A STUDY OF CONCEPTUAL PROCESS DESIGN FOR THE PRODUCTION OF AVIATION BIOFUEL IN THAILAND

NANTANA LAMART

A Dissertation Submitted to University of Phayao
in Partial Fulfillment of the Requirements
for the Doctor of Philosophy Degree in Energy Management and Smart Grid Technology
May 2023

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Submitted by NANTANA LAMART

Approved in partial fulfillment of the requriements for the
Doctor of Philosophy Degree in Energy Management and Smart Grid Technology
University of Phayao

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Title: A STUDY OF CONCEPTUAL PROCESS DESIGN FOR THE PRODUCTION OF AVIATION BIOFUEL IN THAILAND
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Keywords: Aviation Biofuel, Gasification, Fischer-Tropsch, Kerosene

ABSTRACT

This research worked on the design to serve as the optimal way scale-up the production of aviation fuel from biomass in Thailand. There were two experimental studies, and each set lab scale and commercial scale with pilot setting. The first experiment used the most purified syngas yields with RWP and EWC as raw materials via the gasification and FT process. Lab Scale worked to determine the optimum temp using in the pilot-scale operation of purified syngas for feeding the FT process to obtain kerosene. The second experiment operated via the catalytic screw pyrolysis process, and waste vegetable oil (waste palm oil, used cooking oil, and animal fat) was the raw material. Experimental result I: The gasification process provided the gas components; 44.65% of H_2, 23.69% of CO, 17.29% of CO_2, 7.54% of CH_4, 6.82% of N_2, and very low level of O_2 and ratio of $H_2/CO=1.88$, which is the suitable range of 1.75-2.25. The results showed the high performance of the $Co/ZrO_2–SiO_2$ bimodal catalyst via the FTS reaction, which provided a CO conversion of 58.6% and a $C_8–C_{16}$ selectivity of 78.8%. The estimation of cost per kg for production of 10,000 kg/d including operating and investment cost was 70.83 baht/kg, while pricing in the market of sustainable aviation fuel (SAF, or aviation biofuel) is $3,800 US /ton or133 baht/kg ($1 = 35 baht). In summary, the horizontal gasifier is an effective designed gasifier that shows high-performance operation. Experimental result II: Waste palm oil, used cooking oil, and animal fat were used as raw material for biofuel production by using dolomite calcined as catalyst (CaO) in a pilot plant. The lab-scale set to determine that the optimal temp.was 425^0C, and a suitable amount of catalyst was 3 wt% for use in the pilot operation. This process provided product yields ranging from 61-69%. The composition in liquid biofuel was composed of naphtha, kerosene, diesel, and fuel oil, in which kerosene shared approximately 21.95 to 23.90%. The estimated cost per kg of AJF (Kerosene) for the production of 800 kg/d, including operating and investment costs, was 34.75 baht/kg. The advantage of this process was lower cost production than the FT synthesis process and vegatable hydrocracking, whereas the disadvantage was only 25% of aviation fuel produced in the total yields. This research results confirmed gasification and FT–process and pyrolysis are the right technology for converting biomass to AJF that provides feasible and utilized messages for investors and support this revenue.

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CHAPTER I

Introduction

Background and Rationale

Since the last couple of decades, biomass has become more prevalent to supplement traditional fossil energy sources as well as a means by which we can decrease carbon emissions around the world, which is believed to contribute to climate change. In various forms of energy, such as fuel for automobile methane, ethanol, or biodiesel, these biofuels can also be used for the whole community supplier as supplemental energy sources.

Thailand is an agriculturally based-economy or agro-economy country. It might also take advantage of the already ready existing products by making it a part of energy production. There are too many sources of byproducts that have the potential to produce energy instead of just throwing away or burning them up. It will lessen the amount of air pollution and give farmers an alternative source of income as well.

At the 2015 Paris Climate Conference, Thailand committed to reducing its greenhouse gas (GHG) emissions by 110-140 million tons of carbon dioxide (CO_2) or 20-25 percent of 2015 emissions by 2030. The 2016 Nationally Determined Contribution (NDC) roadmap plans to reduce CO_2 emissions by 113 million tons by 2030 in the energy and transport sectors. The NDC was translated into Thailand's National Energy Plan (2015 – 2036), also known as the Thailand Integrated Energy Blueprint (TIEB 2015), which was endorsed in October 2015 and aligned with Thailand's11th National Economic and Social Development Plan.

The Ministry of Energy is reportedly reviewing the current TIEB 2015, including the Alternative Energy Development Plan (AEDP) 2015, due to sluggish global price expectations for petroleum and limited feedstock supplies for ethanol and biodiesel. The production of these agricultural crops is far below the target under the biofuel development plan implemented over the past decade.

According to Energy Management, under the Energy Efficiency Development Plan (EEDP), seven core measures are laid out to increase the country's energy efficiency, aiming at reducing final energy consumption (FEC) in 2036 to 30% of the 2010 baseline. The core measures include energy efficiency improvements in industrial facilities, energy-saving housing promotions, efficiency promotions for electric appliances and eco-stickers, mandatory application of the Energy Efficiency Resource Standard, and soft loan provisions for energy efficiency improvements.

In addition, to obtain more benefit for Thailand, " Air travel is booming" , with the number of air passengers set to double over the next twenty years. Aviation demand is particularly evident in the Asia Pacific region and domestic region as well, where growing economic wealth is opening new travel opportunities. Aviation accounts for approximately 15% of global oil demand growth up to 2030 in the IEA's New Policies Scenario (IEA: International Energy Agency), a similar amount to the growth from passenger vehicles. Such a rise means that aviation will account for 3.5% of global energy-related CO_2 emissions by 2030, up from just over 2.5% today, despite ongoing improvements in aviation efficiency. In Table 1, the amount of consumer jet fuel used has gradually increased every year, with an average of 400 million liters per year.

Table 1 Thailand Fuel Use (2009-2018)

	Fuel Use History (Million Liters)									
Calendar Year	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Gasoline Total	7,524	7,418	7,331	7,705	8,233	8,567	9,714	10,680	11,030	11,300
Diesel Total	18,465	18,480	19,192	20,565	20,892	21,071	21,921	22,708	23,265	23,750
On-road	11,080	11,100	11,510	12,340	12,500	12,640	13,153	13,625	13,959	14,280
Agriculture	3,691	3,670	3,840	4,113	4,160	4,214	4,384	4,540	4,653	4,760
Construction & Mining	157	154	160	165	167	169	174	229	233	239
Shipping & Rail	413	415	420	451	513	466	484	454	465	476
Industry	3,124	3,141	3,262	3,496	3,552	3,582	3,726	3,860	3,955	3,995
Heating	0	0	0	0	0	0	0	0	0	0
Jet Fuel Total	4,432	4,712	5,077	5,091	5,562	5,513	6,033	6,468	6,743	7,050
Total Fuel Markets	30,421	30,610	31,600	33,361	34,687	35,151	37,668	39,856	41,038	42,100

Source: Department of Energy Business, Ministry of Energy

A successful alternative energy source should meet the following feasibility criteria (Saini, j k. et al., 2015) 1. It should be readily available. 2. It should be cheap. 3. It should be GHG neutral. 4.It should not pose a threat to food and land availability. The promising biomass feedstock that meets the requirements is municipal solid waste, agricultural waste, and waste vegetable oil. It is a major agro-industrial residue in many countries, such as Brazil, India, China, and Thailand (Fernanda Resende Ribeiro et al., 2017).

This expansion underscores the need for the aviation industry to tackle its carbon emissions. Currently, liquid hydrocarbon fuels such as jet fuel remain the only means of powering commercial air travel. Therefore, along with a sustained improvement in energy efficiency, sustainable aviation fuel (SAF), such as aviation biofuels, is the key to reducing aviation carbon emissions and obtaining more feasible and suitable technology for producing jet fuel to aviation biofuel to reduce the price and ensure a safe environment in virtual reality.

In Thailand, there is a long history of research on alternative energy: sources. The development of bioethanol and biodiesel has been addressed as part of the Royal Projects since approximately 1970; however, energy from biomass is currently from edible biomass such as palm oil and sugarcane. to refrain from competition against the food market, it is preferable to avoid utilizing enable biomass. Thus, Thailand has recently emphasized developing alternative fuels, especially from nonedible resources. However, there are several challenges for dissemination, such as the quality level of biofuel.

Considering these situations, the Government of Thailand (GOT) requested the support of the Government of Japan (GOJ) under the program Science and Technology Research Partnership for Sustainable Development (SATREPS) with the aim of developing the production technology of alternatives to fossil fuels using nonedible biomass waste resources.

On March 13, 2017; a project agreement was signed in Bangkok, Thailand, agreed upon by Chulalongkorn University and the Japan International Cooperation Agency (JICA). The project name is “The Project for Comprehensive Conversion of Biomass and Waste to Super Clean Fuels by New Solid Catalysts” after both parties confirmed on the project description agreed on the detailed planning survey and meeting. Project Sites are Center of fuels and Energy from biomass, Chulalongkorn University in Saraburi (Biomass Center) and Department of Chemical Technology, Chulalongkorn University, Thailand. Beneficiaries are researchers and enterprises related to the project. The period of the project is 5 years (2017-2021). In the 1st two years, machinery, and equipment (horizontal-type gasification bench facilities for catalytic chemical conversion, FT synthesis laboratory test facilities, methanol synthesis laboratory test facilities, and LPG synthesis laboratory test facilities) were installed and ready to start operation in the next step. All machinery and equipment are factory functional designed for a "commercial approach." In July 2019, the first operation was started with a full process, and rubber tree was the material. There are 4 kinds of material for this operation: rubber tree, eucalyptus, cassava root, and corn cob. They are all biomass waste resources that remain inexpensive and can be utilized permanently in Thailand.

Research Objectives

1. Find feasible and suitable process using biomass as raw material for producing aviation biofuel.
2. Design the Conceptual Process Model for the Production of Aviation Biofuel from Biomass in Thailand, which covers the necessary components from the start-up to the end of operation.

Hypotheses

1. The temperature and volume of the catalyst affect the tar reformer, purified syngas, yields from the gasification and FT-process operation, and pyrolysis operation.
2. The gasification and FT-synthesis, and pyrolysis processes for producing aviation biofuel are feasible and can be scaled up for the business industry in Thailand.

Research Schedules

The research schedules were in May, June, July, and August 2020. The collected data for the primary data were related to the raw materials, conversion process, and operation procedure. Secondary data such as fundamental knowledge, biomass resources, literature review and others were obtained before working at the lab experiment at the pilot site. Organized data to perform Conceptual Process Design will be worked along during the lab and after finishing the lab and should be completed in Oct.2021.

Note: The experimental lab schedule at the site for each kind of biomass is as follows.

1. Gasification Process: Running machine for 24 hours for 10 days.
2. FT-Process: Running Process 50 hours and it is approximately 5 days.
3. Pyrolysis screw reactor: Running for 3 days.
4. Cleaning and setting: 5 days.

The Beneficially of this research:

This research will provide high efficiency to many parts. Beneficiaries are researchers and enterprises related to the project. The beneficiaries should be for many sectors as follows.

1. Technology on Producing Aviation Biofuel: Get more maturity way for the process on BtA (Biomass to Aviation Biofuel) and should be confirmed how Biomass can be the raw materials for producing the Aviation Biofuel.

2. Academic Sector: Data will be used in the development process for producing aviation biofuel from various kinds of biomass, which implements the experiment as a feasible and suitable scheme. Furthermore, new proposal about produces Aviation Biofuel more.

3. Business Sector: Businessmen will be the great supporter for all. They will see the opportunity to create on the promised investment for near future trading because aviation biofuel will change the new pace of transportation.

4. Economic Sector: The valorized biomass will help save the environment and create more workers in society supporting this business.

Scope of this Research

Experimental Scope:

The research operation during 2019- 2022 was under the Project for " Comprehensive Conversion of Biomass and Waste to Clean Fuels by New solid Catalysts" for commercial approaches, which received grants from JICA and JCOAL for installment equipment. Reseachers and scientists were from Toyama University (Japan), Chulalongkorn University (Thailand), and JCOAL Co. (Japan). Operation with Pilot Horizontal Rotary Gasifier and used raw materials (rubberwood, eucalyptus, casava roots, and corn cob) for purified syngas feeding

FT-synthsis and expected the productions are LPG, Gasolene, Diesel, and Methanol). Analized data from FT-Process was taken at Toyama University research's team.

Pyrolysis operation is under the project for "Catalytic pyrolysis in a continuous screw pilot reactor" for commercial approach. Waste palm oil, used cooking oil, and animal fat were raw materials for producing liquid fuels.

This research aims for the produce aviation biofuel with used the same data from both operation but focused on kerosene from the experimental yields (composition element) to analized and syntesised which related to aviation biofuel.

Deffinition in this Research

Conceptual Process: This will cover all these criteria.

- How to do this?
- How can the system procedure for making it be set?

Design: Find the optimal best method or best practice for obtaining more feasibility and benefits for "How to?"

Conceptual Process Design: Find out the best practice (Pathway) to obtain feasible methodology, technology on the producing system and "how to" achieve suitable management (direction) in Thailand. Then, the Conceptual Process Design Model will meet extended for Producing Aviation Biofuel 100,000 liter/day.

Production: The derivation from the experimental system - Laboratory operations on the Aviation fuel – Kerosene which can use by aircrafts. (Operation system, Management Process)

Biomass: Rubber wood, eucalyptus, and waste vegetable oil are the biomass feedstock raw materials for this research, and their character is pellet, chip form, and liquid form.

Data:

Primary data: from the Chula Project at the Biomass Center, Saraburi Province, Thailand

Secondary data: Literature review and reports from DEDE sources and others related to the conversion of biomass to aviation biofuel

Analyze Data: Using Data to Design the Model on producing aviation biofuel from biomass 100,000 liter/day properly and suitable in Thailand.

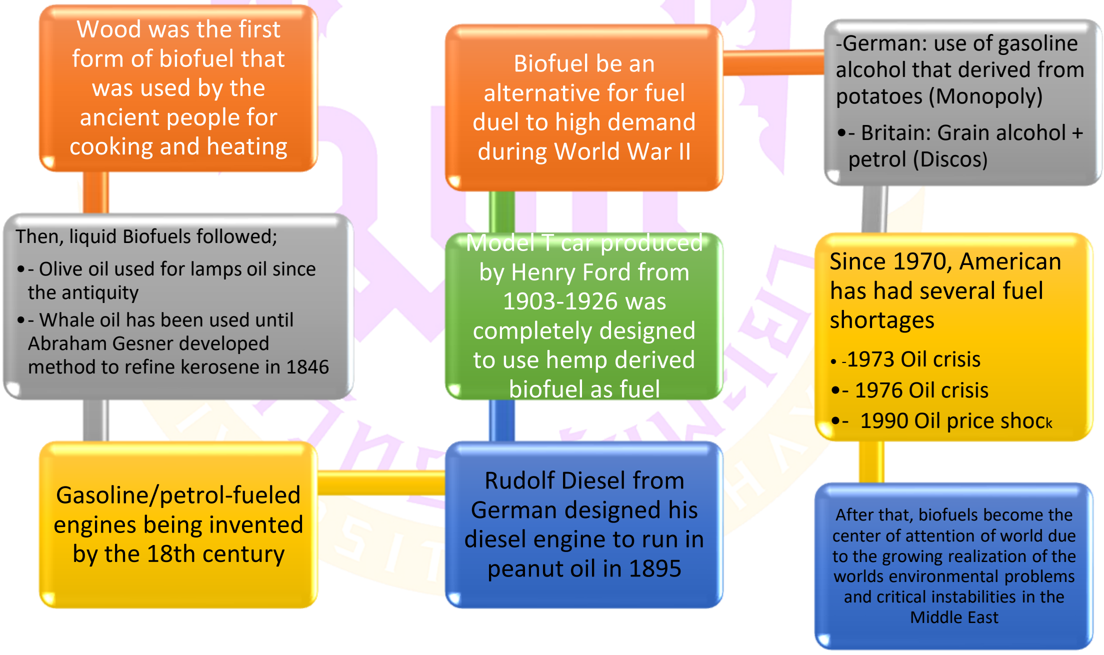
Necessary Components: Elementsrelated to three pillars.There are Environmental Benefits, Diversified Supply, and Economic & Social Benefits: Management, Materials Zoning, Logistics, Cost analysis, Trading effect to economy (price & benefit) and environment, and others to valorization.

CHAPTER II

Theory and Literature Review

Theory and History

Biofuels are the key to mitigating the growth constraints of the aviation industry. Since the petroleum crisis occurred in 1975, the number of fossil–based fuels has become more respected and concerned. The main concern regarding aviation biofuels from biomass is how they differ from biofuels used for ground transportation, such as biodiesel and ethanol. It is important to understand this issue. This section is organized into 2 parts. There are general knowledge, theoretical and practical views, and milestones of aviation biofuels around the globe, especially in Thailand.



Wood was the first form of biofuel that was used by the ancient people for cooking and heating

Then, liquid Biofuels followed;
- - Olive oil used for lamps oil since the antiquity
- - Whale oil has been used until Abraham Gesner developed method to refine kerosene in 1846

Gasoline/petrol-fueled engines being invented by the 18th century

Rudolf Diesel from German designed his diesel engine to run in peanut oil in 1895

Model T car produced by Henry Ford from 1903-1926 was completely designed to use hemp derived biofuel as fuel

Biofuel be an alternative for fuel duel to high demand during World War II

-German: use of gasoline alcohol that derived from potatoes (Monopoly)
- - Britain: Grain alcohol + petrol (Discos)

Since 1970, American has had several fuel shortages
- -1973 Oil crisis
- - 1976 Oil crisis
- - 1990 Oil price shock

After that, biofuels become the center of attention of world due to the growing realization of the worlds environmental problems and critical instabilities in the Middle East

Figure 1 Biofuel History

In spite of the fact that biofuel from biomass has long history and there are the kind of Energy Management for all. Figure 1 shows the development the proper circumstances of feedstocks, technology, designs, and economics for alternative energy.

In 2013, the article about sustainability in Thailand was " An Assessment of Thailand's Biofuel Development." The authors mentioned 1st generation biofuels (ethanol and biodiesel) and second-generation biofuels (ethanol or butanol) that used different kinds of biomass. The details are inTable # 2, and they have discussed the trend to do on commercial scale-up both technology and utilized biomass residues as well. This article did not elaborate on the details of technology in the production process.

Table 2 Biofuel Classification

First-generation biofuels (from seeds, grains or sugers)	**Second- generation biofuels** (from lignocellulosic biomass, such as crop residues, woody crops or energy grasses)
1. Petroleum-gasoline substitutes 1.1 Ethanol or butanol by fermentation of starches (Corn, Wheat, Potato) or sugars (sugar beets, sugar cane)	1. Biochemically produced petroleum-gasoline substitutes 1.1 Ethanol or butanol by enzymatic hydrolysis
2. Petroleum diesel substitutes 2.1 Biodiesel by transesterification of plant oils, also called fatty acid methyl ester (FAME) and fatty acid ethyl ester (FAEE) 2.1.1 From rapeseed (RME), soybeans (SME), sunflowers, coconut, palm, jatropha, recycled cooking oil and animal fats	2. Thermochemically produced petroleum-gasoline substitutes 2.1 Methanol 2.2 Fischer-Tropsch gasoline 2.3 Mixed alcohols
3. Pure plant oil (straight vegetable oil)	3. Thermochemically produced petroleum-diesel substitutes 3.1 Fischer-Tropsch diesel 3.2 Dimethyl ether (also propane substitute) 3.3 Green diesel

In addition, the increase in aviation fuel consumption in Thailand from the DEDE annual report in 2019 and the Thailand EPPO has shown in the 2019 report about the percentages of consumption energy for the transportation sector. Aviation fuel is the highest percentage, increasing to 5.2% , and the factor is reflected in many policies and planning for the economy. The import of aviation fuel is a very high cost for the business. In addition, the number or demand of transport with aircraft is gradually increasing. Not only local air fares but international air fares are not affordable for everyone, and conventional aviation fuel is a limited resource. Thus, aviation biofuel is the right answer for the supportive fast-paced economy in Thailand.

The Department of Alternate Energy Development and Efficiency (DEDE) is a government agent in Thailand that has authority to provide accurate information for alternative energy as needed. Currently, there are no data on producing aviation biofuel with any existing technology or machinery in Thailand. However, biofuel development in Thailand is unlikely to remain noncontentious.

Literature Review

Aviation Biofuel:

Biobased jet fuels also present a tremendous opportunity to transition away from fossil fuels toward domestically produced aviation biofuel that would further reduce U.S. reliance on foreign oil and create jobs, particularly in rural areas, and to advance the mission of the Bioenergy Technologies Office (BETO) for the development of sustainable alternative fuels.

The same results on the substitution of fossil fuels plus the increasing pace of consuming petroleum fuel for transportation sectors such as cars, aircrafts and aviation business are the main concerns for living now and then. The plans of many countries, such as the USA, UK, Europe, and Asia, for the future in 10 yrs., 20 yrs., 30 yrs., and more must focus on renewable energy from different sources that are affordable for all. Biomass has been the 1st choice for conversion to biofuel. Disruptive technologies are precisely merged in the human lifestyle

In addition, the regulation of aviation fuels has been changed since 2011 by the International Air Transport Association (IATA) and provided information to their members via “ BioGuide.” The information is on standard procedures for the use of sustainable aviation fuel (SAF), otherwise known as aviation biofuel and biojet fuel.

This expansion underscores the need for the aviation industry to tackle its carbon emissions. Currently, liquid hydrocarbon fuels such as jet fuel remain the only means of powering commercial air travel. The “main part of the aviation fuel is kerosene”. There are four different aviation fuels:

1. Jet fuel (Jet A-1, kerosene). The fuel type is kerosene. Jet A-1 has a flash point higher than 38°C and freezing point of -47°C.

2. Kerosene-gasoline mixture (Jet B). This kind is used for military jets. This special blend (grade Jet B, also called JP-4) of approximately 65% gasoline and 35% kerosene is low temperature because it is more flammable with a flash point of 20°C, and its freezing point can be as low as -72°C.

3. Aviation gasoline (Avgas) is expensive; there is an increase in diesel fuel and kerosene. Avgas is very volatile and extremely flammable, with a low flash point. Volatility is a term used to describe how readily a substance changes from liquid into vapor.

4. Biokerosene is a fossil fuel and is more expensive. It is based on algae or biofuels from Jatropha and camelina oil or “Solar Jet.” Biokerosene is a mixture of kerosene and biofuels that the aviation industry has been testing for several years in numerous test flights.

The IATA, ASTM, and ICAO are organizations that have authority for controlling aviation business around the globe. Every single aircraft wants to travel to different countries, as International Air Transportation must use biofuel at least 10% to reduce GHG emissions and provide a safe environment. The rules and regulations were announced after the 39th International Conference in 2017 and have been active since then. Now IATA, ASTM, and ICAO have members following their guidelines and rules around the world, including Thailand.

Kerosene/jet fuel:

The kerosene/jet fuel category covers refinery streams and finished products commonly referred to by the generic term “kerosene.” The substances in this category are complex petroleum-derived substances, have a boiling range of approximately 302 to 554 °F (150 -290^{0}C) and a carbon range of approximately C_9 – C_{16}. Kerosene is the lighter end of a group of petroleum substances known as middle distillates, and the heavier end is gas oils. Kerosene may be obtained either from the atmospheric distillation of crude oil (straight–run kerosene) or from cracking of heavier petroleum streams (cracked kerosene). Kerosene can be further treated by a variety of processes to remove or reduce the levels of undesirable components, e.g., sulfur, nitrogen or olefinic materials. This additional processing also reduces compositional variation and enriches components that improve performance (cycloalkanes and isoalkanes).

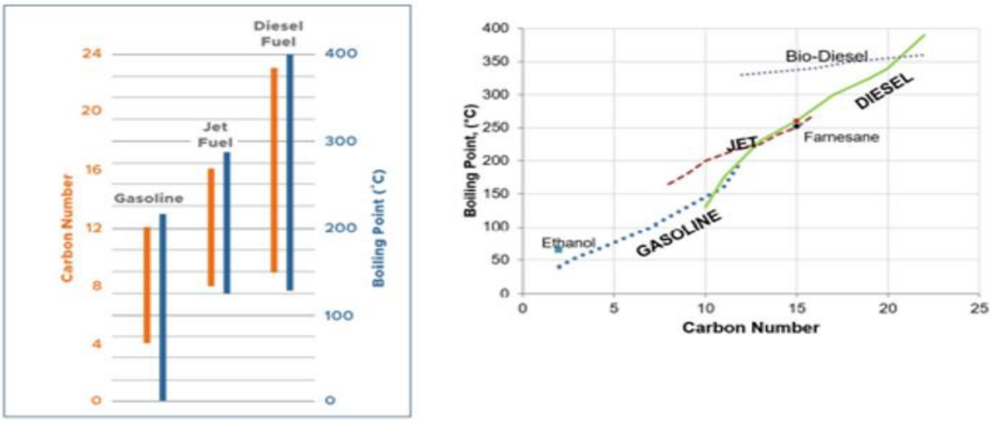


Figure 2 Carbon number and boiling points for gasoline, jet, and diesel fuel (Waste and Biomass Valorization:" Exergoeconomic and Environmental Analysis of a Palm Oil Biorefinery for the Production of Bio–Jet Fuel"

Source: Alisson A, et al., 2021

The guidance from The 39th Session of the ICAO Assembly (International Civil Aviation Organization), held from 27 September to 7 October 2016, adopted Resolution A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection has been prepared to inform ICAO Member States on how sustainable aviation fuels can be deployed to reduce CO_2 emissions from international aviation activities and describes fuel production pathways, usage constraints, environmental and other benefits, and policy perspectives on the use and development of these fuels. It is part of a series of guidance documents developed as part of the capacity-building and assistance project implemented by ICAO, in cooperation with the United Nations Development Program (UNDP), with financing from the Global Environment Facility (GEF). The primary focus of this assistance project is on identifying and facilitating the implementation of measures to reduce CO_2 emissions from international civil aviation. With the support of GEF and UNDP, ICAO is working with SIDS and Developing States to strengthen their national capacities and improve national processes and mechanisms for the reduction of aviation emissions by:

improving the understanding of the costs and environmental benefits associated with the implementation of various mitigation measures for international aviation emissions.

enhancing the policy framework through a series of policy instruments, including the development of guidance documents.

sharing knowledge and resources through an integrated environmental portal, as well as other awareness-raising initiatives; and

developing pilot projects, such as the installation of solar technology at airports, thus equipping developing states and SIDS with tools to carry on similar projects and multiplying their environmental benefits.

The guidance has shown that there are several initiatives in place for research and development of sustainable aviation fuels, which illustrates the fast evolution pace of the SAF industry.

Therefore, the states from the 38th assembly of ICAO regarding aviation fuel have been considered sustainable aviation fuels (SAFs), and they will need to meet sustainability requirements. ICAO is currently developing sustainability criteria as part of the work on the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).

The Assembly also requested states to recognize existing approaches to assess the sustainability of all alternative fuels in general, including those for use in aviation, which should

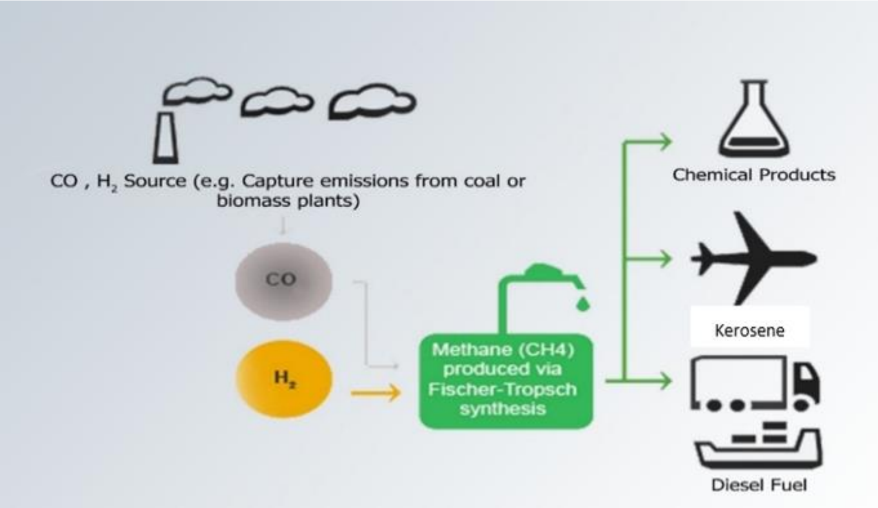


Figure 3 Pathway of Aviation Biofuels

As of May 2016, the American Society for Testing and Materials (ASTM) had certified four different technology pathways to produce biojet fuels. ASTM certification is required before commercial airlines can use fuel for an international flight.

The four pathways are as follows:

Hydroprocessed Esters and Fatty Acids (HEFA biojet), using oleochemical feedstocks such as “oil and fats.” This is the foundation technology, which ASTM certified in 2011.

Gasification through the Fischer - Tropsch method (FT), using municipal “solid waste” (MSW) or “woody biomass” as feedstock. ASTM certified it in 2009.

Synthesized iso-paraffinic fuels (SIP), formerly known as the direct sugar-to-hydrocarbon route (farnesane). Certification came in 2014.

Alcohol-to-jet based on isobutanol (ATJ), certified in 2016.

Beginnings of the FT process

The process was invented in petroleum-poor but coal-rich Germany in the 1920s to produce liquid fuels. The invention of the original process was developed by the German researchers Franz Fischer and Hans Tropschat at the Kaiser Wilhelm Institute. It was used by Germany and Japan during World War II to produce alternative fuels. Germany's annual synthetic fuel production reached more than 124,000 barrels per day in 1944 (from 25 plants, 6.5 million tons)

FT- PROCESS BASICS: Fischer–Tropsch synthesis is a well-known highly exothermic industrial process that allows the conversion of syngas into a mixture of hydrocarbons with low carbon-chain selectivity (C_1–C_{50}) over metal-based catalysts at moderate temperatures and pressures (**). The Fischer-Tropsch process uses hydrogen (H_2) and carbon monoxide (CO) to make different types of hydrocarbons with various H_2:CO ratios.

[**] Steynberg A. Fischer-Tropsch Technology. *Stud. Surf. Sci. Catal.* 2004;152:1.

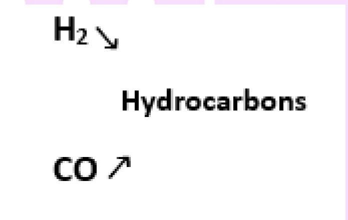


Figure 4 In a CTL facility, H_2 and CO can be supplied from the coal gasifier

Today, the vast majority of currently available commercial volumes of biojet fuels are HEFA biojets, and a number of commercial–scale facilities can produce them. However, the same process also creates renewable diesel. Note that most of these facilities would have to modify their production processto produce jet fuel. (HEFA–diesel), for which there is a larger market and higher sales prices. Producers are therefore focused on this product instead of on HEFA–jet. HEFA–diesel is also known as green diesel or hydrotreated renewable diesel. Two production facilities based on the FT pathway were expected to begin production in late 2016 in the U.S. In total, the operational capacity of the world’s current HEFA facilities is approximately 4.3 billion liters per year. Even if all of this was to be used to make biojets, the supply would still amount to less than 1.5% of the world’s jet fuel requirements.

Although biojet biomass through gasification and subsequent FT conversion is not yet a commercial activity, two facilities are planned. The companies building them are Fulcrum Bioenergy, with a planned production of 37 m L/y of biofuel from MSW and Red

Rock Biofuels, with a planned production of 45 m 1 bln L/y. using wood as the feedstock. Kaidi has proposed a third facility in Finland, with a capacity of 1 L/y. These volumes describe the anticipated total fuel production of each plant, of which biojet would be only one type.

Regarding ASTM certification for standard aviation biofuels from biomass, the FT-syntheses process is one technology that must be performed, and derivation will be the right process for producing aviation biofuels from biomass. The important pathway is the FT-Syntheses Pathway (Figure 4: FT- Process), providing a high yield of kerosene for aviation biofuels.

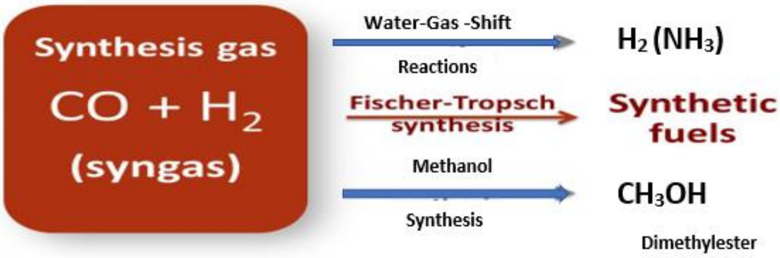


Figure 5 FT Process

The aviation sector uses specific fuels to power aircraft, and these are usually classified as Jet A-1 fuels in most regions. All jet fuel must meet strict specifications, with ASTM providing the most common standards worldwide, including for renewable and sustainable fuels. However, it has been demonstrated during several ASTM certification processes; that certification of a biojet conversion-technology pathway through ASTM can take years and includes rigorous fuel testing and evaluation. The four different advanced technology pathways certified under the ASTM standard D7566 as of June 2016 are briefly assessed below. The FT method uses high-temperature treatment of any type of biomass (such as wood waste, agricultural residues, or municipal solid waste, known as MSW) to produce a synthesis gas, which is then used to generate synthetic hydrocarbon fuels over catalysts. Although this was the first biojet pathway to obtain certification, coal was gasified for jet fuel first, which is termed conventional biojet in this briefing note and includes aviation biofuels derived from the hydroprocessing of oils and fats (oleochemicals) to make HEFA. This pathway accounts for most of the existing biojets. Although several HEFA facilities are currently operating at a commercial scale, they predominantly produce HEFA diesel, not biojet.Only Alt Air Fuels has dedicatedbiojet production capability, partly because of the policy drivers in the U.S. and the state of California and because of the company's off-take agreements with airlines. Other major HEFA producers include Neste (with manufacturing locations in Rotterdam, Singapore, and Finland), Diamond Green Diesel (Louisiana), REG (Geismar, Louisiana), and ENI (Italy). Any HEFA facility that produces biojet also produces HEFA diesel. The other two advanced biojet pathways now certified are SIP and ATJ. SIP biojets are produced biologically through the fermentation of sugars by microorganisms to create a hydrocarbon molecule called farnesene. This is treated with hydrogen to make another molecule called farnesene, which can be blended with petroleum-derived jet to produce a biojet fuel blend. The ATJ route also involves the fermentation of sugars to alcohols, such as ethanol or butanol. These are subsequently upgraded to biojet, as demonstrated by companies such as Swedish Biofuels and Gevo.

Table 3 Effects of five types of synthetic paraffinic kerosene on biofuel

SPK	Production platform	Brief process description
HEFA-SPK	Oil-to-jet	Deoxygenation of oils and fats ⟶ hydroprocessing
FT-SPK	Gas-to-jet	Gasification of biomass ⟶ fischer-tropsch ⟶ hydroprocessing
FT-SPK-A	Gas-to-jet	Gasification of biomass ⟶ fischer-tropsch ⟶ hydrogenation ⟶ increase aromatics content
ATJ-SPK	Alcohol-to-jet	Hydrolysis of biomass ⟶ sugar fermentation to alcohol ⟶dehydration ⟶ oilgomerization ⟶ hydroprocessing ⟶ fractionation
SIP-SPK	Sugar-to-jet	Hydrolysis of biomass ⟶ sugar fermentation to farnesene ⟶ hydroprocessing ⟶ fractionation

Note: Five types of synthetic paraffinic kerosene based on the production platform

Source: Wang, S., et al., 2019

Table 4 Some features of the main routes for the conversion of biomass into Biojet

	OTJ	GTJ	ATJ	STJ
Feedstocks	Vegetables	Lignocellulose, multiple and agriculture residues	Biomass-derived alcohol	Sugars, furanics platform molecules
Reaction step	1.Hydrotreating 2.Fractionation	1.Gasification 2.Fischer-Tropsch 3.Fractionation	1.Dehydration 2.Oligomarization 3.Hydrogination 4.Fractionation	1.Deoxygenation 2. C-C couping 3. Hydrogenation 4. Fractionation
Catalysts	Mostly aluminu-supported metal sulfides	Fe and Co-based supported catalysts	Heterogeneous and homogeneous acid catalysts	A wide range of heterogeneous catalysts
Commercial Readiness	Commercial	Demonstration	Laboralartory – Demonstration	Laboralartory – Demonstration
Minimum selling price ($/Gal)	4.4-5.1	3.9 -4.3	NA	Above 3.5
GHG emissions (g CO_2 MJ)	13 -141	2 -10	NA	15-49
Jet fuel with aromatics	NO	Yes, with FT -SKA	Yes	Yes
ASTM approved fuel	Yes, blend up to 50% h/h with conventional fuel	Yes, blend up to 50% h/h with conventional fuel	Yes, blend up to 50% h/h with conventional fuel	Test Against ASTM but ongoing

Source: Diaz-Pezer and J. C. Serrano-Rulz; Molecules, 2021

The aviation sector requires drop-in biojet fuels that are functionally equivalent to fossil fuel and that are fully compatible with the existing infrastructure (IEA Bioenergy, 2014). Jet fuel is a high-specification fuel that must meet standards as defined in ASTM

D6155 for Jet A1m or by the Ministry of Defense Standard 91-91 in the UK. Biojet fuel must meet these same standards and have an ASTM D7566 certification. In addition to the four pathways that have been certified to date, several others are in the process, such as hydrotreated depolymerized cellulosic jet and green diesel (HDRD or HRD). The ASTM certification procedure is rigorous and can take years and millions of U.S. dollars to complete. The four certified pathways to produce biojet fuels are described here.

HEFA: oleochemical conversion processes, such as hydro processing of lipid feedstocks obtained from oilseed crops, algae, or tallow

FT: thermochemical conversion processes, such as the conversion of biomass to fluid intermediates (gas or liquid) followed by catalytic upgrading and hydro processing to hydrocarbon fuels

SIP: biochemical conversion processes, such as the biological conversion of biomass (sugars, starch, or lignocellulose-derived feedstocks) to longer chain alcohols and hydrocarbons

ATJ: A fourth category includes "hybrid" thermochemical or biochemical technologies; the fermentation of synthesis gas, and catalytic reforming of sugars or carbohydrates for technologies of any type. A technology readiness-level scale is often used to determine the maturity of a technology and its closeness to market.

The Commercial Aviation Alternative Fuels Initiative's fuel readiness level (FRL) scale performs this function for biojet pathways. The scale rates ASTM certified fuels at FRL7 or higher. A recent study by Mawhood et al. (2016) evaluated pathways to biojet against this scale and concluded that HEFA was at FRL9, FT at FRL7 to FRL8, SIP between FRL5 and FRL7, and others in a range from four to six. Based on this scale, the recent ASTM certification of ATJ would give it a rating of FRL7. What these ratings do not capture, however, is the commercial viability of a certain pathway. As noted earlier, the FT biojet was certified based on using coal as the feedstock, not biomass. While the feedstock does not affect fuel properties, it does have an impact on production potential, production cost and technology readiness It will also significantly impact the potential of the fuel to reduce GHG emissions. This leaves questions about the FT pathway, for which certification used coal as a feedstock. This is the closest to commercialization among the advanced pathways based on the FRL classification, but significant challenges still must be resolved if the method is to be useful in meeting emissions-reduction targets. A recent report by France’s Académie des Technologies and Académie de l’Air et de l’Espace concluded that vegetable oil based HEFA biojets are likely to soon be the only economically viable option.

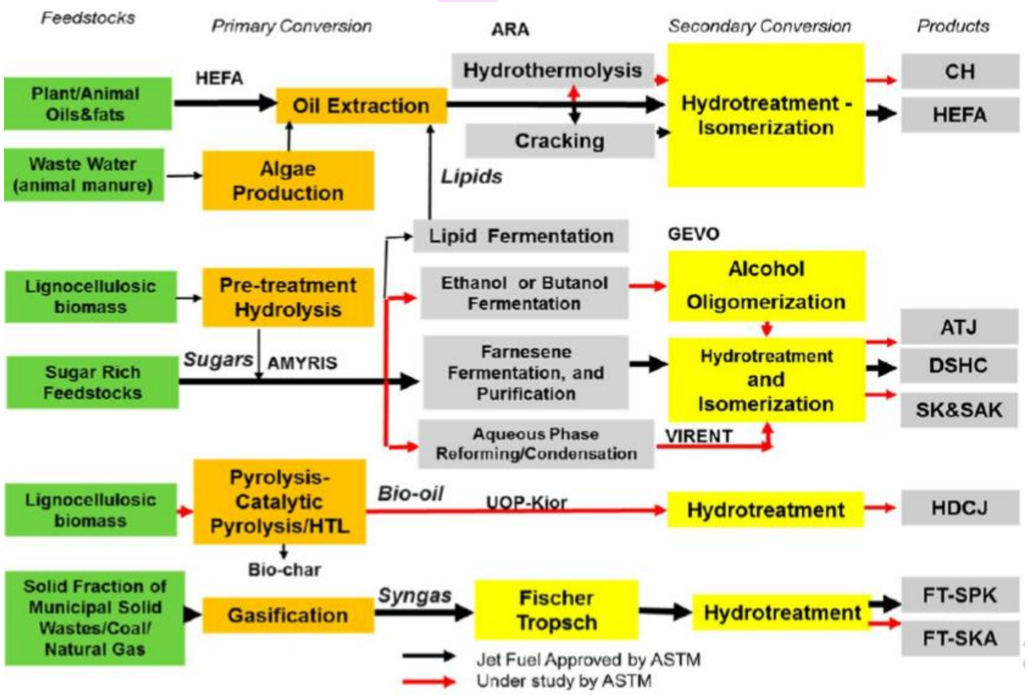


Figure 6 Pathway for the production of alternative jet fuel

Production is the requirement for hydrogen (H_2) to upgrade oxygen-rich carbohydrate, lignocellulosic or lipid feedstocks to hydrogen-rich hydrocarbons that are functionally equivalent to petroleum-derived jet fuel. Thus, some types of hydroprocessing steps will likely be required for most biojet fuel technology platforms, with external sources of hydrogen used to remove oxygen in the form of water from the starting material, or to saturate double bonds in a final polishing step (IEA Bioenergy, 2014). Processes that do not require hydrogen can be used, including chemical and biological processes, but yields will be smaller because of the consumption of a portion of the feedstock.

The major challenges for thermochemical routes to biojets differ mainly in conversion-process efficiency and technology risks, although feedstock choices can also result in qualities in the end product. Thermochemical routes used to turn biomass into biojets involve the production of three main products in different ratios: bio-oil, synthesis gas and char. The two main thermochemical routes to biojets are gasification and pyrolysis, and hydrothermal liquefaction (HTL). The FT process uses gasification combined with synthesis to produce biojets.Several commercial facilities based on gasification and FT- synthesis are planned, and this pathway is discussed in more detail below. The pyrolysis route to the biojet is known as the HDCJ (hydrotreated depolymerized cellulosic jet).

Conversion Technology: Gasification, Pyrolysis, and Fischer-Tropsch Synthesis

Gasification is a process that converts organic- or fossil fuel-based carbonaceous materials into carbon monoxide, hydrogen, and carbon dioxide. This is achieved by reacting the material at high temperatures (>700°C) without combustion with a controlled amount of oxygen and/or steam.

Pyrolysis is a thermochemical treatment, that can be applied to any organic (carbon-based) product. It can be done on pure products as well as mixtures. In this treatment, the material is exposed to high temperature, and in the absence of oxygen, it undergoes chemical and physical separation into different molecules. Decomposition takes place due to the limited thermal stability of the chemical bonds of materials, which allows them to be disintegrated by using heat. Thermal decomposition leads to the formation of new molecules. This allows receiving products with a different, often superior character than the original residue. Pyrolysis has become an increasingly important process for today's industry: as it provides far greater value to common materials and waste. Pyrolysis is frequently associated with thermal treatment. However, in contrast to combustion and gasification processes, which involve entire or partial oxidation of material, " Pyrolysis is based on heating in the absence of air." This makes it a mostly endothermic process that ensures high energy content in the products received. Pyrolysis products always produce solid (charcoal, bio-char), liquid and non-condensable gases (H_2, CH_4, C_nH_m, CO, CO_2 and N). As the liquid phase is extracted from pyrolysis gas only during it is cooling down, in some applications, these two streams can be used together when providing hot syngas directly to the burner or oxidation chamber.

During pyrolysis, a particle of material is heated from the ambient to a defined temperature (setup temperature of Biogreen equipment). The material remains inside the pyrolysis unit and is transported by a screw conveyor at a defined speed until the completion of the process. The chosen pyrolysis temperature defines the composition and yields of products (pyrolysis oil, syngas, and char). The product of " the pyrolysis and gasification process are synthetic gas or syngas."

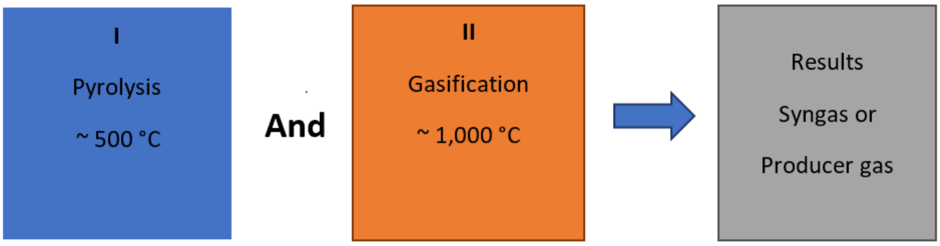


Figure 7 Pyrolysis & Gasification Process

Fischer -Tropsch Synthesis (FTS)

The Fischer–Tropsch process is a collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons. The Fischer–Tropsch process then converts these gases into a synthetic lubrication oil and synthetic fuel. The Fischer–Tropsch process is a collection of chemical reactions that converts a mixture of carbon monoxide and hydrogen into liquid hydrocarbons. These reactions occur in the presence of metal catalysts, typically at temperatures of 150–300 °C (302–572 °F) and pressures of one to several tens of atmospheres. The process was first developed by Franz Fischer and Hans Tropsch at the Kaiser–Wilhelm–Institut für Kohlenforschung in Mülheim an der Ruhr, Germany, in 1925.

As a premier example of C_1 chemistry, the Fischer–Tropsch process is an important reaction in both coal liquefaction and gas to liquids technology for producing liquid hydrocarbons. In the usual implementation, carbon monoxide and hydrogen, the feedstocks for FT, are produced from coal, natural gas, or biomass in a process known as gasification. The Fischer–Tropsch process then converts these gases into a synthetic lubrication oil and synthetic fuel. The Fischer–Tropsch process has received intermittent attention as a source of low–sulfur diesel fuel and to address the supply or cost of petroleum–derived hydrocarbons.

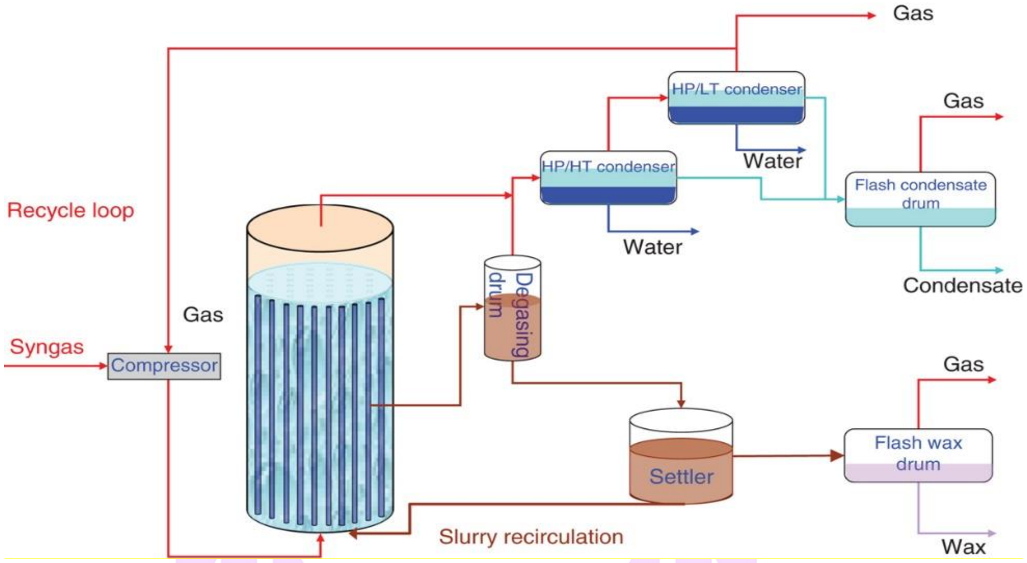


Figure 8 FT infrastructure and production

Source: Robert H. W. et al., 2016

Fischer–Tropsch plants associated with coal or related solid feedstocks (sources of carbon) must first convert the solid fuel into gaseous reactants, *i.e.*, CO, H_2, and alkanes. This conversion is called gasification, and the product is called synthesis gas (syngas). Synthesis gas obtained from coal gasification tends to have a H_2:CO ratio of ~0.7 compared to the ideal ratio of ~2. This ratio is adjusted via the water-gas shift reaction. Coal-based Fischer–Tropsch plants produce varying amounts of CO_2, depending upon the energy source of the lignocellulosic from rubber wood, and eucalyptus wood will be the materials for working in the laboratory.

Standards for renewable jet fuels

In Washington in April 2018, an ASTM International Sub-Committee voted in favor of revising specification D7566 (Standard Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) to include ethanol in addition to isobutanol and to increase the approved blend levels from 30% to 50%, the percentage of alcohol-to-jet fuel allowed when blended with Petro-based jet fuel. These revisions to the D7566 specification will now go to the full ASTM International for final approval, which is expected later in 2018.

To date, five aviation biofuels have been approved to meet ASTM International standards. These aviation biofuels are:

1. Alcohol to Jet Synthetic Paraffinice Kerosene (ATJ-SPK): created from isobutanol derived from feed stocks such as sugar and corn.

2. Synthesized Iso-paraffins (SIP) renewable farnesene hydrocarbon): developed by Total and Amyris, produced by converting plant sugars into farnesene using an 'industrial synthetic biology platform'. In September 2014, Lufthansa made the first scheduled flight in Europe using a 10% blend of farnesene in Germany. In December 2014, Amyris biojet fuel was approved for use in Brazil by the national regulator ANP.

3. Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK): made from vegetable oil-containing feedstock.

4. Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)

5. Fischer-Tropsch Synthetic Kerosene with Aroma

Table 5 Biojet production technologies approved by ICAO. (ICAO CFAAF, 2018)

ASTM D7566 Annex	Abbreviation	Conversion Process	Possible Feedstock	Blending Ratio (volume)	ASTM Qualification
1	FT-SPK	FT-Hydro processed synthesized paraffinic (Syngas to Kerosene)	Coal, Natural gas, Biomass	50%	Sept.2009
2	HEFA-SPK	Synthesized paraffin kerosene produced from hydro processed esters	Vegetable oil and fat, animal fat (tallow) recycle used	50 %	June -2011

		and fatty acids. (Lipid from plants & animal sources)	cooking oil (USO), and algae. Vegetable oil and fat, animal fat		

Table 5 (Cont.)

ASTM D7566 Annex	Abbreviation	Conversion Process	Possible Feedstock	Blending Ratio (volume)	ASTM Qualification
			(tallow) recycle used cooking oil (USO), and algae.	50 %	June -2011
3	HFS-SIP	Synthesized paraffin kerosene from hydro processed fermented sugars	Biomass used for sugar productions (Bagasse)	10%	July -2014
4	FT-SPK/A	Synthesized kerosene with aromatics derived by alkylation of light aromatics from non-petroleum sources. (syngas to kerosene and aromatics)	Coal, Natural gas, and Biomass	50 %	Nov.2012
5	ATJ-SPK	Alcohol-to-jet synthetic paraffin kerosene (through dehydration of the alcohol to olefinic gas, followed by oligomerization to obtain liquid olefins of a longer chain length, hydrogenation, and fractionation.	Biomass used for starch and sugar production, cellulosic biomass for isobutanol production, and ethanol. Category can be expanded to include and C_2-C_5 Feedstock	30% Isobutanol 50% Ethanol	Apr.-2016 for Isobutanol Apr.-2018 for Ethanol

Biofuels in Aviation – Older studies and reports:

A 2003 study by Imperial College investigated renewable alternatives to kerosene, the fuel currently used by jet aircraft. Thus, bioethanol cannot be used for air transport due to its low energy density and because it does not combust effectively in 'thin air' at high altitudes. The Imperial study also concluded that methanol and biogas are unsuitable for air transport for both technical and safety reasons. However, hydrogen, Fischer-Tropsch (FT) kerosene and biodiesel could all theoretically be used in aviation (The Potential for Renewable Energy Sources in Aviation).

The 2007 report published by ETAG (European Technology Assessment Group) for the European Parliament suggested that due to tighter operational and safety criteria for novel aviation fuels, biofuels will predominantly be used in the road transport sector for a feasible future. However, this assessment was made before the successful test flights of Boeing and AIRBUS aircraft and the landmark ASTM Aviation Fuel Subcommittee decision to establish a specification for synthetic aviation fuels (Alternative Technology Options for Road and Air Transport).

In the UK, the Sustainable Aviation strategy group brings together researchers, airlines, and other stakeholders, contributing to a number of key documents proposing a way forward for sustainable air travel. On 10-12 February 2009, the ICAO Workshop on Aviation and Alternative Fuels (WAAF) included 30 presentations, with several covering the use of biofuel.

Michailos S. and Bridgewater A. (2019) They summarized their research on " A comparative techno economic assessment of three bio oil upgrading routes for aviation biofuel production" in the International Journal of Energy Research on 25 July 2019, and the details are as follows. The aviation industry continues to grow, and consequently, more fuel is needed. With the intention of decarbonizing the aviation sector, sustainable routes that have the potential to mitigate emissions, such as biomass fast pyrolysis, can positively contribute to this direction. Within this context, the present study performs a comparative techno-economic evaluation of aviation biofuel manufacture via the main bio-oil upgrading pathways, namely, hydroprocessing (HP), gasification followed by Fischer Tropsch synthesis (G+FT), and zeolite cracking (ZC). This research constitutes the first endeavor to investigate and compare the feasibility of producing biojet fuel via pyrolysis based routes. The presented work provides an inclusive evaluation that comprises process modeling and financial assessment. Based on the simulations, overall energy efficiencies of 48.8% , 45.73%, and 45.38% and jet fuel energy efficiencies of 23.70%, 21.45%, and 20.53% were calculated, while the implementation of a discounted cash flow analysis estimated minimum jet fuel selling prices (MJSPs) of 1.98, 2.32, and 2.21 $/L for the HP, the G+FT, and the ZC, respectively. Sensitivity analysis revealed that the processes are capital and feedstock intensive. while an increase in the bio-oil yield will favor the economic performance of the examined biorefineries. An increase in the plant size from 100 (base case) to 150 dry tons per hour of feedstock will decrease the selling prices by approximately 25% for all cases. Monte Carlo simulations showed that without establishing and/or maintaining appropriate policy schemes, there is no pragmatic prospect for the examined biorefineries to beat the competition against the prevailing oil infrastructures.

Luís A. B. et al. (2016) “Perspectives for Sustainable Aviation Biofuels in Brazil,” in the International Journal of Aerospace Engineering, Research Article Volume 2015. Researchers have studied the potential and possibility of producing aviation biofuels in Brazil. The methodology and collection data were observed and surveyed, and then synthesis data were categorized into the main components of producing aviation biofuel from biomass, feedstock, conversion and refining processes, and sustainability indicators. Logistics of Jet Fuel, the Identified Pathways and R&D Gaps, and the Limiting Factors and Policy Recommendations for Brazil. The summarized-research details are as follows. Substitution of fossil fuels for aviation represents an especially important opportunity for sustainable biofuels, and Brazil has a position of significant comparative advantage in this area and could become a global contributor. There are important challenges to be overcome to create the basis for this new industry in all three segments (feedstocks, refining technologies, and logistics). Only some bioenergy options are sustainable, so fuels should be developed and used by applying strong sustainability criteria and verification to meet the needs of the aviation industry as well as society. Producers of some crops could benefit from more mature agronomic experience, while other crops show good potential but have not yet been put into large-scale production. Based on these arguments, no alternative can be excluded at this stage, justifying a careful screening of the several supply chains available.

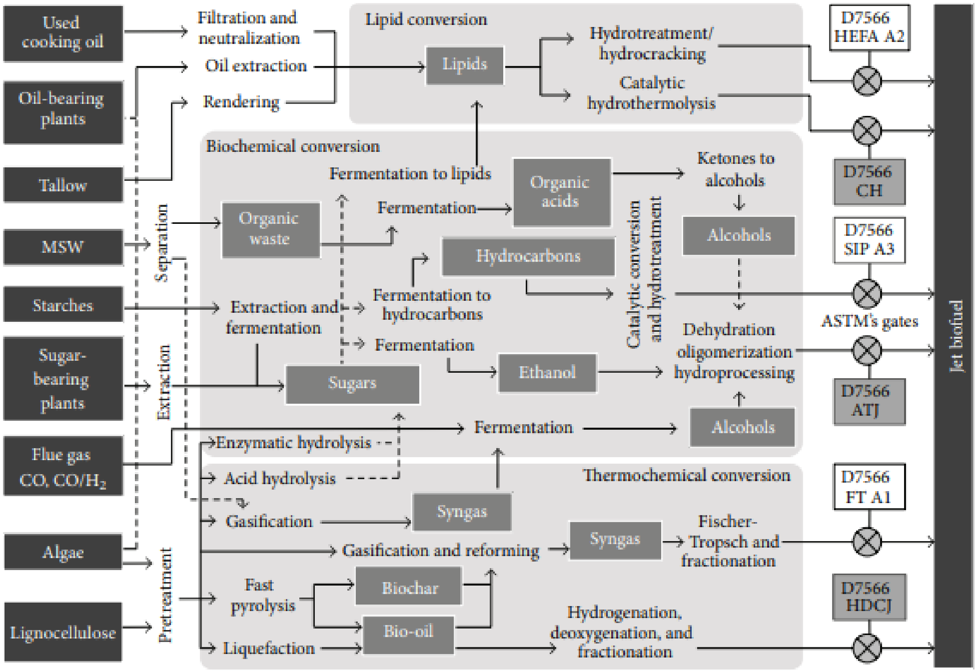


Figure 9 Identified pathways for the production of sustainable jet biofuels in Brazil.

Jie Li, et al., 2016 pp.159–166 The article "Jet fuel synthesis via Fischer–Tropsch synthesis with varied 1–olefins as additives using C/ZrO_2–SiO_2 bimodal catalyst" presents the experimental procedure and results that are more utilized and practical in the aviation industry. The main component for enhancing kerosene yields (C_6 – C_{16}) from the FT process using the Co/ZrO_2–SiO_2 bimodal catalyst worked very well.

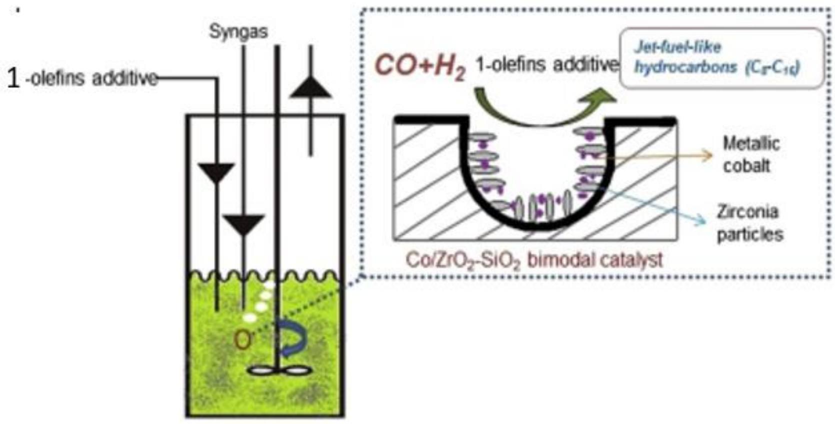


Figure 10 Jet fuel synthesis with the Co/ZrO_2–SiO_2 bimodal FTS catalyst

Figure 9 the research conclusion has shown the benefit yields in the FT process. The obtained 10 wt.% Co/ZrO_2–SiO_2 bimodal catalyst was successfully applied for jet fuel direct synthesis via the FTS reaction with various 1-olefins as additives. The FTS reactions with mixed 1-olefins as additives showed an average product distribution between those obtained with two pure 1-olefins separately for FTS, and the mixed 1-decene & 1-tetradecene as co-fed additives exhibited the highest C_8–C_{16} selectivity of 83.3%. The1-Olefin diffusion efficiency in the solvent of hexadecane, as well as the 1-Olefin concentration and C–C chain growth rate on the bimodal surface played a crucial role in jet-fuel-like hydrocarbon (C_8–C_{16}) direct synthesis via the FTS reaction.

Aviation Biofuel Development in Thailand

In 2009, the results from Thai researchers were reported in “Feasibility study on the Biomass to Liquid for Production of Synthetic Liquid Fuel from Biomass via Fischer-Tropsch Process (Case Study of Thailand)” about technology and process for producing biofuels from biomass should be the Gasification Process and FT – Syntheses Process. They confirmed that various biomasses can be used to convert biofuel. Nevertheless, to scale up this business, biofuels production requires more mature machinery, technicians, operation knowledge and feasible guidelines. In this report, there are many dimensions to using the FT -process, such as awareness of the results fromthe gasification process, which leads to more purification of syngas. There are as follows: 1. % yield of H_2 and CO from Gasification, 2. The ratio of H_2:CO should be less than 2 and 3. Main component gaseous of syngas and toxic gas. Most of the information and data in this research were from the Chemical Engineering Lab. The part is more useful without terminology and fit for the implement on choosing the plant site on producing biofuel which this research can apply for granted. The details are as about.

The following items should be considered when choosing the plant site:

1. Feedstock Proximity: logistic distance < 100 km, cost of biomass, and feedstock supply chain

2. Safety Site from Natural disaster

3. Existing and Plants' Facilities

4. Transportation Infrastructure is eased to work with (Ports, Rail station, proper equipment, and marketing)

There are many conceptual charts and utilized pictures as well. However, this report focuses on producing biofuel from biomass with the technologyof gasification via the FT process. (Figure 10)

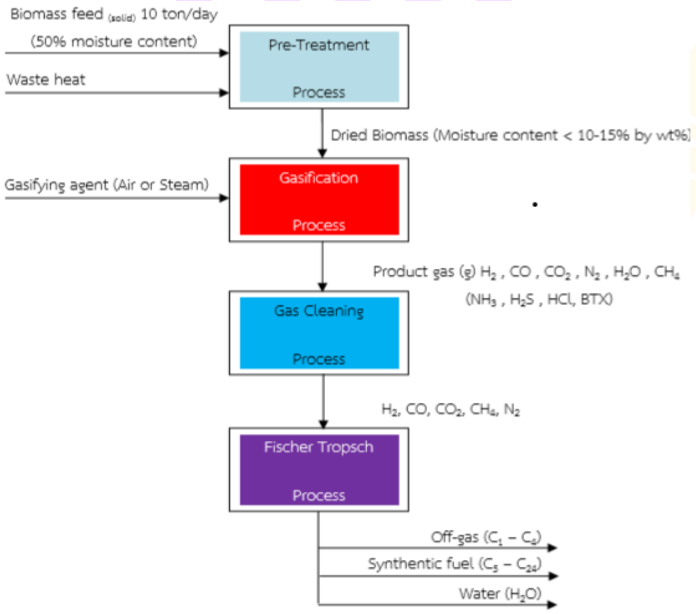


Figure 11 Block Flow Diagram (BFD) of Producing BTL Process

The biofuel in Thailand has been promoted in the news, and Thai Airline used the aviation biofuel only once in 2008, flying from Bangkok to Chiangmai. However, the seminar only once as well on the purpose of Aviation Business supporters in 2011 and details as follows: On 21 December 2011, THAI in conjunction with AEROTHAI, PTT, Airports of Thailand Public Company Limited, Rolls-Royce Company Limited, SkyNRG, and The Boeing Company organized “THAI’s First Flight with Biofuels”. On 22 December 2011, THAI operated “The First Passenger Biofuels Flight in Asia” from Bangkok to Chiang Mai as the first commercial biofuels flight in Asia.

The Thai Aviation and Environmental Workshop – Biofuels and Efficient Flight Operations” on 20 – 21 March at Plaza Atheneee Bangkok, A Royal Meridien Hotel. In addition, PTT' s role in developing alternative fuel and its policy to support aviation environment business has been discussed.

At the experimental pilot site, CU Biomass Center, Saraburi, Thailand; – machinery bench facilities have beeninstalled for the conversion process of biomass to syngas for the yield of aviation biofuels of 100 liters/day. There are 2 sets of machine bench facilities as a commercial type. Step 1 is Gasification & Pyrolysis, and Step II is FT-Synthesis: Syngas Bench Facilities (Figure 11).

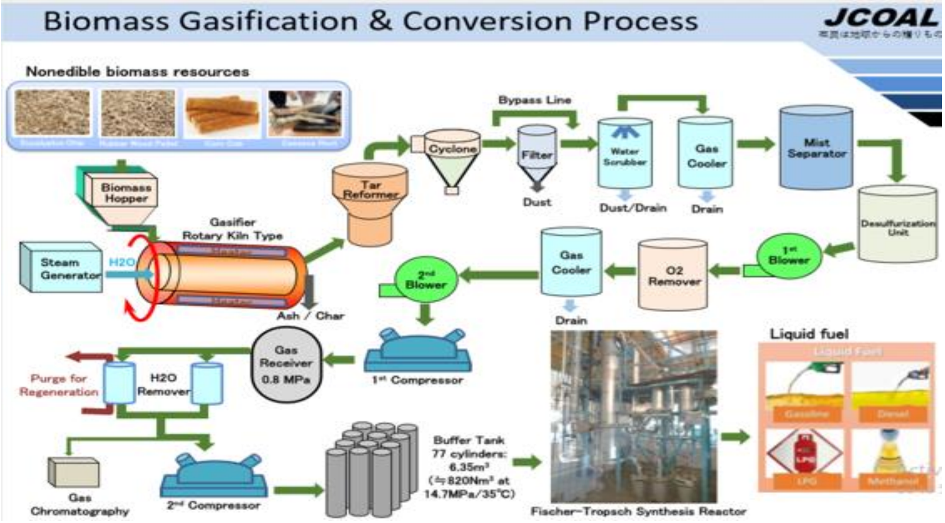


Figure 12 Biomass Gasification & Conversion Process Bench Facility

Tar Formation and Removal Strategies

According to " The End of line or Results" from Biomass Gasification Process should be purified or high yield Syngas which ready to feed to FT – Syngas Syntheses Process. Gasification is a key technology for the conversion of biomass to syngas. It offers high flexibility in using different kinds of feedstock materials as well as in the generation of different products. In principle, all different types of biomasses can be converted by gasification into syngas, mainly comprising hydrogen, carbon monoxide, carbon dioxide and methane. From this syngas, all kinds of energy or energy carriers, heat, power, biofuels, hydrogen, biomethane and chemicals can be provided. Synthesis of Fischer Tropsch (FT) diesel, dimethyl ether (DME), methanol and methane are established technical processes. The use of the available biomass resources needs to be highly efficient and sustainable. The composition and properties of the syngas depend on the biomass feedstock, the gasifier type, and the operation conditions of the gasifier, such as the used oxidant, the temperature, and the residence time in the gasifier.

Tar formation is a main problem in biomass gasification. Tar condensation at lower temperatures can cause clogging or blockage of the pipes, filters, catalyst units or engines. Tar formation also lowers the syngas yield and the heating value of the gas. Tar removal has been the subject of much research leading to the development of primary and secondary measures for tar reduction. Overviews on this topic have recently been given, e.g., by Han and Kim, 2008; by Aravind and de Jong, 2012; and by Shen and Yoshikawa, 2013. The optimal utilization of biomass gasification is requiredto maximize the syngas yield, optimize the gas quality, increase the gas purity, increase the overall process efficiency, and improve the economic viability by decreasing system and production costs.

"Tar" Definition; "Tar" has been operationally defined in gasification work as the material in the product stream that is condensable in the gasifier or in conversion devices. This physical definition covers all the processes shown in Figure 13, although in most uses' "tars" are generally Mixed Oxygenates Phenolic Ethers Alkyl Phenolics Heterocyclic Ethers PAH Larger PAH 400 °C 500 °C 600 ° C 700 °C 800 °C 900 °C (Figure 12). "Tar" maturation scheme proposed by Elliott (1988). assumed to be primarily aromatic. However, this general usage is insufficient for modern gasification technology development because it loses the distinction between classes of compounds that originate under various reaction regimes, such as the primary pyrolysis products that may be in the gasifier effluent because of low-temperature operation or process upsets and high molecular weight polynuclear aromatic hydrocarbons (PAHs) , which are produced under high gas-phase reaction severity and are precursors of particulate matter “soot” (Blackadder et al.; 1994). One goal of this review is to propose a set of definitions for organic residuals in gasifier raw gas and to propose definitions for “destruction” or “conversion” for various contemplated end uses. At this time, laboratory and pilot results on “conversion” are often end-use specific. A goal might be for each study on “tar removal” to have an explicit definition of “tar” and of “conversion” so the results could be extended to other circumstances. This report uses the following starting definition of “tar” throughout: (The organics produced under thermal or partial oxidation in the gasification process of any organic material are called “tars” and are generally assumed to be largely aromatic.) However, newly contemplated applications of gasifier gas, such as fuel cells, may be affected by “noncondensable gases” such as ethylene, cyclopentadiene, and benzene.

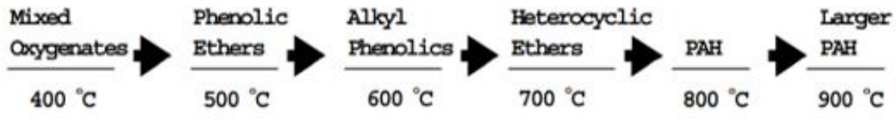


Figure 13 “Tar” maturation scheme proposed)

Note: **PAH = polynuclear aromatic hydrocarbons

Source: Elliott, E.S. 1988

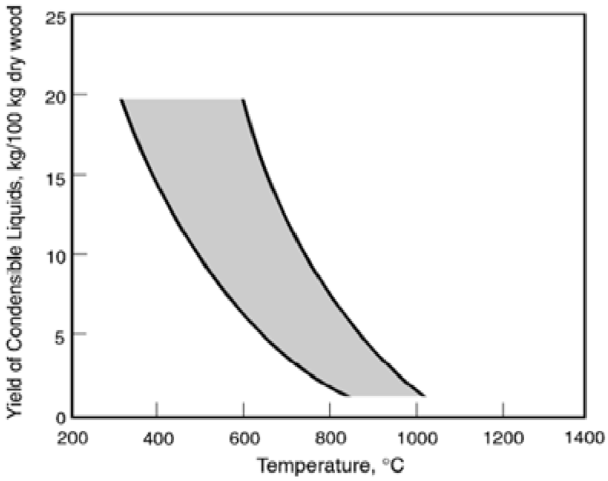


Figure 14 “Tar” yield as a function of the maximum temperature exposure

Source: Kanopoulos N., Vasanthavada N. and Bake R.L., 1988

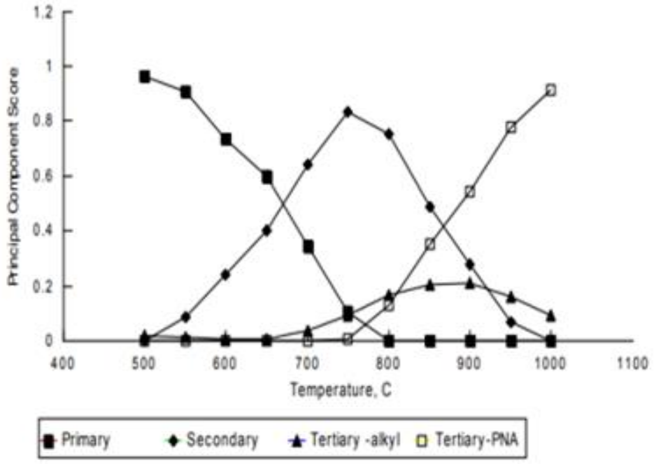


Figure 15 The distribution of th four “Tar” component classes as a function of temperature at 300 ms (0.3 s) gas-phase residence time

Source: Evans and Milne, 1997

Historically " tar" was an operationally defined parameter based largely on organics from gasification that condensed under the operating conditions of boilers, transfer lines, and internal combustion engine (ICE) inlet devices. Such a definition requires a more detailed chemical explanation in light of the greatly expanded uses proposed for both high- and low-energy gas from a variety of biomass and waste materials. At present, the literature contains much data on the "destruction," "conversion," "removal," etc., of "tars," "condensable," "heavy hydrocarbons," etc., without a consistent definition of these terms and a description of the sampling and analytical methods used for the organics of interest.

(BTG 1995b; Kurkela et al. 1995a; Salzmann et al. 1996; Ståhlberg and Kurkela 1990; Brown 1996; Easterling et al. 1985; Techwest 1983; CRE 1997; Delgado et al. 1997).

" Tar" is removed mainly through wet or wet— dry scrubbing. Coalescers, demisters, and cold filtration are also necessary supplements. These well-known commercial methods are easily designed and applied, depending on the specific needs of any gasification process. The main problem arising from "tar" scrubbing is that condensed " tar" components are merely transferred into another phase (water or solids such as scrubbing lime), which then has to be disposed of in an environmentally acceptable manner. The problems associated with the management of these wastewater or solid residues are summarized as follows:

" Tar" and " tar" -contaminated solid-waste streams are considered special waste; consequently, their disposal is usually cumbersome and costly.

"Tar"-bearing wastewater is usually a biphasic mixture requiring various steps of treatment before final disposal.

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“Tar”-bearing wastewater is usually a biphasic mixture requiring various steps of treatment before final disposal.

Most water-soluble “tar” components are refractory to the usual biological wastewater treatments. The applied methods for “ tar” and “ tar” -containing waste streams include solid waste stabilization and landfilling, organic phase skimming off the biphasic wastewater-free surface, wastewater incineration, wet oxidation, adsorption on activated carbon, and final biological treatment. Xi Recommendations: Although chemical (mainly catalytic) conversion of “ tar” at high temperature for eventual use of the gas in gas turbines attracts increasing attention, it is expected that physical removal of “ tar” will continue to be widely used because:

Burners/boilers that are not losely coupled, as well as ICEs, require cold-gas use; it is rather difficult to envision, without serious economic problems, the simultaneous use of high-temperature “tar” conversion reactors combined with cold-gas conditioning modules. Thus, wet or dry gas cooling/scrubbing is the recommended method in such cases.

When high-temperature conversion of “ tar” is usedsome other contaminants (mainly acid gases and volatile alkali metals) remain in the producer gas, which could be detrimental to gas turbines. Thus, cold-gas conditioning, or in-series guard columns, should be used for these contaminants.

Extensive development work in this field is recommended. Government and private funding should be devoted over the next 5 years to improve scientific understanding and technical/technological knowhow on physical “ tar” removal from raw producer gas. This work should focus on the following:

Wet scrubber design for higher efficiencies

Aerosol removal module design and efficiency measurement

Water insoluble “tar” skimming

Skimmed “tar” recycle back to the gasifier; reactivity as a function of the recycle stream nature and quantity; rules for calculating the steady-state conditions

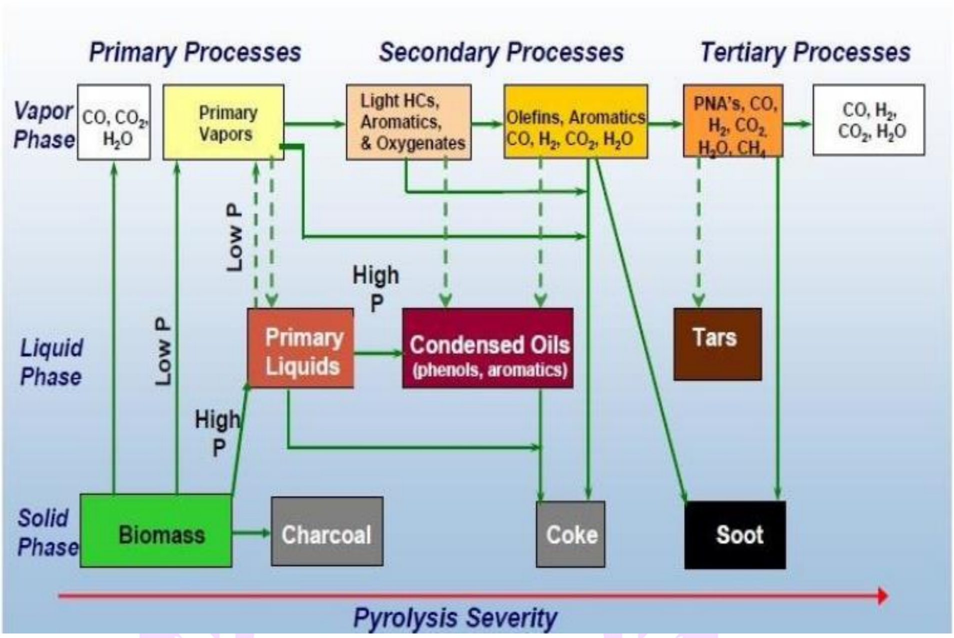


Figure 16 Pyrolysis Pathways

Source: Evans and Milne, 1987

Use of carbon-rich ashes from the gasifier to supplement the adsorption of “tar” on activated carbon; scale-up of bench-scale systems and establishment of design parameters

Optimization of wet-oxidation conditions for treating soluble “tar” containing wastewater. Study and optimization of deep-bed, cold filters for “tar” removal; life cycle analysis.

Catalysts for the Gasification:

Regarding the high yield of the gasification process, syngas is purified by reducing Tar reformation with catalysts. Tar cracking is the method for decreasing Tar in the gasification process by catalyst. There are two types of catalyst cracking: primary catalysts – adding to the feedstock or gasifier and secondary catalysts – adding to the tar reformer in the downstream reactor process. Previous research has used nickel-based materials, olivine, and dolomite for wood or dried raw materials the biomass gasification process. Nickle-based methods are expensive, and more sulfur and coke remain poisoned in the process. Olivine: $(FeMg)_2 2SiO_4$ and dolomite: $CaMg(CO_3)_2$ are natural minerals and effective respectively, in gasification tar cracking. Recently, Dolomite has become more active than Olivine and easier to obtain for use at a low cost. (Morgan, J., 2009) However, nickel-based catalysts have been used in commercial or factory operations and are good as secondary catalysts for more pure syngas in gasification processes.

(Catalytic Gasification of Biomass for the Production of Syngas with Reduced Tar Formation: Dissertation of Lakehead University, Canada)

Arnold, R.A., and Hill, J.M. (2019) have mentioned in “Catalysts for Gasification: a review” in Sustainable Energy & Fuels Journal. The important details are presented in Figure 17. Catalytic gasification is a method for converting carbon feeds to usable products such as hydrogen, carbon monoxide, and methane. This review summarizes the research on potassium, sodium, calcium, magnesium, and heavy metal catalysts, the interactions between these catalysts and other species in typical feeds, and gasifier design considerations.

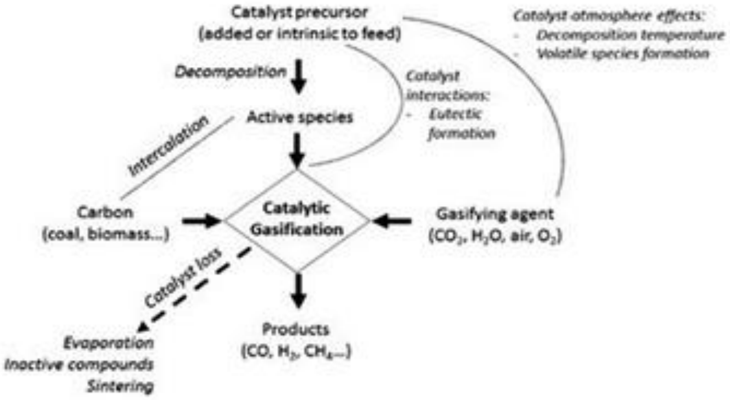


Figure 17 Catalyst Performance for the Gasification Process

Actually, the function of catalyst agent of each kind for conversion biomass to aviation bio jet is very necessary in the process either Gasification or Pyrolysis.

The main concern of biomass conversion by the gasification process is feeding to the FT-synthesis process. The purified syngas must be without tar and sulfur. That is the reason to operate to reduce Tar and Sulfur in the system under controlling Temp as at 900^0C, cleaning Tar at Scrubber, Cao as catalyst, and desulfurization kept Sulfur. The details of the operation process and functioning of each tool will be elaborated in Chapter III...Next.

Biofuel from pyrolysis of waste vegatable oil

Waste oils, such as waste cooking oil inexpensive and abundant sources of carbon (Maryam Moghadam et al, 2020). It is estimated that approximately 74 million liters of waste cooking oil and 0.25 million tons of waste palm oil were produced globally in 2020 in Thailand (EPPO). However, the direct use of waste oils as fuels is not appropriate due to undesirable properties such as high viscosity, low volatility, and high acidity, which cause cooking and carbon deposition in the injector or engine corrosion (Kraiem et al., 2017). Transesterification of waste oil with methanol was propularly commercialized to solve the problems, but this process creates undesired byproducts such as glycerin and wastewater.

Another interesting technique pyrolysis or thermal cracking by breaking chemical bonds without oxygen conditions, has been studied as the most promising waste disposal technology and the best energy recovery method due to its feedstock flexibility, nonrestrictive conditions, high conversion efficiency, limited environmental impact, and compatibility with available engines and fuel standards (Su et al., 2021).

Pyrolysis requires enough thermal energy to break chemical bonds in waste oil. The specific high temperature and reactor design allowing heat and mass transfer are considered. There is a restriction that both low heat and mass transportation induce the production of biosyngas and char. The various reactor configurations play a role in different heat and mass transfers, which affect the energy efficiency, product properties, economic benefits, and environmental impact [Hasan]. Generally, the studied process is batch and continuous, and the catalyst is fixed in the reactor.

In general, there is approximately >20% kerosene in (aviation biofuel) the liquid product from vegetable oil pyrolysis, which the remaining was naptha, diesel and fuel oil. The aviation production from this process requires kerosene separation, which is added as an expenditure, but it will be compensated with a lower cost of operationcompared to FT and hydrocracking. Therefore, this pyrolysis process is another interesting process for aviation biofuel production.

CHAPTER III

Methodology and Technology

Methodology

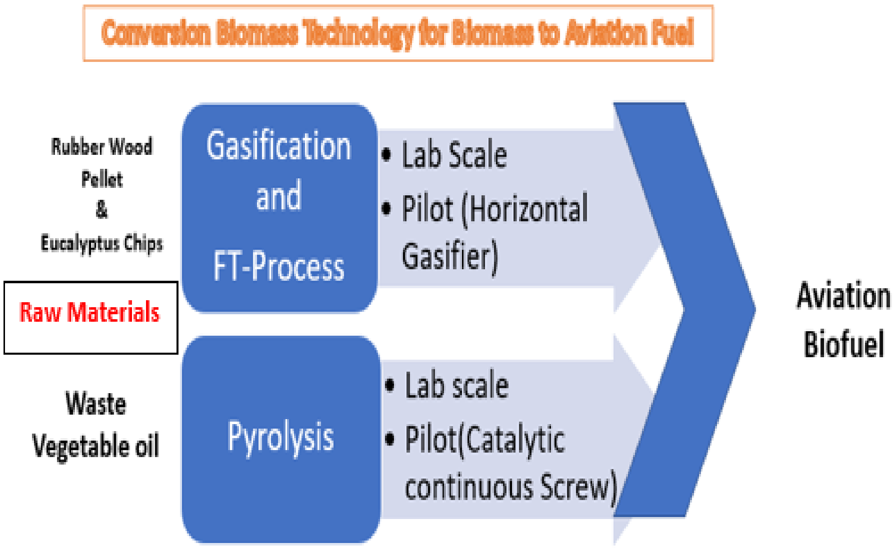


Figure 18 Conversion Biomass Technology for Biomass to Aviation Fuel

This research is about "A Study Conceptual Process Design for the Production of Aviation Biofuel in Thailand." It means this study will be reflected in the pathways on the process of producing Aviation Biofuel via the FT synthesis process from biomass – rubber wood pellets, eucalyptus chips toward the end line which are related to it such as inclusive economic benefitsand other components. In addition, another possible process was proposed. The pyrolysis of waste vegetable oil such as waste palm oil from palm crushing mill factories and used cooking oil.

The raw material for the biojet product in this research was rubber wood pellets, eucalyptus chips and waste vegetable oil. These raw materials were divided into two types of- original structures. Rubber wood pellets and eucalyptus chips are made of lignocellulose, whereas waste vegetable oil is made of triglycerides. The different structures of raw material are used to produce biojets by different reactions. The lignocellulose material will be gasified to obtain syngas followed by FT synthesis, and this process was approved and used in industrial plants by using syngas from coal or natural sources as raw material. While triglycerides could not be gasified to produce proper syngas.

Aviation biofuel via gasification and FT synthesis processes

The research methodology will be elaborated on these opponents: raw materials, conversion technology and others that are more feasible, benefit and facilitate sustainable environmental development and energy management in Thailand. The conceptual process design model will include implementation on scale-up to 100,000 liters per day from 100 liters per day of aviation biofuel in the experiment at the pilot site.

Materials: Biomass - Rubber wood and Eucalyptus will be the raw materials for use in this operational process in pellet form and chip form.

Figure 19 Raw materials –Rubber wood pellets and Eucalyptus chips

Feedstock is Rubber wood and Eucalyptus; Pretreatment is a pellet 2-3 cms; eucalyptus is formed as chips with the size as 2-3 cms as well.The conversion processes are a gasification then Fischer-Tropsch synthesis reactor. Rubber wood which has formed in pellets, and Eucalyptus, which has formed in chips, will be used as biomass feedstock in the process of converting biomass to syngas via a two-step process:

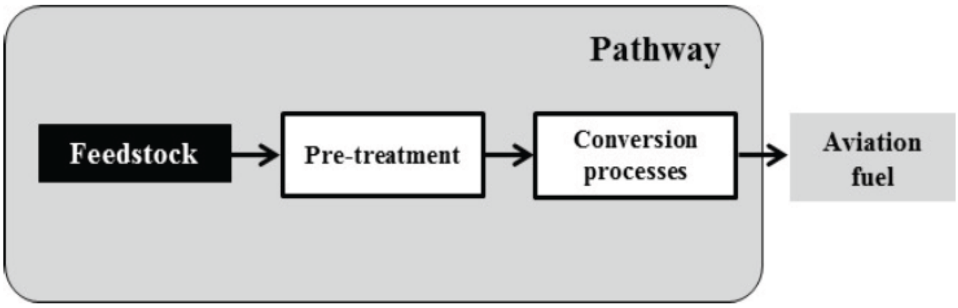
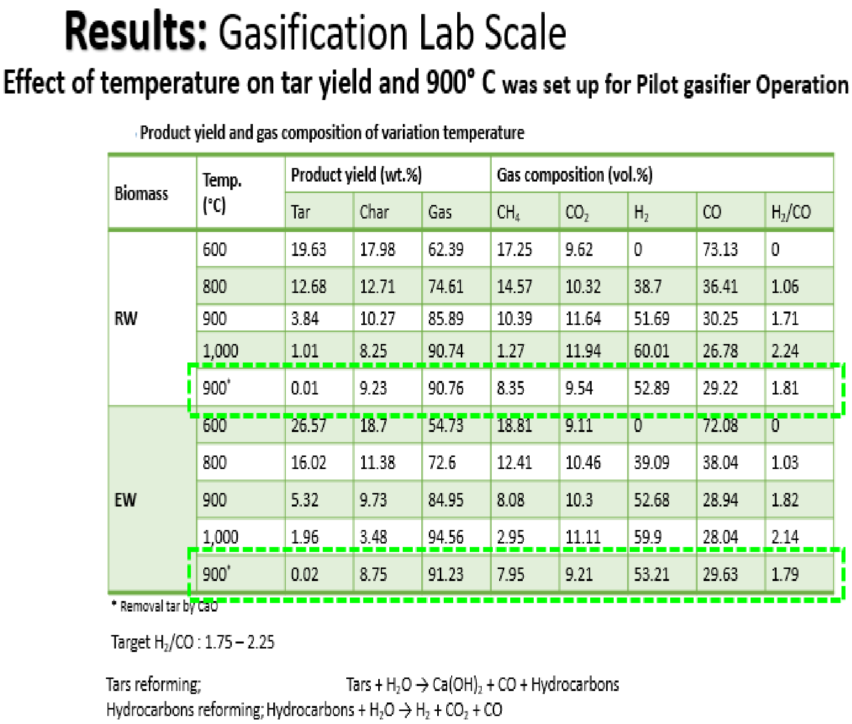


Figure 20 SAF pathway concept

1. Experimental Procedure: There are two parts of the experimental procedure.

Gasification Process with Lab - Scale

It was operated with a " Bench scale or Lab – scale customized gasifier for determining the right temperature" among 600°C, 700°C, 800°C, 900°C and up to 1000°C with excess after vapor and conducted in a fixed bed gasifier. The powders of rubber wood and eucalyptus were used as raw materials. Ten grams of biomass was added to the biomass storage, which was placed on top of the gasifier outside the heater zone. When the temperature reached the desired level. The valve of biomass storage was opened, and biomass dropped inside the gasifier immediately while steam was fed with cocurrent flow with biomass. The gas product was collected in a gas bag and analyzed by GC-TCD. Tar from the experiment was collected by a series of ice traps to confirm that all tar was absolutely condensed. Tar collected in ice traps and biochar were weighed.



Results: Gasification Lab Scale

Effect of temperature on tar yield and 900° C was set up for Pilot gasifier Operation

Product yield and gas composition of variation temperature

Biomass	Temp. (°C)	Product yield (wt.%)			Gas composition (vol.%)				
		Tar	Char	Gas	CH_4	CO_2	H_2	CO	H_2/CO
RW	600	19.63	17.98	62.39	17.25	9.62	0	73.13	0
	800	12.68	12.71	74.61	14.57	10.32	38.7	36.41	1.06
	900	3.84	10.27	85.89	10.39	11.64	51.69	30.25	1.71
	1,000	1.01	8.25	90.74	1.27	11.94	60.01	26.78	2.24
	900*	0.01	9.23	90.76	8.35	9.54	52.89	29.22	1.81
EW	600	26.57	18.7	54.73	18.81	9.11	0	72.08	0
	800	16.02	11.38	72.6	12.41	10.46	39.09	38.04	1.03
	900	5.32	9.73	84.95	8.08	10.3	52.68	28.94	1.82
	1,000	1.96	3.48	94.56	2.95	11.11	59.9	28.04	2.14
	900*	0.02	8.75	91.23	7.95	9.21	53.21	29.63	1.79

* Removal tar by CaO

Target H_2/CO : 1.75 – 2.25

Tars reforming; $Tars + H_2O \rightarrow Ca(OH)_2 + CO + Hydrocarbons$

Hydrocarbons reforming; $Hydrocarbons + H_2O \rightarrow H_2 + CO_2 + CO$

Figure 21 Results of the Gasification Lab Scale

Then, the results were applied to the pilot horizontal gasifier, and CaO was the catalyst for reducing tar reformation in the gasification process. This Part is very important for Scale-up as Commercial Industry. Most previous research results from the literature reviews did not mention exactly the right temperature for the gasification process, showing better yields at temperatures > 700°C. Too many questions on the temp for the best of gasification process. The best yields are related to these components: less Tar and NO sulfur particles for Purified Syngas, which will feed to the FT – Synthesis Process. Before the horizontal gasifier was used, the influence of gasification temperature on tar yield was studied. In addition, the last experiment was carried out to observe tar removal by using CaO, which was packed separately layer after biomass and operated at 900°C.

Conditions;	
Temp.	600^{0}C – 1,000 °C
Fine biomass	10 g
Steam	1.5 g/min
CaO	1.5 g

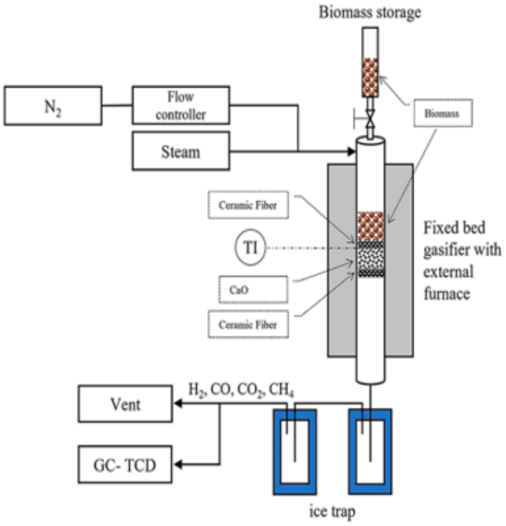


Figure 22 Schematic diagram of the custom-built gasifier at the lab scale.

Gasification Process with Pilot Horizontal Gasifier

This part of the goal was to produce purified syngas for feeding to the FT-synthesis process. The operation was performed with a pilot horizontal gasifier.

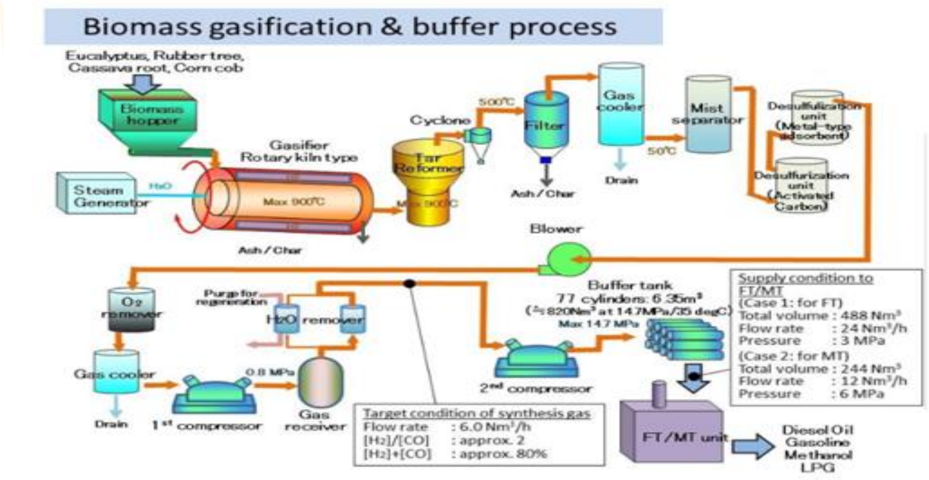


Figure 23 Schematic diagram of the pilot-scale gasification unit.

The research scope will be covered in 3 parts: start-up, operation, and end-line. Each part needs data for feasible and suitable scale-up production of aviation biofuel from biomass. The details of each part are as follows.

1. Startup part: Pre-Treated Raw Materials

It is for answering the questions which concern of 2 things. Data are secondary data obtained from reports, articles, and field trips.The necessary components on this part are Feedstock – supply chain and Location – Plant site.

1.1 Feedstock-Supply Chain: zone and quantity and property of raw materials

1.2 Proper Site -Plant Zoning: logistic nearby feedstock zone and transportation means (train, ship)

2. Operation part: Experimental Process

It is the middle way of project which related to the producing process for scale-up to 100,000 liter/day from 100 liter/day in the pilot scale operation. Data are from the experimental process at the pilot site, and the main components are technology and machinery. It is Primary Data. The details are as follows.

2.1 Conversion Rate of Biomass to Syngas

2.2 Conversion Rate of Syngas to Aviation Biofuel

2.3 Gasification Bench Facilities for producing Syngas.

2.4 FT-Syntheses Process pilot scale

2.5 How to work & How much it cost?

3. End-line part: Yields or Productions

this part will be related to Business components. Data secondary data and gain benefit from production. Aviation biofuels are derived from the operation to involve consumers inside and outside Thailand. Data will relate to cost analysis, marketing, etc.

The knowledge that has been studied for the readiness on the research itself and work on collecting data: primary sources and secondary sources, field study, analyze data concerning aviation business, biomass: rubber wood pellet, and eucalyptus chip are raw materials, conventional and new technology gasification to produce gases and Fischer–Tropsch plants. Otherwise, the part of training with the team was more utilized and feasible very well.

The primary data are from the machinery system during operation at the facilities bench, and then data will be derived from the experimental procedure. There are 3 parts of data as follows.

Part I: Pre-operation: Checking for readiness, i.e., the temperature.

Part II: During operation process for controlling process and fixing problem.

Part III: Production: Obtaining the purity of syngas and other results.

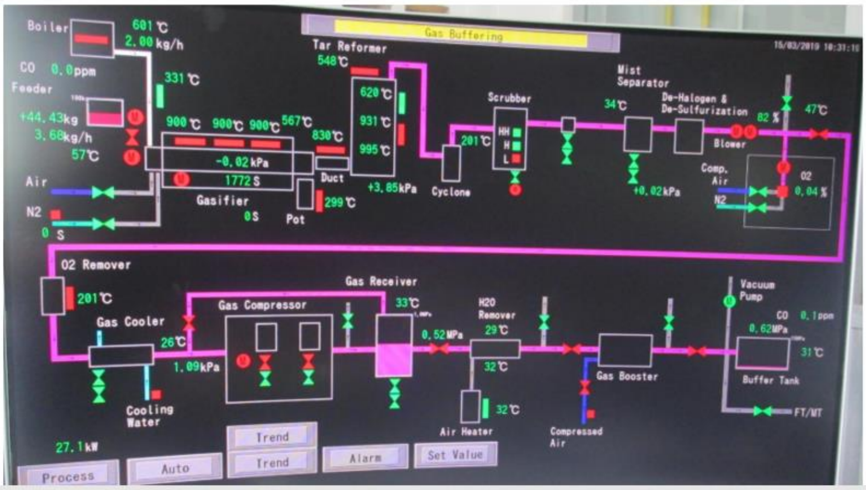


Figure 24 Monitor controlling data on the operation process

The monitors and alarm have been set which crews can see during operation in real time, and the record will be collected on the report sheet, VDO and pictures as well. However, the character of materials is part of the experiment on operation as well. For instance, this experiment used pellets of rubber wood and chip # 2 of Eucalyptus as raw materials in the operational process i.e., the pyrolysis and gasification process, which is converted to syngas and then processed via FT bench facilities to derive aviation fuel. Feedstock is Rubber wood and Eucalyptus; Pretreatment is a pellet 2-3 cms; eucalyptus is formed as chips with the size as 2-3 cms and will be used as biomass feedstock in the process of converting biomass to syngas via a two-step process:

Step I: Gasification & Pyrolysis

This operation process will be run for 10 daysexcluding prechecking and cleaning. Total on this process approximately 15 days. The details of the gasification component are shown in Figure #22.

Step II: Fischer–Tropsch Synthesis (FTS)The FT operation process will be completed in 50 hours. It is approximately 5 days of operation.

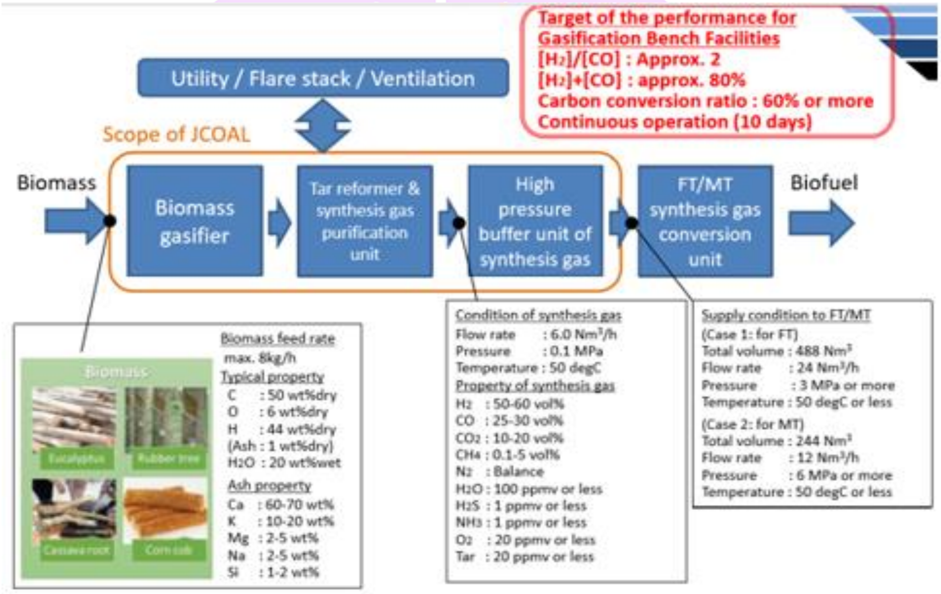


Figure 25 Data Controlling of Gasification Performance Bench Facilities

Biomass gasification was carried out in a pilot horizontal gasifier system consisting of the three zones of the gasifier reactor related to the three heaters to provide a constant temperature of 900°C. The size of the gasifier is 2.5 m in length, 20 cm in diameter, and a 2° decline. The pilot custom-built gasifier system is a horizontal cylindrical shape and has a 1.0 m diameter quipped with insulation to prevent heat loss from the reactor, including several joint connectors, since the feedstock hopper has a capacity of 4 kg/h until the tar reforming unit at the end of the gasification system.

Collecting Data: Primary Data

Data checking from Step I: During the operation process for 10 days; there are two sets of gas data that keep reading from the GC 5 times and calibrate the GC every 12 hours using 1 cc of gas. The time used for analyzing gas is 3 minutes. Therefore, the calibration GC will be performed 240 times to check the gas.

The 1st set is for the regular controlling performance operational process, which will be shown on the monitor. Biomass feed rate: Max. 8 kg/hr. and the typical properties are:

C: 50 wt% dry; O: 6 wt% dry; H 44 wt% dry; H_2O: 20 wt% dry; (Ash:1 wt% dry)

Ash: property: Ca:60-70 wt.% K: 10-20 wt.% Mg:2-5wt% Na:2-5 wt.% Si: 1-2 wt.%

The 2nd set is the target of the performance for gasification bench facilities:

H_2/ CO: Approximate 2

H_2 + CO: Approx. 80%

Carbon Conversion Ratio: 60% or more

2. Material and Method

2.1 Biomass Feedstock

The kiln gasifier unit was tested with two different types of biomass: rubber wood pellets and dried eucalyptus wood chips. The wood pellet was cylindrical and 8 mm in shape. of diameter and 30 – 80 mm in length. The size and shape of wood chips were proven by testing the behavior of biomass in the feeding system, including channel formation and downward movement in the hopper and obstruction into the screw feeder. Sieving should help to control the size and shape of wood chips and is beneficial for the biomass homogeneity in the hopper as well. The average size of wood chips used was 5 –10 mm (#2 or Med size).The physical and chemical properties of the biomass feed stock were analyzed and are presented in Table 6, which shows that the biomass characteristics, including proximate analysis, were determined using the ASTM D3172-3175 standard procedure method. The ultimate analysis was measured by an element analyzer (Leco – CHNS 628) and followed the ASTM D5373 standard procedure method, and the heating value was determined using Leco – AC500 with ASTM D5868.

The advantages and strength of Rotary Kiln Gasifier for Biomass Gasification Conversion Technology as Bio-Fuels;(Rotary Kiln esigned:IspatGuRu;December 26, 2019)

2.1.1 A rotary kiln is an inclined, rotating cylindrical reactor through which a charge moves continuously. The rotary kiln is a thermal processing furnace used for processing solid materials at extremely high temperatures to cause a chemical reaction or physical change.

2.1.2 A rotary kiln is used to heat solids to the point where a chemical reaction or physical change takes place. It works by holding the material to be processed at a specified temperature for a precise amount of time. Temperatures and retention times are determined by creating temperature profiles based on thorough chemical and thermal analyses of the material.

2.1.3 A rotary kiln comprises a rotating cylinder (called the drum), sized specifically to meet the temperature and retention time requirements of the material to be processed. The kiln is set at a slight angle of 2 degrees to allow gravity to assist in moving material through the rotating cylinder.

2.1.4 Rotary kilns can be either of the direct-fired type or the indirect-fired type. In a direct-fired kiln, fuel is burnt in the drum, and the material is processed through direct contact with the flue gas. In an indirect-fired kiln, material is processed in an inert environment and is heated through contact with the shell of the kiln, which is heated from the outside to maintain an inert environment.

2.2 Description of System Configeration

The rotary kiln gasification unit and a schematic view of the gasification unit are shown in Fig. 24-1. There is a feeding system, gasifier, steam generator, tar reformer, gas purification unit, gas compression unit and gas storage. The gasifier was designed with a capacity of 4.0 kg/h for the wood pellet feed rate. Consequently, the biomass size should be applied in this gasifier. Therefore, the downstream process was the FT process. The produced gas required a high caloric value for preventing contamination of inert gas that comes from using air as the gasifier agent. Thus, in this study, steam was used as the gasifier agent. Moreover, there were various types of contaminants formed in the produced gas, and a syngas purification unit was necessary.

Furthermore, this gasifier bench has been set as the computerized control for showing all the data via monitors and alarm for safety control as well. Accordingly, the controlled factors are temperatures and air pressure valves around the system. Otherwise, the main control of the operation system is the content of Tar at the Tar Reformer and syngas purification.

Temperature of **Gasifier Reactor**: Readiness for operation 900⁰C

1st Zone:
2nd Zone: HH 910⁰C LL SV -50⁰C
3rd Zone:

Temperature of **Tar Reformer:**

Top HH 1010⁰C
Lower HH 1100⁰C LL SV-50⁰C
Upper HH 1010⁰C LL SV-50⁰C

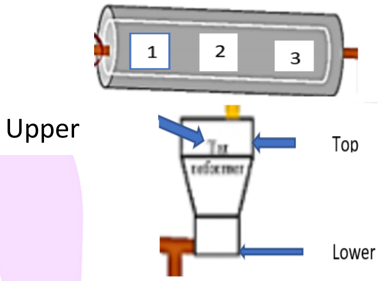


Figure 26 Gasifier Reactor

System Configuration

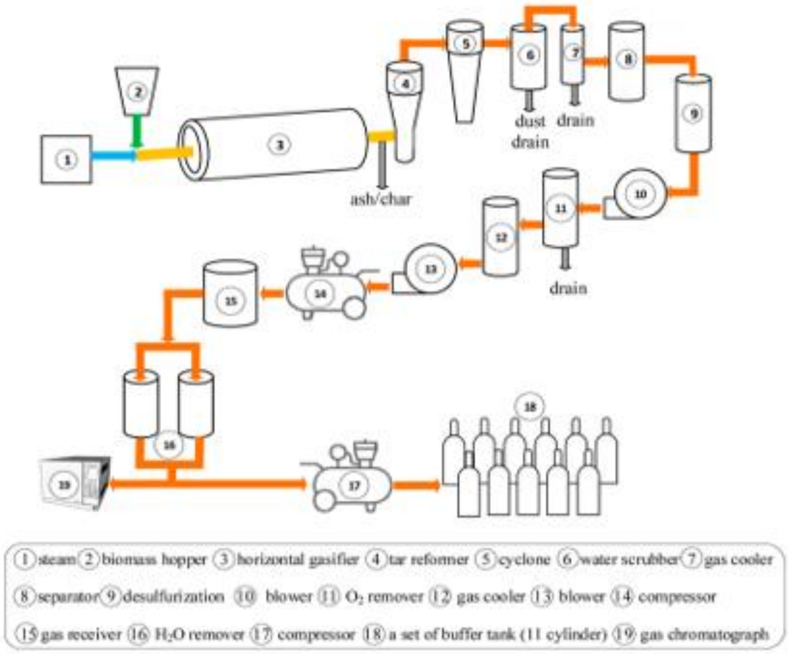
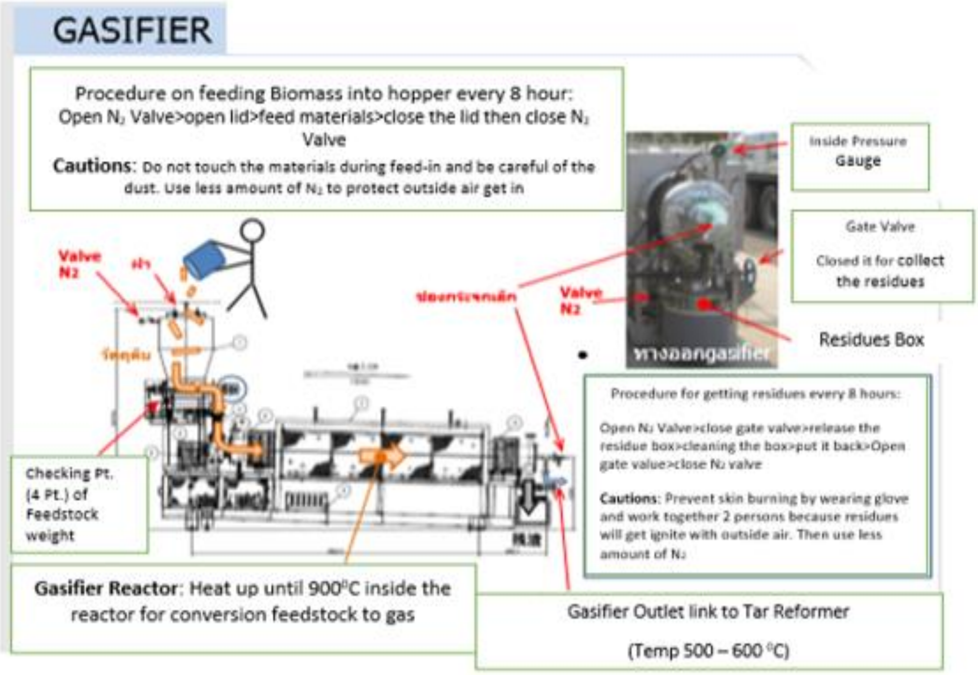


Figure 27 Infrastructure of Gasification Bench Facilities


GASIFIER

Procedure on feeding Biomass into hopper every 8 hour: Open N_2 Valve>open lid>feed materials>close the lid then close N_2 Valve

Cautions: Do not touch the materials during feed-in and be careful of the dust. Use less amount of N_2 to protect outside air get in

Inside Pressure Gauge

Gate Valve

Closed it for collect the residues

Residues Box

Procedure for getting residues every 8 hours:

Open N_2 Valve>close gate valve>release the residue box>cleaning the box>put it back>Open gate value>close N_2 valve

Cautions: Prevent skin burning by wearing glove and work together 2 persons because residues will get ignite with outside air. Then use less amount of N_2

Checking Pt. (4 Pt.) of Feedstock weight

Gasifier Reactor: Heat up until 900°C inside the reactor for conversion feedstock to gas

Gasifier Outlet link to Tar Reformer

(Temp 500 – 600 °C)

Figure 28 Gasifier

Gasifiers are the main equipment for gasification systems to work on the conversion of biomass to gas. This research used pilot horizontal gasifier (rotary kiln reactor). There are 3 zones of the gasifier reactor related to the three heaters for providing a 900^{0}C stable temperature of the gasifier with a length of 2.5 meters, diameter of 20 cm and a 2-degree decline. The shape of the physical gasifier with a 1.0-meter diameter included the brick insulation wall wrapped around the reactor. The starting from the linkage with feedstock hopper and end to the joint to Tar reformer.

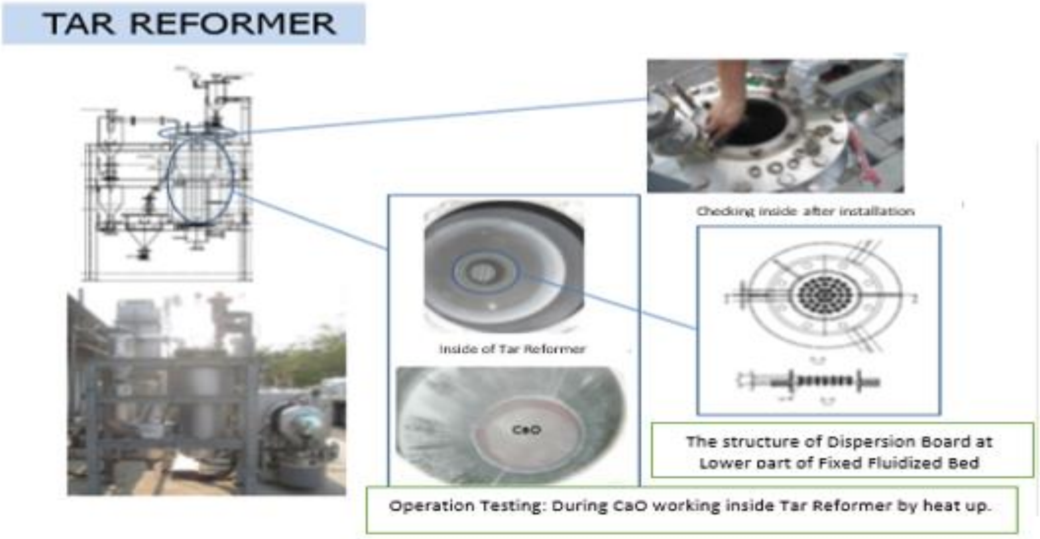
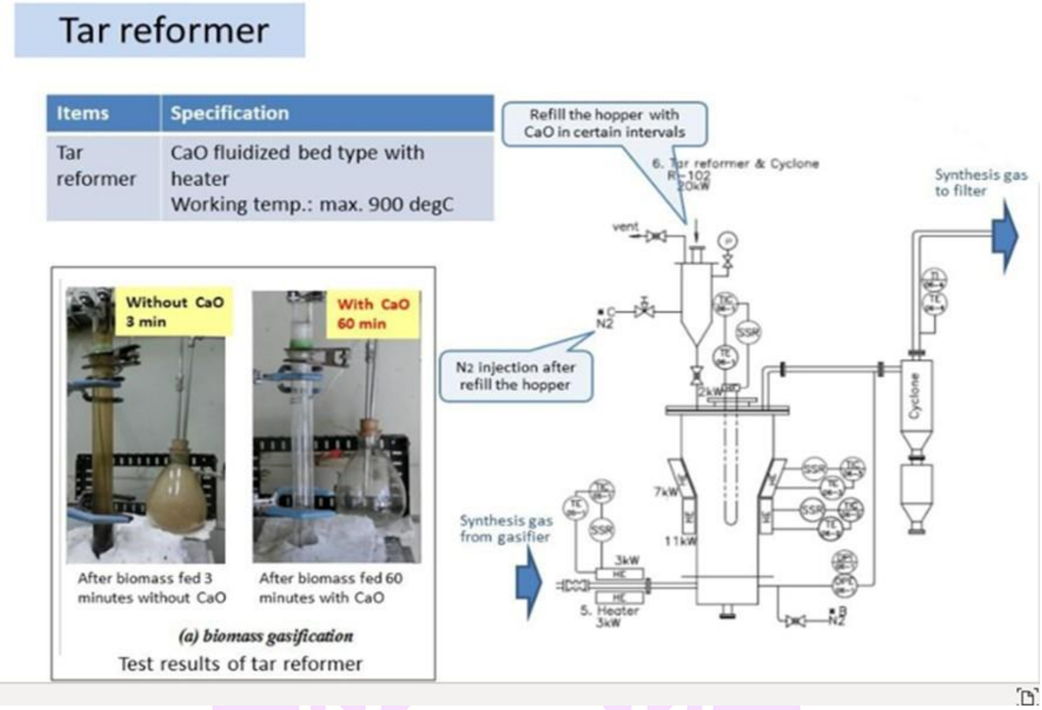


Figure 29 Tar Reformer

Tar Reformer is next to the gasifier and works with the syngas from the gasifier at the same temperature of 900^0C. CaO is the catalyst within the tar reformer and performs as a CaO fluidized bed with a maximum heater temp of 900^0CThe CaO reaction should reduce Tar reformation during theascent of syngas from the bottom to the top. The tar-reforming unit operating during the gasification stage to limit tar formation or to convert tars in the gasification reactor and operating downstream of gasification with various purification processes was conducted at an operating temperature of 900°C. CaO (12 kg) was used as the catalyst within the TR, which performed as a CaO-fluidized bed type. CaO enhanced the tar-reforming eaction to totally remove tar as the syngas moved up from the bottom to enhance the tar-reforming eaction to totally remove tar as the syngas moved up from the bottom to the Top.



Tar reformer

Items	Specification
Tar reformer	CaO fluidized bed type with heater Working temp.: max. 900 degC

Without CaO 3 min

After biomass fed 3 minutes without CaO

With CaO 60 min

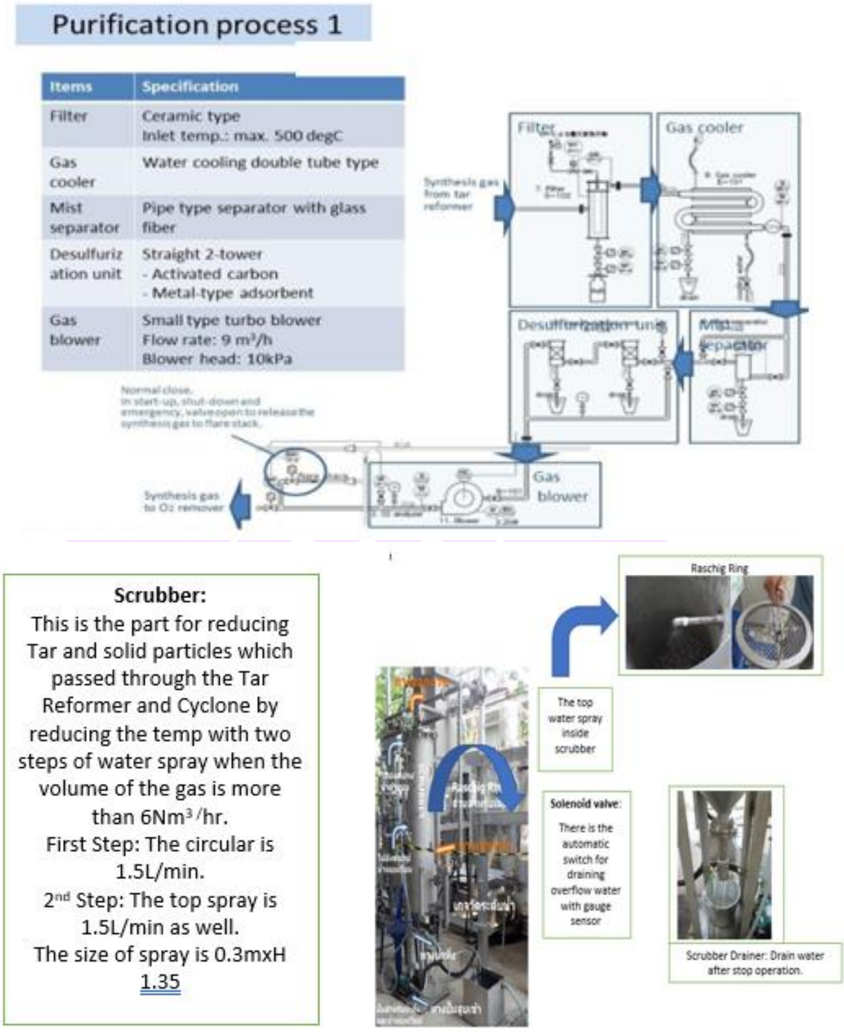
After biomass fed 60 minutes with CaO

(a) biomass gasification

Test results of tar reformer

Figure 30 Ter reformer

The purification process is a group of many tools working on purified syngas after passing through the Tar Reformer. There are 3 parts of this process. Process I: Starting from Cyclone (separating solid particle from gas), Water Scrubber, Gas Cooler, Desulfurization Unit, Mist Separator until Gas Blower. The main work of this section is to separate the small particles in the syngas fromthe tar reformer as much as possible.



Purification process 1

Items	Specification
Filter	Ceramic type Inlet temp.: max. 500 degC
Gas cooler	Water cooling double tube type
Mist separator	Pipe type separator with glass fiber
Desulfurization unit	Straight 2-tower - Activated carbon - Metal-type adsorbent
Gas blower	Small type turbo blower Flow rate: 9 m³/h Blower head: 10kPa

Normal close.
In start-up, shut-down and emergency, valve open to release the synthesis gas to flare stack.

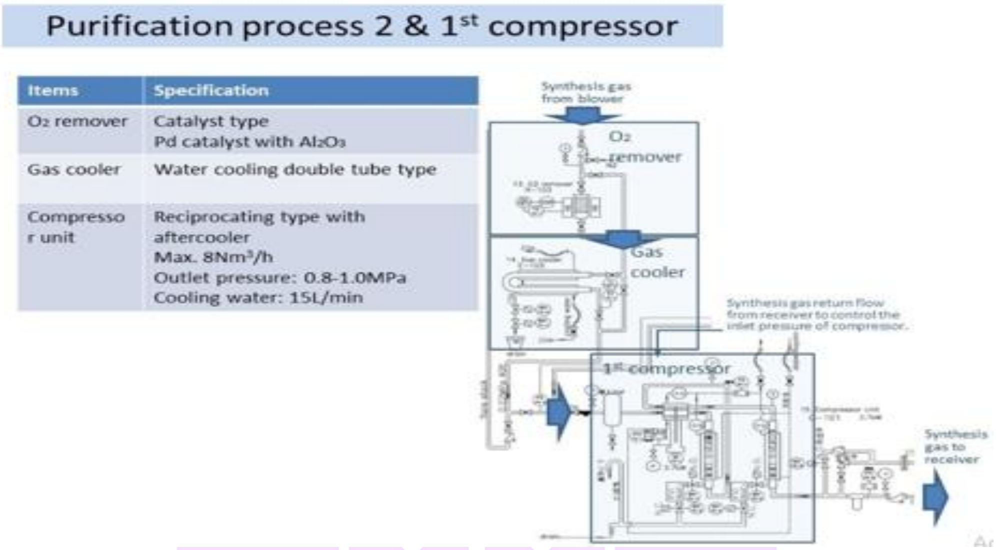
Scrubber:
This is the part for reducing Tar and solid particles which passed through the Tar Reformer and Cyclone by reducing the temp with two steps of water spray when the volume of the gas is more than 6Nm³/hr.
First Step: The circular is 1.5L/min.
2nd Step: The top spray is 1.5L/min as well.
The size of spray is 0.3mxH 1.35

The top water spray inside scrubber

Solenoid valve:
There is the automatic switch for draining overflow water with gauge sensor

Scrubber Drainer: Drain water after stop operation.

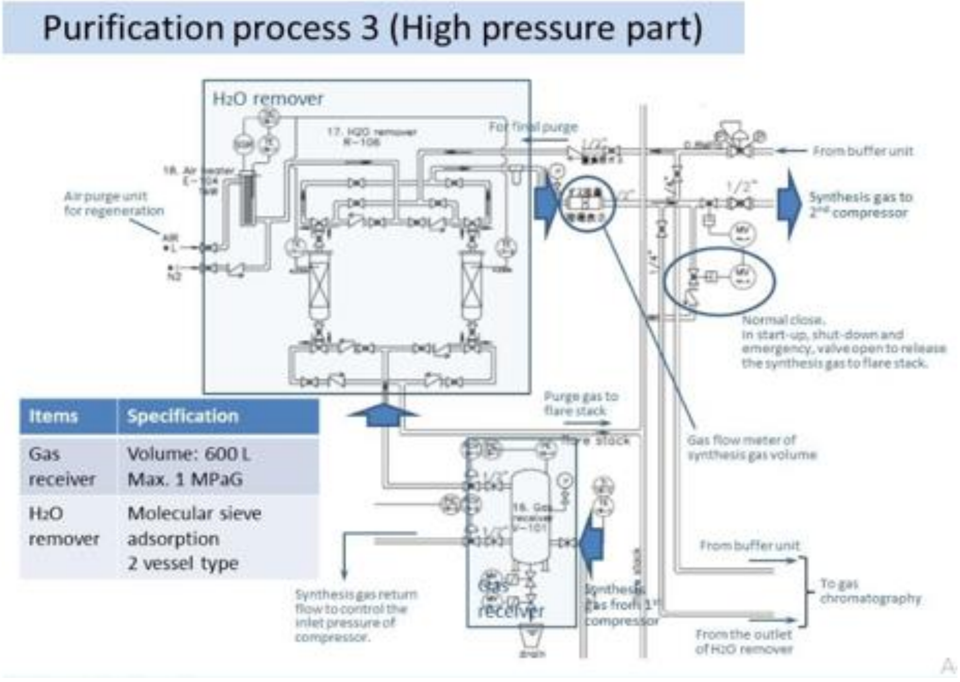
Figure 31 The purification process 1



Purification process 2 & 1st compressor

Items	Specification
O_2 remover	Catalyst type Pd catalyst with Al_2O_3
Gas cooler	Water cooling double tube type
Compressor unit	Reciprocating type with aftercooler Max. 8Nm³/h Outlet pressure: 0.8-1.0MPa Cooling water: 15L/min

Figure 32 The purification process 2 & 1 ST Compressor

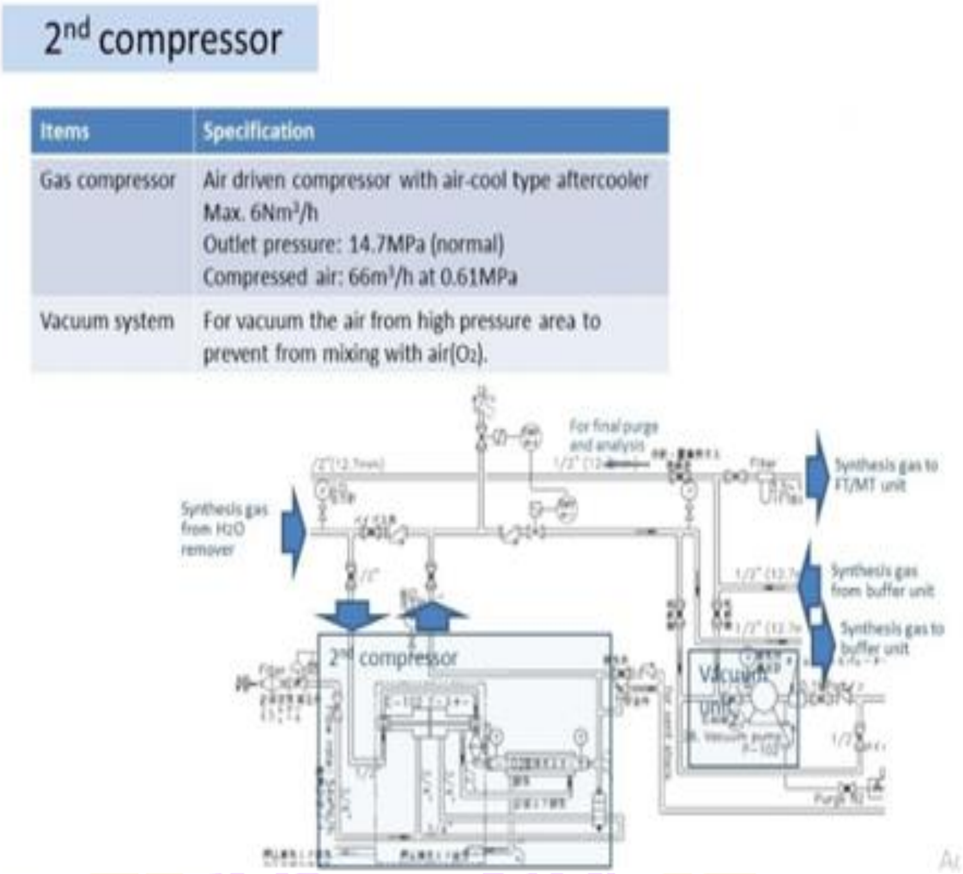


Purification process 3 (High pressure part)

Items	Specification
Gas receiver	Volume: 600 L Max. 1 MPaG
H₂O remover	Molecular sieve adsorption 2 vessel type

Figure 33 The purification process 3 (High Pressure part)

his section is for reducing H_2O with Molecular Sieve adsorption 2 vessel type from gas receiver volume: 600 L Max. 1.0 MPaG. Then, the gasification process produces syngas for feeding to the FT process. Syngas will be sent to the buffer tank by working via compressor unit 2 and the vacuum system, which is a high-pressure area that prevents mixing with air (O_2).

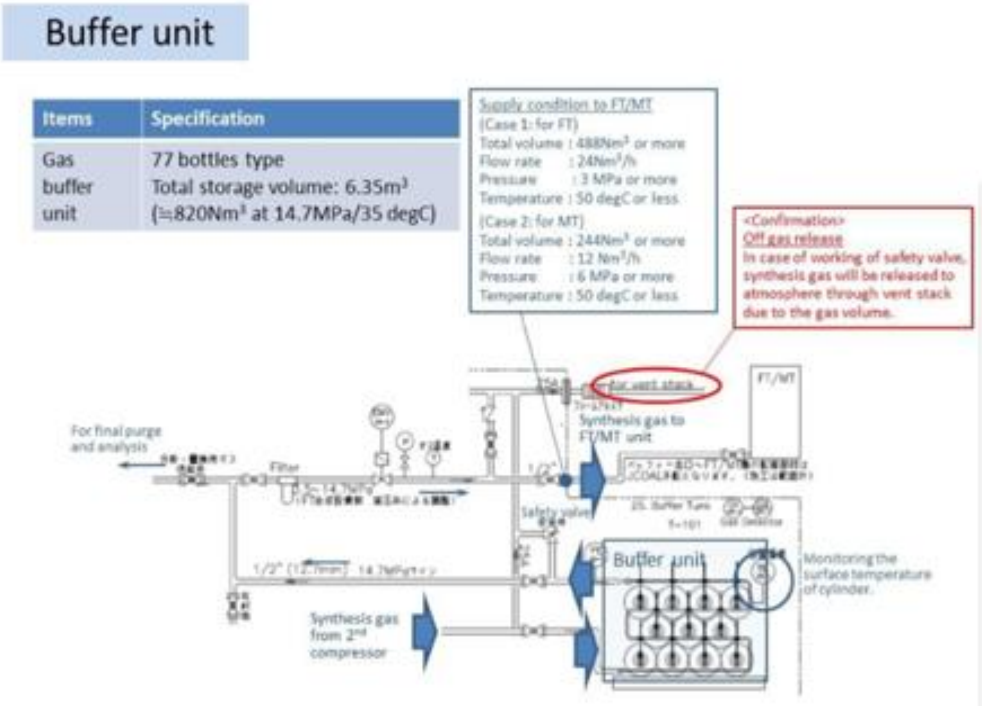


2nd compressor

Items	Specification
Gas compressor	Air driven compressor with air-cool type aftercooler Max. 6Nm³/h Outlet pressure: 14.7MPa (normal) Compressed air: 66m³/h at 0.61MPa
Vacuum system	For vacuum the air from high pressure area to prevent from mixing with air(O_2).

Figure 34 2nd Compressor

The buffer unit is a storage gas unit. Syngas will get to the 11 gas tanks at the same time. There are 7 sets, and the volume of each tank is 6.35 m3 (total gas in the buffer tank = 7x11x6.35 = 820 NM3 at 14.7 MPa/35°C. However, before sending syngas to the buffer tank, syngas still undergoes the final purification process via GC (chromatography unit) every 30 mins as well.



Buffer unit

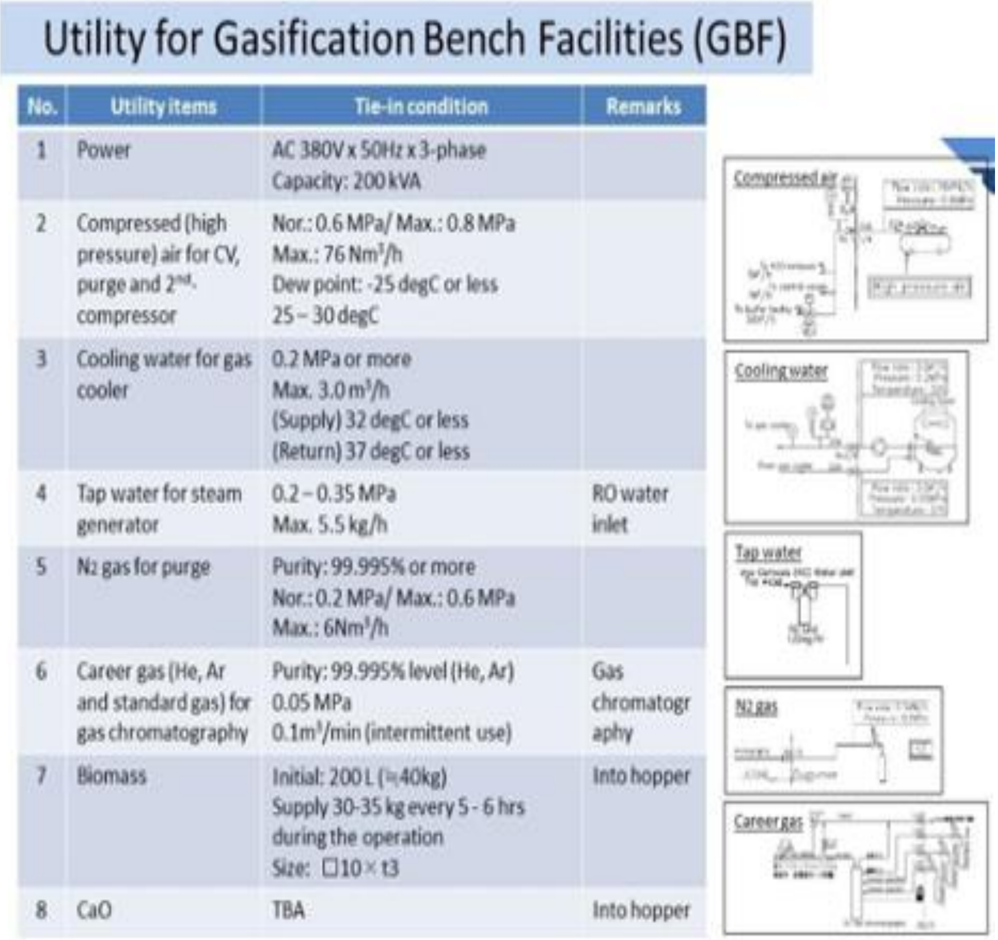
Items	Specification
Gas buffer unit	77 bottles type Total storage volume: 6.35m^3 (≒820Nm^3 at 14.7MPa/35 degC)

Supply condition to FT/MT
(Case 1: for FT)
Total volume : 488Nm^3 or more
Flow rate : 24Nm^3/h
Pressure : 3 MPa or more
Temperature : 50 degC or less
(Case 2: for MT)
Total volume : 244Nm^3 or more
Flow rate : 12 Nm^3/h
Pressure : 6 MPa or more
Temperature : 50 degC or less

<Confirmation>
Off gas release
In case of working of safety valve, synthesis gas will be released to atmosphere through vent stack due to the gas volume.

Figure 35 The buffer unit

Utilities for Gasification: There is a number of gasification bench facility (GBF) utilities. There are many pieces of equipment such as electricity as a power: AC 380 V x 50 Hz x 3 phase and Capability: 200 kVA; Compressor (high pressure) air for CV purge and 2nd compressor: Normal 0.6 MPa/Max 0.8 MPa, Max 76 Nm^3/h, Dew point: −25°C or less than 25–30^{0}C; Cooling water for Gas cooler: 0.2 MPa or more, max 3.0 m^3/h, supply 32^{0}C or less, and return 37^{0}C or less; tap water for steam generator (RO inlet): 0.2–0.35 MPa, Max 5.5 kg/h; N_2 gas for purge: Purity 99.995% or more, Nor 0.2 MPa/Max 0.6 and Max 6 Nm3/h; Career gas (He, Ar, and standard gas) for GC: Purity 99.995% level, He, Ar, 0.05 MPa, 0.1 m3/min (Intermittent use); Biomass into Hopper: size 10x13 mm, Initial 200 L (40 kg); supply 30–35 kg every 5–6 hrs. during the operation; and CaO into hopper TBA.



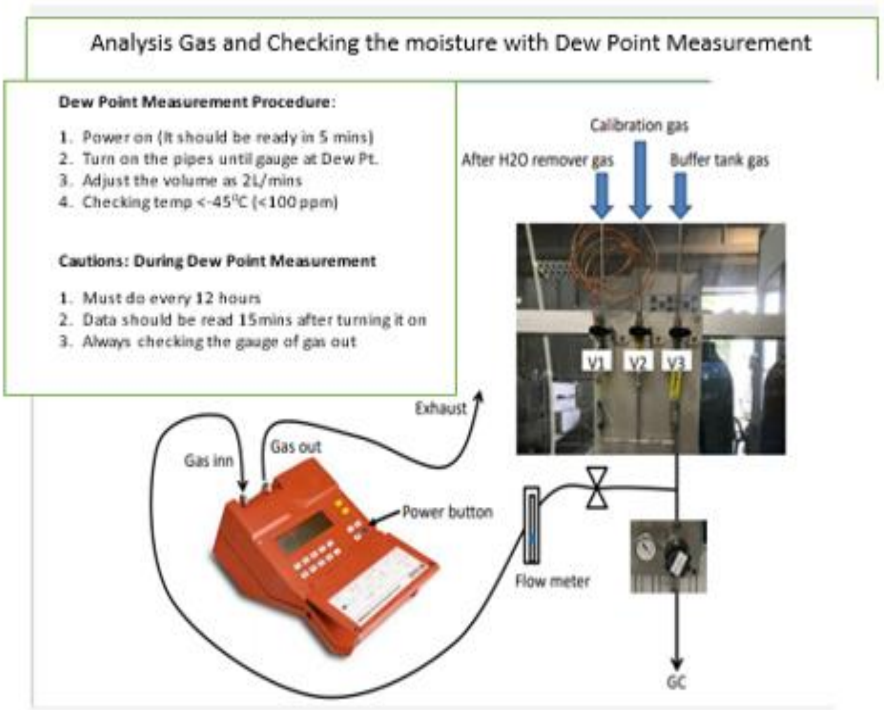
Utility for Gasification Bench Facilities (GBF)

No.	Utility items	Tie-in condition	Remarks
1	Power	AC 380V x 50Hz x 3-phase Capacity: 200 kVA	
2	Compressed (high pressure) air for CV, purge and 2nd. compressor	Nor.: 0.6 MPa/ Max.: 0.8 MPa Max.: 76 Nm³/h Dew point: -25 degC or less 25 – 30 degC	
3	Cooling water for gas cooler	0.2 MPa or more Max. 3.0 m³/h (Supply) 32 degC or less (Return) 37 degC or less	
4	Tap water for steam generator	0.2 – 0.35 MPa Max. 5.5 kg/h	RO water inlet
5	N2 gas for purge	Purity: 99.995% or more Nor.: 0.2 MPa/ Max.: 0.6 MPa Max.: 6Nm³/h	
6	Career gas (He, Ar and standard gas) for gas chromatography	Purity: 99.995% level (He, Ar) 0.05 MPa 0.1m³/min (intermittent use)	Gas chromatography
7	Biomass	Initial: 200 L (≒40kg) Supply 30-35 kg every 5 - 6 hrs during the operation Size: ☐10 × t3	Into hopper
8	CaO	TBA	Into hopper

Figure 36 Utilities for Gasification

The gas chromatography unit (GC) is an important tool for checking purified syngas before being sent to the buffer tank, which is directed online every 30 min. However, the yields ofthe gasification process is to obtain as much purified syngas as possible for the FT-syntheses system.

Gas Chronography System



Analysis Gas and Checking the moisture with Dew Point Measurement

Dew Point Measurement Procedure:

1. Power on (It should be ready in 5 mins)
2. Turn on the pipes until gauge at Dew Pt.
3. Adjust the volume as 2L/mins
4. Checking temp <-45°C (<100 ppm)

Cautions: During Dew Point Measurement

1. Must do every 12 hours
2. Data should be read 15mins after turning it on
3. Always checking the gauge of gas out

Figure 37 Gas Chronography System

The purification and conditioning of raw gaseos produced by gasification contained three parts starting from the cyclone (separating solid particles from gas), water scrubber, gas cooler, desulfurization (DS) unit, and mist separator until the gas blower to provide an effective process to ensure that small particles in syngas were separated from the TR as much as possible.

3. Gasification Procedure

After purging with N_2 to remove air in the gasification system and the gasifier was heated, biomass was filled manually into the hopper and merged to a screw-type feederunder the hopper to control the feed rate into the gasifier. Four load cells were installed at the hopper to measure the feed rate. A superheated steam generator with a feed controller was placed to supply steam as a gasifier agent into the gasifier. The produced gas from the gasifier flowed to the tar reformer (TR) unit and was also sent to the gas cleaning unit. On the other hand, biochar fell into the char box at the outlet of the gasifier. At the tar reformer, produced gas, including tar vapor, flows through the bubble bed of CaO. Tar was converted to syngas in this part. Tar-less syngas was sent to the cleaning part. In this part, syngas was reduced in temperature, and tar was condensed at the water scrubber. Fresh water was supplied to the water scrubber and conventional water treatment system for treatment directed at cooling water with tar. A gas cooler and mist separator were installed next to the water scrubber to remove water that might originate from the gasifier process and water scrubber. Although a small portion or less sulfur content is present in biomass feedstock, desulfurization (DS) unit still needs to be collected because sulfur is an FT catalyst poison. The DS unit was placed after the mist separator unit and connected with the first induced draft (ID) fan to control the syngas flow and balance pressure in the system. The upstream process is the FT process, which is an exothermic and pressurized process. The oxygen content in syngas is a serious concern in terms of safety. Hence, oxygen remover (OR) was applied and placed. Cleaned syngas was compressed and kept in a set of buffer tanks in two step compression. First, syngas flows to the second ID fan from the OR to the first compressor, which raises the pressure and keeps it in the receiver tank. An automatic control valve was placed after the buffer tank to control the pressure in the buffer tank, which was constantly at 0.8 MPa before sending the gas to the second step compression. Before the second compressor unit, syngas at 0.8 MPa of pressure could be moist by water saturation at high pressure, then H_2O remover using molecular sieve was placed to adsorb that moist and dry gas was real time analyzed the gas humidity by dewpoint measurement (Michell Instrument) and gas composition by Micro-GC (Agilent Technology: 490 Micro GC). At the second gas compressor, middle high-pressure gas was compressed to fill the buffer tank at 12 MPa.This gas was ready to use in the downstream unit. The temperature of the gasifier and its downstream unit was monitored by K-type thermocouples.The pressure at each point was measured, and the value in the main monitor was shown. All data and parameters were stored in a computer with A/D convertors.

4. Experimental set up

To investigate the suitable steam/biomass ratio that results in the desired H_2CO ratio (1.75–2.25), two different steam/biomass ratios with other similar parameters were studied, and the parameter list is shown in Table 6. The gasification test was conducted over 5 h of continuous operation for each ratio, and the produced gas was sampled to determine the gas composition every 30 mins until it was constant. A summary of the gasification results is shown in Table 7.

After the steam/biomass ratio demonstrated a suitable ratio, different types of biomass were studied. Rubber wood and Eucalyptus wood characteristics are shown in Table 6. This operation was carried out continuously for 10 days to fill 7 sets of buffer tanks at 12 MPa for each biomass type. For the mass balance and gas yield calculation, the total production gas was determined using the amount of gas that was pressurized into the constant volume of the buffer tank. This procedure revealed the exact amount of produced gas and benefited the whole mass balance investigation.

5. Data analysis and Calculation

To evaluate the performance of this gasification system, common gasification indexes were calculated. Therefore, the total mole and composition of the produced gas was precisely known, and the calculation of gas yields, carbon conversion and gas efficiency were based on the mass basis as follows:

$$\text{Gas yield (wt.\%)} = \frac{\text{total mass of produced gas}}{\text{total mass of fed biomass}} \times 100$$

$$\text{Carbon conversion(wt.\%)} = \frac{\text{mass of carbon in produced gas}}{\text{mass of carbon in total fed biomass}} \times 100$$

$$\text{Gas/Biomass} = \frac{\text{total mass of produced gas, kg}}{\text{total mass of fed biomass, kg}}$$

$$\text{Cold gas efficiency, } \eta_{cold} = \frac{M_{syngas} \times LHV_{syngas}}{M_{biomass} \times LHV_{biomass}} \times 100$$

M_{syngas} = total mass of produced gas, kg

$M_{biomass}$ = total mass of fed biomass, kg

LHV_{syngas} = lower heating value of produced gas, MJ/kg

$LHV_{biomass}$ = lower heating value of biomass feed stock, MJ/kg

In this chapter, the physical performance of each part of the gasification system in producing syngas and fed to the FTsynthesis process until yields are obtained are presented. However, some details as part of results have been presented along as well. The main results will be presented in the next Chapter IV.

2 Aviation biofuel production from waste vegetable oil via pyrolysis:

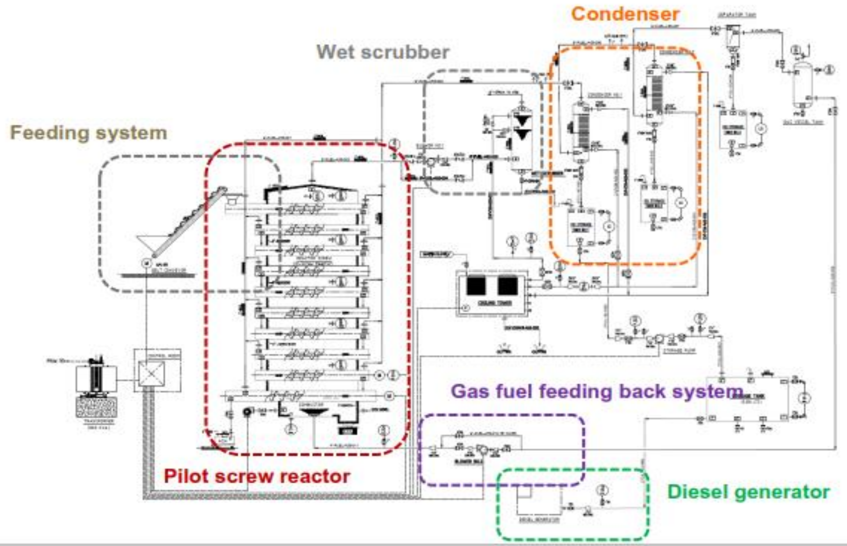
This research aimed to produce liquid fuel for supplying aviation biofuel using waste from vegetable oil by catalytic pyrolysis using calcined dolomite as a catalyst in a continuous pilot reactor. The research work was divided into two parts. The 1st part was an experiment in a bench reactor (lab scale) to determine the optimum conditions, especially the reaction temperature and catalyst loading, which affected the liquid fuel yield and diesel selectivity. The 2nd part was the production of liquid fuel from the raw material mentioned in the pilot screw reactor with a feed rate of 800 kg/d.

a)

b)

Figure 38 a) Lab-scale reactor b) pilot screw reactor

Screw pyrolysis reactor



Screw pyrolysis reactor (800kg feed/d)

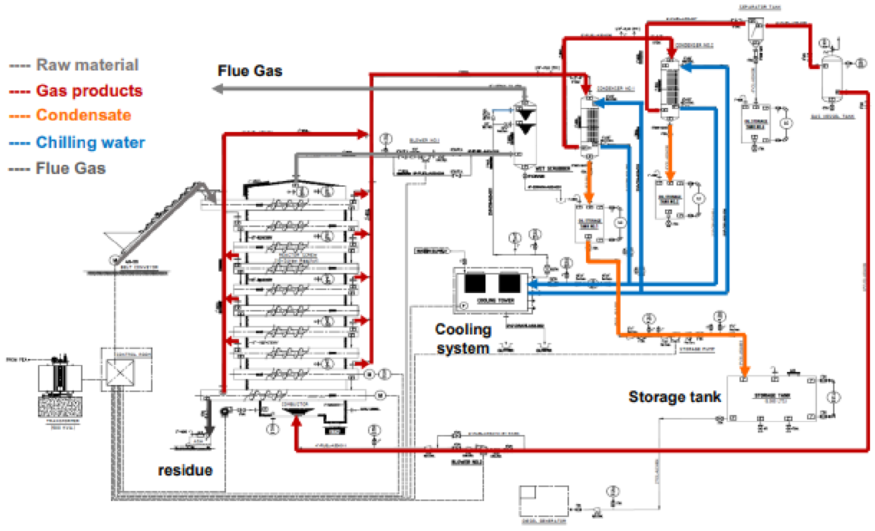


Figure 39 Schematic diagram of the pilot pyrolysis system

2.1 Experiment via Pyrolysis System

2.1.1 Materials: Source and characterization of waste palm oil (WPO)

The WPO used as raw material in this study was extracted from empty palm fruit bunches and provided by Southern Palm Company (1978) in Surat Thani Province, Thailand. The fatty acid composition of the WPO was analyzed by gas chromatography—

mass spectrometry (GC– MS; Agilent GC 7890/GCMS 5978, USA Agilent Technologies, USA). The elemental analysis of the WPO was determined using a CHN LECO-800 analyzer for C, H and N, while the O was obtained from the total weight and the C, H, N percent weight difference. The boiling point fraction of the oil product was analyzed by simulated distillation (SimDis) gas chromatography (Agilent 7890A Gas Chromatograph). The fatty acid and elemental compositions and oil fraction of the WPO, are shown in Table 6. The WPO had a high content of long residue (LR) compounds, which is not suitable for use as fuel. Therefore, it was necessary to convert the large HCs into smaller HCs by catalytic cracking to produce light liquid fuels similar to petroleum fuel.

2.1.2 Catalyst

The calcined dolomite (DC) used as a catalyst was received from coal-fired power plants in Rayong province. Before use, the CFA was heated at 600°C for 1 h to remove remaining impurities. X-ray fluorescence (XRF) analysis was used to characterize the DC catalyst and revealed that it contained 49 wt% SiO_2, 22.1 wt% Al_2O_3, 12.2 wt% Fe_2O_3, 6.3 wt% CaO, 3.04 wt% MgO and 7.46% other compounds. The X-ray diffraction (XRD) analysis of the DC was performed using a Bruker diffractometer D8-advance instrument with Cu-Kα radiation, operating the X-ray tube at 45 kV and 35 mA, and scanning the samples at angles from 10° to 80° (2θ). A representative XRD diffractogram of the DC is shown in Table 6

Table 6 Composition of fatty acids in the raw material

Type of fatty acid	**Fatty acid %**		
	WPO	**UCO**	**AF**
Saturated			
Myristic acid, C14:0	0.93	0.87	0.74
Palmitic acid, C16:0	44.63	35.69	21.62
Stearic acid, C18:0	2.56	4.58	4.73
Other	1.69	0.65	2.46
Total	49.81	41.79	29.55

Table 6 (cont.)

Type of fatty acid	Fatty acid %		
	WPO	UCO	AF
Unsaturated			
Oleic acid, C18:1	39.56	45.96	38.48
Linoleic acid, C18:2	9.56	11.84	25.11
Other	1.07	0.41	6.86
Total	50.19	58.21	70.45

2.2 Gas and solvent

The hydrogen (H_2) gas (99.5% purity) used in the reaction was supplied by Enviromate Co., Ltd. Bangkok, Thailand. Commercial-grade (minimum of 80% purity) toluene (C_7H_8; S. R. Lab Co., Ltd., Bangkok, Thailand) was used as the solvent without further purification.

2.3 Experimental procedure

Catalytic pyrolysis was carried out in twoscale reactors. A horizontal cylinder, 10 cm in diameter and 45 cm in length was used to determine suitable parameters, such as reaction temperature and catalyst loading. For operation, approximately 500 g of WPO and 1, 3 and 5 wt% DC catalyst were loaded into the reactor. Before the start of each run, the reactor was flown with nitrogen (N_2) gas to remove air. The reactor was heated from room temperature to the set temperature (420°C and 450°C) and held until the end of the reaction. After cooling the reactor at the end of the reaction, the oil productand solid were collected and weighed. Another screw reactor composed of 6 screws in cylinders 10 cm in diameter and 4 m in lengthconsec utively installed vertically was equipped inside a kiln. The vapor of oil vapor conducted with low negative pressure was collected in high (20°C) and low (80°C) temperature condensers. The incondensable gas product was recycled and added to biomass used as fuel to heat the reactor system. The flue gas from combustion inside the kiln was cleaned by a wet scrubber and then purged out. The continuous operating condition of the screw reactor was adopted from the bench reactor. Figure 25(a&b) shows both reactors, and the schematic diagram of the pyrolysis system is shown in Fig. 26.

The liquid and gaseous products were collected for determination of the yield and composition analysis, where the yield was calculated from Eq. (1),

$$Yield\ (wt\%) = \frac{Desired\ \ product\ (g)}{Initial\ \ of\ \ WCF\ (g)} \times 100 \qquad (1)$$

2.4 Product analysis

2.4.1 Gaseous product

The gaseous products were collected with a syringe into gas bags to analyze the composition using GC on an HP5890 series II gas chromatograph that was equipped with both flame ionization and temperature-controlled detectors.

2.4.2 Biofuel (Liquid product)

Analysis of the biofuel was conducted using GC—MS with the injector set to 250°C and helium (He) as the carrier gas. Identification of the components was accomplished by comparison with the NIST database. The biofuel product was analyzed by simulated distillation (SimDis) according to the ASTM D2887 standard, and the five main components of the liquid product, gasoline (IBP–220°C), kerosene (221–250°C), diesel (251–350°C), gas oil (351–370°C) and long residues (371°C–FBP), were identified and recorded.

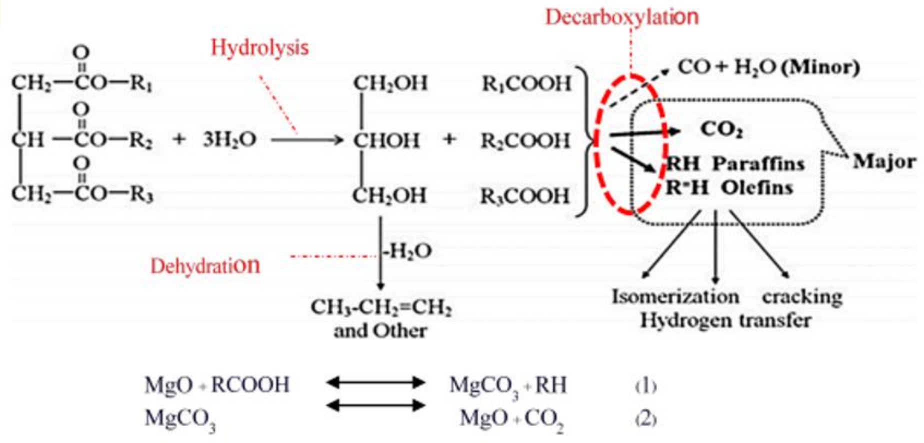


Figure 40 Isomerization Craking by MgO catalyst for Pyrolysis long time operation

CHAPTER IV

Results and Discussion

This experimental research is " A Study Conceptual Process Design for the Production of Aviation Biofuel in Thailand", which received data from assisting real reaction operations, especially FT, gasification, and pyrolysis, anddata from a published paper from our research team. The results and discussion were expressed in 3 topics that were considered in the research content: aviation biofuel production from biomass via the FT synthesis process and gasification and from waste palm oil via pyrolysis and proposed conceptual integral process design study for the production of aviation fuel.

Aviation biofuel production from biomass via the gasification and FT synthesis process

This research topic was conducted in 3 steps. The first was to determine the feasible and suitable process using raw materials –biomass (rubber wood and eucalyptus) for producing the proper synthesis gas for the best effort to achieve energy management and suitable operation conditions with thepilot horizontal gasifier (Rotary Kiln Reactor) operating at Chulalongkorn Biomass Center, Saraburi, Thailand. The second was the conversion of syngas to aviation biofuel from biomass in Thailand, which used published data from Jie Li, Guohui Yang, Yoshiharu Yoneyama, Tharapong Vitidsant, and Noritatsu Tsubaki (Fuel 171 (2016) pp. 159–166). In the article " Jet fuel synthesis via Fischer–Tropsch synthesis. Finally, the aviation cost of biofuel estimation was proposed.

1. Feedstock characterization

Table 7 shows the biomass characteristics, including ultimate analysis, proximate analysis, low heating value of rubber wood pellet (RWP) and eucalyptus wood chips (EWC). Although there were different milling processes for both biomass, feedstocks, the chemical, and some physical properties look similar on a dry basis. For example, the low heating value of RWP was 18.37 MJ/kg, close to the EWC, which was 18.39 MJ/kg for dry basis. In addition, similar properties might affectsimilar gasification results as well. However, the major differences in these biomass feed stocks were shape and moisture content. The shape of the biomass feedstock influenced the bulk density, which could affect transportation and storage facilities. For moisture content, the biomass milling process causes a difference in moisture content in feedstock and results in a variety of biomass feedstock qualities. In other words, the wood pellet milling process, requires a drying process in its production process. Thus, wood pellets are always less moist (8–10 wt.% moisture). On the other hand, the wood chip milling process is a simple milling process of biomass conversion or biomass size reduction that only reduces the size of biomass from wood logs to small chips without any drying process., wood chips generally have high moisture contents, similar to fresh logs. In this study, wood chips were dried by sun drying before use because of the limitations of gasification unit specifications.

Table 7 Characteristics of Biomass

	Rubber Wood Pellet	**Eucalyptus Wood Chips**
Proximate Analysis (wt.%), a.r.		
Moisture content, MC	8.47	8.02
Volatile matter, VM	72.74	74.89
Fixed carbon*, FC	16.46	16.46
Asn	2.33	0.63
Ultimate Analysis (wt.%), d.b.		
C	49.70	47.80
H	5.98	5.78
N	0.31	0.28
O*	44.01	46.14
H/C	1.43	1.44
O/C	0.66	0.72
Heating value, MJ/kg		
LHV, d.b.	18.37	18.39

Note: a.r.: as received

d.b. dry basis

* by difference

4.2 Long- term operation gasification of different feedstocks (Pilot Horizontal Gasifier)

a. Rubber Wood

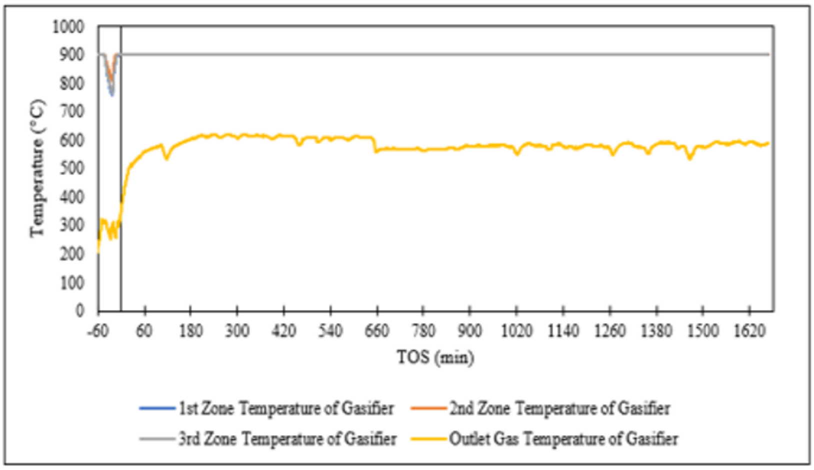


Figure 41 Temperature profiles of the gasifier zone for the rubber wood gasification process

Figure 41 shows that the Gasifier Reactor's temperature during the operational period at the separated zone along the length with the same spot of each heater is the same as 900^{0}C, but the temperature at the Tar Reformer zone in Figure 41 shows the steady temp as well: Lower 900^{0}C, Upper 700^{0}C, and the outlet gas temp 600^{0}C.

During the operational process, a stable temperature is very important for directly controlling the gas composition ratio of H_2/CO. Regarding another cause, the ratio of steam/biomass should be affected by H_2/CO.

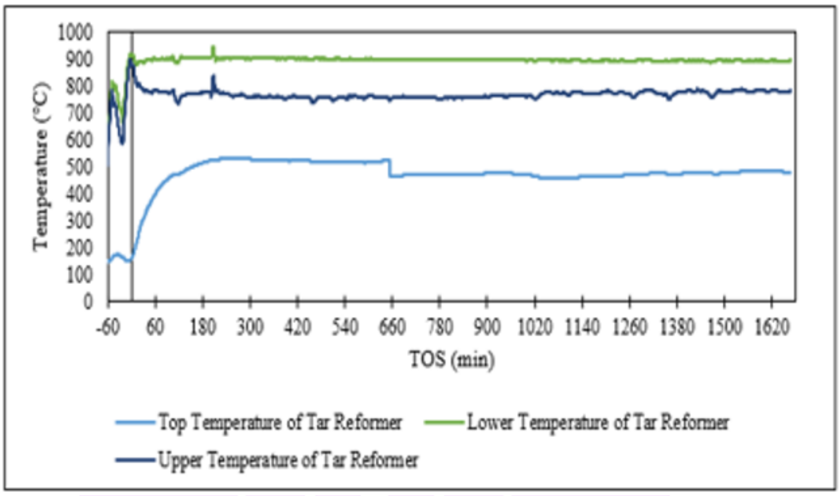


Figure 42 Temperature profile at the tar reformer zone for the rubber wood gasification process

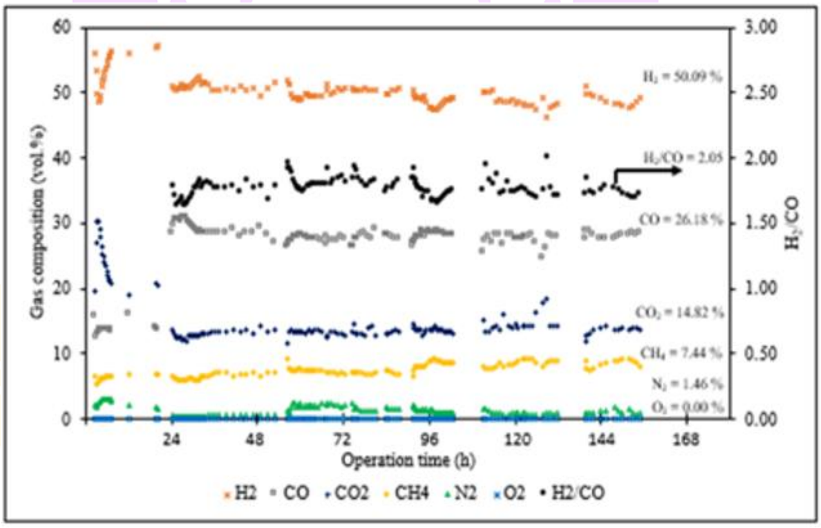


Figure 43 Overall gas of the rubber wood gasification process for a 7-day operational period

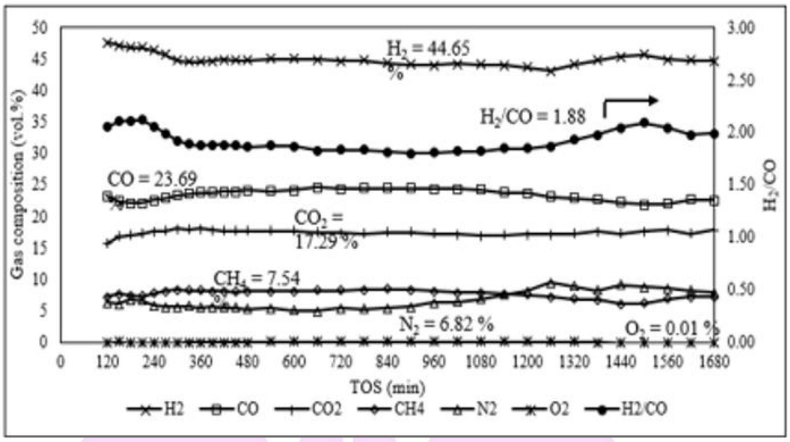
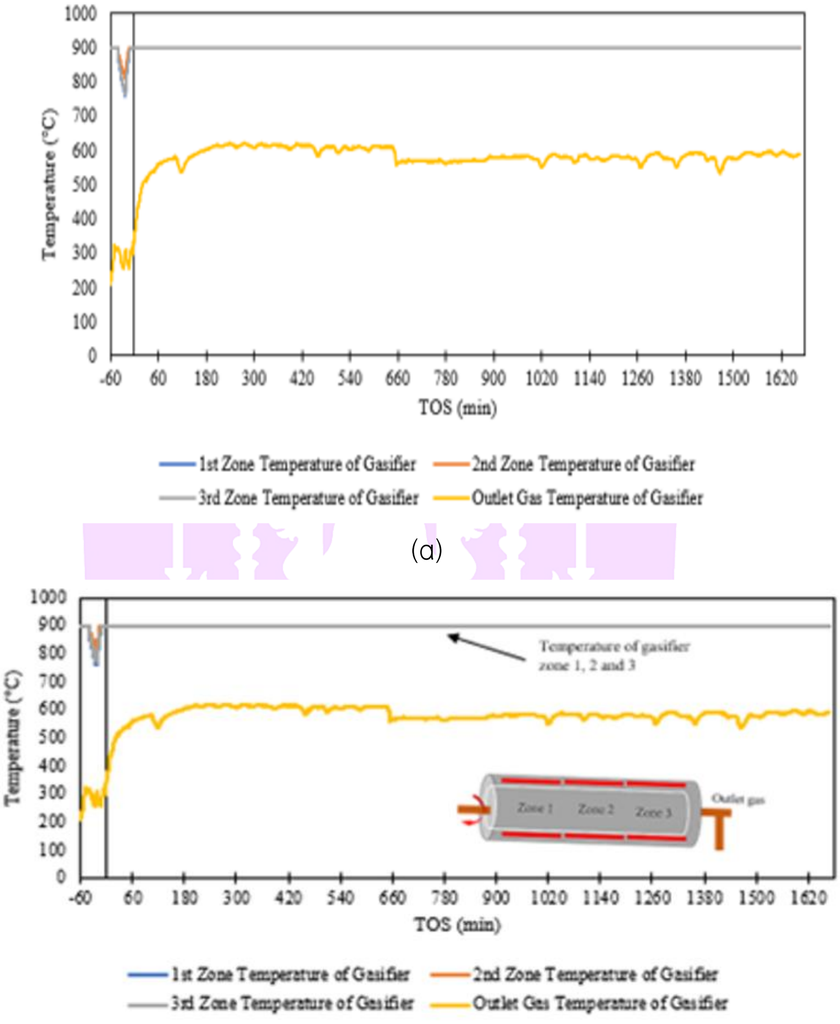


Figure 44 Gas composition for the rubber wood, gasification process

Figure 43 and Figure 44 show the gas composition during the long-term operational period. The average syngas of rubber wood gasification for 7 days tended tostabilize with 1.88 of H_2/CO and low N_2 and O_2. The stability of the syngas composition should be due to the temperature in the Gasifier Reactor and Tar Reform being neither high/low nor stable at 900^{0}C. Otherwise, the influenced-on Gasification Reaction and Tar Reformer are certainly from the steadiness temperature.

Rubber wood and eucalyptus were the feedstock raw materials for this pilot project, which used a pilot horizontal gasifier (Rotary Kiln Reactor) inclined 2 degrees. Rubber wood is a pellet, but eucalyptus is a chip. Both were dried with Sun drying for the retreatment process as needed. Figure 21 and Tables 6 and 7 show the comparison between rubber wood and eucalyptus, and the details will be discussed as follows.

b. Eucalyptus wood



(a)

(b)

Figure 45 (a&b) Temperature profile at the Gasifier zone for the Eucalyptus Gasification Process

The temperature of the Gasifier is shown in Figure 45 –a, and the Tar Reformer is shown in Figure 45 (a & b) during the operational period. The Gasifier is separated into 3 zones along the length with the same spot of each heater. The temperature is the same at 900^{0}C, and the outlet gas temperature is steady at 600^{0}C.

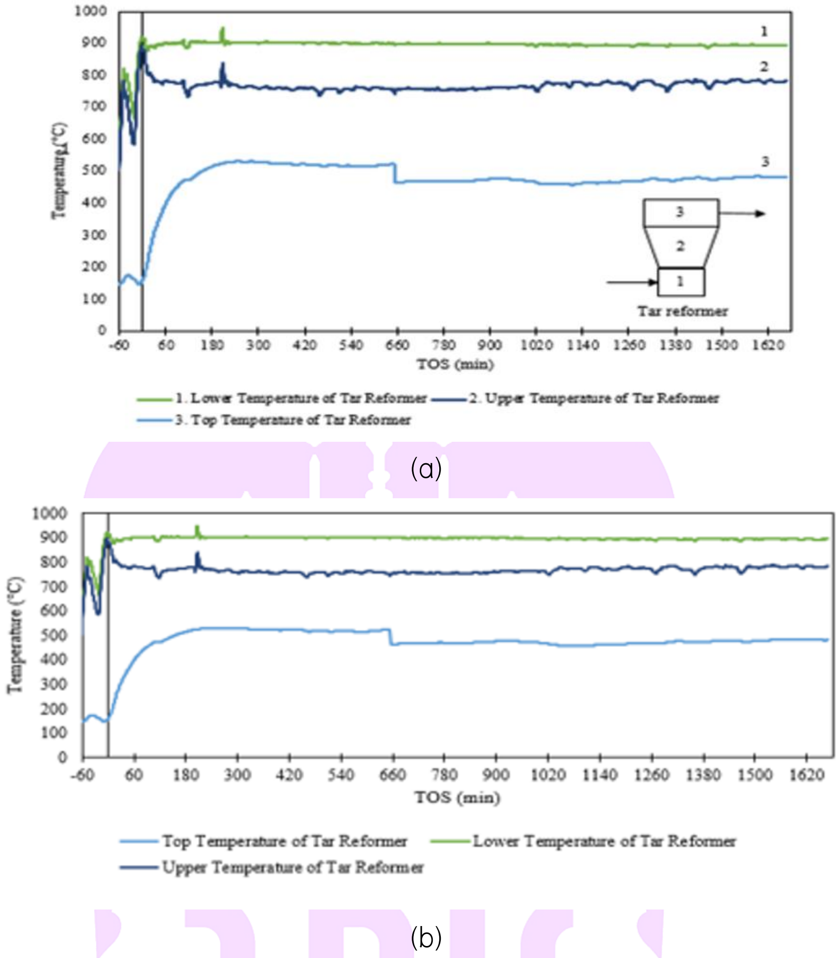


Figure 46 (a&b) Temperature profile at the Tar Reformer zone for the Eucalyptus Gasification Process

The stable temperature of the gasifier is very important because it will be suitable directly for the gas composition. Therefore, it is more effective in controlling the ratio of H_2/CO. During the operation, the stable temperature of the gasifier will not be caused by controlling the process but only the ratio of steam/biomass, which is affected by the ratio of H_2/CO.

Moreover, the Tar Reformer, in the lower zone, is linked to the reactor, andCaO works as a bubble fluid. This reactionoccurred with the behavior of CaO from rich syngas, which flowed from the base to the top. Figure 46 (a&b) The relation between the uniform temperature of syngas from the Gasifier at 900^{0}C and the temperature of the outlet gas from the Tar Reformer at 600^{0}C.

Otherwise, the heater at Tar Reformer settles for the temp at 600°C. The cause of the changing temperature during the operation is from the reaction of CaO and syngas with the behavior of the CaO bubble bed. Thus, the unstable temp, which varies in degree, is difficult to control.

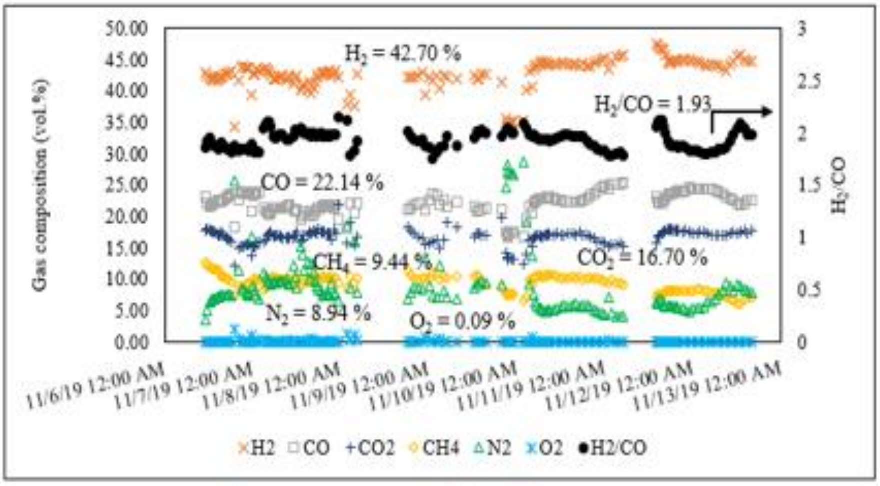


Figure 47 Overall gas of Eucalyptus Gasification Process

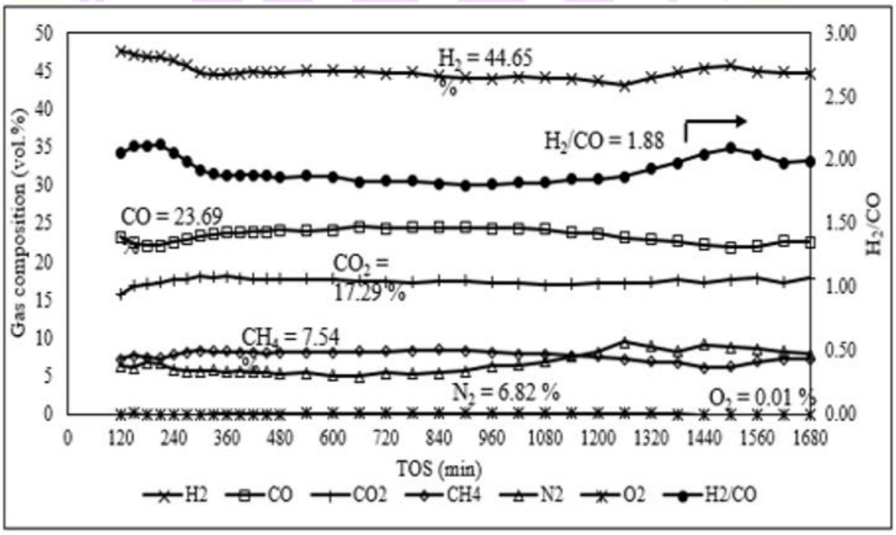
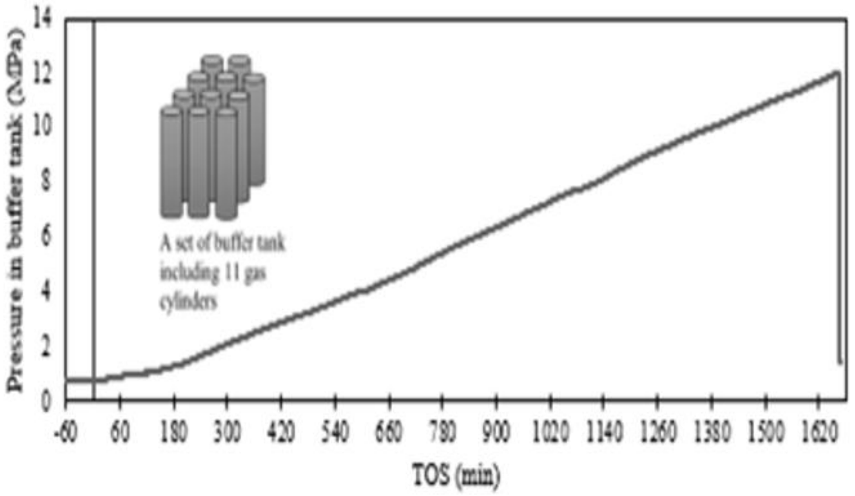
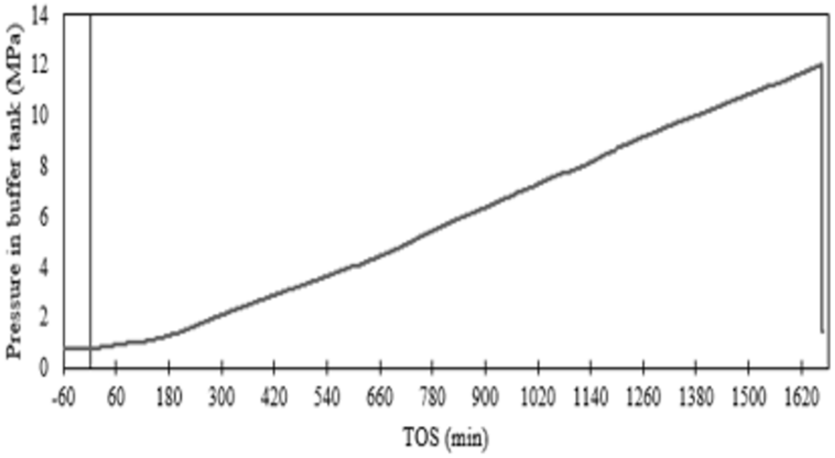


Figure 48 Gas composition of the Eucalyptus Gasification Process



(a)



(b)

Figure 49 (a&b) Pressure Gasification

Table 8 Summary of gasification and results for rubber wood and eucalyptus

	Rubber Wood Pellet	Eucalyptus Wood Chips [set5]
Operating parameters		
Operating time, h	30.5	27.77
Biomass feed rate, kg/h	4.34	3.90
Steam feed rate, kg/h	2.02	2.32
Steam/Biomass, kg/h	0.47	0.59
Gas yield at constant volume of 0.9071 m^3		
Produced gas rate, kg/h	2.48	2.67
Gas/Biomass, kg/kg	0.57	0.68
H2/CO, mole/mole	1.75	1.88
Gas compositions		
H2	47.67	44.65
CO	27.24	23.69
CO2	14.98	17.29
CH4	8.52	7.54
O2	0.00	0.01
N2	1.59	6.82
Low Heating Value, LHV		
MJ/kg	15.36	12.91
MJ/Nm3 []	12.88	11.66
Cold gas efficiemcy	47.77	48.05
Carbon Balance, kg		
Feed stock	55.30	47.66
Produced gas	24.89	23.61
Char (solid)	30.41	24.05
Carbon Conversion, wt%	45.00	49.53

Table 9 Characteristics of Bio Char

	Rubber Bio char	Eucalyptus Bio char
Moisture content, MC	13.48	13.85
Proximate Analysis (wt.%), d.b.		
Volatile matter, VM	3.51	3.60
Fixed carbon*, FC	83.06	88.76
Ash	13.43	7.64
Ultimate Analysis (wt.%), d.b.		
C	82.13	89.63
H	0.95	0.98
N	0.34	0.42
O*	16.58	8.97
B.E.T. (m^2/g)	464.68	N/A

Note: d.b.: dry basis

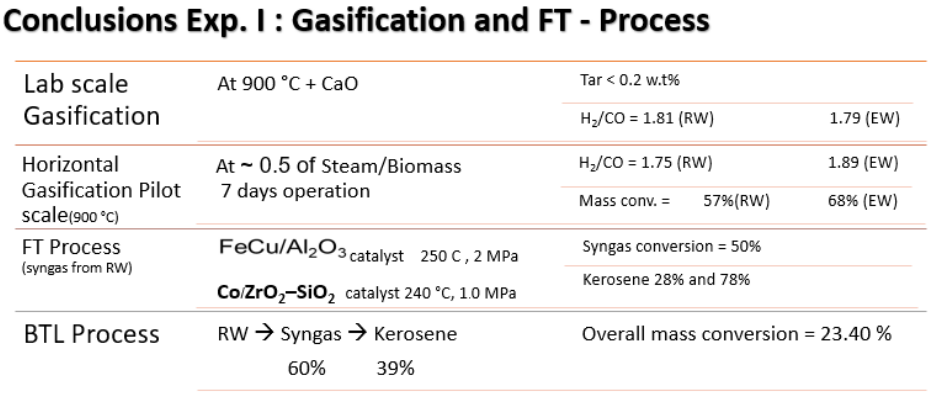
* by difference

Table 7 Summary of Gasification Condition and Results; there are insignificant differences. The numerical number from the experiment as data in the table such as Gas Yields about ratio of H_2/CO from Rubber Wood is 1.75 and Eucalyptus is 1.88. The yields of this ratio are good for the FT- synthesis process of 1.75-2.25, and both the yields from rubber wood and eucalyptus are satisfactory. The N_2 content is higher in Eucalyptus (6.82) than in Rubber Wood (1.59). The cause of N_2 content will be dilutedsyngas. In Table 10: Characteristic of Bio Char; during the operational gasification process, Gasifier reactor will secret Char – burnt Carbon from gasification conversion biomass to gas. The gaseous from the gasification process were analyzed every 30 mins with a GC-directed online system, andFigures 30 and 33 show the gas components fromthe gasification process and the ratio of $H_2/CO=1.88$; 44.65% of H_2, 23.69% of CO, 17.29% of CO_2, 7.54% of CH_4, 6.82% of N_2, and very low level of O_2.

As liquid fuels offer compatibility with available infrastructure for electricity, heat, transportation, and storage, the investigation of FT synthesis (FTS) and reforming with existing renewable energy sources is generated from the anaerobic digestion (AD) of biomass plants. It is an area of considerable interest. Syngas is a mixture of hydrogen (H_2) and carbon monoxide (CO) and can be utilized in the production of various biofuels, including liquid fuels, through the Fischer–Tropsch (FT) process.

Jet fuel synthesis via Fischer–Tropsch synthesis from syngas with varied 1–olefins as additives using $Co/ZrO_2–SiO_2$ bimodal catalyst.

Jie Li, et al., 2016 pp.159–166 The article "Jet fuel synthesis via Fischer–Tropsch synthesis with varied 1–olefins as additives using $Co/ZrO_2–SiO_2$ bimodal catalyst" presents the experimental procedure and results that are more utilized and practical in the aviation industry. The main component for kerosene yields ($C_6 – C_{16}$) from the FT process using the $Co/ZrO_2–SiO_2$ bimodal catalystworked very well.



Conclusions Exp. I : Gasification and FT - Process

Lab scale Gasification	At 900 °C + CaO	Tar < 0.2 w.t% H_2/CO = 1.81 (RW) 1.79 (EW)
Horizontal Gasification Pilot scale(900 °C)	At ~ 0.5 of Steam/Biomass 7 days operation	H_2/CO = 1.75 (RW) 1.89 (EW) Mass conv. = 57%(RW) 68% (EW)
FT Process (syngas from RW)	$FeCu/Al_2O_3$ catalyst 250 C , 2 MPa **$Co/ZrO_2–SiO_2$** catalyst 240 °C, 1.0 MPa	Syngas conversion = 50% Kerosene 28% and 78%
BTL Process	RW → Syngas → Kerosene 60% 39%	Overall mass conversion = 23.40 %

Figure 50 Conclusions the Experimental I (Gasification and FT – Process)

A schematic flow chart of the bimodal $Co/ZrO_2–SiO_2$ catalyst preparation by the incipient wetness impregnation method is illustrated in Figure 51.

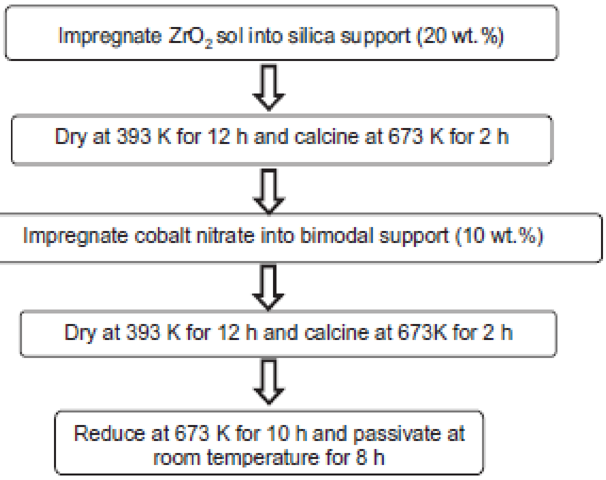


Figure 51 Schematic flow chart of the $Co/ZrO_2–SiO_2$ bimodal catalyst prepared by incipient wetness impregnation method.

Jet fuel synthesis with the $Co/ZrO_2–SiO_2$ bimodal FTS catalyst. A schematic diagram of the slurry FTS apparatus is shown in Figure 52 A mixture of 1.0 g passivated catalyst and 20 mL hexadecane was used. The reaction solvent was first ground into a uniform slurry and poured into the reactor. Then, the reaction system was purged.

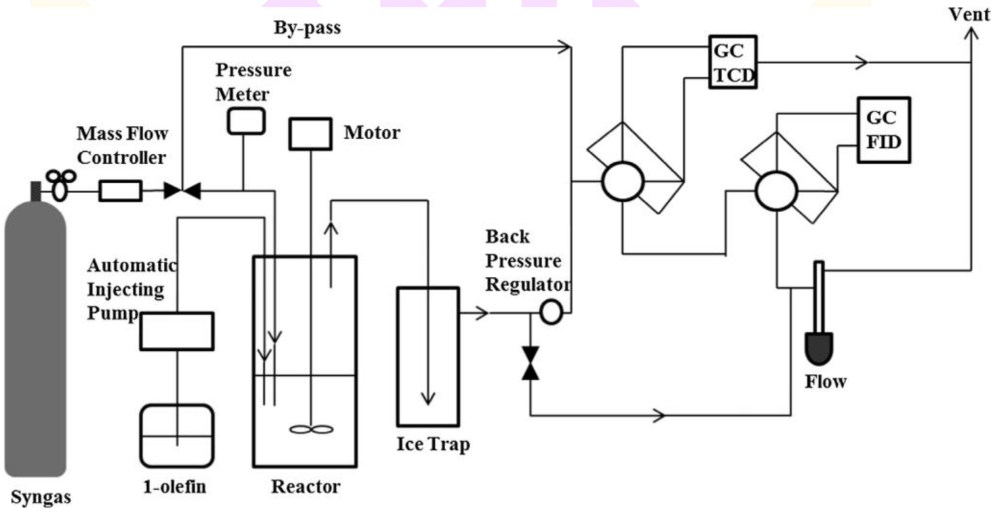


Figure 52 Schematic flow diagram of the slurry phase FTS apparatus.

A schematic diagram of the slurry FTS apparatus is shown in Figure 52 A mixture of 1.0 g of passivated catalyst and 20 mL of hexadecane as the reaction solvent was first ground into a uniform slurry and poured into the reactor. Then, the reaction system was purged three times with syngas to remove the trapped air, followed by heating the reactor system to 513 K with a ramping rate of 3.5 K/min. The stirring speed of the paddle in the reactor was 1200 rpm to eliminate the diffusion control regime. The catalyst was then activated in situ in the slurry reactor (innervolume of 85 mL) at 513 K for 1 h by feeding 0.1 MPa syngas

(H_2:CO:Ar = 63.05:33.8:3.07). Jet fuel synthesis on this Co/ZrO_2–SiO_2 bimodal catalyst via FTS reaction was conducted at 513 K and 1.0 MPa for 6 h. The reaction space velocity (W/F) was 10 g-cat h/mol. In this report, various 1-olefins, as given in Table 10, were selected asfeedstock additives to directly synthesize jet fuel from syngas via the FTS reaction. The 1-olefins were fed into the reactor by an automatic injecting pump with 20 mol% in CO base (molecular mole base). Effluent gas released from the reactor was analyzed by online gas chromatography (GC). CO and CO_2 were analyzed by a thermal conductivity detector (TCD) GC with an active charcoal column, and C_1–C_8 hydrocarbons were analyzed by a flame ionization detector (FID) GC with a Porapak-Q column. The liquid products collected from the ice trap and reactor were analyzed by an off-line FID GC equipped with a capillary column.

Table 10 Varied 1-olefins as co-fed additives for jet fuel synthesis on the 10 wt.% Co/ZrO_2–SiO_2 bimodal catalyst via the FTS reaction.

Additive	CO conversion (%)	Selectivity				
		CH_4	CO_2	C_2–C_4	C_8–C_{16}	C_{16+}
No additive	51.6	13.9	5.8	15.3	29.0	7.2
1-Octene	58.9	2.6	0.9	2.3	67.7	5.7
1-Decene	58.6	2.9	2.0	3.0	78.8	9.0
1-Tetradecene	40.7	2.7	0.7	1.8	77.5	15.8

Table 10 summarizes the reaction results of different 1-olefins used as co-fed additives for jet fuel synthesis on the 10 wt.% Co/ZrO_2–SiO2 bimodal catalyst via the FTS reaction. Without co-fed 1- olefins as additives, the Co/ ZrO_2–SiO_2 bimodal catalyst exhibited a CO conversion of 51.6% , a higher CH_4 selectivity of 13.9% and a lower selectivity of jet fuel composition (C_8–C_{16}) of 29.0%. First, three kinds of pure 1-olefin, 1-octene, 1-decene and 1-tetradecene were co-fed as in Table 9 to test the catalytic performance of the Co/ZrO_2–SiO_2 bimodal catalyst. In comparison with the FTS reaction without additives, the FTS reactions with three pure 1-olefins as additives facilitated the formation of jet fuel hydrocarbons, and the C_8–C_{16} selectivity was obviously increased.

Among these three pure 1-olefins, 1-decene was more effective in promoting both CO conversion and the formation of C_8–C_{16}. CO conversion reached 58.6% , and C_8–C_{16} selectivity was 78.8% , approximately 2.5 times higher than that of the FTS reaction without additives.

Cost of Bio jet fuel estimation

Biomass to liquid via Fischer-Tropsch synthesis (BTL-FT) has gained increasing attention in recent years for the production of renewable fuels such as diesel, gasoline and jet fuel. Usually, these fuels are clean and environmentally friendly and contain little or even no sulfur and other contaminant compounds. Fischer-Tropsch synthesis (FTS) uses syngas (synthesis gas) as a feed, which can be produced from biomass gasification. Gasification is a thermochemical process that converts carbonaceous materials into syngas. The gasification process can be split into four steps: biomass drying, pyrolysis, gasification and combustion.

The syngas originating from biomass mainly consists of hydrogen and carbon monoxide, along with methane, carbon dioxide, water vapor, nitrogen and impurities such as tars, ammonia, hydrogen sulfide and hydrogen chloride. High-quality syngas is often characterized by low N_2 content, high H_2 content, low tar levels and high heating value. Steam gasification is often preferred because it improves the quality of the produced gas by increasing the hydrogen concentration. In addition, the steam gasification process has additional advantages, such as maximizing the heating value, having advantageous residence time characteristics and efficient tar and char reduction. Gasification is a thermochemical process that converts carbonaceous materials into syngas. Fig. 53 shows the material balance from syngas production by steam gasification to biojet (kerosene) synthesis via the FT process.

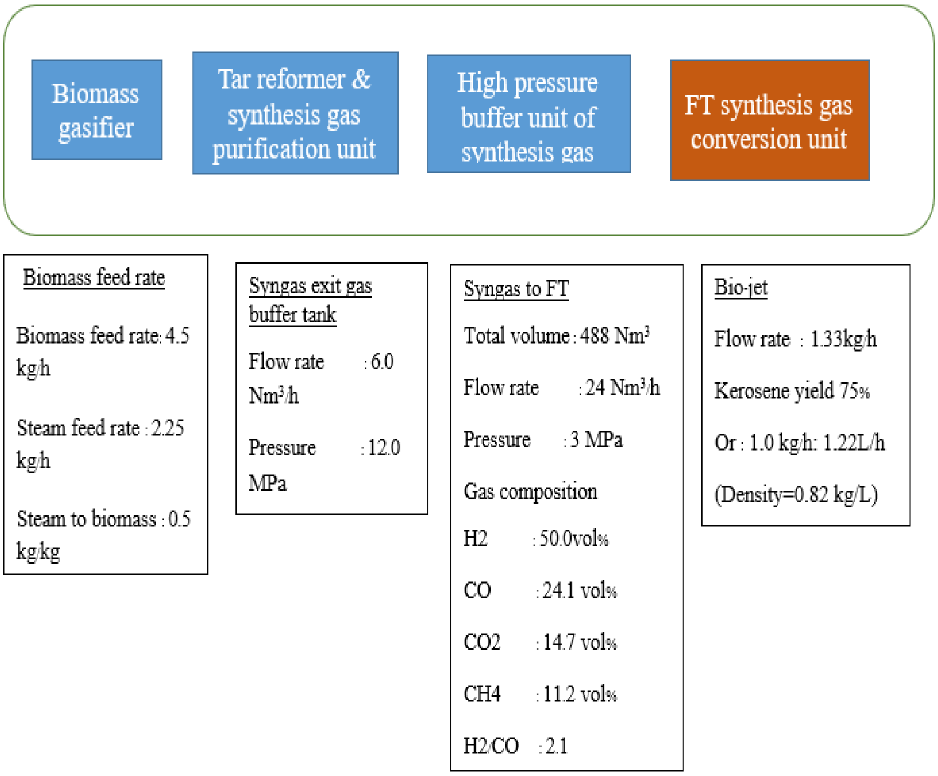


Figure 53 Schematic diagram of the material balance of biojet (kerosene) production via gasification and FT processes

Table 11 shows the data of all expenditures of the two processes, which were gasification and FT processes. For the gasification process, the costs of raw material and electricity were 41.98 and 50.33%, respectively. The electricity in the FT process shared 51.08% . The operating cost of the biojet was 50 baht/kg. The total cost was 70.83 baht/kg, which included an investment cost of 20.83 baht/kg. If selling price of SAF (Biojet) is $3,800/ton (FOB) or 133 baht/kg, it will be feasible for investment.

Table 11 Cost estimation of kerosene production via gasification and FT process

Basis: 10,000 kg liquid/d or 8,000 kg pure kerosene/d					
Investment 500 MB operation 10 years					
No.	**Item**	**Quantity**	**Price/unit**	**Amount (Baht)**	**%**
Gasification process					
1	Biomass and preparation	45, 000 kg	2.50 baht/kg	112,500	41.98
2	Electricity	1 000 kWh x24	5.62 baht/kWh	134,880	50.33
3	Wages	12 person	800 baht/d	9,600	3.58
4	Chemical & gas			6,000	2.23
5	Utilities			15,000	5.59
6	Maintenance			5,000	1.87
		Total for gasification		**267,980**	100
FT synthesis					
1	Catalyst & gas			10,000	7.57
2	Electricity	500 kWh	5.62 baht/kWh	67,440	51.08
3	Wages	12 person	800 baht/d	9,600	7.27
4	Utilities			15,000	11.36
5	Distillation& purification	10,000 kg	2,5 baht/kg	25,000	18.98
6	Maintenance			5,000	
Total for FT synthesis				**132,040**	
Total for operating cost				**400,020**	
80% After purification (kg)				8,000	
Operating cost biojet (baht/kg)				50.00	
Investment cost (baht/kg)				20.83	
Total cost of biojet (baht/kg)				70.83	
Sustainable aviation fuel (SAF) pricing $3,800/ton –> baht/kg (FOB)				133.00	

Figure 54 FT-Synthesis Apparatus and Yields from the FT Process

Aviation biofuel from pyrolysis of waste vegatable oil

This research topic was studied to determine the suitable conditions to produce aviation biofuel via waste vegetable oil pyrolysis in two types of reactors: bench scale and pilot reactor. Therefore, this research work was divided into 2 parts as follows, and the cost of production was proposed.

1. The 1st part was the experiment in the lab-scale reactor to determine the optimum conditions.

This part of the experiment observed the effect of parameters such as the percentage loading of catalyst and reaction temperature on the product yield and composition in the liquid product. Then, the optimum conditions were determined.

Effect of catalyst loading on product yield and composition in liquid product

The yield of the products and the composition of the liquid product are expressed in Figure 50 and Tables 10, respectively. The liquid product yields without and with 1 wt% catalyst was not significantly different, whereas3 wt% gave the same yield and was higher than 1 wt%, as shown in Table 10. The composition in the liquid product contributed the highest fraction of kerosene at 23.72% at 3 wt% catalyst. In conclusion, when using catalyst loading, 3 wt% was selected as the optimum condition to produce kerosene.

Table 12 Effect of catalyst loading on product yield (lab-scale reactor)

Experiment	Product yield(wt.%)		
	Liquid	Solid	gas
Without catalyst	64.25	9.56	26.19
1 wt%	65.23	7.23	27.54
3 wt%	68.22	3.43	28.35
5 wt%	68.25	2.36	29.39

Table 13 Effect of calalyst loading on liquid product composition (lab-scale reactor)

Experiment	Component, wt.%			
	Naphtha	Kerosene	Diesel	Residue
WPO	0.00	10.00	10.00	80.00
Without catalyst	11.60	12.40	46.50	29.50
1 wt%	13.20	18.90	51.70	16.20
3 wt%	14.72	23.72	51.24	10.32
5 wt%	16.26	21.37	50.20	12.17

Effect of temperature on product yield and composition in liquid product

The reaction was carried out at temperatures of 400, 425 and 450°C by using the same catalyst loading of 3 wt%. The product yield and composition in the liquid product are presented in Figures 53 and 54, respectively. The liquid yield showed the highest fraction at 425°C, as shown in Figure 53. The kerosene composition in the liquid product (Fig. 54) slightly increased with reaction temperature. It was observed that temperatures of 425 and 450°C gave the same and lower residue than 400°C, whereas both temperatures produced almost the same composition of kesesene at 22 wt%. The reaction temperature of 425°C was determined as the optimum temperature.

In conclusion, the optimum parameters were 3 wt% catalyst and 425°C. This condition was used to set up the reaction in a continuous pilot screw ractor.

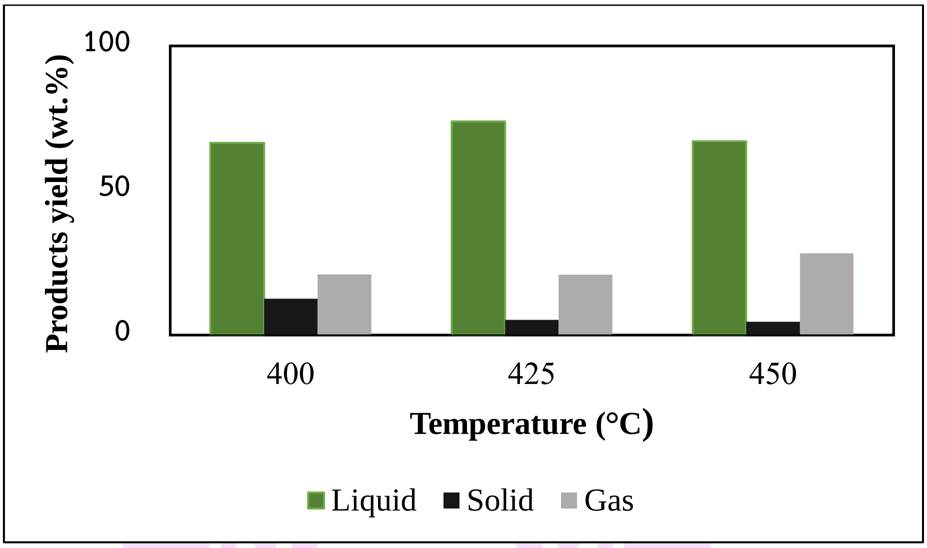


Figure 55 Effect of temperature on product yields

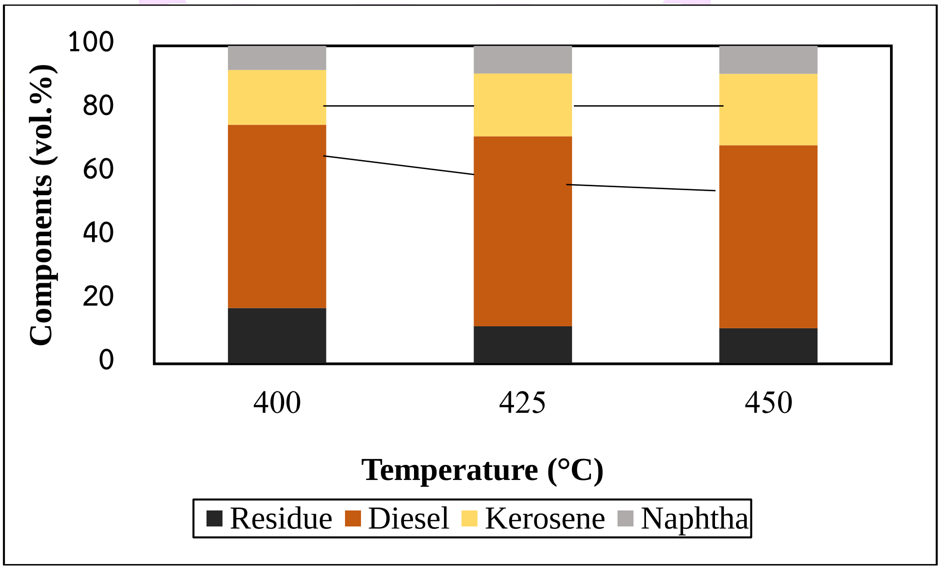


Figure 56 Effect of temperature on the composition of the liquid product

2. The 2nd part was the production of liquid fuel from the raw material mentioned in the pilot screw reactor.

This part employed the optimum conditions from the 1st part, such as 3 wt% catalyst loading and 425°C reaction temperature for continuous operation with a feed rate of 800 kg/d. The three raw materials were WPO, UCO and AF, as shown in Fig. 56. Before use in operation, a moisture content less than 10 wt% was controlled by evaporation.

Waste Palm Oil (WPO) Used Cooking Oil (UCO) Animal Fat (AF)

Figure 57 Three types of raw material

The results of continuously operating the reaction in the pilot screw reactor are expressed in Tables 10 and 11.

Table 10 shows the product yield of each raw material. UCO presented the highest yield of liquid product (69.25%), whereas AF gave the lowest (61.52%). Considering of the composition in the liquid product of each raw material (Table 13), it was observed that the three raw materials gave almost the same composition. The kerosene content ranged from 21.95 to 23.90%. This is because the components of the three types of raw materials have almost the same fatty acids. In addition, comparing the composition before and after the reaction of WPO, the majotity of the residue on raw WPO (80.55%) was largely converted and remained at 5.58%. It was mentioned above that this is an alternative method to produce kerosene by pyrolysis, which is cheaper than hydrocracking using hydrogen, which is a severe process. The disadvantage of pyrolysis is that it only accounts for 20% of kerosene in the liquid product; however, other fractions, such as naptha, diesel and fuel oil, are valuable after distillation.

Table 14 Product yield of each experiment

Raw material	Product yield (wt%)		
	Liquid	Solid	Gas
Waste Palm Oil (WPO)	66.58	8.08	25.34
Used Cooking Oil (UCO)	69.25	10.23	20.52
Animal Fat (AF)	61.52	12.1	26.38

Table 15 Effect of different raw materials on liquid yield and composition

Raw material	Yield and composition				
	Yield (wt.%)	Naphtha	Kerosene	Diesel	Residue
Raw Waste Palm oil	–	0	9.75	9.70	80.55
WPO	66.58	21.63	23.57	48.22	5.58
UCO	69.25	22.90	23.90	47.83	5.37
AF	61.52	24.84	21.95	46.65	6.56

Cost estimation for liquid product from pyrolysis and kerosene production

The cost of kerosene production was estimated by using the following hypotheses:

Hypothesis

1. Using WPO as raw material
2. Basis of calculation: 1 month operation with 800 kg/d feed rate
3. Conversion of WPO to liquid fuel = 66.58% or production rate, 16,000 kg/month

4. Kerosene composition 20% = 3,200 kg/month

5. WPO price = 15,000 baht/ton

Table 16 shows the structure of the cost component, especially the cost of the raw material, which shared 74% , which was the main factor. After summation of the operating and investment costs, the total cost of kerosene was 34.75 baht/kg. However, kerosene was not largely produced by this process, but the total cost of production is quite low compared with FT, hydrocracking processes.

Table 18 Cost estimation of kerosene production

	Item	Quantity	Per unit	Amount	%
1	WPO	24t	15,000 baht/t	360,000	74.36
2	Wood chip for heating	20t	1,500 baht/t	30,000	6.20
3	Grid			17,500	3.61
4	Activated clay and filtration	12,000 l	0.8 baht/t	9,600	1.98
5	Maintenance			5,000	1.00
6	Wages	6 person	10,000 Baht/month/ person	60,000	12.40
7	Miscellaneous			2,000	0.45
	Total			484,100	100%
Operating cost per kg of Pyrolysis oil (baht/kg)				30.25	
Operating cost kerosene from Pyrolysis oil (baht/kg)				30.25	
8	Separation for kerosene (baht/kg of kerosene)			2.50	
	Total Operating cost of kerosene (baht/kg)			32.75	
9	Investment cost (baht/kg)			2.0	
	Total cost of kerosene (baht/kg)			34.75	

they were cracked by pyrolysis to obtain a fraction of approximately 20% of the total liquid yield. The advantage of pyrolysis is that the operating cost is approximately 2.5 times cheaper than that of FT-synthesis. If it requires the production of biojets on a commercial scale of 100,000 L/d in the future, FT-synthesis will need 500 t/d of biomass, whereas pyrolysis consumes 760 t/d. A quantity of 500 t of biomass/d can be provided with appropriate management, but waste vegetables or fresh oil is insufficient to provide this large quantity. Thus, the FT synthesis process is appropriate for biojet production in the near future.

Proposed a study conceptual integral process design for production of aviation fuel.

Aviation fuel relies on consumers' transportation demand for aircrafts among local, international, and logistics. Unfortunately, during the COVID-19 little worldwide. Scientists will have more time to focus on their experiments and research on aviation biofuel. Investors have more chances to make feasible considerations to gain more benefits and better yields as well. The aviation business willbloom quickly and then consume more fuel on aircraft transportation after COVID-19 is controlled very soon.

Renewable energy is always the destiny for transportation fuel. Previously, the goal of conversion technology, especially aviation fuel, kept saying just CO_2 emissions, which are the main cause for all. Despite the famous of research on aviation fuels, conversion technology still relies on raw material type and yields. Nevertheless, 10% of aviation fuels have biojets, and in 2030, air crafts need to use only biojets. This regulation has been set up by ICAO, which is the organization taking care of the International Aviation Business.

Thailand is an agricultural, fast-paced economy country that is rich in biomass resources as well. Thailandstarted biofuels from biomass in 2007. Biofuel production is for only ground transportation. Apparently, there are many pathways for the conversion process for producing aviation biofuels from biomass, and then, what is the readiness of Thailand in this business? Obviously, if the business plan is preferred on the Near Term (start up in 2020), it should be possible must so.

This research has analyzed and synthesized information from the literature reviews related to the conversion process for producing aviation biofuels from biomass and the goal for obtaining the conceptual integral process design as the approach for producing aviation biofuels from biomass in Thailand. Scale-up needs to work not only with suitable sources but also well done on the business plan. The scale-up of aviation biofuel should be effective, efficient, and advantageous in terms of environmental, social, and economic awareness. The reflection from these research results should be precisely appropriated messages for stakeholders and investors.

The essential components to produce AJF from biomass:

The majority of the recommendations on producing AJF from biomass were mentioned about the key elements that worked as the team. In addition to existing efficient technology and rich material, there are too many factors to consider in this business. ICAO has been supported in studying and researching the feasibility and opportunity for producing AJF in Kenya (Reported on 2018), but it is not in Thailand. Indonesia and Singapore have some help in this issue as well. However, if Thailand and other countries in Asia want to produce AJF from biomass, they will use this approach for scale-up or commercial prototypes with high concern.

This research will elaborate on the recommendations and research results from recent papers related to producing AJF from biomass and present the ideas of the staircase approach as a conceptual integral process design. The goal is to assist some ideas of the step-by-step production of aviation biofuels from biomass in Thailand.

The principle and theory of aviation biofuel from biomass should be mentioned before moving on to any essential components for the production process as follows:

1. A mineral kerosene is equivalent to biokerosene.

2. Biomass can substitute for fossil fuel.

3. Biokerosene is chemically and physically similar to mineral kerosene and is therefore broadly compatible with current fuel storage and engines.

4. A biofuel production system leads to net GHG emission savings and reduces atmospheric CO_2 via removal of carbon and use of H_2.

5. Sustainable biojet fuels not only bring environmental benefits for aviation but also help to develop a new industry.

6. Different conversion technologies may result in different amounts and types of GHG emissions due to the variety of feedstock and reaction processes.

7. Receiving the GHG emission data from the conversion pathways will help determine the optimal platform for producing biojet fuels.

8. Biomass is renewable, and different types of biomass have different carbon contents that can affect jet fuel yield.

Therefore, the team producing aviation biofuels from biomass includes people who are involved in every step-by-step move toward goal achievement, such as any kind ofstakeholder, including farmers, scientists, researchers, technicians, business managers, legal teams, and others, as needed. Thus, the production process should be aware from the start up until the end line. Fortunately, many countries have studied and researched it according to the regulation on the aviation sector from the International Civil Aviation Organization (ICAO). International aircraft must use 50% aviation biofuel in 2030 and 10% now. There are not too many years to think for startup then, Thailand.

Each step of the staircase will bea checklist tool for the readiness of producing AJF from biomass. The challenges and opportunities' elements for Scale-up: There are many factors to be aware of and prepare to deal with. Basically, yield and trading should be made more beneficial for investment. Therefore, Derisk & Low-cost are always the main concerns in controlling this business.

The staircase approach as the model has 2 parts that are determined by activities and authorities. Mission isdefined as all ctions or activities for producing a process toward the end line. There are too many people involved with this part to make this business happen and run efficiently and beneficially on the business. The second part is Supportive. This part is particularly important as well. Specifically, the business of producing aviation biofuel from biomass has become an international infrastructure of the aviation industry. This means that every country that has to use transportation by aircraft and needs to use fuels for running must follow the rules with highly respected performance.

Mission: There are 5 approaches from the beginning toward the accomplishment process as follows.

1. Feedstock & Supply Chains
2. Fuel Conversion and Scale-up
3. Technical Competitiveness
4. ASTM Certified Requirement

5. Environmental Sustainability & Life-Cycle Benefits

Supportive: This part is particularly important, and there are two elements.

1. Economic
2. Government

When the production of aviation biofuels from biomass is set up, every element needs to run the process as an integrated action. Knowledge from experiments in the lab or pilot projects needs to be enhanced for the commercialized category, and essential elements should be realized both directly and indirectly.

Figure 58 Staircase Integral Model is approached to produce Biojets from Biomass

Details of the Staircase Approach:

This ideology will be based on the scope of producing aviation biofuels from biomass, and the raw materials for this study will be biomass: rubber wood, eucalyptus (solid materials), and waste vegetable oil (liquid material) in Thailand. The goal of producing AJF is 100,000 liters/day, which is multiplied from the module of 10,000 liters/day. The pilot project is at Chulalongkorn Biomass Center, Saraburi, Thailand. The optimal pilot project is set for scale-up as a commercial prototype machinery bench facility: Pyrolysis, Gasification, and Fischer Tropsch.

The details on the single step will be based on the production of AJF from biomass in Thailand at 100,000 liters/day.

1. First Step as the beginning: Feedstock and Supply chains

DEDE is the organization of the Thai government that provides information on biomass sources, and everyone wants to obtain recent information from their website www.dede.go.th about locations, prices, and suppliers. According to the candidate biomass in Thailand for producing AJF from second-generation biofuels (from lignocellulosic biomass, such as crop residues, woody crops, or energy grasses). At the pilot site, rubber wood, and eucalyptus are the candidate biomass as raw materials for producing AJF. However, the volume or portion of the raw materials relies on the production plan. Normally, feedstock 5 kgs will be provided to yield 1.0 liter of aviation biofuel.

Other considerations should be considered as well, and they are as follows.

1.1 Feedstock Supply or Corps ‘cycle is important for the operation period. The kinds of raw materials are different not only by zone but also by season. Otherwise, some of them are available year after they are sufficiently grown for use. If investors want to grow the raw materials as preparation for the plant, then they should have land around or near the plant. This choice for investors can be in the planning phase during construction of the plant or looking for sorts that can be materials suppliers. The greatest benefit is reduced cost and ease of operation at the factory site. The cost of feedstock (RW and EW) has used in this research (Table 20) about 41.98 % which the price was 2.5 baht/ kg. It means if the price gets higher then the cost will be higher also. However, the price of waste vegetable oil mostly getting free but it will cost some too. Waste palm oil used to produce aviation biofuel in this research cost 74.36% (0.625 baht/kg). The price by itself was free but the cost came from logistic and types of transportation. Issues of feedstoch is very important to aware and should be on the top list for the consideration on start-up business.

1.2 Types of logistics cause profits as well. This means that there are two-coin sites. It will be a supportive reduce your cost or getting small the investors' benefit. The long distance on logistics will add up to costs such as transportation fuels, labor on transportation, and storage for materials. This includes the logistics of the products to market as well.

The supply chain is shown in Figure 45 using a crop-based feedstock, but it is applicable tomost feedstock types.

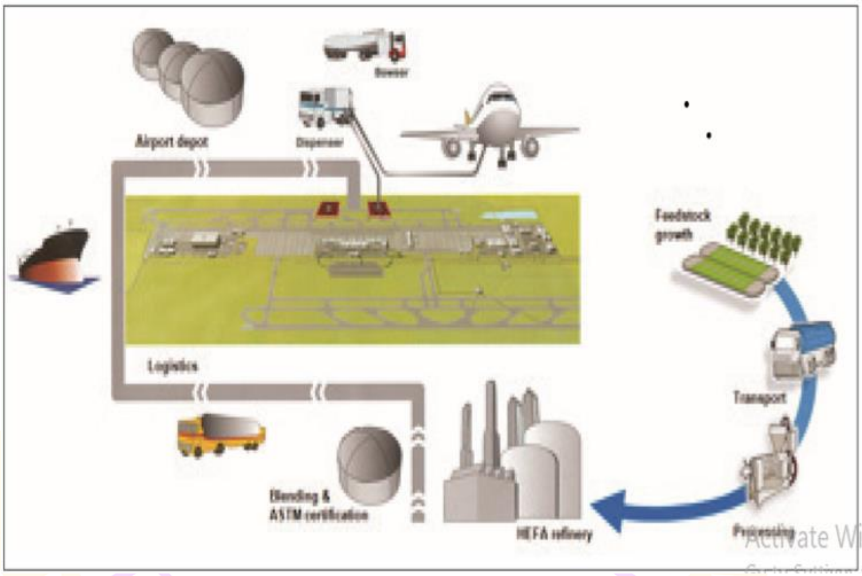
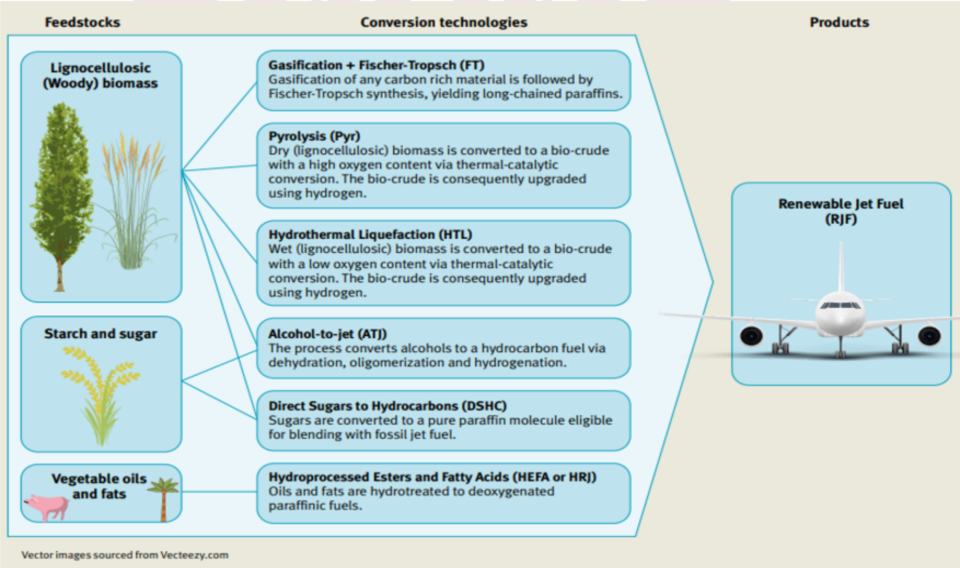


Figure 59 A Schematic Representative of the Sustainable Aviation Fuel Supply Chain (Crop-based)

1.3 Plant 's location & size: this concern should be choosing before the investor has a business plan to pursue such as fund and business consult team then getting the draft for the plant already. The legal start-up certificate must be issued. The financial or budget plan is very related and important to this step not only with the start-up but also the whole cycle of this business. Many feasible options or business plans should be set for righteousness and readiness.The recommendation from Consultation's members such as Financial, Professional Technician, Scientist, Business, Legal, Teamwork, Researcher, and others as needed.

2. Second Step: Fuel Conversion and Scale-up.

According to the Biomass Conversion Technology to Aviation Biofuel, there are various factors related to the production of kerosene. Theoretically, from reviewing research as published some more ideas and details are as follows.



Gasification + Fischer-Tropsch (FT)
Gasification of any carbon rich material is followed by Fischer-Tropsch synthesis, yielding long-chained paraffins.

Pyrolysis (Pyr)
Dry (lignocellulosic) biomass is converted to a bio-crude with a high oxygen content via thermal-catalytic conversion. The bio-crude is consequently upgraded using hydrogen.

Hydrothermal Liquefaction (HTL)
Wet (lignocellulosic) biomass is converted to a bio-crude with a low oxygen content via thermal-catalytic conversion. The bio-crude is consequently upgraded using hydrogen.

Alcohol-to-jet (ATJ)
The process converts alcohols to a hydrocarbon fuel via dehydration, oligomerization and hydrogenation.

Direct Sugars to Hydrocarbons (DSHC)
Sugars are converted to a pure paraffin molecule eligible for blending with fossil jet fuel.

Hydroprocessed Esters and Fatty Acids (HEFA or HRJ)
Oils and fats are hydrotreated to deoxygenated paraffinic fuels.

Vector images sourced from Vecteezy.com

Figure 60 Conversion BtA Pathways

From Figure 47, another elaborates which more details are as follows.

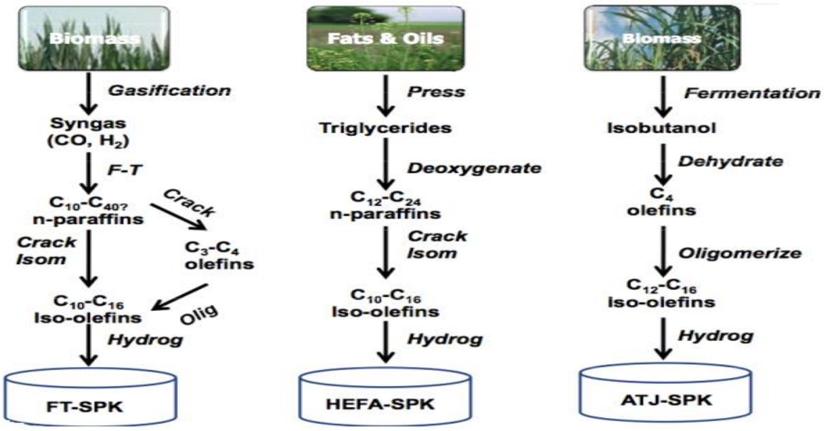


Figure 61 BtA Conversion Details Process

The yields from various kinds of biomass have been the choice for producing aviation biofuel. During the pilot project operation, the yield is used to study how much/which raw materials can provide significantly different amounts of kerosene. It will not project to the cost and cause on producing much. In business or risk management, investors should be concerned because the yield is most related to marketing and benefits.

Arturo Benito, Gustavo Alonso, in Energy Efficiency in Air Transportation, 2018: They have mentioned to Aviation Biofuel and how it should be in the business as follow.

“The task of finding the right product is proving to be extremely difficult. A key element is the number of changes that a new and different fuel might require in the air transport system. Aircraft and airport designs are made based on using gasoline, kerosene orother fuels with similar chemical and mechanical properties. Departingthis assumption leads to a major refurbishment of the complete logistics (transportation, distribution, storage) and, perhaps, new requirements for the engine and fuel tank design. As commercial aircraft architecture is a very integrated discipline, such changes suggest a total redesign of the airplane in a different structure than today’s tube-with-wings. The two main research lines in this area are focused on the production of a liquid so similar to the fossil kerosene that can be mixed with it, keeping the same properties. The term drop-in describes this type of fuel. A second and relatively new approach is the use of some electrical source of energy, if not for a total replacement of the kerosene, for a partial substitution of some of the tasks requiring engine energy in modern aircraft, such as air conditioning systems or hydraulic systems. A second step would be the hybrid concept, with the aircraft using kerosene in high powered phases of the flight (takeoff, initial climb) and going to electricity in low power ones, like cruise or approach.”

Another concern regarding the use of alternative fuels is focused on the environmental cause rather than the economic effect. Thus, there has been a high level of research and consequent testing to find an alternative to kerosene. The reasons are diverse: first, oil is a nonrenewable resource and will be finished at an unknown date in the future; second, having an alternative source might give airlines a choice, and getting some more control on the fuel market than depending of a single provider; and finally, the alternative fuel should be more ecological and its production cycle would leave a smaller carbon footprint, reducing local and climate change emissions.

All biomass energy systems suffer from the economic barrier associated with the energy cost of producing, transporting, and preparing the biomass feedstock. Significant progress has been made in this area, but to be truly economically competitive, new feedstocks and methods for their harvest and preparation must be developed. The harvesting, preparation, transportation, and feeding of a variety of biomass feedstocks suitable for power production must be demonstrated, and new methods developed for reducing costs and energy requirements must be verified. This will reduce the delivered cost of feedstock to the energy facility to a level more competitive with fossil fuels.

Table 16 Alternative Fuel Compared to Conventional Jet Fuel

Route	Feedstock	Biojet GHG emissions gCo2e/MJ	Fossil jet gCO2e/MJ	Saving CO2e%
Gassification and fischer–Tropsch	Energy crops	9–13	87.5	85–90
	Forestry residues	6		95
Pyrolysis	Forestry residues	22–40		54–75
Alcohol to jet	Corn	55		37
	Corn stover	35		60
	Sugar cane	26		70

Direct sugar to hydrocarbons (DSHC)	Sugar cane	72	18
Hydroprocessed esters and fatty acids (HEFA)	Oilseed rape, soy	40–108	20–54
	jatropha	55	37
	Camelina	47	46
	Used cooking oil	27	69

Thermochemical routes to turn biomass into biojet fuel

The major challenges for thermochemical routes to biojets differ mainly in conversion-process efficiency and technology risks, although feedstock choices can also result in qualities in the end product. Thermochemical routes used to turn biomass into biojets involve the production of three main products in different ratios: bio-oil, synthesis gas and char. The two main thermochemical routes to biojets are gasification and pyrolysis, and hydrothermal liquefaction thermochemical routes to biojets differ mainly in conversion-process efficiency and technology risks, although feedstock choices can also result in qualities in the end product. Thermochemical routes used to turn biomass into biojets involve the production of three main products in different ratios: bio-oil, synthesis gas and char. The two main thermochemical routes to biojets are gasification and pyrolysis and hydrothermal liquefaction (HTL). The FT process uses gasification combined with synthesis to produce biojets. Several commercial facilities based on gasification-FT are planned, and this pathway is discussed in more detail below. The pyrolysis route to the biojet is known as the HDCJ (hydrotreated deploy mortised cellulosic jet). An ASTM application for HDCJ was initiated by KiOR, but the company is now in bankruptcy, creating a setback for the certification of this pathway. Biomass pyrolysis is the thermal depolymerization of biomass at modest temperatures in the absence of added oxygen. Pyrolysis as defined is a process of thermal decomposition occurring in the absence of oxygen. Pyrolysis of biomass is a complicated multistage reaction for which many pathways and mechanisms have been proposed. The best known is the model developed by Broido and Shafizadeh for pyrolysis of cellulose that can also be applied, at least qualitatively, to whole biomass. There are two types of pyrolysis: fast and slow

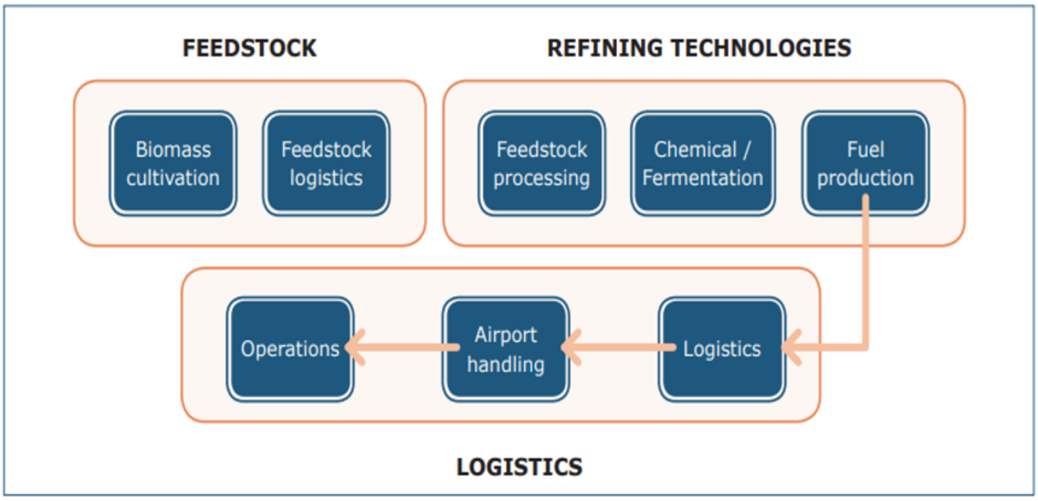


Figure 62 Brazil's Roadmap components for biofuels to the aviation industry

3. The Third Step: Technical Competition

In this step, the main concern is for the great benefit from yields. Benefits are the main part of the business mission. Yields from the operation rely on proper choices that are maintained at low cost. Technology will be a great mission action for producing aviation biofuel from biomass.

Table 17 Biojet Production Technology

Category	Pathway	Feedstocks	Intermediate	Intermediate yield	Jet Fuel Yield		Final Jet Fuel Cost
				GGE/BOT	Gal/BOT	GGE/BOT	$/gal, GGE
GTG (Gas to Jet)	Fisher –Tropsch	Coal, Biomass, Corn Stover, Wood	Syngas to Hydrocarbons	44.11	9.88	9.89	$6.2, $5.8
	Gas Fermentation	Wood, vegetable, and household waste	Syngas to Ethanol	66.77	44.52	45.53	Not Available
ATJ (Alcohol to Jet)	Ethanol to jet	Corn, Wood, Straw, Switchgrass, Sugarcane	Ethanol	16.106	11.79	11.81	$4.1–$14.4, $3.8–$13.4
	Butanol to Jet	Corn, Wheat, and wood chip	N–Butanol Iso–Butanol	31–57, 55	23–43, 41–48	24–43, 42–49	$4.1–$7.5, $3.8–$7.0
	Methanol to jet	Corn, Wheat, and wood chip	Methanol	NA	NA	NA	Not Available
OTJ Oil to Jet	HEFA or HRJ or Bio–SPK (Synthetic Paraffinic Kerosene)	Soybean, Algae, Palm seed, Jatropha seed, Salicornia, Cooking oil	Bio Oil	50–141	28–87	28–98	$2.6–$34.7, $2.4–$32.0
	Catalytic Hydro the osmosis (CH)	Algae Biomass, Soybean, Jatropha, Dairy waste	Bio Oil	50–102	8–122	9–129	$4.8, $3.8–$4.5

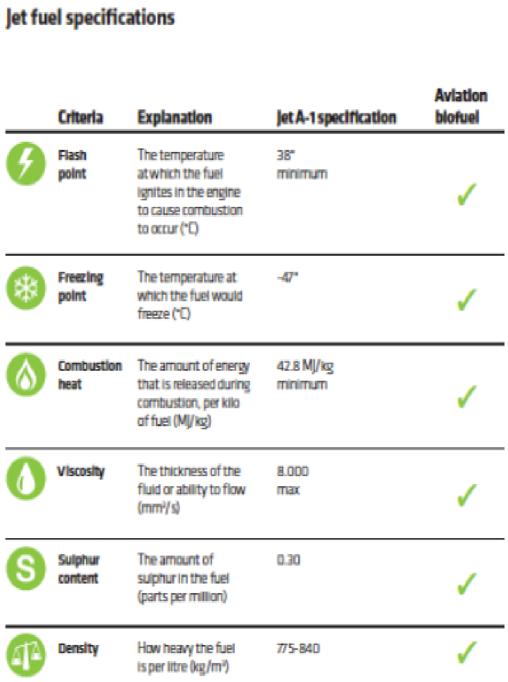
Table 17 (Cont.)

Category	Pathway	Feedstocks	Intermediate	Intermediate yield	Jet Fuel Yield		Final Jet Fuel Cost
				GGE/BOT	Gal/BOT	GGE/BOT	$/gal, GGE
	Hydrotreated Depolymerized Cellulosic Jet (Pyrolysis or HDC)	Corn stover and wood	Pyrolysis Oil	50–153	19	19	$3.9
Sugar to Jet	Catalytic Conversion of sugar APR	Corn stover and wood	Hydrocarbons	45–78	14.25	15–25	NA
	HMF and DMF	Fructose (HMF and DMF)	HMF and DMF	75–90	52–62	53–64	NA
	Direct Sugar Biological to Hydrocarbon (DSHC)	Corn stover, Sugarcane, wood, Wheat Straw	Fatty Acid and Farnesene	59	24–43	24–45	$4.5–$17.3, $4.0–$23.3

Note: GGE = Gallon of gasoline equivalent

BOT = Biomass dried ton

Source: Wei Cheng Wang, et al. 2016



Jet fuel specifications

	Criteria	Explanation	Jet A-1 specification	Aviation biofuel
	Flash point	The temperature at which the fuel ignites in the engine to cause combustion to occur (°C)	38° minimum	✓
	Freezing point	The temperature at which the fuel would freeze (°C)	-47°	✓
	Combustion heat	The amount of energy that is released during combustion, per kilo of fuel (MJ/kg)	42.8 MJ/kg minimum	✓
	Viscosity	The thickness of the fluid or ability to flow (mm²/s)	8.000 max	✓
	Sulphur content	The amount of sulphur in the fuel (parts per million)	0.30	✓
	Density	How heavy the fuel is per litre (kg/m³)	775-840	✓

Image: Beginner's Guide to Aviation Biofuel, Air Transport Action Group

Figure 63 Aviation Biofuel Specification

This research aimed to operate pilot horizontal gasifiers of RWPs and EWCs to produce syngas with a H2//CO ratio range of 1.75–2.25for FT synthesis. A lab-scale gasifier was used with both raw materials to determine the optimum gasifying temperature of 90°C, and the tar yield was less than 2 wt% when CaO was used as the tar reforming catalyst. A temperature 900 °C and CaO were set up in a pilot horizontal gasifier. The pilot gasifier comprised a tar removal system, gas purification system and gas pressurized buffer tank system. The steam/biomass ratio affects the gas product composition and H2/CO ratio. The steam/biomass ratio of 0.47–0.059 gave a H2/CO ratio in the range of 1.75–2.25. The stability of syngas production and gas composition of both raw materials for 7 days was accomplished. The gas production rates were 2.48 and 2.67 kg/h with H/CO ratios of 1.75 and 1.89 for the RWP and EWC, respectively. The supply of an external heat source stabilized the gasifying temperature, resulting in a stable gas composition. In summary, the horizontal gasifier is another effective designed gasifier that shows high-performance operation. The results of this research have confirmed that the gasification and FT process has great performance in the conversion of AJF with rubberwood and eucalyptus as raw materials. Additionally, the pyrolysis process is the right technology for converting waste vegetable oil to AJF.

4. Step # 4: ASTM Certification

At this step, it will be proof that the yields are qualified for use with aircraft. In other words, the production is ready to be in the markets and obtain more profits. This step is about accreditation from IATA before the international aircraft business can purchase it. It will takemore than 2 years before IATA has proven the products. During the waiting time, the product of the process will accumulate the benefit as well. Bio Jet is the main idea for focus on, but aviation biofuel needs more time to get through international qualifications. The stakeholders who invested in this kind of business should be known or foreseen on their business as much. Then, the sample for the result from the lab should be the priority to concern in the business plan.

Facts, during the operation for getting Aviation Biofuel, the production is not obtained totally of only Bio Jet, but others biofuel will be come along such as diesel, ethanol, LPG, and more. Then, the benefits will get more during the operation from others production. Business plans are the most important part for all.

5. Step # 5: Environment & Sustainability

This step is more general on the global or national or local concerned. It means everyone should do the right thing to protect the environment and safe nature. Human beings like us, and animals still live by using natural products and consume many elements from nature and then engage in sustainable actions for sharing goods with others. Many sectors have mentioned CO_2 emissions and reduction or replacement as alternatives to fossil fuels. It is very limited for all. Biofuel is a renewable energy that is highly supportive.

The research results on the volume of CO_2 were less than 18% of the gaseous volume (RWP 14.98% and EWC 17.29%). This means that the gaseous component complied with the reduction in CO_2 emissions. Precisely, farmers and people will get more jobs. Economic should be changed better when people get more jobs and have money for their living. Waste management will get more valuable and circulate all waste for supporting to producing energy as Aviation Biofuel and better environment as need.

6. Step # 6: Economic

This step focuses on the benefits that are directly related to the financial elements. It should be started with the Business Plan for selling ideas to investors, bankers, shareholders, and teammates: scientists, researchers, technicians, attorneys, and secretaries. The business plan is always projected to be 3, 5, 10, and more years with a great vision that shows high yields, optimal choices, and more practicality. However, this step will be in contact with many systems, not only the economy but also society, culture and too many organizations. The commercial site will be in the community, and there are many existing organizations, cultures, and races. Perhaps varieties of careers or different businesses existed already. The economic system will involve two major things people and their activities of living.

Cost benefit analysis is a tool for investors in the long term or short term. Fundamental for cost analysis components are as follows: (Investopedia) What Is a Cost Benefit Analysis?

A cost benefit analysis is a systematic process that businesses use to analyze which decisions to make and which to forgo. The cost benefit analyst sums the potential rewards expected from a situation or action and then subtracts the total costs associated with taking that action. Some consultants or analysts also build models to assign a dollar value to intangible items, such as the benefits and costs associated with living in a certain town.

The 5 steps of cost benefit analysis is to set the analysis plan, determine your costs, determine your benefits, perform analysis of both costs and benefits, and make a final recommendation. These steps may vary from one process to another. The main goal of cost benefit analysis is to determine whether it is worth undertaking a project or task. This decision is made by gathering information on the costs and benefits of that project. Management leverages the findings of a cost benefit analysis to support whether there are more benefits to a project or if it is more detrimental to a company.

Cost Benefit Analysis

Pros

1. Requires data-driven analysis.

2. Limits analysis to only the purpose determined in the initial step of the process.

3. Results in deeper, potentially more reliable findings

4. Delivers insights into financial and nonfinancial outcomes.

Cons

1. May be unnecessary for smaller projects.

2. Requires capital and resources to gather data and make analysis.

3. Relies heavily on forecasted figures; if any single critical forecast is off, estimated findings will likely be wrong.

Cost benefit analysis is a systematic method for quantifying and then comparing the total costs to the total expected rewards of undertaking a project or making an investment. If the benefits greatly outweigh the costs, the decision should go ahead; otherwise, it should probably not. Cost benefit analysis will also include the opportunity costs of missed or skipped projects. The main goal of cost benefit analysis is to determine whether it is worth undertaking a project or task. This decision is made by gathering information on the costs and benefits of that project. Management leverages the findings of a cost benefit analysis to support whether there are more benefits to a project or if it is more detrimental to a company.

The process of performing a cost benefit analysis itself has its own inherent costs and benefits. The costs involve the time needed to carefully understand and estimate all of the potential rewards and costs. This may also involve money paid to an analyst or consultant to carry out the work. One other potential downside is that various estimates and forecasts are required to build the cost benefit analysis, and these assumptions may prove to be wrong or even biased. According to this research's results is whitin of yields (Gasification process was operation 10 days; Pyrolysis process was operation 3 days) 10,000 kgs/days. The idea for the production is 100,000 kgs/day as scale up operation in commercial. It means everything such as raw materials, energy, work cost, and other ingredients should be multiplied by 10. For example, on gasification process used Rubberwood and Eucalyptus for 10 days operation;

Table 18 Cost estimation for Gasification and FT Process for 100,000 kg/days yields

Basis: 10,000 kg liquid/d or 8,000 kg pure kerosene/d x10 = 100,000 kg/d or 80,000kg pure kerosene

Investment 500 MB operation 10 years

No.	Item	Quantity	Price/unit	Amount (Baht)	%
Gasification process					
1	Biomass and preparation	1.5 tons x 10 = 45tons	2.50 baht/kg	112,500x10=1,125,000	41.98
2	Electricity	1 000 kWh x24	5.62 baht/kWh	134,880x10=1,348,800	50.33
3	Wages	12 person	800 baht/d	9,600x10=96,000	3.58
4	Chemical & gas			6,000x10=60,000	2.23
5	Utilities			15,000x10=150,000	5.59
6	Maintenance			5,000x10=50,000	1.87
	Total for gasification			**267,980x10=2,679,800**	100
FT synthesis					
1	Catalyst & gas			10,000x10 = 100,000	7.57
2	Electricity	500 kWh	5.62 baht/kWh	67,440 x 10= 674,400	51.08
3	Wages	12 person	800 baht/d	9,600 x 10 = 96,000	7.27
4	Utilities			15,000 x 10 = 150,000	11.36
5	Distillation& purification	10,000 kg	2,5 baht/kg	25,000 x 10 = 250,000	18.98
6	Maintenance			5,000 x 10 = 50,000	3.74
Total for FT synthesis				**132,040 x 10 = 1,320,400**	100
Total for operating cost				**400,020 x 10 = 4,000,200**	

Table 18 (Cont.)

Basis: 10,000 kg liquid/d or 8,000 kg pure kerosene/d x10 = 100,000 kg/d or 80,000kg pure kerosene					
Investment 500 MB operation 10 years					
No.	**Item**	**Quantity**	**Price/unit**	**Amount (Baht)**	**%**
80% After purification (kg)				8,000 x 10 = 80,000	
Operating cost biojet (baht/kg)				50.00 x 10 = 500	
Investment cost (baht/kg)				20.83x10 = 208.30	
Total cost of biojet (baht/kg)				**70.83**	
Sustainable aviation fuel (SAF) pricing $3,800/ton –> baht/kg (FOB)				**133.00**	

The cost analysis of Biojet from the gasification and FT process (Figure 50 Table 10 and Table 14) showed significantly different prices between the experimental operation and global market per kg 70.84 B and 133 B. Then scaling up this business via this technology is feasible. Another operation from waste vegetable oil is shown to be feasible in terms of economy and environmental friendliness (without the approval of ICAO yet).

7. Step 7: Government Policies

Legality issues for businesses are very important, especially government policies. The Start-up gate for business is the Commercial Registration as Commercial businesses from the Ministry of Commercial after you have applied for Factory License. Otherwise, the previous mentioned should be in the business plan but the main the Government Policies in this staircase is the supportive action for help your business move on into international trading system such as consulting sectors in many categories for helping businessmen, provide the ease legal for registration to work on. There are many stakeholders, private sectors, and Thai Government organizations who should be working together for the policies and planning on producing aviation fuel from biomass: MoEN= Ministry of Energy, MoI= Ministry of Industry, MoC= Ministry of Commerce, MoA= Ministry of Agriculture and Cooperatives, MoT= Ministry of Transportation, MoD= Ministry of Defense, MHESI= Ministry of Higher Education, Sciences and Innovation, MoN= Ministry of National Resources and Environment, MoIn= Ministry of Interior, LGO= Local

Government Organization, AoT= Airport of Authority of Thailand, CAAT= Civil Aviation of Authority of Thailand, DEDE= Department of Alternative Energy Development and Efficiency, DoA=Department of Agriculture. Thai Government has been started at state of Brainstrom for getting ideas and setting the direction

The consideration for producing aviation biofuel from many factors in Thailand via the technologies of either gasification and FT-process (solid raw materials) or pyrolysis process are based on this research, and other sources then used for SWOT analysis are shown in the following table.

Table 19 SWOT analysis of the production and use of aviation biofuel in Thailand

	Strength	Weakness	Opportunity	Treats
1.Raw Material Rubberwood, Eucaryptus, Corn cob, Casava Root, and Bagasse	The cost of raw materials is cheap and low cost of labor.	Uncertainly of quantity and price	Increasing labor and income for farmers	Weather is not stability will be affected on quantity and trade
2. Technology Gasification and FT-Process, and Pyrolysis	Researcher have been worked on this area	Lacking integral work between the groups	The production of Biofuel can be the supplier for producing Biojet	The approved from ICAO and global price should be the big barrier
3. Policy Stakeholder, Investors, Banker, Money Institution, and Government Sectors	Government concern as urgent support on Biojet	No specific plan and lacking integration of information among the relation departments	Thailand should join the CORSIA plan as urgent for extended the commercial industry and the international flight	The uncertainly of raw materials price and quantity plus the measurement rule of ICAO

In general, the government of every country, their authority on the supporting business sectors on running for the better economy. People are the main concern and are the gear for movement in the right direction and good relationship with other countries as well. Many organizations or institutions have to join their mission to set up the best plan and policy on their concerns, such as producing Biojet.

According to this research, the hypotheses are satisfied. The details are as follows:

H-1: The temperature and volume of the catalyst affect the tar reformer, purified syngas, yields from the gasification and FT process operation, and pyrolysis operation.

The research results have proven that the temperature and the volume of catalyst have affected the reduction in Tar for purified yields. Syngas from the gasification process is also fed to the FT-process. In the pyrolysis operation process, the temperature and volume of catalysis affected the yields.

H-2: The pilot reactors (gasification and FT-synthesis, and pyrolysis processes) used in this research for producing aviation biofuel are feasible and can be scaled up for the business industry in Thailand.

The research results have shown that both the gasification and FT process, and the pyrolysis process are appropriate for use in producing aviation biofuel in Thailand.

In addition, the awareness on raw materials type for using on the production aviation biofuel is necessary for proper choosing the right technology because the good number of quality and quantity of yields will be related to the business benefits. Thailand has many kinds of residue (agriculture, foresty, and factories' waste) which need to manage and use for proverting to renewable energy.The investor should be concerned on the quantity of feedstock because in the business factory which always running or operation all the time for getting good benefit.Good plan on Where the plant could be getting feedstocks either purchased them or do farming on the scale up by yourselves on the land of factory plant, and mature for feeding the factory operation enough portion. Things have mentioned in the Stairecase Model could be an assisting tools and project the views of stakeholder and business investor for producing aviation biofuel.

CHAPTER V

Conclusions

The main content of " **A Study Conceptual Process Design for the Production of Aviation Biofuel in Thailand**" was divided into three parts. The first was the study of aviation biofuel via gasification followed by FT synthesis. The second was a new alternative production of aviation by catalystic pyrolysis, and the third was the proposed conceptual integral process design study for the production of aviation fuel. The conclusion of each part was concluded as follows.

Aviation biofuel produced by biomass via gasification and FT synthesis.

Both processes were set up, and the reaction was carried out in a pilot reactor at the Center of Fuels and Energy from Biomass, Chulalongkorn University, Saraburi.

The rubber wood pellets and eucalyptus wood chips used in the gasification process provided the gas components 44.65% H_2, 23.69% CO, 17.29% CO_2, 7.54% CH_4, 6.82% N_2, and a very low level of O_2 and ratio of $H_2/CO = 1.88$, which is the suitable range of 1.75–2.25.

The aviation biofuel (Kerosene, C_8–C_{16}) preparation was reviewed from the article, which was published by a research group operating FT synthesis at Saraburi supported by JICA. The results showed the high performance of the $Co/ZrO_2–SiO_2$ bimodal catalyst via the FTS reaction, which provided a CO conversion of 58.6% and a C_8–C_{16} selectivity of 78.8%. This catalyst will be used for aviation biofuel production in pilot plants by the end of the next year (2023).

The estimation of cost per kg of aviation biofuel for production of 10,000 kg/d including operating and investment cost was 70.83 baht/kg, while pricing in the market of sutainable aviation fuel (SAF, or aviation biofuel) is $3,800 /ton or 133baht/kg ($1 dollar = 35 baht)

Aviation biofuel produced by waste vegetable oil via the pyrolysis process.

Waste palm oil, Used cooking oil and animal fat were used as raw materials for biofuel production by using calcined dolomite as a catalyst in a pilot plant in Saraburi.

This process provides a product yield range of 61-69%. The composition in liquid biofuel was composed of naphtha, kerosene, diesel, and fuel oil, in which kerosene shared approximately 21.95 to 23.90%.

The estimated cost per kg of aviation biofuel (Kerosene) for the production of 800 kg/d, including operating and investment costs, was 34.75 baht/kg. The advantage of this process is lower cost production than the FT synthesis process and vegatable hydrocracking, whereas the disadvantage is only 25% of aviation fuel produced in the total yield.

Proposed conceptual integral process design study for the production of aviation fuel.

Aviation fuel from biomass in Thailand can startup and has a high degree of readiness for operation. In Thailand, there are enough materials, such as corn cobs, casava roots, and wooden debris, for many kinds of biomass at low cost. from furniture factories or forest. In addition, many local projects have been starting to work on producing fuel from waste products from animals, cooking oils, plastic pets, and others. Their products still have **kerosene** at least 25-28%, and then the catalyst can change by cracking carbon to be the aviation fuel. This means that the local sector will be the supplier for producing aviation biofuel really well.

Discussion

The results from this research confirmed the rightness technology for conversion Biomass to AJF via Gasification and FT – Process, and Pyrolysis is the right technology also. The details are in Chapter IV, which provides feasible and utilized messages for investors who want to invest and support this revenue:

Regarding the objectives and scopes of this research, there are 2 objectives, and the primary data and secondary data are suitable for both. The first objective was to determine the best practice of “How to do with the righteousness way for producing

Aviation Biofuel." Beyond the research results from the experiment, we found the important elements (feasible & suitable) for producing Aviation Biofuel via the Pilot Horizonal Gasifier and FT-Process for the Commercial Industry with solid raw materials that pellet and chip form and are based on yields of 100,000 /day (Chapter IV). The raw material of 5 kg will yield 1 liter. A suitable technology for waste vegetable oil as a raw material is the catalytic pyrolysis process. The answer for the second research objective was a study conceptual process design for producing aviation biofuel in Thailand. The staircase model has two parts (Mission & Supportive) and 7 steps. The details of each step are in Chapter IV as well. The Staircase Model will also be a guideline for investors who want to invest in the aviation industry in Thailand or other places. Unfortunately, Thai Government doesn't have specific on the government policies and plan but the good plan will be set on for start-up in near future. However, the International regulation on aviation business has set on the year 2030 and 2050 for aviation biofuel already existing. The extended research on aviation biofuel should be focus on the reduction CO_2 emission of aircrafts which use the production of aviation biofuel in Thailand.

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APPENDIX

Appendix A ACS Omega

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Article

Syngas Production for Fischer–Tropsch Synthesis from Rubber Wood Pellets and Eucalyptus Wood Chips in a Pilot Horizontal Gasifier with CaO as a Tar Removal Catalyst

Nantana Lamart Slatter, Bunyawat Vichanpol, Jaru Natakaranakul, Kanit Wattanavichien, Phorndranrat Suchamalawong, Keiichiro Hashimoto, Noritatsu Tsubaki, Tharapong Vitidsant,* and Witchakorn Charusiri*

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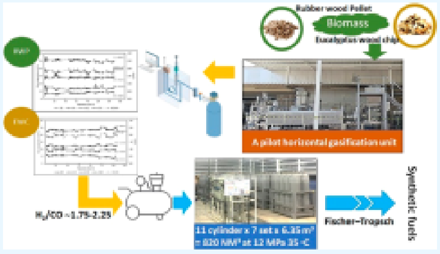

ABSTRACT: This research aims to investigate steam biomass gasification in a pilot horizontal gasifier using rubber wood pellets (RWPs) and eucalyptus wood chips (EWCs) for producing syngas with an H_2/CO ratio range of 1.8 to 2.3 for Fischer–Tropsch synthesis. The study was divided into two parts. One was carried out in a lab-scale reactor to determine the effect of temperature and CaO on the gas product composition and the efficiency of tar removal. Another part was determined by investigating the effect of the steam/biomass (*S*/*B*) ratio on the produced H_2/CO ratios in the pilot horizontal gasifier, which used the optimum conditions of temperature and % loading of CaO for tar removal according to the optimal conditions from the lab-scale gasifier. The lab-scale gasifier results showed that H_2 and CO_2 increased with temperature due to primary and secondary water gas reactions and hydrocarbon reforming reactions. The water gas shift and hydrocarbon reforming reaction depressed the CO and CH_4 contents with increasing temperature, respectively. The optimum gasifying temperature was 900 °C, which obtained H_2/CO ratios of 1.8 for both RWPs and EWCs. The tar yield decreased with increasing temperature and was less than 0.2 wt % when using CaO as a tar-cracking catalyst. The operation of the pilot horizontal gasifier at the operating condition of 900 °C and a *S*/*B* ratio of 0.5 using 0.2 wt % loading of CaO for tar removal also produced a H_2/CO ratio of 2.0. The supply of an external heat source stabilized the gasifying temperature, resulting in a stable syngas composition and production rate of 2.5 and 2.7 kg/h with H_2/CO ratios of 1.8 and 1.9 for the RWPs and EWCs, respectively. In summary, the horizontal gasifier is another effective designed gasifier that showed high-performance operation.

1. INTRODUCTION

With the progress of economic and social development, the rapid increase in global energy demand raises the serious problem of energy supply, whereas the consumption of traditional fossil fuels released from electricity generation, industrial manufacturing, and other activities using fossil fuel is a major impact on greenhouse gas emissions and the global warming phenomenon. The development of super clean alternative renewable energy to replace conventional fossil fuels has attracted more attention and sustainability challenges to reduce greenhouse gas emissions while meeting the rapidly increasing world energy demand. Among the alternative renewable fuels, biomass has attracted interest as a potentially carbon-neutral and abundant energy resource, providing clean fuels to achieve the ambition of negative CO_2 emissions.[1,2]

Gasification of biomass is a promising prominent thermochemical technology that converts a carbonaceous material into a CO and H_2-rich gas at small and medium scales used for energy and chemical applications[1−4] that can be increasingly considered for power generation or further conversion into valuable chemicals such as substitutes for natural gas, biohydrogen, or Fischer–Tropsch (FT) biofuel.

Generally, the direct supply of gas to internal combustion engines is its main advantage. Among all utilizations of biomass, gasification has been presented as a possible process for fuel gas production, synthetic fuels, and chemicals because it has a low investment cost and high rate of gas production.[3,4]

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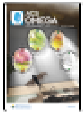

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The principal reactions during the gasification of biomass, coal, or their blends are presented as the following chemical reactions.[5−7]

Boudouard

$$C + CO_2 \rightarrow 2CO \qquad \Delta H = 172.5\ \text{kJ/mol} \tag{1}$$

Primary water gas

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H = 131.3\ \text{kJ/mol} \tag{2}$$

Secondary water gas

$$C + 2H_2O \rightleftharpoons CO_2 + 2H_2 \qquad \Delta H = 90.2\ \text{kJ/mol} \tag{3}$$

Methanation

$$C + 2H_2 \rightleftharpoons CH_4 \qquad \Delta H = -74.9\ \text{kJ/mol} \tag{4}$$

Water gas shift

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \qquad \Delta H = -41.2\ \text{kJ/mol} \tag{5}$$

Steam reforming

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad \Delta H = 206.2\ \text{kJ/mol} \tag{6}$$

Dry reforming

$$CH_4 + CO_2 \rightleftharpoons 2CO + 2H_2 \qquad \Delta H = 247.4\ \text{kJ/mol} \tag{7}$$

The syngas composition normally depends on the biomass feedstock, the gasifier type, the type of oxidizing agent, the temperature, and the residence time in the gasifier.[8] Gasification reactors can be classified into three types: fixed beds, fluidized beds, and entrain beds.[9,10] A fixed bed consists of three configurations: updraft, downdraft, and cross draft.[11] Downdraft gasifiers are used the most for small power plants using internal combustion engines.[12] However, there are some problems when low bulk density biomass is used as the feedstock.[13] A large difference in the temperature profile inside the reactor is one disadvantage of the downdraft reactor because the reaction rate is not uniform over the area.[14] It is difficult to control the feed rate of the feedstock, which is operated in batches instead of continuous feeding. Furthermore, there are potential difficulties with ash fusion and the necessity to have feedstock with a moisture content less than 25%, and the ash discharge rate is another problem as well.[15] Some of these disadvantages were solved by designing a horizontal reactor system,[12,15−18] which can be used with biomass feedstocks that contain moisture up to 30% and has the effective process for syngas production in the appropriate H_2/CO ratio for further FT synthesis. However, the instability of temperature inside the reactor is still a problem; thus, this research attempts to supply the external heat source to control the temperature. The tar formation problem during biomass gasification is the major challenge in current thermal gasification. Tar may condense and tend to form polymers with a more complex structure, such as phenolics, mono- and polyaromatics, heterocyclic aldehydes, and alkyl derivatives of aromatics,[19] which are a serious drawback for the use of syn gas for biofuel synthesis or chemicals. For steam gasification, experiments have reported that increasing the steam/biomass (S/B) ratio reduces the tar yield due to an enhanced steam reforming reaction.[20−22] Moreover, at high temperatures, above 800 °C, higher S/B decreases all tar species. In the case of steam gasification, reported experimental results have shown that increasing the S/B ratio reduces the tar yield due to enhanced steam reforming reactions,[21−26] although the effect on the tar composition depends on the operational temperature. At sufficiently high temperatures, above 800 °C, all tar species decrease with the S/B ratio, but below 750 °C, the increase in the S/B ratio diminishes secondary tars but increases light aromatic tars.[24]

The catalysts that were reported to have high performance in removing tars from the producer gas were classified into three groups: (1) natural catalysts, such as CaO from $CaCO_3$ and CaO and MgO from dolomite; (2) alkali-based catalysts, such as Li, Na, and K; and (3) metal-based catalysts, such as nickel catalysts.[22,27−30] In this work, CaO was used as the catalyst. CaO not only acts as a CO_2 sorbent but also as a tar-reforming catalyst.[23,27] In addition, the catalytic reforming of tar using CaO not only reduces the tar amount in the product gas but also enhances the hydrogen and total gas yields.[31,32] Mahishi and Goswami[33] reported the use of CaO for increasing H_2 and decreasing CO_2 from steam gasification of southern pine bark in a batch-type gasifier and showed the effect of CaO as bed material on produced gas: CO_2 decreased from 28.4 to 26.7 vol %, while H_2 increased from 62.0 to 65.5 vol % at 700 °C.

This research aims to investigate the use of rubber wood pellets (RWPs) and eucalyptus wood chips (EWCs) for biomass gasification in a pilot horizontal gasifier connected with tar removal using CaO as a tar-reforming catalyst. The gasifier, which was designed specifically for FT syngas production, was created in the horizontal rotary vessel, in which the shape was similar to the rotary kiln with a slight degree of inclination.[12,16,17] The advantages of this custom-built pilot horizontal gasification system allowed for the control of the H_2/CO ratio in the required range of the downstream FT synthesis process. All equipment and operation procedures were designed to ensure that syngas production, which focused on the productivity and quality of produced syngas with high purity and high heating value in long-term operation, was conducted for at least 7 days for each operation sequence. In the first step, gasification at the lab scale is carried out, followed by tar removal to determine the optimum temperature, which provides a H_2/CO range of 1.8−2.3 and the lowest tar presented. The gasification temperature of the pilot horizontal gasifier is used from the lab-scale reactor result. The effect of the biomass/steam ratio on the H_2/CO ratio and average gas product composition are investigated. The stability of the operation was also investigated and discussed.

2. METHODS

2.1. Biomass Feedstock. The lab-scale and pilot horizontal gasifier units were operated with two different types of biomasses, which were rubber wood and eucalyptus wood. The lab-scale reactor used fine particles of both raw materials, while the pilot reactor used RWPs and dried EWCs. The wood pellet was cylinder shaped and 8 mm in diameter and 30−80 mm in length. The size and shape of wood chips were proven by testing the behavior of biomass in the feed system, including channeling formation and movement downward in the hopper and obstruction in the screw feeder. Sieving should help control the size and shape of wood chips and is beneficial for homogeneous biomass. The average size of the wood chips used was 5−10 mm. The physical and chemical properties of the biomass feedstock were analyzed, as shown in Table 1. The biomass characteristics and proximate and ultimate analyses were determined using the ASTM D3172-

Table 1. Characteristics of Biomass[a]

	rubber wood pellets	eucalyptus wood chips
moisture content	8.5	8.0
proximate analysis (wt %), d.b.		
volatile matter	79.5	81.4
fixed carbon[b]	18.0	17.9
ash	2.5	0.7
ultimate analysis (wt %), d.b.		
C	49.7	47.8
H	6.0	5.8
N	0.3	0.3
O[b]	44.0	46.1
H/C	1.4	1.5
O/C	0.7	0.7
heating value, MJ/kg		
LHV, d.b.	18.4	18.4

[a] d.b.: dry basis. [b] By difference.

3175 standard procedure method. Ultimate analysis was measured using a LECO CHN-628 instrument (LECO Corporation, USA) following the ASTM D5373 standard procedure method, and the heating value was determined using a LECO AC-500 (LECO Corporation, USA) according to ASTM D5868.

2.2. Experimental Procedure. This research aims to investigate the operation of a pilot horizontal gasifier using RWPs and EWCs for producing syngas with a specific H_2/CO ratio. The study was divided into two parts. The first experiment was a set of experiments, which were carried out in a custom-built lab-scale reactor to determine the effects of temperature on the gas product composition and tar fraction. The second part was the investigation of the operation of the pilot horizontal gasifier, which was specifically set up for the appropriate gasification temperature received from the first part.

2.2.1. Lab-Scale Reactor. Biomass particles of rubber wood and eucalyptus wood were air dried and ground, and both biomasses were subjected to moisture reduction, milled in an SW-2 high-speed rotary cutting mill (Hsiangtai, the People's Republic of China), sieved into a size distribution of 0.5−0.7 mm and used as feedstocks in this test. The custom-built gasifier reactor comprised a steam generator, flow controller, electric furnace, and ice trap, as shown in Figure 1. The custom-built gasifier reactor was a stainless-steel tube with an inner diameter of 27 mm and length of 893 mm. The reactor was heated using an electric furnace and supplied with steam from a steam generator. The flow controller was used to adjust the N_2 flow rate as the carrier gas at 100 mL/min. Tar from the experiment was collected by a series of three ice traps to confirm that entire tar was completely condensed.

Approximately 10 g of the biomass sample was filled into biomass storage, which was placed on the top of the gasifier outside the heater zone. N_2 was fed into the reactor continuously. When the temperature reached the desired level (600, 800, 900, and 1000 °C), the valve of biomass storage was opened, and then biomass dropped into the gasifier immediately at the same time as steam at 0.5 g/min, which was fed continuously into the gasifier with concurrent flow with biomass sample. The complete reaction time was approximately 10 min. The last experiment was carried out to observe tar removal by using CaO, which was packed into separate layers after being operated at 900 °C. Gas production was collected in a sampling bag from the gas drier unit and analyzed by an Agilent GC7820A gas chromatograph coupled with a thermal conductivity detector (Agilent Technologies, USA). Tar was collected in ice traps, while solid biochar weight was classified as solid yield in percent by weight.

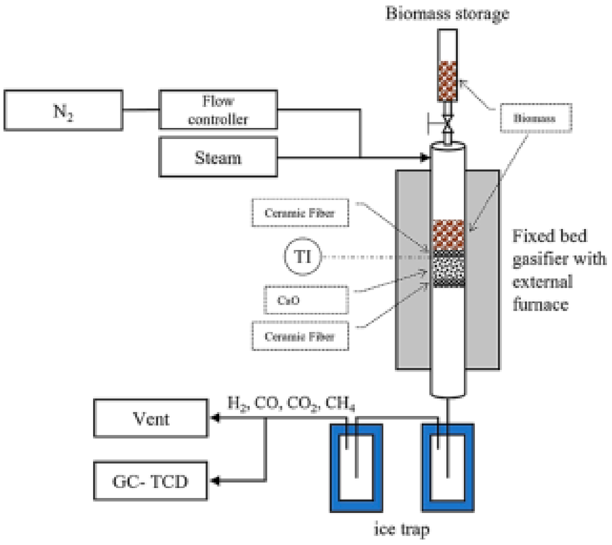

Figure 1. Schematic diagram of the custom-built gasifier at the lab scale.

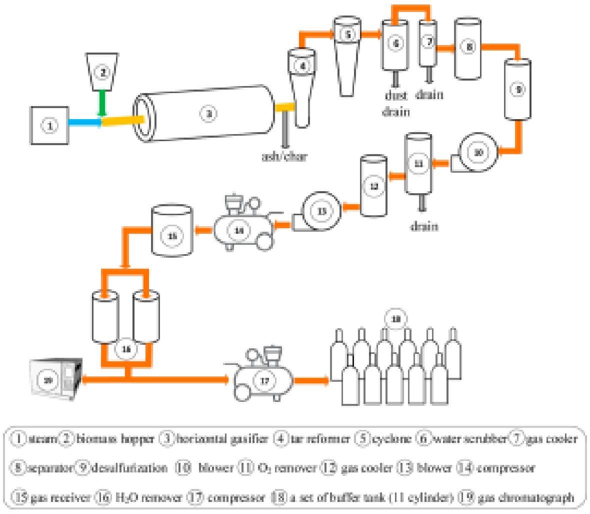

Figure 2. Schematic diagram of the pilot-scale gasification unit.

2.2.2. Pilot Horizontal Gasifier. The pilot horizontal gasification unit and facilities were installed at the Center of Fuel and Energy from Biomass, Chulalongkorn University, Saraburi Province, Thailand. Figure 2 illustrates a schematic view of the gasification unit. It consists of a feeding system, gasifier, steam generator, tar reformer (TR), gas purification unit, gas compression unit, and gas storage.

Biomass gasification was carried out in a pilot horizontal gasifier system consisting of the three zones of the gasifier reactor related to the three heaters to provide a constant temperature of 900 °C. The size of the gasifier is 2.5 m in length, 20 cm in diameter, and a 2° decline. The pilot custom-built gasifier system is a horizontal cylindrical shape and has a 1.0 m diameter quipped with insulation to prevent heat loss from the reactor, including several joint connectors, since the feedstock hopper has a capacity of 4 kg/h until the tar-reforming unit at the end of the gasification system.

The tar-reforming unit operating during the gasification stage to limit tars formation or to convert tars in the gasification reactor and which operate downstream of gasification with various purification processes was conducted at the operating temperature of 900 °C. CaO (12 kg) was used as the catalyst within the TR, which performed as a CaO-fluidized bed type. CaO enhanced the tar-reforming reaction to totally remove tar as the syngas moved up from the bottom to the top. The purification and conditioning of raw gases produced by gasification contained three parts starting from the cyclone (separating solid particles from gas), water scrubber, gas cooler, desulfurization (DS) unit, and mist separator until the gas blower to provide an effective process to ensure that small particles in syngas were separated from the TR as much as possible. The buffer unit was a storage gas unit that simultaneously fed syngas to the 11 gas cylinders. There are seven sets, and the volume of each cylinder is 6.35 m^3. The total amount of gas in the buffer tank contained 820 Nm^3 at 12.0 MPa/35 °C. However, before sending syngas to the buffer tank, syngas still undergoes a final purification process via a gas chromatography unit every 30 min.

2.3. Gasification Procedure. After purging with N_2 to remove air in the gasification system and heating the gasifier, biomass was manually fed into the hopper, and the screw-type feeder placed under the hopper was used to control the feed rate into the gasifier. Four load cells were installed at the hopper to measure the feed rate. The superheated steam generator with a feed controller was placed to supply steam as a gasifier agent into the gasifier. Gas produced from the gasifier flowed to the TR unit 85 cm in diameter and 155 cm in height and was then sent to the gas cleaning unit. Eventually, biochar fell into the char box at the outlet of the gasifier. The TR produced gas, including tar vapor, that flowed through the bubble bed of CaO. Tar was converted to syngas in this part. Tar-less syngas was sent to the cleaning part, then syngas and reduced the temperature, and the tar was condensed at the water scrubber. Fresh water was supplied to the water scrubber, and a conventional water treatment system was used to treat tar with cooling water. A gas cooler and mist separator were installed next to the water scrubber to remove water that might come from the gasifier process and water scrubber. Although there was a very low sulfur content in the biomass feedstock,[32−35] the DS unit was still necessary because sulfur is an FT catalyst poison. The DS unit was placed after the mist separator unit and connected with a first induced draft (ID) fan that used to control the syn gas flow and balance the pressure in the system. Because the downstream process is an FT process, which is an exothermic and pressurized process, the oxygen content in syngas is a serious safety concern. Hence, the oxygen remover (OR) was applied and placed. Cleaned syngas was compressed and kept in a set of buffer tanks in two steps of compression. First, syngas was flowed by a second ID fan from the OR to the first compressor, which was used to build gas pressure and kept in a receiver tank. An automatic control valve was placed after the buffer tank to

Table 2. Product Yields and Gas Compositions of Variation Temperatures

		product yield (wt %)			gas composition (vol %)				
biomass	temp. (°C)	tar	char	gas	CH_4	CO_2	H_2	CO	H_2/CO
RWPs	600	19.6	18.0	62.4	17.3	9.6	n.d.[b]	73.1	n.c.[c]
	800	12.7	12.7	74.6	14.6	10.3	38.7	36.4	1.1
	900	3.8	10.3	85.9	10.4	11.6	51.7	30.3	1.7
	1000	1.0	8.3	90.7	1.3	11.9	60.0	26.8	2.2
	900[a]	0.0	9.2	90.8	8.4	9.5	52.9	29.2	1.8
EWCs	600	26.6	18.7	54.7	18.8	9.11	n.d.[b]	72.1	n.c.[c]
	800	16.0	11.4	72.6	12.4	10.5	39.1	38.0	1.0
	900	5.3	9.7	85.0	8.1	10.3	52.7	28.9	1.8
	1000	2.0	3.5	94.6	4.0	11.1	59.9	28.0	2.1
	900[a]	0.0	8.8	91.2	8.0	9.2	53.2	29.6	1.8

[a] Tar removal using CaO. [b] n.d.—not detected. [c] n.c.—not calculated.

control the pressure in the buffer tank, which remained constant at 0.8 MPa and was steady stored before being sent to the second step of compression. Before reaching the second compressor unit, syngas with 0.8 MPa of pressure could become moist by water saturation at a high pressure, so a H_2O remover using a molecular sieve was placed to adsorb that moisture, and the dry gas was analyzed in real time for the gas humidity by a dewpoint measurement (Michell Instrument) and gas composition by Agilent 490 Micro-GC (Agilent Technologies, USA). At the second gas compressor, middle high-pressure gas was compressed to fill the buffer tank at 12 MPa. This gas was ready to use in the downstream unit. The temperature of the gasifier and its downstream unit was monitored by K-type thermocouples. The pressure at each point was measured and is shown in the main monitor. All data and parameters were stored in a computer with A/D convertors.

To achieve the production of syngas at the desired H_2/CO ratio range of 1.8−2.3 in pilot horizontal gas, two variables, the S/B (RWPs) ratio and gasification temperature, were investigated. The two S/B ratios of 0.5 and 1.4 were set up to gasify for 5 h in a continuous operation. The appropriate gasification temperature received from the lab-scale and S/B ratio were considered to operate syngas for 10 days of continuous production. Both operations of the gas composition were analyzed every 30 min.

2.4. Data Analysis and Calculation.

To evaluate the performance of this gasification system, common gasification indexes were calculated. Therefore, the total mole and composition of the produced gas were precisely known, and the calculation of gas yield, carbon conversion, and gas efficiency were determined based on mass basis, which can be seen from eqs 8−11 as follows

$$\text{Gas yield, wt \%} = \frac{\text{total mass of produced gas}}{\text{total mass of fed biomass}} \times 100 \tag{8}$$

$$\text{Carbon conversion, wt \%} = \frac{\text{mass of carbon in produced gas}}{\text{mass of carbon in total fed biomass}} \times 100 \tag{9}$$

$$\text{Gas/Biomass} = \frac{\text{total mass of produced gas}}{\text{total mass of fed biomass}} \tag{10}$$

$$\text{Cold gas efficiency, } \eta_{\text{cold}} = \frac{M_{\text{syngas}} \times \text{LHV}_{\text{syngas}}}{M_{\text{biomass}} \times \text{LHV}_{\text{biomass}}} \times 100 \tag{11}$$

where M_{syngas} = total mass of produced gas, kg; M_{biomass} = total mass of fed biomass, kg; $\text{LHV}_{\text{syngas}}$ = lower heating value of produced gas, MJ/kg; and $\text{LHV}_{\text{biomass}}$ = lower heating value of biomass feed stock, MJ/kg.

3. RESULTS AND DISCUSSION

3.1. Feed Stock Characterization.

Table 1 illustrates the biomass proximate analysis, including the ultimate analysis and low heating value (LHV) of the RWPs and EWCs. Although there were different milling processes of both biomass feed stocks, the chemical and some physical properties appeared to be similar on a dry basis.

For example, the LHV of RWPs was 18.4 MJ/kg, which was close to the EWCs of 18.4 MJ/kg for dry basis also. In addition, similar properties might affect similar gasification results. However, the major differences in these biomass feed stocks were in shape and moisture content. The shape of the biomass feed stock influenced the bulk density, which could be affected in transportation and storage facilities.[36] For moisture content, the biomass milling process causes the difference in the moisture content in feedstock and results in a variety of biomass feedstock qualities.[37] In other words, for the wood pellet milling process, there must be a drying process in its production process. Thus, wood pellets are always less moist (8−10 wt % moisture). On the other hand, the wood chips milling process is a simple milling process of biomass conversion or biomass size reduction that only reduces the size of biomass from wood logs to small chips without any drying process. Normally, wood chips have a high moisture content similar to a fresh log.[24,38] In this test, wood chips were air dried to be subjected to a moisture reduction before use due to the limitation of the gasification unit and to maintain the efficiency of gasification processes.

3.2. Influence of Temperature on the Tar Yield in the Lab-Scale Reactor.

This study aimed to investigate the influence of gasification temperature on tar yield by using a powder of rubber wood and eucalyptus as raw materials. The temperature ranged from 600 to 1000 °C with excess water vapor. The results of the product yield and gas composition are illustrated in Table 2. Tar decreased with increasing temperature to obtain solid char, while gaseous yield increased for rubber and eucalyptus wood. Tar decreased from 19.6 to 1.0% and 26.6 to 2.0% for RWPs and EWCs, respectively. In particular, there was a shape decreasing between 800 and 900 °C from 12.6 to 3.8% and 16.0 to 5.3% for RWPs and EWCs, respectively.

The components of the gas product as a function of temperature were examined. A higher temperature favors the primary and secondary water gas reactions, secondary cracking, and reforming of heavy hydrocarbons or tars, which are endothermic reactions and increase the formation of H_2.[4,39−44] While CO decreased with higher temperature, Franco et al.[45] reported that during biomass gasification using holm-oak and eucalyptus in a temperature range of 730 to 830 °C, lower CO was produced due to the water gas shift reaction. While the CH_4 content decreased with increasing temperature due to further cracking and reforming reactions, the CO_2 content was slightly increased according to the dominancy of secondary water gasification than the water gas shift that was also observed. It has also been reported that the effect of temperature on methane consumption is highly dependent on gasifying agents such as steam.[45−48]

CO and H_2 are important in the gas product, which requires an H_2/CO ratio range of 1.8−2.3 for FT synthesis. The operating conditions of syngas production to obtain the H_2/CO ratio of both RWPs and EWCs feedstocks are carried out at temperatures of 900 and 1000 °C. Tar removal by using CaO also operated at 900 °C, and the efficiency of CaO for tar removal was investigated under these conditions. The tar composition in both raw materials was less than 0.2 wt %. Tar reforming (eq 12) and hydrocarbon reforming (eq 13) were the principal reactions for tar removal. The catalytic reforming of tar in this experiment not only reduces the tar amount in the product gas but also enhances the hydrogen and CO content, as reported by Tanksale et al.[29] and Balat et al.[30] However, the tar yield was investigated at the operating temperature of 900 °C from both types of raw material which was also an appropriate condition to produce syngas for the target ratio. In this study, the operating temperature in the gasifier and tar reforming of 900 °C was used to operate the pilot horizontal gasifier system.

Tar reforming

$$\text{Tar} + H_2O + CaO \rightarrow Ca(OH)_2 + CO + \text{hydrocarbons} \tag{12}$$

Hydrocarbon reforming

$$\text{Hydrocarbons} + H_2O \rightarrow H_2 + CO_2 + CO \tag{13}$$

3.3. Influence of the *S/B* Ratio on the H_2/CO Ratio in the Pilot Horizontal Gasifier. The effect of *S/B* ratios of 0.5 and 1.4 on the H_2/CO ratio by using RWPs was examined in the pilot horizontal gasifier at 900 °C for 5 days of operation. The results of this operation are presented in Table 3. It revealed that the increasing *S/B* ratio promoted a higher content of hydrogen from 50.0 to 56.7 vol % by primary, secondary water gasification, water−gas shift, and methane steam reforming,[45,47,48] although H_2 was consumed by the methanation reaction. CO_2 was increased from 14.7 to 16.8 vol % with a higher *S/B* ratio by secondary water gasification and water gas shift reactions. The water gas shift reaction was responsible for maintaining the equilibrium between CO and CO_2 contents and found a decrease in CO with increasing *S/B* ratios.[33−36] CH_4 was decreased (11.2 to 9.4 vol %) due to a strong methane steam reforming reaction. Xiao et al.[47] reported the influence of the *S/B* ratio on the gas product composition, as mentioned in this study. However, the *S/B* ratio of 0.5 gave the desired H_2/CO of 2.1, which is in the target range of 1.8−2.3. Thus, for the next continuous operation, the temperature was 900 °C, and the *S/B* ratio was approximately 0.5.

Table 3. Gasification Results for Two Differences in *S/B* at 900 °C

	experiment 1	experiment 2
operating parameters		
operating time, h	5	5
biomass feed rate, kg/h	4.0	1.7
steam feed rate, kg/h	2.1	2.3
steam/biomass, kg/kg	0.5	1.4
gas compositions		
H_2	50.0	56.7
CO	24.1	17.1
CO_2	14.7	16.9
CH_4	11.2	9.4
H_2/CO, mole/mole	2.1	3.3

3.4. Investigation of Long-Term Operation Gasification. The pilot horizontal gasifier operation was carried out for 7 days to produce syngas for storage in 77 gas cylinders, in which syngas was used as the reactant for FT synthesis. The appropriate parameters were a gasifying temperature of 900 °C and a *S/B* ratio of 0.5, whereas RWPs and EWCs were used as raw materials. The target of this operation was to produce syngas with a H_2/CO ratio range of 1.8−2.3.

3.4.1. Temperature Profile. The temperature of the horizontal gasifier was kept at 900 °C using a controlled external heater. The temperature profiles of the gasifier and outlet gas for EWCs and RWPs gasification are represented in Figures 3 and 4, respectively. Although the net heat of gasification was exothermic, an external heat source was needed to keep the temperature constant at the desired high temperature. The constant temperature was 900 °C during operation for 7 days. The gasifier temperature was constant, resulting in a constant temperature of the outlet gas at 600 °C. Then, the gas outlet from the gasifier was purified by tar removal in a TR. For the TR, Figure 3 shows the temperature profile. The tar-reforming reaction with the CaO catalyst took place in zone 1, where the temperature was kept at 900 °C. After the reaction, the temperature dropped to 800 °C and 500 °C in zone 2 and zone 3 of the TR, respectively. The stability of the temperature profile in the TR was observed for 7 days of operation.

3.4.2. Average Syngas Composition and H_2/CO Ratio. The composition of the product gas from pilot horizontal gasifier operation for 7 days of RWPs and EWCs is shown in Figures 5 and 6, respectively. Under these operating conditions, the average *S/B* ratio was 0.5 and 0.6 for the RWPs and EWCs, respectively, and the gasifying temperature was 900 °C. Figure 5 illustrates the composition profile of the gas product for RWPs as a raw material. All gas compositions were almost stable during operation; the average H_2, CO, CO_2, and CH_4 were 48.4, 27.7, 15.2, and 8.7 vol %, respectively, as shown in Table 3, and the H_2/CO ratio was 1.8. The average gas compositions of H_2, CO, CO_2, and CH_4 were 48.0, 25.4, 18.6, and 8.0 vol %, respectively, and the H_2/CO ratio was 1.9 for EWC, as shown in Figure 6. The higher *S/B* ratio of the EWCs resulted in an increase in CO_2 (15.2 to 18.5 vol %) due to the water gas shift reaction and a decrease in CH_4 (8.7 to 8.0 vol %) due to the reverse methane steam reforming reaction.[24−26]

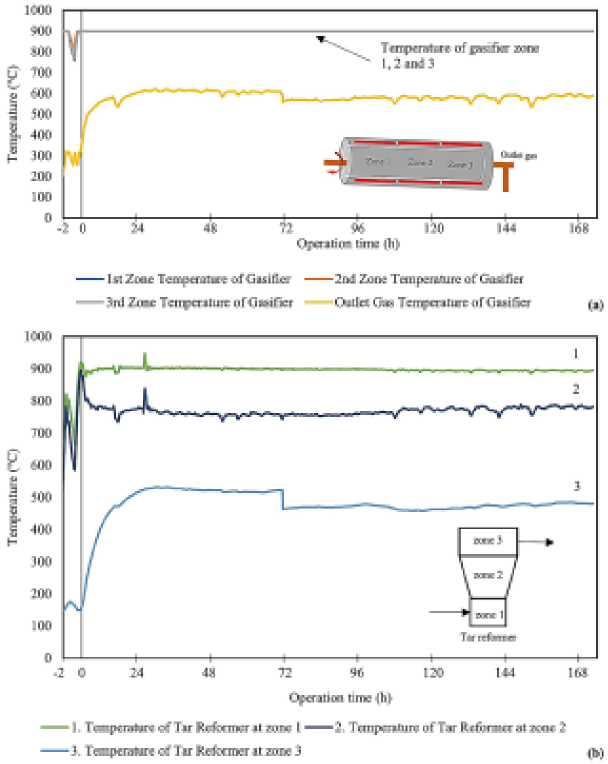

Figure 3. Temperature profile of EWCs gasification: (a) gasifier zone and (b) reformer zone.

This phenomenon was also observed, as in the former study of the effect of the *S*/*B* ratio on the gas composition. In addition, the H_2/CO ratio in both raw materials was the range of this target.

3.4.3. Material Balance of Syngas Production. The syngas production for the 7 days of operation was mentioned above to fill seven sets of buffer tanks, including 11 cylinders, or each set was filled per day. Figure 7 illustrates the pressure development during syngas filling in one set of buffer tanks, and the desired pressure was 120 MPa. The material balance was realized on the basis of 1 day of operation with buffer volumes of 0.9 m^3, 120 MPa, and 30 °C. Table 4 summarizes all of the data, including the operating conditions, gas yield, average gas composition, LHV, and carbon conversion for the RWPs and EWCs. The production gas rate and produced gas/biomass ratio were 2.5 kg/h and 0.5 kg/kg for RWPs, respectively, while the production gas rate and produced gas/biomass ratio from EWCs were 2.7 kg/h and 0.7 kg/kg, respectively. The biomass feed rates of these tests were 4.3 and 3.9 kg/h for RWPs and EWCs, respectively, whereas the steam feed rate of 2.0 kg/h for RWPs was less than that of 2.3 kg/h for EWCs. It seemed that the higher CO_2 and lower CO content in the gas product for EWCs promoted by the water gas shift reaction played an important role in increasing the production gas rate and decreasing the LHV. The LHV from the calculation was 12.9 and 11.7 MJ/Nm^3 for RWPs and EWCs, respectively.

In addition, the carbon conversion in the gas product was 49.5 vol % for RWPs, which was higher than the value of approximately 45.0 vol % for EWCs. However, both raw materials did not give much difference in the product gas property, especially the cold gas efficiency, which was approximately 47−48 wt % for both raw feedstocks.

One of the byproducts was solid biochar, which could be collected after gasifying termination. Carbon in char was approximately half of the total carbon in feed that was observed for RWPs and EWCs. High carbon contents of 83.1 and 88.8 wt % were found for the RWPs and EWCs, respectively, as shown in Table 5.

The solid biochar behaves as activated carbon, which has Brunauer−Emmett−Teller (BET) surface areas of 464.7 and 497.3 m^2/g for RWPs and EWCs, respectively. The BET surface area of EWCs activated carbon was higher than that of RWCs due to the higher steam feed rate, which was the activating gas.

4. CONCLUSIONS

This research aimed to operate a pilot horizontal gasifier of RWPs and EWCs to produce syngas with a H_2/CO ratio range

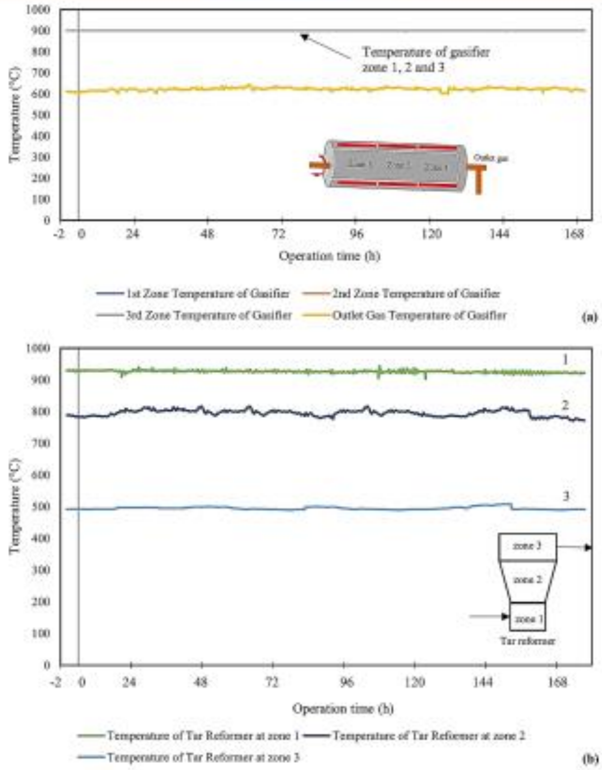

Figure 4. Temperature profile of RWPs gasification: (a) gasifier zone and (b) reformer zone.

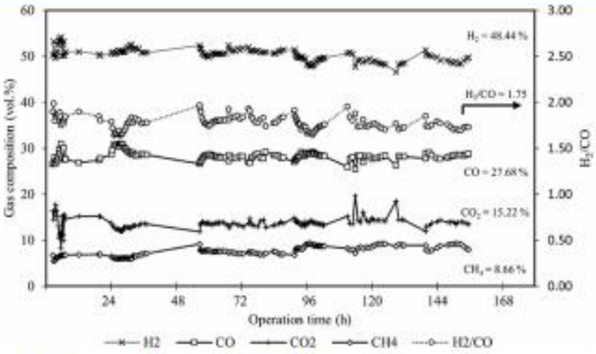

Figure 5. Gas composition and H_2/CO ratio of RWPs gasification for 7 days of operation.

of 1.8−2.3 for FT synthesis. A lab-scale gasifier was conducted with both raw biomass feedstocks to determine the optimum gasifying temperature as 900 °C, and the tar yield was less than 0.2 wt % using CaO as a tar-reforming catalyst. The temperature was 900 °C, and CaO was used in the pilot horizontal gasifier. The pilot gasifier comprised a tar removal system, gas purification system, and gas pressurized buffer tank system. The *S*/*B* ratio affects the gas product composition and

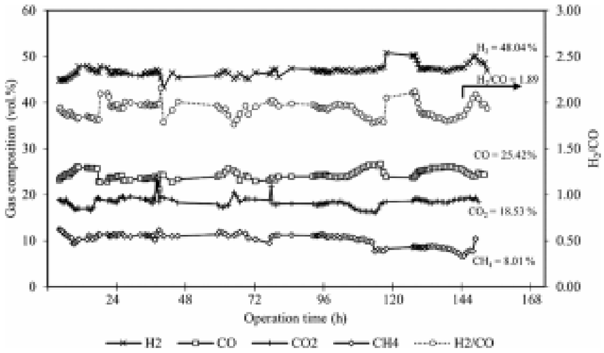

Figure 6. Gas composition and H_2/CO ratio of EWCs gasification for 7 days of operation.

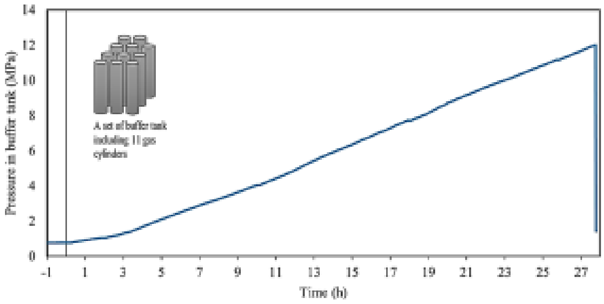

Figure 7. Pressure accumulation in a set of buffer tanks for eucalyptus gasification.

Table 4. Summary of Gasification Conditions and Results for Two Types of Biomasses

	RWPs	EWCs
operating parameters		
operating time, h	30.5	27.8
biomass feed rate, kg/h	4.3	3.9
steam feed rate, kg/h	2.0	2.3
steam/biomass, kg/kg	0.5	0.6
gas yield at constant volume of 0.9071 m^3		
produced gas rate, kg/h	2.5	2.7
gas/biomass, kg/kg	0.6	0.7
H_2/CO, mole/mole	1.8	1.9
gas compositions		
H_2	48.4	48.0
CO	27.7	25.4
CO_2	15.2	18.6
CH_4	8.7	8.0
low heating value, LHV		
MJ/Nm^3	12.9	11.7
carbon balance, kg		
feed stock	47.7	55.3
produced gas	23.6	24.9
char (solid)	24.1	30.4
cold gas efficiency, η_{cold}	47.8	48.1
carbon conversion in gas product, wt %, η_{carbon}	49.5	45.0

Table 5. Characteristics of Biochar[a]

	biochar from RWPs	biochar from EWCs
moisture content	13.5	13.9
proximate analysis (wt %), d.b.		
volatile matter	3.5	3.6
fixed carbon*	83.1	88.8
Ash	13.4	7.6
ultimate analysis (wt %), d.b.		
C	82.1	89.6
H	1.0	1.0
N	0.3	0.4
O*	16.6	9.0
BET (m^2/g)	464.7	497.3

[a] d.b.: dry basis, * by difference.

H_2/CO ratio. The results revealed that a S/B ratio of 0.5–0.6 gave an H_2/CO ratio in the range of 1.8–2.3. The stability of syngas production and gas composition of both raw materials for 7 days were determined. The gas production rates were 2.5 and 2.7 kg/h with H_2/CO ratios of 1.8 and 1.9 for the RWPs and EWCs, respectively. The supply of an external heat source stabilized the gasifying temperature, resulting in a stable gas composition. In summary, the horizontal gasifier is another effective designed gasifier that showed high-performance operation.

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Notes

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Appendix B วารสารมหาวิทยาลัยศรีนครินทรวิโรฒ

ที่ อว 8722.5/24

กองบรรณาธิการวารสารมหาวิทยาลัยศรีนครินทรวิโรฒ
(สาขาวิทยาศาสตร์และเทคโนโลยี)

ข้าพเจ้า รองศาสตราจารย์ ดร.วิชชากร จารุศิริ บรรณาธิการวารสารมหาวิทยาลัยศรีนครินทรวิโรฒ (สาขาวิทยาศาสตร์และเทคโนโลยี) ขอรับรองว่า บทความวิจัย เรื่อง **“กระบวนการไพโรไลซิสเชิงตัวเร่งของน้ำมันพืชใช้แล้วไปเป็นน้ำมันเชื้อเพลิงชีวภาพสำหรับเครื่องบินในเครื่องปฏิกรณ์แบบสกรูต่อเนื่อง”** โดย **นันทนา ลามาตย์ สเนลตเตอร์ บุญวัฒน์ วิจารณ์พล** และ **ธราพงษ์ วิทิตศานต์** ได้ผ่านเกณฑ์การประเมินคุณภาพทางวิชาการจากผู้ทรงคุณวุฒิ (Peer Review) และอนุมัติให้เผยแพร่ในวารสารมหาวิทยาลัยศรีนครินทรวิโรฒ (สาขาวิทยาศาสตร์และเทคโนโลยี) ปีที่ 15 ฉบับที่ 30 เดือนกรกฎาคม พ.ศ. 2566 ถึงเดือนธันวาคม พ.ศ. 2566

อนึ่ง วารสารมหาวิทยาลัยศรีนครินทรวิโรฒ (สาขาวิทยาศาสตร์และเทคโนโลยี) ได้ผ่านการประเมินคุณภาพจากศูนย์ดัชนีการอ้างอิงวารสารไทย (TCI) โดยได้รับการจัดให้อยู่ในกลุ่มที่ 1 วารสารที่ผ่านการรับรองคุณภาพของ TCI (1 มกราคม 2563 ถึงวันที่ 31 ธันวาคม 2567)

ออกให้ไว้ ณ วันที่ 2 พฤษภาคม 2566

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(สาขาวิทยาศาสตร์และเทคโนโลยี)

ฝ่ายบริหารจัดการข้อมูลและเผยแพร่ผลงานวิจัย
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