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Total Site Heat Integration of the Coal-Based Synthetic Natural Gas Process

Yang Liu, Siyu Yang, Yu Qian*

School of Chemical Engineering, South China University of Technology, Guangzhou, 510640, China
ceyuqian@scut.edu.cn

China is now boosting coal-based synthetic natural gas (SNG) process for clean energy supply. However, recent studies show that the plantwide energy efficiency is at a low level. One of the reasons is that the Total Site Heat system has not been well integrated. In this work, we develop detail models for the complete flowsheet. Total Site Heat Analysis method is introduced to diagnose and analyse the low energy efficiency. Studies reveal that the low temperature waste heat recovery and heat integration between coal gasification unit and water gas shift unit can provide considerable energy savings. Total Site Profile is constructed to obtain the maximum heat recovery and cogeneration potential at the Total Site level. Site utility system with minimum fuel coal consumption is designed based on mathematical optimization. The results show that the energy conversion efficiency of integrated process improves from 55.6 % to 57.9 %. The production cost will reduce 3.6 % from 1.65 CNY/Nm^3 to 1.59 CNY/Nm^3 without additional investment, which can bring extra 240 M CNY profits for the enterprise.

1. Introduction

Natural gas is a clean and efficient energy, constituting a larger and larger proportion in energy consumption. However conventional natural gas production level could not meet the demand in China, due to the low reserves. To alleviate this situation, efforts have been made to develop coal-based synthetic natural gas (SNG) technology (Yang et al., 2014). As of 2016, three large-scale SNG projects are putting into commercial operation and supplying gas for customers. Moreover, more than 20 coal-based SNG projects have been planned to build in the next five years with capacity of 81.5 10^9 m^3/y (Man et al., 2014).

Coal-based SNG technology converts coal to syngas by a thermo-chemical process via gasification and subsequent methanation for synthetic natural gas production (Yu et al., 2015). The commercial-scale coal to SNG projects in the United States and China are all based on this technology. However, there are still many serious problems in design and operation of the coal to SNG process. One of these problems is that the energy utilization efficient is relatively low. Some researchers mainly focused on energy efficient improvement of unit equipment (Kopyscinski et al., 2010). There is fewer research on the optimization of heat recovery system and site utility system, which consumption accounts for about 30 % of total uses.

Conventional heat integration is usually conducted within the scope of units, while the Total Site Heat Integration is an advance for further energy saving in a larger area termed Total Site (Klemeš et al., 2013). The total site heat integration is composed of two major components, heat recovery system and utility system. In recent years, there have been several successful Total Site Integration studies and implementations involving large petrochemical plants (Chew et al., 2013). However, little study has been done in coal chemical industry. The coal-based SNG process mainly involves reaction process, while distillation is relatively few. This is quite different from the petrochemical process. Consequently, the Heat Integration experience in the petrochemical industry cannot be simply copied to coal-based SNG industry.

In this work, authors developed rigorous process models for all the units involving in the coal to SNG process, and the complete flowsheet is simulated. Pinch analysis method is then introduced to diagnose and integrate for the total site heat system. At last, site utility system with minimum fuel coal consumption is designed.

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2. Process modelling and Total Site Heat Integration

2.1 Process modelling

A general scheme of coal-based SNG process is illustrated in Figure 1. The process consists of four main units: coal gasification unit, water gas shift unit, acid gas removal unit and methanation unit. Coal is fed into the gasifier with oxygen and steam to produce crude syngas. The crude syngas is sent to water gas shift unit, where H_2/CO ratio is adjusted to 3.1 ~ 3.3. Acid gas removal unit is equipped to remove CO_2 and H_2S from the syngas, and the H_2S is sent to Claus unit for sulphur production. The last section of this process is methanation unit. In this unit, sweet syngas with adjusted H_2/CO ratio is reacted to form methane, which is the major component in synthetic natural gas. The capacity of coal-based SNG process is 4 10^9 Nm^3/a. The process modelling and simulation are carried out in Aspen Plus V8.4 software. The simulation for the complete sheet has been discussed in our previous work (Liu et al., 2016).

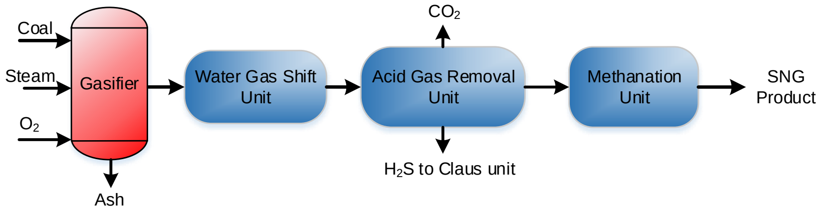

Figure 1: The general scheme of coal-based SNG process

2.2 Total Site heat recovery analysis

The coal to SNG process is composed of different physicochemical processes, so the heat systems are also different. Total Site Profile, constructed from individual unit, is performed for analysing the heat recovery potential across the total site. It gives heat demand in Sink Site Profile and heat surpluses in Source Site Profile (Chew et al., 2015). Heat recovery can be either directly between units, or indirectly through an intermediate medium (Klemeš et al., 2010). Indirect heat recovery by steam is preferred in coal to SNG process, since it offers more operational flexibility and stability. Based on previous industrial practice of SNG projects, the number of steam mains and specifications of them are shown in Table 1.

Table 1: Specifications of steams

Steam conditions	Pressure/MPa	Temperature/°C	Enthalpy/kJ·kg-1
VHP	9.8	540 (overheated)	3,470
HP	4.8	450 (overheated)	3,317
MP	1.6	205	2,790
LP	0.6	152	2,637

The four steam mains are then added to the Total Site Profiles, as shown in Figure 2 (a). The amount of steam used at each steam mains to satisfy the heat sinks and steam generated from the heat source are obtained. The steam generated at any level can be used to provide heating at the same pressure level, or at a lower pressure level via steam turbine with the potential of cogeneration shaft work generation, as illustrated in Figure 2(b). The maximum heat recovery is obtained by maximum overlap between the Source and Sink Profiles.

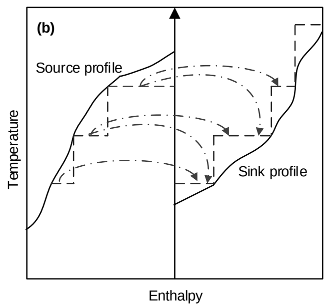

Figure2: (a) Total Site Profiles with steam levels. (b) Total Site Profiles with potential steam heat recovery.

2.3 Site utility system model formulation

The site utility system is equipped to provide heat, power, and shaft work to chemical production processes in SNG project. It consists of boilers, turbines, and other auxiliary facilities. The boilers convert chemical energy of the fuel coal into heat energy, and provide VHP steam. Turbines consume VHP steam to generate lower level steams, power and shaft work. The utility system is configured according to the needs of the entire plant, and its optimal structure can be solved by mathematical programming (Shang et al., 2005). However, the demands vary with the production periods, such as seasonal changes, in the coal-based SNG processes. In this work, a MILP approach for synthesis of utility system of SNG process is developed. This model can be solved with GAMS software.

Objective function: The objective function minimizes the fuel coal consumption:

$$\min f = \sum_{ib \in IB} Q_{ib} \tag{1}$$

Boiler hardware model:

$$Q_{ib} H = (C_p \Delta T^{sat} + q)((1+b) M_{ib}^{B,\max} + a M_{ib}^{B}), ib \in IB \tag{2}$$

Boiler constraints:

$$M_{ib}^{B,\min} y_{ib} \le M_{ib}^{B} \le M_{ib}^{B,\max} y_{ib}, ib \in IB \tag{3}$$

Turbine hardware model:

$$E_{ibp}^{BT} = \frac{5}{6} \frac{1}{B_{ibp}} (EIS_{ibp} - \frac{A_{ibp}}{M_{ibp}^{BT,\max}})(M_{ibp}^{BT} - \frac{1}{6} M_{ibp}^{BT,\max} y_{ibp}), ibp \in IBP \tag{4}$$

Turbine constraints:

$$M_{ibp}^{BT} \le M_{ibp}^{BT,\max} y_{ibp}, ibp \in IBP \tag{5}$$

VHP steam balance:

$$\sum_{ib \in IB} M_{ib}^{B} = \sum_{ibp \in IBP} M_{ibp}^{BT} + \sum_{ic \in IC} M_{ic}^{CT} \tag{6}$$

Steam balance:

$$\sum_{ibp \in IBP} M_{ibp}^{BT} + M_{ibp}^{pro} = M_{ibp}^{dem}, ibp \in IBP \tag{7}$$

Power balance:

$$\sum_{ibp \in IBP} E_{ibp} + \sum_{ic \in IC} E_{ic} + E_{buy} = E^{dem} \tag{8}$$

3. Results and discussion

3.1 Energy saving analysis

According to the simulation, the stream information is listed in Table 2, and the Total Site Profiles of conventional coal-based SNG process is shown in Figure 3a. The Site Source Profile is shown in the left part, while the Sink Profile in the right part. In the conventional process, the site processes supply with VHP and LP steam 680 t/h and 1,400 t/h. The remaining low-temperature waste heat is disposed of cooling air and cooling water. The cooling capacity of -40 °C is provided by the ammonia refrigeration (AR) unit. The system uses MP and LP steam, which can be provided by the source profiles. Figure 3a also shows that the heat released by the system is 1,881.5 MW, while the heat required by the system is only 180.2 MW. The heat released is much higher than that required by the system. It indicates that a reasonable heat recovery is significant for energy saving.

However, current heat recovery practice in the conventional coal-based SNG process does not reach cascade utilization. Amount of low temperature waste heat has not been reused efficiently. The Total Site Profiles indicate that there is still large space to recycle VHP steam. The waste heat (90 ~ 150 °C) released by air cooler (AC) in conventional process can be recovered by Organic Rankine Cycle (ORC) technology to produce power. The conversion efficiency is about 15 %. In this work, the heat system is integrated based on the total site integration method, and the Total Site Profiles of the integrated process is shown in Figure 3b. Compared with the conventional process, there are two improvements in the integrated process: the heat (180 ~ 260 °C) used to produce LP steam in conventional process is used to heat boiler feed water (BFW) of VHP level, while the heat released by methanation unit is used to produce VHP steam. Another improvement is addition of waste heat recovery device to replace the air cooler in conventional process. Base on the efficiency of Organic Rankine device published in the literature, the steam can produce additionally 8.4 MW power.

Table 2: Heat Integration data

Stream	T_S (°C)	T_T (°C)	mCp (MW/°C)	ΔH (MW)
Coal gasification				
H_1	225	181	7.33	645.4
Water gas shift				
H_2	320	175	0.19	25.0
H_3	175	130	2.75	247.8
H_4	130	80	1.60	160
H_5	80	40	0.71	56.4
H_6	-16	-28	2.66	66.4
H_7	84	46	0.76	58.0
H_8	45	41	1.37	10.4
Acid gas removal				
C_1	102	103	146.0	146.0
C_2	143	144	13.40	26.8
Methanation				
H_9	620	350	0.47	340.8
H_{10}	620	480	0.47	176.2
H_{11}	480	382	0.70	183.4
H_{12}	292	170	0.22	70.8
H_{13}	170	155	0.44	17.8
H_{14}	292	170	0.17	54.2
H_{15}	65	40	0.10	7.0
H_{16}	165	70	0.14	35.4

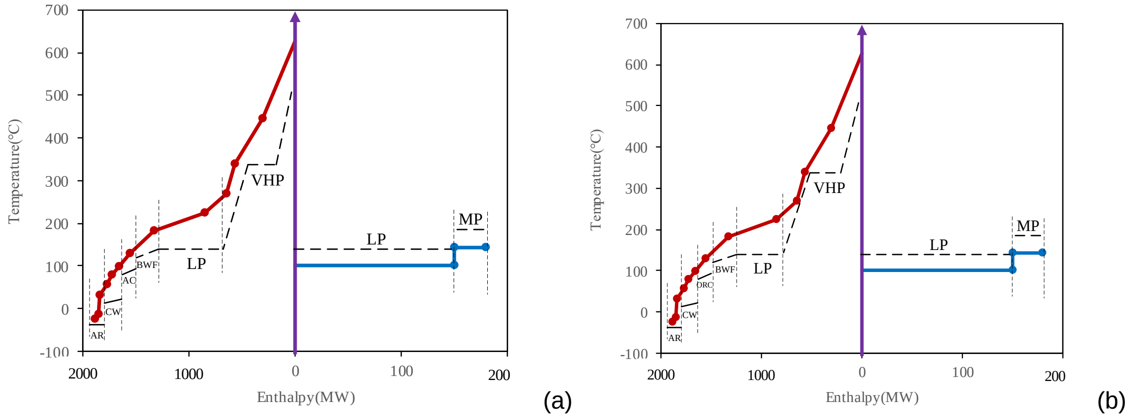

Figure 3: (a) *The Total Site Profiles of conventional process; (b) The Total Site Profiles of integrated process*

3.2 Site utility system implementation

Besides the consumption of heating steam in the coal-to-SNG process, there still needs to consume amounts of process steam, shaft work and electricity. The consumption of heating steam is calculated from total site profiles, while that of process steam, shaft work, and electricity are calculated through simulation. The results are presented in Table 2. In the system, high pressure boiler and the waste heat boiler in methanation unit generates VHP steam. The HP steam is used to gasification agent, which is obtained by means of VHP steam through a back-pressure turbine. At the same time, the MP steam from the back pressure is used in the acid gas removal unit. The LP steam mainly generated from the gasification unit, which can be used to supplying heat for the acid gas removal unit as well as to eliminate the oxygen in thermal power station, deal with waste water, and building heating. While building heating is affected by the seasons, thus the amount of steam used in different production lifetime is different, as shown in Table 2. In the air separation unit and refrigeration unit, amount of shaft work is needed to drive compressors. These shaft work is supplied by VHP pressure steam turbines. Additionally, the electricity consumption is mainly concerned in circulating cooling water pump, high pressure water pump and boiler fan. Part of these electricity is provided by the back-pressure steam turbine and low temperature waste heat recovery device, while the rest is supplied by generator sets. Specially, the plant power consumption is provided by the on-site thermal power stations, thus there need not to purchase electricity.

According to the consumption of steam, shaft work, and electricity of each section from Table 3 and the calculation by Eqs(1) - (8), we obtain the minimum utility system of coal-to-SNG process, as shown in Figure 4. This optimized utility system contains three VHP steam boilers, a steam extraction back pressure steam turbine, a steam extraction turbine, a small gas turbine, and a steam turbine driven compressor. In Figure , the operation load of each equipment in each stage is marked clearly. It is seen that the load of the three boilers in summer is very close to that in winter, which ensures that the boiler runs at a high efficiency in the whole period. Turbine#1 is the extraction steam back pressure steam turbine, where the VHP steam extraction generates the HP steam, then HP steam back pressure to produce LP grade steam. As the small amount of demand of low pressure steam in summer, the steam turbine does not extract steam in summer. Turbine#2 is a back-pressure steam turbine that provides the MP steam to the system. In addition, the system sets up a small generator sets to provide the remaining electricity. This is mainly because the electricity generated from Turbine#1 and Turbine#2 cannot meet the whole electricity demand of the plant. In order to reduce energy loss, one effective mean is to recover all steam condensate and send to the deaerator for recycle use.

Table 3: Steam, shaft power, and power production and command

Item	VHP (t/h)		HP (t/h)		MP (t/h)		LP (t/h)		SP (MW)		POW (MW)	
	pro	con	pro	com	pro	con	pro	con	pro	con	pro	con
Period1	696	0	0	1466	0	490	1064	1064	0	286	8.4	280
Period2	696	0	0	1466	0	490	1064	1476	0	286	8.4	280

SP: Shaft power; POW: power; pro: production; com: command;

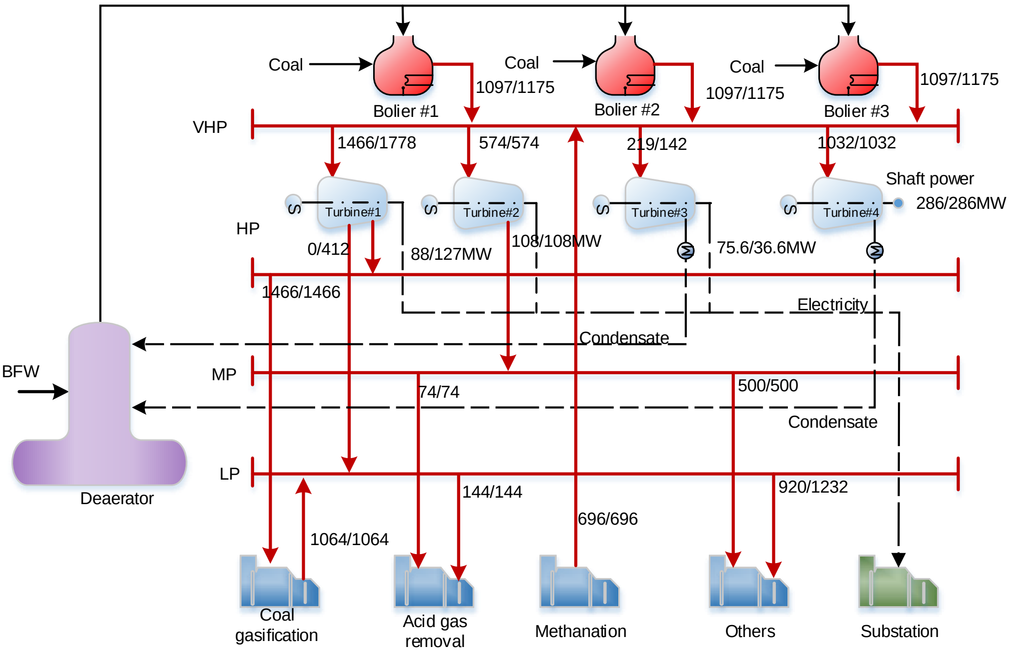

Figure 4: The utility system of the integrated process

Fuel saving is achieved by global energy integration and utility network optimization, as shown in Figure 5a. In the conventional process, the annual consumption of fuel coal is 1.805 Mt/y. In the integrated process, however, the fuel coal annual consumption is 1.574 Mt/y, saving 12.8 %. Due to the energy saving of the system, energy efficiency of the whole plant increases from 56.2 % to 58.7 %. For economic analysis of the optimized utility system, the total investment and production cost of the whole plant are investigated. The results are shown in Figure 5b. The total investment of the optimized process is basically the same as that of the conventional process. In the optimization process, the heat recovery system and utility system are adjusted, and the size of the equipment before and after optimization does not change much, only a set of waste heat recovery device is added. Thus, investment increases little. The utility consumption has a certain effect on the production cost because of the large proportion of the fuel consumption in the utility system. Unit production cost of SNG decreases from 1.65 CNY/Nm^3 to 1.59 CNY/Nm^3. An annual increase of 240 M CNY economic benefit could be achieved corresponding to an annual output of 4 10^9 m^3 of natural gas plant.

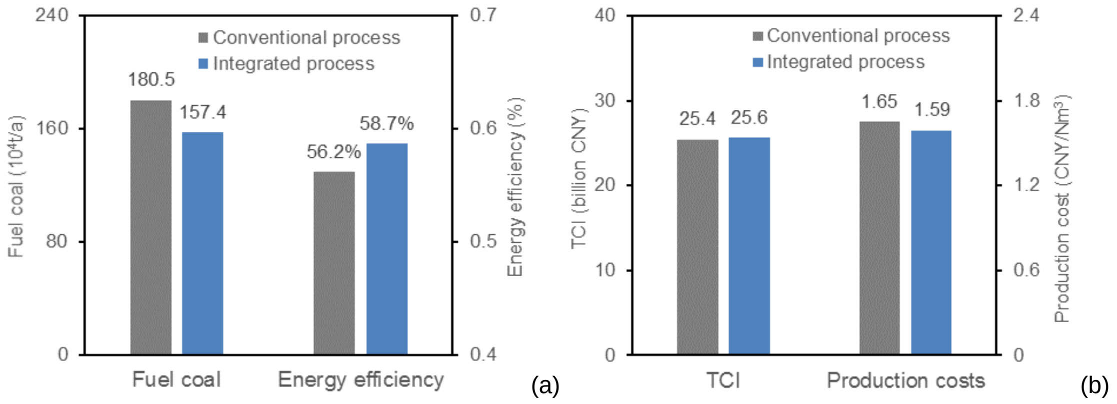

Figure 5: (a) Fuel coal consumption and energy efficiency; (b) Total cost investment and production costs

4. Conclusions

For better energy utilization of coal-based synthesis natural gas process, plantwide energy system is analysed by the Total Site Analysis method. A novel scheme of Heat Integration and site utility structure is presented. Total site heat analysis reveals that there is a potential for heat recovery through the integration of the water gas shift unit and the methanation unit. The integration updates 25 MW heat by the original form of LP steam recovery in the form of VHP steam recovery. The low temperature waste heat could be recovered via Organic Rankine device, to provide 8.4 MW power additionally. The utility system of the integrated process is characteristics of the change of steam demand, and the minimum fuel consumption. Compared to the conventional process, fuel coal consumption of integrated process reduces by 12.8 %, while energy efficiency increases from 56.2 % to 58.7 %. Total investments of the conventional process and integrated process are basically the same. The production cost reduces 3.6 % from 1.65 CNY/Nm^3 to 1.59 CNY/Nm^3, which can bring extra 240 M CNY profits for the enterprise.

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