MASS, ENERGY AND EXERGY BALANCE ANALYSIS OF LIGHT OLEFIN PRODUCTION PROCESS VIA GASIFICATION AND METHANOL SYNTHESIS FROM FORESTRY RESIDUES

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ABSTRACT

Process simulation with stoichiometric mass, energy and exergy balance analysis of a pilot bio-light olefin production facility via gasification and methanol synthesis from forestry residues were investigated using Aspen Plus software. The mass yield of the process was 0.127kg light olefins per kg dry feedstock, which was comparable to the current status for biofuel production. 40.7% of potential energy of the forestry residue feedstock leaves as bio-light olefin, together with 2.33% as electricity export. The exergetic analysis of the whole process indicated that 22.6%, 22.2% and 11.5% of feedstock exergy were irreversible lost in the boiler/turbogenerator, gasifier and light olefin separation. And the exergetic efficiency of light olefins was 32.1%. The calculation procedure and balance evaluation criterial presented offered a valuable theoretical basis for improving process performance for bio-light olefin production application.

Keywords: light olefins; forestry residue; energy and exergy; gasification; methanol synthesis

1. INTRODUCTION

To lessen reliance on coal or natural gas and decrease greenhouse gas emission, alternative feedstocks and pathways for light olefin production is under developing[1]. The combination of bio-methanol synthesis with MTO could compensate for light olefin production from lignocellulosic biomass of agricultural and forestry residues, which is carbon-neutral resource[2]. As a result, it is of interest to evaluate the potential feasibility and analysis the performance of biomass-olefin process before industrial application, especially for the relatively mature technology of biomass- methanol -olefin technology(BMTO). Previously, the process evaluation of biomass technology has been widely adapted to the production of bio-ethanol, bio-diesel, bio-FT, bio-oil[3]. The few open literatures on exergy analysis of biomass-to-olefin technology limited its discussion on separate conversion pathway, not the whole process[4].

The main objective of this paper is to present an assessment of a tandem biomass-to-olefin process via gasification and methanol synthesis from forestry residues for exhausting its potential prediction and optimizing performance. The modeling results of mass, energy and exergy balance for each operation unit, as well as the whole process are assessed.

2. PROCESS DESCRIPTION
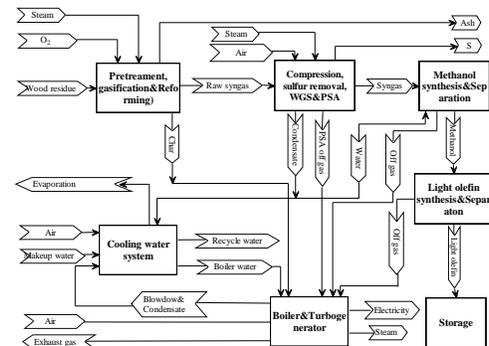
Fig.1 Simplified flow diagram for light olefin production process from agricultural and forestry residues via gasification and methanol synthesis

The simplified block flow diagram of the current design of the biomass-olefins facility can be seen in Fig.1. This process is divided into seven areas. The as-received forestry residue is dried, followed by gasification and gas cleanup. The syngas is then synthesized into methanol prior to the conversion into light olefins. The process design also includes boiler/turbogenerator and utilities, which provide steam/electricity and cooling water for the system.

3. METHODOLOGY

The process simulation was conducted using Aspen Plus software. The process involves several sections, including drying/gasification/ reforming, raw syngas cleaning and composition adjustment, methanol synthesis, light olefin synthsis/separation, boiler/turbogenerator and cooling water system. The model of RStoic,RYield,RGibbs and REquil was used for the section of drying, decomposition, gasification and synthesis respectively. Off gases from light olefin synthesis and PSA unit were combusted to generate high-pressure steam for electricity production to meet the demands of the plant. The condensate from the process, together with make-up water and recycled water from cooling water heat exchangers, was introduced to a cooling water system to determine the requirements of cooling tower.

The feedstock is forestry residues and its properties are summarized in Table 1. Main parameters of the process simulation are shown in table 2.

Table1 Proximate and ultimate analysis of forestry residue

Proximate analysis(%)			Ultimate analysis (%)				
Fixed carbon	Volatile	Ash	C	H	N	S	O
15.3	83.8	0.90	50.9	6.04	0.17	0.09	42.0

Table 2 Main parameters of the process simulation

Items	Paramters
Feedstock	Feed rate: 600t/d(moisture:50%);Water content after drying: 12%
Electricity for O_2 production	0.325 KWh/kg_{O2}（O_2:95vol%）
Gasifier	Temperature:725°C,Pressure: 0.16MPa,O/B:0.12, S/B:0.26
Reformer	Temperature: 850°C, Pressure: 0.15 MPa
Compressor	Pressure: 0.3/1.0/2.0/4.0MPa
Sulfur removal	LO-CAT: 43°C, ZnO: 375°C；Pressure 2.0MPa
WGS reactor	Temperature:350°C,Pressure: 2.0MPa
Methanol synthesis reactor	Temperature:240°C,Pressure: 4.0MPa

Light olefin synthesis reactor	Temperature:400°C,Pressure: 0.4MPa, Light olefin yield: 90%
Combustor:	Temperature:1050°C,Pressure: 0.11MPa
Turbogenerator	Inlet pressure: 5.8/2.0/0.4MPa; Isentropic efficiency: 85%；
Others	Cooling water supply temperature: 32.2°C; Cooling water return temperature 47.8 °C; Air-cooled stream temperature: 60°C; Water-cooled stream temperature: 43°C

4. RESULTS AND DISCUSSION

4.1 Sensitivity analysis

The sensitivity analysis of main operation parameters on process performance was investigated, which was obtained under the condition of S/B=0.26, O/B=0.14, H_2/CO_{syngas}=2.0 and methanol synthesis temperature of 245°C. The generated electricity was sufficient for the plant usage, of which compressor and air-cooling fan were the main equipment of electricity consumption. Light olefin efficiency and total energy efficiency was 40.7% and 43.0% respectively.

System water loss was mainly from the air evaporation in cooling tower by blower.

4.2 Overall mass and energy balances

The overall process balance of mass and energy under optimized condition is shown in Table 3. The energy values are listed as percentages of the forestry residue fed to the process with the light olefin production capacity of ca.10,000tonne/a. The mass yield of purified production of light olefin is approximately 0.127kg/kg dry feedstock. This value is relatively lower than the literature data, deriving from the conservative conversion of syngas in methanol synthesis section(X_{CO}<55%). The air used in cooling tower is ca.22.3-fold of the feedstock, which could attribute to the multiple water-cooling exchangers in the process, such as raw syngas cooling, compressor, off gas cooling from methanol and light olefin synthesis.. That has also caused heavy cooling water duty. Thus, the exhaust air from cooling tower evaporated quite amount of water to lower the temperature of the recycled cooling water, which resulted in relatively high makeup water use of 25615kg/h. Apparently, the low yield of light olefins and high process water use resulted to the high consumptive water usage of 15.87kg/ kg light olefins.

Table 3 Overall mass and energy balance of light olefin production process
via forestry residue gasification and methanol synthesis

Input			Outputs		
Material Streams	Mass （kg/h）	Energy (MJ/hr)	Material Steams	Mass （kg/h）	Energy (MJ/hr)
Feedstock（Moisture: 50w%）	25368	202542	Ash	111	781
O_2-rich gas for gasification	1776	178	Sulfur	17	88
Air for sulfur removal	30	0	Waste water	2409	-6124
Caustic solution for light olefin separation	2908	-6493	Waste caustic solution	3100	-
					2323
Air to combustor	51033	0	Exhaust gas(CO₂, 26.7w%)	77523	7594

Air to cooling tower	565451	0	Evaporation gas from cooling tower	587263	7721
Make-up water	25615	-63543	Light olefins(92% purity)	1756	82341
			Heat from air-cooled exchangers		33482
Process electricity Use		23960	Process electricity generation		28679
Total	672181	156644	Total	672181	152238

The philosophy of defining the energy potential of a stream is based upon the lower heating values(LHV) of each component to remove the background contribution of the water in this context. As show in table 3, the feedstock of forestry residue was the primary energy input. O_2-rich gas and air was also required for gasifier and combustor respectively. The large negative energy flow values for the streams of make-up water and caustic solution were because they entered the process as a liquid, especially for the former. The sum of energy outputs represented greater than 97% of the energy inputs. The unbalanced energy (<3%) was due to ambient heating effects and work efficiency(pump, fan, compressor, et al). The primary energy output was light olefin products. Three of the larger energy outputs came from heat loss from air-cooled exchangers(compressor interstage cooling and shift gas cooling, et al),exhaust gas and evaporation in cooling tower. Together they represent 32% of the energy could not be recovered with the process. The process is electricity sufficient, which generated electricity energy of 28.7GJ/hr with net electricity energy export of 4.72GJ/hr. The electricity energy use is relatively high of 4.12KWh/kg light olefins, primary due to its low yield.
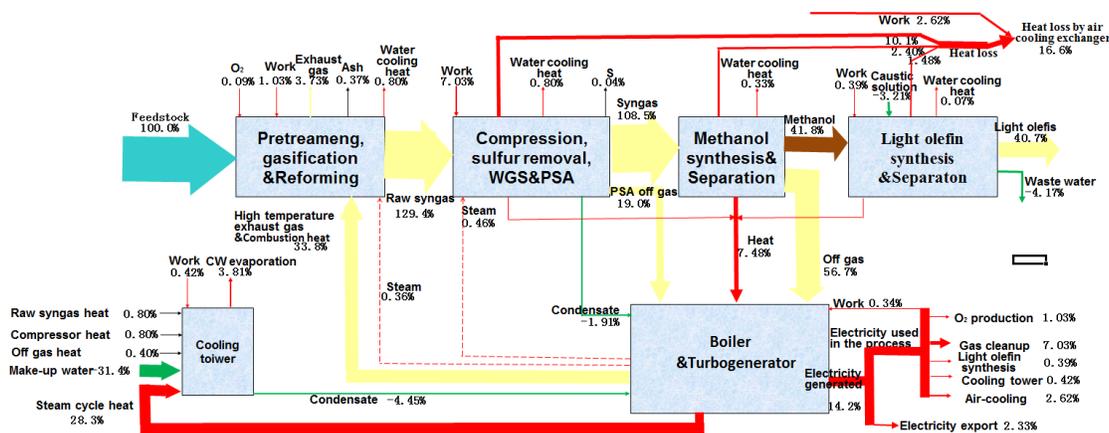
Fig.2 Energy flow of light olefin production process from forestry residues via gasification and methanol synthesis

The overall energy flow for the current design is depicted graphically in Fig.2. The energy values are listed as percentages of the feedstock fed to the process(202.5GJ/h).

Combustion heat and high temperature exhaust gas from boiler had provided relatively high amount of heat(30.1%) for feedstock drying(50%moisture), gasification and reforming. Raw syngas(129.4%), work(7.03%, mainly for compression) and steam(0.46%) enters the section of gas cleanup. While condensate (-1.91%), syngas(108.5%), PSA off gas(19.0%) all exited. And heat loss by air-cooling exchangers and water-cooling exchangers was 10.1% and 0.8% respectively. The former had a larger value because of air-cooled interstage cooling of the compressors and air-cooled cooling duty for PSA inlet. Methanol(41.8%), off gas of methanol synthesis(56.7%) and reaction heat(7.48%) exited methanol synthesis section, which were about 38.5%, 52.3% and 6.89% of the enter syngas energy. The heat of 7.48% mainly derived from reaction heat of methanol synthesis, which was going to the steam cycle that got distributed throughout the process.

The main energy flows entered the boilor/turbogenerator were off gases from PSA and methanol synthesis(75.7%) and reaction heat(7.48%). The exiting energy flows were the generated steam(0.82%), electricity(14.2%), heat for gasification section(33.8%), steam cycle heat to cooling tower for steam condensation(28.3%). The steam cycle heat for steam condensation was relatively high due to the heavy cooling duty of the condenser. The evaporation heat from cooling tower is 3.81%. The 40.7% value listed for light olefin product represented light olefin efficiency and the process efficiency is 43% with the exported electricity. The process energy loss was comprised of cooling tower heat, air-cooling heat and exhaust gas, which represented 24.1% of feedstock energy.

The overall exergy flow for the process is depicted graphically in Fig.3. Then exergy values are listed as

percentages of the feedstock fed to the process(264GJ/h). The overall exergetic efficiency to the process is 33.9%, which is lower than its energy value.

Feedstock(100%), steam(1.49%) and heat exergy from boiler(21.7%) entered the section of gasification, while raw syngas(95.8%), exhaust gas(6.29%) and water-cooling heat exergy(0.13%) exited. Thus the relative irreversibility is 22.2% for the decomposition of solid feedstock to raw syngas. The high exergy loss here is mainly attributed to the severe thermal decomposition of solid forestry residue to small gas component, which had caused intrinsic energy degradation in gasification.
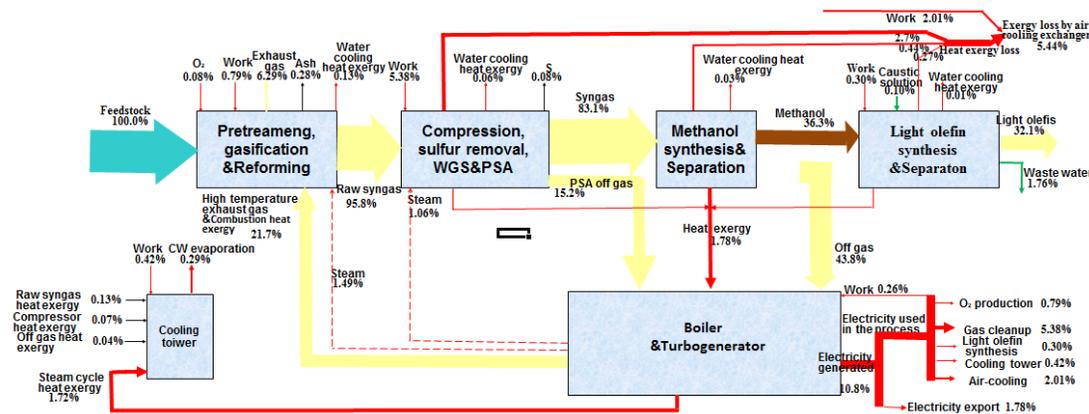
Fig.3 Exergy flow of light olefin production process from forestry residues via gasification and methanol synthesis

Other major exergy losses existed in the section boiler/turbogenerator and olefin synthesis, which was 22.6% and 11.5% of the feedstock respectively. The irreversibility losses from heat exchange of air-cooling and water cooling system were 3.45% and 2.38%. The large exergy loss within the steam cycle is mainly due to the temperature difference for water evaporation, steam expansion and condensation. That had caused the large change of stream entropy for the irreversibility of process energy. A feasible approach might carry out pinch analysis for process heat integration to optimize heat exchanger network. That will be investigated in the following study, together with the optimization of gasification condition for process improvement.

5. CONCLUSION

The design and process simulation of a pilot bio-olefin facility with the capacity of 10,000tonne via gasification and methanol synthesis from forestry residue was investigated. The conservatively conversion design has caused high use of feedstock, water and electricity, which was 7.87kg, 15.87kg and 4.12KWh respectively for per kg of light olefin production. The process was self-sufficient of steam and electricity. The energetic and exergetic efficiencies of biomass-olefin process were 40.7% and 32.1% respectively, without considering small fraction of exported electricity. The major irreversible exergy losses existed in the section of boiler/turbogenerator and gasifier, which was 22.6% and 22.2% 11.5% of feedstock exergy respectively. That

indicated potential improvement of process via advanced gasification technology like chemical looping process and heat network optimization in future study.

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