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Thermal performance analysis of advanced partial gasification combined cycle

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Abstract: This paper presents the thermodynamic performance analysis and comparison of four kinds of advanced pressurized fluidized bed combustion combined cycle (APFBC-CC) system schemes, two based on pressurized fluidized bed (PFB) combustion and the other two based on atmospheric circulating fluidized bed (CFB) combustion. The results show that the first scheme avoids high temperature gas filter, but has the lower cycle efficiency and syngas heating value. The second scheme can gain the highest cycle efficiency, however it is better to now lower the filter operating temperature. The third and fourth schemes, based on CFB, have lower efficiencies than the second one. But the fourth one, with preheating air/steam for gasification, can obtain the highest heating value of syngas and gain higher efficiency than the third one.

Key words: partial gasification; thermal performance; combined cycle; advanced pressurized fluidized bed combustion combined cycle (APFBC-CC)

Coal is the primary energy source of the power industry in China. The advanced pressurized fluidized bed combustion combined cycle (APFBC-CC) is one of the most promising clean coal power generation technologies. In the first-generation pressurized fluidized bed combustion combined cycle (PFBC-CC), the inlet temperature of the gas turbine cannot exceed 850 ℃ owing to the limited combustion temperature in the pressurized fluidized bed. Thus use of advanced gas turbine is limited, and the overall net efficiency of the combined cycle is also limited. In APFBC-CC, only partial gasification is necessary, and this can be realized more easily than full gasification. It overcomes the disadvantages of PFBC-CC, so APFBC-CC has been widely studied in some industrial countries in recent years[1-3]. In China, laboratory research on the APFBC-CC is also in progress[4]. In this paper, the system presentation and thermal performance analysis are carried out for different schemes of APFBC-CC.

1 APFBC-CC System Schemes

In APFBC-CC, coal, air, steam and sorbent are fed to a pressurized partial gasifier, where coal is partially gasified to produce a low-Btu syngas and char. The syngas passes through a cyclone and a filter to remove the particles contained in it. The clean syngas is burned in the topping combustor to produce high temperature combustion products to drive a gas turbine. This gas turbine drives a generator and an air compressor. Char from the gasifier enters an atmospheric circulating fluidized bed (CFB) or a pressurized fluidized bed (PFB) to produce steam. It drives steam turbine to produce power. In this paper four typical configurations are discussed.

In the first scheme (APFBC-CC/1, EPDC of Japan is a representative[1]) as shown in Fig. 1(a), char is burned in a pressurized fluidized bed, and exhausted flue gas enters the gasifier. Syngas from the gasifier is cooled to 500 ℃, then enters the medium temperature filter avoiding high temperature operation. In the second scheme(APFBC-CC/2, Foster Wheeler is a representative[2]) as shown in Fig. 1(b), char is also burned in the pressurized fluidized bed, but syngas from the gasifier and flue gas from PFB respectively pass through high temperature filter.

The third and fourth schemes (APFBC-CC/3 and APFBC-CC/4, proposed respectively by CRE of UK[3] and Southeast University of China) are shown in Fig. 1 (c) and Fig. 1 (d). In these two systems, syngas is cooled to 500 ℃ then fed to filter, and chars from the gasifier are fed to atmospheric CFB to produce steam. In order to improve the syngas heating value in APFBC-CC/4, the air and steam for gasification are preheated to 800 ℃, passing through a regenerative preheater, in which a small fraction of syngas is burned.

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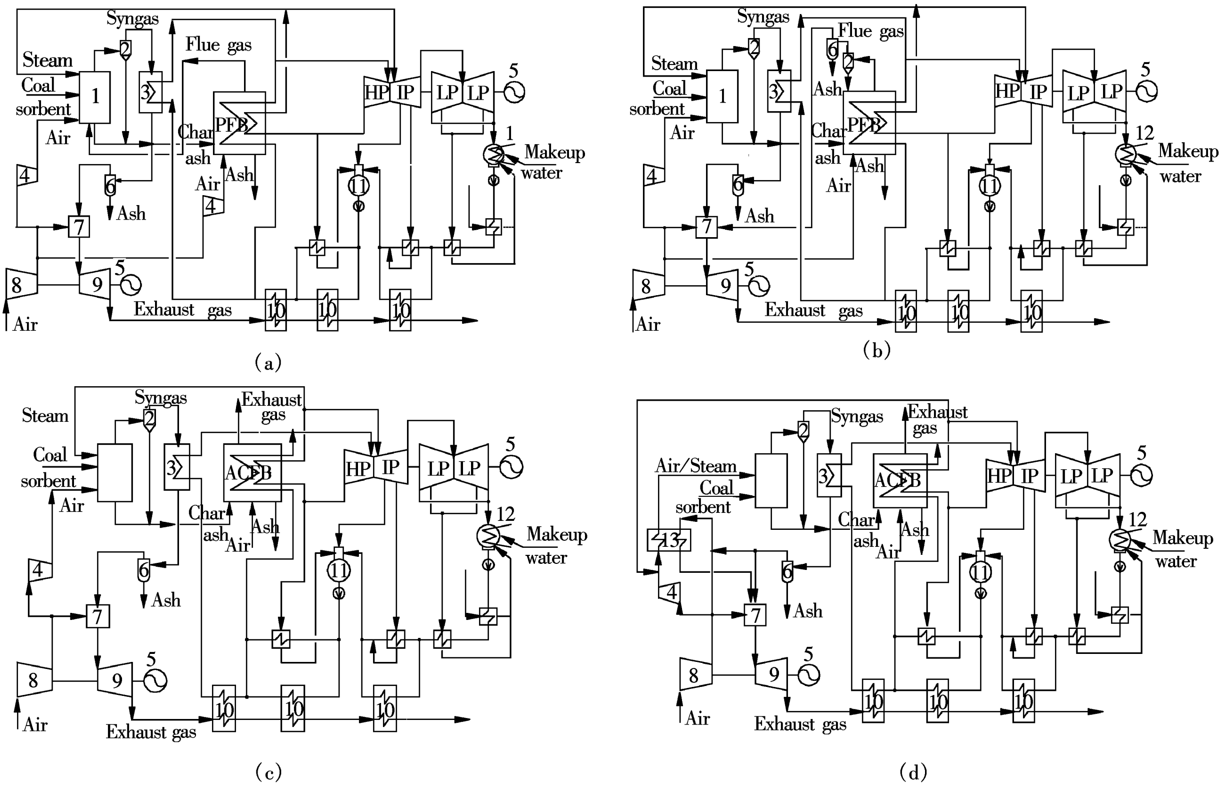

1—Partial gasifier; 2—Cyclone; 3—Syngas cooler; 4—Booster; 5—Power generator; 6—Filter; 7—Topping combustor; 8—Air compressor; 9—Gas turbine; 10—Exhaust gas heat recovery; 11—Deaerator; 12—Condensator; 13—**Regenerative preheater**

Fig.1 APFBC-CC systems. (a) APFBC-CC/1 system; (b) APFBC-CC/2 system; (c) APFBC-CC/3 system; (d) APFBC-CC/4 system

2 Thermal Performance Calculation and Analysis

The pressurized partial gasification combined cycle is a complex thermal system. In order to calculate the thermal performance of the different systems, the modular approach[5,6] has been adopted. The thermodynamic models based on mass balances, energy balances and chemical equilibrium, for the main components of the system, such as gasifier, compressor, gas turbine, fluidized bed, and steam turbine are developed.

2.1 Calculation basis and assumptions

In performance calculation, the compositions of the sorbent and coal are presented in Tab.1 and Tab.2 and calculation basis and assumptions are given in Tab.3.

Tab.1 Sorbent composition

Composition	$CaCO_3$	$MgCO_3$	Moisture	Inert
Mass percent/%	85.2	2.1	4.1	8.29

Tab.2 Coal composition

Ultimate analysis	C	H	O	N	S	A	W	LHV/(kJ · kg^{-1})
Received basis	0.525	0.034 5	0.073 9	0.010 1	0.010 6	0.235 6	0.110 3	20 535

Tab.3 Calculation basis and assumptions

Equipment	Calculation parameters
Partial gasifier	Operating temperature T_g = 970 ℃; pressure P_g = 1.90 MPa; steam-air ratio is 0.2; pressure loss is 6%; heat loss is 1%; carbon conversion rate Q_c = 0.7; syngas temperature after syngas cooler is 500 ℃
Air compressor	Compression ratio is 15.4; isentropic efficiency is 88%
Topping combustor	Combustion efficiency is 99%; heat loss is 1%; pressure loss is 4%
Gas turbine	Gas turbine inlet temperature T_3 = 1 288 ℃; isentropic efficiency is 90%; net power is 250 MW; exhaust gas temperature after heat recovery is 150 ℃
PFB/CFB	Bed temperature T_b = 870 ℃; combustion efficiency is 99%; heat loss is 0.5%; PFB flue gas temperature T_y = 850 ℃; CFB exhaust gas temperature T_y = 150 ℃
Steam turbine	Main steam pressure is 16.2 MPa; temperature is 550 ℃; reheat temperature is 550 ℃

2.2 Performance calculation results and analyses

Using the calculation basis and assumptions given in Tabs. 1 to 3, thermal performance calculations are carried out for the four APFBC-CC schemes. The calculations are based on a plant of 250 MW output power of gas turbine. Results of four APFBC-CC main thermal performances are given in Tab.4.

Tab.4 Results of four APFBC-CC main thermal performances

Item	APFBC-CC/1	APFBC-CC/2	APFBC-CC/3	APFBC-CC/4
Air and steam temperature into gasifier/℃	315, 450	315, 450	315, 450	800, 800
Air for gasfication/(kg · kg^{-1} coal)	1.30	1.66	1.66	1.34
Steam for gasification/(kg · kg^{-1} coal)	0.259	0.332	0.332	0.268
Gas/(kg · kg^{-1} coal)	4.95	2.59	2.59	2.20
LHV of gas/(kJ · m^{-3})	3 188	5 378	5 378	6 632
Coal fed to gasifier/(kg · s^{-1})	51.1	42.4	51.9	50.3
Air into air compressor/(kg · s^{-1})	651.9	660.6	657.0	661.0
Power consumed by air compressor/MW	239.0	242.2	240.8	242.3
Gas turbine net power/MW	250	250	250	250
Steam turbine power/MW	289.5	219.0	295.2	290.1
Total power generation/MW	539.5	469.0	545.2	540.1
Auxiliary power rate/%	6.0	6.0	7.5	7.5
Net LHV efficiency/%	44.0	45.9	42.9	43.9

From Tab. 4, in APFBC-CC/1, the high temperature flue gas from PFB enters the partial gasifier, so as to avoid high temperature flue gas filter and simplify the system. On the other hand, high temperature flue gas with a great deal of heat into the gasifier reduces the air for gasification, but flue gas contains large proportions of CO_2 and N_2, so CO_2 and N_2 compositions of the syngas increase, whereas heating value of the syngas decreases to 3 188 kJ/m^3 while carbon conversion rate is 0.7. The syngas will be affected to combust steadily in topping combustor due to its lower heating value. In addition, the air inlet pressure of PFB must be increased, as flue gas from PFB is transferred to the partial gasifier, namely system energy loss increases. In fact the net LHV efficiency of APFBC-CC/1 is only 44.0%, reducing 1.9% than that of APFBC-CC/2.

Because the high temperature syngas from gasifier and flue gas from PFB respectively enter the topping combustor and the gas turbine without cooling, APFBC-CC/2 can make the energy utilization reach the highest net LHV efficiency value 45.9% in four schemes, but the gas filter has some technology difficulties in high temperature operation by now[2]. At present the temperature of gas is planned to decrease to approximately 500 ℃ before the filter, however the net LHV efficiency will be less 0.9%, and yet higher than the other schemes.

The net LHV efficiency of APFBC-CC/3 based on atmospheric CFB has approximately 1.1% and 3.0% lower than APFBC-CC/1 and APFBC-CC/2, respectively. In APFBC-CC/4 not only heating value of syngas is improved, but also net LHV efficiency is greatly increased. The net LHV efficiency of APFBC-CC/4 is 1.0% higher than APFBC-CC/3, and even approaches APFBC-CC/1, that is 43.9%. Of course, the system is more complex than APFBC-CC/3, because a small part of syngas is burned to preheat air and steam. But the air and steam for gasification consumed less, and the ratio of the gas turbine power increases, so the system's net LHV efficiency is improved. Although the net LHV efficiency of APFBC-CC/3 and APFBC-CC/4 are 3.0% and 2.0% lower than that of APFBC-CC/2, both schemes avoid high temperature gas filter and the system complexity also decreases, so APFBC-CC/3 and APFBC-CC/4 are more suitable for commercial development.

2.2.1 Effect of compression ratio and gas turbine inlet temperature on performance

The system compression ratio and gas turbine inlet temperature have influences on system thermodynamic performance. While carbon conversion rate is 0.7, steam and air ratio is 0.2, the effects of gas turbine inlet temperature T_3 and compression ratio β_c on net cycle efficiency of the four APFBC-CC schemes are presented in Figs.2 to 5. The four figures all show that the net efficiency increases with increasing T_3. The figures also show that there is an optimum compression ratio at a given gas turbine inlet temperature, and the optimum compression ratio increases with T_3. At the same T_3 and β_c, APFBC-CC/3 net efficiency is the lowest, and APFBC-CC/2 is the highest. The APFBC-CC/2 is 3.0% higher than APFBC/3 at the same T_3 and the correspondingly optimum compression ratio. Because the heating value of syngas from APFBC-CC/1 is lower, the highest gas turbine inlet temperature of APFBC-CC/2 is not more than 1 400 ℃, so that T_3 and net efficiency are limited. With the development

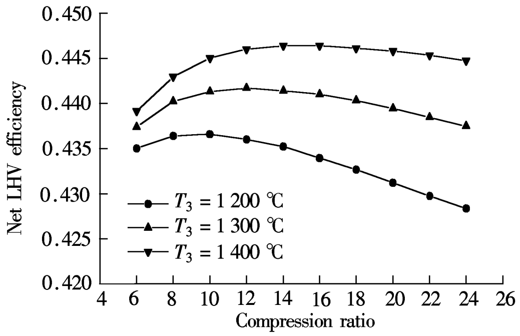

Fig.2 Effect of β_c and T_3 on performance of APFBC-CC/1

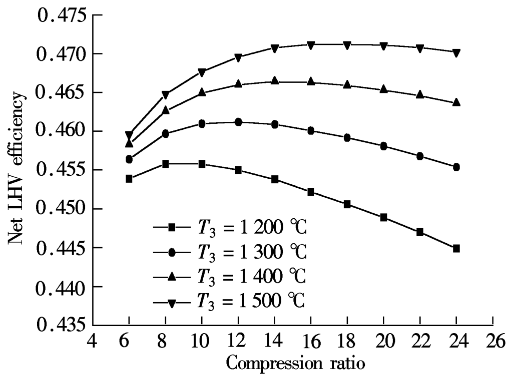

Fig.3 Effect of β_c and T_3 on performance of APFBC-CC/2

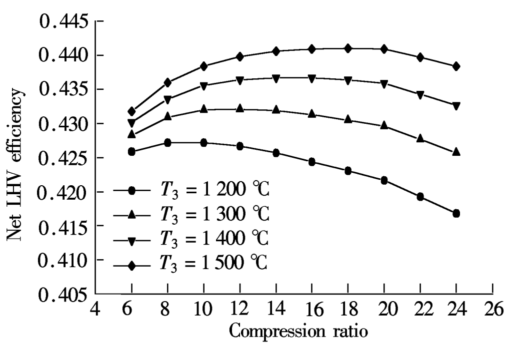

Fig.4 Effect of β_c and T_3 on performance of APFBC-CC/3

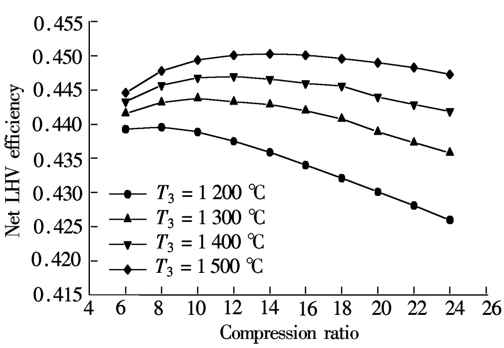

Fig.5 Effect of β_c and T_3 on performance of APFBC-CC/4

of gas turbine, T_3 can reach 1 400 to 1 500 ℃[7], so the heating value of syngas improvement is availed not only to combust in topping combustor, but also to help improve T_3 and net cycle efficiency. From Fig.2 and Fig.4, as T_3 is up to 1 500 ℃, net efficiency of APFBC-CC/3 is only 0.5% less than APFBC-CC/1 while T_3 = 1 400 ℃, that is approximately 44.6%. Compared APFBC-CC/4 with APFBC-CC/1 at the same condition, the net efficiency of APFBC-CC/4 can reach that of APFBC-CC/1.

2.2.2 Effect of air and steam inlet temperature T_a of gasifer on system performance

For the gasification air and steam temperature effect on the syngas, the heating value of syngas and the cycle net efficiency are calculated in different temperatures of air and steam. The advantages of high temperature preheating air and steam are clearly shown in Figs.6 and 7 while other parameters are constant.

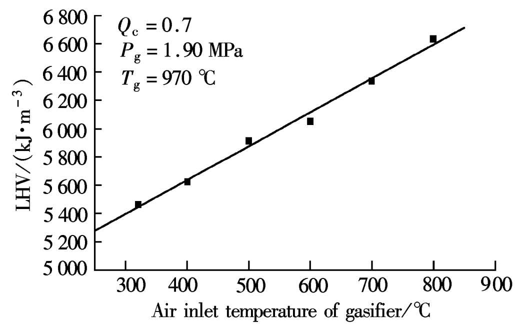

Fig.6 Effect of air/steam inlet temperature on LHV of syngas

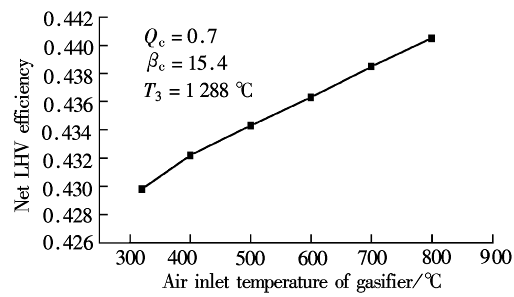

Fig.7 Effect of air/steam inlet temperature on efficiency

Air and steam are heated to 800 ℃ passing through the regenerative preheater, thus the heating value of syngas can be up to 6 632 kJ/m^3, that is heating value increases 250 kJ/m^3 while inlet temperature 100 ℃ improving. It is beneficial to burn for syngas in topping combustor. The net cycle efficiency also increase 1.0% compared with no air and steam preheating at the same compression ratio and gas turbine inlet temperature, and that can be closer to net efficiency of APFBC-CC/2. As gas filter has some technology difficulties in high temperature operation at present, APFBC-CC/4 based on CFB is more practical, though it has lower efficiency. In practice, coal is partially gasified to produce low-Btu syngas, so this way to generate a higher heating value syngas has more significant advantages in the low-quality coal to combust steadily in topping combustor and to improve gas turbine inlet temperature T_3.

Compared with obtaining higher heating value syngas using the rich-oxygen blown system, the high temperature preheating air and steam for gasification is more economical.

3 Conclusions

1) There is an optimum compression ratio at a given gas turbine inlet temperature. The net cycle efficiency and the optimum compression ratio improve with increasing gas turbine inlet temperature.

2) The thermodynamic performance analysis results show that it is available to improve the heating value of syngas by high temperature preheating gasification air and steam. This approach has significant advantages in low-quality coal gasification to burn in the topping combustor and increase gas turbine inlet temperature.

3) In APFBC-CC/1, flue gas from PFB enters gasifier avoiding high temperature flue gas filter, but heating value of syngas and cycle efficiency are lower compared with APFBC-CC/2. The APFBC-CC/2 can gain the highest system efficiency, but it is better to now lower the filter operating temperature. The APFBC-CC/3 based on CFB has the lowest system efficiency, but its cost is less and technique is relatively easier. The APFBC-CC/4 using preheating air/steam for gasification, has the highest syngas heating value and helps syngas to burn steadily in the topping combustor. In addition, it can obtain the higher efficiency than APFBC-CC/3. According to the above results, the APFBC-CC/3 and APFBC-CC/4 are more suitable for development at present.

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部分气化联合循环发电系统热力性能分析

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摘要: 针对增压部分气化2种增压流化床(PFB)锅炉半焦燃烧和2种常压流化床(CFB)半焦燃烧的先进增压流化床燃烧联合循环(APFBC-CC)方案,进行了系统热力性能计算, 分析比较了主要参数对系统性能的影响. 结果表明,将PFB锅炉高温烟气引入部分气化炉的方案一避开了高温烟气过滤式除尘器, 但降低了煤气热值和系统效率; 方案二则可获得较高的系统效率, 然而高温过滤式除尘器目前技术上有一定困难, 需降温运行; 方案三、四采用CFB锅炉半焦燃烧系统, 其中方案四采用气化空气/蒸汽预热方法, 不仅可获得较高的煤气热值, 而且可提高系统效率.

关键词: 部分气化; 热力性能; 联合循环; APFBC-CC

中图分类号: TK11+2