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THERMODYNAMIC ANALYSIS OF A POLYGENERATION SYSTEM BASED ON COAL-STEAM GASIFICATION TECHNOLOGY WITH THERMOCHEMICAL REGENERATIVE PROCESS

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ABSTRACT

Polygeneration technology is an important way to realize clean and efficient coal utilization. Coal-steam gasification technology with thermochemical regenerative process is effective to enhance cold gas efficiency of coal gasification. In this paper, a novel methanol-electricity polygeneration system based on coal-steam gasification is proposed. In this novel polygeneration system, the component adjustment is cancelled and unreacted syngas partially recycled is adopted. The Aspen Plus software is selected to simulate the polygeneration systems. As a result, the energy efficiency of the novel polygeneration system based on coal-steam gasification is 53.5% when chemical to power output ratio is 1.1, while energy efficiency of polygeneration system based on traditional gasification is 47.3%. Furthermore, the energy saving effects of system integration method and gasification process improvement are distinguished.

Keywords: coal-steam gasification; polygeneration system; coal utilization; thermochemical regenerative;

NONMENCLATURE

Abbreviations	
AGR	Air gas removal
ASU	Air separation unit
CGE	Cold gas efficiency
COG	Coke Oven Gas
CPOR	Chemical to power output ratio
E_{in}	Energy input of coal
E_m	Energy output of methanol
ESR	Energy Saving Ratio
GT	Gas turbine
IGCC	Integrated Gasification Combined Cycle
LHV	Lower heating value
P	Power output
PC	Pulverized coal
ST	Steam turbine
WHB	Waste heat boiler
WGS	Water gas shift
Symbols	
η	Energy efficiency of polygeneration system
η_c	Energy efficiency of IGCC system
η_m	Energy efficiency of Methanol production system

1. INTRODUCTION

Coal, which accounts for approximately 30% of the global primary energy consumption, will play a significant role in the future global energy system [1]. However, conventional coal utilization for chemical production and power generation is with high energy consumption and serious environmental pollution. Power generation system focuses on integration of thermal energy, while coal based chemical production system pursues maximum chemical product output. Coal-based polygeneration technology has been proved an important way to achieve high chemical conversion and effective energy utilization through the cascade utilization of chemical energy.

Synergetic integration between chemical process and power system significantly affects performance of polygeneration systems. Gao [2] investigated a parallel polygeneration system and compared with corresponding individual systems, conclusion indicated that the chemical to power output ratio (CPOR) is a key criterion in polygeneration systems. Compared with parallel polygeneration system, the sequential polygeneration system has a better energy saving effect [3]. In the sequential polygeneration system, considering the sharply exergy destruction increasing after the "turning point", the component adjusting unit is canceled and unreacted syngas partially recycled is adopted [4].

Coal gasification is the main contributor to the exergy destruction in polygeneration systems. There are two main problems for current gasification technology: high energy consumption for air separation and limited cold gas efficiency. The current commercial air separation technology requires electricity of 0.4-0.5 kWh/m^3 O_2, at least 0.28-0.3 kWh/m^3 O_2 for the advanced air separation technology [5]. For a typical IGCC system, the electricity consumption of air separation accounts for 10-20% of electricity generation. On the other hand, the cold gas efficiency (CGE) is limited to 74-81% in current gasification technology. In order to enhance the cold gas efficiency of coal gasification, Li [6] proposed a novel coal-steam gasification method with thermochemical regenerative process. In the coal-steam gasification method, high temperature steam is generated in thermochemical regenerative process and then sent to react with char from coking room. Through such a thermochemical regenerative process, the sensible heat of syngas is converted to chemical energy of syngas. Researches before have proved that the IGCC and coal to SNG system based on coal-steam gasification have a better thermodynamic performance compared with systems based on traditional gasification [6-7]. However, the energy integration between chemical process and power system should be further studied for the polygeneration system based on the coal-steam gasification.

This paper aims to integrate a novel methanol-power polygeneration system based on coal-steam gasification. In this novel polygeneration system, the component adjustment is cancelled and unreacted syngas partially recycled is adopted. Besides, the energy saving characteristics of system integration method and gasification process improvement is investigated.

2. SYSTEM DESCRIPTION

2.1 Polygeneration systems based on coal-steam gasification and traditional gasification

In the novel methanol-power ploygeneration system, coal is divided into heating coal and gasification coal. Gasification coal is firstly sent to coking room and decomposed into char, tar and COG. Char from coking room is sent to react with high temperature steam. The heat requirement for coking and steam-char gasification is supplied by the combustion of heating coal. After heat recovery and sulfur removal, syngas from steam-char gasification and coke oven gas (COG) are mixed and sent to methanol synthesis without component adjustment. Raw methanol from synthesis unit is distilled and high purity methanol is produced at distillation unit. Then the unreacted gas is partially recycled into the synthesis reactor after compression. The unrecycled syngas is combusted for power generation in the combined cycle unit. The simplified flowsheet of the novel polygeneration system based on coal-steam gasification is shown as Fig. 1(a).

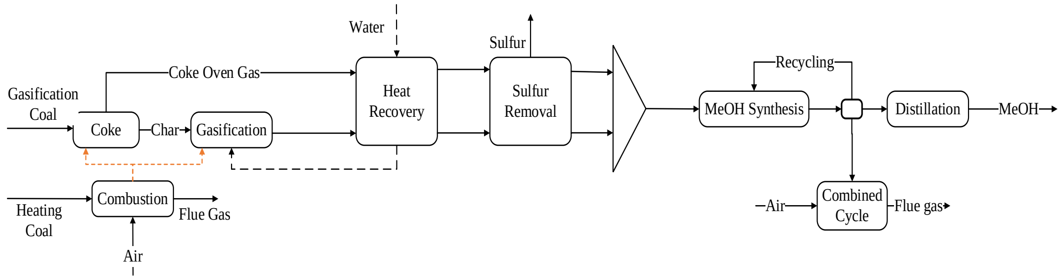
In the traditional polygeneration system (Fig. 1(b)), Texaco gasification technology is employed. In the Texaco gasification technology, pure O_2 and coal-slurry is reacted at 1346 °C. Syngas from gasifier is sent to the acid gas removal (AGR) unit after heat recovery in waste heat boiler (WHB). In the synthesis unit, unreacted gas partially recycled is adopted, the unrecycled syngas is sent to generate electricity in the combined cycle unit.

Compared with the polygeneration system based on traditional gasification, the novel polygeneration system has such advantages as following: (1) The violent partially oxidant reaction is substituted by moderate coal-steam gasification. The coal-steam gasification has smaller exergy destruction. (2) Via heat recovery of steam agent, sensible heat of syngas is converted to chemical energy, which increases the CGE of coal gasification. (3) Air separation unit is eliminated and power consumption for air separation is avoided. (4) The H/C molar ratio of coal-steam gasification is 1.2, higher than that in traditional gasification.

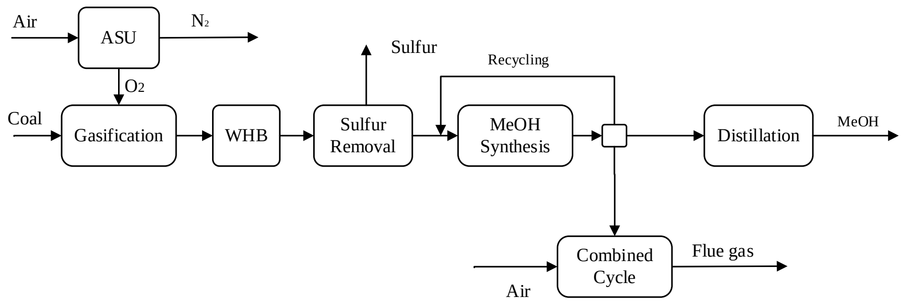
2.2 Individual systems based on traditional gasification

In the methanol production system based on traditional gasification (Fig 2(a)), syngas from gasifier is cooled to 230 °C through quenching bath. After quenching process, a shift unit is used to adjust the syngas H/C molar ratio to 2. The fresh gas is compressed and sent to synthesis reactor after acid gas removal unit. In the acid gas removal unit, CO_2 and sulfur is removed to prevent catalysts poisoned and side reactions. In the methanol synthesis unit, high recycling ratio is adopted to achieve maximum methanol production. Then raw methanol is separated by flash and sent to distillation unit for high purity methanol production. A pulverized coal (PC) power plant with thermal efficiency of 35% is required to satisfy the requirement of work and steam in the entire process. The equivalent thermal efficiency of methanol production based on the Texaco gasification is 43.1%.

In the IGCC system based on Texaco gasification (Fig 2(b)), sensible heat of syngas from Texaco gasifier is

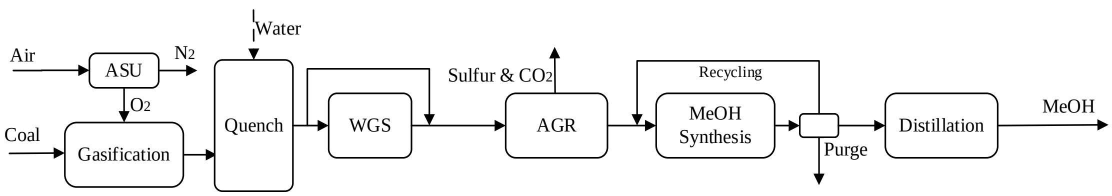


(a) Polygeneration system based on coal-steam gasification

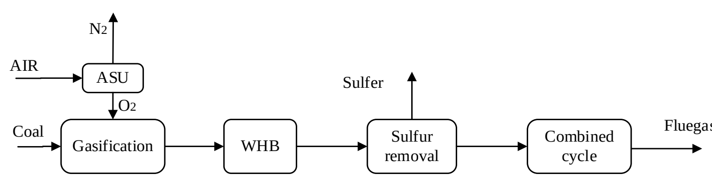


(b) Polygeneration system based on traditional gasification

Fig 1 Polygeneration systems based on coal-steam gasification and traditional gasification



(a) Methanol production system based on traditional gasification



(b) IGCC system based on traditional gasification

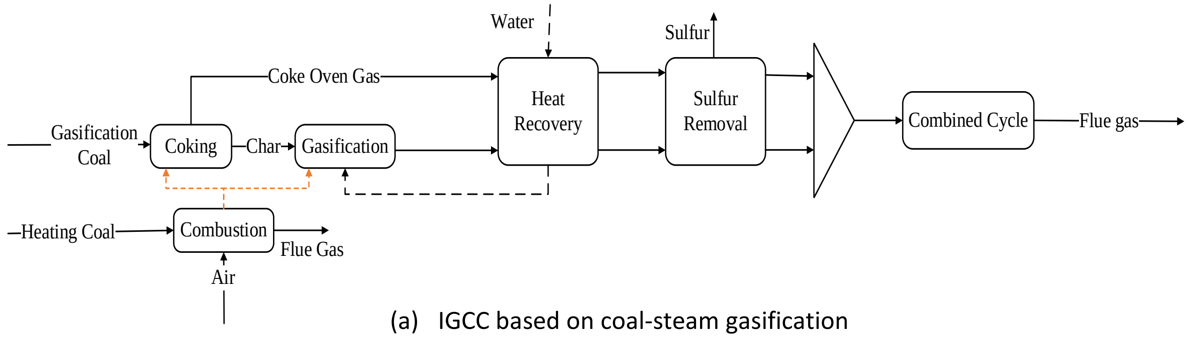
Fig 2 Individual systems based on traditional gasification

recovered for steam generation by WHB. After sulfur removal, the syngas is compressed and combusted to generate electricity in the combined cycle unit. The thermal efficiency of IGCC system based on traditional gasification is 43.6%.

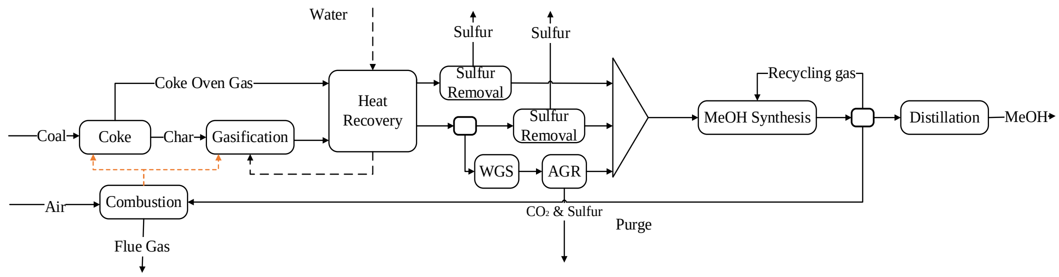
2.3 Individual systems based on coal-steam gasification

In the IGCC system based on coal-steam gasification, the sensible heat of COG and syngas is recovered by gasify agent. After sulfur removal, the compressed COG and syngas are mixed and sent to combined cycle unit for electricity generation. the thermal efficiency of IGCC system based on coal-steam gasification is 46.7%. the simplified flowsheet of the IGCC system based on coal-steam gasification is shown in Fig. 3(a).

The simplified flowsheet of methanol production system based on coal-steam gasification is shown in Fig 3(b). In the methanol production system based on coal-steam gasification, CH_4 from COG is enriched in the purge. Therefore, the heat requirement of coking and gasification process is supplied by the combustion of purge from distillation. Syngas from gasification are partially shifted to adjust the H/C mole ratio to 2 for



(a) IGCC based on coal-steam gasification



(b) Methanol production system based on coal-steam gasification

Fig 3 Individual systems based on coal-steam gasification

methanol synthesis. After acid gas removal unit, the compressed COG and syngas are mixed and sent to methanol synthesis reactor. The high purity methanol is produced in the distillation unit. In order to satisfy the heat requirement of coking and steam-char gasification, the unreacted gas partially recycled is adopted. Besides, the work requirement in the entire process is supplied by a pulverized coal (PC) power plant. The equivalent thermal efficiency of methanol production system based on steam-coal gasification is 53.1%.

3. EXPERIMENTS AND KEY DESIGN PARAMETERS

3.1 Experiments of coking and steam-char gasification process

The coking experiments are conducted based on a vertical tubular furnace. After drying, coal is heated at 900 °C and atmospheric pressure for 3 h. In the coking process, the long-flame coal is decomposed into char, tar and COG. The experiment results of coking are shown in Table 1. For the steam-char gasification process, a fixed-bed reactor with electricity heating furnace is adopted. The experiments are carried out under 1100 °C and atmospheric pressure. When the reaction is over, the syngas is collected by a gas bag and gas composition is detected by Micro GC 490. The experimental results of syngas composition are shown in Table 2.

3.2 Key design parameters

The systems described are simulated using Aspen Plus v8.4, PR-BM is chosen as the global method. Coal and char are designated as non-conventional components, while tar is represented by C_6H_6. The RYield reactor is adopted to model coking process according to experiment results. The mass flow rate of input coal is 28.64 kg/s and other key design parameters are shown in Table 3.

Table 1 Experimental results of coking

Products yields (Mass, fraction %)			
COG	31.9	Char	59.3
Tar	1.5	H_2O	7.3
Coal ultimate analysis (Mass, fraction %)			
C	71.63	H	4.53
O	10.28	N	0.84
S	0.33	W	3.60
Ash	3.60	LHV (kJ/kg)	28670
COG component (Volume, %)			
H_2	51.7	O_2	1.7
N_2	9.0	CH_4	11.6
CO_2	3.5	CO	21.9
C_2H_4	0.5	H_2S	0.1
Char ultimate analysis (Mass fraction, %)			
C	91.86	H	1.38
O	0.14	N	0.87
S	0.44	Ash	5.31

Table 2. Experimental results of syngas composition [6]

Content of syngas (Volume fraction, %)			
H_2	52.9	O_2	1.4
CH_4	0.77	CO	39.62
CO_2	5.3	C_2H_4	0.01

Table. 3 Key design parameters

Item	Description
Texaco gasification	T=1346 °C; P=40bar; Heat loss: 5.0%; Slurry concentration=66.5%.
Steam-char gasification	T=1100 °C; P=40 bar;
Air separation unit	Cryogenic technology; electricity consumption=0.48 kWh/Nm^3; oxygen concentration=98.6%.
Acid gas removal	Selexol Technology.
Gas Turbine	Pressure Ratio:16.7 bar; Gas turbine initial temperature:1327 °C; Isentropic efficiency of GT: 0.92.
WHB & Steam Turbine	Triple-pressure reheat steam: 126/25/5.5 bar, Steam temperature: 566 °C, Isentropic efficiency of ST: 0.88/0.89/0.87.
Methanol Synthesis	T=255 °C; P=83 bar.
Methanol distillation	Double-column distillation.

4. RESULTS AND DISCUSSION

4.1 System performance evaluation

Some performance evaluation criteria are presented for the system performances evaluation, including energy efficiency and energy saving ratio.

The energy efficiency is defined as:

$$\eta=\frac{P+E_m}{E_{in}} \quad (1)$$

Where P and E_m represent the power output and methanol energy output, respectively. E_{in} represents the energy input of coal.

The energy saving ratio is defined as Eq (2), which represents the energy saving effect of polygeneration system compared to reference systems. In the Eq (2), η_c and η_m present the energy conversion efficiency of corresponding reference system (IGCC and Methanol production system), respectively.

$$ESR=\frac{(P/\eta_c+E_m/\eta_m-E_{in})}{P/\eta_c+E_m/\eta_m} \quad (2)$$

System performance evaluation should consider the comparability between chemical product and power. In other words, comparison between polygeneration system should be carried out under fixed chemical to power output ratio (CPOR). Chemical to power output ratio is defined as total chemical production output (Lower Heating Value) divided by net power output.

4.2 Energy analysis

In this section, energy balance of polygeneration system based on coal-steam gasification and traditional gasification is calculated at fixed CPOR, respectively. From the energy analysis results, the thermal efficiency of the novel system is 53.5%, 8.2% higher than traditional system. The efficiency upgrade is mainly caused by the improvement of cold gas efficiency and elimination of air separation. The elimination of air separation unit reduces 47677.5 kW power consumption, and the improvement of cold gas efficiency results in a higher methanol production output of 26019.6 kW.

4.3 Energy saving ratio

To distinguish the energy saving effect of gasification process improvement and system integration, energy saving ratio are calculated based on different reference systems, the energy saving ratio of the novel polygeneration systems are presented. Through system integration, the ESR firstly rises and then falls with the increase ratio of chemical to power output, resulting an optimal ratio of chemical to power output for maximum

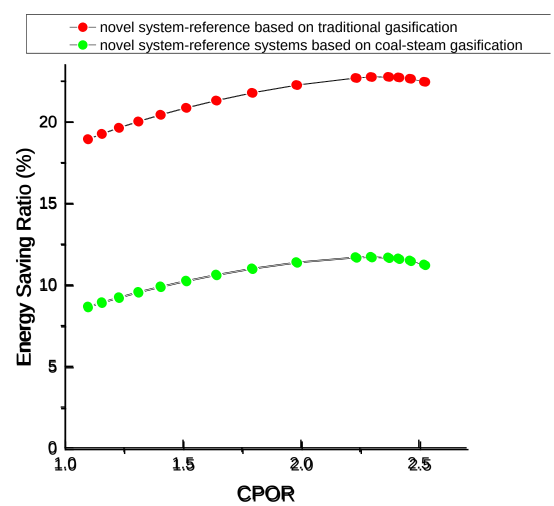


Fig 4 ESR of polygeneration systems based on different individual systems

Table. 2 Energy analysis of polygeneration systems

Item		Traditional System	Novel System
Energy Input	Coal (kW)	821069	821069
Energy Output	Methanol output (kW)	203719.6	229739.2
	Net Power output (kW)	184992.3	209633.7
	Total (kW)	388711.9	439672.9
Energy efficiency		47.3%	53.5%
Utility consumption	ASU (kW)	35435.4	0
	Oxygen compression	12242.1	0
	Pumps	1182.0	839.8
	Mill & fan (kW)	3203.8	3203.8
	AGR (kW)	3072.8	2906
	Syngas compression (kW)	7931.7	6080.7
	COG Compression (kW)	0	8173.4
	Subtotal (kW)	63068	21983.7
Power output	GT (kW)	127345.3	151860.1
	ST (kW)	120715.0	78977.3
	Subtotal (kW)	248060.3	230837.4
CPOR		1.1	1.1

ESR. Furthermore, the synergetic energy saving effect of gasification process improvement are calculated when individual systems based on traditional gasification technology are selected, shown as the red line. the energy saving effect of system integration in the novel polygeneration system is calculated when individual systems based on coal-steam gasification technology are selected as reference systems. Therefore, the energy saving effect of gasification process improvement can be represented by the difference of the red line and the green line.

5. CONCLUSION

A novel polygeneration system based on coal-steam gasification is introduced and studied. As a result, the novel polygeneration system has a higher energy efficiency at CPOR of 1.1, 8.2% higher than traditional polygeneration system. The elimination of air separation unit reduces 47677.5 kW power consumption, and the improvement of cold gas efficiency results in a higher methanol production output of 26019.6 kW. Furthermore, the energy saving effects of gasification process improvement and system integration method are qualitative illustrated respectively.

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