.8%, and less than 27.8%, the net efficiency loss is less than 1%.

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