# THESIS APPROVAL

## GRADUATE SCHOOL, KASETSART UNIVERSITY

Master of Engineering (Chemical Engineering)
**DEGREE**

Chemical Engineering
**FIELD**

Chemical Engineering
**DEPARTMENT**

**TITLE:** Plastic pyrolysis with gas recycling in a fluidized bed reactor

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THESIS

# PLASTIC PYROLYSIS WITH GAS RECYCLING IN A FLUIDIZED BED REACTOR

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A Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of
Master of Engineering (Chemical Engineering)
Graduate School, Kasetsart University
2010

Waranyou Tuntanatewin 2010: Plastic Pyrolysis with Gas Recycling in a Fluidized Bed Reactor. Master of Engineering (Chemical Engineering), Major Field: Chemical Engineering, Department of Chemical Engineering. Thesis Advisor: Associate Professor Sunun Limtrakul, D.Sc. 164 pages.

A pyrolysis process is a thermal degradation in absence of oxygen/air. Plastic pyrolysis may be a process for disposal of plastic waste with recovery of valuable liquid fuel-range hydrocarbons. However, pyrolysis is a high endothermic reaction, which is required heat supply to the system. A partial oxidation is an exothermic reaction. Therefore, combining pyrolysis with partial oxidation reaction is one of the challenges for saving energy in a plastic pyrolysis process. Recycling of the product gas is proposed to reduce inert gas usage and energy requirement. In the experiments of a semi batch reactor, the results showed that the presence of partial oxidation and gas recycling increases the temperature rising of *5-30* $^{o}C$ leading to reduction of liquid product by *5.80 %*. On the other hand, the yield of gasoline increases by *8.35 %*. A fluidized bed reactor was also introduced to test the applicability. The effects of LPG and air feed rates for combustion and plastic feed rate on the bed temperature were studied. Increasing of LPG and air feed rates increases the average reactor temperature. In addition, the effects of feed rate of secondary air for partial oxidation and feed rate of gas recycling on bed temperature profiles, production rate and product distribution were studied. Addition of partial oxidation has a significant effect on the reactor temperature and production rate. Increase of partial oxidation increases the system temperature in the range of *5-10* $^{o}C$. The present of partial oxidation can save energy of *0.70 %*. Gas recycling can reduce the inert gas usage of *34.28 %* and save the energy input of *5.47 %*.

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Student's signature Thesis Advisor's signature

# ACKNOWLEDGEMENTS

First, I would like to express my sincere gratitude and deep appreciation to my advisor, Assoc. Prof. Dr. Sunun Limtrakul for all the guidance, supervision, comments, discussions and invaluable suggestions throughout this project. She also gives me many good opportunities. This work would not be accomplished without her help. I would like to thank Assoc. Prof. Therdthai Vatanatham for supporting experimental equipment, valuable comments and guidance.

I am extremely grateful to Assoc. Prof. Dr. Muenduen Phisalaphong and Assist. Prof. Dr. Manop Charoenchaitrakool for their helpful suggestions and corrections of this work.

I deeply thank to the Kasetsart University Research and Development Institute (KURDI), Department of Chemical Engineering, Kasetsart University and the National Center of Excellence for Petroleum, Petrochemical and Advanced Materials for financial support.

Additional thanks extend to Ms. Patarawan Klomkum and all colleagues in both Assoc. Prof. Dr. Sunan’s research group and Assoc. Prof. Therdthai’s research group for their warm friendship, suggestion and all supports. They always make me enjoy my life during study in this program.

My deepest appreciation goes to my parents for their unconditional love, understanding and pride in having me as an engineer in the family and also financial support.

Waranyou Tuntanatewin
April 2010

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# LIST OF ABBREVIATIONS

ASTM = American Society for Testing and Materials
BFB = Bubbling fluidized bed reactor
CFB = Circulating Fluidized Bed
DSC = Differential scanning calorimetry
ER = Equivalence ratio
F = Fixed carbon
FC = Elutriable fines
HDPE = High density polyethylene
ID = Inner diameter
LDPE = Low density polyethylene
LPG = Liquid petroleum gas
MPW = Municipal plastic waste
PE = Polyethylene
PET = Polyethylene terephthalate
PMMA = Poly methyl metacrylate
PP = Polypropylene
PS = Polystyrene
PVC = Poly(vinyl chloride)
Q = Plastic feed rate
SBR = Styrene butadienerubber
T = Temperature
TGA = Thermogravimetric Analysis
U = Velocity
$U_{mf}$ = Minimum fluidizing velocity
V = Velocity

# PLASTIC PYROLYSIS WITH GAS RECYCLING IN A FLUIDIZED BED REACTOR

## INTRODUCTION

Currently, world plastic production from industrial and municipal is increasing significantly. As a consequence, the eradication of plastic waste has become an extreme problem with high environmental impact. The most common way to handle plastic waste is landfills and incineration.

Landfilling of plastic waste is not a solution, essentially because it has been increasingly difficult to find suitable places for building technically adequate landfills. This is due to the resistance imposed by the nearby populations and since there is the danger of leaching and soil impregnation, with the subsequent contamination of underground waters. Furthermore, it is still not well established what the long-term effects of their degradation could lead to. On the other hand, this process does not allow the recovery of the organic content of plastic waste, which is even more important due to the small lifetime of known petroleum reserves (Pinto et al., 1999).

Incineration of plastic waste to produce heat may be a possibility, but its organic content would totally be destroyed and converted only into $CO_2$ and $H_2O$. In addition, depending on its nature, combustion may produce pollutants like light hydrocarbons, nitrous and sulphur oxides, dusts, dioxins and other toxins, which have a highly negative impact on the environment. An alternative approach to upgrade plastic waste and its further use could be achieved through pyrolysis reaction.

Pyrolysis or thermal cracking has been paid to recycling of waste polymer to recover value added products or energy via the production of high-value petro-chemical feedstock.  It has been investigated at laboratory and pilot plant, and some semi-commercial installations have been built for the treatment of plastic waste (Murty *et a.l*, 1996; Ding et al, 1997; Horvat and Ng, 1996; Cardona and Corma, 2000; Wong and Broadbelt, 2001; Ucar *et al*., 2002)

This process consists of the thermal degradation of the wastes in the absence of oxygen/air. Plastics pyrolysis may provide for disposal of plastic waste with recovery of valuable gasoline-range hydrocarbons. In pyrolysis, the polymeric materials are heated to high temperatures, so their macromolecular structures are broken down into smaller molecules and a wide range of hydrocarbons are formed. The decomposition product of pyrolysis can be used as liquid fuel instead gasoline or used as feedstock in high quality plastic production. The product of pyrolysis is separated into 3 types namely gas, liquid and residuals. The components of liquid part are paraffins, olefins, naphthenes and aromatics (Derbirmas, 2004).

However, the pyrolysis reaction is an extremely endothermic reaction, which is required supply heat to its system. Therefore, the partial oxidation reaction is one of the greatest challenges for saving energy which is required for pyrolysis reaction. Because the partial oxidation is an exothermic reaction, some heat is generated to compensate the endothermic reaction in pyrolysis system. Moreover, the productions of large amounts of char and tars, which are difficult to handle, are reduced.

The fluidized bed is particularly suitable for pyrolysis since it provides very good heat and material transfer rates thus constant temperature can be obtained. It provides largely uniform products has no moving parts in the hot region, and can be a wholly closed system due to easy sealing (Kaminsky *et al*., 2004). A fluidizing gas is required to obtain the fluidization condition. In this work nitrogen gas is used for fluidizing particles. Recycling gas outlet of the fluidized bed reactor to reuse is proposed to reduce the inert gas consumption.

# OBJECTIVES

This research work aims to develop a fluidized bed reactor with gas recycling for plastic pyrolysis. The scopes of the research are listed as follows:

1. The partial oxidation of plastic and recycling gas will be studied to minimize the energy consumption into the reactor.

2. The effect of operating conditions on the reactor performance such as plastic feed rate, temperature will be studied.

## Places and duration

| | |
|---|---|
| Place | Chemical Engineering at Kasetsart University Bangken |
| Period of time | Since January 2006 to April 2010 |

## Benefits

1. Plastic pyrolysis in a fluidized bed reactor with gas recycling will be understood.

2. The information of the saving energy of plastic pyrolysis in a fluidized bed reactor with gas recycling by using partial oxidation reaction is useful for development of pyrolysis system.

3. This work can be used to develop the chemical and petrochemical processes in the future.

# LITERATURE REVIEW

## 1. Sources of plastic waste

Plastic waste can be classified as industrial and municipal plastic waste according to their origins; these groups have different qualities and properties and are subjected to different management strategies (Demirbas, 2004).

### 1.1 Industrial plastic waste

Industrial plastic waste is those arising from the plastics manufacturing and processing industry. Usually they are homogeneous or heterogeneous plastic resins, relatively free of contamination and available in fairly large quantities. Recycling technologies for industrial plastic waste are currently based on pelletization and molding into low grade plastic products; the recycled products have poor mechanical and color qualities and a lower market value. The reclaimed product outputs of Japan in the early 1980s already amounted to some 15% of total industrial plastic waste. Thus for industrial plastic waste, repelletization and remolding seem to be a simple and effective means of recycling. But when plastic waste are heterogeneous or consist of mixed resins, they are unsuitable for reclamation. In this case thermal cracking into hydrocarbons may provide a suitable means of recycling, which is termed chemical recycling.

### 1.2 Municipal plastic waste

Municipal plastic waste normally remains a part of municipal solid waste as they are discarded and collected as household wastes. Plastics usually account for about 7% of the total MSW by weight and much more by volume. In order to recycle municipal plastic waste, separation of plastics from other household wastes is required. Although MSW separation technologies have been studied extensively, it is still not possible to classify MSW mechanically and obtain marketable fractions. So waste separation at the household is required with regard to recycling of municipal plastic waste. If household wastes are separately disposed into three parts: (1) combustibles such as paper, kitchen waste, textiles, and wood, (2) incombustibles such as metals, glass, ceramics, and (3) plastics, then the collected plastics will be mixed plastic waste with major components of PE, PP, PS, PVC, etc. For mixed plastics some mechanical separation equipment is currently available. For example, using a wet separation process mixed plastics can be separated into two groups: those with a density greater than water such as PS and PVC, and those with a density lower than that of water such as PE, PP and expanded PS. The latter group is much larger than the first group. Consequently, recycling of municipal plastic waste should deal with plastic mixtures of PE, PP and PS, provided that the above separation procedures are practiced. Typical distribution of such plastic mixture will be three parts PE, one part PP and one part PS. More investigations are needed to identify the sources and properties of plastic waste, and their suitability for various recycling methods such as repelletization, remolding and pyrolysis (Lee, 2007).

## 2. The procedure of plastic waste recycling

### 2.1 Mechanical recycling

Mechanical recycling of plastic waste is the simplest and relatively cheap recycling method. The steps of mechanical recycling are as follows:

The large plastic parts are cut by saw or shears for further processing and then chopped into small flakes. The contaminants (e.g. paper) is separated from plastic in cyclone separator.  Different types of plastics are separated in a floating tank according to their density.  The flakes are also washed and dried.  The flakes are fed into an extruder where they are heated to melting state and forced through the die converting into a continuous polymer product (strand).  The strands are cooled by water and cut into pellets, which may be used for new polymer products manufacturing.

### 2.2 Chemical recycling

Chemical or feedstock recycling is a process, in which a plastic polymer is broken down into its constituents - monomers. This process is called depolymerization. The monomers may be then used as raw material for manufacturing a new polymer. Chemical recycling (feedstock recycling) is more expensive than mechanical recycling.

There is a range of chemical recycling methods:

2.2.1 Pyrolysis, chemical decomposition of polymers induced by heat in the absence of oxygen.

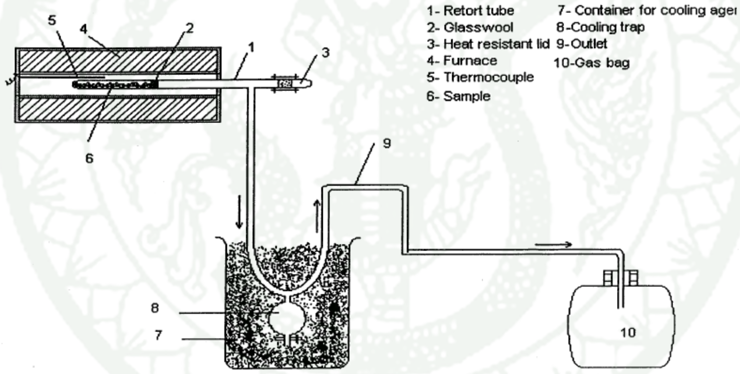


**Figure 1** Schematic illustration of Gray-King apparatus

**Source:** Kiran *et al*. (2000)

Pyrolysis processes are generally classified into low, medium and high temperatures based on the range of temperatures used to destroy the plastic structure. The corresponding temperatures defining the pyrolysis states are with the following temperature ranges less than or equal to 600°C, 600–800°C and greater than 800°C (Kaminsky, 2004). The products obtained from pyrolysis of plastics depend on the type of plastics, feeding arrangement, residence time, temperatures employed, reactor type and condensation arrangement.

### 2.2.2 Gasification, conversion of polymers into a mixture of carbon monoxide (CO) and hydrogen.

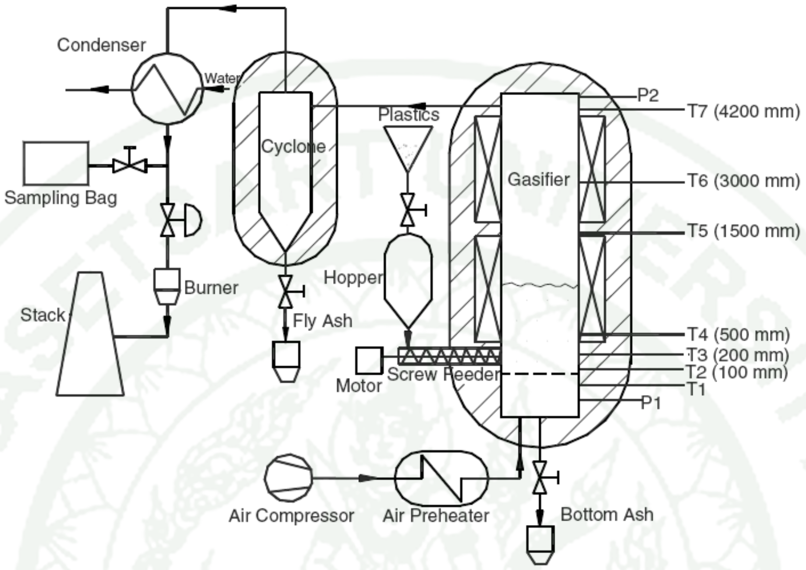


**Figure 2** Schematic diagram of the gasification apparatus

**Source:** Xiao *et al*. (2007)

The gasification process can convert solid or liquid hydrocarbon feed stocks into a synthesis gas that is suitable for use in electricity production or for the manufacture of chemicals, hydrogen or transportation fuels. Air gasification of plastic waste uses air as a gasifying agent to convert plastics to combustible gas to obtain high energetic utilization efficiency and low emission of pollutants.

The advantage of using air instead of oxygen as the gasifying agent is to simplify the gasification process and reduce operating and maintenance cost because air separation to obtain oxygen is a more complex and expensive process (Xiao et al, 2007). On the other hand, in the case of gasification using air, its nitrogen content remains as an inert component in the producer gas that dilutes the fuel gas and leads to a low caloric value fuel.

## 3. Thermal cracking mechanism

Pyrolysis and gasification of plastics and other carbonaceous fuels have been studied extensively in the past. Recent progress in converting plastic waste into petrochemicals by means of pyrolysis in the absence of a catalyst has been reviewed by Kaminsky (Kaminsky, 1991). A comprehensive treatment of the mechanism of plastics pyrolysis has been presented (Cullis and Hirschler, 1981) Four types of mechanisms of plastics pyrolysis have been proposed following this table

**Table 1** The explanation of plastic pyrolysis mechanism

| Mechanism | Explanation |
|---|---|
| End-chain scission or depolymerization | The polymer is broken up from the end groups successively yielding the corresponding monomers. |
| Random-chain scission | The polymer chain is broken up randomly into fragments of uneven length |
| Chain-stripping | Elimination of reactive substitutes or side groups on the polymer chain, leading to the evolution of a cracking product on one hand, and a charring polymer chain on the other. |
| Cross-linking | Formation of a chain network, which often occurs for thermosetting polymers when heated. |

Theses different mechanisms and product distributions are to some extent related to bond dissociation energies, the chain defects of the polymers, and the aromaticity degrees, as well as the presence of halogen and other hetero-atoms in the polymer chains. For common plastics the decomposition mechanisms and associated monomer yield are listed in this table

**Table 2** Decomposition mechanisms and monomeric yields of some polymer

| Polymers | Decompositions mechanism | Monomeric yields (Weight) |
|---|---|---|
| Polyacrylonitrile | Chain-stripping | 5 |
| Polyvinyl fluoride | Chain-stripping | 0 |
| Polyvinylchloride | Chain-stripping | 0-0.07 |
| Polybutadiene | End-chain scission | 1 |
| Polypropylene | Random-chain scission | 0–17 |
| Polyethylene | Random-chain scission | 0.03 |
| Polyisobutene | End-chain and random-chain scission | 18–25 |
| Polystyrene | Random-chain scission | 42–45 |
| Polyethylstyrene | End-chain scission | 82–94 |
| Polymethacrylonitrile | End-chain scission | 90 |
| Polymethylmetacrylate | End-chain scission | 95 |
| Polytetrafluorethylene | End-chain and random-chain scission | 91–98 |

**Source:** Cullis (1981); Buekens (1989)

### 3.1 Product distributions of thermal cracking

The major factors of influence determining the product distribution resulting from plastics pyrolysis are summarized in Table 3

**Table 3** Product distributions of thermal cracking

| Factor of influence | Effect |
|---|---|
| Chemical distribution of the resins | The primary pyrolysis products relate directly to the chemical structure and distribution of the resin, and also to the mechanism of its decomposition (purely thermal or catalytic) |
| Pyrolysis temperature and heating rate | Higher operating temperatures and high heating rates both enhance bond breaking and favour the production of small molecules |
| Pyrolysis time | Longer residence times favor a secondary conversion of primary products, yielding more coke, tar, as well as thermally stable products, thus gradually obscuring the effect of original polymer structure |
| Reactor type | Determines mainly the quality of heat transfer, mixing, gas and liquid phase residence times, and the escape of primary products |
| Operating pressure | Low pressure reduces the condensation of reactive fragments forming coke and heavies |
| Presence of reactive gases, such as (air) oxygen or hydrogen | Such presence internally generates heat, dilutes the products and influences upon equilibriums, kinetics, and mechanisms |
| Use of catalysts | Their use influences upon kinetics and mechanisms, and hence, the product distribution |
| Additives incorporated | The additives generally either evaporate or decompose. Some may influence kinetics and mechanism |

**Source:** Scheirs and Kaminsky (2006)

Temperature is the most important operating variable, since it determines both the rate of thermal decomposition and the stability of feedstock and reaction products. High temperature (>600˚C) and both vacuum and product dilution favor the production of simple small gaseous molecules, low temperature (<400˚C) and increased pressure lead to more viscous liquid products, higher rates of pyrolysis, a higher coking tendency, more secondary products and dehydrogenation

The required reaction time is determined principally by reaction temperature. The formation of primary products, e.g. monomers, is favoured by short residence times, the formation of more thermodynamically stable products ($H_2$, $CH_4$, aromatics, carbon) by long ones. Low pressure (under vacuum, or in the presence of inert diluent) favors the production of primary products, including monomer, high pressure that of complex, liquid fractions

Product distribution of Thermal cracking of plastic waste by the Hamburg process is shown in Table 4 which can categorize in to 3 parts namely gas, oil and solid. The type of plastic waste feedstock effect on the quantity of each part.

**Table 4** Product distribution in plastics pyrolysis or Thermal cracking (%wt. of feed)

| Feed | Pyrolysis temperature (°C) | Product (%wt) | | | |
|---|---|---|---|---|---|
| | | Gas | Oil | Solid | Other |
| Polyethylene (PE) | 760 | 55.8 | 42.4 | 1.8 | - |
| Polypropylene (PP) | 740 | 49.6 | 48.8 | 1.6 | - |
| Polystyrene (PS) | 580 | 9.9 | 24.6 | 0.6 | 64.9 Styrene |
| Poly methyl metacrylate (PMMA) | 450 | 1.25 | 1.4 | 0.15 | 97.2 MMA |
| | 740 | 6.8 | 28.1 | 8.8 | |
| Poly(vinyl chloride) (PVC) | | | | | 56.3 HCl |

**Source:** Kaminsky (2004)

The amount of gas, oil and solid product from Thermal cracking process of plastic waste are shown in Figure 3 which demonstrated the increasing amount of gas product when temperature rise from *500-900 K*. After that when increase the temperature from *750-900 K*, The reducing of oil production occur. The reverse proportion when increasing temperature is investigated for solid product.

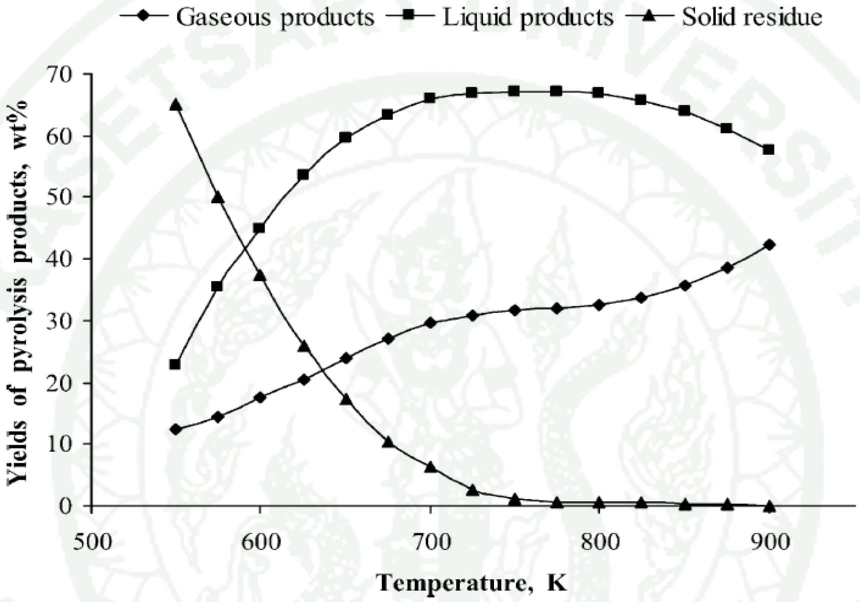


**Figure 3** Product from thermal cracking of plastic waste at each temperature

**Source:** Demirbas (2004)

## 4. Reactor types for plastic pyrolysis

The reactor type is selected mainly on the basis of technical considerations, mainly its heat transfer and feed and residue handling characteristics. In many processes proposed the polymer is first dissolved in a bath of molten polymer or wax, or dispersed in a salt bath, to reduce the viscosity of the melt. Other processes suggest the use of the excellent heat transfer and mixing properties of fluidized bed thermal or catalytic reactors.

**Table 5** Reactor types and their characteristics

| Reactor type | Particular characteristic | Application |
|---|---|---|
| Extruder | Operating temperature is limited. Degassing of premature decomposition products is essential | Production of waxes from PE |
| Tubular reactor | Simplicity | Molten polyolefins |
| Stirred tank reactor, possibly with external heating loop and/or reflux cooler | Conventional liquid phase reactor. Stirring improves heat transfer. Clogging of downstream ducting has to be avoided | Mixed plastics: BASF, Ludwigshafen Chiyoda Engineering, Niigata |
| Fixed bed reactor | Mainly for catalytic reactions, converting vapours from a first reactor | PMMA pyrolysis |
| Salt or lead bath reactor | The bath acts as a heat transfer agent. Residues accumulate on top of the layer, requiring a periodic shutdown for cleaning | |
| Fluidized bed reactor | The fluidized bed acts as a heat transfer agent, dispersing the melting plastic in thin layers. Residues are carried out with the products, requiring a delicate filtration of fines (pigments, fillers) | |
| Rotary kiln | Simple units, featuring tumbling action and gravity feed. Sealing is delicate. | NKK PVC-pyrolysis process |
| Autoclave | Reactor for operating under pressure, generally in a batch mode | Hydrogenation |

**Source:** Scheirs and  Kaminsky (2006)

## 5. Fluidized Bed Pyrolysis of Plastic waste

Gas–solid fluidization is the operation by which a bed of solid particles is led into a fluid-like state through suspension in a gas. Compared with other methods of gas–solid contacting (such as fixed beds, rotary cylinders, flat hearths, etc.), fluidized beds have some rather unusual and useful properties that can lead to desirable characteristics for waste thermal treatments in general, and for plastic waste pyrolysis in particular (Scheirs and Kaminsky, 2006).

The following main advantages can be listed for fluidized-bed reactors utilized for thermal treatments of waste (Kunii and Levenspiel, 1991).

- The rapid and good mixing of solids, which leads to almost uniform isothermal conditions throughout the fluidized bed. This allows an easy and reliable process control.

- The whole reactor of well-mixed solids represents a large thermal flywheel that resists to rapid temperature changes and avoids formation of cold or hot spots. The range of operating temperatures is generally lower than that of other gas–solid reactors.

- Heat and mass transfer between gas and particles are high when comparing with those of other gas–solid reactors and there is a very good quality of contact between reactants of a gas–solid reaction.

- The liquid-like feed of particles allows continuous controlled operations with easy handling. In particular, the circulation of solids between two fluidized beds makes it possible to remove or add the high quantities of heat produced or needed in large reactors as well as to substitute part of the (sticky or agglomerated) bed material with fresh solids.

- The high process flexibility makes possible to utilize different fluidizing agents, operating temperatures and gas residence times and to operate with or without a specific catalyst.

**Table 6** Summary of pyrolysis processes for plastic waste, auto shredder residues, tires and other wastes carried out with different fluidized bed reactors.

| Process | Actors involve | Technology | Process description | Input/Output | Technical status |
|---|---|---|---|---|---|
| Akzo | Akzo Nobel (NL) | Two circulating fluidized beds | Fast pyrolysis in a CFB reactor (700-900˚C), where waste is converted with steam into fuel gas, HCl and residual tar, and combustion in the second CFB. The process is based on the Battelle process for biomass gasificaition. | I: shredded MPW with high percentage of PVC, PVC cable, pipe scrap<br>O: HCl, CO, $H_2$, $CH_4$, other hydrocarbons, fly ash | Pilot (30 kg/h) since 1994. Some tests on a large scale (200–400 kg/h) |
| Amoco | Amoco Chem. Corp. | Bubbling fluidized bed | Catalytic cracking at 490–580˚C | I: PE, PP, PS, plastic waste mixed with vacuum gas oil<br>O: naphtha, light mineral oil gases | Pilot since 1991 |
| AMRA | Center of Competence on Env. Risks (I) | Bubbling fluidized bed | Gasification in a BFB of sand, fluidized by air, steam and nitrogen at a temperature between 750 and 900˚C | I: polyolefins and RDF shredded at a size<2.5 cm<br>O: syngas, energy | Pilot (20–50 kg/h) in Caserta (I) |

**Table 6** (Continue)

| Process | Actors involve | Technology | Process description | Input/Output | Technical status |
|---|---|---|---|---|---|
| Battelle | Battelle Memorial Inst. (USA) | Two circulating fluidized beds | Gasification in a CFB of sand, fluidized by steam and nitrogen at a temperature between 800 and 1000°C | I: PE, PS, PVC and MPW shredded at a size<2.5 cm<br>O: ethylene, $H_2$,$CH_4$ | Pilot (9 kg/h) in Vermont (USA) since 1992 |
| BP polymer cracking | BP Chemicals, Elf Atochem, DSM, Enichem, Fina | Bubbling fluidized bed | Low-temperature pyrolysis (500°C) in a BFB of sand. The product is cleaned from HCl and fine particles and then fractionated | I: clean plastic waste (<2% PVC)<br>O: mainly waxy hydrocarbon products to be used in existing petrochemical plants | Pilot (50 kg/h) in Grangemouth (UK) |
| Ebara | Tsukishima (J) | Two fluidized beds | Pyrolysis in a fluidized bed and combustion of the products in the second fluidized bed reactor | I: plastic waste<br>O: energy | Operational: 4 t/h,Yokohama |

**Table 6** (Continue)

| **Process** | **Actors involve** | **Technology** | **Process description** | **Input/Output** | **Technical status** |
|---|---|---|---|---|---|
| Ebara TwinRec | Ebara Corp. (J), Alstom Power until 2002 | Internally revolving fluidized bed + ash-melting system | Gasification of the shredded waste material in a revolving fluidized bed, operated at 500- 600°C, which separates combustible part from inert and metallic ones. Combustion of syngas and char in a cyclone combustor (1350-1450°C) at a low excess air ratio | I: ASR, plastic and electronic wastes, sewage sludge, MSW<br>O: energy, ferrous and non-ferrous metals, glass granulate | Pilots (0.3 t/h) in Sodeguara (J) and (1 t/h) in Fujisawa(J) since 1997. |
| Hamburg-ABB | University of Hamburg (D), Asea Brown Boveri | Bubbling fluidized bed | High-temperature pyrolysis (600–800°C) in a BFB, fluidized with liquid-free pyrolysis gas or inert (steam + $N_2$) gas | I: shredded plastic waste (having as low as possible Cl content)<br>O: high yield of olefins, BTX-rich oil | Pilot (40 kg/h) at the Univ.of Hamburg. Demonstration (5,000 t/y) |

**Source:** Scheirs and Kaminsky (2006)

**Table 7** Lists the operating conditions used in the cited experiments, i.e. polymer type, reactor size, reactor temperature, bed material type and size, fluidizing agent, fluidization velocity, as these are reported in the papers.

| Plastic feed; bed material | Apparatus | Operating condition | Main result |
|---|---|---|---|
| HDPE; sand | Bubbling fluidized bed, 69 mm ID | Batch feeding<br>*U* = 0.036 m/s<br>*T* = 500, 600,700, 800, 900°C | Gas yield progressively increases from 5.7 to 96.5%. Methane, benzene, toluene formation is favored by high residence times. Gas yield reaches maximum at 800°C. |
| Mixed plastics, HDPE; quartz sand | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: nitrogen; nitrogen/steam<br>*U* = 0.17 m/s<br>*T* = 600, 700, 800°C<br>*Q* = 1.1–1.4 kg/h | Pyrolysis with steam as fluidizing gas demonstrates that the olefins yield is increased due to water–gas reaction.<br>Mixed plastics pyrolysis does not allow optimization of process temperature since styrene production from PS requires low temperatures while olefins production from PE and PP requires high temperatures. |

**Table 7** (Continue)

| Plastic feed; bed material | Apparatus | Operating condition | Main result |
|---|---|---|---|
| Mixed plastics; quartz sand | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: pyrolysis gas<br>*U* = 0.2 m/s<br>*T* = 730°C | Pyrolysis of mixed plastics lead to aromatics without chlorine yield of 48%. Chlorine is present, together with heavy metals, in the solid Fraction |
| Polyolefin | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: steam<br>*T* = 605, 655, 690, 700, 750, 805°C<br>*Q* = 1–3 kg/h | With the exception of experiments at 605°C, the gas fraction is the main product (58–71%), having a maximum yield at a temperature of about 700°C. BTX-aromatics increase from 1.6% at 605°C up to 16% at 805°C. Distillation residue is higher at lower temperature (at which heavier hydrocarbons are produced) and at the highest (since more condensed aromatics are present). Chlorine is present in the water and in the solids |
| Mixtures of LDPE,HDPE, PP, PS, PVC, PET | Bubbling fluidized bed, 100 mm ID | Batch feeding. Fluidizing gas: steam<br>*U* = 0.072 m/s<br>*T* = 500–700◦C | Liquid and gas phase distribution is given. Gas yield reaches its maximum value at 650°C |

**Table 7** (Continue)

| Plastic feed; bed material | Apparatus | Operating condition | Main result |
|---|---|---|---|
| Mixed plastics from DSD; quartz sand | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: nitrogen<br>*T* = 685, 710, 716, 730°C<br>*Q* = 0.4–0.9 kg/h | Two different mixtures of plastics having different PVC content have been pyrolysed in order to evaluate aromatics and light gas yields. BTX represent the 20% of input, gases the 44%. Chlorine is absent in the aromatics compounds due to reaction with $CaCO_3$. |
| HDPE; silica sand | Bubbling fluidized bed, 48 mm ID | Fluidizing gas: air/nitrogen<br>ER = 0.06–0.07<br>*U* = 0.11, 0.18 m/s<br>*T* = 640, 700, 730, 780, 850°C | The gas yield reaches the maximum value at 780°C. The oxygen increases the reactivity of degradation. Comparison between aromatics yield with the two processes is reported |
| Filled or not PMMA; quartz sand | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: nitrogen<br>*T* = 450–480°C<br>*Q* = 0.3–3 kg/h (lab scale)<br>*Q* = 30 kg/h (pilot plant) | PMMA with and without filler has been pyrolysed at low temperature (450 and 480°C). High monomer recovery has been obtained (98%). The experiments were carried out also in a pilot plant 20 times larger than the lab-scale |

**Table 7** (Continue)

| **Plastic feed; bed material** | **Apparatus** | **Operating condition** | **Main result** |
|---|---|---|---|
| SBR (styrene-butadienerubber); Quartz sand | Bubbling fluidized bed, 154 mm ID | Fluidizing gas: nitrogen, steam<br>*U* = 0.12, 0.28 m/s<br>*T* = 500, 550, 600°C<br>*Q* = 1–3 kg/h | Low temperature pyrolysis (500–600°C) of tires produces a high carbon black yield (40% at 600°C), styrene and butadiene. Butadiene yield increases if nitrogen is used instead of pyrolysis gas due to suppression of secondary and ternary reactions. |
| Recycled PE; silica sand | Bubbling fluidized bed, 55 mm ID | Fluidizing gas: nitrogen<br>*U* = 0.15, 0.28 m/s<br>*T* = 550–750°C | The effect of bed temperature appears to play a crucial role in defining yield and distribution |
| HDPE; silica sand | Bubbling fluidized bed, 48 mm ID | Fluidizing gas: air/nitrogen<br>ER = 0, 0.06<br>*U* = 0.11, 0.17 m/s<br>*T* = 640, 700, 730, 780, 850°C<br>*Q* = 3–4 g/min | High yield of waxes and oils found at 640 and 700°C. The presence of an in characterized char is highlighted |

**Source:** Scheirs and Kaminsky (2006)

### 6. Difference stages in the fluidized bed pyrolysis of a plastic waste.

In a fluidized-bed reactor, the interactions between the injected polymer particles and the bed material define the peculiar mechanisms of a series of these steps. Figure 4 provides a list of them as deduced by batchwise and continuous experiments (Arena and Mastellone, 2000) highlights the region of a bubbling bed where each of them mainly occurs and indicates the paths by which the carbon, under its different forms of fixed carbon (FC), volatile (V) and elutriable fines (F), moves inside the reactor.

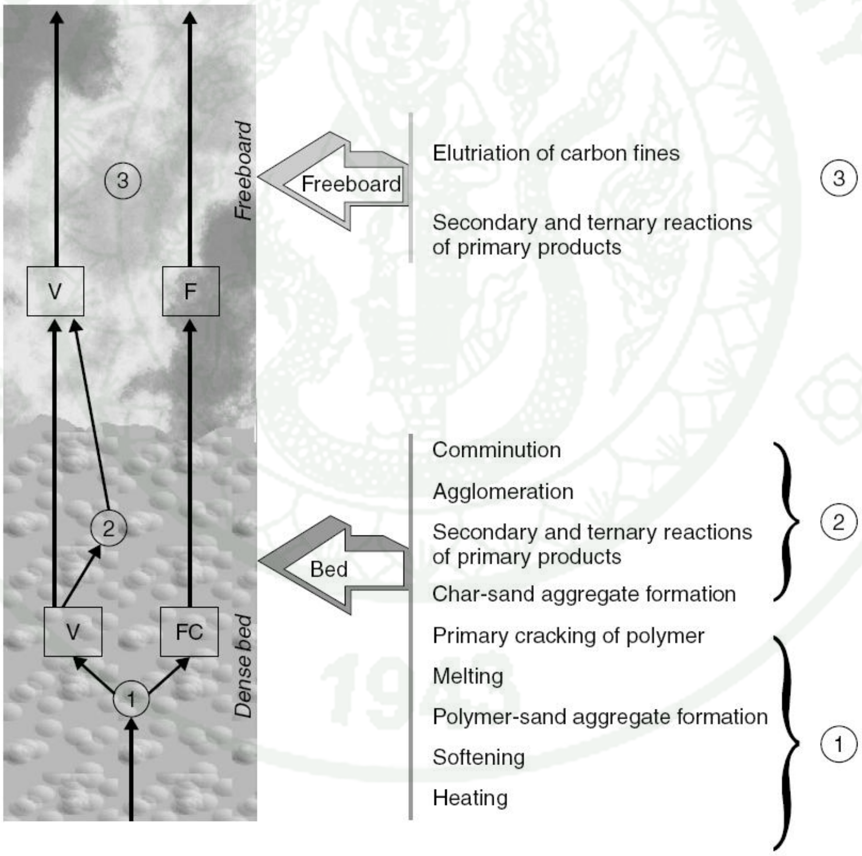


**Figure 4** Different steps that a polymer particle undergoes after the injection into a fluidized-bed pyrolyser

**Source:** Mastellone *et al*. (2002)

Figure 5 visualizes the same series/parallel sequence of steps, but by following the fate of a single polymer pellet just after its injection into the hot fluidized-bed pyrolyser. The pellet is fast heated up by a high-rate heat transfer mechanism that leads external surface up to the softening temperature (step 1 in Figure 5). Several sand particle stick on the plastic surface, forming a polymer–sand aggregate that has the external shell made of sand particles and the internal core made of polymer not yet molten. When the temperature further increases, the surface of the pellet reaches the melting temperature and the polymer feeds throughout the bed particles of the external shell, so forming a uniform coating over and between them (steps 2–4).

The peculiar features of fluidized beds make this heating and coating process very fast, so that the beginning of the pyrolysis, i.e. the cracking of the weak carbon–carbon bonds of the polymer chain, starts when the polymer has already covered the bed particles. The primary cracking (step 7) is then not related to the whole molten pellet, but to a layer of polymer, which coats and adheres on the external surfaces of single sand particles.

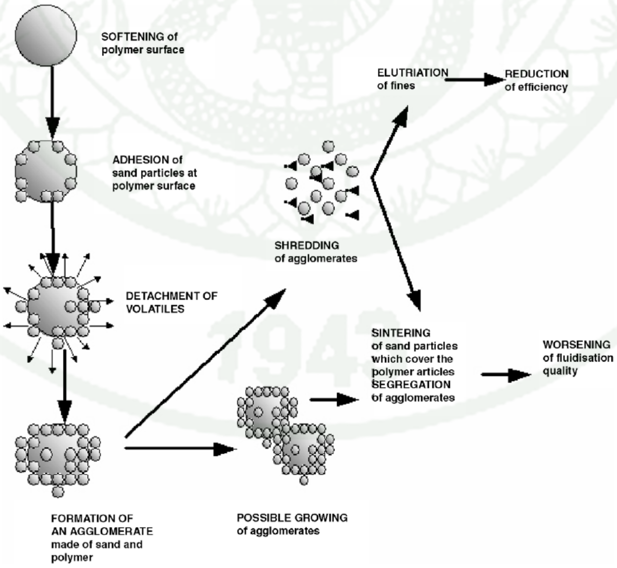


**Figure 5** Stages of plastic particles in the fluidized bed

**Source:** Aznar *et al*. (2006)

# MATERIALS AND METHODS

## Materials

### 1. PP plastic

The PP was obtained from TPI Polene Public Company Limited, Bangkok, Thailand. The particle size was 0.03 mm in a pellet shape without additive.

### 2. Reactor

Two types of reactors were used in this study.

#### 2.1 Semi batch reactor

A semi-batch reactor made of stainless steel having an internal capacity of 1 l was set up as show in Figure 6. An electrical furnace driven by a volt transformer was used to heat the system and to keep the reaction temperature at a desired value. The voltage adjustment procedure is shown in Table 8. A thermocouple was used to monitor the temperature in the reactor. The feed rate of nitrogen used as a carrier gas was measured by an orifice. The compressed air was fed to the system for partial oxidation reaction and the feed rate was also measured by a rotameter. The product gas was condensed in a water baths. The non-condensable product was recycled to the reactor in gas recycling experiments. The feed rate of the recycled gas was measured by an orifice.

**Table 8** Adjustment procedure for volt transformer

| Time (min) | Voltage (V) |
|---|---|
| 0 - 26 | 220 |
| 27 - 32 | 110 |
| › 32 | 120 |

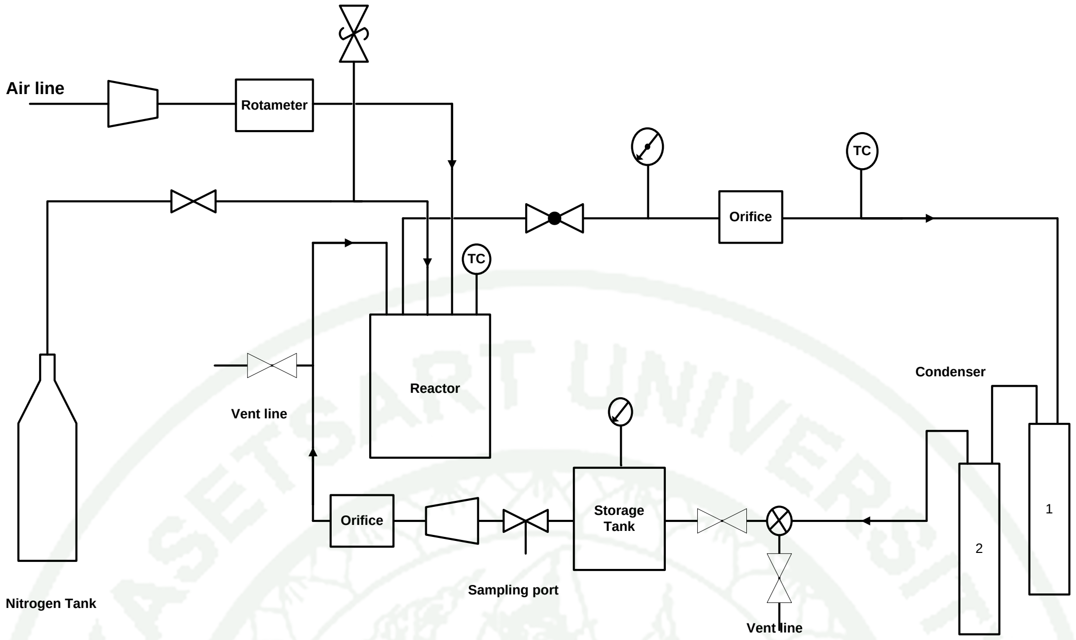


**Figure 6** Schematic diagram of the semi-batch reactor

2.2 Fluidized bed reactor.

The fluidized bed reactor was designed based on the information of plastic pyrolysis in a semi-batch reactor. It was constructed of stainless steel insulated with asbestos. Silica sand as a bed material was used in the reactor above a gas distributor. The temperature in the reactor was maintained at the required temperature by using LPG burner at the bottom of the reactor. The amount of LPG and air was optimized. The temperature was monitored at several points in the fluidized bed. Temperature sensors were installed at *3* cm below the gas distributor and every *25.4* cm above distributor to the height of 177.8 cm. The PP was gravity fed via a screw feeder into the fluidized bed. The pyrolysis vapors were passed through the inner tube of the heat exchanger and condensed in the condensers.

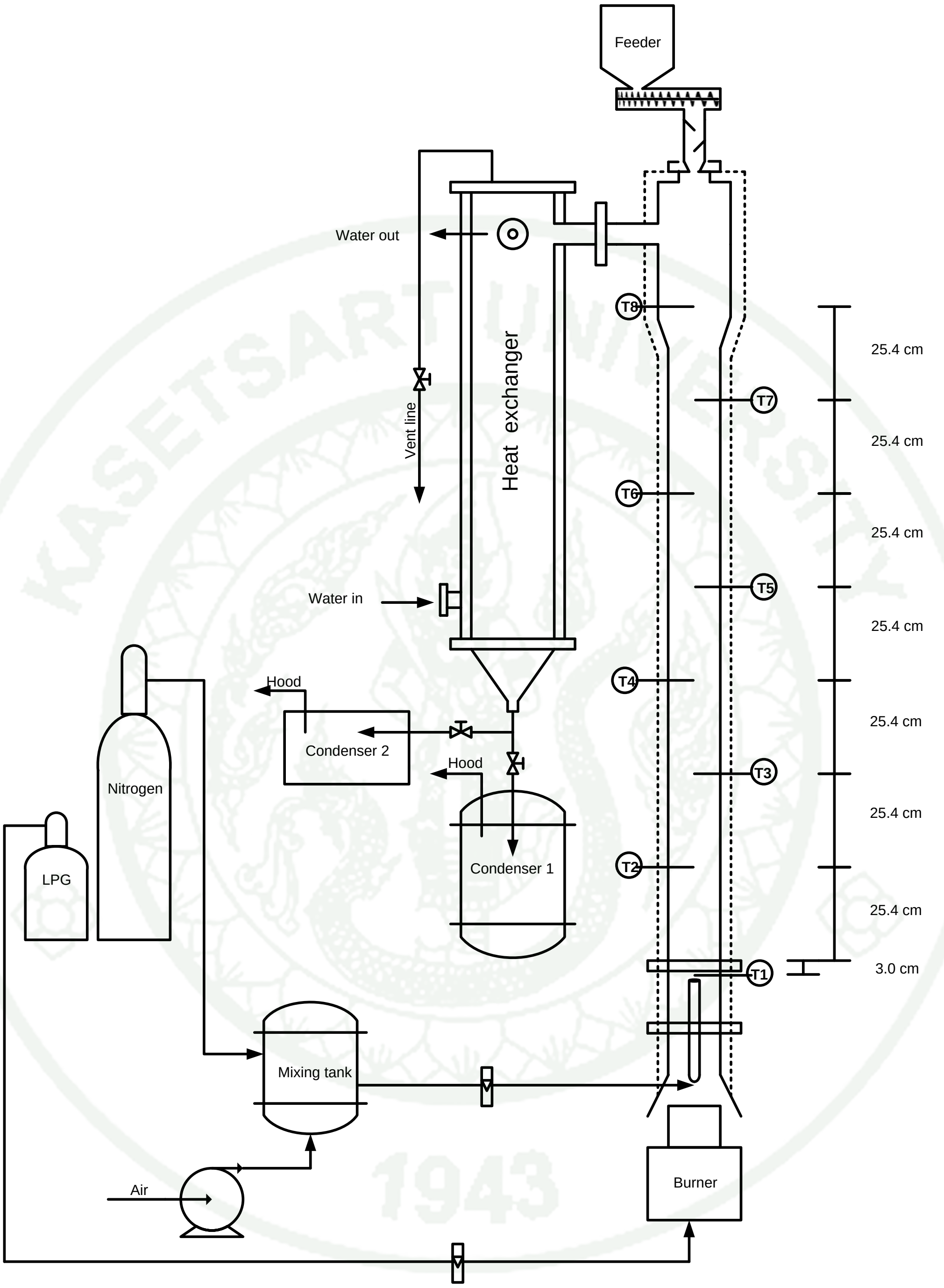


**Figure 7** Schematic diagram of the fluidized bed reactor

### 1. Product analysis

The gases evolved throughout the pyrolysis experiment were collected and analyzed off line. Hydrocarbons up to $C_4$, hydrogen, nitrogen, and oxygen were analyzed using Porapak Q packed column gas chromatography with thermal conductivity detector.

The liquid hydrocarbon products from pyrolysis process was weighted and distilled following ASTM D-86 to separate into Gasoline ($C_5$-$C_{12}$), Kerosene ($C_{13}$-$C_{17}$), and Gas Oil (more than $C_{18}$).

## Methods

The pyrolysis or thermal cracking is a process of chemical and thermal decomposition, generally leading to smaller molecules and are endothermic reaction. Therefore, ensuring a supply of heat to the reacting material is essential and generally rate-determining. Partial oxidation supplies such heat internally, but the pyrolysis products are diluted by oxidation or combustion products. The suitable operating conditions were investigated to minimize the energy input and obtain acceptable amount of valuable products in both of semi-batch and fluidized bed reactor. The feed stock used was virgin PP pellet and experiments were carried out at atmospheric pressure. The effects of operating conditions were investigated.

### 1. Effect of temperature on the pyrolysis of PP pellet by DSC-TGA

The effect of temperature on the pyrolysis of PP pellet was investigated by DSC-TGA. Nitrogen was used as a carrier gas at *0.12 kg/h* with *20 $^oC$/min* of temperature program. The weight loss and weight difference were detected until the degradation was completed.

## 2. Effect of voltage adjustment

The effect of voltage adjustment, which regulates heat supplying rate, on the system temperature was studied. The voltage regulator was used to vary the supplied voltage for electrical furnace of semi- batch reactor. The voltage between *0-220 volts* with time was varied to achieve the desired temperature.

## 3. Effect of pyrolysis condition

The effect of pyrolysis condition on the PP degradation was studied. The decreasing of temperature from endothermic reaction of pyrolysis was investigated in comparison with reactor temperature without reaction. The degradation products were analyzed.

## 4. Effect of partial oxidation

The effect of partial oxidation on the temperature profile and product distribution was studied. The variation of air in the range of *5.22 to 11.28 ml/s* were studied. The experiments were done in a semi-bath reactor.

## 5. Effect of product gas recycling

The effect of product gas recycling on the temperature profile and product distribution was studied. The amount of gas recycling from *5.85* to *10.27 ml/s* were studied. The experiments were done in a semi-bath reactor.

Summary of the experiment and their operating conditions in a semi batch reactor are shown in Table 9.

**Table 9** Summary on the operating condition for investigation of their effects on PP pyrolysis in a semi-batch reactor.

| Condition | PP ( g ) | Nitrogen ( ml/s ) | Air ( ml/s ) | Gas recycling ( ml/s) |
|---|---|---|---|---|
| DSC-TGA | 0.0078 | 28.13 | - | - |
| No reaction | - | 23.29 | - | - |
| Pyrolysis | 50 | 23.29 | - | - |
| Partial oxidation 1 | 50 | 18.07 | 5.22 | - |
| Partial oxidation 2 | 50 | 14.78 | 8.51 | - |
| Partial oxidation 3 | 50 | 11.51 | 11.78 | - |
| Gas recycling 1 | 50 | 8.93 | 8.51 | 5.85 |
| Gas recycling 2 | 50 | 6.51 | 8.51 | 8.27 |
| Gas recycling 3 | 50 | 4.51 | 8.51 | 10.27 |

### 6. Effects of LPG feed rate on the fluidized bed reactor temperature and combustion products

The effect of LPG feed rate on the system temperature and combustion products were investigated. The LPG feed rates were varied from *5.22 to 10.23 ml/s* at constant air feed rate of *300 L/min*. The fluidizing gas was controlled to be *1.5 Umf* by nitrogen. The experiments were operated in a fluidized bed reactor.

### 7. Effects of air feed rate on the fluidized bed reactor temperature and combustion products

The effects of amount of air on the system temperature and combustion products were investigated. The feed rates of air were varied at *100, 300, 400* and *500 l/min* at constant feed rate of LPG of 7*.32 l/min*. The fluidizing gas was kept constant at 1.5 $U_{mf}$. The experiments were done in the fluidized bed reactor.

## 8. Effect of plastic feed rate

The plastic feed rates of *25, 40, 50* and *60 g/min* were fed through the screw feeder for *2 min* into the reactor which caused the temperature to drop. After 2 minutes, the feeding was stopped. LPG and air feed rate were fixed at *300 l/min* and *7.32 l/min,* respectively. The fluidizing gas was controlled to be *1.5 Umf* by nitrogen. After the temperature approach to initial starting, the experiment was repeated again for *9 times* (*10 times for total*). The experiments were operated in a fluidized-bed reactor and temperature profiles were investigated.

## 9. Effect of bed temperature

The bed temperature at *3 cm* below distributor was controlled to be *450* and *480* $^oC$ by using *300 L/min* of air with *7.31 and 7.69 of LPG*, respectively. The fluidizing gas of *1.5 Umf* was used. The plastic feeding of *25 g/min* was fed for *2 min* which caused the temperature to drop. The experiment was repeated again for *9 times*. The experiments were done in a fluidized-bed reactor and the product distribution was investigated.

## 10. Effect of secondary air feed rate for partial oxidation

The bed temperature was set at *450* $^oC$ by using *7.31* and *300 l/min* of LPG and air, respectively. The fluidizing gas was controlled to be *1.5 Umf* by nitrogen. The secondary air feed rate of *25, 50* and *100 L/min* was mixed with nitrogen and fed to the system for partial oxidation. The plastic feeding at *25 g/min* was fed for *2 min* which caused the temperature to drop. The experiment was repeated again for *9 times*.

## 11. Effect of energy saving by partial oxidation

The temperature with secondary air feed rate of *100 l/min* for partial oxidation was adjusted by variation of LPG feed rates to obtained the temperature to be the same as that using *7.31* and *300 l/min* of LPG and air (without partial oxidation), respectively. The LPG feed rate was decreases carefully to keep the temperature closed to desired temperature. The fluidizing gas was controlled to be *1.5 Umf* by nitrogen. The plastic feeding at *25 g/min* was fed for *2 min* which caused the temperature to drop. The experiment was repeated again for *9 times*.

## 12. Effect of gas recycling

The bed temperature was set at $450\ ^{o}C$ by using *7.31* and *300 l/min* of LPG and air, respectively. The fluidizing gas at of *1.5 Umf* was fed into the reactor. The secondary air feed rate of *100 l/min* as well as *100 l/min* of gas product recycled by air pump was mixed with fresh nitrogen in mixing tank and then fed to the system. The plastic feeding at *25 g/min* was fed for *2 min* which caused the temperature to drop. The experiment was repeated again for *9 times*.

Summary of the experiment and their operating conditions in the fluidized bed reactor are shown in Table 10.

**Table 10** Summary on the operating condition for investigation the effect of PP pyrolysis in the fluidized-bed reactor.

| Run | Studied | Bed Temperature ( °C ) | Air + Secondary air (L/min) | LPG (L/min) | Plastic feed rate (g/min) | Time period for plastic feeding |
|---|---|---|---|---|---|---|
| 1 | Effect LPG feed rate | - | 300 | 5.22, 7.31, 9.50,10.23 | - | - |
| 2 | Effect of Air feed rate | - | 100, 200, 300, 400 | 7.31 | - | - |
| 3 | Effect plastic feed rate | 450 | 300 | 7.31 | 25, 40<br>50, 60 | 2 min |
| 4 | Effect of bed temperature | 450, 480 | 300 | 7.31, 7.69 | 25 | 2 min/10 cycle |
| 5 | Effect of air for partial oxidation | 450 | 300<br>+ 25, 50, 100 | 7.31 | 25 | 2 min/10 cycle |
| 6 | Effect of energy saving by partial oxidation | 450 | 300, 300+100 | Varied | 25 | 2 min/10 cycle |

**Table 10** (Continue)

| Run | Case | Bed Temperature ( °C ) | Air + Secondary air (l/min) | Gas Recycling (l/min) | LPG (l/min) | Plastic feed rate (g/min) | Time period for plastic feeding |
|---|---|---|---|---|---|---|---|
| 7 | Effect of gas recycling | 450 | 300<br>+ 100 | 100 | 6.59 | 25 | 2 min/10 cycle |

# RESULTS AND DISCUSSIONS

This research was divided into two parts; the main purpose of the first part is to investigate the influences of operating condition on the plastic pyrolysis in a semi-batch reactor. The experiments were conducted with the variations of the oxygen, and gas recycling feed rate. The temperature profiles were used to study the effect of pyrolysis with and without partial oxidation and gas recycling. The product was also analyzed in each case for comparison.

## 1. The result of semi batch reactor

### 1.1 The thermogram of PP degradation by DSC-TGA

Figure 8 shows the thermogram of PP degradation by DSC-TGA. The weight loss and weight different were detected at the heating rate of $20\,^{o}C/min$ under nitrogen atmosphere. It was found that the weight loss was initially observed at about $360\,^{o}C$ and then increases sharply in the range of $405\text{-}470\,^{o}C$. After $473\,^{o}C$, the percent weight of PP decreased to $0\%$ which can be concluded that the degradation of sample was completed.

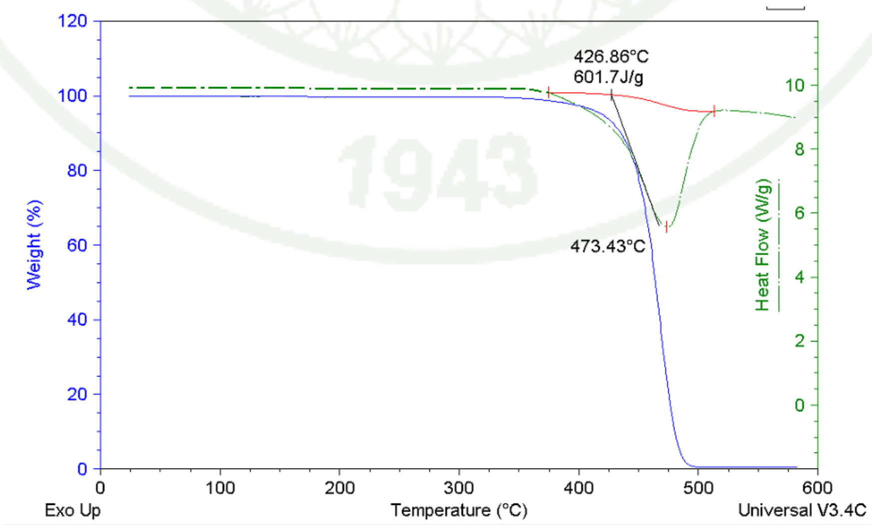


**Figure 8** The thermogram of PP degradation by DSC-TGA

1.2 The temperature profile in the system without reaction

For a base line, the temperature profile of the system with a stream of nitrogen (*23.92 ml/s* at room temperature) and without PP was monitored. The temperature profile according to the voltage (Table 8) for *60 mins* is shown in Figure 9. The result shows that the temperature of the system reaches *450 $^{o}C$* within *25 mins*. Then, the temperature remains constant.

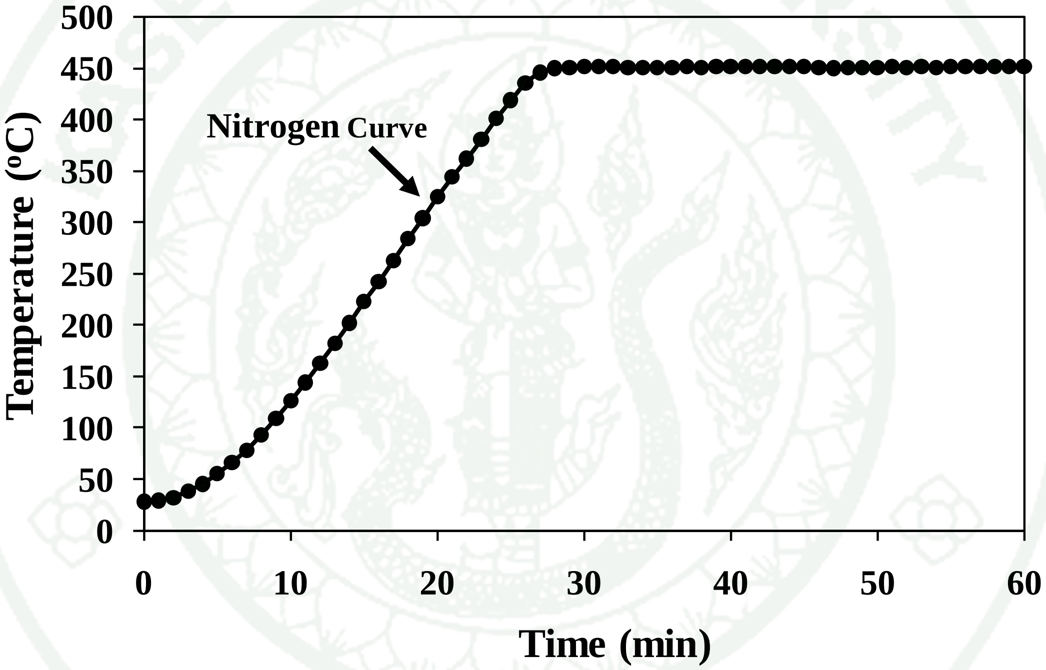


**Figure 9** Temperature profile of the system with a stream of nitrogen only without reaction

1.3 The temperature profile in the pyrolysis

Figure 10 shows the comparison between the temperature profiles of the pyrolysis system and the temperature profile of the system with a stream of nitrogen only. The heat input for both runs was adjusted according to Table 8. As expected, the lower temperature of the pyrolysis system was observed due to the endothermic reaction. The temperature difference between these two systems slightly increased at the initial of the experiment. Although at low temperature no reaction occurred in the pyrolysis system, sensible heat was required for the pyrolysis. The initial degradation temperature of PP under nitrogen stream is *380 °C* [4].

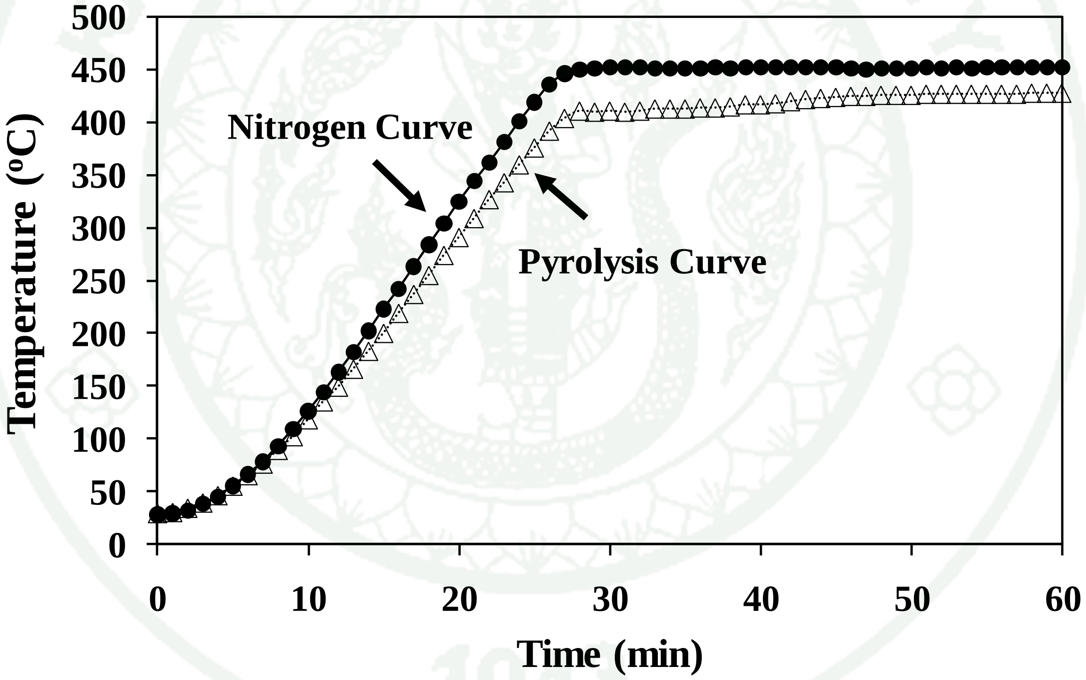


**Figure 10** Comparison of temperature profiles of the systems with pyrolysis and without reaction

The temperature difference of *35-43 °C* was found in the degradation period when the temperature is above *380 °C*. It can be explained that the PP degradation operated in oxygen absent gas mainly occurred in this range. Finally, the temperature difference slowly decreased because of the running out of feedstock and reducing of pyrolysis reaction.

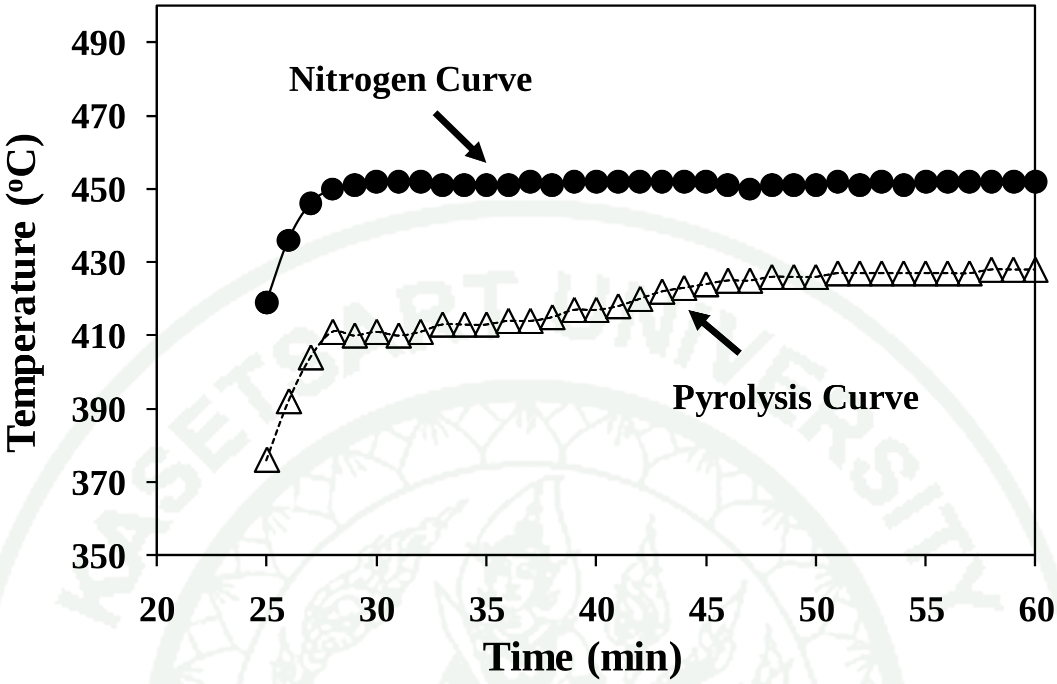


**Figure 11** The enlarged temperature profiles of the systems with pyrolysis and without reaction

1.4 The temperature profile in the pyrolysis with partial oxidation

Pyrolysis combined with partial oxidation was carried out with the air feed rates in the range of *5.22 to 11.79 ml/s*. At low air feed rate of *5.22 ml/s*, temperature difference in pyrolysis system and pyrolysis system combined with partial oxidation were not significant at the beginning. Then, the generated heat from partial oxidation leads to the rising of system temperature and the different temperature was observed. The temperature of pyrolysis with partial oxidation is *2 to 10* $^{o}C$ higher than that of pyrolysis. After the period of pyrolysis of PP, gas products were still oxidized. Thus the temperature difference still existed although it decreased.

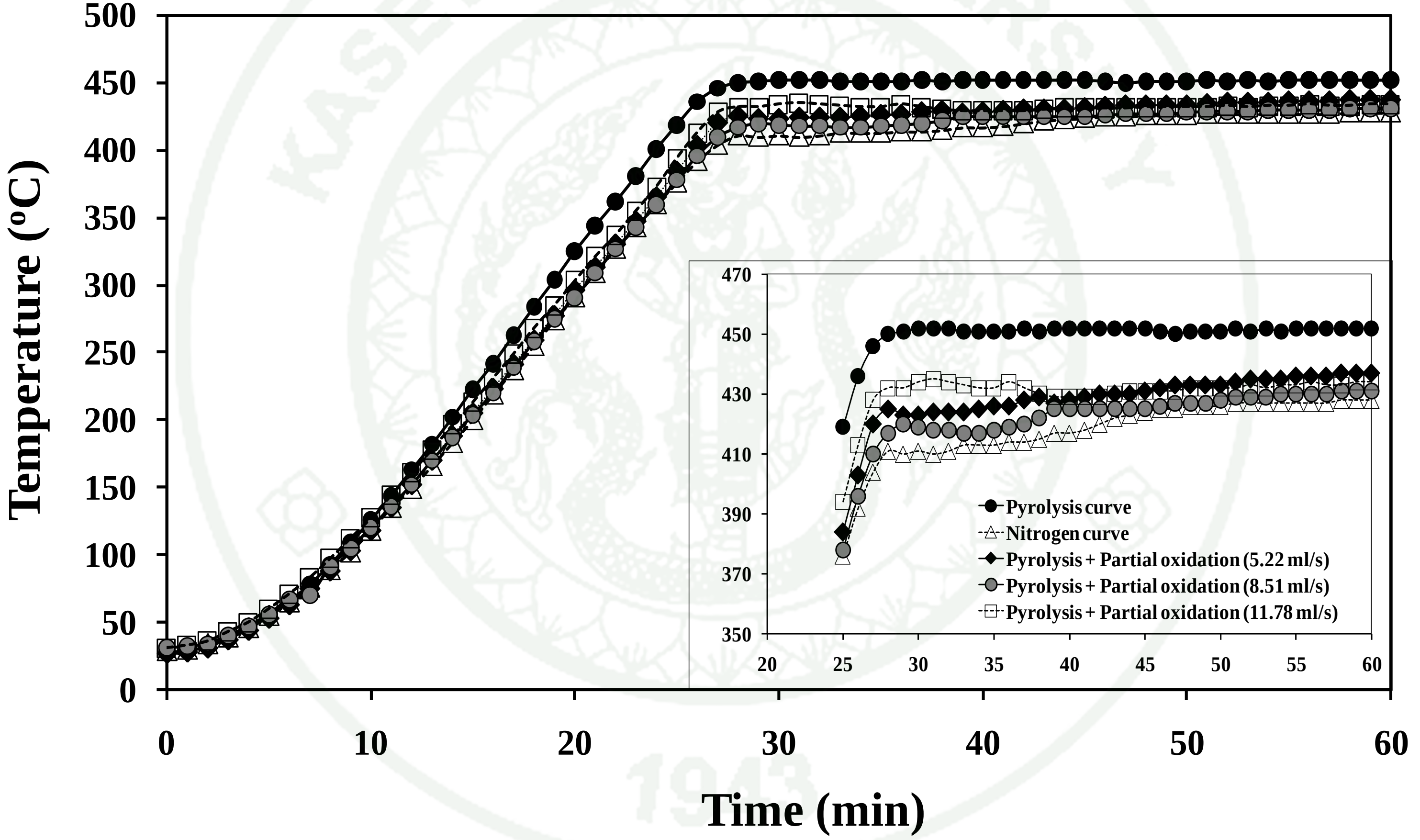


**Figure 12** Temperature profile for pyrolysis combined with partial oxidation

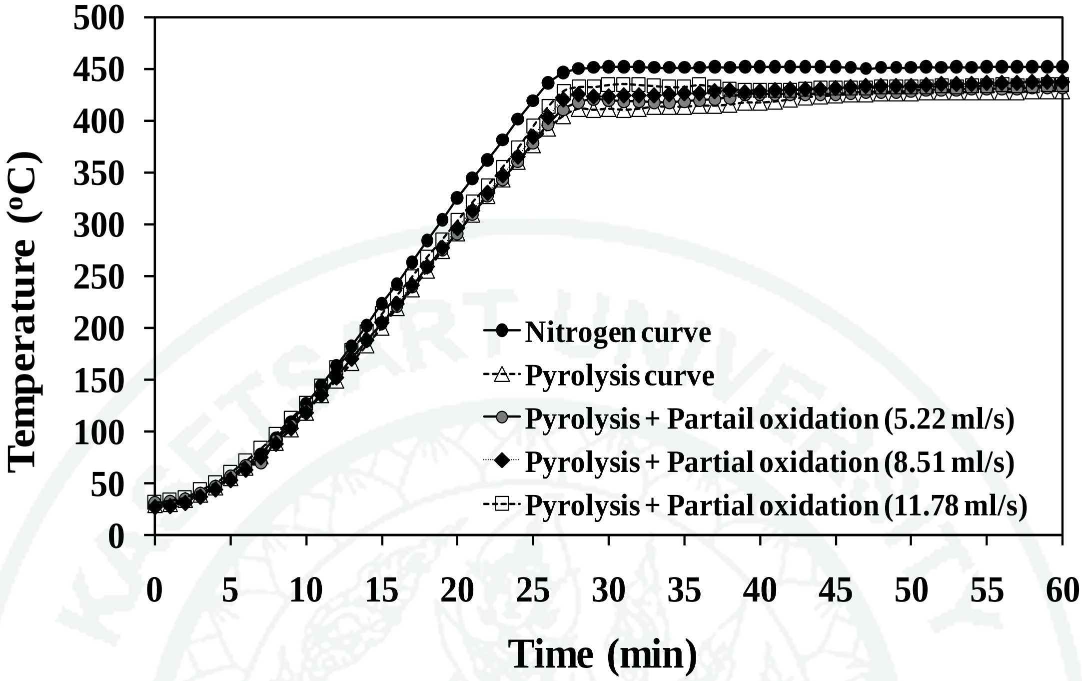


**Figure 13** Temperature profile for pyrolysis combined with partial oxidation at *5.22 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

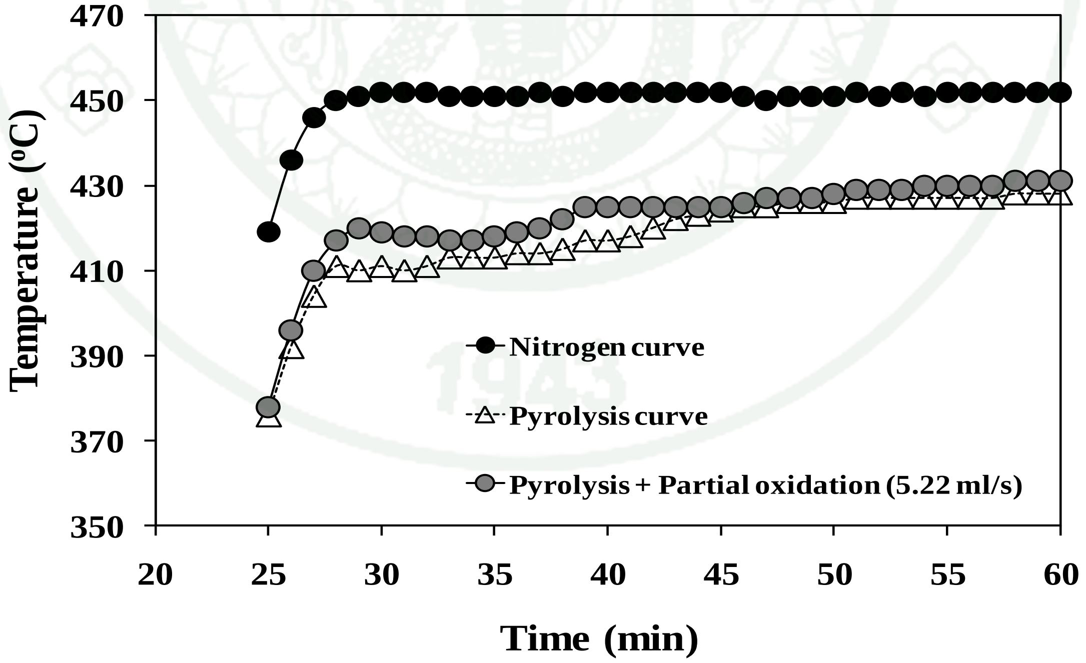


**Figure 14** The enlarged temperature profile for pyrolysis combined with partial oxidation at *5.22 ml/s* compared with the temperature profiles of the systems with pyrolysis and without reaction.

At higher feed rate of air, *8.51 ml/s*. The temperature difference between the pyrolysis and pyrolysis-partial oxidation increased dramatically. The temperature of pyrolysis-partial oxidation system is *13$^{o}$C* higher than that of the pyrolysis during *25-42 mins*. It demonstrates that the partial oxidation of PP or gas products still be the main effect on the increasing of temperature.

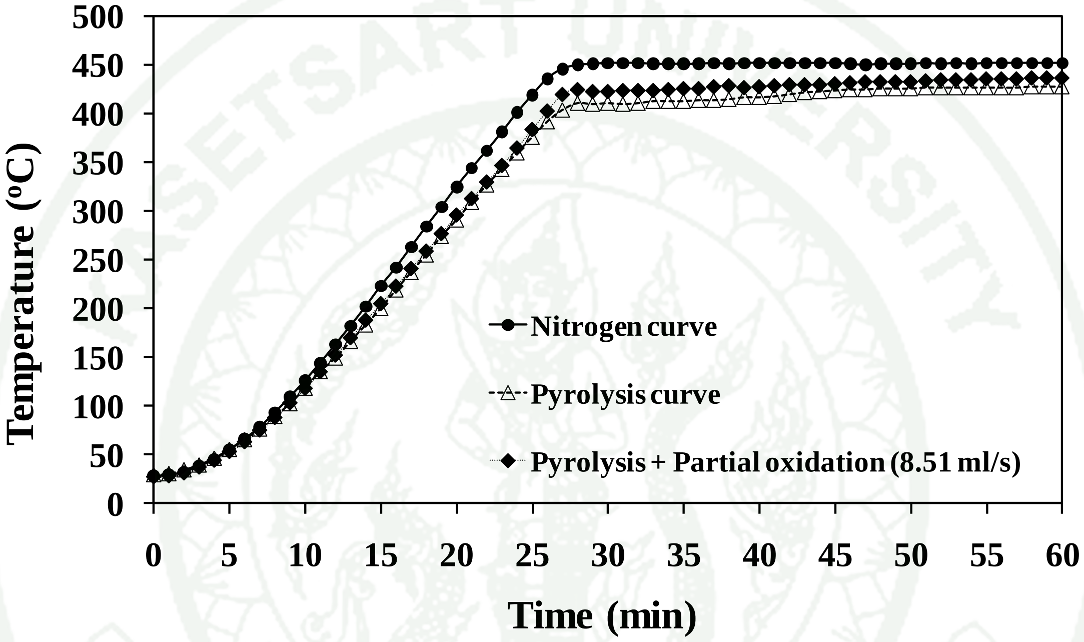


**Figure 15** Temperature profile for pyrolysis combined with partial oxidation at *8.51 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

At higher feed rate of air, *11.78 ml/s*, high temperature difference between pyrolysis and pyrolysis combined with partial oxidation was observed. This is caused by the increasing amount of air feeding. More than 20 $^{o}$C of temperature difference was observed between *25-37 min*s. When PP was all consumed, the temperature difference almost unchanged at *5 $^{o}$C*.

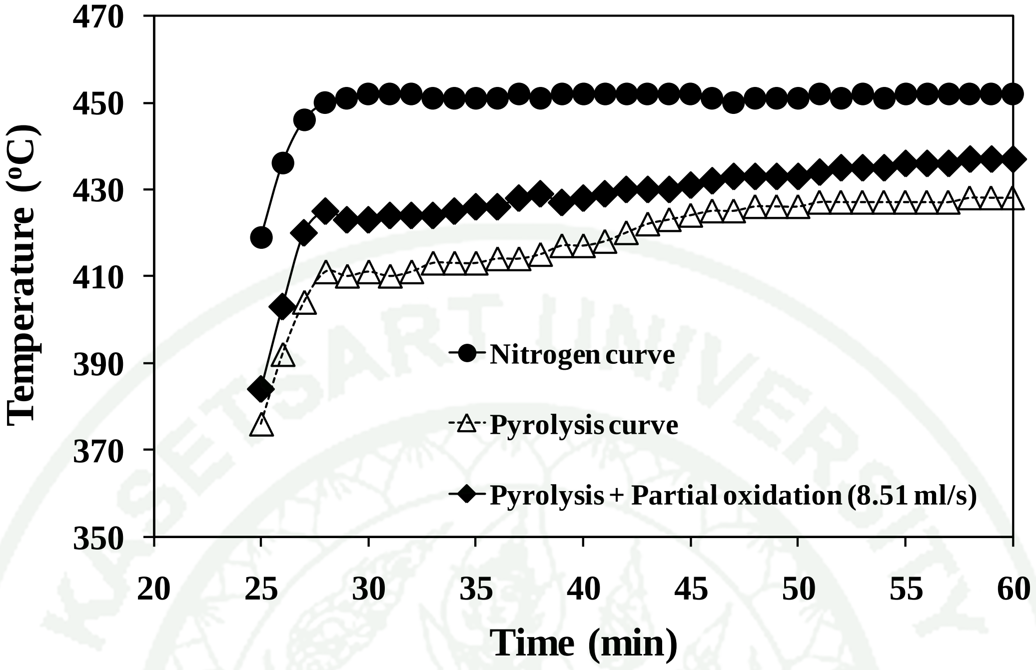


**Figure 16** The enlarged temperature profile for pyrolysis combined with partial oxidation at *8.51 ml/s* compared with the temperature profiles of the systems with pyrolysis and without reaction

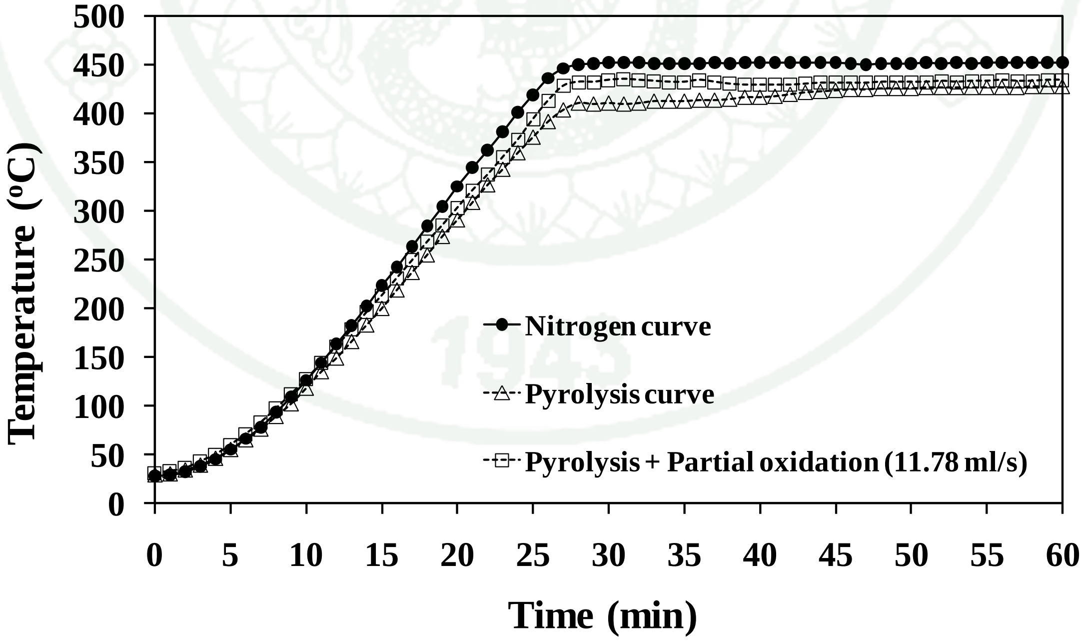


**Figure 17** Temperature profile for pyrolysis combined with partial oxidation at *11.78 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

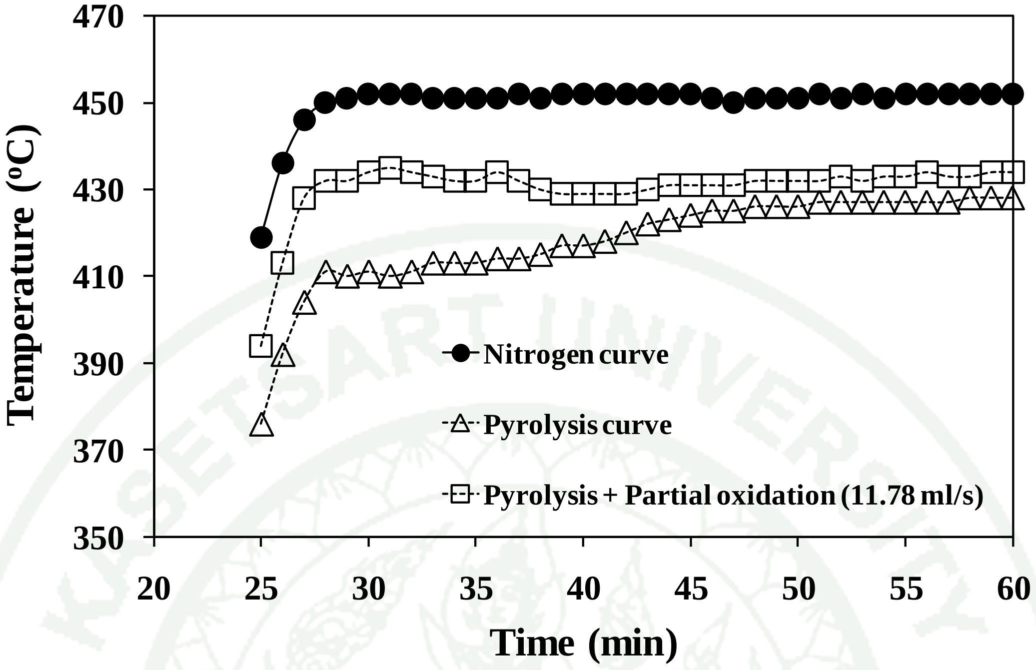


**Figure 18** The enlarged temperature profile for pyrolysis combined with partial oxidation at *11.78 ml/s* compared with the temperature profiles of the systems with pyrolysis and without reaction

1.5 The temperature profile in the pyrolysis with partial oxidation and gas recycling

As depicted in Figure 19, this pyrolysis process combined with partial oxidation and gas recycling was conducted. The feed rate of gas recycling was varied at *5.85, 8.27 and 10.7 ml/s*. Constant feed rate of air at *8.51 ml/s* was used for each experimental run.

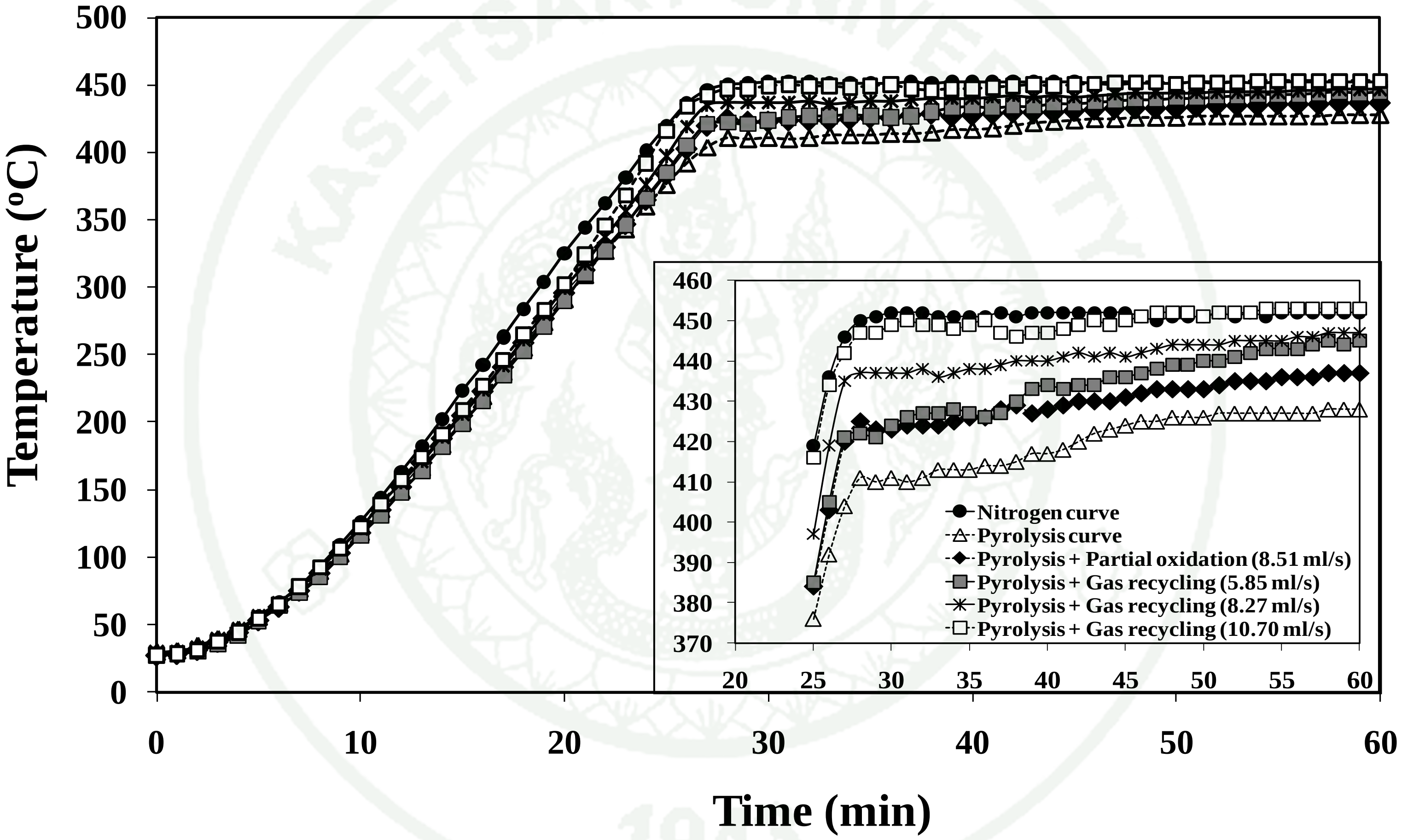


**Figure 19** The effect of gas recycling on temperature variation

At low gas recycling feed rate, *5.85 ml/s*, the temperature differences between pyrolysis combined with partial oxidation and pyrolysis combined with partial oxidation and gas recycling in the reaction period (*25-37 mins*) are in the range of *1 to 3* $^{o}C$. It can be explained that the small amount of product gas which is recycled to the system slightly affects to the temperature in the system. After *37 mins*, the temperature profile of pyrolysis combined with partial oxidation and gas recycling was higher than without gas recycling about *7* $^{o}C$. This is due to the heat release from the oxidation of recycled gas.

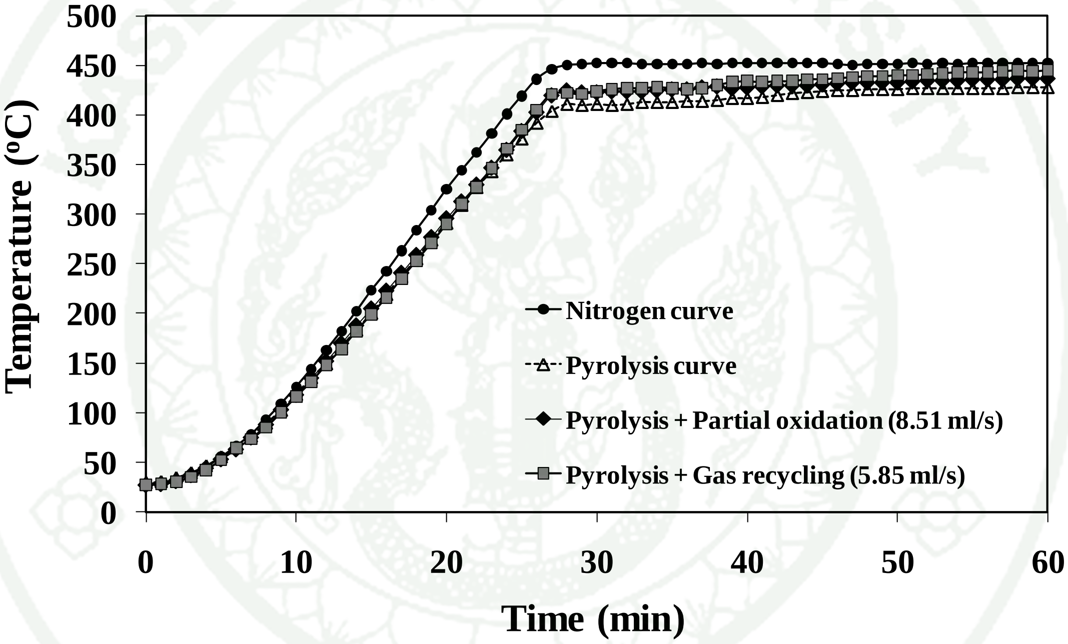


**Figure 20** Temperature profile for pyrolysis combined with gas recycling at *5.85 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

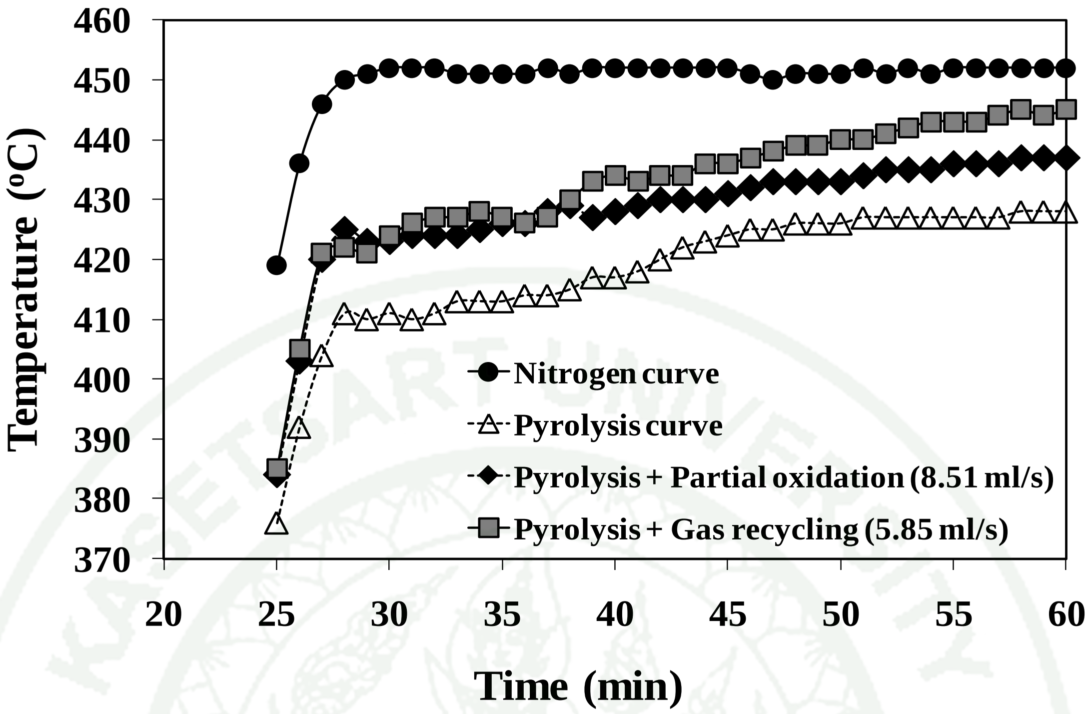


**Figure 21** The enlarge temperature profile for pyrolysis combined with gas recycling at *5.85 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

At higher gas recycling of *8.27 ml/s*, the temperature difference between the pyrolysis-partial oxidation and the pyrolysis-partial oxidation-gas recycling increased. The system with gas recycling had $25^oC$ higher than the system without gas recycling in the period of *25-42 mins*. The generated heat from the partial oxidation of gas recycling leads to the rising of the temperature. After *42 mins*, the temperature difference slightly increased until the end of the experiment.

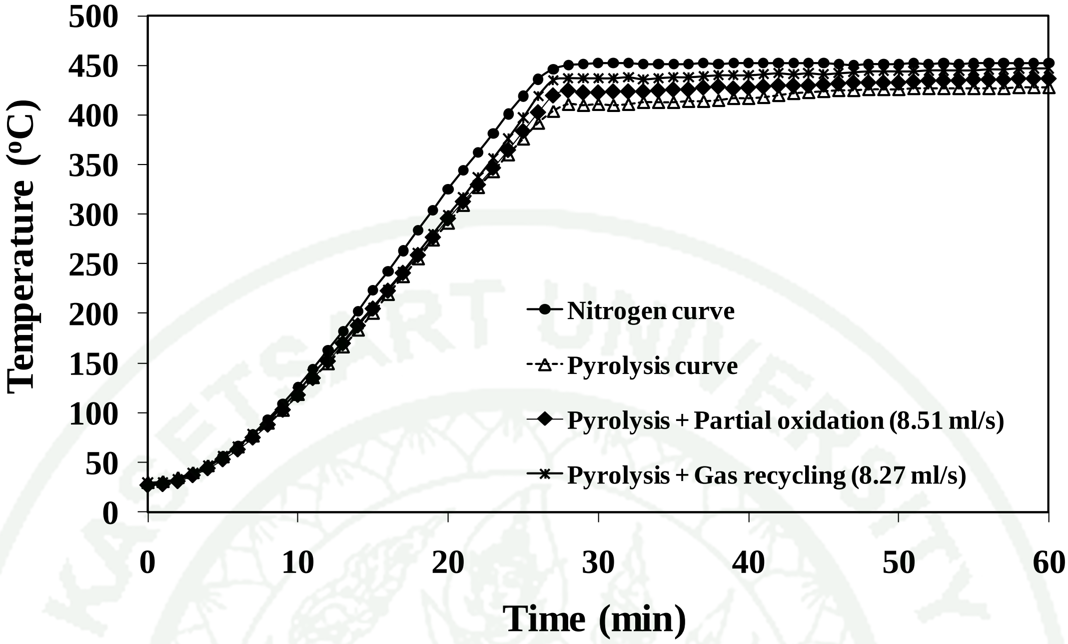


**Figure 22** Temperature profile for pyrolysis combined with Gas recycling at *8.27 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

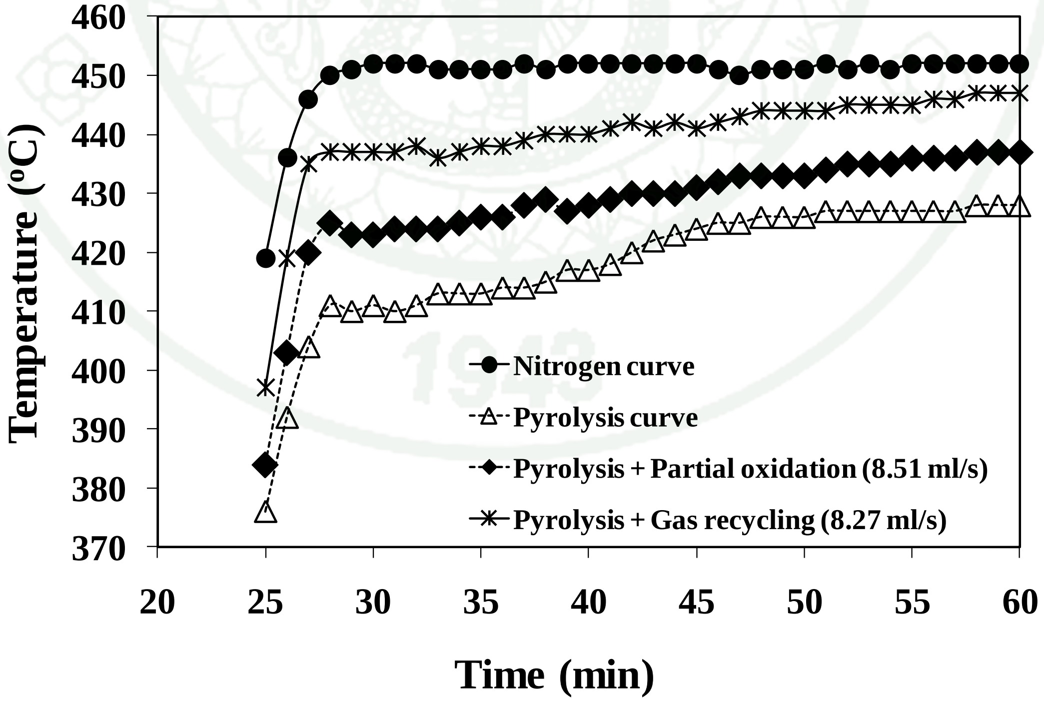


**Figure 23** The enlarged temperature profile for pyrolysis combined with gas recycling at *8.27 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

At higher gas recycling feed rate of *10.70 ml/s*, the temperature difference of the systems with and without gas recycling was increased dramatically. It had *35$^o$C* higher than the temperature of pyrolysis without gas recycling in the period of *24-41 mins.* After PP was consumed, the temperature remained constant and higher than the temperature of the system without gas recycling for *20 $^o$C.*

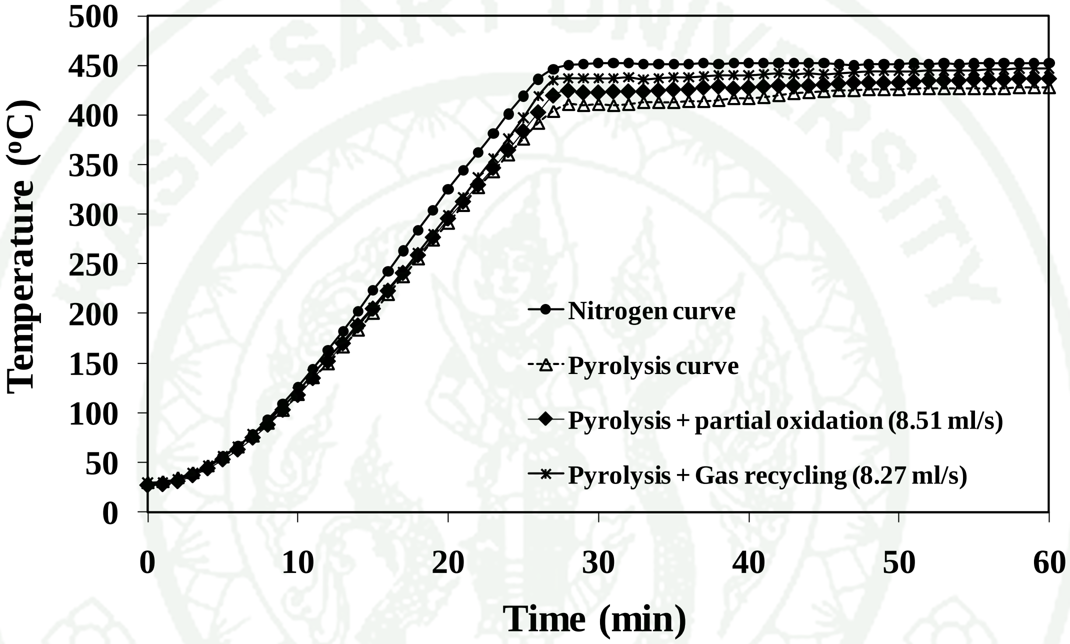


**Figure 24** Temperature profile for pyrolysis combined with gas recycling at *10.70 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

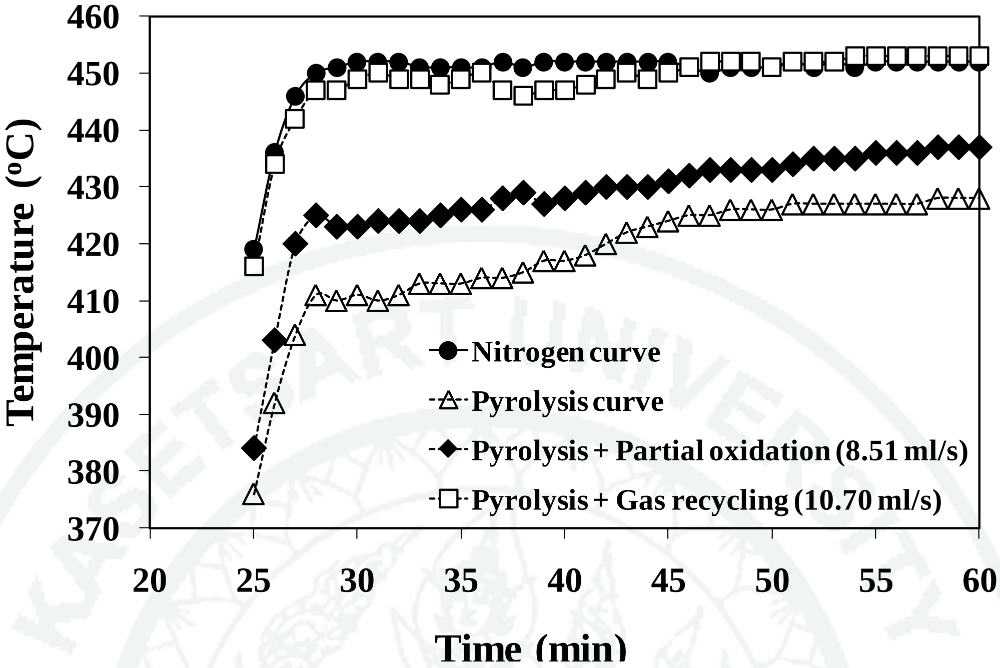


**Figure 25** The enlarged temperature profile for pyrolysis combined with gas recycling at *10.70 ml/s* compared with temperature profiles of the systems with pyrolysis and without reaction

1.6 Product distribution of semi-batch reactor

Analysis of hydrocarbon products is essential to ascertain their potential values as fuels or refinery feed stocks. ASTM D-86 was used to determine the proportion of liquid products. As appeared in Figure 26, the percent by weight of liquid product in the pyrolysis-partial oxidation decreases from the pyrolysis case. The increasing of air feed rate in the range of *5.22-11.79 ml/s* leads to the decreasing of liquid product from *63.24 to 51.64 % wt.* It showed that some PP and gas product were consumed to release heat to the system. The increasing of temperature because of released heat from partial oxidation causes increasing of gas product fraction. The total liquid fraction of pyrolysis-partial oxidation-gas recycling is also lower than that of the pyrolysis with partial oxidation. The rising of temperature due to the partial oxidation of some PP, gas product, and recycling gas leads to further cracking. The gas fraction increases with the gas recycling feed rate (see Figure 26).

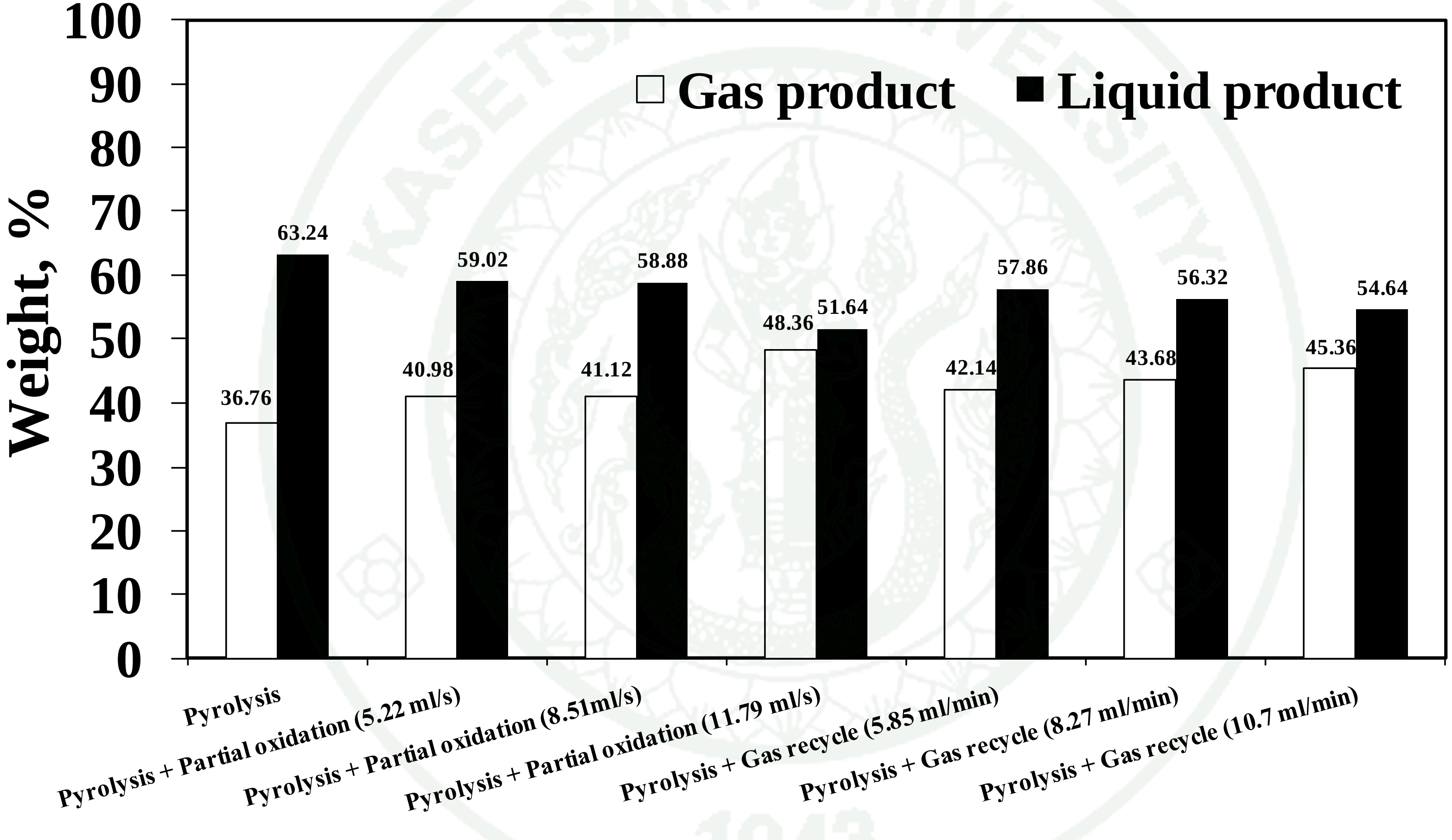


**Figure 26** The percent by weight of gas and liquid products of semi-batch reactor

### 1.7 The liquid product distribution of semi-batch reactor

Figure 27 shows percent yield of liquid product of *50 g* PP. For pyrolysis, the main product was kerosene components with *53.18%* yield. On the contrary, gasoline and long chain hydrocarbon products (C›18) showed low yield which were *6.55* and *3.50 %* respectively. For pyrolysis-partial oxidation, yield of kerosene dramatically reduced to *27.93 %*. Increasing yield of gasoline from *6.55 to 7.72 %* was achieved. The highest yield of gasoline, *7.72 %,* was obtained by using the air feeding at *8.51 ml/s*. Some kerosene product is degraded to gasoline product at this condition. The gas oil fractions at the air feed rates of *5.22* and *8.51 ml/s* were almost the same. At higher feed rate of air, *11.79 ml/s*, the gas oil fraction was the lowest at *15.20 %* due to the rising of the temperature from partial oxidation. Addition of partial oxidation leads to the decreasing of the total amount of liquid product due to increasing of system temperature. However, the yield of gasoline in liquid product increases up to *9.00 %*. For pyrolysis-partial oxidation-gas recycling, the reducing of gas oil yield from *13.34* to *3.56 %* was observed with the increasing of gas recycling from *5.85* to *10.7 ml/min*. It can be deduced that the rising of temperature leads to the degradation of long chain hydrocarbon into the kerosene and gasoline product. On the other hand, the yield of gasoline and kerosene increased from *14.55* to *14.90 % and 29.97* to *36.18 %* respectively with the increasing of gas recycling. It can be explained that some PP and gas product used to partial oxidation was compensated by recycled gas.

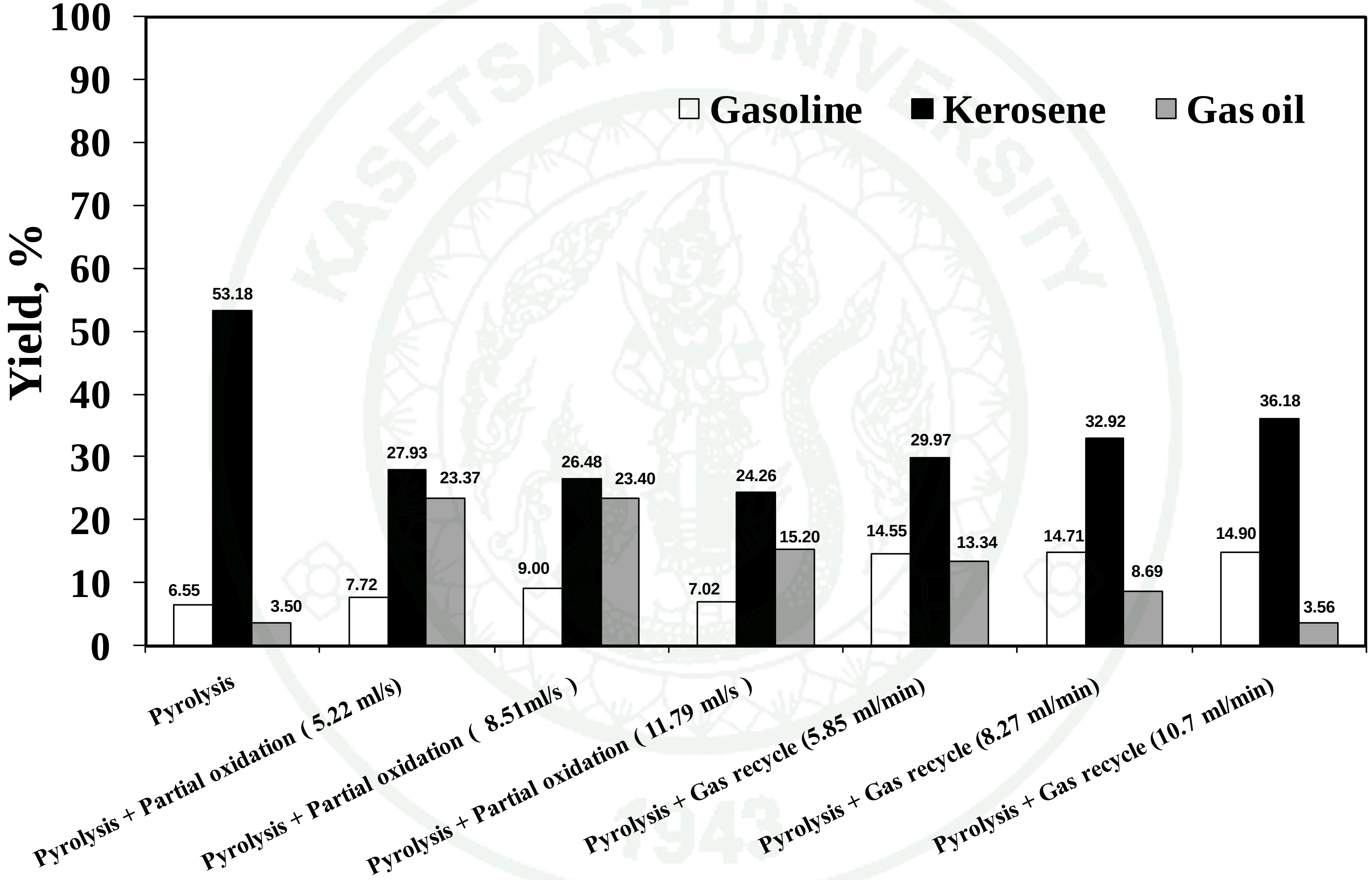


**Figure 27** The effect of partial oxidation and gas recycling on the percent yield of liquid product distribution

In the second part, experiments were carried out in a fluidized bed reactor. In the fluidized bed, LPG and air are fed to the burner which located about *45 cm* below fluidized bed distributor for combustion. Without plastic feeding, the effects of LPG and air feed rate for burner combustion on the temperature and combustion products were investigated. With plastic feeding, the effect of plastic feed rate, bed temperature obtained by varying LPG and air feed rates, secondary air feed rate for partial oxidation, and gas recycling feed rate on product distributions and production rate were also studied. The temperature profiles, production rate and distribution of gas and liquid were analyzed for comparison among various experimental cases.

## 2. The result of fluidized bed reactor

### 2.1 Effect of LPG feed rate on system temperature and combustion products

To ensure the effective combustion of LPG was obtained, the effect of LPG feed rate on system temperature and combustion gases without plastic feeding was investigated. The LPG feed rate was varied in the range of *5.22-10.23* l/min at a fixed air feed rate of *300 l/min*. At all LPG feed rates, the highest temperature was detected at the point 3 cm below the distributor where is the nearest measuring point to the burner. The temperature decreases along the reactor height from *336 to 235* $^oC$, *454 to 349* $^oC$, *502 to 417* $^oC$ and *543 to 449* $^oC$ for the LPG feed rate of *5.22, 7.32, 9.50 and 10.23 l/min*, respectively (See Figure 28). The temperature dropped due to heat loss though the wall to the environment.

At the lowest LPG feed rate of *5.22 l/min*, an unstable flame from the burner was observed due to the insufficient amount of LPG. The average temperature was *272.84* $^oC$. At higher LPG feed rate of *7.31 l/min*, the flame is more stable and the temperature increases considerably due to effective combustion. It is the result of high LPG feed rates at suitable fuel/air ratios which correspond to the fuel/air ratio of *41.04, 31.58 and 29.32*. The average temperatures at the LPG feed rate of *7.31, 9.50* and *10.23 l/min* were *402, 450 and 496* $^oC$, respectively (See Figure 29). It can be concluded that, in this experimental range, the more LPG feed rate results the higher reactor temperature due to more heat supplied to the system caused by more combustion reactions.

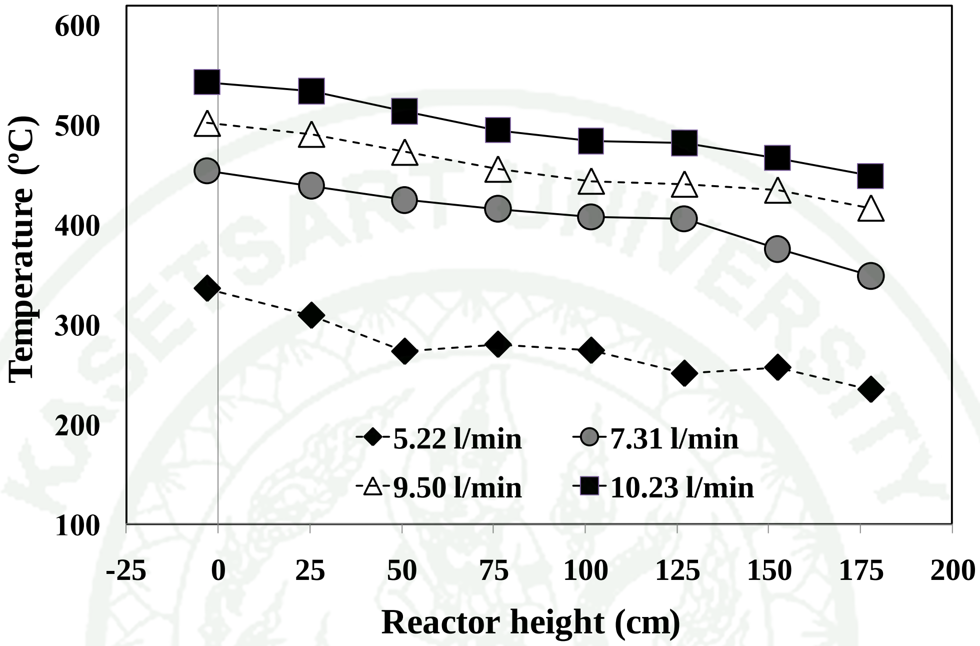


**Figure 28** Temperature profile at various LPG feed rates. The air feed rate is kept constant at *300 l/min*

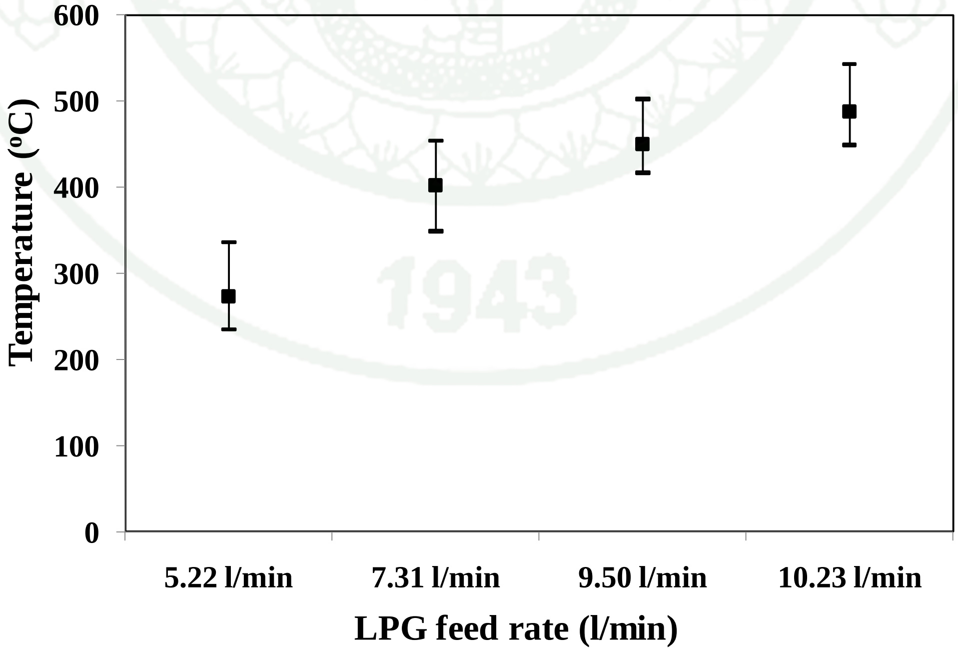


**Figure 29** The average temperature at various LPG feed rates . The air feed rate is kept constant at *300 l/min*

The combustion product consists of carbon dioxide, carbon monoxide and oxygen. Increasing the LPG feed rate from *5.22 to 10.23 l/min*, carbon dioxide increases from *2.91 to 5.42% mol* (See Figure 30). At higher feed rate of LPG, more combustion of LPG leads to more carbon dioxide production. This corresponds to decreasing of residual oxygen from *10.91 to 7.00% mol*. At the LPG feed rate at and below *9.50 l/min*, no carbon monoxide was observed. At the highest feed rate, *10.23 l/min*, small amount of carbon monoxide, *0.39 % mol*, was found due to incomplete combustion caused by less excess oxygen. The total flow rates of combustion products fed into the fluidized bed reactor are obtained as shown in Figure 31.

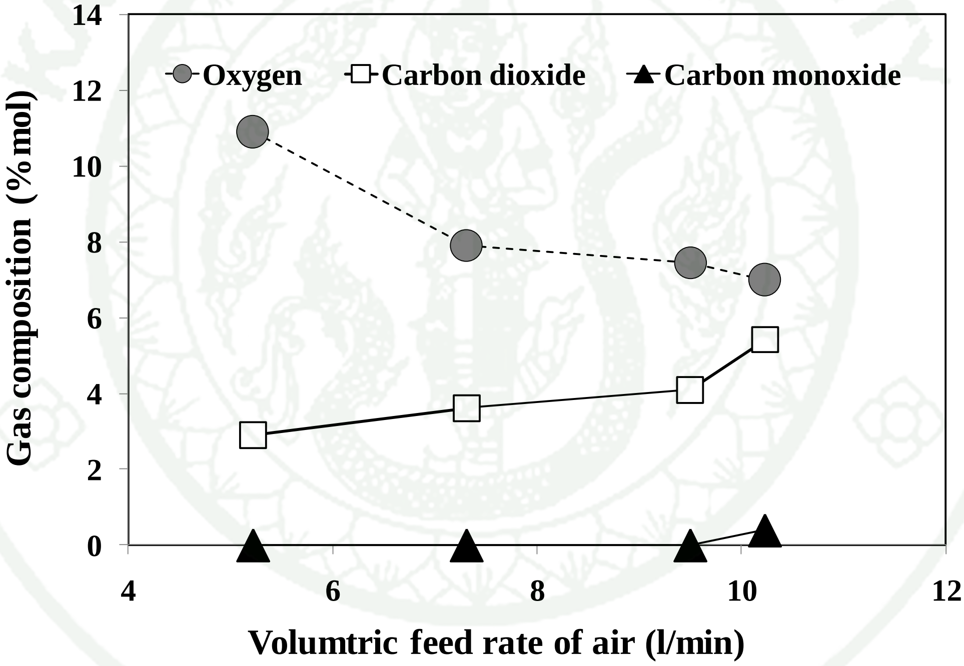


**Figure 30** Distribution of combustion product at various LPG feed rates. The air feed rate is kept constant at *300 l/min*

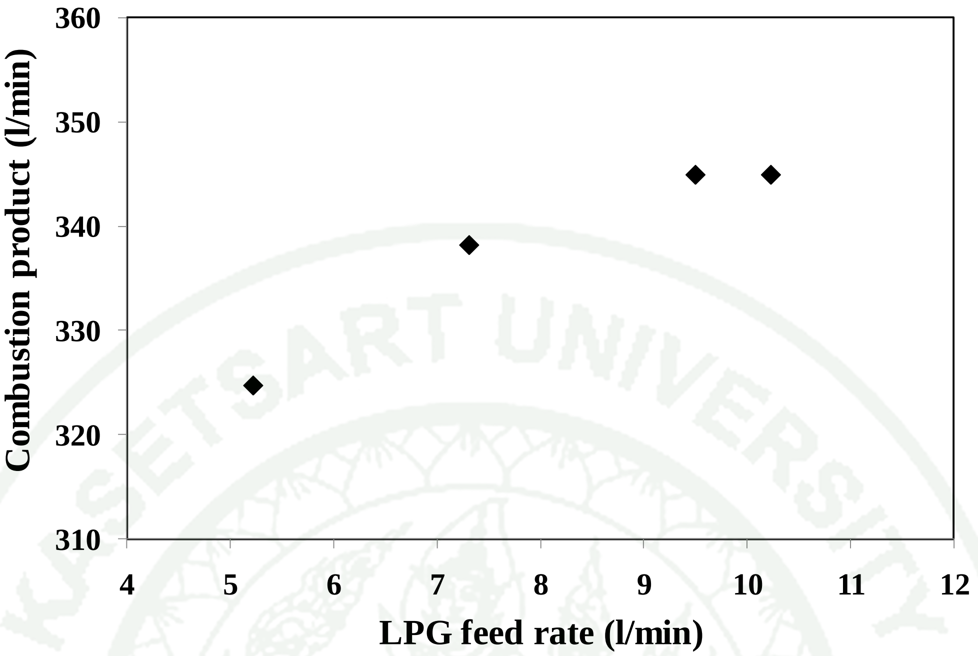
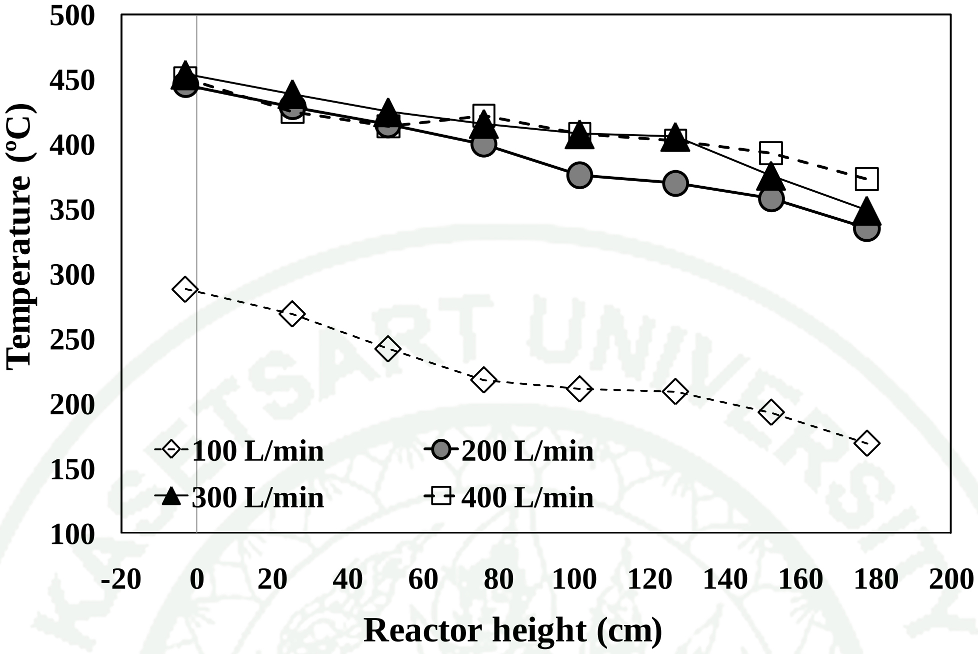


**Figure 31** Volumetric flow rate of combustion gas product at various LPG feed rates. The air feed rate is kept constant at *300 l/min*

2.2 Effect of air feed rate for burner on system temperature and combustion products

Figure 32 illustrates the effect of air feed rate on the temperature of system without plastic feeding. The air feed rate was varied from *100 to 400 l/min* at the fixed LPG feed rate of *7.31* l/min. The temperature along the reactor height for the air feed rates of *100, 200, 300* and *400 l/min* decreases from *288 to 169* $^{o}$*C, 446 to 335* $^{o}$*C, 454 to 349* $^{o}$*C and 451 to 373* $^{o}$*C*, respectively.



**Figue 32** Temperature profile at various air feed rates. The LPG feed rate is kept constant at *7.31 l/min*

At the lowest air feed rate of *100 l/min*, the flame was not stable and troublesome ignition was occurred. The average temperature in the system is too low (*224 $^{o}$C* ). Insufficient amount of air results in the incomplete combustion which was confirmed by the presence of carbon monoxide (see also in Figure 34). In contrast, the amount of oxygen is adequate to obtain stable flame and smooth ignition at higher air feed rate, *200-400* l/min. The temperatures were much higher than that obtained at air feed rate of *100 l/min*. At the air feed rates of *200, 300 and 400 l/min*, the average temperatures along the reactor height were *391, 409, and 411$^{o}$C*, respectively (see Figure 33). It can be seen that, when the air feed rate is enough (*200-400 l/min*), the air feed rate does not affect the system temperature significantly.

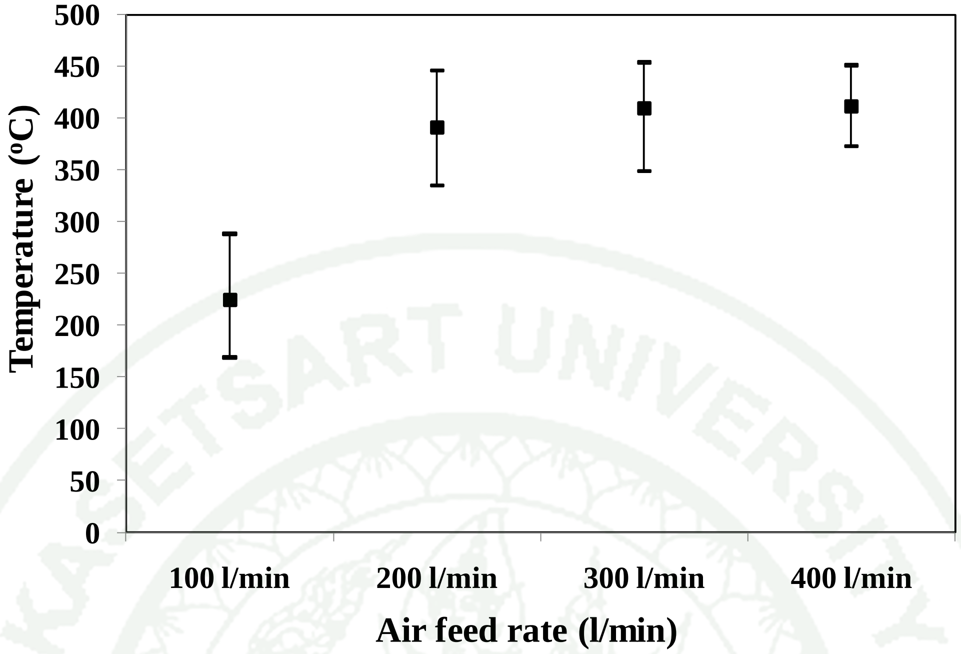


**Figure 33** The average temperature at various air feed rates . The LPG feed rate is kept constant at *7.31 l/min*

With increasing air feed rate from *100 to 400 l/min*, carbon dioxide increases sharply from *1.03 to 3.41% mol* due to the sufficient amount of air for combustion reaction while carbon monoxide decreases from *0.57 to 0 % mol* (see Figure 34). More oxygen leads to more carbon monoxide conversion to carbon dioxide. The oxygen in emission gas increases from *4.08 to 8.18%* with the increasing of air fed rate from *100 to 400 l/min*. The oxygen for combustion reaction is enough and then increases in emission gas. The total flow rates of combustion products fed into the fluidized bed reactor are obtained as shown in Figure 35.

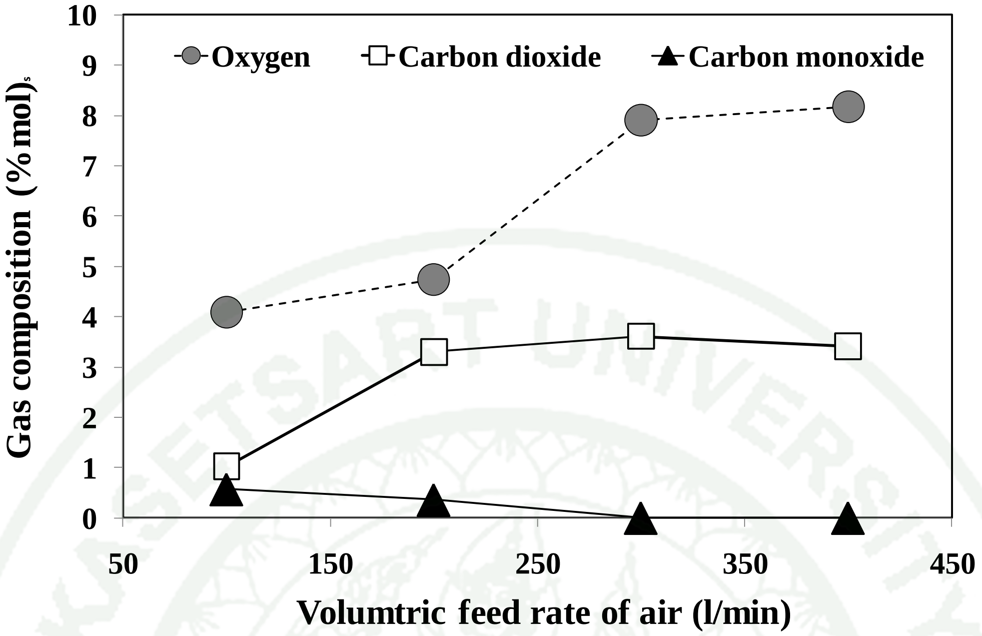


**Figure 34** Distribution of combustion product at various air feed rates. The LPG feed rate is kept constant at *7.31 l/min*

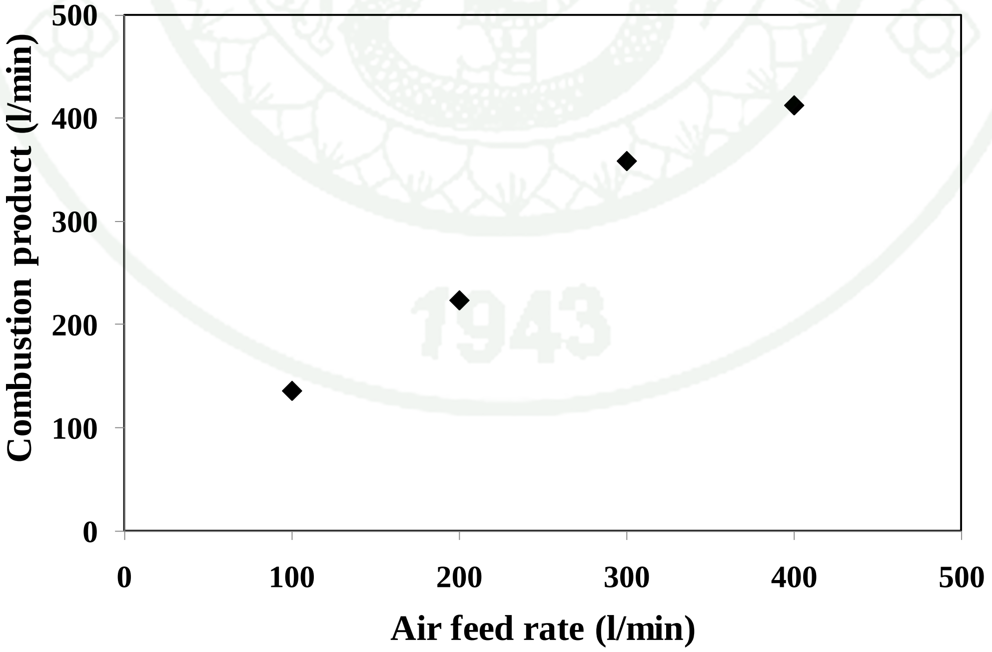


**Figure 35** Volumetric flow rate of combustion gas product at various air feed rates. The LPG feed rate is kept constant at *7.31 l/min*

### 2.3 Effect of plastic feed rate on system temperature

During plastic feeding into the reactor, the temperature can be reduced due to endothermic reaction of pyrolysis and sensible heat loss to the plastic. In this section, the effect of plastic feed rate on the system temperature was studied.

The effect of the plastic feed rate on the temperature profile has been studied at the plastic feed rates of *25, 40, 50 and 60 g/min*. The temperature at *3 cm* below distributor was controlled to be *450* $^{o}$*C* by using *300 l/min* air and *7.31 l/min* LPG. At steady state, plastics were fed via a screw feeder into the reactor in period of 2 min with various loadings namely *50, 80, 100 and 120 g (25, 40, 50 and 60 g/min).* As depicted in Figure 36, the temperature decreases immediately after plastic feeding. At higher plastic feed rates, the temperature drops more. The temperature drops for some periods of time depending on the extension of the reaction. Higher plastic feed rate causes the longer dropping periods. After the reaction was completed, the temperature rises up to the temperature before plastic feeding and then keeps constant.

As depicted in Figure 37, the time average temperature decreases from *444 to 338* $^{o}$*C, 425 to 325* $^{o}$*C, 408 to 310* $^{o}$*C and 395 to 304* $^{o}$*C* at plastic feed rate of *25, 40, 50, and 60 g/min*, respectively. It indicates that due to sensible heat and required heat for pyrolysis reaction, an increase of plastic feed rate causes a decrease of time average temperature at all position. From the results, it can be seen that at plastic feed rate at and higher than *40 g/min*, heat supplied to the system is inefficiency to keep the system at appropriate temperature.

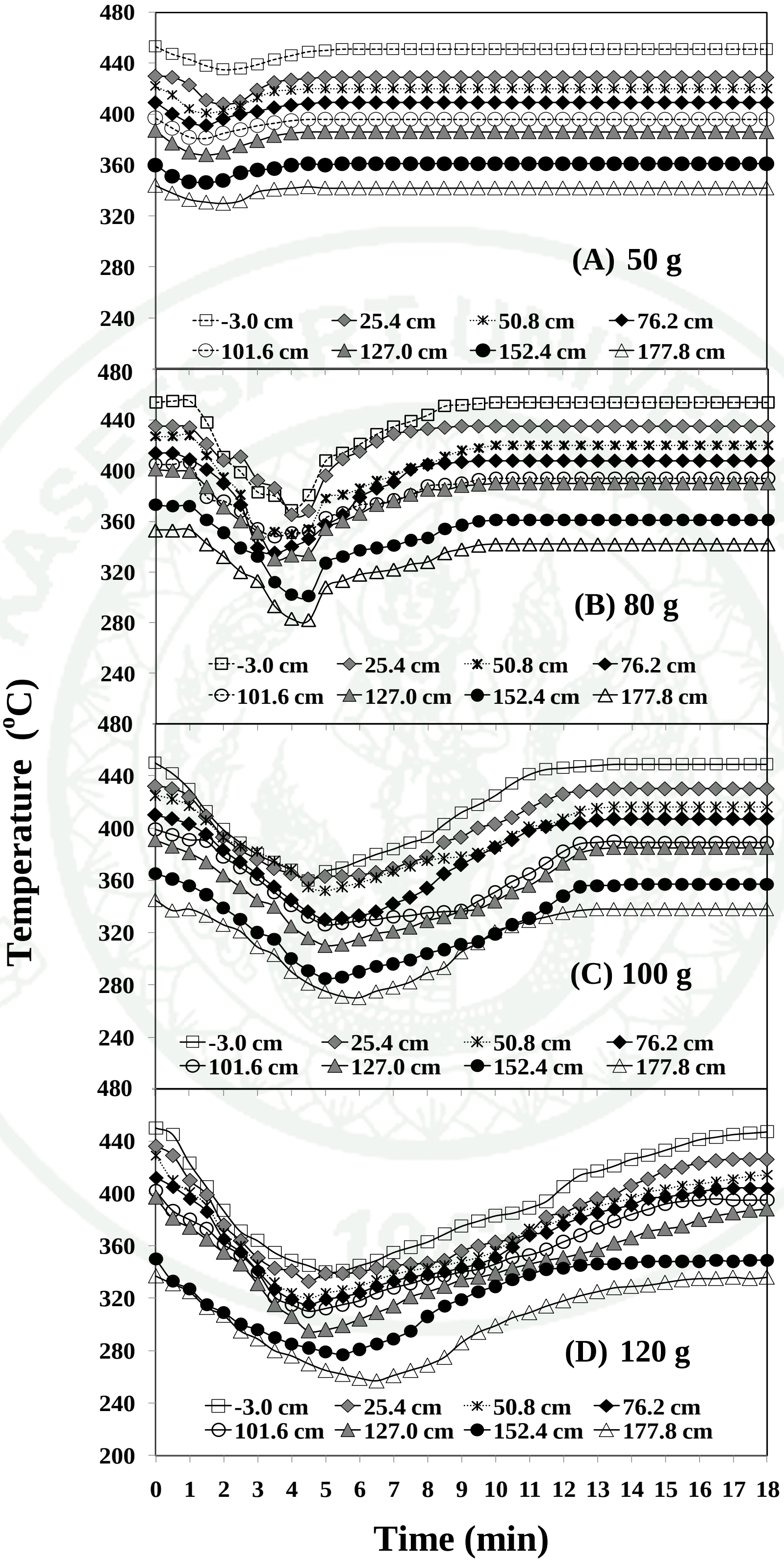
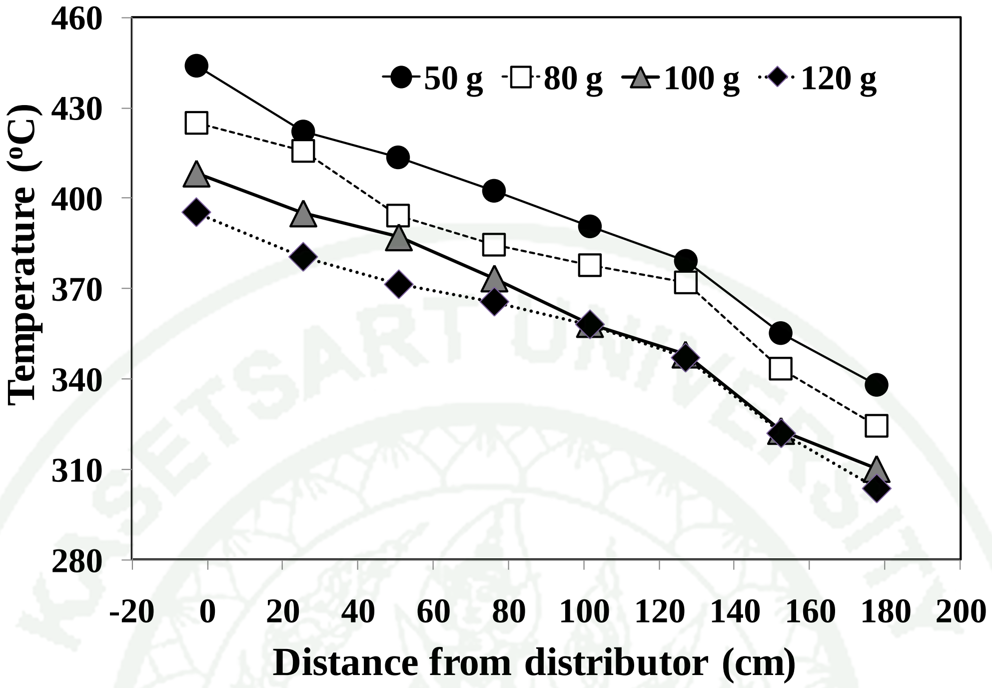


**Figure 36** Temperature profile in the system with plastic feeding of *(A) 50 g, (B) 80 g, (C) 100 g and (D) 120 g,* time for plastic feeding is *2 min*



**Figue 37** The time average temperature at various plastic feed rates. The LPG and air feed rate is kept constant at *7.31 and 300 l/min*, respectively.

2.4 Effect of bed temperature on product distributions

The bed temperature is one of the variables which has more influence on the product distributions. Therefore, the effect of bed temperature was investigated. At the beginning, the bed temperature was controlled to be *450 and 480 °C*. The LPG feed rates of *7.31 l/min* and *7.69 l/min* with air feed rate of *300 l/min* was used and then keeps constant. After the temperature approached to steady state condition, *50 g* of PP was fed into the reactor in period of *2 min*. The temperature of the system expected to drop due to the reaction. Plastic feeding was stopped until the system reached to the new steady state condition. Then plastic was fed into the reactor again as a pause cycle and carried for *10 times.*

### 2.4.1 Temperature profile at fixed bed temperature of *450 and 480* $^oC$

As shown in Figure 38, the pattern of temperature changes with plastic feeding is almost the same at both of bed temperature. The time average temperature along reactor height decreases from *471 to 350* $^oC$ *and 435 to 335* $^oC$ at bed temperature of *450 and 480* $^oC$, respectively (see Figure 39).

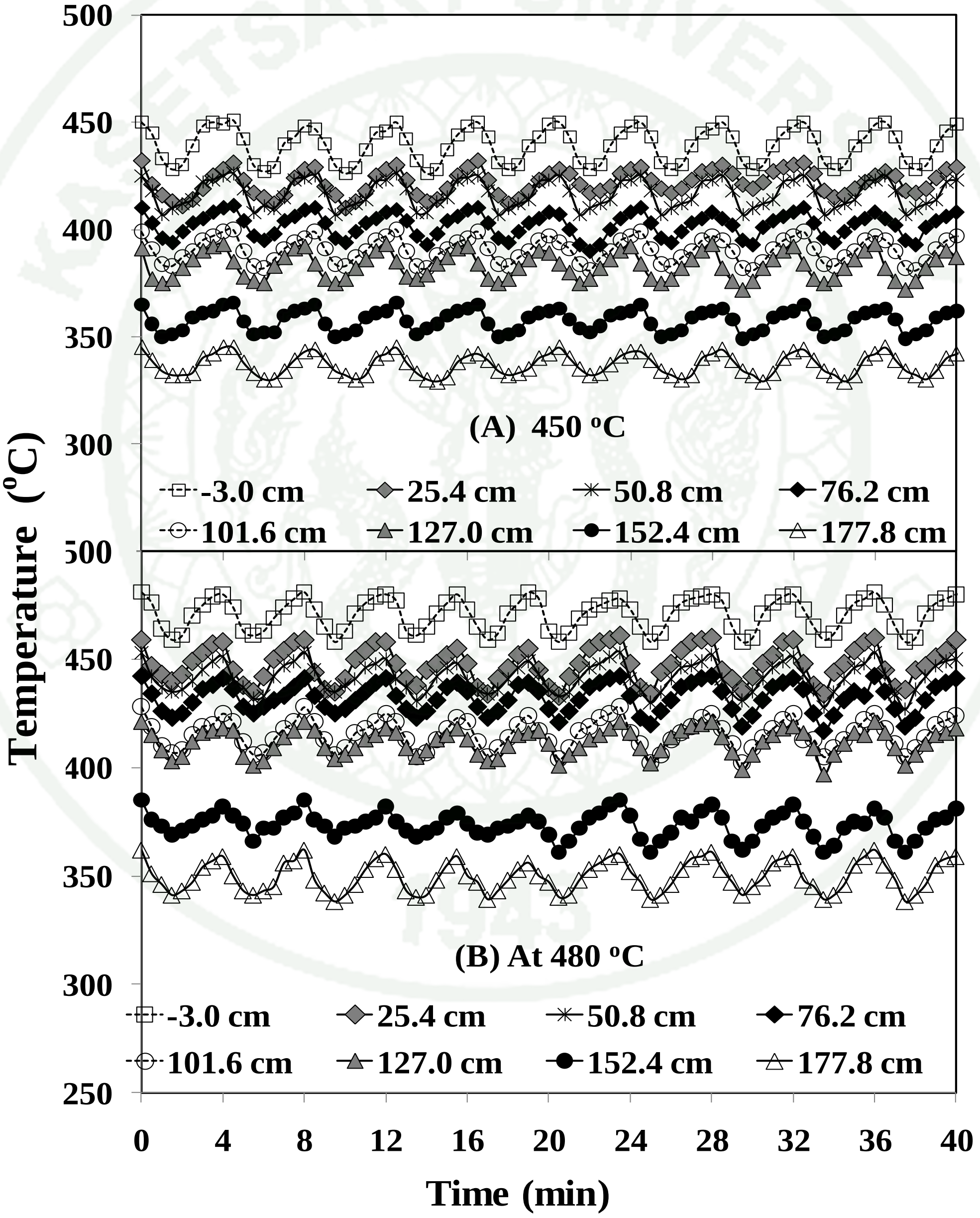
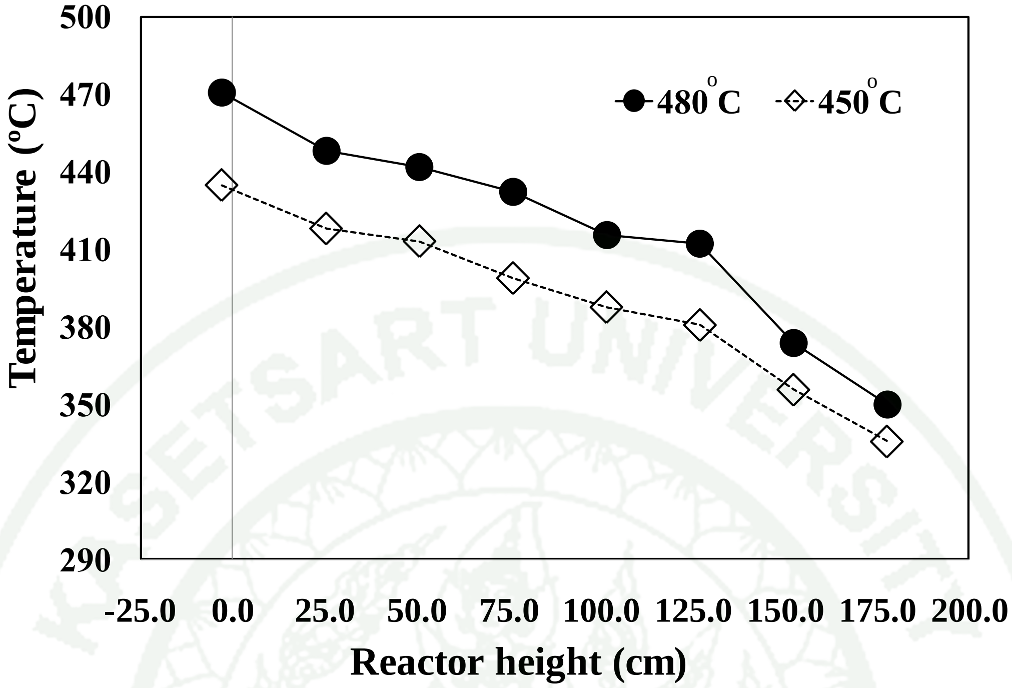


**Figure 38** Temperature profile in the system with plastic feeding at different bed temperature



**Figue 39** The time average temperature at different bed temperature

2.4.2 Pyrolysis product distribution at fixed bed temperature of *450 and 480 °C*

As depicted in Figure 40, total liquid product decreases from *33.25* to *22.68 wt%* whereas gas distribution increases from *66.75 to 77.32 wt%* with the increasing of bed temperature from *450 to 480 °C*. Higher bed temperature causes more cracking of plastic which prefers to produce lower molecular weight product like gas.

The gas product from pyrolysis reaction consists of methane ($CH_4$), carbon dioxide ($CO_2$), carbon monoxide (CO) and propane ($C_3H_8$) (see Figure 41). The production rate of methane is *3.83 g/min* and then increases to *4.29 g/min* when increases bed temperature from *450 to 480 °C*. The breaking polymer from the end group (end-chain scission) leading to more methane production. Production rate of CO was almost the same at both of bed temperature which is *0.28* and *0.30 g/min*, respectively. Whereas $CO_2$ increases from *4.14 to 4.96 g/min* with increasing bed temperature from *450 to 480 °C*. The results show that other than pyrolysis reaction, there are some partial oxidation due to residual oxygen from the burner which produced CO and $CO_2$. At higher bed temperature of *480 °C, 0.51* g/min of propane was detected due to random chain scission of plastic. At both of bed temperature, there are no C2-C4 was detected as shown in appendix F1.

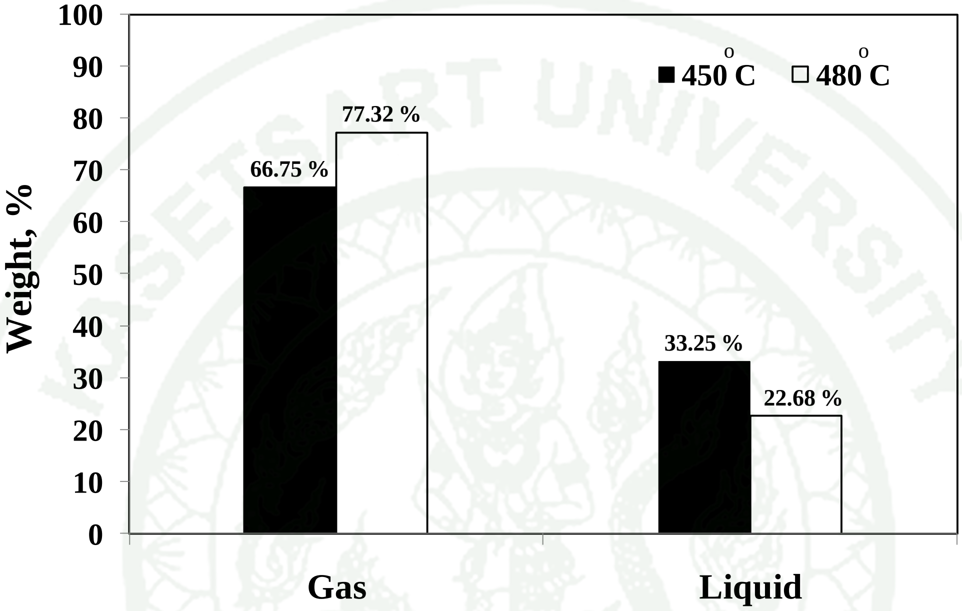


**Figure 40** Pyrolysis product distribution at different bed temperature

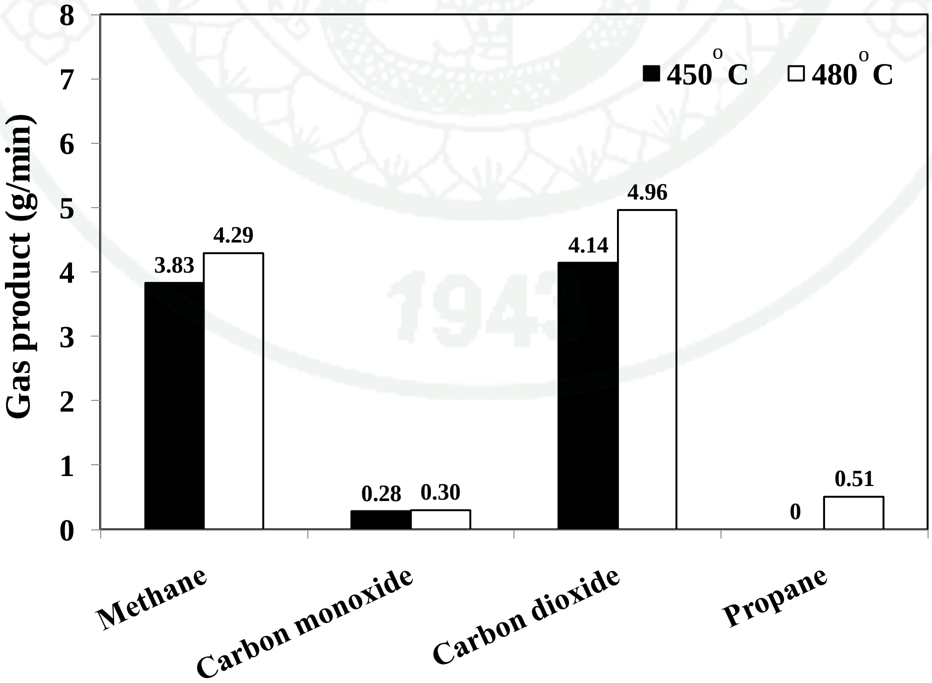


**Figure 41** Production rate of gas product at different bed temperature

As shown in Figure 42, liquid product consists of gasoline (C5-C12), kerosene (C13-C17) and gas oil (> C18). As expected, the increasing bed temperature from *450 to 480* $^{o}$*C* causes the decreasing all of liquid production rate. It decreases from *2.46 to 1.50, 1.43 to 1.13 and 0.22 to 0.17 g/min* for gasoline, kerosene and gas oil, respectively. It was due to more cracking of liquid product to be gas which is agree well with the increasing of methane when increasing bed temperature. The decreasing of production rate of gasoline is higher than kerosene and kerosene higher than gas oil because the cracking of low molecular weight is easier.

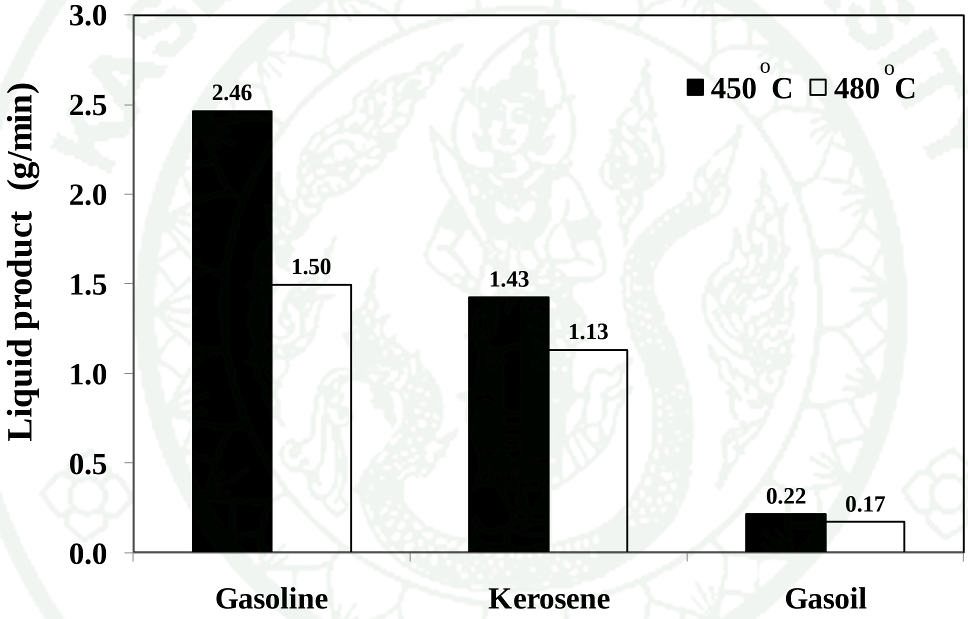


**Figure 42** Production rate of liquid product at different bed temperature

### 2.5 Effect of secondary air for partial oxidation on product distributions

To reduce external heat supplied to the system, secondary air should be added to the system for oxidation of combustible gases. Oxidation is usually exothermic reaction. Therefore, some heat adding is expected from oxidation of light gases with secondary air. The secondary air was mixed with the nitrogen gas in the mixing tank and then fed to the bed of the reactor.

In this section, the effect of secondary air feed rate for partial oxidation on temperature profile, production rate and distribution of gas and liquid were studied. The summary of production rate and distribution of gas and liquid were shown in appendix F3. The secondary air feed rate was varied in the range of *25 to 100 l/min* at a fixed LPG feed rate of *7.31 l/min* with *300 l/min* primary air.

#### 2.5.1 Temperature profile at various secondary air feed rates

As shown in Figure 43, the time average temperature decreases along reactor height from *435 to 336* $^{o}$*C in* the case without partial oxidation and decreases from *441 to 337, 442 to 338 and 441 to 337* $^{o}$*C* for the beds with the secondary air feed rates of *25, 50* and *100 l/min*, respectively. The results show that the presence of secondary air increases the bed temperature compared with the bed without partial oxidation, especially at the lower part of reactor (below *50.8 cm*). Increasing of system temperature due to partial oxidation was clearly observed at *25.4 cm* height (see Figure 44). At this position, the time average temperature of the system without partial oxidation was *418* $^{o}$*C*. It increases from *423 to 427* $^{o}$*C* with increasing of air feed rate from *25 to 100 l/min*. It can be explained that the majority partial oxidation of some plastic occurred nearby this area. However, the presence of partial oxidation can increase temperature of the system, the liquid product need to scarify with the energy saving.

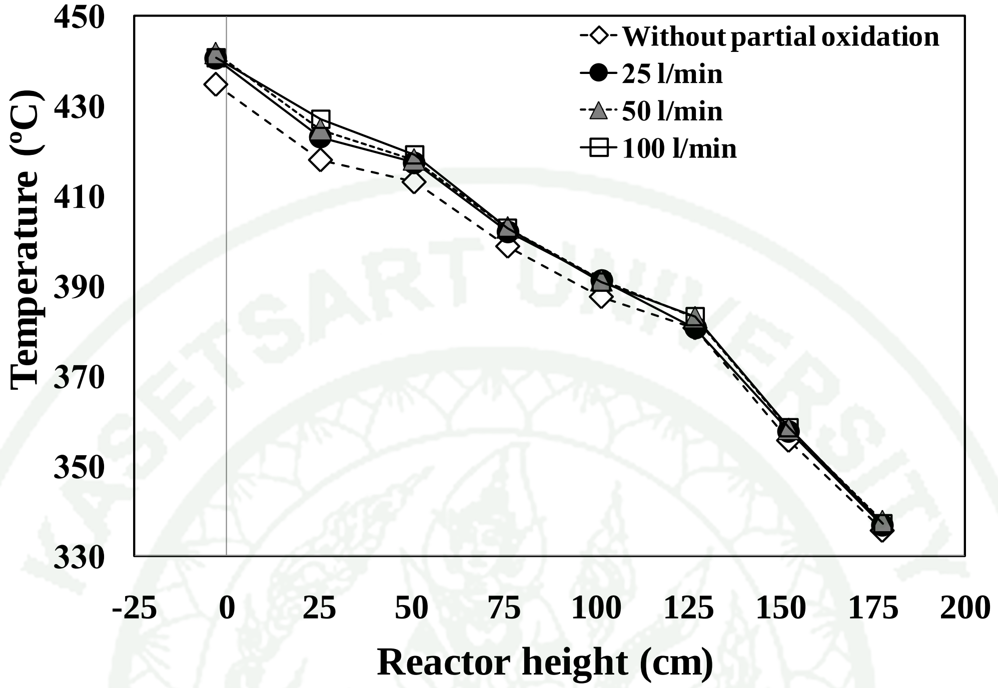


**Figure 43** The time average temperature at various secondary air feed rates.

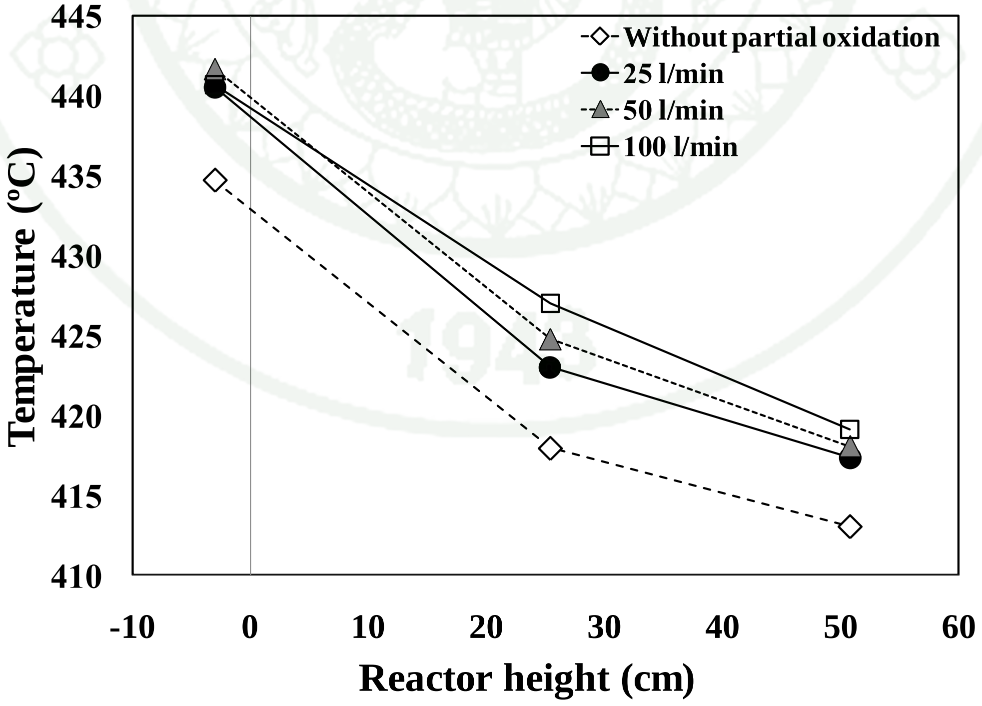


**Figure 44** The time average temperature in the area near the distributor at various secondary air feed rates

### 2.5.2 Production rate and product composition at various secondary air feed rates

Liquid product slightly decreases with increasing secondary air feed rate for partial oxidation. As seen in Figure 45, it was *33.25 wt %* in the case without partial oxidation and *30.31, 28.16 and 27.09 wt %* with secondary air feed rates of *25, 50,* and *100 l/min*, respectively. More air feed rate leads to more partial oxidation some of liquid resulting in increasing of gas product.

When increasing secondary air feed rate from *0* to *100 l/min*, the production rate of methane decreases from *3.83 to 3.68 g/min*. While, the production rate of carbon dioxide and carbon monoxide increases from *4.14 to 4.97 g/min* and *0.28 to 0.32 g/min*, respectively (see Figure 46). The gas product, carbon number between C2 to C4 was not detected (see appendix F2). Light gas and light liquid can be further oxidized by secondary air to carbon monoxide and carbon dioxide. Increasing secondary air feed rate increases partial oxidation.

Liquid product consists of gasoline, kerosene and gas oil. Increasing of secondary air feed rate from *0* (without partial oxidation) to *100 l/min* leads to decreasing of gasoline and kerosene from *2.46 to 1.87 g/min* and *1.43 to 1.28 g/min*, respectively as shown in Figure 47. While, the production rate of gas oil slightly decreases from *0.22 to 0.20 g/min* with increasing of secondary air feed rate *100 l/min*. It can be concluded increasing secondary air feed decreases liquid product due to product loss by partial oxidation. Decreasing of lower molecular products is significant at higher secondary air feed rate due to their ease of oxidation.

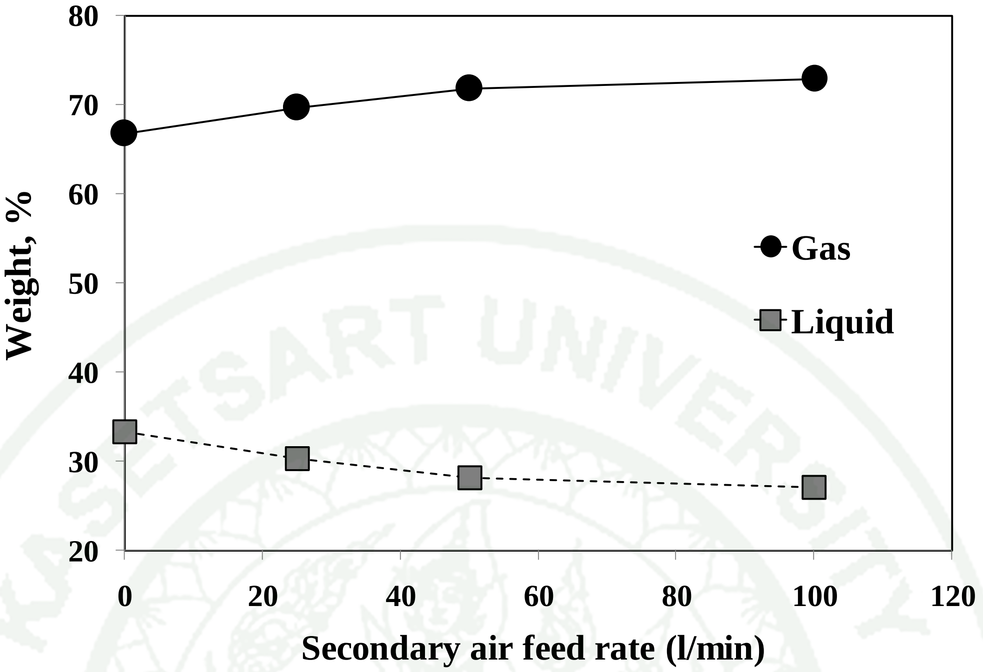


**Figure 45** Pyrolysis product distribution at various secondary air feed rates

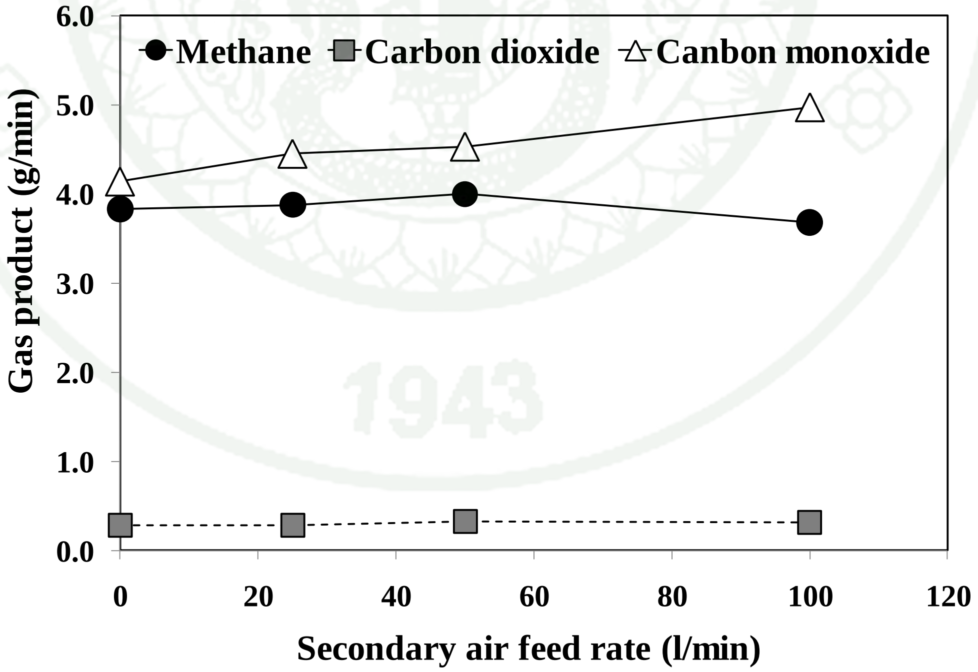


**Figure 46** Production rate of gas product at various secondary air feed rates

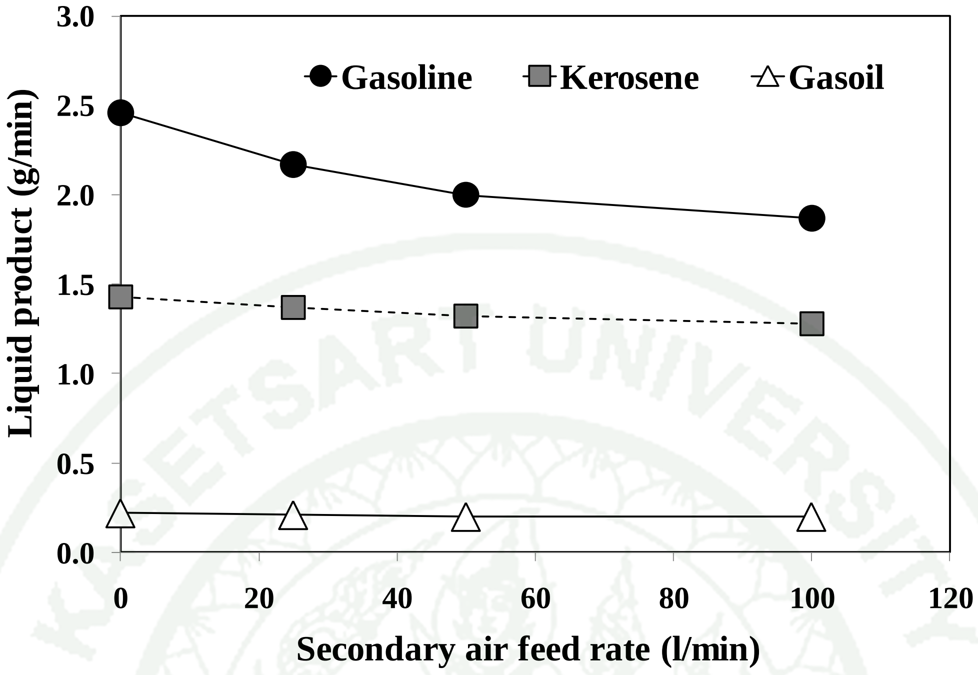


**Figure 47** Production rate of liquid product at various secondary air feed rates

## 2.6 Energy saving by partial oxidation

This section aims to show energy saving by reduction of LPG consumption. Compensation of energy required in reaction is made by the energy from partial oxidation of cracking product with secondary air. The temperature profile of the system with partial oxidation was adjusted to approach that without partial oxidation by adjusting LPG feed rate. The energy supplied to the system of both cases as well as the production rate of gas and liquid were analyzed for comparison.

### 2.6.1 Production rate and product distribution in the system with and without partial oxidation

Addition partial oxidation into the pyrolysis, addition partial oxidation into the pyrolysis liquid product decreases from *33.25 to 26.95%* (see Figure 48). As mentioned before, some liquid product was consumed for partial oxidation. Oxidation of hydrocarbons including plastic, liquid and gas products (especially gas which tends to be easily oxidized at lower temperature) can supply heat for endothermic cracking reaction. This leads to energy saving by reducing the LPG consumption. The increasing of gas fraction from *66.75* to *73.04 wt %* due to the presence of partial oxidation for energy saving was observed. The details of production rates and product distribution of liquid and gas product were reported in appendix F3.

Methane production in the system with partial oxidation (*3.42 g/min*) is lower than that obtained in the system without partial oxidation (*3.83 g/min*) as shown in Figure 49. This is due to its consumption in partial oxidation with addition of oxygen which corresponds well with the increasing of oxidation products of carbon dioxide from *4.14 to 4.92 g/min*. On the other hand, the presence of partial oxidation does not affect the production rate of carbon monoxide. The gas product from C2 to C4 was not observed in this condition.

As shown in Figure 50, all liquid production rates decrease when the systems include partial oxidation. Gasoline, kerosene and gas oil decrease from *2.46* to *1.84 g/min*, *1.43* to *1.31 g/min*, and *0.22* to *0.17 g/min*, respectively. Decreasing of lighter product (gasoline) is higher than medium product (kerosene) and heavy product (gas oil). Liquid product with lower carbon number was easier cracked than that with higher carbon number.

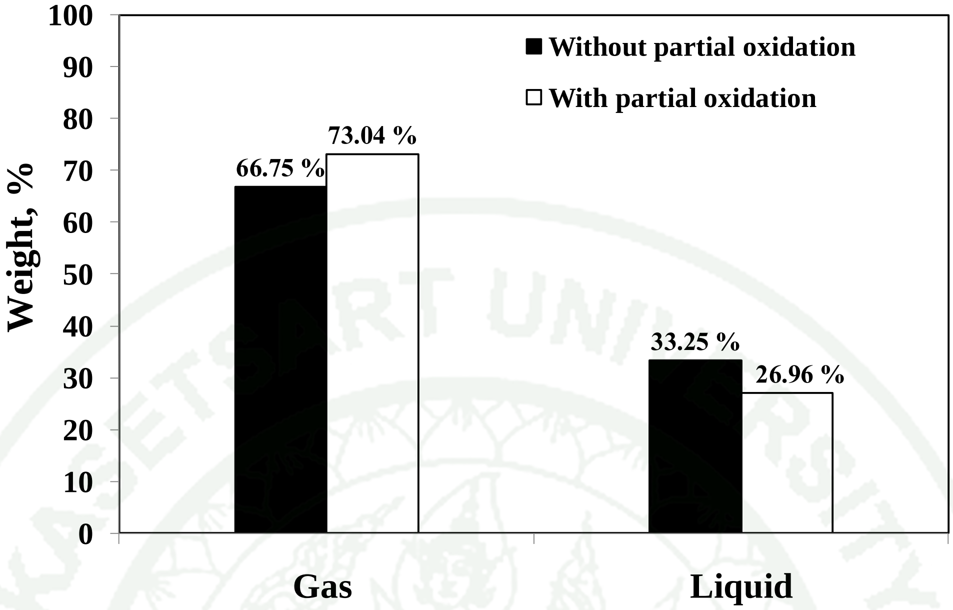


**Figure 48** Pyrolysis product distribution in the system with and without partial oxidation. The percent by weight of product is based on total feed weight

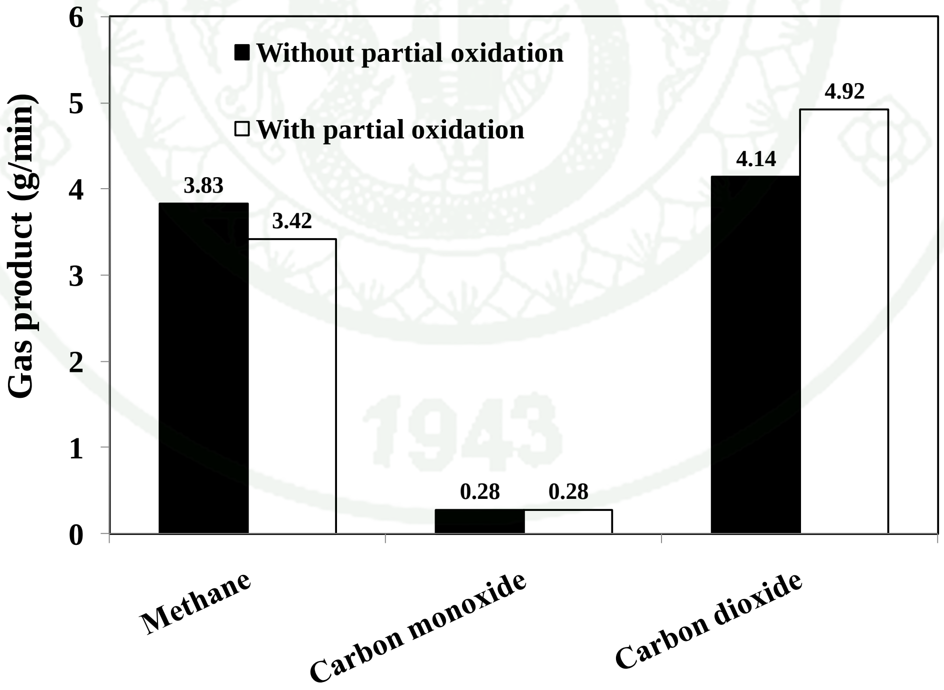


**Figure 49** Production rate of gas product in the system with and without partial oxidation. The numbers show the production rates in g/min of each species

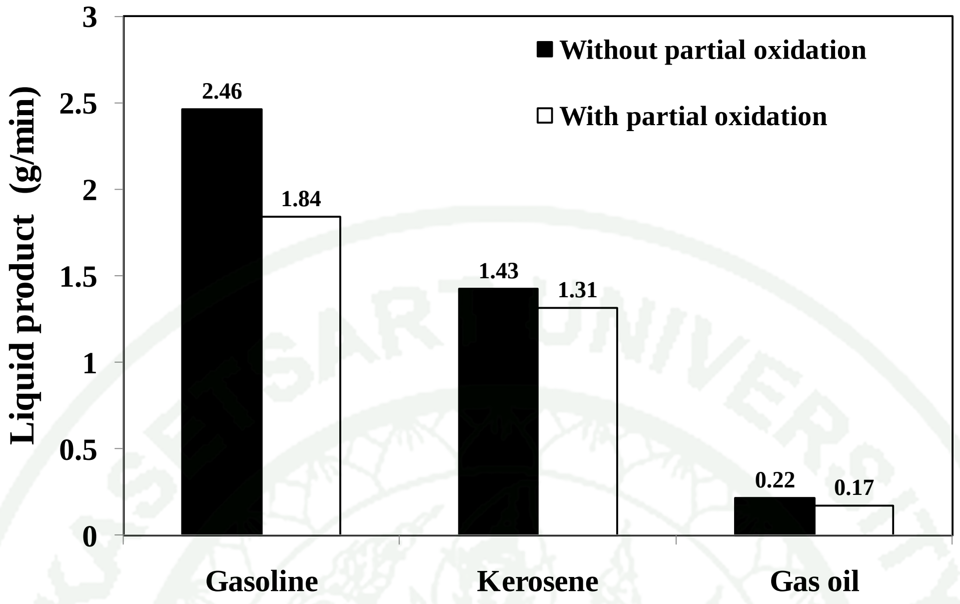


**Figure 50** Production rate of liquid product in the system with and without partial oxidation

2.6.2 The amount of energy supplied to the system with and without partial oxidation

By decreasing LPG feed rate from *7.31 l/min* to *6.59 l/min* along the operation time, the partial oxidation with secondary air feed rate of *100 l/min* and plastic loading of *50 g* fed as a pulse cycle gave almost the same time average temperature with that of the system without partial oxidation (see Figure 51 (B)). The experiments were repeated for *10 times*. The heat obtained from partial oxidation can be used to compensate the heat supplied to the system. Including partial oxidation in the pyrolysis can save LPG requirement. LPG feed rate can be reduced from *7.3* to *6.59* l/min. Thus energy requirement is reduced from *26,460* to *23,854 kJ based on 0.5 kg feeding plastic or* reduced *9.85 %.*

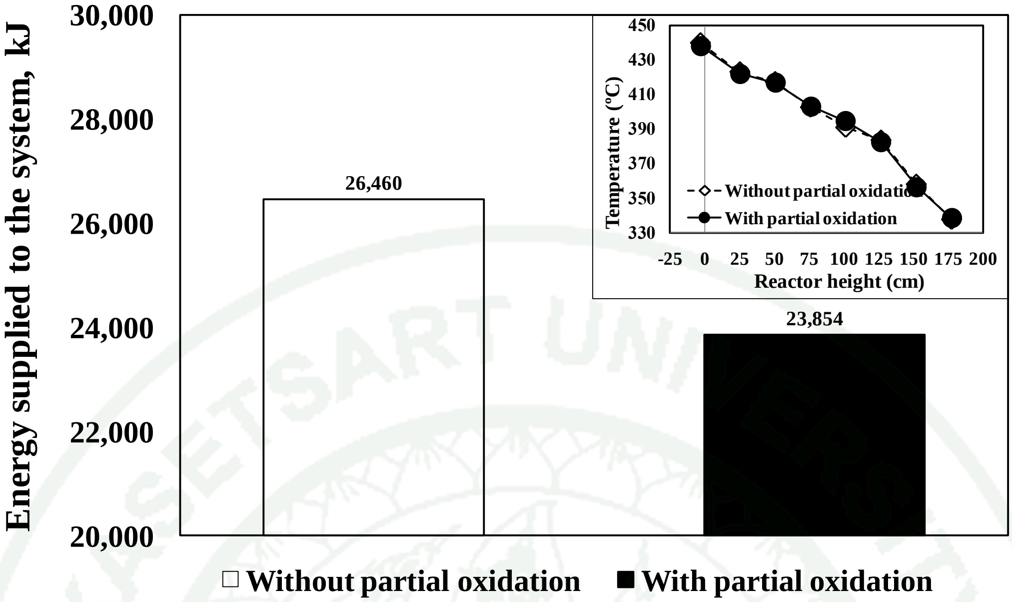


**Figure 51** (A) The amount of energy supplied to the system and (B) the time average temperature of the systems with and without partial oxidation

2.6.3 Heating values of liquid fuels obtained from the systems with and without partial oxidation

The heating value is the heat released when one kilogram of a compound undergoes complete combustion with oxygen. The heating value of each liquid species was reported in Table 11.

**Table 11** Heating values of liquid fuels

| Liquid fuel | Heating value (MJ/kg) |
|---|---|
| Gasoline | 47.30 |
| Kerosene | 46.20 |
| Gas oil | 42.80 |

The heating values of the product liquid can be obtained from the heating values of each component and product distribution (Figure 51).

Lower heating of all liquid products in the systems with partial oxidation were observed (see Table 12). The total heating value of liquid products in the system with partial oxidation was reduced with *19.29 %*.

**Table 12** Heating values of liquid products in the systems with and without partial oxidation

| Liquid fuel | Total weight (g) | | Heating values (kJ) | |
|---|---|---|---|---|
| | Without partial oxidation | With partial oxidation | Without partial oxidation | With partial oxidation |
| Gasoline | 99.63 | 74.52 | 4,712.50 | 3,524.80 |
| Kerosene | 57.92 | 53.06 | 2,675.90 | 2,451.37 |
| Gas oil | 8.91 | 6.89 | 381.35 | 294.89 |
| Total | 166.46 | 134.47 | 7,769.75 | 6,271.06 |

2.6.4 Heating values of gas product obtained from the systems with and without partial oxidation

The heating value of gas product, carbon monoxide and methane, were reported in Table 13.

**Table 13** Heating values of fuel gas

| Gas fuel | Heating value (MJ/kg) |
|---|---|
| Carbon monoxide | 10.11 |
| Methane | 55.50 |

Gas product contained fuel gases such as $CO_2$ and $CH_4$. Heating values of the product gases can be calculated from heating values of each gas and gas composition. Table 14 shows the heating values of product gas.

As shown in Table 14, heat values of product gases in the system without partial oxidation is higher that the system with partial oxidation by *10.57 %.* Some methane gas in the case with partial oxidation was consumed in oxidation which provided heat for compensating the supplied heat decrease due to decreased LPG feed rate.

**Table 14** Heating values of fuel gas

| Gas fuel | Total weight (g) | | Heating value (kJ) | |
|---|---|---|---|---|
| | Without partial oxidation | With partial oxidation | Without partial oxidation | With partial oxidation |
| Methane | 155.12 | 138.51 | 8,609.16 | 7,687.31 |
| Carbon monoxide | 11.20 | 11.20 | 113.12 | 113.12 |
| Total | 166.32 | 149.71 | 8,722.28 | 7,800.43 |

### 2.6.5 Total energy saving by partial oxidation

Based on *0.5 kg* of PP feeding, the energy saving by partial oxidation due to the decreasing of LPG feed rate was *2,606 kJ*. The presence of partial oxidation decreases gas and liquid products with heating value of *922* and *1,499 kJ*, respectively. Therefore the total energy saving was *185 kJ* which is *0.70 %.*

### 2.7 Effect of gas recycling

Some gas products from pyrolysis are combustible such as $CH_4$ and CO. Recycling of the product gas can reduce inert gas usage. Moreover, the fuel gas can be oxidized then the energy will be released. In the system with gas recycling, *100 l/min* of gas product and inert gas were recycled to the system by an air pump. It was mixed with *50 l/min* of fresh nitrogen (decrease from *150 l/min* in the system without gas recycling) and *100 l/min* secondary air for partial oxidation. The LPG and air feed rates of *6.59* and *300 l/min,* respectively coupled with *100 l/min* secondary air were kept constant in both of the systems with and without gas recycling. Plastic loading of *50 g* was fed to the system as a pulse cycle for *10 times*. Temperature profile, production rate and product distribution of gas and liquid were analyzed for comparison.

#### 2.7.1 The effect of gas recycling on system temperature and fluidizing gas saving

With gas recycling of *100 l/min*, nitrogen can be reduced from *28.03* to *18.69 kg* (based on *0.5 kg* of plastic) which was *34.28 %* reduction to keep the fluidizing gas constant at $1.5\ U_{mf}$ (see Figure 52). As shown in Figure 53, the system temperature with gas recycling was higher than that in the system without gas recycling at all positions especially at *25.4 cm* height where the main reaction occurs (see Figure 54). The combustible gases containing $CH_4$, CO (see section 2.6.2) recycled to the system were oxidized and then produced heat was supplied to the system leading to higher temperature.

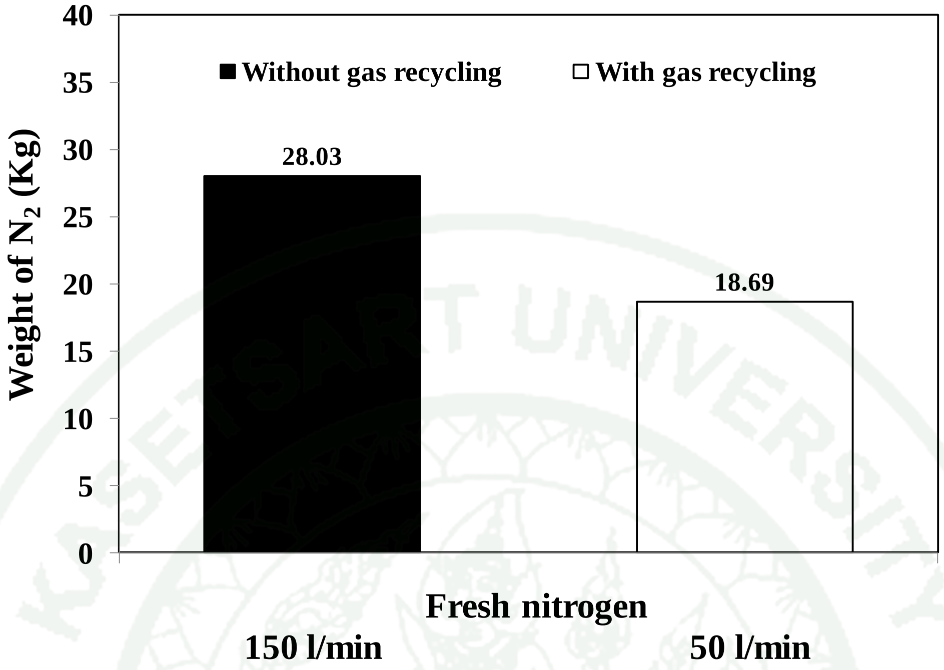


**Figure 52** Weight of nitrogen used as fluidizing gas in the system with and without gas recycling

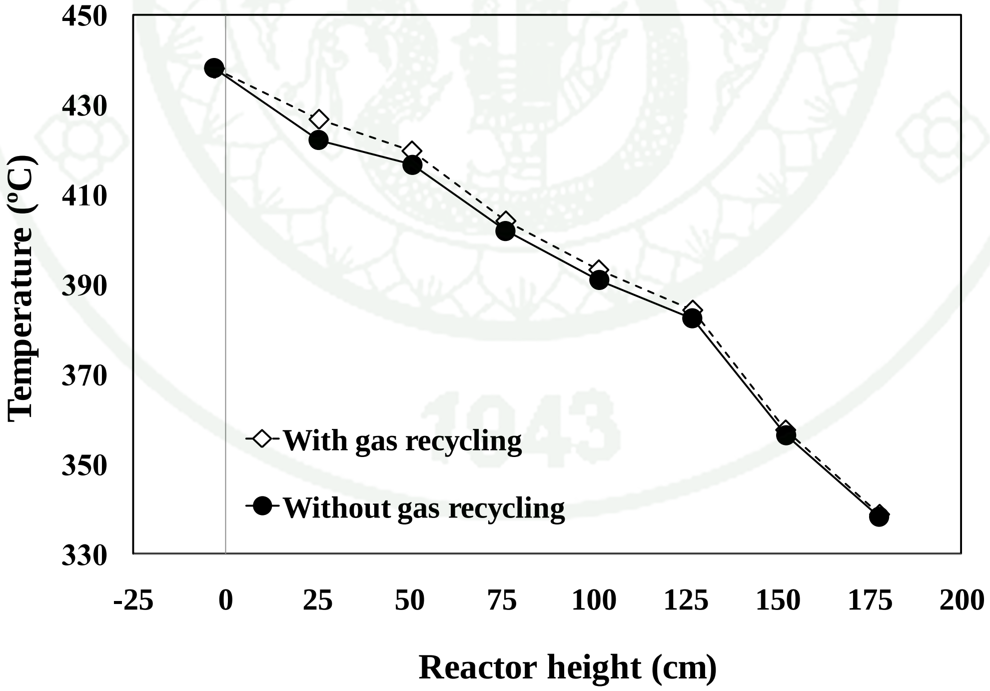


**Figure 53** The time average temperature in the systems with and without gas recycling

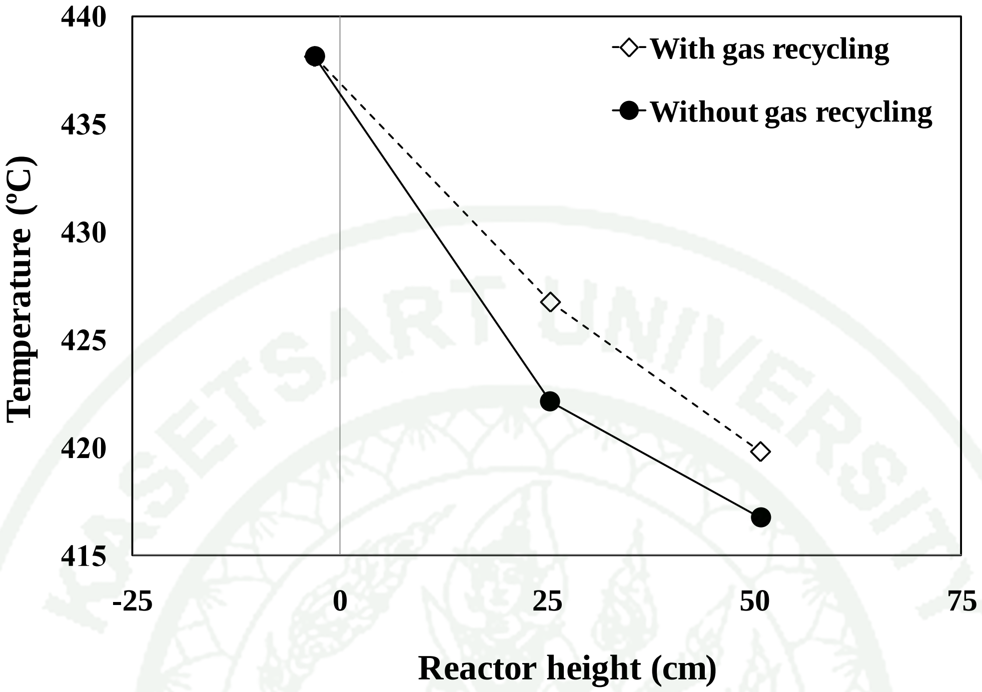


**Figure 54** The time average temperature in the area near the distributor in the systems with and without gas recycling

2.7.2 Production rate and product distribution in the systems with and without gas recycling

Liquid and gas products in the systems with and without gas recycling were almost the same. Liquid product in the system with recycling was slightly with higher gasoline (see Figures 55 and 57). The maximum temperature increase of *5 $^oC$* is not enough to affect the change of products. Methane increases due to methane recycling although combustible gases recycled are expected to be oxidized, however, methane and carbon monoxide in the outlet gas are still higher as seen in Figure 56 (Although, slightly). It means that methane was not all consumed for oxidation. The results of this section show that slightly higher bed temperature in the system with recycling provides similar liquid product. More work in testify with higher recycling rate of gas should be tested for better explanation.

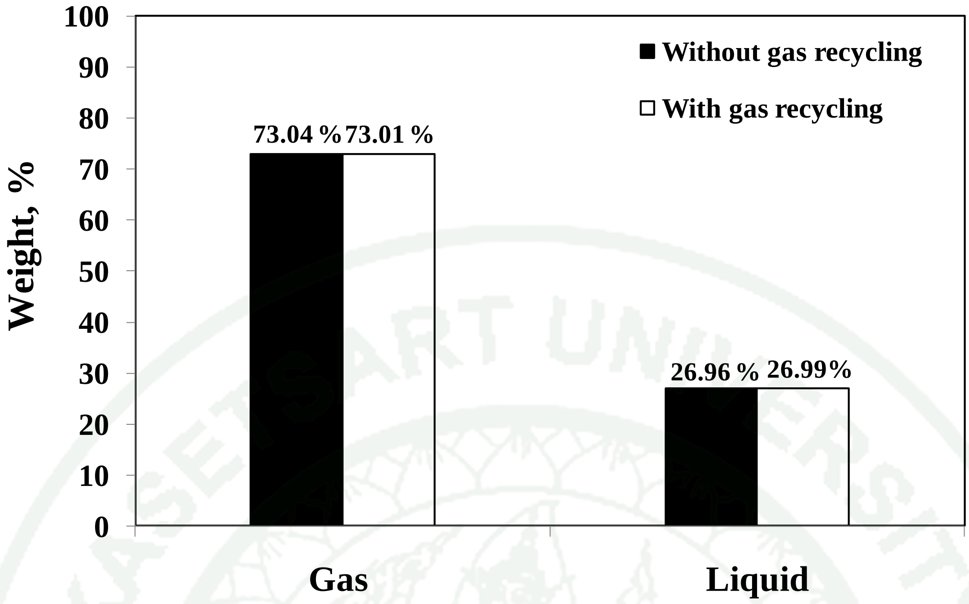


**Figure 55** Pyrolysis product distribution in the systems with and without gas recycling

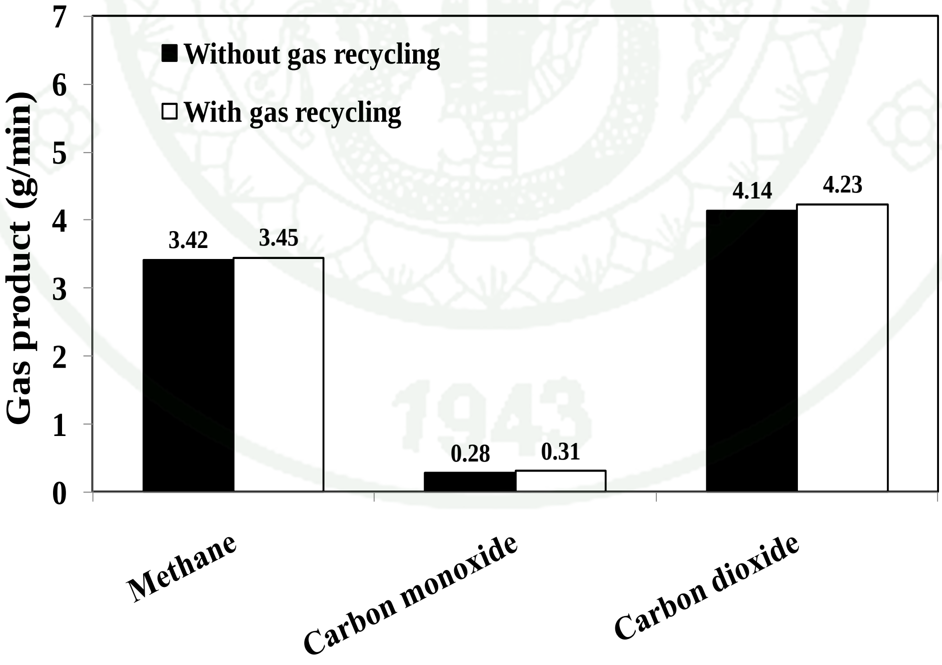


**Figure 56** Production rate of gas product in the systems with and without partial gas recycling

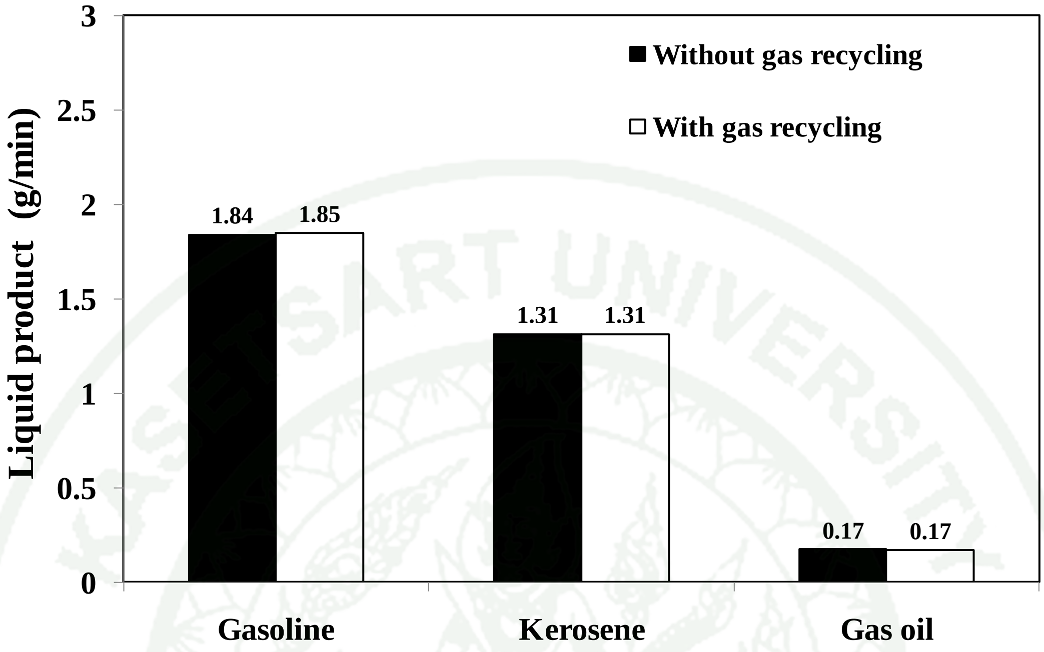


**Figure 57** Production rate of liquid product in the systems with and without gas recycling

2.8 Energy saving by gas recycling

The energy saving by partial oxidation of recycled gas and pyrolysis product gas are shown in this section. In the system with gas recycling, *100 l/min* mixture of gas product and inert gas was recycled to the system by an air pump. The primary air and secondary air feed rates were kept constant at *300* and *100 l/min, respectively* in both systems with and without gas recycling. The temperature profile of the system with gas recycling was adjusted to approach that in the system without gas recycling by adjusting LPG feed rate. The energy supplied to the systems for both cases as well as production rate were analyzed for comparison.

### 2.8.1 Production rate and product distribution in the systems with and without gas recycling operated at the same temperature

At almost the same system temperature, the liquid fraction from the system with gas recycling (*27.02 wt %)* is slightly higher than without gas recycling (*26.96 wt %)* as shown in Figure 58. Whereas, methane production rate decreases with the reduction of LPG feed rate from *3.42 to 3.39 wt %.* The decreased methane was consumed for compensating the reduced LPG feed rate as shown in Figure 59. Decreasing supplied heat to the system leads to higher methane consumption for partial oxidation which is corresponding well with the increasing of combustion product (carbon dioxide and carbon monoxide). The production rate of gasoline in the system with gas recycling is slightly higher than that of the system without gas recycling. It means that recycled gas can reduce the consumption of gasoline for oxidation. Thus gasoline production is higher. However, the presence of gas recycling does not affect the production rates of kerosene and gas oil as shown in Figure 60. More work with higher recycling rate of gas should be tested for better explanation.

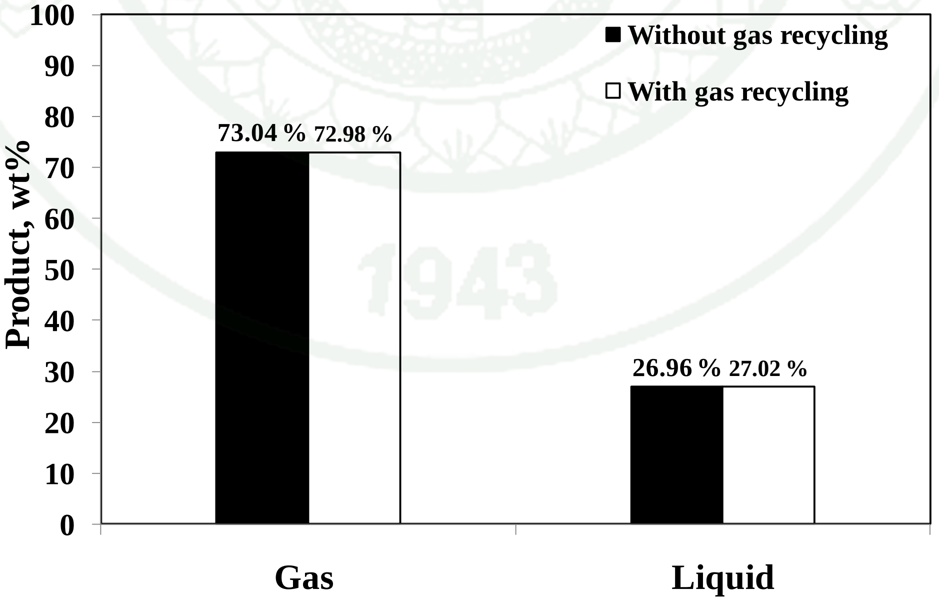


**Figure 58** Pyrolysis products in the systems with and without gas recycling at the same operating temperature conditions

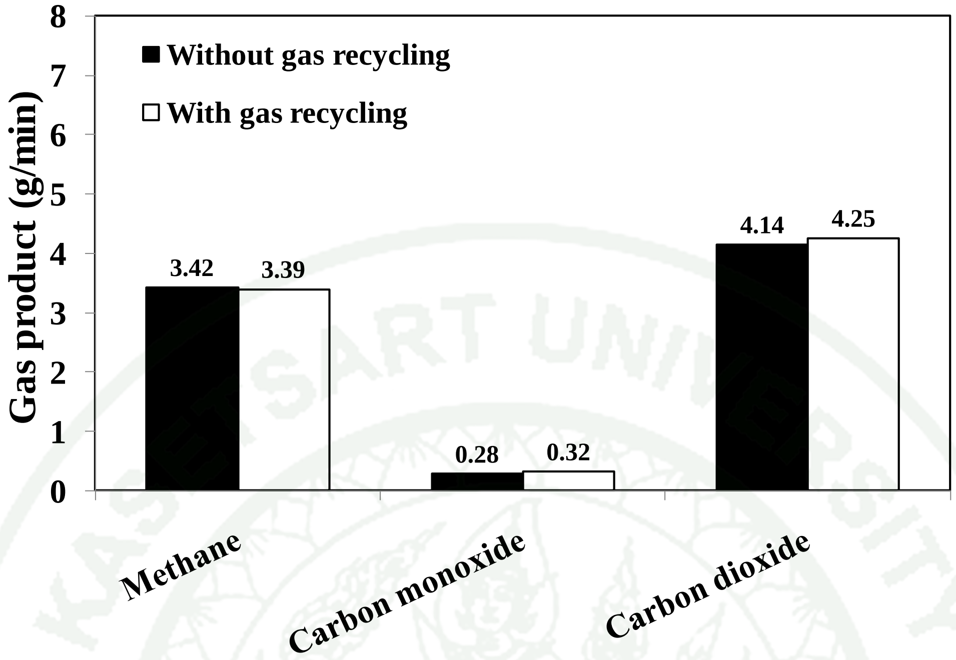


**Figure 59** Production rate of gas product in the systems with and without gas recycling at the same operating temperature conditions

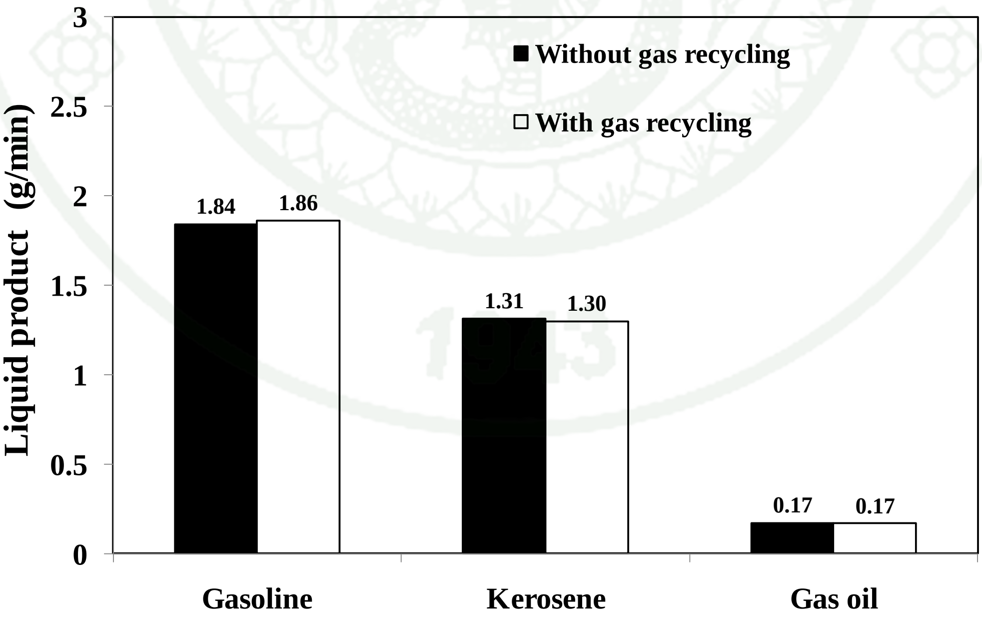


**Figure 60** Production rate of liquid products in the systems with and without gas recycling at the same operating temperature conditions

2.8.2 The amount of energy supplied to the systems with and without gas recycling at the same operating temperature conditions

As shown in Figure 61, when the systems are operated without gas recycling and with gas recycling at the same temperature, the system with gas recycling requires less LPG. Therefore operation with gas recycling can save required energy. Based on 0.5 *kg* of plastic feeding, 5.62 *%* energy saving was found as in Figure 61. It can be explained that the heat obtained from oxidation of recycled gases can reduce *5.62 %* energy input requirement.

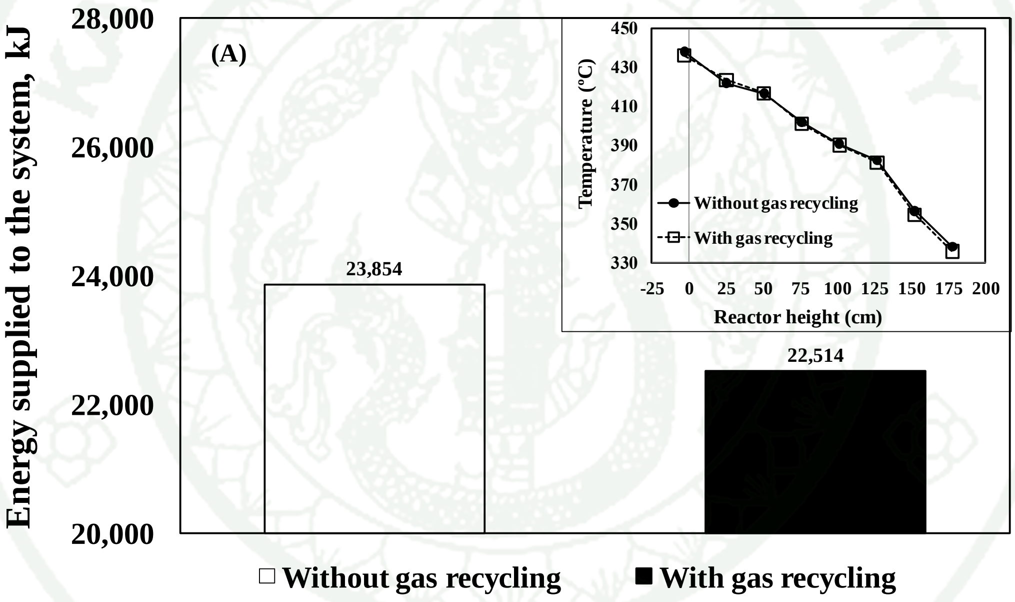


**Figure 61** (A) The amount of energy supplied to the systems and (B) the time average temperature in the systems with and without gas recycling at the same operating temperature conditions

### 2.8.3 Heating values of liquid fuels in the systems with and without gas recycling operated at the same temperature

The heating values of liquid products in the systems with and without gas recycling at the same operating temperature conditions is shown in Table 15.

**Table 15** Heating values of liquid products in the systems with and without gas recycling operated at the same temperature

| Liquid fuel | Total weight (g) | | Heating values (kJ) | |
|---|---|---|---|---|
| | Without gas recycling | With gas recycling | Without gas recycling | With gas recycling |
| Gasoline | 74.52 | 75.33 | 3,524.80 | 3,563.11 |
| Kerosene | 53.06 | 52.65 | 2,451.37 | 2,432.43 |
| Gas oil | 6.89 | 6.89 | 294.89 | 294.68 |
| Total | 134.47 | 134.87 | 6,271.06 | 6,290.22 |

In the system operated with *0.5 kg* of plastic, the heating values of liquid products with and without gas recycling at the same operating temperature conditions are shown in Table 15. With gas recycling, the heating value is slightly higher than that in the system without gas recycling due to higher amount of gasoline. On the other hand, the heating values of kerosene and gas oil show insignificantly different between both cases.

### 2.8.4 Heating values of gas fuels obtained from the systems with and without gas recycling operated at the same temperature

As shown in Table 16, the heating values of gases in the system with gas recycling is lower than that the system without gas recycling operated at the same temperature.  Less LPG was used in the system with gas recycling leading to lower methane.  Methane gas was recycled and oxidized.  Thus lower methane rate was found in the system with recycling leading to lower heating value. However, carbon monoxide is increased.  The increasing of carbon monoxide in the system with gas recycling does not significantly affect the total gas product heat values due to its lower heating value.

**Table 16**  Heating values of gas products

| Gas fuel | Total weight (g) | | Heating values (kJ) | |
|---|---|---|---|---|
| | Without gas recycling | With gas recycling | Without gas recycling | With gas recycling |
| Methane | 138.51 | 137.29 | 7,687.31 | 7,619.60 |
| Carbon monoxide | 11.34 | 12.96 | 114.65 | 131.03 |
| Total | 149.85 | 150.25 | 7,801.96 | 7,750.63 |

### 2.8.5 Total energy saving in the system with gas recycling

Based on *0.5 kg* of PP feeding, the energy saving by gas recycling due to the decreasing of LPG feed rate was *1,340 kJ*.  The presence of partial oxidation combined with gas recycling increases liquid products with the heating value of *19.16 kJ*.  On the other hand, gas product is lower with *51.33 kJ*.  Therefore the total energy saving is *1,307.83kJ* which is *5.48 %.*

### 2.9 Effect of quenching in upper zone of reactor on the reactor performance

The pyrolysis product flowing out from the reactor can be further thermal cracked at hot zone in the upper zone of the reactor leading to lower liquid production, especially, at very high bed temperature (i.e *500 $^oC$*). In this section, upper zone quenching by feeding cold nitrogen at the upper part of reactor (*152.4 c*m height) is proposed. *50 l/min* of fresh nitrogen at room temperature is injected to the upper zone to quench. The bed temperature was controlled at *500 $^oC$* with *9.50 l/min* LPG with *300 l/min* air. The temperature in the upper zone of the system is expected to drop due to cold nitrogen feeding. The rapid cooling of product stops further cracking to reduce lower molecular weight products. Temperature profile, production rate and product distribution of gas and liquid were analyzed for comparison.

#### 2.9.1 Effect of upper zone quenching on temperature profile

The temperature profiles of the system with and without product quenching are shown in Figure 62. In the lower part (below *75.4 cm* height), quenching does not affect the temperature profiles. However above *107.0 cm* where is the feeding point the temperature drops significantly and drops to *332 $^oC$* at the top of the reactor.

#### 2.9.2 Effect of quenching on product distributions

The effect of quenching with cold nitrogen feeding *(50 l/min)* with high bed temperature on product distribution was studied. The liquid product was extremely lower than that in the system at lower bed temperature (see Section 2.4.2). At higher bed temperature, thermal cracking of plastic is higher producing low molecular weight products. However, the liquid product in the system with quenching is slightly higher than that of the system without quenching (higher by *0.42 %).*

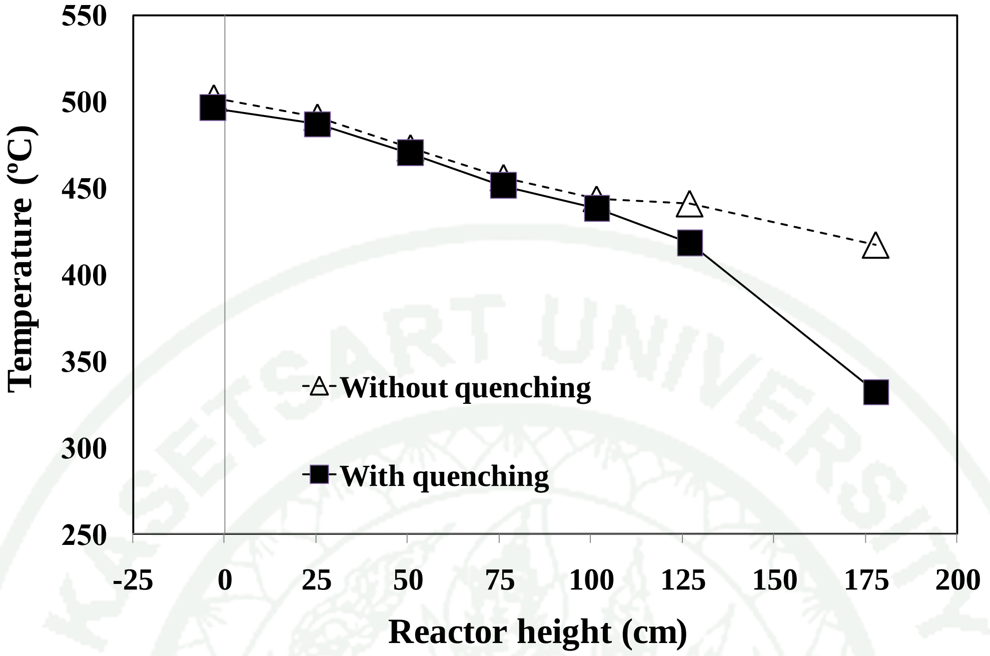


**Figure 62** The time average temperature of the reactor with and without quenching

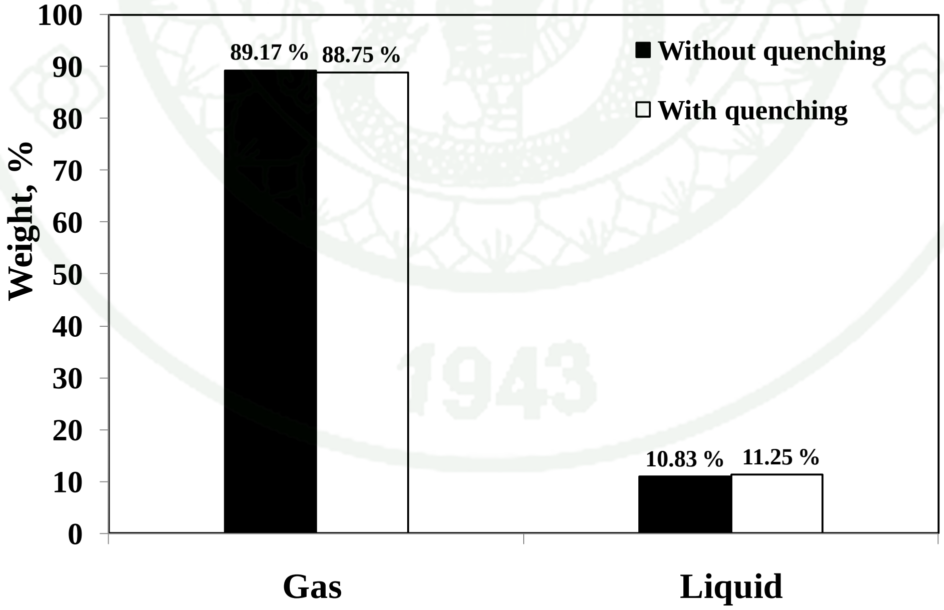


**Figure 63** Pyrolysis product distribution in the systems with and without product quenching

The production rate of methane in the system at 500 oC is extremely higher than that in the system at 450 oC (see Section 2.4.3). At higher bed temperature, overcracking leads to more production of lower molecular weight products. The production rate of methane of the system with quenching is slightly lower than that without product quenching. This is due to lower temperature in the upper zone leading to less low molecular weight gas production. However, quenching does not affect the production rate of carbon dioxide and carbon monoxide (see Figure 64).

As seen in Figure 65, the production rate of gasoline with quenching is higher than that without product quenching. Similarly, the production rates of kerosene and gas oil of the system with quenching are also higher than that of without quenching. It can be concluded that the presence of quenching can help stopping further cracking leading to high liquid production. However, more work in testify with lower bed temperature combined with quenching or higher flow rate of cold nitrogen for quenching should be tested for more information.

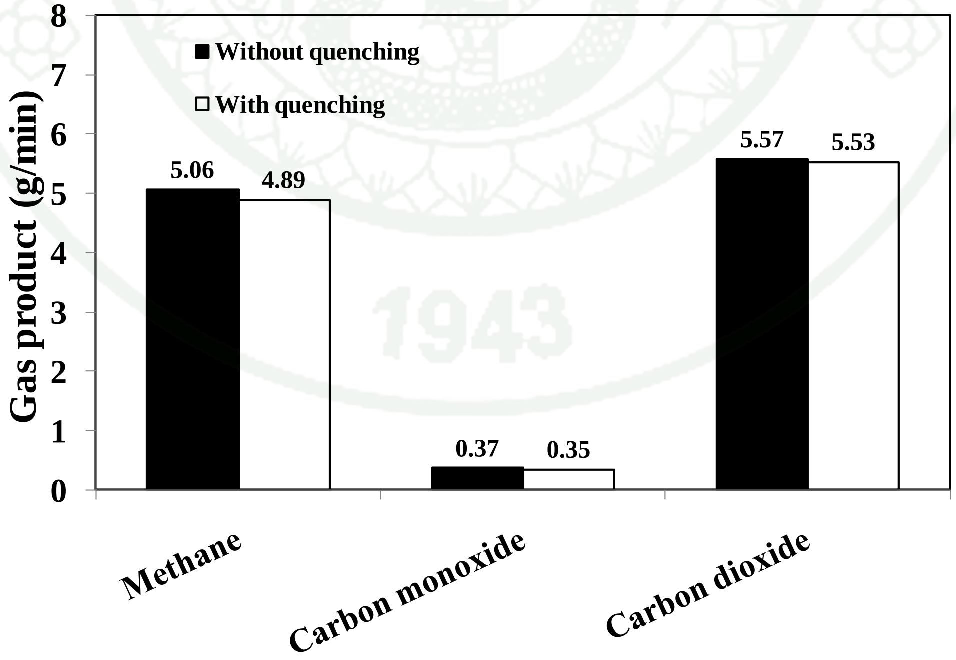


**Figure 64** Production rates of gas products in the systems with and without quenching

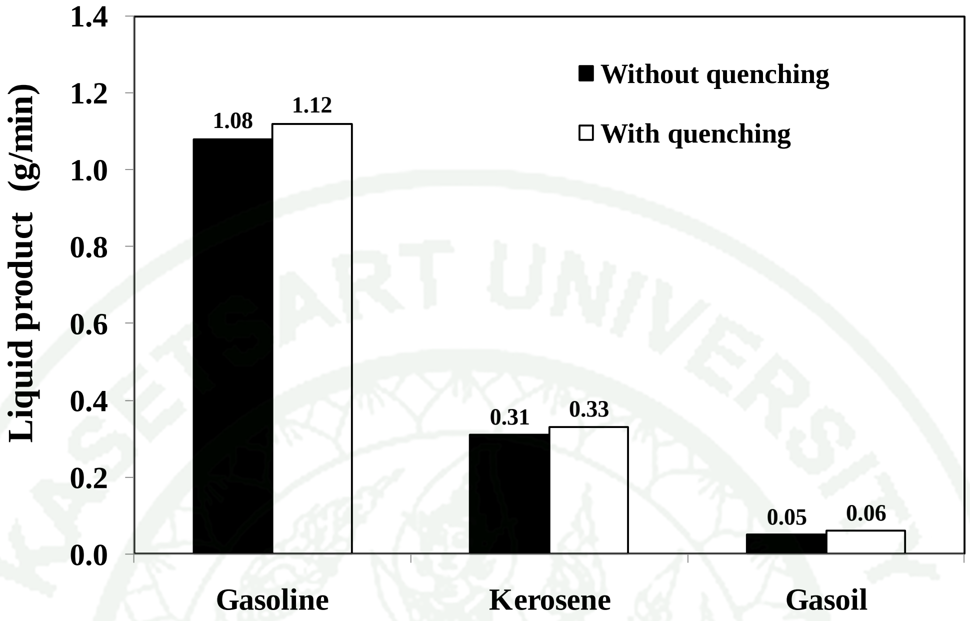


**Figure 65** Production rates of liquid products in the system with and without quenching

# CONCLUSIONS

1. In semi batch reactor, the increasing of temperature of *5-30* $^{o}C$ showed clearly to be the effects of oxygen and gas recycling adding. The presence of gas recycling leads to the decreasing of the total amount of liquid product. However, the yield of gasoline in liquid product increases up to *9.00 %*.to *14.30 %*.

2. The increasing of LPG and air feed rate increases the fluidized bed reactor temperature. The increasing bed temperature form *450 to 480* $^{o}C$ causes the decreasing liquid fraction from *33.25* to *22.68 %*.

3. The partial oxidation appeared to have a significant effect on the fluidized bed reactor temperature and product distribution. The increase of partial oxidation increases the system temperature of *5-10* $^{o}C$. Base on *0.5 kg* of plastic feeding, the present of partial oxidation also provides energy saving of *0.70 %*.

4. Base on *0.5 kg* of plastic feeding, the gas recycling can reduce the inert gas usage of *18.68 kg* and can save the energy input of *5.48 %* due to the oxidation of combustible gases.

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# APPENDICES

# Appendix A

The temperature profile in semi-batch reactor

**Table A1** The system without reaction

| Time (min) | Temperature ($^{o}$C) | Time (min) | Temperature ($^{o}$C) |
|---|---|---|---|
| 0 | 28 | 31 | 452 |
| 1 | 29 | 32 | 452 |
| 2 | 32 | 33 | 451 |
| 3 | 38 | 34 | 451 |
| 4 | 45 | 35 | 451 |
| 5 | 55 | 36 | 451 |
| 6 | 66 | 37 | 452 |
| 7 | 78 | 38 | 451 |
| 8 | 93 | 39 | 452 |
| 9 | 109 | 40 | 452 |
| 10 | 126 | 41 | 452 |
| 11 | 144 | 42 | 452 |
| 12 | 163 | 43 | 452 |
| 13 | 182 | 44 | 452 |
| 14 | 202 | 45 | 452 |
| 15 | 223 | 46 | 451 |
| 16 | 242 | 47 | 450 |
| 17 | 263 | 48 | 451 |
| 18 | 284 | 49 | 451 |
| 19 | 304 | 50 | 451 |
| 20 | 325 | 51 | 452 |
| 21 | 344 | 52 | 451 |
| 22 | 362 | 53 | 452 |
| 23 | 381 | 54 | 451 |
| 24 | 401 | 55 | 452 |
| 25 | 419 | 56 | 452 |
| 26 | 436 | 57 | 452 |
| 27 | 446 | 58 | 452 |
| 28 | 450 | 59 | 452 |
| 29 | 451 | 60 | 452 |
| 30 | 452 | | |

**Table A2** The system with pyrolysis reaction

| Time (min) | Temperature (°C) | Time (min) | Temperature (°C) |
|---|---|---|---|
| 0 | 29 | 31 | 410 |
| 1 | 30 | 32 | 411 |
| 2 | 34 | 33 | 413 |
| 3 | 39 | 34 | 413 |
| 4 | 46 | 35 | 413 |
| 5 | 55 | 36 | 414 |
| 6 | 65 | 37 | 414 |
| 7 | 76 | 38 | 415 |
| 8 | 89 | 39 | 417 |
| 9 | 102 | 40 | 417 |
| 10 | 118 | 41 | 418 |
| 11 | 135 | 42 | 420 |
| 12 | 149 | 43 | 422 |
| 13 | 166 | 44 | 423 |
| 14 | 183 | 45 | 424 |
| 15 | 200 | 46 | 425 |
| 16 | 219 | 47 | 425 |
| 17 | 237 | 48 | 426 |
| 18 | 255 | 49 | 426 |
| 19 | 274 | 50 | 426 |
| 20 | 291 | 51 | 427 |
| 21 | 309 | 52 | 427 |
| 22 | 327 | 53 | 427 |
| 23 | 343 | 54 | 427 |
| 24 | 360 | 55 | 427 |
| 25 | 376 | 56 | 427 |
| 26 | 392 | 57 | 427 |
| 27 | 404 | 58 | 428 |
| 28 | 411 | 59 | 428 |
| 29 | 410 | 60 | 428 |
| 30 | 411 | | |

**Table A3** The system with pyrolysis combined with partial oxidation at *5.22 ml/s*

| Time (min) | Temperature ($^{o}$C) | Time (min) | Temperature ($^{o}$C) |
|---|---|---|---|
| 0 | 31 | 31 | 418 |
| 1 | 32 | 32 | 418 |
| 2 | 34 | 33 | 417 |
| 3 | 40 | 34 | 417 |
| 4 | 47 | 35 | 418 |
| 5 | 56 | 36 | 419 |
| 6 | 67 | 37 | 420 |
| 7 | 70 | 38 | 422 |
| 8 | 91 | 39 | 425 |
| 9 | 105 | 40 | 425 |
| 10 | 120 | 41 | 425 |
| 11 | 136 | 42 | 425 |
| 12 | 152 | 43 | 425 |
| 13 | 170 | 44 | 425 |
| 14 | 187 | 45 | 425 |
| 15 | 204 | 46 | 426 |
| 16 | 220 | 47 | 427 |
| 17 | 239 | 48 | 427 |
| 18 | 258 | 49 | 427 |
| 19 | 275 | 50 | 428 |
| 20 | 291 | 51 | 429 |
| 21 | 309 | 52 | 429 |
| 22 | 327 | 53 | 429 |
| 23 | 343 | 54 | 430 |
| 24 | 360 | 55 | 430 |
| 25 | 378 | 56 | 430 |
| 26 | 396 | 57 | 430 |
| 27 | 410 | 58 | 431 |
| 28 | 417 | 59 | 431 |
| 29 | 420 | 60 | 431 |
| 30 | 419 | | |

**Table A4** The system with pyrolysis combined with partial oxidation at *8.51 ml/s*

| Time (min) | Temperature ($^{o}$C) | Time (min) | Temperature ($^{o}$C) |
|---|---|---|---|
| 0 | 29 | 31 | 410 |
| 1 | 30 | 32 | 411 |
| 2 | 34 | 33 | 413 |
| 3 | 39 | 34 | 413 |
| 4 | 46 | 35 | 413 |
| 5 | 55 | 36 | 414 |
| 6 | 65 | 37 | 414 |
| 7 | 76 | 38 | 415 |
| 8 | 89 | 39 | 417 |
| 9 | 102 | 40 | 417 |
| 10 | 118 | 41 | 418 |
| 11 | 135 | 42 | 420 |
| 12 | 149 | 43 | 422 |
| 13 | 166 | 44 | 423 |
| 14 | 183 | 45 | 424 |
| 15 | 200 | 46 | 425 |
| 16 | 219 | 47 | 425 |
| 17 | 237 | 48 | 426 |
| 18 | 255 | 49 | 426 |
| 19 | 274 | 50 | 426 |
| 20 | 291 | 51 | 427 |
| 21 | 309 | 52 | 427 |
| 22 | 327 | 53 | 427 |
| 23 | 343 | 54 | 427 |
| 24 | 360 | 55 | 427 |
| 25 | 376 | 56 | 427 |
| 26 | 392 | 57 | 427 |
| 27 | 404 | 58 | 428 |
| 28 | 411 | 59 | 428 |
| 29 | 410 | 60 | 428 |
| 30 | 411 | | |

**Table A5** The system with pyrolysis combined with partial oxidation at *11.78 ml/s*

| Time (min) | Temperature ($^oC$) | Time (min) | Temperature ($^oC$) |
|---|---|---|---|
| 0 | 31 | 31 | 435 |
| 1 | 33 | 32 | 434 |
| 2 | 36 | 33 | 433 |
| 3 | 43 | 34 | 432 |
| 4 | 50 | 35 | 432 |
| 5 | 60 | 36 | 434 |
| 6 | 71 | 37 | 432 |
| 7 | 83 | 38 | 430 |
| 8 | 97 | 39 | 429 |
| 9 | 112 | 40 | 429 |
| 10 | 127 | 41 | 429 |
| 11 | 144 | 42 | 429 |
| 12 | 161 | 43 | 430 |
| 13 | 178 | 44 | 431 |
| 14 | 196 | 45 | 431 |
| 15 | 213 | 46 | 431 |
| 16 | 231 | 47 | 431 |
| 17 | 249 | 48 | 432 |
| 18 | 268 | 49 | 432 |
| 19 | 285 | 50 | 432 |
| 20 | 303 | 51 | 432 |
| 21 | 321 | 52 | 433 |
| 22 | 337 | 53 | 432 |
| 23 | 355 | 54 | 433 |
| 24 | 373 | 55 | 433 |
| 25 | 394 | 56 | 434 |
| 26 | 413 | 57 | 433 |
| 27 | 428 | 58 | 433 |
| 28 | 432 | 59 | 434 |
| 29 | 432 | 60 | 434 |
| 30 | 434 |  |  |

**Table A6** The system with pyrolysis combined with gas recycling at *5.85 ml/s*

| Time (min) | Temperature ($^oC$) | Time (min) | Temperature ($^oC$) |
|---|---|---|---|
| 0 | 27 | 31 | 426 |
| 1 | 28 | 32 | 427 |
| 2 | 30 | 33 | 427 |
| 3 | 35 | 34 | 428 |
| 4 | 42 | 35 | 427 |
| 5 | 52 | 36 | 426 |
| 6 | 64 | 37 | 427 |
| 7 | 73 | 38 | 430 |
| 8 | 85 | 39 | 433 |
| 9 | 100 | 40 | 434 |
| 10 | 116 | 41 | 433 |
| 11 | 131 | 42 | 434 |
| 12 | 148 | 43 | 434 |
| 13 | 164 | 44 | 436 |
| 14 | 182 | 45 | 436 |
| 15 | 199 | 46 | 437 |
| 16 | 216 | 47 | 438 |
| 17 | 235 | 48 | 439 |
| 18 | 253 | 49 | 439 |
| 19 | 271 | 50 | 440 |
| 20 | 290 | 51 | 440 |
| 21 | 310 | 52 | 441 |
| 22 | 327 | 53 | 442 |
| 23 | 346 | 54 | 443 |
| 24 | 366 | 55 | 443 |
| 25 | 385 | 56 | 443 |
| 26 | 405 | 57 | 444 |
| 27 | 421 | 58 | 445 |
| 28 | 422 | 59 | 444 |
| 29 | 421 | 60 | 445 |
| 30 | 424 | | |

**Table A7** The system with pyrolysis combined with gas recycling at *8.27 ml/s*

| Time (min) | Temperature ($^{o}$C) | Time (min) | Temperature ($^{o}$C) |
|---|---|---|---|
| 0 | 29 | 31 | 437 |
| 1 | 30 | 32 | 438 |
| 2 | 33 | 33 | 436 |
| 3 | 39 | 34 | 437 |
| 4 | 46 | 35 | 438 |
| 5 | 56 | 36 | 438 |
| 6 | 66 | 37 | 439 |
| 7 | 78 | 38 | 440 |
| 8 | 91 | 39 | 440 |
| 9 | 106 | 40 | 440 |
| 10 | 121 | 41 | 441 |
| 11 | 139 | 42 | 442 |
| 12 | 155 | 43 | 441 |
| 13 | 171 | 44 | 442 |
| 14 | 189 | 45 | 441 |
| 15 | 206 | 46 | 442 |
| 16 | 224 | 47 | 443 |
| 17 | 242 | 48 | 444 |
| 18 | 261 | 49 | 444 |
| 19 | 280 | 50 | 444 |
| 20 | 299 | 51 | 444 |
| 21 | 317 | 52 | 445 |
| 22 | 337 | 53 | 445 |
| 23 | 356 | 54 | 445 |
| 24 | 376 | 55 | 445 |
| 25 | 397 | 56 | 446 |
| 26 | 419 | 57 | 446 |
| 27 | 435 | 58 | 447 |
| 28 | 437 | 59 | 447 |
| 29 | 437 | 60 | 447 |
| 30 | 437 | | |

**Table A8** The system with pyrolysis combined with gas recycling at *10.70 ml/s*

| Time (min) | Temperature ($^oC$) | Time (min) | Temperature ($^oC$) |
|---|---|---|---|
| 0 | 27 | 31 | 450 |
| 1 | 28 | 32 | 449 |
| 2 | 31 | 33 | 449 |
| 3 | 37 | 34 | 448 |
| 4 | 44 | 35 | 449 |
| 5 | 54 | 36 | 450 |
| 6 | 65 | 37 | 447 |
| 7 | 78 | 38 | 446 |
| 8 | 92 | 39 | 447 |
| 9 | 106 | 40 | 447 |
| 10 | 122 | 41 | 448 |
| 11 | 139 | 42 | 449 |
| 12 | 157 | 43 | 450 |
| 13 | 174 | 44 | 449 |
| 14 | 191 | 45 | 450 |
| 15 | 209 | 46 | 451 |
| 16 | 227 | 47 | 452 |
| 17 | 246 | 48 | 452 |
| 18 | 265 | 49 | 452 |
| 19 | 283 | 50 | 451 |
| 20 | 302 | 51 | 452 |
| 21 | 324 | 52 | 452 |
| 22 | 346 | 53 | 452 |
| 23 | 368 | 54 | 453 |
| 24 | 392 | 55 | 453 |
| 25 | 416 | 56 | 453 |
| 26 | 434 | 57 | 453 |
| 27 | 442 | 58 | 453 |
| 28 | 447 | 59 | 453 |
| 29 | 447 | 60 | 453 |
| 30 | 449 | | |

# Appendix B

The temperature profiles in fluidized bed reactor

**Table B1** The system with *5.22 l/min* of LPG by fixing air feed rate at *300 l/min*

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 28 | 28 | 28 | 28 | 28 | 28 | 28 | 28 |
| 1 | 156 | 124 | 57 | 103 | 94 | 82 | 87 | 68 |
| 2 | 193 | 175 | 94 | 143 | 135 | 117 | 119 | 92 |
| 3 | 225 | 203 | 121 | 179 | 161 | 141 | 138 | 107 |
| 4 | 232 | 213 | 137 | 195 | 174 | 155 | 153 | 120 |
| 5 | 248 | 230 | 155 | 210 | 192 | 171 | 169 | 133 |
| 6 | 256 | 240 | 169 | 218 | 204 | 183 | 181 | 145 |
| 7 | 268 | 248 | 181 | 224 | 213 | 192 | 189 | 153 |
| 8 | 270 | 254 | 191 | 231 | 221 | 201 | 198 | 162 |
| 9 | 282 | 264 | 202 | 241 | 231 | 210 | 208 | 171 |
| 10 | 295 | 275 | 214 | 253 | 243 | 219 | 219 | 181 |
| 11 | 314 | 285 | 226 | 263 | 253 | 227 | 228 | 189 |
| 12 | 324 | 293 | 237 | 271 | 262 | 236 | 237 | 205 |
| 13 | 327 | 297 | 246 | 273 | 266 | 242 | 241 | 223 |
| 14 | 329 | 301 | 258 | 275 | 270 | 246 | 249 | 231 |
| 15 | 331 | 303 | 263 | 277 | 273 | 248 | 253 | 233 |
| 16 | 333 | 305 | 267 | 278 | 273 | 249 | 255 | 234 |
| 17 | 334 | 307 | 271 | 279 | 274 | 250 | 256 | 235 |
| 18 | 335 | 308 | 273 | 280 | 274 | 251 | 257 | 235 |
| 19 | 336 | 309 | 273 | 280 | 274 | 251 | 257 | 235 |
| 20 | 336 | 309 | 273 | 280 | 274 | 251 | 257 | 235 |

**Table B2** The system with *7.31 l/min* of LPG by fixing air feed rate at *300 l/min*

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| 1 | 113 | 98 | 80 | 85 | 77 | 72 | 75 | 56 |
| 2 | 145 | 137 | 125 | 114 | 107 | 96 | 100 | 74 |
| 3 | 178 | 161 | 153 | 139 | 130 | 117 | 120 | 92 |
| 4 | 201 | 182 | 177 | 158 | 150 | 136 | 140 | 108 |
| 5 | 229 | 210 | 208 | 186 | 177 | 159 | 165 | 130 |
| 6 | 245 | 232 | 225 | 211 | 199 | 182 | 185 | 150 |
| 7 | 268 | 256 | 247 | 229 | 220 | 202 | 206 | 169 |
| 8 | 289 | 277 | 265 | 257 | 240 | 223 | 224 | 191 |
| 9 | 316 | 302 | 283 | 274 | 265 | 250 | 248 | 212 |
| 10 | 340 | 321 | 307 | 295 | 286 | 272 | 266 | 230 |
| 11 | 355 | 339 | 328 | 315 | 305 | 295 | 286 | 252 |
| 12 | 369 | 353 | 338 | 326 | 318 | 316 | 300 | 271 |
| 13 | 384 | 363 | 349 | 340 | 331 | 333 | 322 | 287 |
| 14 | 395 | 385 | 370 | 358 | 351 | 349 | 337 | 304 |
| 15 | 408 | 392 | 381 | 365 | 357 | 359 | 347 | 317 |
| 16 | 415 | 398 | 390 | 375 | 368 | 367 | 354 | 329 |
| 17 | 418 | 398 | 394 | 380 | 370 | 370 | 357 | 336 |
| 18 | 423 | 403 | 398 | 390 | 376 | 375 | 364 | 340 |
| 19 | 425 | 414 | 405 | 397 | 385 | 383 | 370 | 343 |
| 20 | 433 | 425 | 414 | 405 | 394 | 391 | 371 | 345 |
| 21 | 440 | 434 | 420 | 410 | 403 | 399 | 373 | 346 |
| 22 | 445 | 433 | 423 | 413 | 405 | 402 | 374 | 347 |
| 23 | 447 | 434 | 424 | 415 | 407 | 404 | 375 | 349 |
| 24 | 449 | 436 | 424 | 416 | 408 | 405 | 376 | 348 |

**Table B2** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25 | 453 | 439 | 425 | 415 | 409 | 405 | 375 | 349 |
| 26 | 454 | 439 | 425 | 416 | 408 | 406 | 376 | 349 |

**Table B3** The system with *9.50 l/min* of LPG by fixing air feed rate of *300 l/min*

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| 1 | 178 | 169 | 234 | 203 | 181 | 173 | 170 | 140 |
| 2 | 254 | 237 | 294 | 277 | 244 | 232 | 225 | 188 |
| 3 | 300 | 281 | 305 | 289 | 278 | 267 | 256 | 217 |
| 4 | 315 | 301 | 316 | 298 | 295 | 288 | 274 | 236 |
| 5 | 331 | 312 | 325 | 308 | 301 | 300 | 282 | 250 |
| 6 | 346 | 324 | 339 | 314 | 302 | 303 | 283 | 257 |
| 7 | 364 | 342 | 355 | 327 | 314 | 318 | 302 | 273 |
| 8 | 375 | 355 | 371 | 349 | 335 | 333 | 318 | 291 |
| 9 | 387 | 367 | 379 | 352 | 346 | 344 | 328 | 299 |
| 10 | 398 | 375 | 381 | 366 | 350 | 367 | 331 | 305 |
| 11 | 410 | 391 | 402 | 371 | 367 | 378 | 350 | 322 |
| 12 | 419 | 408 | 408 | 383 | 377 | 388 | 359 | 331 |
| 13 | 426 | 421 | 417 | 394 | 386 | 397 | 369 | 342 |
| 14 | 435 | 432 | 427 | 404 | 396 | 409 | 380 | 352 |
| 15 | 444 | 445 | 439 | 412 | 408 | 415 | 391 | 362 |
| 16 | 465 | 455 | 446 | 421 | 416 | 420 | 398 | 370 |
| 17 | 475 | 461 | 453 | 430 | 419 | 425 | 405 | 376 |
| 18 | 481 | 467 | 454 | 439 | 425 | 431 | 422 | 380 |
| 19 | 489 | 474 | 460 | 442 | 431 | 437 | 423 | 390 |
| 20 | 493 | 481 | 463 | 445 | 436 | 438 | 425 | 397 |
| 21 | 495 | 482 | 464 | 448 | 437 | 442 | 428 | 399 |
| 22 | 497 | 483 | 465 | 451 | 442 | 442 | 430 | 402 |
| 23 | 499 | 487 | 467 | 453 | 441 | 440 | 432 | 406 |
| 24 | 500 | 488 | 468 | 454 | 442 | 439 | 434 | 409 |

**Table B3** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25 | 501 | 489 | 470 | 455 | 443 | 439 | 435 | 412 |
| 26 | 502 | 490 | 471 | 456 | 444 | 440 | 434 | 414 |
| 27 | 502 | 491 | 473 | 456 | 444 | 441 | 435 | 416 |
| 28 | 503 | 490 | 473 | 456 | 444 | 441 | 435 | 417 |
| 29 | 502 | 491 | 473 | 456 | 444 | 441 | 435 | 417 |

**Table B4** The system with *10.23 l/min* of LPG by fixing air feed rate at *300 l/min*

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| 1 | 215 | 189 | 249 | 211 | 195 | 193 | 188 | 156 |
| 2 | 284 | 264 | 315 | 295 | 269 | 260 | 245 | 209 |
| 3 | 334 | 318 | 352 | 322 | 309 | 300 | 288 | 243 |
| 4 | 356 | 347 | 360 | 342 | 334 | 325 | 311 | 271 |
| 5 | 376 | 367 | 375 | 360 | 346 | 340 | 325 | 280 |
| 6 | 399 | 384 | 389 | 367 | 356 | 354 | 333 | 300 |
| 7 | 415 | 403 | 400 | 380 | 369 | 366 | 348 | 318 |
| 8 | 426 | 417 | 418 | 397 | 385 | 381 | 365 | 330 |
| 9 | 437 | 430 | 431 | 405 | 395 | 394 | 374 | 340 |
| 10 | 452 | 440 | 440 | 415 | 402 | 411 | 383 | 350 |
| 11 | 467 | 451 | 448 | 426 | 415 | 421 | 394 | 367 |
| 12 | 483 | 468 | 458 | 437 | 426 | 429 | 405 | 376 |
| 13 | 490 | 481 | 465 | 445 | 435 | 437 | 412 | 388 |
| 14 | 510 | 490 | 472 | 454 | 443 | 448 | 425 | 398 |
| 15 | 515 | 499 | 481 | 460 | 451 | 456 | 433 | 406 |
| 16 | 521 | 507 | 488 | 466 | 457 | 462 | 439 | 414 |
| 17 | 523 | 512 | 493 | 475 | 461 | 465 | 447 | 421 |
| 18 | 526 | 517 | 498 | 481 | 468 | 472 | 458 | 424 |
| 19 | 530 | 523 | 503 | 486 | 471 | 477 | 461 | 429 |
| 20 | 534 | 527 | 507 | 488 | 475 | 478 | 462 | 434 |
| 21 | 536 | 528 | 508 | 490 | 479 | 479 | 463 | 439 |
| 22 | 538 | 529 | 509 | 492 | 481 | 480 | 465 | 441 |
| 23 | 539 | 530 | 510 | 493 | 483 | 480 | 465 | 444 |
| 24 | 540 | 532 | 512 | 494 | 483 | 481 | 466 | 446 |

**Table B4** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25 | 542 | 533 | 513 | 495 | 484 | 481 | 466 | 448 |
| 26 | 542 | 534 | 513 | 495 | 484 | 481 | 467 | 449 |
| 27 | 543 | 535 | 514 | 496 | 484 | 482 | 468 | 449 |
| 28 | 543 | 534 | 514 | 495 | 484 | 482 | 467 | 449 |
| 29 | 543 | 534 | 514 | 495 | 484 | 482 | 467 | 449 |

**Table B5** The system with *100 l/min* of air by fixing LPG feed rate at *7.31 l/min*

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 |
| 1 | 201 | 183 | 156 | 121 | 108 | 93 | 89 | 68 |
| 2 | 215 | 191 | 166 | 137 | 133 | 115 | 105 | 84 |
| 3 | 221 | 205 | 171 | 148 | 134 | 124 | 113 | 88 |
| 4 | 235 | 210 | 180 | 155 | 142 | 133 | 125 | 97 |
| 5 | 243 | 219 | 186 | 164 | 151 | 145 | 132 | 105 |
| 6 | 250 | 225 | 199 | 172 | 164 | 155 | 142 | 114 |
| 7 | 259 | 231 | 211 | 189 | 173 | 169 | 156 | 125 |
| 8 | 264 | 241 | 223 | 194 | 185 | 182 | 166 | 137 |
| 9 | 272 | 253 | 230 | 203 | 197 | 190 | 174 | 144 |
| 10 | 278 | 260 | 232 | 209 | 198 | 194 | 179 | 149 |
| 11 | 282 | 262 | 233 | 211 | 201 | 198 | 183 | 157 |
| 12 | 284 | 263 | 235 | 213 | 204 | 201 | 186 | 157 |
| 13 | 285 | 264 | 237 | 214 | 208 | 205 | 190 | 165 |
| 14 | 286 | 265 | 238 | 215 | 209 | 207 | 191 | 166 |
| 15 | 287 | 267 | 239 | 216 | 210 | 208 | 192 | 167 |
| 16 | 287 | 268 | 240 | 217 | 211 | 209 | 193 | 166 |
| 17 | 287 | 268 | 241 | 218 | 211 | 210 | 192 | 168 |
| 18 | 288 | 269 | 241 | 218 | 212 | 210 | 192 | 169 |
| 19 | 289 | 269 | 242 | 218 | 212 | 210 | 193 | 170 |
| 20 | 288 | 269 | 242 | 218 | 211 | 209 | 193 | 169 |

**Table B6** The system with *200 l/min* of air by fixing LPG feed rate at *7.31 l/min*

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 27 | 27 | 27 | 27 | 27 | 27 | 27 | 27 |
| 1 | 96 | 85 | 75 | 68 | 65 | 64 | 61 | 51 |
| 2 | 140 | 120 | 113 | 98 | 95 | 93 | 87 | 68 |
| 3 | 175 | 147 | 142 | 122 | 111 | 112 | 105 | 86 |
| 4 | 195 | 173 | 164 | 135 | 123 | 124 | 121 | 94 |
| 5 | 218 | 201 | 191 | 154 | 138 | 139 | 134 | 112 |
| 6 | 226 | 212 | 210 | 189 | 176 | 178 | 171 | 131 |
| 7 | 257 | 241 | 231 | 213 | 194 | 192 | 184 | 153 |
| 8 | 269 | 263 | 251 | 239 | 221 | 223 | 203 | 168 |
| 9 | 284 | 291 | 274 | 254 | 231 | 230 | 221 | 186 |
| 10 | 300 | 313 | 296 | 277 | 254 | 248 | 234 | 201 |
| 11 | 321 | 325 | 315 | 295 | 287 | 283 | 252 | 213 |
| 12 | 355 | 341 | 321 | 305 | 295 | 294 | 276 | 234 |
| 13 | 376 | 353 | 334 | 319 | 307 | 301 | 289 | 251 |
| 14 | 381 | 377 | 355 | 334 | 321 | 318 | 301 | 264 |
| 15 | 393 | 381 | 372 | 351 | 346 | 335 | 314 | 278 |
| 16 | 405 | 389 | 383 | 361 | 351 | 346 | 324 | 297 |
| 17 | 418 | 395 | 388 | 370 | 359 | 353 | 336 | 310 |
| 18 | 429 | 400 | 393 | 374 | 364 | 360 | 348 | 324 |
| 19 | 435 | 410 | 398 | 380 | 366 | 363 | 351 | 329 |
| 20 | 439 | 419 | 403 | 384 | 368 | 365 | 353 | 332 |
| 21 | 441 | 425 | 409 | 389 | 371 | 368 | 355 | 333 |
| 22 | 443 | 429 | 413 | 395 | 373 | 369 | 356 | 334 |
| 23 | 444 | 430 | 414 | 398 | 375 | 369 | 357 | 335 |
| 24 | 444 | 431 | 415 | 400 | 376 | 370 | 358 | 336 |
| 25 | 445 | 430 | 415 | 401 | 377 | 369 | 358 | 334 |

**Table B6** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 26 | 446 | 429 | 415 | 400 | 377 | 370 | 359 | 335 |
| 27 | 446 | 429 | 415 | 400 | 376 | 370 | 358 | 335 |

**Table B7** The system with *300 l/min* of air by fixing LPG feed rate at *7.31 l/min*

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| 1 | 113 | 98 | 80 | 85 | 77 | 72 | 75 | 56 |
| 2 | 145 | 137 | 125 | 114 | 107 | 96 | 100 | 74 |
| 3 | 178 | 161 | 153 | 139 | 130 | 117 | 120 | 92 |
| 4 | 201 | 182 | 177 | 158 | 150 | 136 | 140 | 108 |
| 5 | 229 | 210 | 208 | 186 | 177 | 159 | 165 | 130 |
| 6 | 245 | 232 | 225 | 211 | 199 | 182 | 185 | 150 |
| 7 | 268 | 256 | 247 | 229 | 220 | 202 | 206 | 169 |
| 8 | 289 | 277 | 265 | 257 | 240 | 223 | 224 | 191 |
| 9 | 316 | 302 | 283 | 274 | 265 | 250 | 248 | 212 |
| 10 | 340 | 321 | 307 | 295 | 286 | 272 | 266 | 230 |
| 11 | 355 | 339 | 328 | 315 | 305 | 295 | 286 | 252 |
| 12 | 369 | 353 | 338 | 326 | 318 | 316 | 300 | 271 |
| 13 | 384 | 363 | 349 | 340 | 331 | 333 | 322 | 287 |
| 14 | 395 | 385 | 370 | 358 | 351 | 349 | 337 | 304 |
| 15 | 408 | 392 | 381 | 365 | 357 | 359 | 347 | 317 |
| 16 | 415 | 398 | 390 | 375 | 368 | 367 | 354 | 329 |
| 17 | 418 | 398 | 394 | 380 | 370 | 370 | 357 | 336 |
| 18 | 423 | 403 | 398 | 390 | 376 | 375 | 364 | 340 |
| 19 | 425 | 414 | 405 | 397 | 385 | 383 | 370 | 343 |
| 20 | 433 | 425 | 414 | 405 | 394 | 391 | 371 | 345 |
| 21 | 440 | 434 | 420 | 410 | 403 | 399 | 373 | 346 |
| 22 | 445 | 433 | 423 | 413 | 405 | 402 | 374 | 347 |
| 23 | 447 | 434 | 424 | 415 | 407 | 404 | 375 | 349 |
| 24 | 449 | 436 | 424 | 416 | 408 | 405 | 376 | 348 |
| 25 | 453 | 439 | 425 | 415 | 409 | 405 | 375 | 349 |

**Table B7** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 26 | 454 | 439 | 425 | 416 | 408 | 406 | 376 | 349 |
| 27 | 446 | 429 | 415 | 400 | 376 | 370 | 358 | 335 |

**Table B8** The system with *400 l/min* of air by fixing LPG feed rate at *7.31 l/min*

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 26 | 26 | 26 | 26 | 26 | 26 | 26 | 26 |
| 1 | 111 | 96 | 79 | 84 | 75 | 70 | 69 | 63 |
| 2 | 139 | 135 | 121 | 110 | 105 | 93 | 98 | 71 |
| 3 | 176 | 160 | 150 | 135 | 128 | 110 | 115 | 95 |
| 4 | 198 | 179 | 173 | 151 | 145 | 134 | 129 | 110 |
| 5 | 225 | 208 | 201 | 181 | 168 | 152 | 148 | 128 |
| 6 | 242 | 229 | 219 | 205 | 185 | 178 | 167 | 149 |
| 7 | 264 | 248 | 245 | 224 | 211 | 197 | 189 | 165 |
| 8 | 283 | 265 | 264 | 258 | 235 | 217 | 210 | 188 |
| 9 | 313 | 289 | 283 | 276 | 260 | 246 | 235 | 210 |
| 10 | 336 | 312 | 301 | 289 | 281 | 269 | 250 | 228 |
| 11 | 351 | 321 | 320 | 310 | 301 | 287 | 271 | 247 |
| 12 | 364 | 341 | 331 | 321 | 313 | 308 | 297 | 267 |
| 13 | 383 | 352 | 340 | 335 | 325 | 324 | 315 | 285 |
| 14 | 396 | 378 | 359 | 355 | 345 | 339 | 331 | 300 |
| 15 | 405 | 389 | 376 | 361 | 350 | 354 | 343 | 310 |
| 16 | 413 | 387 | 389 | 373 | 361 | 363 | 351 | 325 |
| 17 | 420 | 394 | 391 | 375 | 365 | 367 | 359 | 336 |
| 18 | 424 | 405 | 395 | 379 | 372 | 369 | 364 | 347 |
| 19 | 426 | 409 | 400 | 387 | 381 | 371 | 369 | 356 |
| 20 | 430 | 412 | 406 | 395 | 392 | 384 | 375 | 364 |
| 21 | 435 | 420 | 408 | 401 | 399 | 395 | 386 | 369 |
| 22 | 441 | 421 | 410 | 408 | 403 | 399 | 388 | 371 |
| 23 | 445 | 423 | 412 | 414 | 405 | 401 | 389 | 372 |
| 24 | 448 | 425 | 413 | 420 | 406 | 402 | 392 | 373 |
| 25 | 449 | 425 | 414 | 421 | 407 | 403 | 393 | 373 |

**Table B8** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 26 | 450 | 424 | 413 | 422 | 408 | 403 | 394 | 373 |
| 27 | 451 | 425 | 414 | 422 | 408 | 403 | 393 | 373 |

**Table B9** The variation of system temperature after *50 g* of plastic feeding

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 453 | 430 | 422 | 409 | 397 | 387 | 360 | 344 |
| 0.5 | 447 | 429 | 415 | 400 | 389 | 377 | 351 | 338 |
| 1 | 443 | 423 | 404 | 393 | 382 | 370 | 347 | 333 |
| 1.5 | 438 | 411 | 401 | 391 | 381 | 368 | 346 | 331 |
| 2 | 435 | 408 | 403 | 396 | 385 | 370 | 348 | 330 |
| 2.5 | 436 | 410 | 407 | 400 | 388 | 375 | 354 | 332 |
| 3 | 439 | 419 | 413 | 402 | 391 | 379 | 356 | 339 |
| 3.5 | 443 | 425 | 418 | 405 | 393 | 383 | 357 | 341 |
| 4 | 446 | 427 | 419 | 407 | 395 | 385 | 360 | 342 |
| 4.5 | 449 | 428 | 420 | 408 | 396 | 386 | 361 | 343 |
| 5 | 450 | 429 | 420 | 409 | 396 | 386 | 360 | 342 |
| 5.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 6 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 6.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 7 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 7.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 8 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 8.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 9 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 9.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 10 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 10.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 11 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 11.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 12 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 12.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |

**Table B9** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 13.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 14 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 14.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 15 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 15.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 16 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 16.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 17 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 17.5 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |
| 18 | 451 | 429 | 420 | 409 | 396 | 386 | 361 | 342 |

**Table B10** The variation of system temperature after *80 g* of plastic feeding

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 454 | 435 | 427 | 414 | 405 | 401 | 373 | 353 |
| 0.5 | 455 | 435 | 427 | 414 | 405 | 400 | 372 | 353 |
| 1 | 455 | 434 | 428 | 409 | 406 | 399 | 372 | 353 |
| 1.5 | 438 | 421 | 412 | 401 | 379 | 387 | 361 | 342 |
| 2 | 411 | 408 | 395 | 390 | 376 | 371 | 351 | 332 |
| 2.5 | 399 | 411 | 381 | 373 | 368 | 360 | 339 | 320 |
| 3 | 383 | 392 | 348 | 339 | 354 | 351 | 332 | 313 |
| 3.5 | 380 | 386 | 352 | 335 | 348 | 330 | 312 | 293 |
| 4 | 369 | 365 | 350 | 340 | 351 | 333 | 302 | 283 |
| 4.5 | 381 | 368 | 354 | 346 | 352 | 334 | 301 | 282 |
| 5 | 408 | 396 | 378 | 357 | 363 | 354 | 327 | 308 |
| 5.5 | 414 | 409 | 381 | 365 | 367 | 360 | 332 | 313 |
| 6 | 421 | 415 | 386 | 379 | 373 | 366 | 337 | 318 |
| 6.5 | 429 | 423 | 392 | 386 | 374 | 373 | 339 | 320 |
| 7 | 435 | 429 | 396 | 391 | 377 | 376 | 341 | 322 |
| 7.5 | 439 | 431 | 402 | 401 | 381 | 381 | 345 | 326 |
| 8 | 444 | 433 | 405 | 405 | 388 | 385 | 347 | 328 |
| 8.5 | 451 | 434 | 411 | 406 | 389 | 385 | 354 | 335 |
| 9 | 452 | 435 | 416 | 407 | 390 | 388 | 357 | 338 |
| 9.5 | 453 | 435 | 418 | 408 | 393 | 389 | 360 | 341 |
| 10 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 10.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 11 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 11.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 12 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 12.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |

**Table B10** (Continued)

| Time (min) | Temperature ($^{o}C$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 13.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 14 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 14.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 15 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 15.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 16 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 16.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 17 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 17.5 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |
| 18 | 454 | 435 | 420 | 408 | 394 | 390 | 361 | 342 |

**Table B11** The variation of system temperature after *100 g* of plastic feeding

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 450 | 432 | 425 | 410 | 399 | 391 | 365 | 345 |
| 0.5 | 442 | 430 | 422 | 407 | 395 | 386 | 361 | 337 |
| 1 | 430 | 424 | 417 | 403 | 391 | 381 | 356 | 338 |
| 1.5 | 413 | 409 | 406 | 395 | 390 | 374 | 349 | 333 |
| 2 | 399 | 393 | 393 | 383 | 378 | 364 | 339 | 326 |
| 2.5 | 389 | 383 | 386 | 374 | 370 | 355 | 330 | 321 |
| 3 | 380 | 376 | 382 | 365 | 361 | 345 | 320 | 309 |
| 3.5 | 374 | 369 | 375 | 355 | 351 | 340 | 315 | 303 |
| 4 | 368 | 365 | 368 | 345 | 341 | 325 | 300 | 290 |
| 4.5 | 360 | 361 | 355 | 336 | 332 | 316 | 291 | 281 |
| 5 | 367 | 363 | 352 | 330 | 326 | 310 | 285 | 275 |
| 5.5 | 370 | 363 | 355 | 331 | 327 | 311 | 286 | 271 |
| 6 | 375 | 364 | 358 | 333 | 329 | 315 | 290 | 270 |
| 6.5 | 380 | 366 | 362 | 336 | 330 | 319 | 294 | 275 |
| 7 | 384 | 369 | 367 | 342 | 332 | 321 | 296 | 278 |
| 7.5 | 389 | 374 | 371 | 347 | 333 | 324 | 299 | 282 |
| 8 | 393 | 378 | 375 | 354 | 335 | 329 | 304 | 289 |
| 8.5 | 403 | 389 | 377 | 365 | 336 | 332 | 307 | 293 |
| 9 | 412 | 393 | 378 | 372 | 337 | 336 | 311 | 305 |
| 9.5 | 418 | 400 | 381 | 379 | 344 | 338 | 313 | 312 |
| 10 | 425 | 403 | 386 | 385 | 351 | 344 | 319 | 321 |
| 10.5 | 434 | 408 | 394 | 391 | 359 | 351 | 326 | 325 |
| 11 | 441 | 415 | 401 | 398 | 365 | 356 | 331 | 329 |
| 11.5 | 445 | 421 | 402 | 401 | 373 | 364 | 339 | 332 |
| 12 | 446 | 426 | 407 | 403 | 382 | 373 | 348 | 335 |
| 12.5 | 447 | 428 | 413 | 404 | 388 | 381 | 355 | 337 |

**Table B11** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 448 | 429 | 415 | 406 | 389 | 384 | 356 | 338 |
| 13.5 | 449 | 430 | 416 | 407 | 390 | 385 | 356 | 338 |
| 14 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 14.5 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 15 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 15.5 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 16 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 16.5 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 17 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 17.5 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |
| 18 | 449 | 430 | 416 | 407 | 389 | 385 | 357 | 338 |

**Table B12** The variation of system temperature after *120 g* of plastic feeding

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 450 | 436 | 429 | 412 | 402 | 397 | 350 | 337 |
| 0.5 | 445 | 429 | 410 | 405 | 387 | 381 | 333 | 331 |
| 1 | 423 | 410 | 401 | 396 | 380 | 374 | 327 | 325 |
| 1.5 | 405 | 399 | 391 | 386 | 373 | 365 | 315 | 313 |
| 2 | 387 | 376 | 370 | 365 | 361 | 355 | 309 | 307 |
| 2.5 | 371 | 364 | 360 | 355 | 353 | 346 | 300 | 295 |
| 3 | 364 | 351 | 346 | 341 | 340 | 331 | 296 | 289 |
| 3.5 | 355 | 343 | 332 | 327 | 321 | 315 | 290 | 280 |
| 4 | 349 | 341 | 324 | 319 | 315 | 306 | 285 | 276 |
| 4.5 | 345 | 333 | 320 | 315 | 310 | 295 | 282 | 270 |
| 5 | 340 | 339 | 324 | 319 | 312 | 296 | 279 | 265 |
| 5.5 | 341 | 339 | 326 | 321 | 315 | 299 | 277 | 262 |
| 6 | 345 | 340 | 329 | 324 | 318 | 304 | 281 | 259 |
| 6.5 | 349 | 343 | 334 | 329 | 324 | 309 | 285 | 257 |
| 7 | 355 | 345 | 338 | 333 | 328 | 314 | 289 | 261 |
| 7.5 | 359 | 346 | 341 | 336 | 331 | 321 | 295 | 265 |
| 8 | 363 | 347 | 343 | 338 | 335 | 325 | 306 | 269 |
| 8.5 | 369 | 349 | 345 | 340 | 337 | 329 | 314 | 275 |
| 9 | 375 | 356 | 348 | 343 | 340 | 334 | 319 | 286 |
| 9.5 | 379 | 360 | 351 | 346 | 342 | 336 | 325 | 294 |
| 10 | 383 | 363 | 356 | 351 | 346 | 339 | 329 | 299 |
| 10.5 | 385 | 365 | 364 | 359 | 351 | 343 | 334 | 305 |
| 11 | 389 | 370 | 373 | 368 | 353 | 346 | 338 | 309 |
| 11.5 | 394 | 382 | 375 | 370 | 357 | 349 | 342 | 314 |
| 12 | 405 | 385 | 381 | 376 | 363 | 351 | 343 | 318 |
| 12.5 | 414 | 391 | 386 | 381 | 368 | 354 | 345 | 322 |

**Table B12** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 417 | 396 | 390 | 385 | 374 | 357 | 346 | 325 |
| 13.5 | 421 | 399 | 393 | 388 | 379 | 362 | 346 | 328 |
| 14 | 426 | 406 | 396 | 391 | 384 | 366 | 347 | 329 |
| 14.5 | 429 | 411 | 401 | 396 | 388 | 371 | 348 | 330 |
| 15 | 433 | 417 | 403 | 397 | 392 | 373 | 348 | 332 |
| 15.5 | 437 | 420 | 406 | 399 | 394 | 375 | 348 | 334 |
| 16 | 441 | 423 | 407 | 401 | 395 | 380 | 348 | 335 |
| 16.5 | 443 | 425 | 409 | 403 | 396 | 383 | 349 | 335 |
| 17 | 445 | 426 | 411 | 404 | 395 | 385 | 348 | 336 |
| 17.5 | 446 | 426 | 413 | 404 | 395 | 387 | 349 | 335 |
| 18 | 447 | 426 | 414 | 404 | 395 | 388 | 349 | 336 |

**Table B13** The system temperature with fixing the bed temperature at *450 °C*

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 450 | 432 | 425 | 410 | 399 | 391 | 365 | 345 |
| 0.5 | 445 | 421 | 418 | 403 | 391 | 377 | 356 | 339 |
| 1 | 433 | 416 | 407 | 396 | 384 | 375 | 350 | 334 |
| 1.5 | 428 | 413 | 410 | 394 | 383 | 377 | 351 | 332 |
| 2 | 430 | 411 | 412 | 399 | 387 | 382 | 353 | 332 |
| 2.5 | 439 | 414 | 414 | 403 | 390 | 386 | 359 | 333 |
| 3 | 448 | 419 | 422 | 405 | 395 | 390 | 361 | 340 |
| 3.5 | 450 | 425 | 423 | 408 | 397 | 392 | 362 | 342 |
| 4 | 449 | 428 | 425 | 410 | 399 | 393 | 365 | 345 |
| 4.5 | 451 | 431 | 426 | 411 | 400 | 385 | 366 | 345 |
| 5 | 442 | 423 | 419 | 404 | 390 | 378 | 357 | 338 |
| 5.5 | 430 | 417 | 408 | 397 | 383 | 376 | 351 | 333 |
| 6 | 427 | 415 | 411 | 395 | 382 | 375 | 352 | 330 |
| 6.5 | 429 | 412 | 410 | 398 | 386 | 383 | 352 | 330 |
| 7 | 440 | 416 | 415 | 404 | 391 | 387 | 360 | 334 |
| 7.5 | 443 | 424 | 423 | 406 | 394 | 391 | 362 | 339 |
| 8 | 448 | 428 | 424 | 409 | 396 | 392 | 363 | 343 |
| 8.5 | 447 | 429 | 425 | 410 | 399 | 384 | 365 | 344 |
| 9 | 440 | 420 | 418 | 403 | 391 | 377 | 356 | 339 |
| 9.5 | 430 | 416 | 407 | 396 | 384 | 375 | 350 | 334 |
| 10 | 426 | 410 | 410 | 394 | 383 | 377 | 351 | 332 |
| 10.5 | 429 | 413 | 412 | 399 | 387 | 382 | 353 | 330 |
| 11 | 437 | 418 | 414 | 403 | 390 | 386 | 359 | 332 |
| 11.5 | 445 | 425 | 422 | 405 | 395 | 390 | 361 | 340 |
| 12 | 446 | 428 | 423 | 408 | 397 | 393 | 362 | 342 |
| 12.5 | 450 | 430 | 426 | 409 | 400 | 385 | 366 | 345 |

**Table B13** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 442 | 423 | 419 | 404 | 390 | 378 | 357 | 338 |
| 13.5 | 432 | 416 | 408 | 397 | 383 | 377 | 351 | 333 |
| 14 | 426 | 413 | 408 | 393 | 382 | 379 | 354 | 330 |
| 14.5 | 428 | 414 | 413 | 398 | 388 | 384 | 356 | 329 |
| 15 | 437 | 419 | 415 | 404 | 391 | 387 | 360 | 331 |
| 15.5 | 444 | 425 | 423 | 406 | 394 | 391 | 362 | 338 |
| 16 | 448 | 429 | 424 | 409 | 396 | 392 | 363 | 341 |
| 16.5 | 450 | 432 | 425 | 410 | 399 | 384 | 365 | 342 |
| 17 | 443 | 423 | 418 | 403 | 391 | 377 | 356 | 339 |
| 17.5 | 431 | 416 | 407 | 396 | 384 | 375 | 350 | 334 |
| 18 | 428 | 412 | 410 | 394 | 383 | 377 | 351 | 332 |
| 18.5 | 430 | 414 | 412 | 399 | 387 | 382 | 353 | 333 |
| 19 | 439 | 418 | 414 | 403 | 390 | 386 | 359 | 335 |
| 19.5 | 443 | 423 | 422 | 405 | 395 | 390 | 361 | 340 |
| 20 | 449 | 426 | 423 | 408 | 397 | 389 | 362 | 342 |
| 20.5 | 450 | 428 | 425 | 407 | 394 | 384 | 363 | 345 |
| 21 | 443 | 426 | 418 | 400 | 391 | 380 | 358 | 340 |
| 21.5 | 431 | 421 | 407 | 393 | 384 | 375 | 354 | 335 |
| 22 | 428 | 417 | 410 | 390 | 381 | 377 | 352 | 332 |
| 22.5 | 430 | 418 | 412 | 393 | 387 | 382 | 355 | 333 |
| 23 | 439 | 420 | 414 | 400 | 390 | 386 | 360 | 337 |
| 23.5 | 445 | 426 | 422 | 405 | 395 | 390 | 361 | 341 |
| 24 | 448 | 428 | 423 | 408 | 397 | 392 | 362 | 343 |
| 24.5 | 450 | 429 | 425 | 410 | 399 | 384 | 365 | 343 |
| 25 | 443 | 423 | 418 | 403 | 391 | 377 | 356 | 339 |

**Table B13** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25.5 | 431 | 419 | 407 | 396 | 384 | 375 | 350 | 334 |
| 26 | 428 | 417 | 410 | 394 | 383 | 377 | 351 | 332 |
| 26.5 | 430 | 419 | 412 | 399 | 387 | 382 | 353 | 330 |
| 27 | 439 | 423 | 414 | 403 | 390 | 386 | 359 | 332 |
| 27.5 | 445 | 427 | 422 | 405 | 395 | 390 | 361 | 340 |
| 28 | 447 | 428 | 423 | 408 | 397 | 393 | 362 | 342 |
| 28.5 | 450 | 430 | 425 | 405 | 395 | 382 | 363 | 344 |
| 29 | 443 | 426 | 418 | 402 | 390 | 376 | 358 | 339 |
| 29.5 | 431 | 421 | 407 | 395 | 382 | 372 | 349 | 334 |
| 30 | 428 | 419 | 410 | 393 | 381 | 376 | 351 | 332 |
| 30.5 | 430 | 422 | 412 | 401 | 385 | 382 | 353 | 329 |
| 31 | 439 | 427 | 414 | 404 | 391 | 386 | 359 | 333 |
| 31.5 | 445 | 429 | 422 | 406 | 395 | 390 | 361 | 340 |
| 32 | 448 | 430 | 423 | 408 | 397 | 392 | 362 | 343 |
| 32.5 | 450 | 431 | 425 | 410 | 399 | 384 | 365 | 344 |
| 33 | 443 | 426 | 418 | 403 | 391 | 377 | 356 | 339 |
| 33.5 | 431 | 418 | 407 | 396 | 384 | 375 | 350 | 334 |
| 34 | 428 | 415 | 410 | 394 | 383 | 377 | 351 | 332 |
| 34.5 | 430 | 416 | 412 | 399 | 387 | 382 | 353 | 329 |
| 35 | 439 | 419 | 414 | 403 | 390 | 386 | 359 | 332 |
| 35.5 | 443 | 422 | 422 | 405 | 395 | 390 | 361 | 340 |
| 36 | 449 | 425 | 423 | 408 | 397 | 393 | 362 | 342 |
| 36.5 | 450 | 427 | 425 | 405 | 395 | 382 | 363 | 345 |
| 37 | 443 | 425 | 418 | 402 | 390 | 376 | 358 | 339 |
| 37.5 | 431 | 418 | 407 | 395 | 382 | 372 | 349 | 334 |
| 38 | 428 | 417 | 410 | 393 | 381 | 376 | 351 | 332 |

**Table B13** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 38.5 | 430 | 419 | 412 | 401 | 385 | 382 | 353 | 330 |
| 39 | 439 | 424 | 414 | 404 | 391 | 386 | 359 | 334 |
| 39.5 | 446 | 428 | 422 | 406 | 395 | 390 | 361 | 340 |
| 40 | 449 | 429 | 423 | 408 | 397 | 387 | 362 | 342 |
| 40.5 | 450 | 430 | 425 | 408 | 395 | 386 | 365 | 344 |

**Table B14** The system temperature with fixing the bed temperature at *480 $^oC$*

| Time (min) | Temperature ($^o$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 481 | 459 | 453 | 442 | 428 | 421 | 385 | 362 |
| 0.5 | 476 | 447 | 442 | 434 | 419 | 415 | 376 | 351 |
| 1 | 464 | 443 | 437 | 426 | 410 | 408 | 373 | 346 |
| 1.5 | 459 | 440 | 435 | 423 | 407 | 403 | 369 | 341 |
| 2 | 461 | 443 | 436 | 425 | 408 | 405 | 371 | 343 |
| 2.5 | 470 | 449 | 440 | 430 | 415 | 412 | 373 | 347 |
| 3 | 475 | 453 | 445 | 436 | 419 | 416 | 376 | 354 |
| 3.5 | 479 | 457 | 449 | 438 | 420 | 417 | 378 | 357 |
| 4 | 480 | 458 | 451 | 441 | 425 | 418 | 382 | 359 |
| 4.5 | 474 | 445 | 441 | 436 | 421 | 417 | 378 | 350 |
| 5 | 463 | 438 | 437 | 428 | 412 | 405 | 374 | 343 |
| 5.5 | 461 | 435 | 432 | 425 | 406 | 401 | 366 | 341 |
| 6 | 463 | 442 | 433 | 428 | 407 | 403 | 372 | 343 |
| 6.5 | 469 | 450 | 442 | 431 | 413 | 409 | 372 | 345 |
| 7 | 474 | 454 | 447 | 433 | 418 | 414 | 377 | 356 |
| 7.5 | 478 | 458 | 449 | 437 | 421 | 417 | 379 | 357 |
| 8 | 481 | 459 | 453 | 441 | 428 | 421 | 385 | 362 |
| 8.5 | 473 | 444 | 445 | 433 | 421 | 417 | 376 | 348 |
| 9 | 465 | 436 | 437 | 428 | 413 | 409 | 373 | 342 |
| 9.5 | 458 | 435 | 435 | 425 | 406 | 404 | 368 | 338 |
| 10 | 463 | 441 | 438 | 427 | 409 | 406 | 372 | 341 |
| 10.5 | 471 | 450 | 441 | 431 | 416 | 409 | 373 | 346 |
| 11 | 476 | 454 | 446 | 435 | 418 | 413 | 375 | 353 |
| 11.5 | 479 | 458 | 448 | 439 | 421 | 415 | 377 | 358 |
| 12 | 480 | 458 | 450 | 441 | 425 | 418 | 382 | 360 |
| 12.5 | 477 | 448 | 441 | 433 | 421 | 416 | 375 | 353 |

**Table B14** (Continued)

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 463 | 441 | 437 | 427 | 413 | 409 | 371 | 343 |
| 13.5 | 461 | 438 | 431 | 423 | 405 | 405 | 368 | 340 |
| 14 | 465 | 445 | 435 | 426 | 407 | 408 | 370 | 341 |
| 14.5 | 471 | 448 | 442 | 431 | 413 | 413 | 372 | 348 |
| 15 | 476 | 452 | 446 | 437 | 418 | 415 | 377 | 355 |
| 15.5 | 480 | 455 | 448 | 439 | 423 | 418 | 379 | 359 |
| 16 | 473 | 448 | 440 | 435 | 421 | 413 | 374 | 350 |
| 16.5 | 465 | 437 | 436 | 428 | 412 | 406 | 370 | 347 |
| 17 | 459 | 434 | 434 | 423 | 405 | 403 | 369 | 339 |
| 17.5 | 462 | 441 | 436 | 426 | 409 | 404 | 372 | 343 |
| 18 | 471 | 446 | 441 | 431 | 414 | 410 | 373 | 348 |
| 18.5 | 476 | 452 | 446 | 438 | 420 | 415 | 375 | 353 |
| 19 | 481 | 455 | 449 | 439 | 424 | 416 | 378 | 356 |
| 19.5 | 478 | 445 | 443 | 435 | 417 | 417 | 375 | 350 |
| 20 | 463 | 437 | 436 | 427 | 412 | 411 | 369 | 347 |
| 20.5 | 458 | 433 | 433 | 421 | 404 | 401 | 361 | 340 |
| 21 | 462 | 442 | 435 | 426 | 409 | 406 | 366 | 341 |
| 21.5 | 469 | 448 | 441 | 431 | 417 | 409 | 372 | 348 |
| 22 | 473 | 455 | 446 | 437 | 419 | 413 | 377 | 353 |
| 22.5 | 475 | 458 | 448 | 439 | 423 | 415 | 379 | 356 |
| 23 | 477 | 459 | 451 | 441 | 425 | 418 | 383 | 359 |
| 23.5 | 478 | 461 | 453 | 442 | 428 | 421 | 385 | 360 |
| 24 | 473 | 448 | 441 | 433 | 416 | 416 | 378 | 352 |
| 24.5 | 465 | 437 | 436 | 423 | 411 | 409 | 367 | 347 |
| 25 | 458 | 434 | 430 | 420 | 402 | 402 | 361 | 339 |

**Table B14** (Continued)

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25.5 | 462 | 444 | 435 | 426 | 406 | 408 | 366 | 341 |
| 26 | 471 | 448 | 441 | 431 | 413 | 414 | 370 | 346 |
| 26.5 | 476 | 454 | 446 | 437 | 416 | 417 | 377 | 353 |
| 27 | 478 | 458 | 447 | 439 | 419 | 419 | 375 | 358 |
| 27.5 | 479 | 459 | 449 | 441 | 423 | 420 | 380 | 359 |
| 28 | 480 | 460 | 452 | 442 | 425 | 421 | 383 | 361 |
| 28.5 | 477 | 445 | 441 | 435 | 418 | 414 | 377 | 353 |
| 29 | 465 | 441 | 434 | 427 | 411 | 407 | 366 | 347 |
| 29.5 | 458 | 436 | 431 | 419 | 402 | 399 | 362 | 341 |
| 30 | 460 | 442 | 435 | 424 | 409 | 406 | 366 | 345 |
| 30.5 | 471 | 448 | 441 | 431 | 414 | 412 | 373 | 349 |
| 31 | 476 | 452 | 446 | 437 | 418 | 415 | 377 | 356 |
| 31.5 | 479 | 458 | 449 | 439 | 422 | 418 | 379 | 358 |
| 32 | 480 | 459 | 451 | 441 | 425 | 419 | 383 | 359 |
| 32.5 | 473 | 448 | 443 | 436 | 413 | 416 | 375 | 348 |
| 33 | 465 | 438 | 436 | 425 | 413 | 409 | 368 | 345 |
| 33.5 | 459 | 434 | 428 | 417 | 405 | 397 | 361 | 339 |
| 34 | 462 | 444 | 435 | 424 | 409 | 406 | 364 | 341 |
| 34.5 | 470 | 448 | 441 | 431 | 413 | 411 | 372 | 346 |
| 35 | 476 | 454 | 446 | 435 | 417 | 416 | 375 | 355 |
| 35.5 | 478 | 458 | 448 | 433 | 422 | 415 | 374 | 359 |
| 36 | 481 | 460 | 453 | 442 | 425 | 421 | 381 | 362 |
| 36.5 | 475 | 445 | 443 | 435 | 418 | 416 | 377 | 355 |
| 37 | 465 | 437 | 434 | 427 | 411 | 409 | 366 | 348 |
| 37.5 | 458 | 436 | 427 | 419 | 405 | 401 | 361 | 338 |
| 38 | 460 | 445 | 436 | 423 | 409 | 406 | 366 | 341 |

**Table B14** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 38.5 | 471 | 447 | 442 | 431 | 414 | 411 | 372 | 346 |
| 39 | 476 | 451 | 447 | 437 | 420 | 415 | 376 | 355 |
| 39.5 | 478 | 454 | 449 | 439 | 422 | 416 | 377 | 358 |
| 40 | 480 | 459 | 450 | 441 | 424 | 418 | 381 | 359 |
| 40.5 | 480 | 459 | 450 | 441 | 424 | 418 | 381 | 359 |

**Table B15** The system temperature with air *25 l/min* for partial oxidation

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 450 | 433 | 426 | 411 | 400 | 392 | 364 | 345 |
| 0.5 | 446 | 422 | 420 | 405 | 391 | 378 | 355 | 338 |
| 1 | 432 | 417 | 408 | 397 | 385 | 376 | 351 | 335 |
| 1.5 | 427 | 414 | 412 | 394 | 394 | 378 | 350 | 331 |
| 2 | 431 | 413 | 413 | 397 | 386 | 383 | 353 | 333 |
| 2.5 | 440 | 415 | 414 | 404 | 391 | 386 | 358 | 335 |
| 3 | 447 | 420 | 423 | 403 | 396 | 391 | 362 | 341 |
| 3.5 | 451 | 425 | 423 | 407 | 397 | 393 | 363 | 345 |
| 4 | 449 | 428 | 426 | 409 | 400 | 394 | 366 | 345 |
| 4.5 | 452 | 432 | 427 | 412 | 401 | 386 | 337 | 346 |
| 5 | 441 | 425 | 419 | 405 | 392 | 379 | 359 | 339 |
| 5.5 | 431 | 419 | 408 | 398 | 384 | 377 | 356 | 335 |
| 6 | 427 | 417 | 411 | 394 | 381 | 374 | 351 | 331 |
| 6.5 | 431 | 414 | 411 | 396 | 385 | 382 | 350 | 330 |
| 7 | 443 | 418 | 416 | 399 | 392 | 388 | 358 | 333 |
| 7.5 | 445 | 425 | 423 | 403 | 395 | 390 | 361 | 338 |
| 8 | 451 | 430 | 425 | 405 | 397 | 391 | 364 | 341 |
| 8.5 | 449 | 431 | 426 | 410 | 400 | 383 | 366 | 343 |
| 9 | 442 | 422 | 419 | 406 | 392 | 376 | 357 | 338 |
| 9.5 | 431 | 418 | 408 | 394 | 384 | 374 | 349 | 335 |
| 10 | 427 | 411 | 411 | 395 | 382 | 376 | 351 | 331 |
| 10.5 | 431 | 414 | 413 | 398 | 388 | 381 | 352 | 331 |
| 11 | 439 | 420 | 414 | 402 | 391 | 386 | 360 | 330 |
| 11.5 | 447 | 428 | 423 | 406 | 394 | 390 | 362 | 338 |
| 12 | 448 | 430 | 425 | 409 | 397 | 392 | 363 | 340 |
| 12.5 | 451 | 431 | 426 | 410 | 401 | 385 | 367 | 344 |

**Table B15** (Continued)

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 444 | 425 | 420 | 406 | 392 | 379 | 359 | 339 |
| 13.5 | 434 | 417 | 407 | 398 | 385 | 376 | 354 | 335 |
| 14 | 428 | 414 | 405 | 392 | 381 | 379 | 351 | 331 |
| 14.5 | 430 | 415 | 415 | 396 | 384 | 385 | 356 | 328 |
| 15 | 439 | 420 | 416 | 401 | 392 | 386 | 361 | 333 |
| 15.5 | 446 | 427 | 425 | 405 | 394 | 390 | 362 | 335 |
| 16 | 450 | 431 | 426 | 408 | 396 | 393 | 364 | 339 |
| 16.5 | 451 | 433 | 425 | 411 | 398 | 384 | 365 | 342 |
| 17 | 446 | 425 | 418 | 404 | 400 | 376 | 361 | 340 |
| 17.5 | 433 | 416 | 408 | 398 | 385 | 377 | 354 | 335 |
| 18 | 431 | 413 | 411 | 395 | 384 | 378 | 351 | 331 |
| 18.5 | 432 | 415 | 412 | 400 | 386 | 383 | 353 | 332 |
| 19 | 442 | 418 | 415 | 404 | 391 | 386 | 358 | 336 |
| 19.5 | 444 | 423 | 422 | 406 | 396 | 391 | 361 | 341 |
| 20 | 451 | 427 | 424 | 409 | 398 | 390 | 363 | 343 |
| 20.5 | 452 | 429 | 425 | 408 | 395 | 385 | 365 | 344 |
| 21 | 445 | 427 | 419 | 401 | 392 | 379 | 360 | 341 |
| 21.5 | 432 | 421 | 408 | 394 | 385 | 975 | 352 | 336 |
| 22 | 430 | 418 | 411 | 391 | 380 | 378 | 351 | 331 |
| 22.5 | 431 | 419 | 412 | 394 | 386 | 381 | 356 | 334 |
| 23 | 440 | 421 | 414 | 401 | 390 | 386 | 359 | 338 |
| 23.5 | 444 | 426 | 423 | 406 | 396 | 390 | 360 | 342 |
| 24 | 450 | 430 | 424 | 409 | 396 | 391 | 361 | 345 |
| 24.5 | 451 | 430 | 426 | 411 | 400 | 385 | 364 | 343 |
| 25 | 445 | 424 | 419 | 402 | 392 | 378 | 356 | 340 |

**Table B15** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25.5 | 432 | 420 | 408 | 394 | 384 | 376 | 351 | 335 |
| 26 | 429 | 418 | 411 | 392 | 383 | 378 | 352 | 331 |
| 26.5 | 431 | 420 | 412 | 396 | 387 | 383 | 354 | 330 |
| 27 | 441 | 423 | 413 | 400 | 391 | 387 | 360 | 331 |
| 27.5 | 446 | 428 | 423 | 404 | 395 | 391 | 362 | 339 |
| 28 | 449 | 429 | 424 | 406 | 397 | 392 | 363 | 341 |
| 28.5 | 451 | 431 | 426 | 407 | 396 | 382 | 364 | 343 |
| 29 | 445 | 427 | 419 | 403 | 391 | 376 | 360 | 338 |
| 29.5 | 432 | 422 | 407 | 394 | 382 | 373 | 350 | 333 |
| 30 | 430 | 419 | 411 | 391 | 383 | 375 | 352 | 331 |
| 30.5 | 431 | 423 | 412 | 399 | 386 | 381 | 353 | 330 |
| 31 | 440 | 428 | 415 | 403 | 392 | 385 | 359 | 331 |
| 31.5 | 446 | 430 | 423 | 405 | 396 | 391 | 362 | 338 |
| 32 | 449 | 431 | 424 | 407 | 398 | 393 | 363 | 342 |
| 32.5 | 451 | 432 | 426 | 408 | 400 | 385 | 365 | 343 |
| 33 | 444 | 427 | 418 | 402 | 392 | 377 | 357 | 338 |
| 33.5 | 432 | 419 | 408 | 395 | 385 | 376 | 351 | 333 |
| 34 | 430 | 416 | 411 | 393 | 384 | 375 | 349 | 331 |
| 34.5 | 431 | 417 | 412 | 398 | 388 | 381 | 353 | 328 |
| 35 | 440 | 419 | 415 | 403 | 391 | 385 | 360 | 331 |
| 35.5 | 443 | 423 | 422 | 406 | 396 | 390 | 362 | 339 |
| 36 | 449 | 425 | 423 | 409 | 398 | 393 | 363 | 341 |
| 36.5 | 451 | 428 | 426 | 406 | 396 | 381 | 364 | 344 |
| 37 | 445 | 426 | 418 | 403 | 391 | 374 | 360 | 338 |
| 37.5 | 432 | 419 | 407 | 396 | 383 | 371 | 349 | 333 |
| 38 | 430 | 418 | 411 | 394 | 382 | 377 | 352 | 331 |

**Table B15** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 38.5 | 431 | 420 | 413 | 402 | 384 | 381 | 353 | 330 |
| 39 | 440 | 425 | 414 | 405 | 392 | 389 | 358 | 333 |
| 39.5 | 447 | 429 | 423 | 407 | 396 | 392 | 362 | 339 |
| 40 | 449 | 430 | 424 | 409 | 398 | 391 | 363 | 341 |
| 40.5 | 450 | 431 | 426 | 410 | 394 | 387 | 365 | 343 |

**Table B16** The system temperature with air *50 l/min* for partial oxidation

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 451 | 432 | 426 | 411 | 400 | 390 | 366 | 346 |
| 0.5 | 446 | 422 | 419 | 405 | 390 | 376 | 357 | 340 |
| 1 | 435 | 417 | 410 | 397 | 383 | 374 | 350 | 335 |
| 1.5 | 430 | 415 | 413 | 395 | 384 | 376 | 352 | 333 |
| 2 | 432 | 413 | 414 | 399 | 389 | 381 | 354 | 334 |
| 2.5 | 439 | 416 | 415 | 403 | 391 | 387 | 359 | 335 |
| 3 | 447 | 421 | 423 | 406 | 396 | 391 | 362 | 341 |
| 3.5 | 449 | 428 | 425 | 409 | 398 | 393 | 363 | 343 |
| 4 | 450 | 431 | 426 | 411 | 399 | 394 | 364 | 346 |
| 4.5 | 452 | 433 | 428 | 413 | 401 | 384 | 367 | 347 |
| 5 | 443 | 425 | 420 | 405 | 391 | 379 | 358 | 339 |
| 5.5 | 435 | 419 | 411 | 398 | 384 | 375 | 352 | 335 |
| 6 | 430 | 417 | 413 | 396 | 383 | 376 | 353 | 331 |
| 6.5 | 431 | 415 | 411 | 397 | 387 | 374 | 354 | 332 |
| 7 | 439 | 419 | 417 | 406 | 392 | 386 | 361 | 335 |
| 7.5 | 442 | 427 | 425 | 408 | 395 | 391 | 363 | 340 |
| 8 | 450 | 431 | 427 | 410 | 397 | 393 | 364 | 345 |
| 8.5 | 447 | 433 | 428 | 411 | 400 | 385 | 367 | 346 |
| 9 | 442 | 425 | 421 | 405 | 392 | 376 | 357 | 340 |
| 9.5 | 438 | 419 | 408 | 397 | 385 | 376 | 349 | 336 |
| 10 | 432 | 415 | 411 | 395 | 384 | 378 | 352 | 333 |
| 10.5 | 431 | 419 | 413 | 400 | 388 | 383 | 354 | 331 |
| 11 | 438 | 423 | 415 | 404 | 390 | 376 | 358 | 334 |
| 11.5 | 444 | 429 | 423 | 406 | 394 | 391 | 362 | 339 |
| 12 | 448 | 430 | 424 | 409 | 396 | 374 | 363 | 341 |
| 12.5 | 449 | 432 | 427 | 410 | 401 | 384 | 365 | 344 |

**Table B16** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 445 | 428 | 421 | 406 | 391 | 380 | 358 | 339 |
| 13.5 | 436 | 419 | 411 | 398 | 382 | 376 | 352 | 334 |
| 14 | 431 | 418 | 412 | 394 | 383 | 380 | 355 | 330 |
| 14.5 | 432 | 417 | 414 | 399 | 389 | 385 | 357 | 331 |
| 15 | 438 | 423 | 415 | 405 | 392 | 389 | 361 | 332 |
| 15.5 | 446 | 429 | 424 | 407 | 395 | 392 | 363 | 338 |
| 16 | 449 | 431 | 425 | 410 | 397 | 391 | 364 | 340 |
| 16.5 | 451 | 433 | 426 | 411 | 400 | 385 | 366 | 343 |
| 17 | 446 | 427 | 417 | 404 | 392 | 376 | 357 | 340 |
| 17.5 | 435 | 420 | 408 | 395 | 385 | 374 | 351 | 335 |
| 18 | 433 | 417 | 411 | 396 | 384 | 378 | 353 | 333 |
| 18.5 | 431 | 416 | 413 | 400 | 388 | 383 | 351 | 334 |
| 19 | 439 | 423 | 415 | 404 | 391 | 385 | 357 | 336 |
| 19.5 | 445 | 427 | 423 | 406 | 396 | 391 | 360 | 340 |
| 20 | 448 | 430 | 424 | 409 | 397 | 390 | 363 | 343 |
| 20.5 | 451 | 432 | 426 | 408 | 395 | 385 | 364 | 346 |
| 21 | 445 | 428 | 419 | 400 | 392 | 381 | 359 | 341 |
| 21.5 | 438 | 425 | 408 | 394 | 385 | 376 | 355 | 336 |
| 22 | 432 | 420 | 411 | 391 | 382 | 377 | 353 | 333 |
| 22.5 | 436 | 419 | 413 | 394 | 388 | 380 | 356 | 334 |
| 23 | 440 | 423 | 415 | 399 | 391 | 386 | 361 | 338 |
| 23.5 | 446 | 429 | 423 | 406 | 396 | 391 | 362 | 342 |
| 24 | 450 | 431 | 425 | 409 | 396 | 392 | 363 | 344 |
| 24.5 | 452 | 433 | 426 | 411 | 398 | 383 | 364 | 343 |
| 25 | 446 | 425 | 417 | 404 | 392 | 377 | 354 | 340 |

**Table B16** (Continued)

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25.5 | 435 | 423 | 408 | 395 | 385 | 374 | 351 | 334 |
| 26 | 432 | 421 | 411 | 395 | 384 | 376 | 350 | 331 |
| 26.5 | 435 | 420 | 413 | 400 | 388 | 383 | 352 | 330 |
| 27 | 438 | 427 | 415 | 404 | 391 | 387 | 359 | 331 |
| 27.5 | 448 | 429 | 423 | 406 | 396 | 391 | 360 | 341 |
| 28 | 450 | 431 | 425 | 409 | 398 | 394 | 361 | 343 |
| 28.5 | 453 | 432 | 426 | 406 | 396 | 383 | 364 | 345 |
| 29 | 445 | 427 | 419 | 403 | 391 | 377 | 357 | 341 |
| 29.5 | 436 | 423 | 409 | 396 | 383 | 373 | 350 | 335 |
| 30 | 432 | 421 | 411 | 394 | 381 | 375 | 352 | 331 |
| 30.5 | 438 | 425 | 413 | 402 | 386 | 383 | 355 | 330 |
| 31 | 443 | 428 | 415 | 405 | 392 | 387 | 360 | 331 |
| 31.5 | 448 | 431 | 423 | 407 | 396 | 391 | 362 | 341 |
| 32 | 449 | 433 | 425 | 409 | 398 | 393 | 363 | 344 |
| 32.5 | 452 | 431 | 426 | 411 | 400 | 385 | 366 | 345 |
| 33 | 446 | 427 | 419 | 404 | 392 | 376 | 358 | 340 |
| 33.5 | 435 | 418 | 409 | 397 | 385 | 376 | 352 | 335 |
| 34 | 432 | 416 | 411 | 395 | 384 | 376 | 350 | 331 |
| 34.5 | 436 | 415 | 414 | 400 | 388 | 383 | 354 | 330 |
| 35 | 440 | 421 | 415 | 404 | 391 | 387 | 358 | 331 |
| 35.5 | 445 | 425 | 423 | 406 | 396 | 391 | 362 | 341 |
| 36 | 450 | 427 | 424 | 408 | 398 | 394 | 362 | 343 |
| 36.5 | 452 | 429 | 427 | 405 | 397 | 383 | 364 | 344 |
| 37 | 445 | 431 | 420 | 402 | 393 | 377 | 360 | 340 |
| 37.5 | 435 | 425 | 408 | 396 | 383 | 373 | 355 | 335 |
| 38 | 430 | 419 | 412 | 394 | 380 | 377 | 350 | 331 |

**Table B16** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 38.5 | 436 | 425 | 414 | 399 | 384 | 383 | 352 | 329 |
| 39 | 441 | 429 | 415 | 403 | 390 | 387 | 358 | 335 |
| 39.5 | 448 | 430 | 423 | 405 | 394 | 391 | 362 | 341 |
| 40 | 452 | 431 | 425 | 409 | 398 | 388 | 363 | 343 |
| 40.5 | 453 | 433 | 426 | 408 | 396 | 387 | 365 | 345 |

**Table B17** The system temperature with air *100 l/min* for partial oxidation

| Time (min) | Temperature ($^{o}$C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 0 | 451 | 433 | 424 | 410 | 400 | 392 | 366 | 344 |
| 0.5 | 444 | 423 | 419 | 405 | 393 | 380 | 356 | 340 |
| 1 | 432 | 420 | 410 | 395 | 384 | 376 | 351 | 335 |
| 1.5 | 427 | 417 | 412 | 393 | 382 | 378 | 352 | 333 |
| 2 | 430 | 416 | 414 | 400 | 386 | 381 | 354 | 333 |
| 2.5 | 440 | 417 | 416 | 402 | 390 | 387 | 360 | 334 |
| 3 | 449 | 421 | 424 | 406 | 394 | 390 | 362 | 341 |
| 3.5 | 451 | 426 | 425 | 408 | 396 | 393 | 363 | 343 |
| 4 | 450 | 431 | 427 | 410 | 398 | 394 | 364 | 346 |
| 4.5 | 449 | 433 | 429 | 411 | 401 | 386 | 367 | 347 |
| 5 | 445 | 425 | 425 | 405 | 391 | 379 | 358 | 337 |
| 5.5 | 434 | 421 | 416 | 396 | 384 | 377 | 352 | 331 |
| 6 | 430 | 418 | 413 | 394 | 383 | 376 | 353 | 331 |
| 6.5 | 431 | 416 | 412 | 397 | 386 | 377 | 353 | 332 |
| 7 | 442 | 419 | 418 | 404 | 392 | 388 | 361 | 334 |
| 7.5 | 445 | 428 | 425 | 405 | 395 | 392 | 362 | 338 |
| 8 | 450 | 431 | 426 | 408 | 397 | 393 | 364 | 344 |
| 8.5 | 449 | 433 | 423 | 410 | 398 | 385 | 366 | 343 |
| 9 | 442 | 423 | 419 | 403 | 392 | 378 | 357 | 338 |
| 9.5 | 433 | 420 | 414 | 396 | 385 | 376 | 351 | 335 |
| 10 | 427 | 418 | 412 | 385 | 384 | 378 | 352 | 331 |
| 10.5 | 431 | 423 | 411 | 399 | 386 | 383 | 354 | 329 |
| 11 | 439 | 427 | 416 | 402 | 391 | 387 | 360 | 331 |
| 11.5 | 447 | 431 | 425 | 406 | 386 | 390 | 362 | 339 |
| 12 | 448 | 433 | 426 | 409 | 398 | 394 | 363 | 343 |
| 12.5 | 451 | 435 | 427 | 408 | 401 | 386 | 366 | 346 |

**Table B17** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 13 | 443 | 427 | 423 | 405 | 391 | 379 | 358 | 347 |
| 13.5 | 434 | 423 | 413 | 396 | 384 | 378 | 351 | 332 |
| 14 | 427 | 417 | 410 | 392 | 383 | 378 | 356 | 331 |
| 14.5 | 430 | 423 | 415 | 397 | 389 | 385 | 357 | 329 |
| 15 | 439 | 428 | 417 | 405 | 392 | 386 | 361 | 330 |
| 15.5 | 446 | 432 | 425 | 407 | 395 | 392 | 361 | 337 |
| 16 | 449 | 434 | 426 | 410 | 397 | 390 | 362 | 340 |
| 16.5 | 451 | 435 | 423 | 411 | 400 | 385 | 364 | 341 |
| 17 | 445 | 427 | 419 | 405 | 390 | 376 | 357 | 338 |
| 17.5 | 432 | 421 | 413 | 397 | 385 | 374 | 352 | 332 |
| 18 | 430 | 418 | 412 | 395 | 384 | 376 | 352 | 331 |
| 18.5 | 431 | 425 | 415 | 400 | 386 | 383 | 354 | 331 |
| 19 | 440 | 429 | 416 | 405 | 391 | 385 | 360 | 333 |
| 19.5 | 445 | 431 | 420 | 406 | 396 | 391 | 362 | 339 |
| 20 | 451 | 433 | 424 | 409 | 398 | 388 | 363 | 341 |
| 20.5 | 452 | 434 | 426 | 408 | 395 | 383 | 364 | 343 |
| 21 | 445 | 429 | 420 | 409 | 392 | 380 | 359 | 339 |
| 21.5 | 432 | 425 | 412 | 394 | 384 | 374 | 355 | 334 |
| 22 | 430 | 419 | 411 | 391 | 382 | 376 | 353 | 331 |
| 22.5 | 431 | 425 | 414 | 394 | 388 | 381 | 356 | 332 |
| 23 | 440 | 427 | 417 | 400 | 391 | 387 | 361 | 338 |
| 23.5 | 446 | 430 | 424 | 406 | 386 | 390 | 362 | 342 |
| 24 | 449 | 432 | 425 | 409 | 398 | 391 | 363 | 344 |
| 24.5 | 451 | 433 | 426 | 411 | 400 | 385 | 365 | 345 |
| 25 | 444 | 427 | 423 | 404 | 392 | 376 | 357 | 340 |

**Table B17** (Continued)

| Time (min) | Temperature ($^oC$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 25.5 | 432 | 425 | 412 | 397 | 385 | 376 | 351 | 335 |
| 26 | 430 | 421 | 413 | 395 | 382 | 377 | 352 | 333 |
| 26.5 | 432 | 425 | 415 | 400 | 386 | 383 | 354 | 331 |
| 27 | 440 | 428 | 416 | 404 | 391 | 385 | 359 | 333 |
| 27.5 | 447 | 432 | 423 | 406 | 394 | 391 | 360 | 339 |
| 28 | 449 | 433 | 424 | 409 | 398 | 392 | 363 | 343 |
| 28.5 | 451 | 435 | 426 | 408 | 396 | 381 | 364 | 345 |
| 29 | 444 | 430 | 421 | 404 | 391 | 375 | 359 | 340 |
| 29.5 | 432 | 427 | 411 | 396 | 383 | 371 | 350 | 335 |
| 30 | 430 | 424 | 413 | 394 | 382 | 375 | 352 | 331 |
| 30.5 | 431 | 428 | 415 | 402 | 386 | 381 | 354 | 330 |
| 31 | 441 | 430 | 417 | 405 | 392 | 387 | 360 | 332 |
| 31.5 | 446 | 431 | 423 | 407 | 396 | 391 | 362 | 339 |
| 32 | 449 | 433 | 425 | 409 | 398 | 393 | 363 | 342 |
| 32.5 | 451 | 434 | 426 | 411 | 400 | 385 | 365 | 345 |
| 33 | 445 | 429 | 421 | 404 | 392 | 376 | 357 | 340 |
| 33.5 | 432 | 426 | 413 | 395 | 385 | 374 | 351 | 335 |
| 34 | 429 | 423 | 415 | 395 | 384 | 376 | 352 | 331 |
| 34.5 | 431 | 427 | 416 | 400 | 386 | 383 | 354 | 330 |
| 35 | 442 | 430 | 419 | 404 | 391 | 387 | 357 | 333 |
| 35.5 | 445 | 432 | 425 | 406 | 396 | 391 | 362 | 340 |
| 36 | 451 | 433 | 426 | 409 | 396 | 394 | 363 | 341 |
| 36.5 | 451 | 434 | 425 | 406 | 396 | 383 | 365 | 343 |
| 37 | 445 | 432 | 423 | 403 | 391 | 377 | 360 | 340 |
| 37.5 | 432 | 428 | 413 | 396 | 383 | 372 | 350 | 335 |
| 38 | 429 | 425 | 412 | 394 | 382 | 375 | 352 | 333 |

**Table B17** (Continued)

| Time (min) | Temperature (°C) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Distance from distributor (cm) | | | | | | | |
| | -3.0 | 25.4 | 50.8 | 76.2 | 101.6 | 127.0 | 152.4 | 177.8 |
| 38.5 | 432 | 423 | 415 | 402 | 386 | 381 | 354 | 331 |
| 39 | 441 | 426 | 417 | 405 | 392 | 386 | 360 | 335 |
| 39.5 | 447 | 429 | 422 | 407 | 396 | 391 | 362 | 341 |
| 40 | 450 | 430 | 424 | 409 | 398 | 386 | 363 | 341 |
| 40.5 | 451 | 431 | 425 | 409 | 396 | 387 | 365 | 341 |

# Appendix C

The liquid product distribution in condenser

**Table C1** Liquid product distribution in semi-batch reactor.

| Condition | Componenet | Weight (g) | % by weight of liquid |
|---|---|---|---|
| Pyrolysis | Liquid | 31.62 | 100% |
| | - $C_5$-$C_{12}$ | 3.28 | 10.36% |
| | - $C_{13}$-$C_{17}$ | 26.59 | 84.10% |
| | - $>C_{18}$ | 1.75 | 5.54% |
| Pyrolysis + | Liquid | 29.51 | 100% |
| Partial oxidation ( 5.22 ml/s ) | - $C_5$-$C_{12}$ | 3.86 | 13.08% |
| | - $C_{13}$-$C_{17}$ | 13.96 | 47.32% |
| | - $>C_{18}$ | 11.69 | 39.60% |
| Pyrolysis + | Liquid | 29.44 | 100% |
| Partial oxidation ( 8.51 ml/s ) | - $C_5$-$C_{12}$ | 4.50 | 15.29% |
| | - $C_{13}$-$C_{17}$ | 13.24 | 44.97% |
| | - $>C_{18}$ | 11.70 | 39.74% |
| Pyrolysis + | Liquid | 25.82 | 100% |
| Partial oxidation ( 11.78 ml/s ) | - $C_5$-$C_{12}$ | 3.51 | 13.59% |
| | - $C_{13}$-$C_{17}$ | 12.13 | 46.98% |
| | - $>C_{18}$ | 10.18 | 29.43% |
| Pyrolysis + | Liquid | 28.93 | 100% |
| Partial oxidation ( 8.51 ml/s ) + | - $C_5$-$C_{12}$ | 7.20 | 25.15% |
| Recycle ( 5.85 ml/min ) | - $C_{13}$-$C_{17}$ | 14.18 | 51.80% |
| | - $>C_{18}$ | 6.32 | 23.05% |
| Pyrolysis + | Liquid | 28.16 | 100% |
| Partial oxidation ( 8.51 ml/s ) + | - $C_5$-$C_{12}$ | 7.35 | 26.12% |
| Recycle ( 8.27 ml/min ) | - $C_{13}$-$C_{17}$ | 16.46 | 58.45% |
| | - $>C_{18}$ | 4.35 | 15.43% |
| Pyrolysis + | Liquid | 27.32 | 100% |
| Partial oxidation ( 8.51 ml/s ) + | - $C_5$-$C_{12}$ | 7.45 | 27.27% |
| Recycle ( 10.27 ml/min ) | - $C_{13}$-$C_{17}$ | 18.09 | 66.22% |
| | - $>C_{18}$ | 1.78 | 6.51% |

**Table C2** Liquid product distribution at bed temperature of *450* and *480 °C*

| Condition | Condenser 1 | | | | Condenser 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Gas (g) | Liquid (g) | | | Gas (g) | Liquid (g) | | |
| 450 °C | 286.1 | 142.5 | C5-C12 | 85.5 | 47.7 | 23.8 | C5-C12 | 14.3 |
| | | | C11-C17 | 49.5 | | | C11-C17 | 8.3 |
| | | | > C18 | 7.5 | | | > C18 | 1.3 |
| 480 °C | 331.4 | 97.2 | C5-C12 | 51.9 | 55.3 | 16.2 | C5-C12 | 8.7 |
| | | | C11-C17 | 39.3 | | | C11-C17 | 6.6 |
| | | | > C18 | 6.0 | | | > C18 | 1.0 |

**Table C3** Liquid product distribution at various secondary air feed rates for partial oxidation.

| Condition | Condenser 1 | | | | Condenser 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Gas (g) | Liquid (g) | | | Gas (g) | Liquid (g) | | |
| Without partial oxidation | 286.1 | 142.5 | C5-C12 | 427.5 | 47.7 | 23.8 | C5-C12 | 14.3 |
| | | | C11-C17 | 247.5 | | | C11-C17 | 8.3 |
| | | | > C18 | 37.5 | | | > C18 | 1.3 |
| 25 l/min | 298.7 | 129.9 | C5-C12 | 376.5 | 49.8 | 21.7 | C5-C12 | 12.6 |
| | | | C11-C17 | 237.0 | | | C11-C17 | 7.9 |
| | | | > C18 | 36.0 | | | > C18 | 1.2 |
| 50 l/min | 307.9 | 122.4 | C5-C12 | 348.0 | 51.3 | 20.4 | C5-C12 | 11.6 |
| | | | C11-C17 | 229.5 | | | C11-C17 | 7.7 |
| | | | > C18 | 34.5 | | | > C18 | 1.2 |
| 100 l/min | 312.5 | 116.1 | C5-C12 | 324.0 | 52.1 | 19.4 | C5-C12 | 10.8 |
| | | | C11-C17 | 222.0 | | | C11-C17 | 7.4 |
| | | | > C18 | 34.5 | | | > C18 | 1.2 |

**Table C4** Liquid product distribution in case with and without partial oxidation for energy saving

| Condition | Condenser 1 | | | | Condenser 2 | | | |
|---|---|---|---|---|---|---|---|---|
| | Gas (g) | Liquid (g) | | | Gas (g) | Liquid (g) | | |
| With partial oxidation | 115.5 | 312.9 | C5-C12 | 63.9 | 52.2 | 19.3 | C5-C12 | 10.7 |
| | | | C11-C17 | 45.6 | | | C11-C17 | 7.6 |
| | | | > C18 | 6 | | | > C18 | 1.0 |
| Without partial oxidation | 116.1 | 312.6 | C5-C12 | 64.8 | 52.1 | 19.4 | C5-C12 | 10.8 |
| | | | C11-C17 | 44.4 | | | C11-C17 | 7.4 |
| | | | > C18 | 6.9 | | | > C18 | 1.2 |

# Appendix D

## The calculation of the production rate of liquid product

**Appendix D1** The calculation of production rate of liquid and gas product

Sample; Section 2.4 at bed temperature of *450 $^{o}$C*

In the effect of bed temperature (section 2.4), the LPG feed rates of *7.31 l/min* with air feed rate of *300 l/min* was used to keep the system temperature at 3 cm below distributor to be *450 $^{o}$C*. In this condition, *50 g* of PP was fed to the reactor for 10 times. The operating time of plastic pyrolysis for *10 cycles* was *40.5 min*.

- Total plastic feeding

= (Amount of plastic feeding) × (Number of time)
= 50 g × 10
= 500 g

- Production rate of plastic gas

= (Amount of total plastic) / (operating time)
= 500 g / 40.5 min
= 12.36 g/min

Plastic gas of *12.36 g/min* was controlled by valve to flow into condenser 1 and condenser 2 at the ratio of *6:1* which is *10.59 and 1.77 g/min*, respectively.

The total liquid product in condenser 1 and condenser 2 was *142.25 and 23.75 g* which was *(142.25/40.5) = 3.51 g/min* for condenser 1 and *(23.75/40.5) = 0.59 g/min* for condenser 2, respectively

- Production rate of gas product

= (Production rate of plastic gas) – (Production rate of liquid)
Condenser 1 = 10.59-3.51 = 7.08 g/min
Condenser 2 = 1.77-0.59 = 1.18 g/min

# Appendix E

The calculation of production rate of gas product

Sample; Section 2.4 at bed temperature of *480 $^{o}$C.*

In this condition, the gas product consists of methane ($CH_4$), carbon dioxide ($CO_2$) and carbon monoxide (CO). The peak area of each gas components were reported in following table.

**Table E1** The peak area of each gas components

| Gas distribution at 450 $^{o}$C | Peak area | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | Avg |
| - Methane | 88,214.00 | 87,976.00 | 81,989.00 | 86,059.67 |
| - Carbon monoxide from partial oxidation | 2,042.00 | 2,144.00 | 2,198.00 | 2,128.00 |
| - Carbon dioxide leaving | 120,134.00 | 118,535.00 | 119,211.00 | 119,293.33 |
| - Carbon dioxide from burner | 90,134.00 | 91,219.00 | 91,352.00 | 90,901.67 |

**Table E2** The standard equation of each gas components

| Gas | Standard equation | $R^2$ | Remark |
|---|---|---|---|
| Hydrogen ($H_2$) | Y= 12,006X-621.15 | 0.9972 | $X = 10^{-6}$ |
| Carbon monoxide (CO) | Y= 124,228X-1,432.9 | 0.9949 | $X = 10^{-6}$ |
| Carbon dioxide ($CO_2$) | Y = 30,744X + 147.74 | 0.9985 | $X = 10^{-6}$ |
| Oxygen ($O_2$) | Y = 90,998X + 24344 | 0.9981 | $X = 10^{-5}$ |
| Methane ($CH_4$) | Y= 12,006X-621.15 | 0.9972 | $X = 10^{-6}$ |
| Propylene ($C_3H_6$) | Y = 200,000X + 563,955 | 0.9976 | $X = 10^{-5}$ |
| Propane ($C_3H_8$) | Y = 5,3836X – 6,941.9 | 0.9936 | $X = 10^{-6}$ |

*Y is peak area and X is mol of gas*

The standard equation as shown in table appendix E2 was used to convert peak area of each gas components to be mol. The volumetric of gas sample analyzed by GC was *2 ml*. Therefore, the mol of each gas components obtained was the mol in *2 ml* of gas sample.

For example; Methane

Average peak area of methane

$$= 86{,}059.67 \qquad \text{(from Appendix E1)}$$

The standard equation of methane

$$Y = 12{,}006X - 621.15$$

$$86059.67 = 12{,}006X - 621.15 \qquad {}^{*}X = 10^{-6}$$

$$X = 7.22$$

$$X = 7.22 \times 10^{-6} \text{ mol/ 2 ml of gas sample}$$

The others gas components were calculated following procedure mentioned before. The result of converting peak area to be mol was reported in Appendix E3

**Table E3** The mol of each gas components

| Gas distribution at 480 °C | Average peak area | mol x $10^{-6}$ |
|---|---|---|
| - Methane | 8,6059.67 | 7.22 |
| - Carbon monoxide from partial oxidation | 2,128.00 | 0.29 |
| - Carbon dioxide leaving | 11,929.33 | 3.88 |
| - Carbon dioxide from burner | 95,568.33 | 3.10 |

The mol of each gas components was converted to be weight per 1 ml of gas sample by using molecular weigh

For example; Methane

Mol of methane in *2 ml* of gas sample = $7.22 \times 10^{-6}$ mol

= $7.22 \times 10^{-6}$ mol × 16 g/mol

= $1.1552 \times 10^{-4}$

Mol of methane in *1 ml* of gas sample = $5.776 \times 10^{-5}$ g

The others gas components were calculated following procedure mentioned above. The result of converting mol of gas to be mass was reported in Appendix E4

Basis: $X = \dfrac{\text{mol of } CO_2 \text{ from LPG}}{\text{mol of } CO_2 \text{ from Total}}$

mol of each component is:

mol of $CO_2$ from PP = $1.94 \times 10^{-6}$ (1-X) mol/ml

mol of CO from PP = $0.155 \times 10^{-6}$ mol/ml

mol of $CH_4$ from PP = $3.76 \times 10^{-6}$ mol/ml

Convert mol to be weight using MW of each component

Weight of $CO_2$ from PP = $44 \times 1.94 \times 10^{-6}$ (1-X) g/ml = $8.54 \times 10^{-5}$(1-X) g/m

Weight of CO from PP = $28 \times 0.155 \times 10^{-6}$ g/ml = $4.34 \times 10^{-6}$ g/ml

Weight of $CH_4$ from PP = $16 \times 3.76 \times 10^{-6}$ g/ml = $6.01 \times 10^{-5}$ g/ml

Total weight = $(14.98+8.54X) \times 10^{-5}$ g/ml

Therefore, weight fraction of $CO_2$ from PP is:

$$= \frac{8.54 \times 10^{-5}(1-X)}{(14.98+8.54X) \times 10^{-5}}$$

Mass flow rate of $CO_2$ from PP is:

$$= \frac{8.54 \times 10^{-5}(1-X)}{(14.98+8.54X) \times 10^{-5}} \times \frac{333.8}{40.5}$$

Mass flow rate of $CO_2$ from PP is:

$$= \frac{70.35\ (1-X)}{(14.98+8.54X)} \ \frac{\text{g}}{\text{min}}$$

Mass flow rate ratio of $CO_2$ from LPG/ Total is:

$$X = \frac{1.3 \text{ g/min}}{\dfrac{70.35\ (1-X)}{(14.98+8.54X)} + 1.3}$$

$$1.3 = \frac{70.35X\ (1-X) + 1.3X}{(14.98+8.54X)}$$

$$1.3 = \frac{70.35X - 70.35X^2 + 1.3X}{(14.98+8.54X)}$$

$$19.47-11.097X = 70.35X-70.35X^2+19.47X-11.097X^2$$

$$0 = 81.447X^2-100.917X+19.47$$

$$X = 0.24$$

Replace X in this Eq.

Weight of $CO_2$ from PP = 44 x 1.94 x $10^{-6}$ (1-X) g/ml = 8.54 x $10^{-5}$(1-X) g/m

Weight of $CO_2$ from PP = 6.50 x $10^{-5}$ g/ml

Weight of each component/ml of gas product is:

Weight of $CO_2$ from PP = 6.50 x $10^{-5}$ g/ml

Weight of CO from PP = 4.34 x $10^{-6}$ g/ml

Weight of $CH_4$ from PP = 6.01 x $10^{-5}$ g/ml

Total weight

= 1.30 x $10^{-4}$ g/ml

Convert weight/ml of gas to be weight fraction

$y_{CO2}$ from $CH_4$ = 50.21% ($CO_2$)

$y_{CO}$ from $CH_4$ = 3.36 % (CO)

$y_{CH4}$ = 46.43 % ($CH_4$)

This fraction multiply by 333.8 g of gas

Mass flow rate of $CO_2$ = (333.8 x 0.54021)/40.5 = 4.45 g/min

Mass flow rate of CO = (333.8 x 0.0336)/40.5 = 0.28 g/min

Mass flow rate of $CH_4$ = (333.8 x 0.4643)/40.5 = 3.83 g/min

# Appendix F

The production rate and distribution of gas and liquid product

**Table F1** Summary of the production rate and distribution of gas and liquid at fixed bed temperature of *450 and 480* $^{o}C$

| Product distribution | Condition | | | |
|---|---|---|---|---|
| | 450 $^{o}$C | | 480 $^{o}$C | |
| | Weight (g) | Mass flow (g/min) | Weight (g) | Mass flow (g/min) |
| - Combustion product and residual oxygen from burner | | | | |
| - Oxygen ( $O_2$ ) | 83.9 | 2.1 | 79.6 | 2.0 |
| - Carbon dioxide ( $CO_2$ ) | 52.6 | 1.3 | 55.3 | 1.4 |
| - Gas product | 333.8 | 8.2 | 386.6 | 4.29 |
| - Methane ( $CH_4$ ) | 155.1 | 3.8 | 173.7 | 6.2 |
| - Carbon monoxide ( CO ) | 11.3 | 0.3 | 12.2 | 0.3 |
| - Carbon dioxide ( $CO_2$ ) | 167.7 | 4.14 | 200.9 | 4.96 |
| - Ethylene ( $C_2H_4$ ) | nd | nd | nd | nd |
| - Ethane ( $C_2H_6$ ) | nd | nd | nd | nd |
| - Propylene ( $C_3H_6$ ) | nd | nd | nd | nd |
| - Propane ( $C_3H_8$ ) | nd | nd | 27.3 | 0.7 |
| - Butane ($C_4H_{10}$) | nd | nd | nd | nd |
| - Liquid product | 166.2 | 4.1 | 113.4 | 2.8 |
| - Gasoline ( C5-C12 ) | 99.8 | 2.5 | 60.6 | 1.5 |
| - Kerosene ( C13-C17 ) | 57.8 | 1.4 | 45.9 | 1.1 |
| - Gas oil ( > C18 ) | 8.8 | 0.2 | 7.0 | 0.2 |

**Table F2** Summary gas and liquid product distribution at various secondary air feed rates

| Product distribution | Condition | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Without partial | | 25 l/min air | | 50 l/min air | | 100 l/min air | |
| | Weight (g) | Mass flow (g/min) | Weight (g) | Mass flow (g/min) | Weight (g) | Mass flow (g/min) | Weight (g) | Mass flow (g/min) |
| - Combustion products and residual oxygen from burner | | | | | | | | |
| - Oxygen ( $O_2$ ) | 83.9 | 2.1 | 83.9 | 2.1 | 83.9 | 2.1 | 83.9 | 2.1 |
| - Carbon dioxide ( $CO_2$ ) | 52.6 | 1.3 | 52.6 | 1.3 | 52.6 | 1.3 | 52.6 | 1.3 |
| - Gas product | 333.8 | 8.2 | 349.9 | 8.6 | 359.2 | 8.9 | 364.5 | 9.0 |
| - Methane ( $CH_4$ ) | 155.1 | 3.8 | 157.1 | 3.9 | 162.0 | 4.0 | 220.1 | 5.4 |
| - Carbon monoxide ( CO ) | 11.3 | 0.3 | 11.3 | 0.3 | 13.4 | 0.3 | 13.0 | 0.3 |
| - Carbon dioxide ( $CO_2$ ) | 167.7 | 4.14 | 180.2 | 4.5 | 183.5 | 4.53 | 201.3 | 5.0 |
| - Ethylene ( $C_2H_4$ ) | nd | nd | nd | nd | nd | nd | nd | nd |
| - Ethane ( $C_2H_6$ ) | nd | nd | nd | nd | nd | nd | nd | nd |
| - Propylene ( $C_3H_6$ ) | nd | nd | nd | nd | nd | nd | nd | nd |
| - Propane ( $C_3H_8$ ) | nd | nd | nd | nd | nd | nd | nd | nd |
| - Butane ($C_4H_{10}$) | nd | nd | nd | nd | nd | nd | nd | nd |
| - Liquid product | 166.0 | 4.1 | 151.55 | 3.74 | 140.80 | 3.48 | 135.45 | 3.34 |
| - Gasoline ( C5-C12 ) | 99.8 | 2.5 | 87.85 | 2.17 | 81.2 | 2.00 | 75.60 | 1.87 |
| - Kerosene ( C13-C17 ) | 57.8 | 1.4 | 55.30 | 1.37 | 53.55 | 1.32 | 51.80 | 1.28 |
| - Gas oil ( > C18 ) | 8.8 | 0.2 | 8.40 | 0.21 | 8.05 | 0.20 | 8.05 | 0.20 |

**Table F3** Summary gas and liquid product distribution in case of with and without partial oxidation

| Product distribution | Condition | | | |
|---|---|---|---|---|
| | Without partial oxidation | | Energy saving by partial oxidation | |
| | Weight (g) | Mass flow (g/min) | Weight (g) | Mass flow (g/min) |
| - Combustion products and residual oxygen from burner | | | | |
| - Oxygen ( $O_2$ ) | 59.8 | 1.5 | 59.8 | 1.5 |
| - Carbon dioxide ( $CO_2$ ) | 31.4 | 0.8 | 31.4 | 0.8 |
| - Gas product | 333.8 | 8.2 | 365.2 | 9.1 |
| - Methane ( $CH_4$ ) | 155.1 | 3.8 | 138.5 | 3.4 |
| - Carbon monoxide ( CO ) | 11.3 | 0.3 | 0.3 | 0.7 |
| - Carbon dioxide ( $CO_2$ ) | 167.7 | 4.1 | 199.3 | 4.9 |
| - Ethylene ( $C_2H_4$ ) | nd | nd | nd | nd |
| - Ethane ( $C_2H_6$ ) | nd | nd | nd | nd |
| - Propylene ( $C_3H_6$ ) | nd | nd | nd | nd |
| - Propane ( $C_3H_8$ ) | nd | nd | nd | nd |
| - Butane ($C_4H_{10}$) | nd | nd | nd | nd |
| - Liquid product | 166.0 | 4.1 | 134.8 | 3.3 |
| - Gasoline ( C5-C12 ) | 99.8 | 2.5 | 74.6 | 1.8 |
| - Kerosene ( C13-C17 ) | 57.8 | 1.4 | 53.2 | 1.3 |
| - Gas oil ( > C18 ) | 8.8 | 0.2 | 7.0 | 0.2 |

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