

Analysis of Hybrid Configuration of Coal-Based Methanol-Power Polygeneration System*

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Abstract

A novel hybrid configuration of a coal-based polygeneration system, which bears the configuration characteristics of both parallel and sequential polygeneration systems, is proposed and investigated. Due to its configuration characteristics, the new system performs flexible production distribution (power and methanol) to coordinate the performance and capacity ratio of chemical to power and facilitate peak shaving of power generation. The performance of the new system is simulated by means of Aspen Plus. The new system has a wider range of product capacity than the sequential polygeneration system, with a range of energy saving rate of 2~14%. Compared with the two other polygeneration systems the new system has better performance at each capacity ratio. Especially at a capacity ratio of chemical production to power generation of 0.5, it is about 2% higher than sequential polygeneration system and 4.5% higher than the parallel polygeneration system. Exergy analysis is performed. Better chemical energy utilization of the syngas is obtained without component adjustment but with proper recycling of the unreacted gas.

Keywords: *Hybrid configuration polygeneration system, performance analysis, flexibility of production distribution, cascading utilization of chemical energy.*

1. Introduction

In China, it is expected that coal will remain as the main energy source for many years to come. Thus, efficient and clean utilization of coal is very important in ensuring the sustained development of China's economy. A simple coal utilization method consists of burning coal in a boiler, and producing steam for a steam turbine. In this method, however, efficiency is limited by the low turbine inlet temperature and pollutants such as NO_x and SO_x are difficult to control. More than ever, global warming resulting from greenhouse gas (CO₂) emission is threatening our living environment (IPCC, 2001). Coal gasification is one of the clean coal technologies (DOE, 2000; Fan, 2006; Benjamin, 1996) being studied to combat this problem. Integrated gasification combined cycle (IGCC) and chemical production process are two basic energy systems based on coal gasification. However, for energy utilization, chemical production energy systems have disadvantages in achieving high production yield. Power energy systems suffer much exergy destruction in combustion processes. By integrating chemical and physical energy utilization of syngas, the polygeneration system can deal with these negative impacts resulting from individual energy systems (Jin, 1999; Sun, 2007).

The configuration of a polygeneration system has a significant impact on performance and product capacity. The energy saving effect of a parallel polygeneration system is less significant than that of a sequential one (Jin, 2007; Gao, 2004). In a sequential polygeneration system, the component adjusting unit is canceled and partial recycling of the unreacted syngas is applied, resulting in

reasonable component and chemical energy conversions. However, there is a strong constraint on the production ratio, such as methanol and power, for a sequential polygeneration system. A higher proportion of power generation (which is more proper ratio of chemical production to power generation for the market) will result in decreased performance.

To avoid the disadvantages of the sequential and parallel polygeneration systems, a hybrid configuration polygeneration (called hybrid polygeneration below for abbreviation) system is proposed in this paper. This hybrid polygeneration system coordinates the performance and capacity ratio of chemical to power and facilitates peak shaving of power generation. The configuration characteristics and performance was analyzed, and the character of energy utilization was investigated by second law analysis.

2. Proposal of the hybrid configuration polygeneration system

2.1 Description of the reference systems

As shown in Fig. 1(a), the individual coal gas-based power system (IGCC) is based on a TEXACO O₂-blown and slurry-feed gasifier with O₂ provided by an air separation unit (ASU) (Jiao, 1996). The hot coal gas from the gasifier was cooled in a waste heat boiler (WHB) and then allowed to flow to a fines removal and low temperature purification unit. The cleaned coal gas fuels the following power generation subsystem including the gas turbine (GT), heat recovery steam generator (HRSG), and steam turbine (ST).

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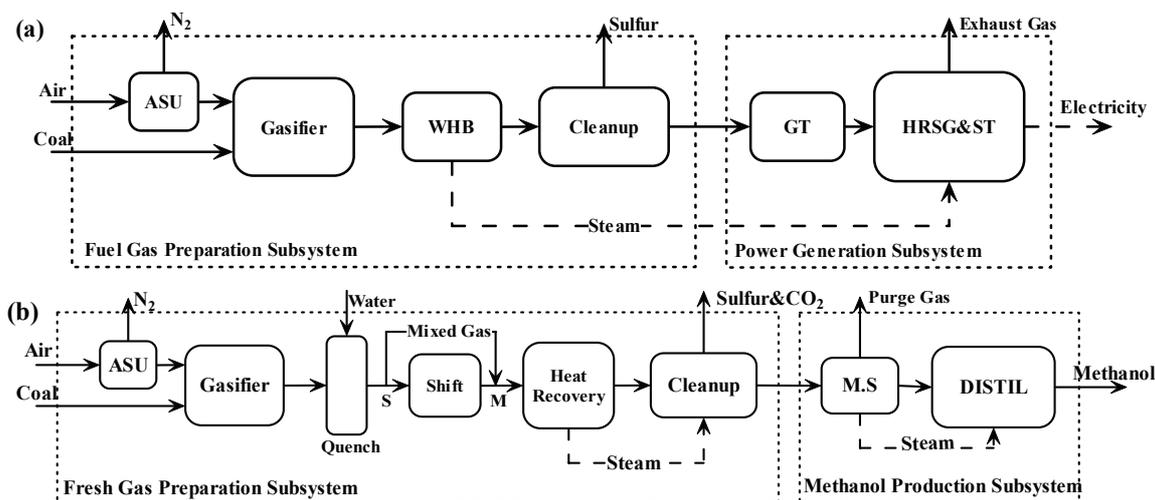


Figure 1. Flow diagrams of individual processes: (a) IGCC system; (b) MP.

The methanol production (MP) system is shown in Fig. 1(b). The coal was gasified in a gasifier similar to that used in IGCC. To fit the methanol synthesis reaction, the pressure of the gasifier was increased to 6.8 MPa. The hot gas from the gasifier was quenched from about 1619 to 513 K. After the quenching process, about 56% of the gas from the quenching unit was divided to the shift unit to adjust the CO/H₂ ratio via the water-gas shift reaction. The rest of the stream bypassed the shift unit and mixed with the shifted gas. After cooling down in a heat recovery unit, where low-pressure steam and medium pressure hot water were produced, the mixed gas flowed into the purification unit where impurities such as sulfur compounds and carbon dioxide were absorbed by methyl diethanol amine (MDEA) (Mednick, 1988). From the purification process, the clean syngas was sent to the methanol synthesis unit equipped with Lurgi technology (Zhong, 1984). The temperature of the synthesis process was kept at about 523 K by controlling the evaporation temperature of the cooling water. After cooling down, the unreacted gas was compressed and recycled to the synthesis unit, and the raw methanol was purified in the flash drum and in the distillation unit. In the distillation unit, there were two columns (L-C and H-C) used to remove the light components containing H₂, CO, DME (dimethyl ether), and

aldehyde and the heavy components including ethanol, water, and higher alcohol.

2.2 Configuration characteristics of the parallel and sequential polygeneration systems

The flow diagrams of the parallel polygeneration system (a) and sequential polygeneration system (b) are presented in Fig. 2 (Jin, 2007; Gao, 2005). In the parallel polygeneration system, the characteristics of the individual production systems (IGCC system and methanol production system) are clearly demonstrated. As can be seen, the chemical subsystem and power subsystem are similar to the individual methanol production system and IGCC power system, respectively, except for some material and heat interactions between the two subsystems. For the sequential polygeneration system, the power subsystem was arranged downstream of the chemical subsystem fueled by the unreacted gas from the chemical subsystem. Thus, the chemical process upstream had a constraint and significant effect on the power subsystem. It is necessary to stress that the chemical subsystem was reformed by canceling the component adjustment process and partially recycling the unreacted gas.

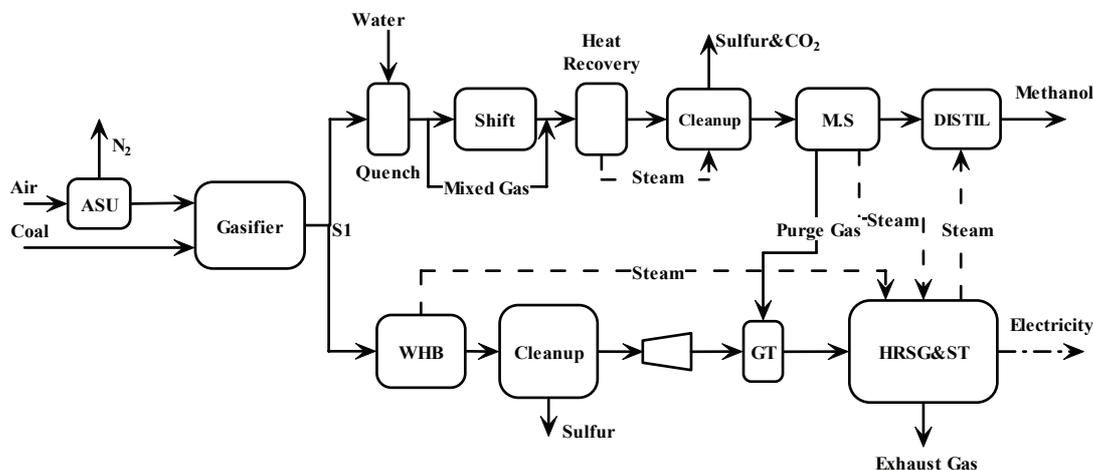


Figure 2. (a) The flow diagrams of the parallel polygeneration system.

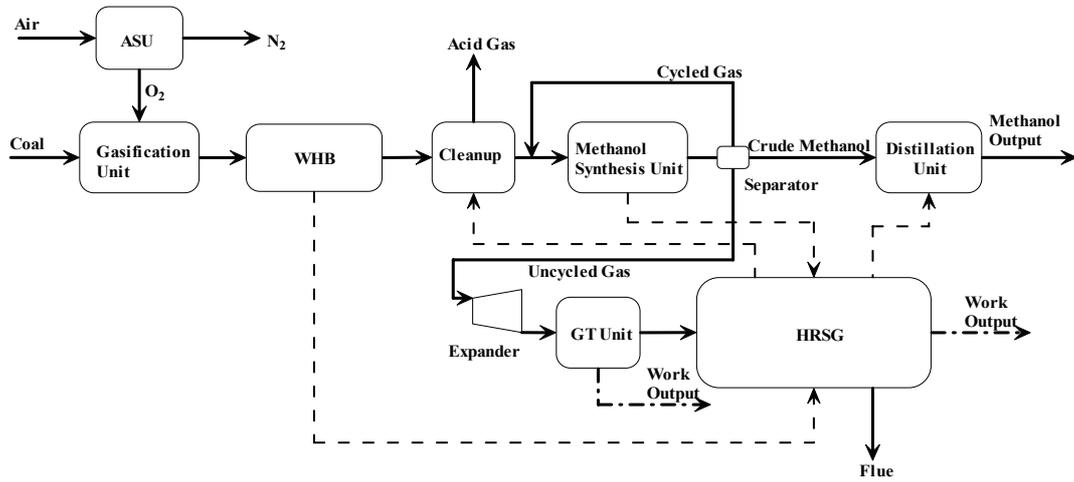


Figure 2. (b) The flow diagrams of the sequential polygeneration system.

2.3 Description and characteristics of the hybrid polygeneration system

From the description above, it can be seen that the parallel polygeneration system cannot efficiently utilize the chemical component and thermal energy of the syngas, and that it is difficult to balance the chemical subsystem and power system in the sequential polygeneration system. A novel hybrid polygeneration system, which combines the configuration characteristics of both systems to solve their shortcomings, is proposed in this paper.

The flow sheet of the hybrid polygeneration system is presented in Fig. 3. Coal was gasified in a gasifier similar to that of the individual chemical methanol production system. The raw syngas was cooled down in the waste heat boiler and then divided into two streams in the R1 ($r1$ refers to the split fraction of the syngas going to the chemical subsystem), one to the chemical subsystem and the other to the power subsystem. Both of the streams were purified by MDEA, but the stream that went to the power system did not remove CO_2 in the purification unit. The clean syngas sent to the chemical subsystem synthesized methanol in the synthesis unit. After cooling down in the heat regenerator,

the raw methanol and the unreacted gas were separated. Part of the unreacted gas that was divided in the R2 went to the recycle compressor (RC), through which part of the unreacted gas was recycled to the synthesis unit. Let RCR represent the recycle ratio, which is the mole ratio of the unreacted stream recycled to the synthesis unit to the fresh coal gas. Then, the raw methanol from the synthesis unit was distilled. Both the unreacted gas from the chemical subsystem and part of the syngas from the cleanup unit went to the power subsystem to fuel the combined cycle. The power needed in the syngas preparation subsystem and chemical subsystem was provided by the power subsystem. The heat integration among the three subsystems was carried out by water/steam with proper pressure.

From the configuration character description, it can be seen that the hybrid polygeneration system had both of the characteristics of the parallel and sequential polygeneration systems. Compared with the parallel polygeneration system, the hybrid polygeneration system removed the component adjustment process with proper recycling of unreacted gas. It resulted in proper conversion of the syngas chemical energy to methanol in the chemical subsystem. The

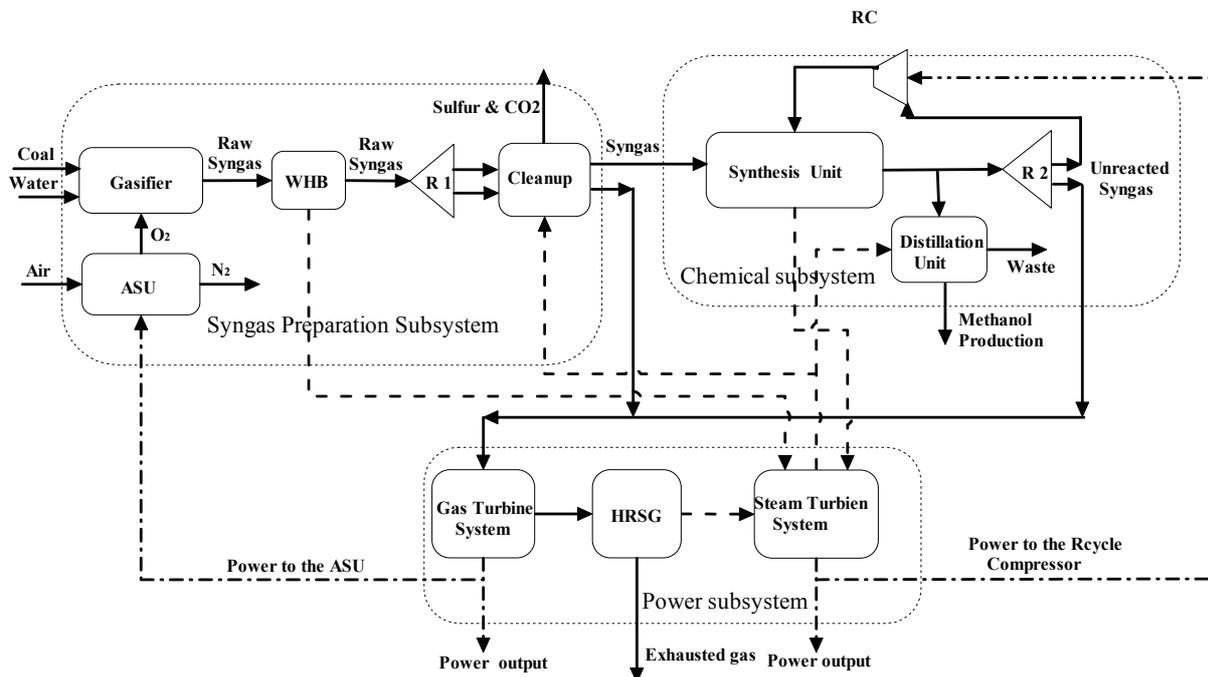


Figure 3. The flow sheet of the hybrid polygeneration system.

unreacted gas went to the power subsystem when it became difficult to convert it to methanol. Compared with sequential polygeneration system, not all of the components from the syngas preparation subsystem went to the chemical subsystem. Thus, the stream splitter R1 has a negative effect on the performance. However, when the production capacity required more power production, the hybrid polygeneration system can perform better than the sequential one mainly due to its flexible configuration. For a higher power generation requirement, the sequential polygeneration has to choose a nonsufficient recycling of the unreacted gas in the chemical subsystem to increase the power generation. The chemical subsystem of the hybrid polygeneration system manages the proper utilization of the chemical energy of the effective components at each rI .

3. Performance of the novel system

3.1 Evaluation criterion and basic assumption

The performance of the hybrid polygeneration system is evaluated by energy saving rate (ESR), which can be defined by:

$$ESR = [(E_{pi} + E_{ci}) - E_{pg}] / (E_{pi} + E_{ci}), \quad (1)$$

where E_{pi} and E_{ci} represent the total energy input to the individual power generation and the individual methanol production system, respectively, and E_{pg} represents the energy input to the polygeneration system. It must be ensured that the polygeneration system and the individual systems have the same amount of production when they are compared. The ESR stands for the fuel saving rate of the polygeneration system compared with the individual systems with the same production.

The simulations were performed using Aspen Plus and were carried out according to the present technology. The thermodynamic properties of syngas and methanol were calculated using the Peng-Robinson and Redlich-Kwong equations, respectively. Datong coal, with an LHV (low heat value) of 26710 kJ/kg, was assumed as the basis for

Table 1. Basic Assumptions.

Base coal analysis (weight %)			
C^f	68.54	H^f	3.97
O^f	6.85	N^f	0.74
S^f	1.08	Ash ^f	9.98
W^f	8.84		
Assumption for Gas Turbine			
Parameter		Assumption	
Turbine inlet temperature (° C)		1250	
Pressure ratio		17	
Mechanical efficiency (%)		98	
Isentropic efficiency, turbine (%)		92	
Isentropic efficiency, compressor (%)		87	
Assumption for Steam Cycle			
Turbine inlet temperature (° C)		535	
Turbine inlet pressure (bar)		120	
Mechanical efficiency (%)		98	
Isentropic efficiency of steam turbine high/middle/ low pressure (%)		85/85/87	
Pinch temperature difference (° C)		25	
Feed water temperature (° C)		30	

this study. The coal components and some other basic conditions are given in Table 1.

3.2 Performance of the hybrid polygeneration system

The performance of the polygeneration system was simulated. The results are presented in Fig. 4. From the figure, it can be seen that the main parameters affecting the ESR are rI and RCR . For each rI there is an optimal RCR around 4.4, which means that proper recycling of the unreacted gas results in the best performance. Without recycling, the unreacted gas ($RCR=0$) generates the worst performance. The RCR decides the conversion degree of the syngas to methanol in the chemical subsystem. By recycling the unreacted gas properly, the chemical energy of the syngas can be distributed reasonably to the chemical and power subsystems.

For each RCR , the ESR increases as the rI increases. Compared with the reference systems, the new system improves the performance of the chemical subsystem, while the power subsystem is almost the same, except for the fuel components. Thus, when the rI increases, more energy is distributed to the chemical subsystem, resulting in better performance. From Fig. 3 it can be seen that, both the IGCC power system and the sequential polygeneration system are special cases of the hybrid polygeneration system. When rI equals zero, the hybrid polygeneration system transforms to IGCC power system with the $ESR=0$. When rI equals 1, the hybrid polygeneration system becomes the sequential polygeneration system, and the best performance presents at $rI=1$ and RCR around 4.4, with the highest ESR of 13.8%.

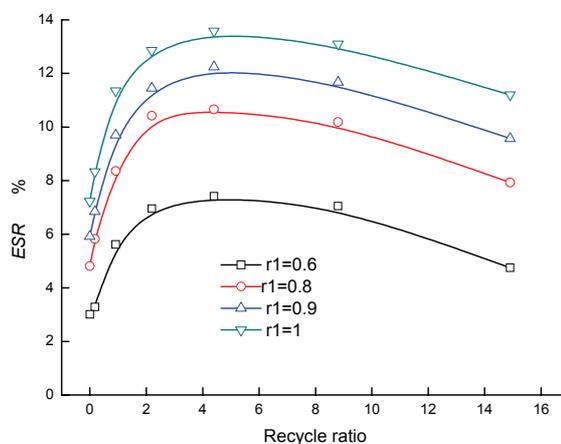


Figure 4. Performance of the hybrid polygeneration system.

3.3 The variation of product capacity ratio of chemical to power

The capacity ratio is an important parameter to judge the output of a polygeneration system. In this study, the ratio of the energy (low heat value based) of the methanol output to the power output is called the capacity ratio of chemical to power. Both the RCR and rI decide the capacity ratio of chemical to power. Figure 5 presents the variation of the capacity ratio of chemical to power depending on rI and RCR . The capacity ratio increases as both rI and RCR increase. From Fig. 4, we can see that a RCR between 2.2 and 4.4 results in the best performance at each rI . Thus, for a specific capacity ratio, the best performance appears with a RCR between 2.2 and 4.4. This means that the RCR must be a constant value and rI must

be used as the parameter to adjust the capacity ratio if we want to design an effective polygeneration system.

Nevertheless, rI also decides the energy distributions to the chemical and power subsystems. The main exergy benefit is from the improvement of the chemical subsystem, so the higher rI , the better the performance will be without considering the capacity ratio. If the power subsystem can also be improved, such as through chemical looping combustion (Jin, 1997), the impact of rI on performance will be largely decreased.

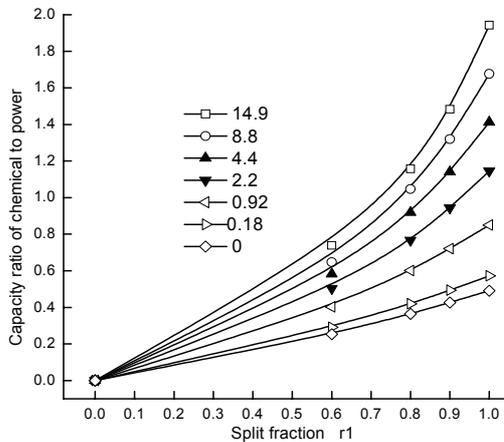


Figure 5. The variation of capacity ratio of chemical to power depending on the rI and RCR .

3.4 The performance of the hybrid polygeneration system at each capacity ratio of chemical to power

The performance of the hybrid polygeneration system at each capacity ratio of chemical to power is presented in Fig. 6. It can be seen that, for each rI as the capacity ratio increases the ESR firstly rises and then falls, resulting in an optimal capacity ratio for each rI . The optimal capacity ratio decreases as the rI decrease, and it is easy to see that, the optimal capacity ratio is corresponding to the optimal RCR for each rI . The envelope of each rI is also presented in Fig.5, which will stand for the performance of the hybrid polygeneration system at each capacity ratio. When $rI=1$, the hybrid polygeneration system becomes the sequential polygeneration system. So, the line of $rI=1$ represents the performance of the sequential polygeneration system at each capacity ratio. And according to Fig. 2 (a), the performance of the parallel polygeneration system at each capacity ratio is also presented in Fig. 6.

The hybrid polygeneration system performs better than both the sequential and parallel polygeneration systems at each capacity ratio of chemical production to power generation. For higher rI , the configuration of the hybrid polygeneration system is similar to the sequential one, so they have the near performance. When the rI decreases, the hybrid polygeneration system can still implement the principle of properly recycling the unreacted gas. However, the sequential polygeneration system has to loosen the recycle ratio to obtain a smaller product capacity ratio. Compared with the hybrid polygeneration system, the parallel polygeneration system conditions the syngas to synthesize methanol, resulting in a lower energy saving rate than those of the other two polygeneration systems. Especially at the capacity ratio around 0.5, the ESR of the hybrid polygeneration system is 2% higher than that of the sequential polygeneration system and 4.5% higher than the parallel polygeneration system.

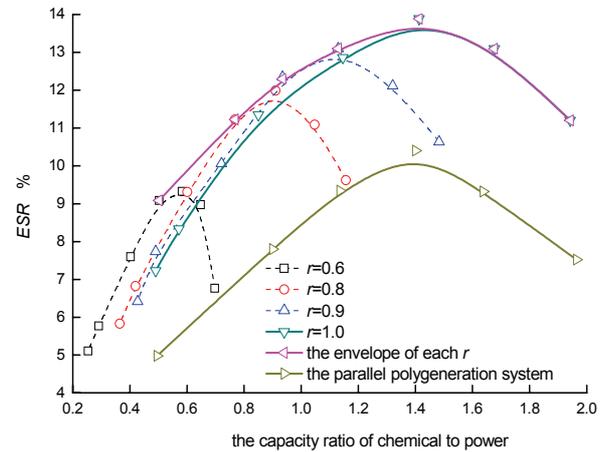


Figure 6. The performances at different production capacity ratios.

In the hybrid polygeneration system, the range of the capacity ratio of chemical to power is decided by the parameters of both rI and RCR . As rI and RCR increase, the methanol output is increased, resulting in an increase of the capacity ratio. But the maximum capacity ratio is limited by the composition of the syngas (syngas conditioning process is removed). Nevertheless, when rI is decreased, the capacity ratio can be decreased as less as to be designed. While in the sequential polygeneration system, the minimum capacity ratio is about 0.5 (when $RCR=0$). That is to say, the capacity ratio of the sequential polygeneration system is limited by its configuration. So we can conclude that the sequential polygeneration system has a strong constraint on the product capacity ratio resulting from the strong constraint of the chemical subsystem on the power system. The parallel polygeneration system cannot convert the syngas components to chemical and power as efficiently as the sequential polygeneration system does. The hybrid polygeneration system can coordinate those problems.

4. Discussions

4.1 Integrated utilization of the chemical and physical energy of the hybrid polygeneration system

This part will build the character equation of chemical energy utilization for the studied polygeneration system, in which the coupling relation of the methanol synthesis process and power generation process is illustrated. To stress the cascading utilization of the syngas chemical energy, the gasification process and high temperature syngas cooling process will not be considered in this analysis. That is to say the input of the studied systems is the cooled syngas, and the systems boundaries for the exergy balance analysis are presented in Fig. 7.

The exergy balance equations of the studied system and the reference systems are presented below:

$$\Delta E_{syn}^{PG} = \Delta E_{d,CU}^{PG} + \Delta E_{d,M}^{PG} + \Delta E_{d,D}^{PG} + \Delta E_{d,TB}^{PG} + \Delta E_{d,C}^{PG} + \Delta E_{d,HRS}^{PG} + W^{PG} + E_M^{PG}, \quad (2)$$

$$\Delta E_{syn}^m + W^m + \Delta E_{st}^m = \Delta E_{d,SH}^m + \Delta E_{d,CU}^m + \Delta E_{d,M}^m + \Delta E_{d,D}^m + E_M^{PG}, \quad (3)$$

$$\Delta E_{syn}^I = \Delta E_{d,TB}^I + \Delta E_{d,C}^I + \Delta E_{d,HRS}^I + W^I, \quad (4)$$

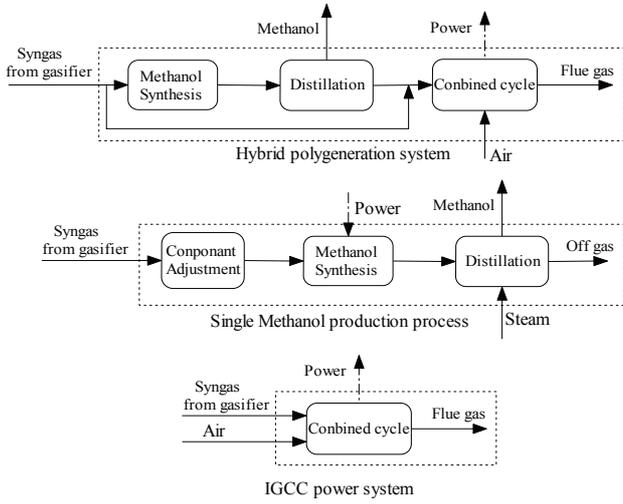


Figure 7. System boundaries for the comparison between the hybrid polygeneration and individual systems.

where, $\Delta E_{d,CU}^{PG}$, $\Delta E_{d,M}^{PG}$, $\Delta E_{d,D}^{PG}$, $\Delta E_{d,TB}^{PG}$, $\Delta E_{d,C}^{PG}$ and $\Delta E_{d,HRSG}^{PG}$ represent the exergy destruction in the cleanup process, the methanol synthesis unit, the methanol distillation process, the turbine process, the combustion process and the HRSG unit in the polygeneration system, respectively; $\Delta E_{d,SH}^m$, $\Delta E_{d,CU}^m$, $\Delta E_{d,M}^m$ and $\Delta E_{d,D}^m$ represent the exergy destruction in the shift process, the cleanup process, the methanol synthesis unit, the methanol distillation process in individual methanol production process, respectively; W^m and ΔE_{st}^m represent the exergy input of the power and the steam in the individual methanol production process, respectively; $\Delta E_{d,TB}^I$, $\Delta E_{d,C}^I$, $\Delta E_{d,HRSG}^I$ represent the exergy destruction in the turbine process, the combustion process and the HRSG unit in IGCC power system, respectively; E_M^m , W^I and E_M^{PG} , W^{PG} represent the exergy outputs of the methanol and the power, respectively in individual reference systems and in the polygeneration system; and, ΔE_{syn}^{PG} , ΔE_{syn}^m and ΔE_{syn}^I represent the chemical exergy input of the syngas in the polygeneration system, the methanol production process and the IGCC power system, respectively.

Combining equations (2), (3) and (4), we can express the saved exergy input of polygeneration system compared with the individual systems with the same output (E_M^{PG} , and W^{PG}):

$$\begin{aligned} \Delta E_{gain} &= \frac{\Delta E_{syn}^m + W^m + \Delta E_{st}^m}{E_M^m} E_M^{PG} + \frac{\Delta E_{syn}^I}{W^I} W^{PG} - \Delta E_{syn}^{PG} \\ &= \frac{\Delta E_{d,SH}^m + \Delta E_{d,CU}^m + \Delta E_{d,M}^m + \Delta E_{d,D}^m}{E_M^m} E_M^{PG} \\ &\quad + \frac{\Delta E_{d,TB}^I + \Delta E_{d,C}^I + \Delta E_{d,HRSG}^I}{W^I} W^{PG} \\ &\quad - (\Delta E_{d,CU}^{PG} + \Delta E_{d,M}^{PG} + \Delta E_{d,D}^{PG}) \\ &\quad - (\Delta E_{d,TB}^{PG} + \Delta E_{d,C}^{PG} + \Delta E_{d,HRSG}^{PG}), \end{aligned} \quad (5)$$

From equation (5) we can see that, the saved exergy input equals the reduction of the exergy destruction of the polygeneration system compared with the individual

systems with the same output (E_M^{PG} , and W^{PG}). Then equation (5) can be further expressed as:

$$\begin{aligned} \Delta E_{gain} &= \Delta e_d^m E_M^{PG} + \Delta e_d^I W^{PG} \\ &\quad - (\Delta e_{d,CH}^{PG} E_M^{PG} + \Delta e_{d,PW}^{PG} W^{PG}), \end{aligned} \quad (6)$$

where, Δe_d^m represents the exergy destruction per unit methanol production in the individual methanol production process; Δe_d^I represents the exergy destruction per unit power generation in the IGCC power system; $\Delta e_{d,CH}^{PG}$ represents the exergy destruction per unit methanol production in the chemical subsystem of the polygeneration system; and, $\Delta e_{d,PW}^{PG}$ represents the exergy destruction per unit power generation in the power subsystem of the polygeneration system. Then the character equation of cascading utilization of the syngas chemical energy in the polygeneration system can be expressed:

$$\begin{aligned} R_C &= \frac{\Delta E_{gain}}{\Delta e_d^m E_M^{PG} + \Delta e_d^I W^{PG}} \\ &= \frac{\Delta e_d^m E_M^{PG} + \Delta e_d^I W^{PG} - (\Delta e_{d,CH}^{PG} E_M^{PG} + \Delta e_{d,PW}^{PG} W^{PG})}{\Delta e_d^m E_M^{PG} + \Delta e_d^I W^{PG}} \\ &= \frac{(\Delta e_d^m - \Delta e_{d,CH}^{PG}) + (\Delta e_d^I - \Delta e_{d,PW}^{PG}) / \lambda}{\Delta e_d^m + \Delta e_d^I / \lambda} \\ &= \frac{R_{C,CH}}{1 + \frac{1}{\alpha \lambda}} + \frac{R_{C,PW}}{\alpha \lambda + 1} \\ &= f(R_{C,CH}, R_{C,PW}, \alpha \lambda), \end{aligned} \quad (7)$$

where, on the right side of equation (7), λ represents the product ratio of chemical to power in the polygeneration system; $\alpha = \frac{\Delta e_d^m}{\Delta e_d^I}$ is the ratio of the exergy destruction per

unit methanol production to the exergy destruction per unit power generation in the individual production systems, and it also represents the ratio of the maximum chemical energy utilization potential of chemical subsystem to that of the power subsystem; $R_{C,CH} = \frac{\Delta e_d^m - \Delta e_{d,CH}^{PG}}{\Delta e_d^m}$ represents the

reduction rate in exergy destruction of the chemical subsystem in the polygeneration system compared with individual methanol synthesis process; and,

$R_{C,PW} = \frac{\Delta e_d^I - \Delta e_{d,PW}^{PG}}{\Delta e_d^I}$ represents the reduction rate in exergy destruction of the power subsystem in the polygeneration system compared with IGCC power system.

On the left side of equation (7), R_C is the reduction rate in exergy destruction of the polygeneration system compared with the individual systems. This means R_C can represent the degree of the cascading utilization of the syngas chemical energy. From equation (7) we can see that, R_C is a function of $R_{C,CH}$, $R_{C,PW}$ and λ , and it gives the

analytic relation of how the chemical and power subsystems are coupled in the polygeneration system.

From equation (6) and (7), we can see that the main reason behind the ability of the polygeneration system to save energy is the reduction in exergy destruction in both the chemical and power subsystems. The energy utilization character of the hybrid polygeneration can be summarized by the following:

(1) Cascading utilization of the thermal energy. In the polygeneration system, the heat produced in methanol synthesis subsystem is used to produce the proper pressure steam for the power subsystem and most of the low pressure saturated steam needed in the methanol synthesis subsystem is supplied by extracting steam from the power subsystem. While for the individual methanol synthesis process, almost all the heat available is used to produce the low pressure steam needed in methanol process. Thus, the heat integration between the chemical subsystem and power subsystem decreases the exergy destruction in the heat exchange process.

(2) Cascading utilization of the chemical energy of the syngas. In the polygeneration system, the syngas conditioning process is removed, so the syngas is converted properly to methanol according to the syngas composition character and can then be used to generate power. This idea of the syngas utilization prevents the high energy cost for pursuing high chemical conversion rate which is an obvious character in the individual methanol synthesis process. To pursue a high methanol conversion rate, the syngas has to be conditioned in the methanol production process. It not only consumes a large amount of steam, but also converts chemical energy of fuel to low temperature heat. And sequentially the heat loads of the cleaning unit and distillation unit is increased greatly. On the other hand, the composition change of the syngas through the synthesis process will be slightly lower than the irreversibility destruction rate in the combustion process.

4.2 The coupling relation between the chemical and power subsystems in the hybrid polygeneration system

In this part, the parameter rI is set at 0.8. Then the parameter affecting R_C is the RCR . The thermodynamic performances of individual production systems are considered to be constant. In Fig. 8 the exergy destruction per unit methanol production of the hybrid polygeneration

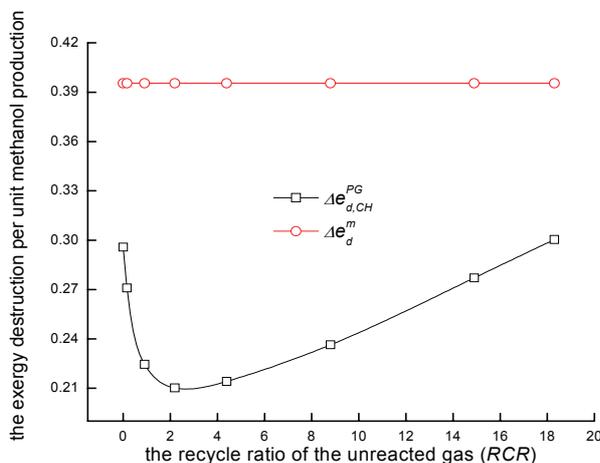


Figure 8. The variation of the exergy destruction per unit methanol production.

system is compared with that of the individual methanol production processes. From the figure we can see that as RCR increases from 0 to 18, the $\Delta e_{d,CH}^{PG}$ firstly decreases sharply and then increases slowly. The $\Delta e_{d,CH}^{PG}$ is largely decreased compared with the Δe_d^m . At the RCR of 2.2 the $\Delta e_{d,CH}^{PG}$ reaches the lowest value 0.21. This means that by removing the component adjustment process the performance of the chemical subsystem is largely improved compared with the individual methanol production. And a proper recycle of the unreacted gas will optimize the performance of the chemical subsystem.

Figure 9 shows the variations of the exergy destruction per unit power generation both in the hybrid polygeneration system and IGCC power system depending on the recycle ratio. From the figure we can see that as the RCR increases the $\Delta e_{d,PW}^{PG}$ decrease sharply and then keeps almost the same. The $\Delta e_{d,PW}^{PG}$ is only slightly decreased compared with the Δe_d^I . This means the power subsystem is only slightly improved compared with the IGCC power system.

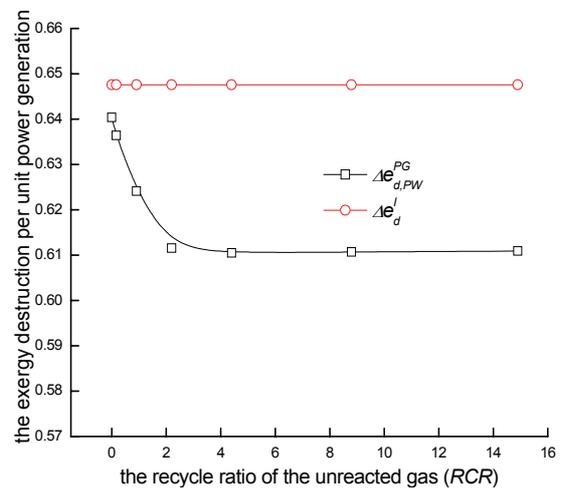


Figure 9. The variation of the exergy destruction per unit power generation

From Fig. 8 and Fig. 9 it can be concluded that the exergy destruction reduction of the hybrid polygeneration system compared with the individual systems is mainly from the improvement of the chemical transform processes, such as the shift reaction process, the cleanup process, the synthesis reaction process, the distillation process, and the combustion process. The contribution of the physical processes, such as the heat exchange process in HRSG and the turbine process, to the R_C is not so significant for the same technique parameters, such as the minimum temperature difference of the heat exchange process, the turbine isentropic efficiency and etc. So, the main reason for the hybrid polygeneration system to save energy is cascading utilization of chemical energy.

Figure 10 shows the coupling relation between the chemical and power subsystems in the hybrid polygeneration system. As the RCR increases from 0 to 18, the $R_{C,CH}$ rises sharply from 25% and at $RCR=0.22$ reaches the optimal point with the value of 47%, and then decreases to 23%. While the $R_{C,PW}$ rises from 2% to 5.5%. The product ratio of chemical to power in the

polygeneration system λ rises sharply as RCR increases, after which the increment slows down. The λ decides the contribution degrees of the two subsystems to the whole polygeneration system in the aspect of energy saving. With the interaction among $R_{C,CH}$, $R_{C,PW}$ and λ , the degree of the energy cascading utilization R_C increases as RCR increase, and at about RCR=4.4 it reaches the optimal point (20%) and then decreases. For the $R_{C,CH}$ is much larger than $R_{C,PW}$, a larger λ will result in better performance. Thus, the optimal RCR corresponding to R_C is a little large than that corresponding to $R_{C,CH}$. The ratio of the maximum energy cascading utilization potential of chemical subsystem to that of the power subsystem α is 0.611. That is to say the main (about 62%) exergy destruction occurs in the power subsystem. This means that although the improvement of the chemical subsystem is the main factor for energy saving, the power subsystem has a significant effect on whole system performance.

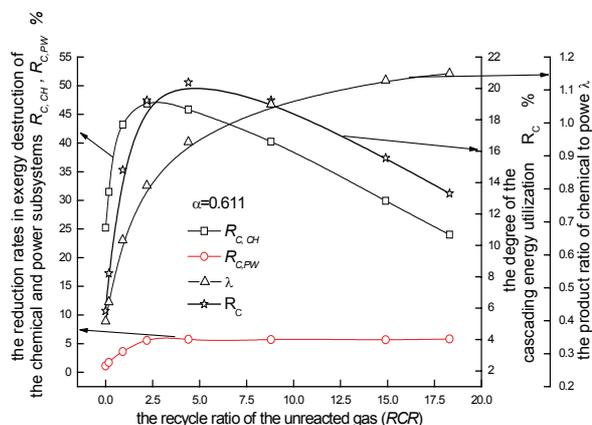


Figure 10. The coupling relation between the chemical and power subsystems

5. Conclusion

A novel hybrid configuration of a coal-based polygeneration system has been proposed and studied. Due to its configuration characteristics, the hybrid polygeneration system performed flexible production distribution and provided the convenience of stable and reliable power generation. The performance of the novel system was simulated by means of Aspen Plus along with an exergy analysis. The new system has an energy saving rate ranging from 2~14%. From the exergy analysis, it has been found that the main reason why the new system can save energy is due to the integrated utilization of the chemical and physical energies of the syngas. Compared with the two other polygeneration systems, the new system has more freedom on production capacity ratio with better performance, which is about 2% higher than sequential polygeneration system and 4.5% higher than the parallel polygeneration system at a capacity ratio of chemical production to power generation of 0.5. This means that the hybrid polygeneration system coordinates the contradiction between the performance and the product capacity ratio.

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