Study on heat integration of supercritical coal-fired power plant with post-combustion CO_2 capture process through process simulation

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Abstract

Coal-fired power plant (CFPP) is one of the main sources of anthropogenic CO_2 emissions. Capturing CO_2 from CFPP by post-combustion process plays an important role to mitigate CO_2 emissions. However, a significant thermal efficiency drop was observed when integrating CFPP with post-combustion carbon capture (PCC) process due to the steam extraction for capture solvent regeneration. Thus research efforts are required to decrease this energy penalty. In this study, a steady state model for 600 MW_e supercritical CFPP was developed as a reference case with a low heating value (LHV) based efficiency of 41.6%. A steady state model for MEA-based PCC process was also developed and scaled up to match the capacity of the CFPP. CO_2 compression process was simulated to give an accurate prediction of its electricity consumption and cooling requirement. Different integration cases were set up according to different positions of steam extraction from the CFPP. The results show that the efficiency penalty is 12.29% and 14.9% when steam was extracted at 3.64 bar and at 9.1 bar respectively. Obvious improvements were achieved by utilizing waste heat from CO_2 capture and compression process, taking part of low pressure cylinders out of service, and adding an auxiliary turbine to decompress the extracted steam. The efficiency penalty of the best case decreases to 9.75%. This study indicates that comprehensive heat integrations can significantly improve the overall energy efficiency when the CFPP is integrated with PCC and compression process.

Keywords: process simulation; heat integration; supercritical coal-fired power plant; post-combustion CO_2 capture; CO_2 compression.

1. Introduction

Greenhouse gases emissions have been on the increase since the start of industrial revolution. CO_2 is the main greenhouse gas accounting for over 60% of total greenhouse gas emissions [1]. The Intergovernmental Panel on Climate Change (IPCC) indicates that CO_2 emissions need to be cut by a minimum of 50% to limit the average global temperature increment to 2°C in 2050 [2]. Carbon capture and storage (CCS) is considered the key technology to mitigate CO_2 emissions from fossil fuel-based power generation.

A great portion of CO_2 emissions is generated from the electricity and heat industry. Coal combustion is estimated to be the largest source of electricity and heat generation, particularly in South Africa (93%), Poland (92%), China (79%), India (69%), and United States (49%) [3, 4]. The majority of existing CFPPs are based on subcritical steam cycles, however, supercritical CFPPs are rapidly spreading to replace subcritical CFPPs, with advantages of higher thermal efficiency and lower CO_2 emissions [5, 6]. The average thermal efficiency of subcritical CFPPs is 35%, while supercritical CFPPs have about 5%pt higher net efficiency [7]. Supercritical CFPPs would play an important role in global power generation and the reduction of coal consumption.

Monoethanolamine (MEA)-based chemical absorption technology remains the first choice for CFPP due to its high operational flexibility because it can be easily integrated into both the existing power plants and new installations [8]. Moreover, this technology is characterized by a relatively high separation selectivity [9-12], so that it is well-suited for treating low CO_2 partial pressure flue gas from CFPP [13].

Previous studies [14-16] indicates that there is a significant energy penalty when CFPP is couple with PCC process, because of the steam extraction from CFPPs for solvent regeneration. This high energy penalty constitutes the main barrier of the commercial deployment of CCS technology. There are two solutions to reduce the energy penalty: (1) improving the performance of PCC process, or (2) retrofitting the steam cycle of power plant with comprehensive heat integrations with PCC process.

The absorption process has been extensively researched to decrease its reboiler duty. Freguia and Rochelle [17] performed sensitivity analyses on process variables to find operating conditions at low energy requirement. Moullec et al. [18] and Babatunde et al. [19] evaluated various process modifications through modelling and simulation. A variety of single solvents and blended solvents are studied and compared to find advanced solvents possessing good performance and low price [20-22]. These processes are run in the scale of pilot plant, however, another difficulty of commercial application of PCC technology in CFPP is to evaluate the performance of PCC plants in industrial scale. Lawal et al. [16] scaled up the process according to chemical engineering principles to match a specific CFPP.

Several other researchers focus on the thermal efficiency of CFPPs to improve the steam conditions in boiler. Weitzel et al. [24] improved the overall CFPP thermal efficiency by 6% through adopting 700 ℃ technology in steam generator instead of 600 ℃ technology. However, the steam conditions are related to the materials in steam generator, critical steam piping and steam turbine. Thus this method is infeasible for retrofits of existing CFPPs. One main strategy is recovering the waste heat of PCC plant to heat circulating water, which contributes to a reduction of steam extraction for solvent regeneration. Hanak et al. [3] reduced the efficiency penalty by 0.43% through heat exchanger network (HEN) analysis. In the study of Gibbins and Crane [25], extracted steam is desuperheated through exchanging heat with part of the reboiler condensate, and waste heat from CO_2 capture and compression process is recovered by heating circulating water, decreasing the efficiency penalty by 2.9% for MEA and by 2.5% for KS-2. Besides, Lucquiaud and Gibbins [26] compared three capture ready steam turbine options (clutched LP turbine, throttled LP turbine and Floating IP/LP crossover pressure), revealing that the case with clutched LP turbine presented lowest efficiency penalty.

Based on above research, this paper focuses on the integration of steam cycle and PCC plant, comprehensively considering heat exchanger network analysis, utilization of the superheat of extracted steam, capture ready steam turbine options and steam-extraction locations. To do this, the steam cycle of a 600MW$_e$ supercritical CFPP was modelled and simulated, as well as the CO_2 capture and compression process. The CO_2 capture process is scaled up to match the capacity of the 600MW$_e$ supercritical CFPP. Furthermore, eight cases were simulated and compared regarding the energy efficiency improvement.

Two novelties can be claimed for this paper: 1) detailed study on scale-up of PCC process to match the flue gas flowrate of a specific 600 MW$_e$ supercritical CFPP was performed. 2） comprehensive heat integration options were studied for two different stream extraction from LP I (at 3.64 bar) and IP-LP crossover (at 9.1 bar) respectively for solvent regeneration. Compared with previous studies such as Lawal et al. (2012) [16], this study considered not only how to extract steam from steam turbine in power plant for PCC reboiler, but also heat integrations between PCC, CO_2 compressors and CFPP. More important is that these possibilities have been combined in the case study.

2. Model development

2.1. Model development of Supercritical CFPP

Selected as the reference power plant was a 600 MW$_e$ supercritical CFPP (24.2 MPa/571℃/569℃) in China (Figure1), in which approximately 1677.5t/h of high-pressure steam generated in the steam generator passes through HP, IP, and LP turbines successively for electric power generation. In this power plant, the exhausted steam is next condensed to water in the condenser at pressure of 0.0588bar, and eight-stage steam (HP I & HP II; IP I & IP II; LP I, LP II, LP III & LP IV) is drawn off to heat the circulating water (see Table 1). The first three-stage steam extraction is for HP feedwater heaters; the fourth-stage steam extraction is for deaerator; and the last four-stage steam extraction is for LP condensate heaters. In addition, fuel combustion produces a large amount of flue gas. Before entering the CO_2 capture process, flue gas is often treated with a series of chemical processes and scrubbers to remove particulate matter and sulphur dioxide.

This supercritical CFPP is modelled in Aspen Plus® as base case to explore the influence of PCC integration. The *STEAMNBS* property method is used to properly evaluate the steam process. All turbines are simulated using *Compr* blocks set as isentropic turbines, and circulating water heaters are modelled as *HeatX* blocks [23]. The boiler is replaced as a *HeatX* block to simplify the process. The overall performance is shown in Table 2.

2.2. Model development and scale-up of PCC process

2.2.1. PCC process description

Figure 2 shows a typical CO_2 chemical absorption process. CO_2 from flue gas is chemically absorbed by an MEA solution in the absorber column and then released from the top of the regenerator column with high concentration. In this study, a closed-loop rate-based CO_2 absorption model is developed in Aspen Plus® and validated using the data from a pilot plant at University of Texas, Austin [27, 28]. All parameters in the model and validation process are stated by Canepa, et al [23]. In the pilot plant, both the absorber and regenerator column are 0.427m in diameter and packed with two sections of 3.05m packing. The absorber is operated at atmospheric pressure with a random metal packing, IMTP no.40, while the regenerator is operated at apressure of 1.7 bar and filled with a structured packing, Flexi Pac1Y.

2.2.2. Model scale-up

To match the capacity of a 600 MW_e supercritical CFPP, the CO_2 capture plant model has been scaled up based on chemical engineering principles. As an initial input of Aspen Plus® model, a first-guess diameter is required for the absorber and the regenerator. One engineering practice is to calculate the column diameter from the maximum flooding vapour velocity which could be estimated by empirical correlation equations and figures. In this study, a generalised pressure drop correlation figure (see Figure 11.46. in [29]) adapted from a figure by the Norton Co. was used. The abscissa and ordinate are presented in Equation (1) and Equation (2) respectively [29].

$$F_{LV} = \frac{L_w^*}{V_w^*}\sqrt{\frac{\rho_V}{\rho_L}} \quad (1)$$

$$K_4 = \frac{13.1(V_w^*)^2 \cdot F_p \cdot (\mu_L / \rho_L)^{0.1}}{\rho_V(\rho_L - \rho_V)} \quad (2)$$

F_{LV} is a flow parameter which is related to L/G ratio; K_4 is a modified load which is evaluated from Figure 11.46. in [29] according to the value of F_{LV} and assumed pressure drop. F_p is a packing factor. Based on this, V^*_w (vapour mass flow rate per unit cross-sectional area) is calculated, then the total cross-sectional area can be obtained given the flue gas flow rate. This methodology has also been applied in numerous similar literatures [3, 16, 23].

Flooding and minimum liquid load are two primary limitations for the operating region of packed columns. Flooding defines the upper operating line of packed column. The minimum liquid load is set to ensure that the entire packing surface is wetted [16, 30]. In order to achieve good liquid and gas distribution, pressure drop between 15 and 50 mmH_2O per meter packing for absorber and regenerator columns was recommended [29]. In this paper, pressure drop of 42 mmH_2O per meter packing is selected for the scale-up [3]. Here one important thing should be noticed that the design of the column internals such as gas/liquid distributors and re-distributors is crucial to ensure good gas and liquid distribution inside the absorber and regenerator in such large diameters.

The boundary conditions data can be seen in Table 3. A first-guess diameter of the absorber and regenerator can be calculated using the above method. Starting from this, these parameters will be improved in the development of the closed-loop CO_2 absorption model in Aspen Plus®. In the simulation of the closed-loop capture plant, lean loading (mol CO_2/mol MEA) is an important parameter related to reboiler duty. The change of reboiler duty at different lean loadings is presented in Figure 3; here it can be seen that the reboiler duty first decreases as lean loading increases, and then it increases with the increase of lean loading. Minimum reboiler duty is attained when lean loading is 0.23 mol CO_2/mol MEA.

The relationship of different numbered columns and diameters is given in Figures 4 and 5. Considering structural limitations, it is better to keep the column diameter less than 12.2m—thus, for the absorber, at least three columns with diameters of 11.66m are needed [16, 31] whilst a two-column regenerator with a diameter of 10.78m is selected. The overall performance of the capture plant with improved parameters is shown in Tables 4 and 5.

2.3. Simulation of compression process

After the CO_2 captured from the power plant, it will be pressurized at a pressure as high as 110 -150 bar for pipeline transport and geologic sequestration [32, 33]. Thus a compression train is needed. In this study, CO_2 is pressurized to 90 bar by a four-stage compressor and then pressurized to 110bar by a pump. Between two adjacent stages of the compressor, an intercooler cools the stream. A flash tank is set after the intercooler of the first stage and second stage to draw off liquid water (Figure 6). In the simulation, isentropic compression model is selected with 90% isentropic efficiency [18]. And the pressure drop of intercoolers is assumed as 2% [34]. Simulation results are given in Table 6. There are four hot streams that need to be cooled in the process, and the heat can be integrated into the steam cycle.

3. Integration of CFPP with PCC and compression process

A large amount of steam is drawn off from steam cycle to heat the reboiler because of the huge energy required for solvent regeneration, as shown in Figure 7. In this way, all of the low-pressure condensate heaters are removed, and a throttling valve (V1 in Figure 7) is added at the steam extraction location to ensure the plant's stability [35]. The solvent regeneration temperature in the reboiler of the capture plant is 120℃, meaning that hot steam used to heat the reboiler should be 130℃with 10℃ mean temperature difference—that is to say that steam of 2.7 bar is required for solvent regeneration. However, the steam extraction point is not casual; Table 1 details the eight stages of steam extraction in the steam cycle. Consequently, the steam drawn off for solvent regeneration is usually decompressed to 2.7 bar by a throttling valve V2 and cooled down to just above saturated temperature through transferring heat with circulating water in H4. The power plant without PCC process has been simulated as the Base Case in Section 2.2. In this section, this study focuses on the effect of PCC plant integration on power plant performance.

3.1. Steam extraction from LP I (i.e. 3.64 bar)

3.1.1. Considerations

For the location selection of steam extraction for solvent regeneration, LP I (at 3.64 bar) is appropriate because it is closest to 2.7 bar as seen in Table 1. After the steam is drawn from LP I, the steam is decompressed to 2.7 bar and then cooled to its saturated state before entering the reboiler in PCC process.

In the steam cycle, thermal energy is needed to heat circulating water. In general, this energy is provided by eight-stage steam extraction for a standalone CFPP. Once CFPP is integrated with CO_2 capture and compression process, energy saving could be achieved by coupling the hot streams of capture and compression process with the steam cycle to heat circulating water. The properties of hot streams are presented in Table 7. The stream named 'CO_2 cooling' is from the last compressor and required to be condensed to enter a pump. It should be noted that the heat load of the stream shown here does not involve the heat of condensation because the condensation temperature is too low to be utilized. The highest temperature of hot streams in Table 7 is 167℃ whilst circulating water is heated from 34℃ to 175.9℃ in LP condensate heaters and then is heated from 175.9℃ to 272℃ in HP feedwater heaters. Therefore, only circulating water in the low-temperature section can be heated by waste heat from CO_2 capture and compression process.

Moreover, a great amount of steam is drawn off for solvent regeneration; thus a throttling valve is generally added to keep the stability, resulting in a throttling loss. On the other hand, there are usually several sets of LP cylinders in the plant to avoid the turbine blade becoming too long when steam expanding in power generation process. Consequently, if part of the LP turbine is taken out of service, the rest LP turbine can work at conditions close to normal operating state; accordingly, the throttling loss is avoided.

3.1.2. Case studies

For the scenario of steam extraction from LP I stream (3.64 bar) for solvent regeneration, three cases are set up to study the effect of utilizing waste heat and taking part of the LP turbine out of service in below:

Case 1A: Basic integration of PCC into supercritical CFPP with steam extraction from LP I for PCC reboiler.

Case 2A: Utilizing waste heat from the PCC and CO_2 compression process for feedwater pre-heating in CFPP & steam extraction from LP I in CFPP for PCC reboiler.

Case 3A: Taking part of LP cylinders out of service & Utilizing waste heat from the PCC and CO_2 compression process for feedwater pre-heating in CFPP & steam extraction from LP I in CFPP for PCC reboiler.

These three cases are set progressively, and the flow chart of case 3A is shown in Figure 8. In the process of waste heat utilization, ΔT for heat transfer is set to 10℃. The circulating water is heated to 74℃ by the condenser of regenerator first, then it is divided into four parts and exchange heat with the four intercoolers of compression process respectively, as a result, the four streams are heated to 138℃, 125℃, 131℃ and 157℃ respectively, and the average temperature is 139℃. So that the effect of PCC integration can be investigated, the performance of the cases is presented as net power output, generating efficiency and CO_2 emissions, and compared with the base case described in section 2.2.Simulation results comparison between these three cases and the base case are given in table 8. Generally introduction of the CO_2 capture process results in a large efficiency penalty in the supercritical CFPP. In Case 1A, the efficiency penalty is 12.29% points and equals a decrease of 29.5% in the economic benefits of the power plant. Waste heat is recovered in Case 2A, which makes an improvement of 0.54% points in generating efficiency. This is because waste heat utilization decreases the flow rate of steam extraction for circulating water heating. Furthermore, more than half of the LP steam is drawn off, and a throttling valve is added to ensure the power plant stability. However, if half of the LP turbine is taken out of service, the other half can still work in approximately normal condition; therefore, the throttling loss is avoided. The power plant performance is shown in case 3A in which generating efficiency is improved by 0.9% after taking half of the LP turbine out of service. Moreover, for new power plants, the capacity of every LP cylinder can be designed according to the flow rate of steam extraction, which allows the corresponding LP cylinder to shut down when integrating with PCC.

3.2. Steam extraction from IP-LP crossover (i.e. 9.1 bar)

3.2.1. Considerations

The overall performance of the power plant with steam extraction from LP I (i.e. 3.64 bar) was studied in Section 3.1. Theoretically it is feasible to draw steam from any stage of steam turbine with pressure higher than 2.7bar for solvent regeneration. However, it is not economical to draw steam when steam pressure is too high considering the large throttling loss. As a typical case, we study steam extraction from IP-LP crossover with steam pressure at 9.1 bar. The consideration of setting up Cases 1B, 2B and 3B is similar to what has been analysed in Section 3.1.

3.2.2. Case studies

Three cases are developed to compare the performance of power plant with 9.1 bar steam extraction:

Case 1B: Basic integration of PCC into supercritical CFPP with steam extraction from IP-LP crossover for PCC reboiler.

Case 2B: Utilizing waste heat from the PCC and CO_2 compression process for feedwater pre-heating in CFPP & steam extraction from IP-LP crossover in CFPP for PCC reboiler.

Case 3B: Taking part of LP cylinders out of service & Utilizing waste heat from the PCC and CO_2 compression process for feedwater pre-heating in CFPP & steam extraction from IP-LP crossover in CFPP for PCC reboiler.

In Case 2B and Case 3B, the temperature of the steam, which is freshly decompressed from 9.1 bar steam, is too high to be cooled down to the saturated temperature by preheated circulating water. For such a situation, part of the steam cooled down in the reboiler is returned back to mix with high-temperature steam to effect the appropriate temperature, as shown in figure 9. In this way, less steam is drawn off and more is used to generate electricity. Meanwhile, more condensate is produced from the condenser, resulting in that waste heat from PCC plant is not able to improve the circulating water to the same temperature in Case 3A. In the heat exchanger network, circulating water is heated to 74℃ first, then it is divided into four streams which are heated to 133℃, 115℃, 127℃ and 152℃ respectively, the average temperature is 133℃. The overall performance of these cases is presented in table 9.

From results (for steam extraction at IP-LP crossover) shown in Table 9, the net efficiency penalty in Cases 1B, 2B and 3B are 14.9%, 14.04% and 13.0% respectively. However from results (for steam extraction at LP I) shown in Table 8, the net efficiency penalty in Cases 1A, 2A and 3A are 12.29%, 11.75% and 10.85% respectively. By comparison, steam extraction at lower pressure is more economical. This can be explained theoretically that the throttling loss of decompressing higher pressure steam (9.1 bar) to 2.7 bar is more serious. On the other hand, the reduction of efficiency penalty from Case 1B to Case 3B (1.9%) is lightly higher than it from Case 1A to Case 3A (1.44%). This is because the 9.1 bar steam saved in Case 3B due to heat integration is higher grade stream, resulting in a higher power output increment.

3.3. Auxiliary turbine

From Section 3.1 and Section 3.2, the net power output is improved through utilizing waste heat and taking half of LP turbine out of service. However, the throttling valve V2 is still causing energy loss, especially in Case 3B. In this section, the addition of an auxiliary turbine to decompress the steam extracted from IP-LP crossover at 9.1 bar is considered. The throttling valve V2 is no longer necessary. As this case is a further extension of Case 3B, this case is called Case 4B:

Case 4B: adding an auxiliary turbine (see Figure 10) to decompress the extraction steam & taking part of LP cylinders out of service & utilizing waste heat from the PCC and CO_2 compression process for feedwater pre-heating in CFPP & steam extraction from IP-LP crossover in CFPP for PCC reboiler.

In Case 4B, the steam decompressed by the auxiliary turbine possesses less superheat to heat circulating water and reboiler condensate. Thus more 9.1 bar steam than that in Case 3B is extracted to match the reboiler duty, resulting in less condensate from condenser. In this way, circulating water from condenser is able to be heated to higher temperature than that in Case 4B through waste heat recovery. Specifically, the circulating water from condenser is heated to 74℃ first, then it is divided into four streams which are heated to 138℃, 125℃, 131℃ and 157℃ respectively. The average temperature is 139℃. The performance can be seen in Table 10. The net efficiency penalty in Case 4B is 9.75%, this result demonstrates a substantial improvement of a 4% increment compared with Case 3B. Thus it can be seen that the throttling loss in Case 3B is huge. The net efficiency penalty in this case is 9.75%, 1.1% points less than it in Case 3A. Among all cases presented, Case 4B represents the best performance.

4. Conclusions

In this study, a steady state model for 600 MW_e supercritical CFPP was developed, and seven cases were studied to investigate the effect of integration with PCC process and CO_2 compression process. Generating efficiency for the reference case is 41.6%. It reduced to 29.31% when more than half of the steam was extracted from LP I (at 3.64 bar) for solvent regeneration. Two methods, utilization of waste heat from PCC process and CO_2 compression process and taking half of LP turbine out of service, were adopted to decrease the efficiency penalty, which improved the generating efficiency to 30.75%. Similar study was performed in the cases of extracting steam from IP-LP crossover at 9.1 bar. The generating efficiency reduced to 26.7% in the basic integration, and improved to 28.6% through adopting the two methods. Extracting steam from IP-LP crossover at 9.1 bar caused more serious efficiency penalty due to the higher throttling loss. However, an auxiliary turbine was added to decompress the 9.1 bar steam, which contributed to a reduction of 3.25% in efficiency penalty. In this way, net generating efficiency is 31.85% and the efficiency penalty is reduced to 9.75%. According to the results, comprehensive heat integration modifications can effectively reduce the energy penalty when the CFPP is integrated with PCC and CO2 compression process.

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Table 1. Eight-stage steam extraction

Extraction-stage	HP I	HP II	IP I	IP II	LP I	LP II	LP III	LP IV
Extraction pressure (bar)	61.54	41.48	18.52	9.1	3.64	1.11	0.546	0.175

Table 2. Overall performance of the supercritical CFPP without CO_2 capture process

Gross power output（MW_e）	603.0
Power consumption（MW_e）	15.5
Net power output（MW_e）	587.5
Fuel input（MW_{th}）	1414
Generating efficiency（%LHV net）	41.6
Flow rate of flue gas（kg/s）	707.8
CO_2 concentration in flue gas (wt%)	19.54
CO_2 emissions（g/kWh）	841.5

Table 3. Boundary conditions of PCC process

Flue gas flowrate (kg/s)	707.8
Flue gas CO_2 content (Mole %)	13.09
Flue gas temperature (℃)	44
Solvent MEA content (wt%)	30
Lean solvent flowrate (t/h)	6000
Lean loading (mol CO_2/mol MEA)	0.23
Capture level	90%
CO_2 stream purity (wt%)	95

Table 4. Absorber and regenerator design

	Absorber	Regenerator
Pressure drop (mm water/m)	42	42
Column diameter (m)	11.66	10.78
Column number	3	2
Column packing	IMTP no.40	Flexi Pac1Y
Packing height (m)	30	30
Column pressure (bar)	1	1.7

Table 5. Overall performance of capture plant

Lean solvent flowrate (t/h)	6995
L/G ratio (mass basis)	2.75
Lean loading (mol CO_2/ mol MEA)	0.23
Rich loading (mol CO_2/ mol MEA)	0.54
Lean Solvent MEA content (wt%)	30.04
CO_2 stream purity (wt%)	94.98
Condenser duty (MW_{th})	40.79
Reboiler duty (MW_{th})	572
Reboiler temperature (℃)	120.46

Table 6. Performance of CO_2 compression process.

Inlet pressure(bar)	1.7
Outlet pressure (bar)	110
Power consumption(MW_e)	37.8
CO_2 compression work(kWh/tCO_2)	84.8
Cold utilities (MW)	84.24

Table 7. Property of hot streams

Stream	**Stream type**	**Inlet temperature (℃)**	**Outlet temperature (℃)**	**Heat load (MW_{th})**
Condenser in Regenerator	Hot	84	59	40.79
CO_2 intercooling 1	Hot	148	51	25.37
CO_2 intercooling 2	Hot	135	54	11.67
CO_2 intercooling 3	Hot	141	73	8.98
CO_2 cooling	Hot	167	36	36.02

Table 8. Thermal performance of Cases with 3.64 bar steam extraction.

Case	Base case	Case 1A	Case 2A	Case3A
Gross power output（MW_e）	603.0	468.08	475.7	488.35
Pumping work （MW_e）	15.4	15.8	15.8	15.8
Compression work（MW_e）	--	37.8	37.8	37.8
Total energy consumption（MW_e）	15.4	53.6	53.6	53.6
Net power output（MW_e）	587.6	414.48	422.1	434.75
Fuel input（MW_{th}）	1414	1414	1414	1414
Generating efficiency（%）	41.6	29.31	29.85	30.75
Net energy penalty（%）	--	29.46	28.17	26.01
Net efficiency penalty（%）	--	12.29	11.75	10.85
CO_2 emissions（g/kWh）	847.3	120.12	117.95	114.52
CO_2 emission reduction（g/kWh）	--	727.18	729.35	732.78

Table 9. Thermal performance of Cases with steam extraction from IP-LP crossover at 9.1 bar

Case	Base case	Case 1B	Case 2B	Case 3B
Gross power output（MW_e）	603.0	431.15	443.25	458.03
Pumping work （MW_e）	15.4	15.8	15.8	15.8
Compression work（MW_e）	--	37.8	37.8	37.8
Total energy consumption（MW_e）	15.4	53.6	53.6	53.6
Net power output（MW_e）	587.6	377.55	389.65	404.43
Fuel input（MW_{th}）	1414	1414	1414	1414
Generating efficiency（%）	41.6	26.7	27.56	28.60
Net energy penalty (%)	--	35.75	33.69	31.25
Net efficiency penalty（%）	--	14.9	14.04	13.0
CO_2 emissions（g/kWh）	847.3	131.87	127.77	123.10
CO_2 emission reduction（g/kWh）	--	715.43	719.53	724.20

Table 10. The performance of Case 4B with an auxiliary turbine

Case	Base case	Case 4B
Gross power output（MW_e）	603.0	503.98
Pumping work （MW_e）	15.4	15.8
Compression work（MW_e）	--	37.8
Total energy consumption（MW_e）	15.4	53.6
Net power output（MW_e）	587.6	450.38
Fuel input（MW_{th}）	1414	1414
Generating efficiency（%）	41.6	31.85
Net energy penalty (%)	--	23.35
Net efficiency penalty（%）	--	9.75
CO_2 emissions（g/kWh）	847.3	110.55
CO_2 emission reduction（g/kWh）	--	736.75

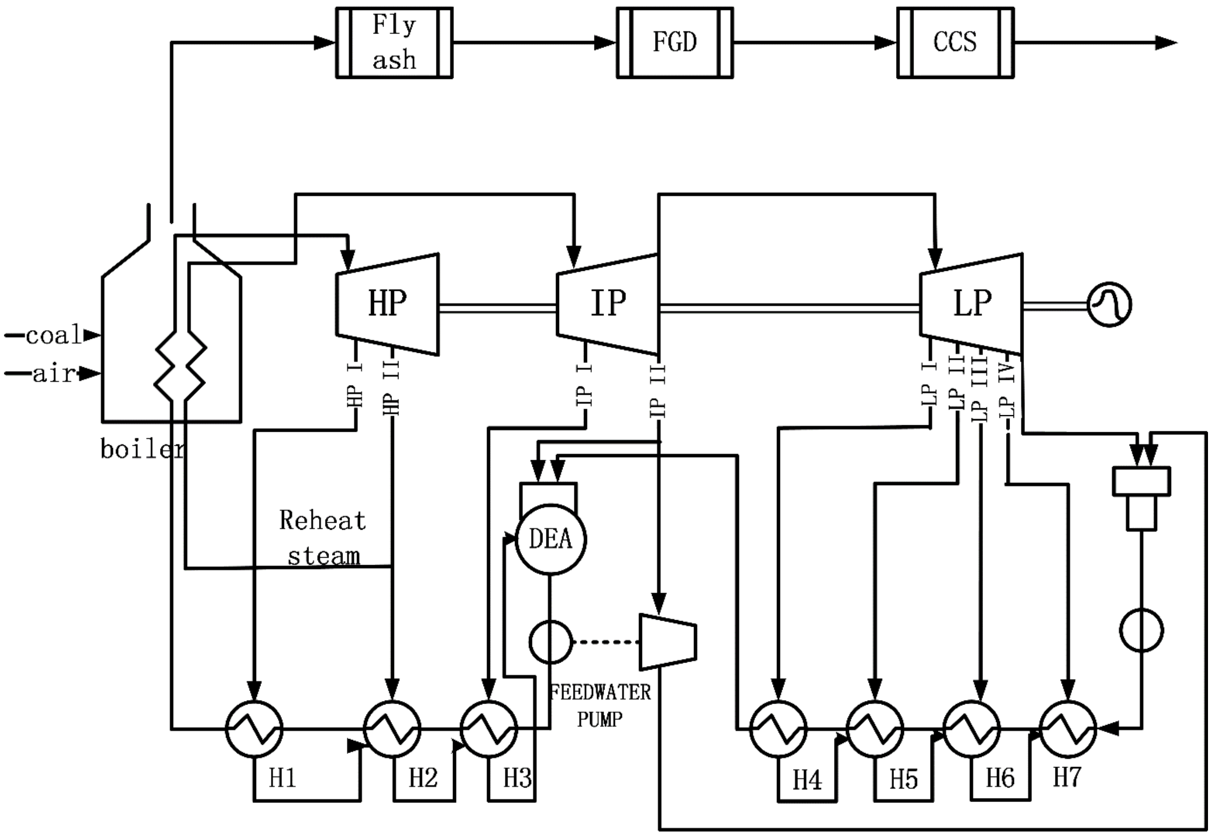

Figure 1. Flow diagram of a 600 MW_e supercritical CFPP

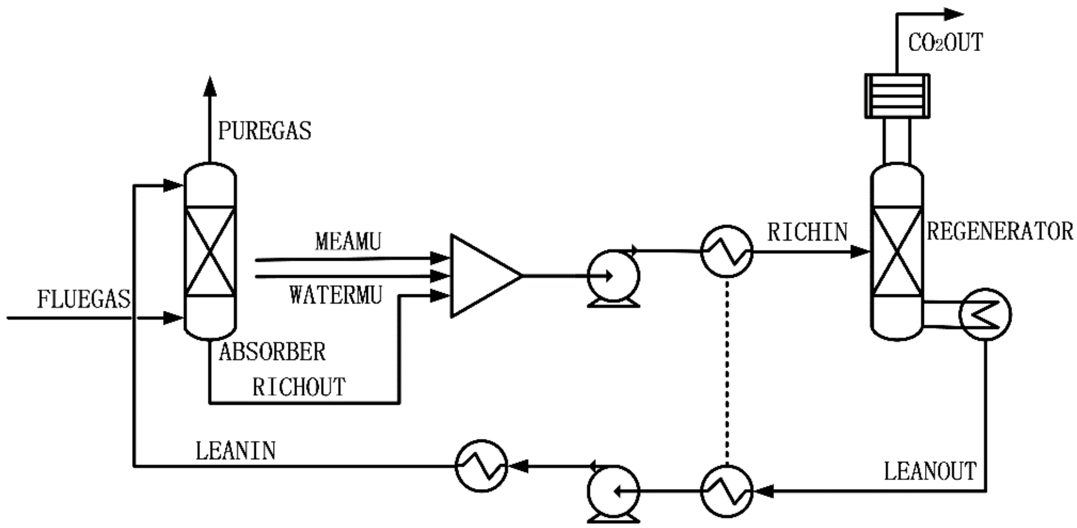

Figure 2. Flowsheet of PCC process

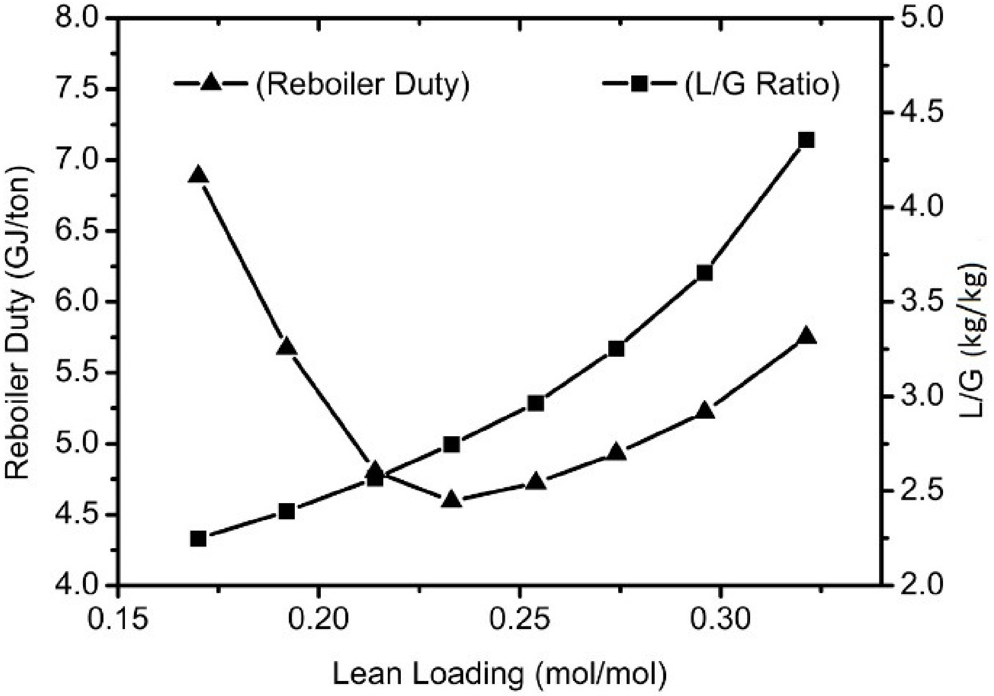

Figure3. Impact of lean loading on reboiler duty and L/G ratio at 90% capture level.

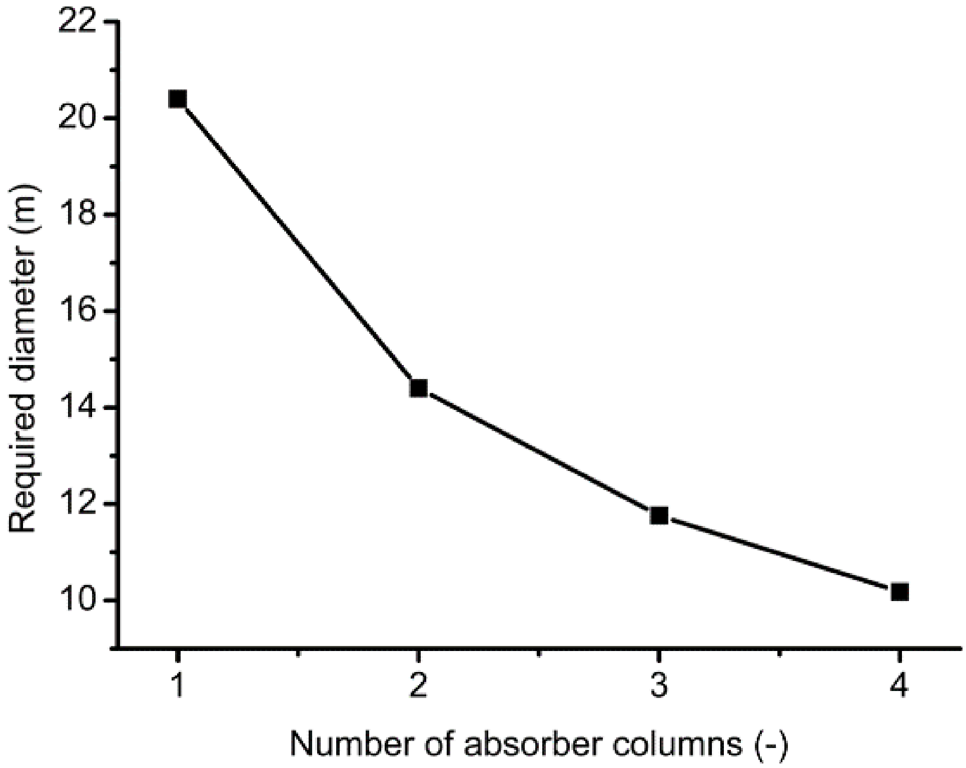

Figure 4. Absorber diameter as function of the number of columns

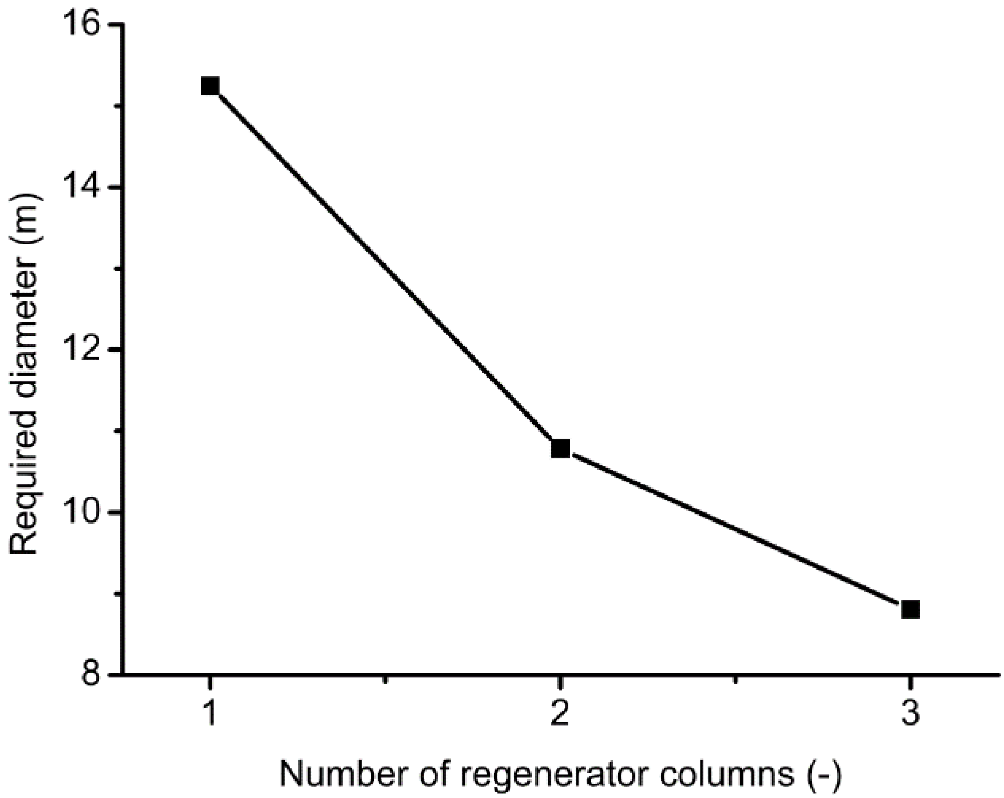

Figure 5. Regenerator diameter as function of the number of columns

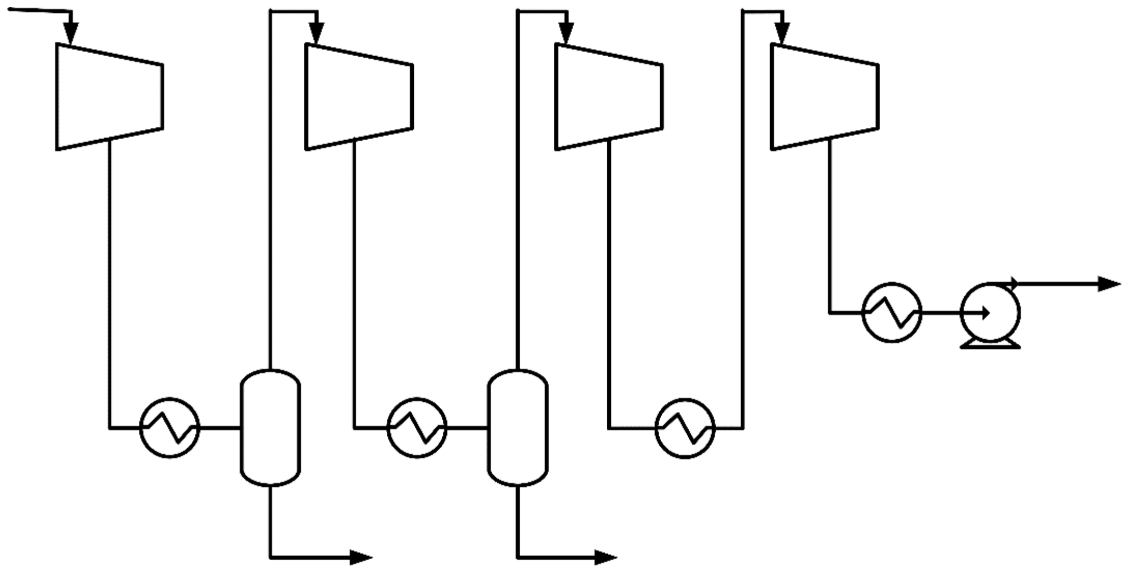

Figure 6. Flowsheet of CO_2 compression process

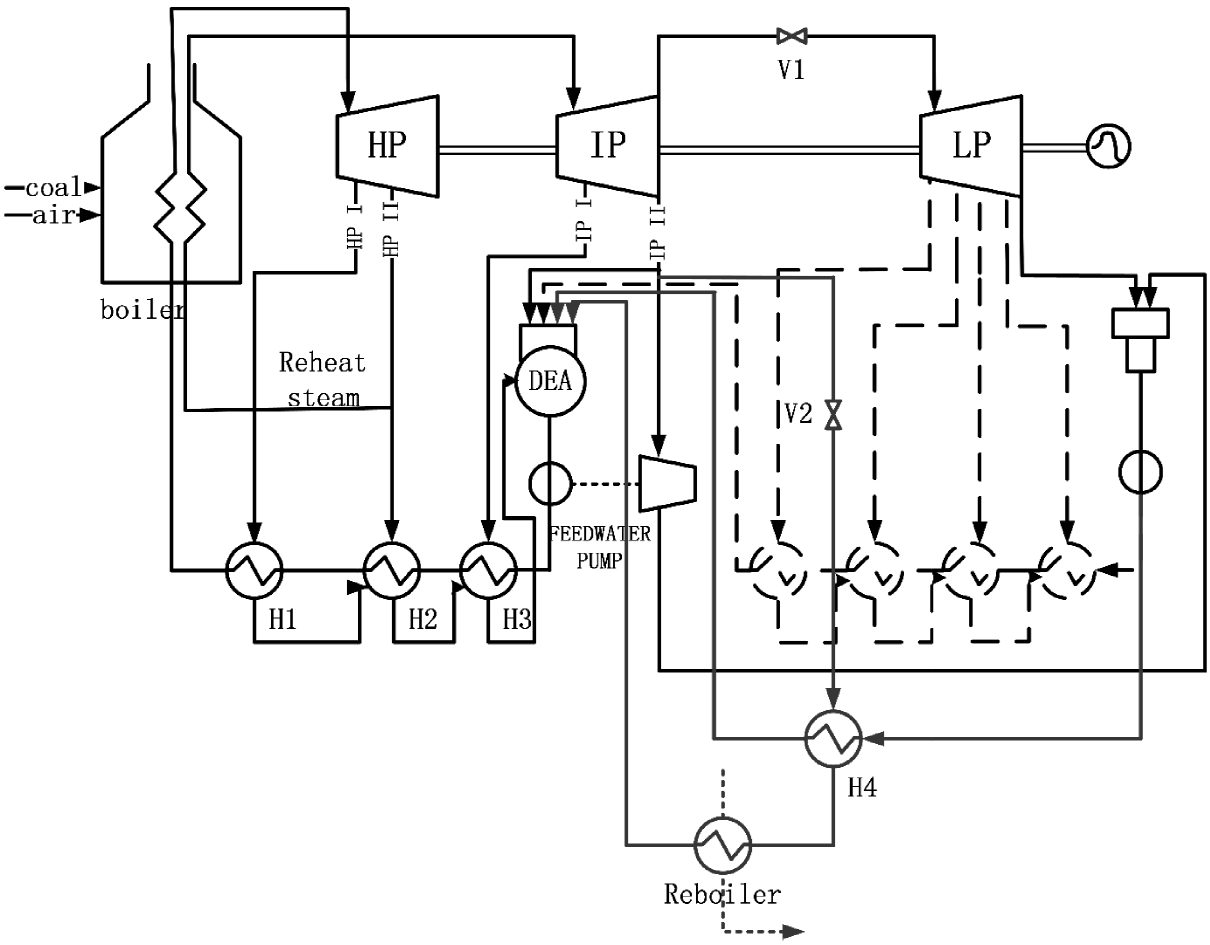

Figure 7. Flow diagram of retrofitted CFCC with CO_2 capture process

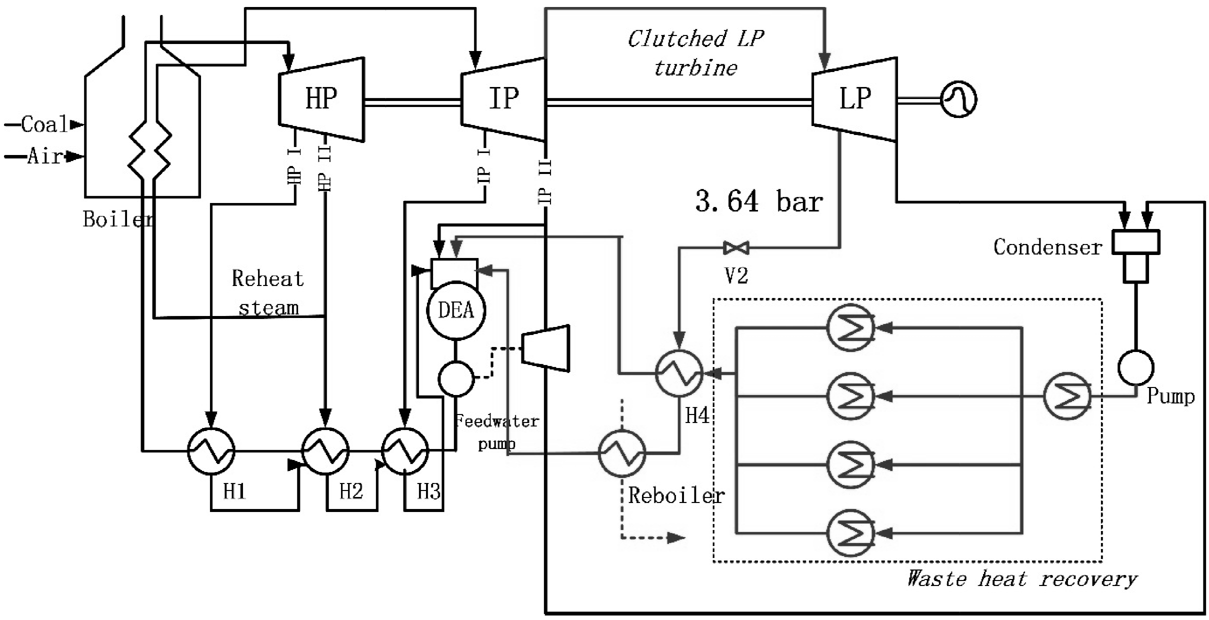

Figure 8. Flow diagram for Case 3A.

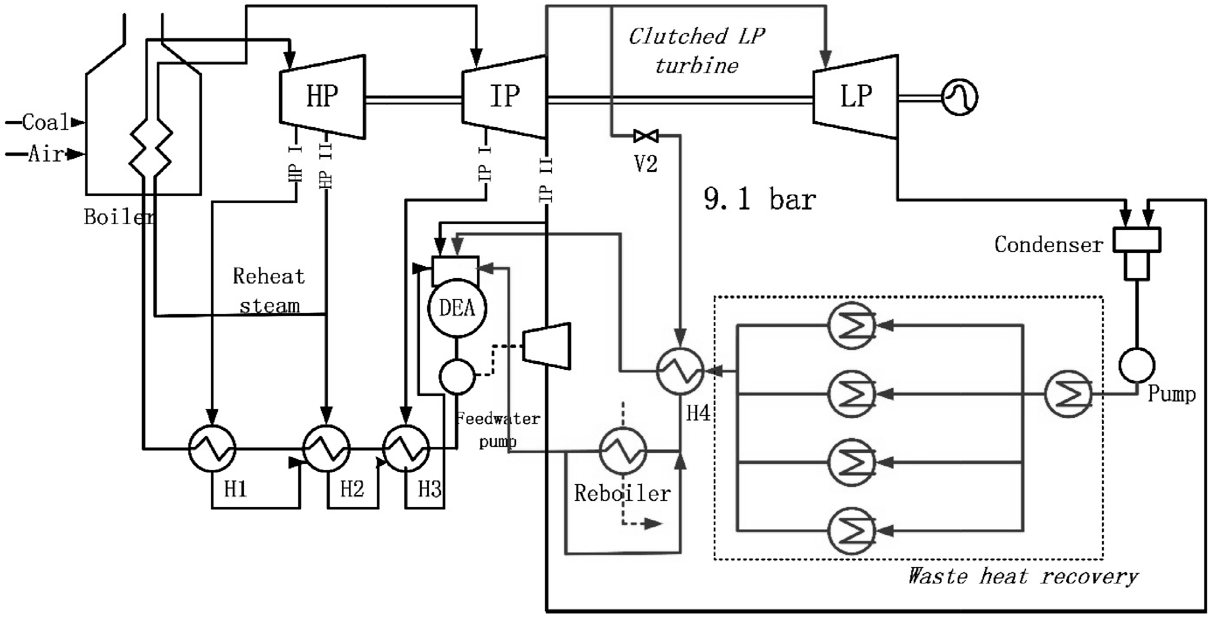

Figure 9. Flow diagram for Case 3B

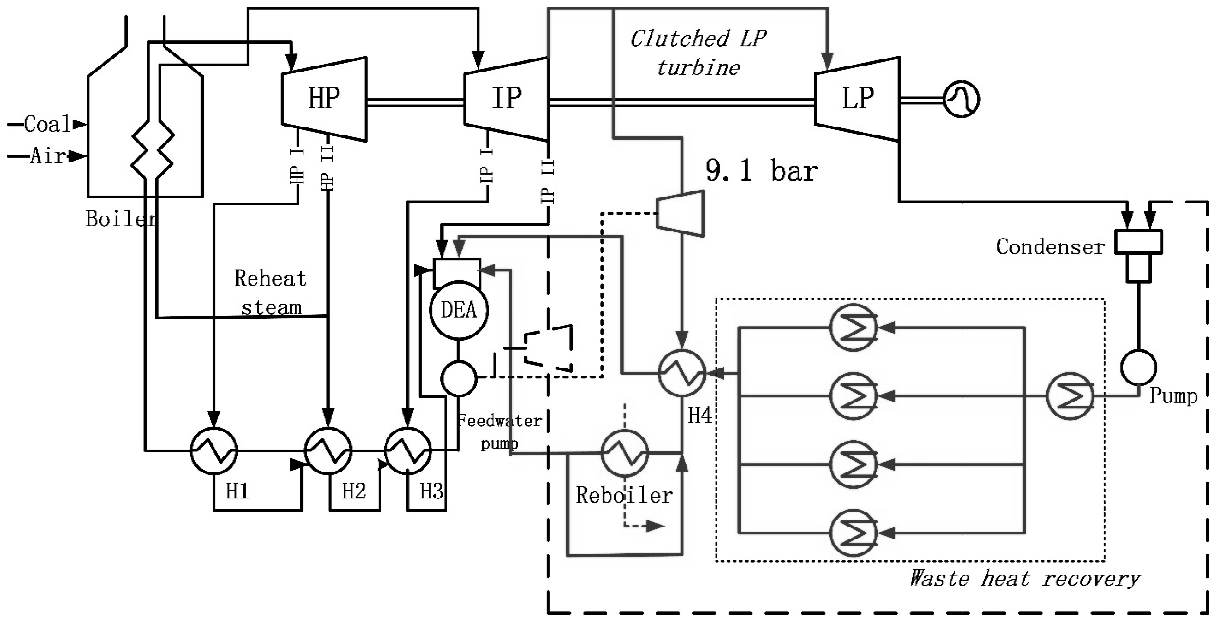

Figure 10. Flow diagram of Case 4B in Section 3.3