Effect of Different Gas Turbine on Integrated Gasification Poly-Generation Plant with Methanol and Power Generation

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The present study performed a system-level simulation model for poly-generation applications, based on gasification technology with the commercial chemical process simulator, Pro/II$^{®}$ V8.1.1. There are five major blocks in the poly-generation plant, i.e. air separation unit (ASU), gasification island, gas clean-up unit, combined-cycle power block, and methanol synthetic unit.

In order to simulate the actual situation in Taiwan, the kaltim prima coal (KPC) from Indonesia which is general used in Taiwan was adopted in the study as feedstock. The gasification technology is adopted GE gasifier. In the power block, two gas turbine types of GE 7FB and MHI M501G are considered in the study. The others processes are referred from commercial processes.

Two poly-generation cases are evaluated in the study based on the two gas turbine types. The ratio of syngas delivered to methanol synthetic unit and power block is difference due to the total syngas flow rate from gasification island is kept as constant based on two commercial gasifiers. In the GE 7FB case, the ratio of syngas delivered to methanol synthetic unit and power block is nearly half to half, the CO_2 emission is 265.7 t/h, net system efficiency is 46.1 %(HHV). In the MHI M501G case, the ratio of syngas delivered to methanol synthetic unit and power block is nearly 31 % to 69 %, gross system efficiency is 50 %(HHV) and net system efficiency is 43.5 %(HHV). Although the performance of MHI M501G is higher than GE 7FB, the higher efficiency is obtained in syngas converted to methanol. The lower amount of syngas delivered to methanol synthetic unit decreases the overall system efficiency. The simulated results showed the benefit of the poly-generation plant. The higher efficiency is expected to adopt relative higher efficiency gas turbine in the poly-generation system if the ratio of syngas delivered to methanol synthetic unit and power block is set as the same in the two cases.

1. Introduction

British Petroleum (2012) has reported that the world reserves of oil, natural gas, and coal are 1,652.6 trillion barrels, 208.4 trillion m^3 and 860,938 Mt at the end of 2011, and the reserves-to-production ratio for oil, natural gas and coal are 54.2, 63.6 and 112 y. Fossil fuels still play a major role of energy generation and chemical production in the 21st century. Taiwan is an isolated island and over 99 % of domestic energy demand is dependent on import from abroad. It means Taiwan is higher dependence on fossil fuels. There are several ways to reduce the dependence on fossil fuels, such as renewable energy, multiple fuel supply, alternative fuel, efficiency improvement of fuel utilization, etc. Conversion of solid fuel to gas fuel, liquid fuel or chemical products by adopting gasification technology is a better way to achieve the replacement of oil and natural gas by solid fuel.

Gasification is a manufacturing process that converts carbonaceous solid fuel such as coal, biomass and mixture of them into gas fuel which is called synthesis gas or syngas. The main components of the syngas are CO, H_2, CO_2, H_2O and pollutants. Syngas can be applied to chemical production such as hydrogen and methanol, Fischer-Tropsch (F-T) process to generate synthetic fuels, integrated gasification

combined-cycle (IGCC) process to generate power, and combined chemical production and electricity generation called poly-generation processes (Wender, 1996).

Zheng and Furinsky (2005) built an IGCC model to compare the effect of four gasification technologies, i.e. Shell, Texaco (now GE), BGL, KRW, and three coals, such as bituminous, sub-bituminous, lignite, on efficiency. The results showed that the performance of IGCC plant depends on the type of gasifier and the properties of feedstock. Feedstock properties have a great influence on KRW gasifier. Lignite is more suitable than the others for feeding the KRW gasifier. Kuchonthara et al. (2005) simulated a model of IGCC combined with solid oxide fuel cell (SOFC). They indicated that the system efficiency increases from 39.5%(HHV) without the SOFC to about 45%(HHV) with the SOFC.

Vaswani (2000) built an ASPEN Plus process model for the liquid-phase methanol (LPMEOH) process, and utilized syngas as starting material for methanol production. Kumabe et al. (2008) discussed three process design cases of woody biomass converting to methanol with PRO/II simulator. The better case is a process independent of heat and power for CO_2 reduction in the results of three cases. Chyou et al. (2010) reported a study of CO_2-cycle and energy systems analysis for a coal gasification-based poly-generation Plant. The plant operation is occupied 84.6 % of CO_2 emission in the plant life cycle. The second one is mining and transportation and the value is 13.25 %. Chen et al. (2010) has reported a simulation study of coal converted to methanol and electricity via gasification, and the net system efficiency is 46.42 %(HHV). Chen et al. (2012) performed a simulation study to convert coal to dimethyl ether (DME) and electricity, and the net system efficiency is 46.13 %(HHV). In summary, a poly-generation system is able to produce power, chemical products and synthetic fuels simultaneously or alternatively by employing gasification fed with fossil fuels, renewable biomass and mixture of them.

The purposes of this study are to simulate a poly-generation case, and compared two gas turbine types of GE 7FB and MHI M501G are considered in the study. The evaluated results could be used to propose feasible choices to reduce the dependence on fossil fuels, especially crude oil, in Taiwan, R.O.C. In order to simulate the actual situation in Taiwan, the kaltim prima coal (KPC) from Indonesia which is general used in Taiwan was adopted in the study as feedstock and the ambient temperature is set as 25 °C.

2. Processes description

The five major blocks for the gasification technology shown above are described in the following sections.

2.1 Air separation unit (ASU)
Cryogenic air separation is the most common technology to produce large quantities of oxygen and nitrogen as gaseous or liquid products in the efficient and cost-effective means. A conventional, multi-column cryogenic rectifying process, which produces oxygen from compressed air at high recoveries and purities, is used in ASU. The ASU delivers oxygen with purity of 95 % by volume to the gasification island as gasification agent and nitrogen with purity over 99 % by volume to the combined-cycle block to control the NOx formation

2.2 Gasification island
Gasification technology can convert solid fuel to gas fuel with a useable heating value. The gasifier operates at a high temperature in the range of 800 °C to 1,800 °C. The exact temperature depends on the characteristics of the feedstock (Higman and Burgt, 2003).

Gasification reaction is a partial-oxidation reaction and it is sometimes called incomplete combustion reaction. The main compositions of syngas in the gasification reaction are H_2 and CO. There are three major reaction equations for gasification, which are listed as follows. Eq(1) and Eq(2) are endothermic gasification reactions, to which the heat is supplied from pyrolysis. Eq(3) is the CO shift reaction that can decide the ratio of H_2 and CO in the syngas.

$$C + CO_2 \rightarrow 2\,CO \qquad \Delta h_r^0 = 167 \text{ kJ/mol} \qquad (1)$$

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta h_r^0 = 125.4 \text{ kJ/mol} \qquad (2)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \qquad \Delta h_r^0 = -42 \text{ kJ/mol} \qquad (3)$$

where Δh_r^0 is the heat of reaction at standard temperature and pressure, i.e. 298 K and 1 atm

The ratio of components is decided from the feedstock composition, gasifying agent (oxygen or air) and actual gasification temperature. GE entrained-bed gasifier is adopted to convert coal to synthesis gas (syngas) in this study.

2.3 Gas clean-up unit

The clean-up system includes two parts: sulfur compounds removal and sulfur recovery processes. The sulfur removal process is used to remove H_2S in the raw syngas generated from gasification. In general, ethanolamine such as Methyldiethanolamine (MDEA) is adopted to remove H_2S. Due to MDEA solvent has higher selectivity for H_2S than CO_2, hence, MDEA is a cost-effective choice in the case without handling CO_2. If CO_2 handling is taken into consideration, another solvent named "Selexol" (UOP technology) is better than MDEA (UOP, 2009). In the previous study (Chen et al., 2010), the MDEA was used to remove H_2S. The Selexol technology is instead of MDEA to use in the study, because of the CO_2 capture will be consider in the power block to further reduce CO_2 emission. (Chiu et al., 2012)The sulfur recovery process is used to produce elemental sulfur from H_2S stream which is stripped by steam. The process includes Claus process, Shell Claus off-gas treatment (SCOT) process and combustion of tail-gas.

The molar ratio of H_2S/SO_2 must be controlled to 2 after combusting excess sulfur gas in the Claus process. Then, 1/3 of H_2S is oxidized to SO_2 and generates heat to supply the energy needed from 2/3 of H_2S reacts with SO_2 to form elemental sulfur. The overall sulfur conversion is about 94 ~ 97% in the Claus process.

The SCOT process is used to clean up the tail gas from the Claus sulfur recovery unit, and increase the recovery rate of elemental sulfur. The overall sulfur recovery efficiency can be higher than 99.8% with standard Claus and SCOT unit. The tail gas of SCOT unit contains rare H_2S which can be treated by a burner.

2.4 Combined-cycle power block

The power block employed in the study is combined-cycle which is generally fed with natural gas (NG), i.e. natural gas combined-cycle (NGCC). A combined-cycle is consisted of three major parts which are gas turbine (GT), heat recovery steam generator (HRSG) and steam turbine (ST). For applications in gasification field, syngas rather than NG is used as fuel.

Gas turbine or turbo set consists of an upstream compressor connected to downstream turbine with a spindle and a combustion chamber. Air is compressed via compressor and mixed with fuel in the combustor. The mixture gas is burned in the combustor, then goes through the turbine blades and spins the turbine to drive the compressor and generate electricity.

In general, the temperature of exhaust gas from gas turbine is higher than 500 °C. The best way is to recover the energy to generate steam, which drives the steam turbine for electricity generation. The steam is generated from heat recovery steam generator (HRSG) which consists of evaporator, superheater and economizer. HRSG is a commercial module and can be categorized by a number of ways such as he tdirection of exhaust gases flow or the number of pressure levels. The pressure level can be single pressure or multi-pressure.

Two gas turbine types of GE 7FB and MHI M501G are considered in the study. The main operation data of GE 7FB is shown as follows: turbine inlet temperature is 1,371°C, compression ratio is 18.5, and throughput is 232 MW. MHI M501G could be treated as the next generation of GE 7FB, and has 1,500 °C turbine inlet temperature, 20 compression ratio, and 320 MW throughput.

2.5 Methanol synthetic unit

Methanol is a chemical with formula CH_3OH and often simply abbreviated as MeOH, and major used in three directions, hydrogen carrier, fuel and chemical synthesis (Gallucci et al., 2007). Syngas which consists primarily of H_2 and CO is the first step in the production of MeOH. The LPMEOH process represents a major departure from traditional gas-phase routes to methanol in the method of removing the heat of reaction. The reactions of H_2 and CO and CO_2 to form methanol are highly exothermic. Two main representative reactions in the synthesis of methanol are listed in the following as Eq(4) and Eq(5) Cheng, (1994): and later Heydorn et al. (2003.

$$CO + 2H_2 \rightarrow CH_3OH \qquad \Delta h_r^0 = -90{,}790 \text{ kJ/mol} \qquad (4)$$

$$CO_2 + 3 H_2 \rightarrow CH_3OH + H_2O \qquad \Delta h_r^0 = -49{,}500 \text{ kJ/mol} \qquad (5)$$

The typical operating condition for the LPMEOH process reactor is 50 atm to 100 atm pressure, and near 250 °C temperature.

The production of methanol can be further divided into a series of steps including removal of water to produce dry syngas, methanol production, methanol condensation, unreacted gas recycle, and methanol distillation to desired purity. The purity of methanol in the top product is over 99.9 %weight . (Marion, 1975)

3. Simulation model

Table 1 shows the proximate and ultimate analyses of KPC. The specific features of KPC are low-sulphur and high-carbon constituents.

Table 1: The properties of Kaltim Prima Coal

Total Moisture % as received	10.5		
Proximate Analysis % air dried basis		**Ultimate Analysis (dry ash-free, DAF)%**	
Moisture	5	Carbon	80
Ash	5	Hydrogen	5.5
Volatile Matter	41	Nitrogen	1.6
Fixed Carbon	49	Sulphur	0.7
		Oxygen	12.2
Calorific Value kcal/kg			
Air dried	7,100		
Gross as received	6,689		
Net as received	6,389		

Figure 1 shows the simulation processes flow diagram of poly-generation plant proposed to reduce the dependence on fossil fuels in Taiwan, R.O.C. The commercial chemical process simulator, Pro/II® V8.1.1, was adopted to evaluate the system performance with two gas turbine types of GE 7FB and MHI M501G. The main difference of the two cases is the ratio of syngas delivered to methanol synthetic unit and power block. The ratio in the GE 7FB case is half to half, and in MHI M501G is nearly 31 % to 69 %. The flow rate of feedstock is keep as the same in present study, the higher syngas flow rate is needed in M501G due to it has higher throughput. Thus, the flow rate of syngas should be decreased to balance the mass.
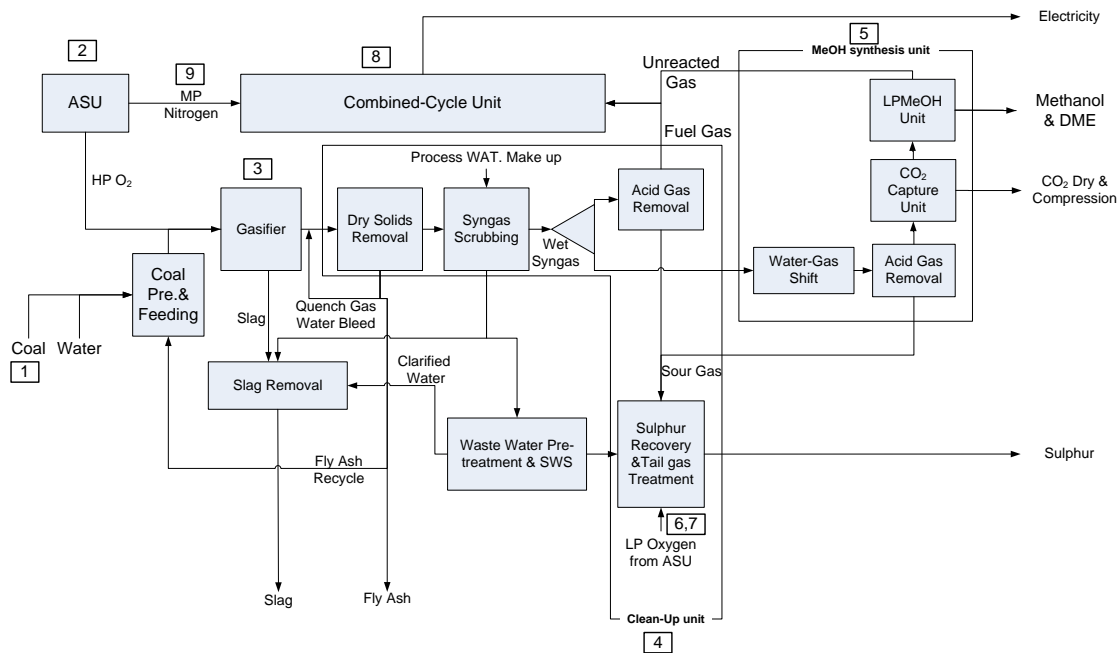

Figure 1: Simulation model of poly-generation plant

Table 2 shows the major blocks and the setting description in the model. The item number could be referred in figure 1. Due to the fact that H_2S concentration requirements in MeOH synthetic unit is higher than the counterpart in gas turbine, the gas clean-up unit employs two trains in the case to meet the requirements. In addition, higher selexol solvent flow rate is set in the MeOH synthetic unit to reach lower CO_2 concentration requirement.

Table 2: Descriptions of major blocks and the parameters setting in the simulation model

	Item	Description
1	Feedstock	Indonesia kaltim prima coal (KPC)
2	ASU	Independent, w/o integrated with gas turbine, O_2 purity 95%
3	Gasification Process	GE quench type gasifier, slurry feed, specified ratio of raw syngas moves to MeOH synthetic unit and the other moves to gas clean-up unit, power block
4	Gas Clean-Up	Raw syngas goes through COS hydrolysis unit and Selexol to remove H_2S
5	MeOH synthetic unit	Specified ratio of clean syngas goes through desulfurization process, CO_2 absorption and MeOH reactor to product MeOH, purity 99.95wt%.
6	Sulfur Recover System	Two stages Claus reactions and SCOT processes, overall sulphur recovery efficiency achieved is above 99%
7	Tail-gas Treatment Unit	SCOT process
8	Gas Turbine	GE 7FB (50 % syngas feed) or MHI M501G (69 % syngas feed)
9	Dilution Agent of NOx Control	N_2, purity 98%

4. Results and discussion

Table 3 shows the simulation results of two cases. Due to the MHI M501G has higher output than GE 7FB. The gross throughputs are 374.83 MW and 509.44 MW in GE 7FB and MHI M501G based combined-cycle, respectively. It also means the higher amount syngas provided to M501G combined-cycle, and the ratio is 69 %. Due to the ratios of syngas moved to the GE 7FB and MHI M501G cases are 50 % and 31 %, respectively. The MeOH production rates are 73.7 t/h and 45.69 t/h in GE 7FB and MHI M501G cases, respectively. As the same results, the flow rates of byproduct DME are 0.2 t/h and 0.12 t/h, respectively.

Table 3: The performances of the poly-generation plant with two difference gas turbine

Item	Unit	GE 7FB case	MHI M501G case
Ambient Temperature (Site Condition)	°C	25	
Coal Flowrate (Dry Basis)	t/h	182.60	
Coal HHV (including Inh. Moisture and Ash)	kJ/kg	31,230	
Thermal Energy of Feedstock (Based on Coal HHV) (A)	MWt	1,584.06	
Ratio of syngas delivered to power block	%	50	69
Gross Electric Power Output of IGPG Complex (B)	MWe	374.83	509.44
Auxiliary power consumption	MWe	110.3	109.61
Methanol Production	t/h	73.70	45.69
Methanol Heating Value	kJ/kg	22,691.60	
Methanol Heating Value Production (C)	MW	464.55	288.02
Net Electric Power Output of IGPG (D)	MWe	262.35	398.83
DME Production	t/h	0.20	0.12
DME Heating Value	kJ/kg	31,681.00	
DME Heating Value Production (E)	MW	1.76	1.06
Gross Efficiency ((B+C+E)/A *100) (Based on Coal HHV)	%	53.1	50.4
Net Efficiency ((C+D+E)/A*100) (Based on Coal HHV)	%	46.1	43.5
CO_2 capture	t/h	92.40	57.29
CO_2 emission	t/h	265.76	366.75

The net efficiency of GE 7FB and MHI M501G cases are 46.1 %(HHV) and 43.5 %(HHV). The reason is syngas to MeOH has higher conversion efficiency than used to generate electricity. Although MHI M501G based combined-cycle has higher efficiency than GE 7FB one, the ratio of syngas provided to MeOH conversion is lower than GE 7FB one. The overall poly-generation efficiency of MHI M501G case is lower GE 7FB one.

Partial amount CO_2 is captured in the MeOH synthetic unit, due to the CO_2 content will affect the synthesis efficiency. It is the additional benefit of CO_2 emission reduction in the poly-generation plant. The CO_2 emission rates of the MHI M501G case is 366.75 t/h, and it is higher than the value of 265.76 t/h in GE 7FB one. If the CO_2 emission is limited in the future, the syngas could be treated to capture CO_2 before delivered to power block.

5. Conclusions

Two poly-generation cases are evaluated in the study based on the two gas turbine types. The total syngas flow rate from gasification island is kept as constant based on two commercial gasifiers. It results the ratio of syngas delivered to power block and MeOH synthetic unit due to the syngas flow rate needed in MHI M501G case is higher than GE 7FB one. The ratio of syngas delivered to MeOH synthetic unit and power block is 31 % to 69 % in M501G case and half to half in 7FB one. It is also effect the system efficiency in the two cases because the MeOH synthetic has higher conversion efficiency than used to generate electricity. The net efficiency of M501G case is 43.5 %(HHV), and slightly lower than the value of 46.1 %(HHV) in 7FB one. The additional benefit of CO_2 emission reduction could yield in the poly-generation plant, partial amount CO_2 is captured in the MeOH synthetic unit. The ratio in the 7FB and M501G cases are 17.38 % (92.4 t/h) and 10.78% (57.29 t/h), respectively.

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