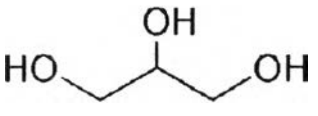
CHAPTER II
LITERATURE REVIEW

2.1 Glycerol

Glycerol (1,2,3-propanetriol) is a colorless, odorless and viscous compound which can be found in the nature such as in the form of ester from animal and vegetables fats and also in the intermediates of the living organisms. Glycerol is produced as a by-product in many industries which divides into four main productions: ester production, soap production, fatty acid production and microbial fermentation. Glycerol can also be used as a raw material in many industrial processes for example: food industry, cosmetic, plastic, drug and tobacco etc. therefore glycerol can be transformed to many other important and valuable derivatives.



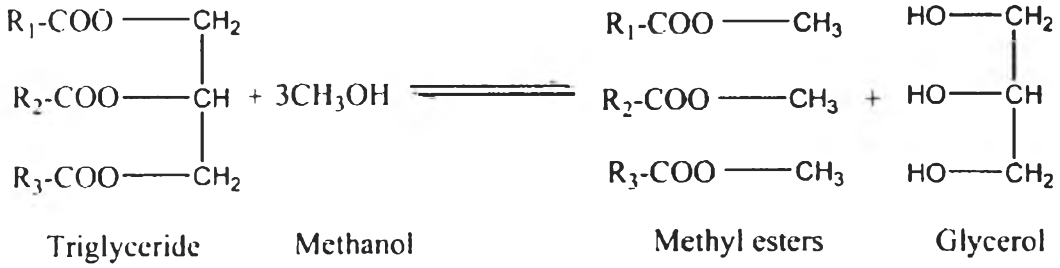
Glycerol
1,2,3-propanetriol

$C_3H_8O_3$
MW: 92.09
mp: 17.8 °C
bp_{760}: 290 °C (decomp).
Density @ 20 °C = 1.2375
Flash point 176 °C

Figure 2.1 Glycerol properties (Kenar, 2007).

2.2 Reaction of Glycerol to Other Products

Currently, biodiesel industry plays a major role in glycerol production. Biodiesel is not only the renewable product, but it is also environmental friendly and clean energy. Biodiesel is produced by transesterification of vegetable oils with methanol. If the methanolysis of triglyceride is completed, for one molecule of triglyceride, one molecule of glycerol and three molecules of methyl ester will be generated as shown in Figure 2.2.



with R_1, R_2, R_3 = hydrocarbon chain from 15 to 21 carbon atoms

Figure 2.2 Transesterification reaction for produced biodiesel production (Zhou *et al.*, 2008).

Because the growth rate of biodiesel production is increasing in such a high rate, the market price of glycerol drops rapidly due to the oversupply of glycerol as a by-product that shown in Figure 2.3. With this situation, glycerol is becoming a new major material in the biodiesel plant.

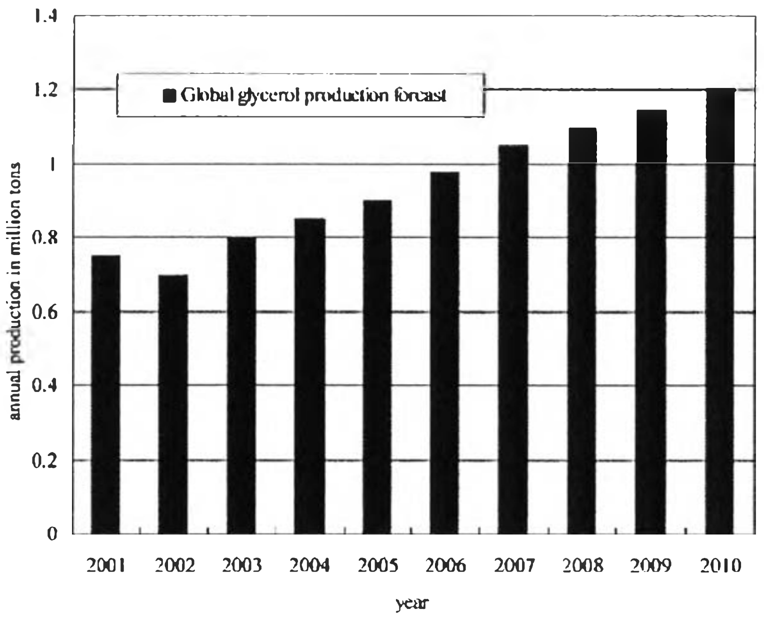


Figure 2.3 The global projection of glycerol production, from P&G (http://beag.ag.utk.edu/pp/biodiesel.pdf).

To increase the overall economics of biodiesel industry, the utilization of glycerol in the way that helps increase its value is interested. Glycerol can be converted to many derivative products. Possible pathway to increase glycerol consumptions has been reported and shown in Figure 2.4 (Zhou *et al.*, 2008).

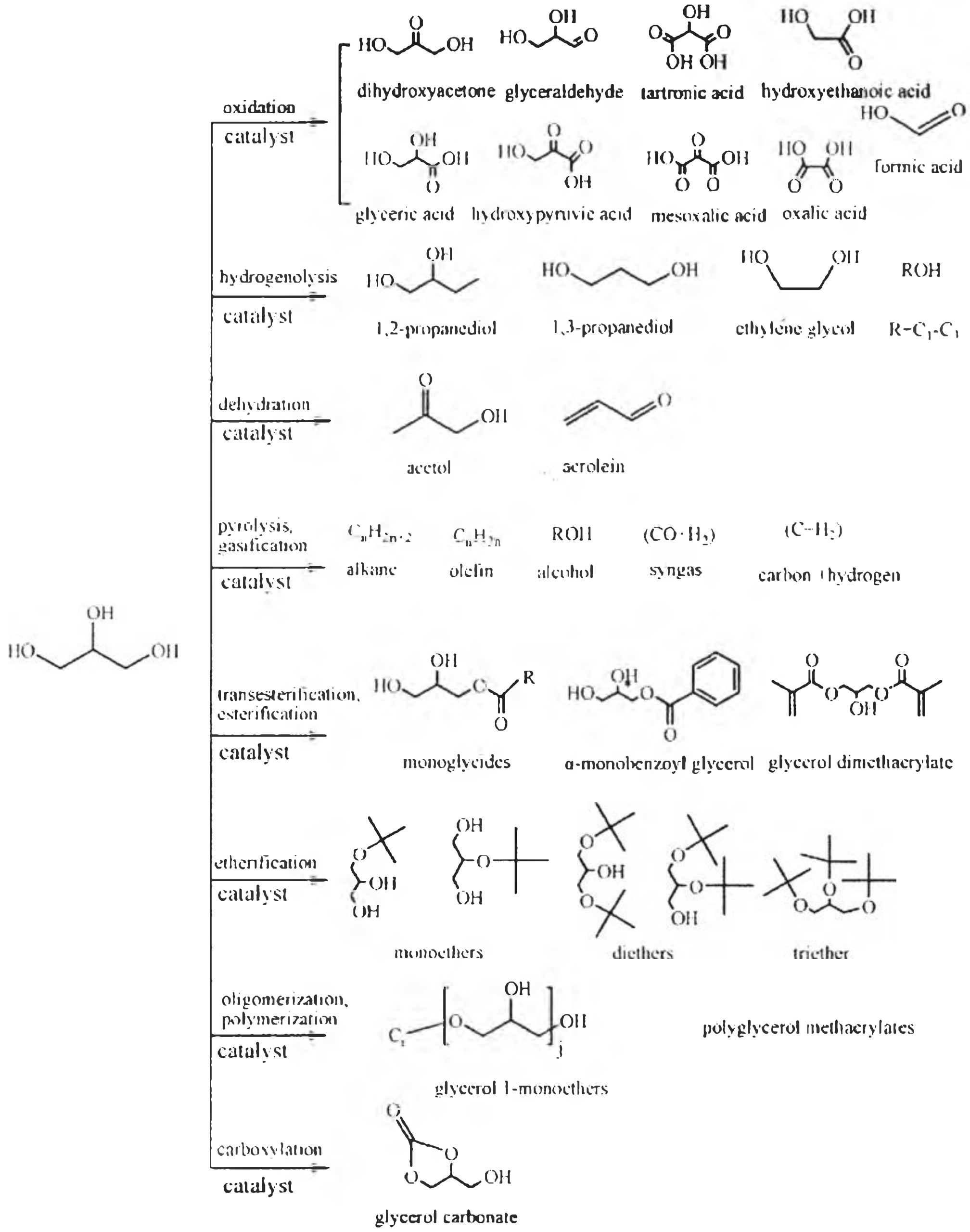


Figure 2.4 The conversion of glycerol into the useful products (Zhou *et al.*, 2008).

2.2.1 Glycerol with Oxidation Reaction

The advantage of glycerol is a highly functionalized molecule compared to hydrocarbon. The oxidation of glycerol can produce various products from its complex pathways such as glyceric acid, dihydroxyacetone, hydroxypyruvic acid, mesooxalic acid, tartronic acid and etc (shown in Figure 2.5). The applications for these products are the valuable chelating agents for the synthesis of fine chemicals and novel polymers. Moreover the products can be obtained from two processes.

- Chemoselective catalytic oxidation of glycerol

  This process uses catalyst with supported noble-metal- particles for example: palladium, platinum and gold because these catalysts give a high boiling point. Normally oxidation reaction is reacted glycerol with air or oxygen directly by using water as a solvent.

- Electrocatalytic oxidation of glycerol

  This process uses anodic oxidation of glycerol by using a silver oxide electrode. Moreover they use the stable organic nitroxyl radical to increase the rate of reaction to produce oxidation products.

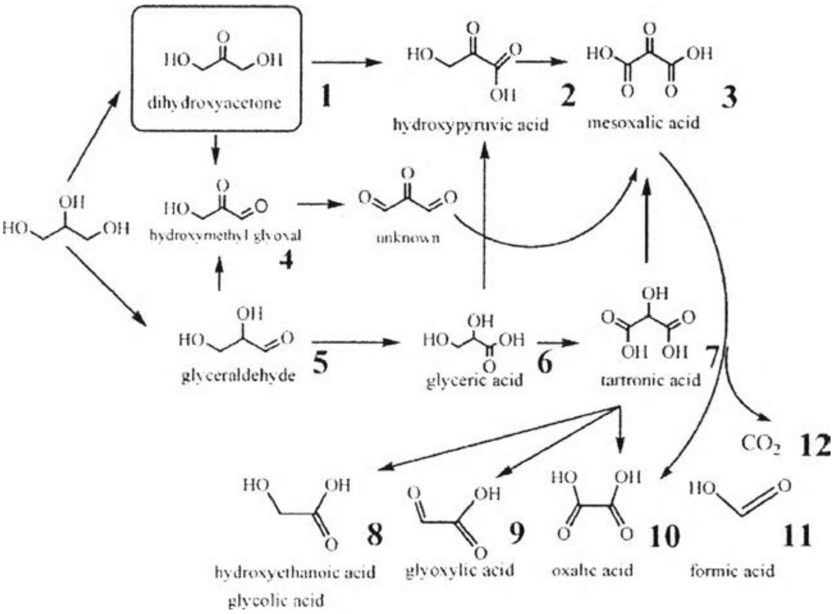


Figure 2.5 The complex pathways from oxidation reaction (Zhou *et al.*, 2008).

2.2.2 Glycerol with Hydrogenolysis Reaction

Hydrogenolysis reaction is a reaction which adds hydrogen to break chemical bonds in an organic molecule. Most processes use metallic catalysts and hydrogen. The products from this reaction are 1,2-propanediol, 1,3-propanediol and ethylene glycol. The applications of these products are intermediates for polyester resin, detergency, personal care application and antifreeze. This reaction is very interesting for using glycerol as a raw material because glycerol can be transformed to other compound by hydrogenolysis reaction as shown in Figure 2.6. 1,2-propanediol and 1,3-propanediol can be produced via three methods. First method is the use of heterogeneous catalysts. This method has advantage in separation of the products and the catalysts but the selectivity is very low. Second method is the use of homogeneous catalysts which the advantage is high selectivity. Last method is using biocatalyst or enzyme with fermentation to produce oxidation products.

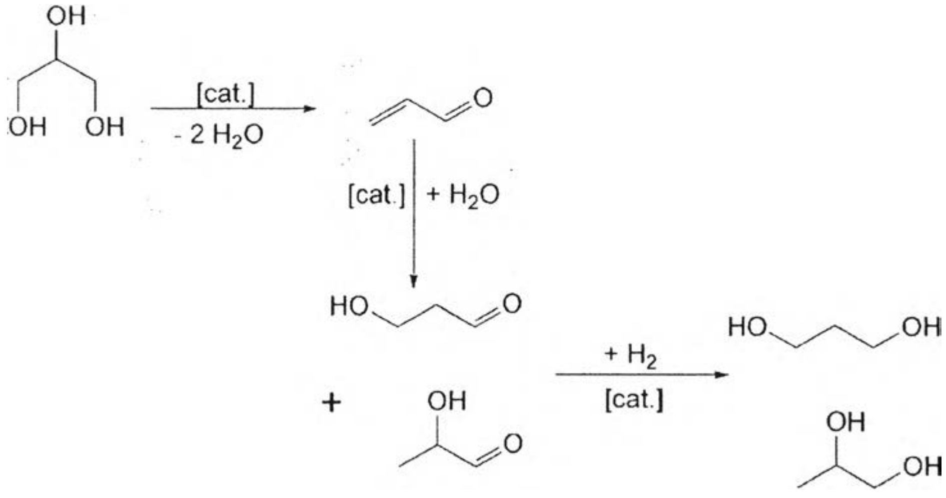


Figure 2.6 Hydrogenolysis reaction process with catalysts (Behr *et al.*, 2007).

2.2.3 Glycerol with Dehydration Reaction

Acrolein can be derived from dehydration reaction of glycerol with Bi/Mo-mixed oxide catalysts as commercial catalysts. Acrolein can also be produced from propene. The applications of acrolein are in detergency, absorber polymer, and production of acrylic acid esters. The process starts by using heterogenous or homogenous catalyst with high pressure (Pressure=300 bar) and temperature (around 250 °C to 350 °C) as shown in Figure 2.7.

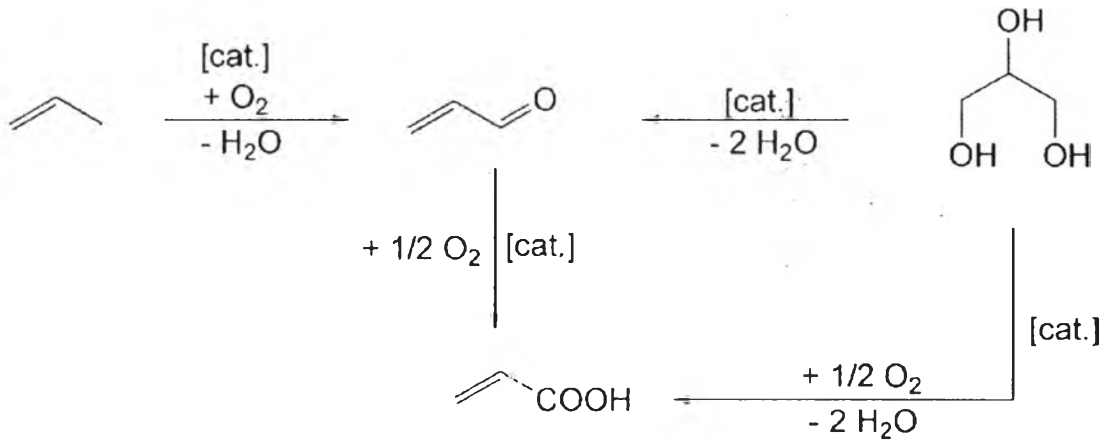


Figure 2.7 Pathway for produced acrolein by glycerol or propene (Behr *et al.*, 2007).

2.2.4 Glycerol with Pyrolysis and Gasification Reaction

Pyrolysis and gasification reaction look similar but the major different between both processes is that gasification uses oxygen as presence in form of air or steam. Pyrolysis process can be divided into two processes. Low temperature pyrolysis (673 K to 873 K) is for the liquid products and high temperature pyrolysis (more than 1023 K) is for the gas products. These processes are used to crack glycerol into small hydrocarbons. The main products are hydrogen, carbon monoxide, methane and ethane. Carbon monoxide can be converted to carbon dioxide and produced more hydrogen by using water-gas shift reaction. Figure 2.8 is shown the overall of reaction for pyrolysis or gasification glycerol.

$$\begin{array}{rcll} C_3H_8O_3 & \longrightarrow & 3\,CO + 4\,H_2 & (1) \\ 3\,CO + 3\,H_2O & \rightleftharpoons & 3\,CO_2 + 3\,H_2 & (2) \\ \hline C_3H_8O_3 + 3\,H_2O & \longrightarrow & 3\,CO_2 + 7\,H_2 & (3) \end{array}$$

Figure 2.8 Overall of reaction for pyrolysis or gasification glycerol (1) Pyrolysis glycerol (2) Water-gas shift reaction (3) Overall reaction (Behr *et al.*, 2007).

2.2.5 Glycerol with Transesterification and Esterification Reaction

Monoglyceride and polyglycerol esters are the main products from transesterification and esterification reaction of glycerol. In commercial process, catalysts normally used are basic catalysts such as potassium hydroxide and calcium oxide. The applications of the products are in cosmetics, pharmaceutical, food industries, synthetic lubricants, detergency and etc. Especially polyglycerol esters are now popular in surfactants applications because they are the new marketable product and biodegradable product for environmental friendly. Monoglyceride can be produced from three commercial processes.

- Direct esterification of glycerol with fatty acid
- Transesterification of triglycerides with glycerol
- Glycerolysis of triglycerides

The product of direct esterification (shown in Figure 2.9) and transesterification (shown in Figure 2.10) contain 40% to 60% monoglyceride and 35% to 45% diglyceride. Moreover, the purification is required including the neutralization step and the removed of salts.

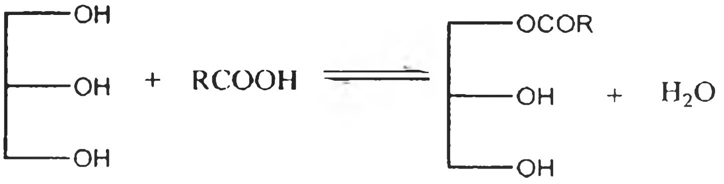


Figure 2.9 Reaction for direct esterification of glycerol with fatty acid (Zhou *et al.*, 2008).

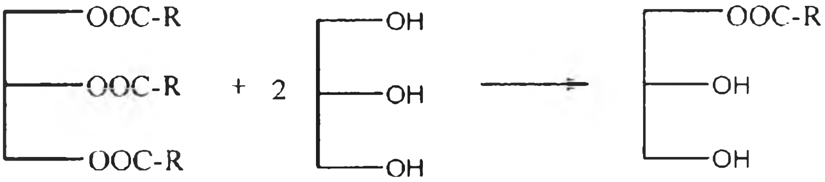


Figure 2.10 Reaction for transesterification of triglycerides with glycerol (Zhou *et al.*, 2008).

2.2.6 Glycerol with Etherification Reaction

Glycerol can be burnt directly as a fuel, and it also can be converted to fuel additive or solvent for example: glycerol reacts with alcohol group (methanol or ethanol) or alkenes (isobutene) by catalytic etherification to produce methyl tertiary butyl ether or ethyl tertiary butyl ether for additives in gasoline to boost the octane number.

Moreover the important for the etherification production from glycerol are polyglycerol and polyglycerol esters which are colourless, biodegradable, high thermal stability and environmental friendly. Polyglycerol esters are also used in many various applications for instance: surfactants, detergent, food, deliver drugs and synthetic lubricants. Polyglycerols have more advantage than glycerol. According to the properties of polyglycerols are similar to glycerol but polyglycerols offer the greater flexibility and functionality than glycerol. Polyglycerols are obtained from glycerol oligomerization which the glycerol units are linked between them from ether bonding (shown in Figure 2.11). The oligomerization of glycerol can be converted to many isomers of glycerol when a higher number of glycerol linked between each other such as linear, branch or cyclic compounds as shown in Figure 2.12.

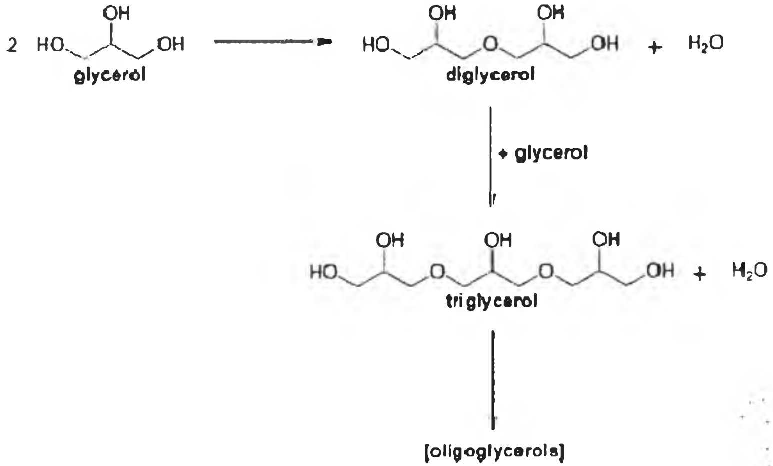


Figure 2.11 Oliogomerization of glycerol to polyglycerols (Behr *et al.*, 2007).

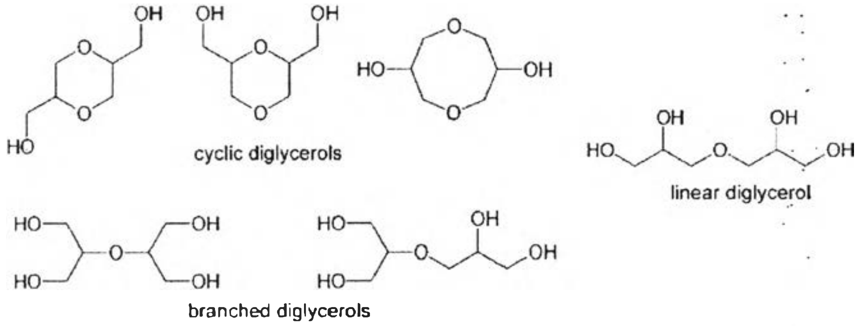


Figure 2.12 Isomers of polyglycerols (Ruppert *et al.*, 2008).

Polyglycerols can be produced by homogenous catalysts such as sodium carbonates. The advantages of homogeneous catalysts are high conversion and high rate of reaction. But recently, researchers are interested in the development of the heterogeneous catalysts systems for example: based solid as calcium oxide, zeolite, ion exchangers and mesoporous molecular sieves etc. Heterogeneous catalysts have many advantages for polyglycerols. First, heterogeneous catalysts can be separated easily when compare to homogeneous catalyst. And, a high selectivity of product can be observed when heterogeneous catalysts are used. The disadvantages of heterogeneous system are low conversion and often most of products are branch oligomers. Table 2.1 gives some information for comparison between heterogeneous and homogeneous catalysts.

Table 2.1 Comparisons between homogeneous and heterogeneous catalysts (Zhou *et al.*, 2008)

Catalyst	Na_2CO_3	CS-MCM_41	Amberlyst 16	Amberlyst 31
Conversion (%)	80 (8hours)	95 (24hours)	35-40	35-40
Selectivity (%)				
Diglycerol	31	59	85	75
Triglycerol	28	30	15	25
Tetraglycerol	17	11	<1	<1
Higher oliogomers	24	<1	<1	<1

Boonpokkrong (2005) studied homogeneous and heterogeneous catalysts for production of polyglycerol with nitrogen atmosphere and temperature at 250 °C for 4 hours. In homogeneous catalysts, he found that sodium hydroxide is the optimum catalysts with 65.5% glycerol conversion, 52.4% diglycerol selectivity and 34.5% diglycerol yields compare to potassium hydroxide and calcium hydroxide. Moreover, in heterogeneous catalysts they found that calcium oxide is the optimum catalysts with 37.7% glycerol conversion, 70.5% diglycerol selectivity and 26.5% diglycerol yields compare to zirconium oxide and magnesium oxide.

Thanasanvisut (2008) investigated heterogeneous basic catalysts for synthesis of diglycerol. They found that the optimum condition for barium oxide and calcium oxide catalysts in 1 hour is nitrogen atmosphere with temperature at 240 °C. Barium oxide gave 31% glycerol conversion, 94% diglycerol selectivity and 29% diglycerol yields. Calcium oxide also gave 55% glycerol conversion, 69% diglycerol selectivity and 38% diglycerol yields.

Ruppert *et al.* (2008) studied the effects of catalysts basicity on the etherification of glycerol under argon flow with temperature at 220 °C for 20 hours. They found that, with increasing catalysts basicity the conversion increases. The sequence of strong basicity is barium oxide, strontium oxide, calcium oxide and magnesium oxide respectively. However, if the catalysts activities and toxicity are considered, calcium oxide is suggested to be a suitable catalyst for commercial application. They also investigated in lewis acidity on the catalysts with different calcium oxide catalyst. They concluded that high conversion of glycerol depended on the right balance between basicity and lewis acidity.

Barrault *et al.* (2004) investigated in selective oligomerization of glycerol over mesoporous catalysts by using zeolite for shape selection. The reaction took place at 260 °C under nitrogen atmosphere for 8 hours. The results showed that cesium catalysts over mesoporous solid act as shape selection material but if it was compared to the pore size of catalyst, it cannot be justified as a direct shape selective. The impregnation method for catalysts preparation gave the highest activity and high selectivity and yield to (di and tri) glycerol. The drawback of these catalysts is the low conversion (15% to 20%).

Krisnandi *et al.* (2008) investigated the catalysts activities in homogeneous catalysts and the different cations over microporous zeolites as heterogeneous catalysts at atmosphere pressure under argon flow at temperature at 260 °C. The advantage of using microporous zeolites was also shape selectivity. In the result, the sequence in the effect of alkali cations on base strength of zeolite was cesium ion, rubidium ion, potassium ion, sodium ion and lithium ion respectively. Moreover from the results of sodium ion, the sequence of the most activity catalysts was NaX, NaY, NaBeta respectively. Unfortunately, diglycerol selectivity did not show any significant different among the catalysts and the water which formed during the reaction could not be removed fast enough from the pore system. For the cesium ion, glycerol conversion with CsX was higher than 20% NaX at 8 hours. The disadvantage of using the zeolite catalysts were the difficult to separate between the viscous products and the zeolite therefore the profile became similar as the homogeneous catalysts.

Clacen *et al.* (2002) used a impregnated basic MCM-41 type mesoporous catalyst for selective etherification of glycerol in atmosphere pressure under nitrogen with temperature at 260 °C. In homogeneous system, they found that sodium carbonate gave the most conversion (94%) at 8 hours. Unfortunately, there was no selectivity for di and triglycerol. For the case using modified zeolite (Cs ZSM-5(1000)), it gave the highest selectivity but there was very low conversion

(13%) at same condition. Moreover, they concluded that cesium catalyst which prepared by impregnation was very selective comparing to cesium hydroxide which was homogeneous catalyst.

Richter *et al.* (2008) studied cesium hydrogencarbonate as a homogeneous catalyst for etherification glycerol with temperature at 260 °C. They found that cesium hydrogen carbonate catalyst with 0.4% by weight gave high selectivity on diglycerol and linear diglycerol is a main product isomer (65% to 75% selectivity), but glycerol conversion is still low (10% to 20%). Moreover they concluded that the probability ratio of diglycerol isomers is 4:2:1 as linear diglycerol (αα'-position), branched diglycerol (αβ-position) and branched diglycerol (ββ'-position) subsequently.

Chaimbault *et al.* (1999) suggested the use of liquid chromatography combined with Mass Spectrometry for better identified isomers with the same molecular weight. In liquid chromatography, they recommended the ratio of acetonitrile and water as mobilephase by 90:10 (volume/volume) for separation of isomers of diglycerol. This mobile phase could be able to show an excellent separation of diglycerol isomers. Mass spectrometry used for determination of the ion source furnishing the best fingerprint. They also recommended detecting by heat nebulizer which had greater sensitivity than the ion-spray.

Barrault *et al.* (2004) showed the interesting result in analysis of diglycerol isomers because they can separate the isomers of diglycerol into different peaks by using GPC after silylation. Analysis conditions was GPC equipped with a column injector, FID detector, and a polar column (HT5) supplied by SGE (L=25meter, ID= 0.22 millimeter, thickness of the film = 0.10 micrometer).

Krisnandi *et al.* (2008) can separate the isomer of diglycerol after silylation using gas chromatography with capillary column HP-5 (Agilent tech.) from 60 °C to 250 °C with mixed dried pyridine and *n*-dodecanol as the internal standard. After dissolution, they added hexamethyldisilazane and trimethylchlorosilane and heated to 70 °C for 1 hour. An aliquot of the solution was diluted in toluene after that injected the sample into GC system.

Richter *et al.* (2008) analyzed isomers of diglycerol which contains 84% by weight of linear diglycerol, 14% by weight of branched diglycerol and cyclic diglycerol less than 1% by weight by using the same condition as Krisnandi *et al.*

2.2.7 Glycerol with Carboxylation Reaction

Glycerol carbonate (4-hydroxymethyl-1,3-dioxolan-2-one) is a clear liquid with a freezing point below -70 °C and highly soluble in water. It is also the most important products from carboxylation of glycerol. The applications of glycerol carbonate are surfactant component, polyurethanes foams and a component of gas separation, coatings, painting and detergents. In the past glycerol carbonate could be produced by two steps reaction. First reaction was a reaction between ethylene oxide and carbon oxide to produce cyclic ethylene carbonate and then cyclic ethylene carbonate reacted with glycerol to make a glycerol carbonate (shown in Figure 2.13A). Nowadays the direct reaction between glycerol and carbon dioxide is very interesting for scientists to produce glycerol carbonate because they are more economically product (Figure 2.13B).

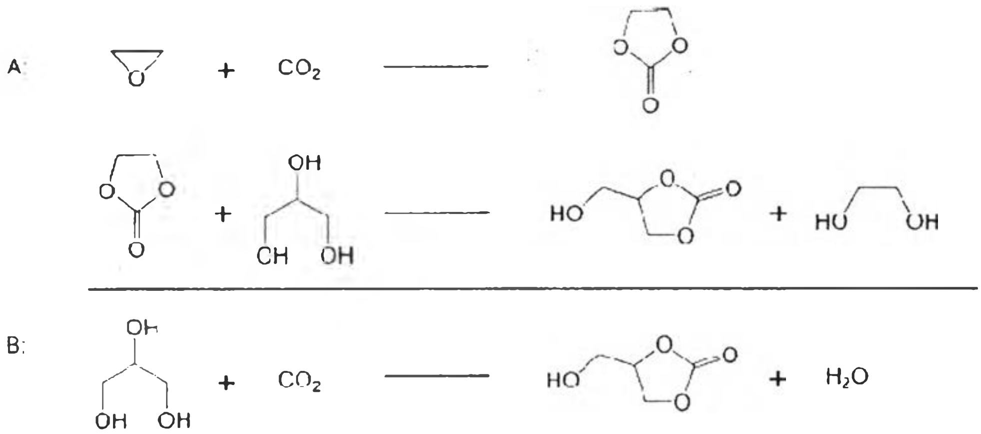


Figure 2.13 Synthesis glycerol carbonate. A) Two step reaction. B) Direct reaction. (Behr *et al.*, 2007).

2.2 Protecting Group in the Organic Synthesis

2.3.1 Protecting Group Principle

The protecting group is an organic compound which is used for protection of particular functional groups in a multifunctional compound to have only one reactive site. Moreover this protecting group must be temporarily blocked the sites. Preferably they should be non toxic reagents and easily separated and removed. A protecting group process generally has three steps. First step is protection step, followed by reaction step and the last is deprotection step. In conventional process, hydroxyl group is the functional group which commonly applied the protecting group method to produce the selective isomer product. (Greene and Wuts., 2007).

2.3.2 Protection of Hydroxyl Group

Hydroxyl groups are commonly found in biological and synthetic compounds such as steroids, polyethers, carbohydrates and amino acids. Protecting of hydroxyl groups are often found in the synthesis of mono-, di-, triglycerides. However during the reaction (e.g.oxidation, halogenation or acylation reactions), the hydroxyl group must be protected because this group can be reacted quickly with the reagents. In this case, the organic group for protecting hydroxyl group can generally divided into three groups.

2.3.2.1 Protecting Hydroxyl Group by Ethers

Ethers are the most common used in the protection groups for organic synthesis because they are stable, easily formed and removed. There many types of ether groups that can be used such as alkyl ethers, silyl ethers and alkoxyalkyl ethers as shown in Figure 2.14.

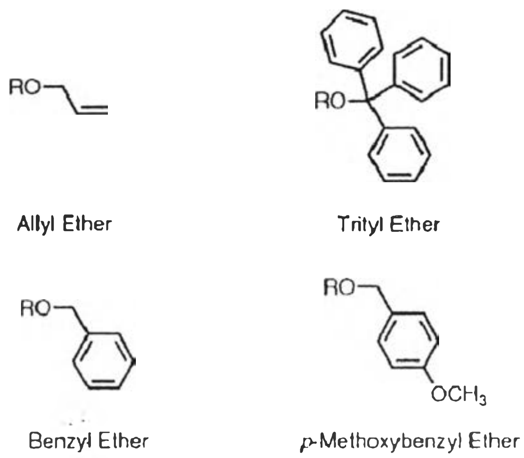


Figure 2.14 Example of protecting reagents by ethers as protection group (Greene and Wuts., 2007).

One of the other important ether groups is silyl ether. From its structure silyl ether has carbonchain with many different groups as shown in Figure 2.15. This advantage gives silyl ether to install or remove selectively under mild conditions.

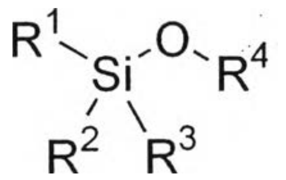


Figure 2.15 Silyl ether structure (http://en.wikipedia.org/wiki/Silyl_ether).

2.3.2.2 Protecting Hydroxyl Group by Ester and Carbonate

Ester protects hydroxyl group by ester linkage, occurred by the reaction of carboxylic acid and alcohol. In generally, ester is stable in acid and mild base condition. Carbonate is an organic compound which contains a carbon atom bound with three oxygen atoms. Carbonate has less susceptible to hydrolysis because they have their resonance effect of the second oxygen (shown in Figure 2.16). Ester and carbonate can be cleaved by basic hydrolysis.

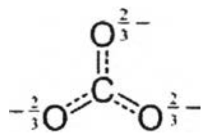
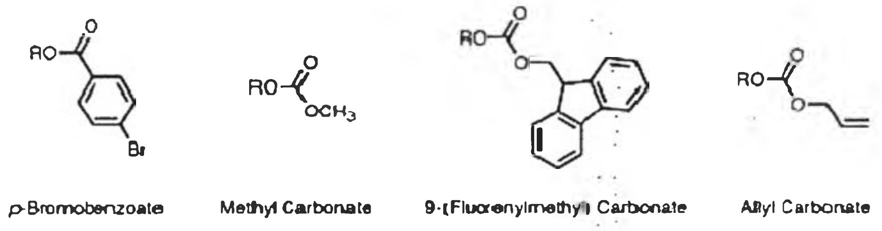


Figure 2.16 Carbonate resonance structure (http://en.wikipedia.org/wiki/Carbonate).

In addition, ester and carbonate are also used as a protection group in wide applications. Figure 2.17 shows some of reagent that can protect the hydroxyl as ester or carbonate groups.



p-Bromobenzoate Methyl Carbonate 9-(Fluorenylmethyl) Carbonate Allyl Carbonate

Figure 2.17 Reagents for protection hydroxyl group as ester and carbonate. (Greene and Wuts., 2007.)

2.3.2.3 Protecting Hydroxyl Group by Acetal, Ketal, 1,2 and 1,3 Diols

Acetal and ketal are the molecules which have two single bonded oxygen atoms attach to the same carbon. Ketal can be classified as a subset of acetal because ketal has similar structure but the different between ketal and acteal is a number of carbon-bonded groups (see in Figure 2.18). Acetal is used as protecting group in organic synthesis because it is very stable and can be hydrolyzed by bases.

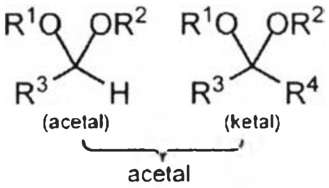


Figure 2.18 Acetal and Ketal structure (http://en.wikipedia.org/wiki/Acetal).

The formation of acetal or acetonide is occurred by protonation of a hydroxyl group of hemiacetal. Then the produced carbocation is attacked rapidly by molecule of alcohol (see also in Figure 2.19 and Figure 2.20).

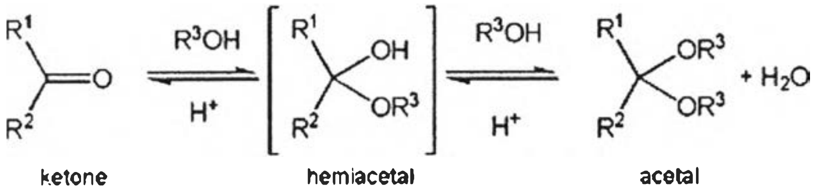
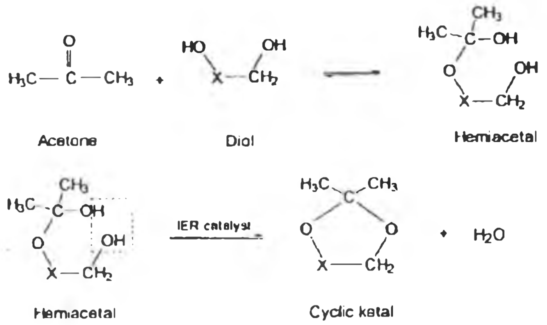


Figure 2.19 Acetal formation (http://en.wikipedia.org/wiki/Acetal).



where.

cis-but-2-ene-1,4-diol: $X = -CH{=}CH-CH_2-$
1,4-butanediol: $X = -CH_2-CH_2-CH_2-$
1,2-propanediol: $X = -CH-(CH_3)-$
1,2-ethanediol: $X = -CH_2-$

Figure 2.20 Cyclic ketal formation (Chopade., 1999).

Acetonide formation is mostly used for protection 1,2 and 1,3-diols. This formation can be applied in sugar production such as glucose and maltose because its selectivity of hydroxyl groups is very good. For the thiols which have three alcohol groups, the acetonide formation is generally favored on 1,2-deriative more than 1,3-derivative. For example: the 1,2 selectivity for the ketal from 3-pentanone is better than from acetone (shown in Figure 2.21). The classical method for acetonide formation is the reaction between the diols and acetone with acid catalyst.

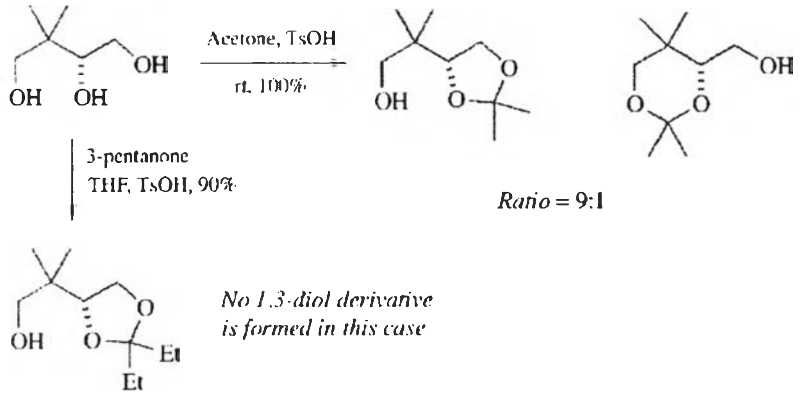


Figure 2.21 Selectivity of ketal product between acetone and 3-pentanone (Greene *et al.*, 2007).

Jahn and Karpovich (2006) investigated in producing solketal with molecular sieve. Solketal which also knew as protected glycerol can be used as additive in biodiesel as depressants. The advantage of using molecular sieve was to eliminate water as by product from the reaction and to help push the reaction forward. They concluded that the optimum ratio of glycerol, acetone, catalysts and molecular sieve was 1:1:0.1:1.25 respectively for three days.

Clarkson *et al.* (2001) reported the scale up solketal production by continuous reactor. From lab scale with semi batch reactor, they found that the optimum condition was using amberlyst DPT-1 as a catalyst with temperature at 70 °C. From this information, they designed with the concept as eliminated water to push the reaction forward by using multitray reactive distillation reactor as a continuous reactor. This reactor was a counter current system which added preheated acetone at the last tray of reaction and preheated glycerol above the column. Under the last reaction tray, there were three distillation trays for purified solketal with 99.94% by weight.

Garcia *et al.* (2008) blended solketal into the biodiesel. They found that 5%wt of solketal could improved the viscosity of biodiesel (B100). The standard test for viscosity was from EN ISO 3104. Unfortunately, the flash point and oxidation stability were out of specification.

Claudio *et al.* (2010) used solketal for fuel additives in gasoline with the concentration ranged between 1% to 5% volume. Due to its antioxidant property, solketal does not only decrease the gum formation but also improves the octane number of gasoline. Solketal affected on pure gasoline more than gasoline with ethanol. This result dedicated the potential use of solketal as a fuel additive.

Yu *et al.* (2003) found that Amberlyst-15-Ethanol system can be used to selectively and efficiently deprotect acetonide. Moreover, the purification of this method was very simple.

Makkam (2010) investigated the synthesis of mono-, di-, triglyceride from the protected glycerol. This work divided into 3 steps. The first step is protection of glycerol by ketalization which can protect two of hydroxyl groups. The conversion of glycerol was 82.7% at 16 hours. The second step is etherification the protected glycerol which can be reacted with only one hydroxyl group with triglyceride. They suggested the 3:2 solketal to palm oil ratio for the optimum condition. The last step is the deprotection of protected monoglycerides by using Dowex ion exchange resin. The yield of monoglycerides was 65.8%.

da Silva *et al.* (2009) studied in the etherification of glycerol with benzyl alcohol catalyzed by solids acids. The desired product was mono benzyl glycerol ether. But this reaction also produced dibenzyl ether, dibenzyl glycerol ether and tribenzyl glycerol ether. The optimum condition was 1:3.5:0.1 glycerol to benzyl alcohol to acid catalysts ratio for 2 hours. The solid catalysts in this research were Amberlyst 35, K10, Zeolite and niobic acid compared *p*-tolunensulfonic acid as homogenous catalyst. It was found that zeolite gave the highest selectivity of mono benzyl glycerol ether (55%).

Merino *et al.* (2004) suggested the synthesis of benzyl solketal ether with solvent. First, solketal and NaH with mineral oil were well stirred in DMF as a solvent in ice bath. Then, the solution stirred at 0 °C for 5 minutes before adding dropwise of benzyl bromide. After that, the reaction took place at the ambient temperature for 8 hours and then treated with solid NaOMe to destroy the remaining benzyl bromide. The aqueous layer was separated and extracted twice by EtOAc for the remaining benzyl solketal ether. Finally, the combined organics layer was washed, dried by $MgSO_4$ and distillated by rotary evaporation to produce benzyl solketal ether.