

CONTINUOUS AND SELECTIVE SYNTHESIS OF GLYCEROL ACETATES IN SUPERCRITICAL CARBON DIOXIDE

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ABSTRACT

Continuous esterification of glycerol with acetic acid was investigated in scCO₂ using Amberlyst[®] 15 as a heterogeneous catalyst. The effect of pressure at (65-300) bars on the substrates conversion and selectivity was studied. With increasing the pressure, the percent of total conversion decreases from 82% to 61.4% and the selectivity of triacetin (TA) synthesis increased while the selectivity was decreased for mono and diacetin (DA). The effect of temperature on the conversion and the selectivity at (100-150)°C was also investigated. With increasing temperature, the selectivity of triacetin decreased while it was increased for monoacetin (MA). With increasing the mole ratio of acetic acid to glycerol to 24, selectivity of 100% was achieved while the conversion was 51.5% for the continuous triacetin synthesis in scCO₂. Use of scCO₂ alone as solvent with no catalyst, had the MA selectivity of 100%, with the conversion of 29.5%. Moreover, the total conversion using the high pressure system when esterification reaction is performed at the presence of the catalyst alone without scCO₂, was 99.3% and the reaction selectivity was 47% for TA, 48% for DA, and 5% for MA.

INTRODUCTION

Fatty acid esters have wide variety of applications as emulsifying and stabilizing compounds, raw materials in food, cosmetic, and pharmaceutical industries [1,2]. Glycerol triacetate or triacetin was known as a solvent for dissolving or diluting drug and organic compounds, also, as an antimicrobial and emulsifying agents in cigarette filters [3,4]. Triacetin is used especially in pharmaceutical industries as a skin pH controller for treatment of skin disorder and some pathological disease and is used as a drug delivery compound via raising the transdermal or transmucosal delivery of a basic drug having pKa of about 8.0 [5,6]. Glycerol acetates have been synthesized via esterification of glycerol with acetic acid or acetic anhydride with or without a homogeneous or heterogeneous catalyst using an organic solvent, in a batch or continuous process [7-9]. Usually, the produced esters are accompanied with some by-products, which change its color and the solution odor so that makes its purification difficult and costly. As a result selective synthesis of the ester with high purity has been a great challenge for researchers and industries.

Supercritical carbon dioxide (scCO₂) is the most used solvent in a supercritical fluid (SCF) system because of being chemically inert, non-flammable, environmentally benign, and cheap with moderate critical conditions (T=31.2 °C, P=73.8 bar) [10-12]. Performing a chemical reaction with heterogeneous catalyst in scCO₂ under continuous process, not only increases the safety of operation, but also is more attractive than the batch type for chemical industries in terms of operating cost [13-16]. In addition, it is not necessary to depressurizes the system for introduction of reagents or recovery of products [17]. Indeed, scCO₂ with continuous mode improves performance of the heterogeneous catalyst during the reaction, because of anti-coking property of scCO₂ [11,17-18] and easy separation of products and unreacted reagents. Moreover, investigations have shown that tuning pressure and temperature on the reaction could change the selectivity and the reaction yield fantastically [18,19-23].

In this work, the synthesis of glycerol esters was studied, especially for synthesis of triacetin by continuous esterification of glycerol with acetic acid in the presence of a strong solid-acid heterogeneous catalyst, namely Amberlyst 15[®], under scCO₂. The effects of scCO₂ pressure, temperature, molar ratio of acetic acid to glycerol, and the catalyst on the reaction conversion and selectivity was investigated.

MATERIALS AND METHOD

APPARTUES AND PROCEDURE

A continuous flow apparatus (Figure 1) was used to carry out the esterification reaction. The CO₂ used as the fluid was stored in a cylinder in liquid form and pumped by a JASCO PU-980 reciprocating pump. The head of the pump was cooled by circulation of an aqueous ethylene glycol solution from a home made cooling circulator within the pump head cooler. Also, a liquid homogeneous mixture of substrates was pumped using a JASCO PU-1580 pump. The preheater consisted of a 316 stainless steel coil, allowing the liquid CO₂ to reach supercritical condition. The scCO₂ and the mixture of the substrates flow lines were connected by a tee connector and were pumped through a 1/8 inch tubing mixer, about 2 m length, which was filled with glass beads (mesh of 20-40) then passed over the catalytic bed reactor. The reactor used in our experiments was a 10 mm (ID), 316-stainless steel tubing with an internal volume of about 19 mL, contained about 9.5 g catalyst all placed in an air oven with a good control (± 1 °C) of temperature during the whole experiment. The pressure was maintained by a backpressure regulator (JASCO BP-1580-81), keeping the pressure within ± 1 bar. The sample trapping chamber was similar to our previous work [23]. The volume of CO₂ was determined using a wet gas meter (model W-NK-1B, Shinagawa Corp., Japan), which was connected to the line vent to measure the expanded gas volume to calculate the flow rate (± 5 mL/min). When the system was set at the desired pressure and temperature, a homogeneous mixture of the substrates and scCO₂ at a set flow rate were introduced by two HPLC pumps into the tubular mixer and passed over the catalyst bed. The products were collected at different times and were prepared for analyses with a GC-FID.

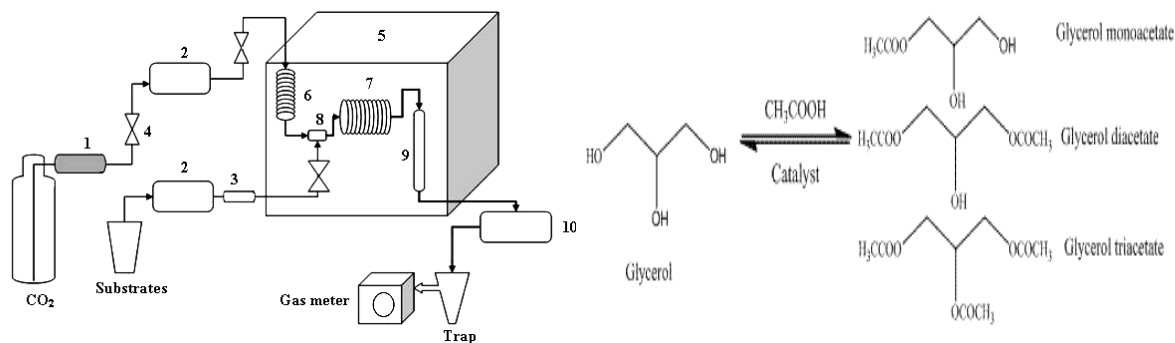


Figure 1. The schematic diagram of the setup used for the esterification reaction. 1, Molecular sieve trap; 2, Liquid pumps; 3, Check valve; 4, Needle valve; 5, Air oven; 6, preheating coil; 7, Static mixer; 8, T piece connector; 9, Catalyst reactor; 10, back pressure regulator

Scheme 1

ANALYTICAL METHOD

Analysis of the collected samples was carried out using a GC-FID (Agilent Technologies, model 6890N). The carrier gas was helium and a capillary column of HP-5 (with 30 m length, 0.25 mm ID, and 0.25 μ m of film thickness). The GC injection port and the detector temperature were set at 240 and 260 °C, respectively. The initial column temperature was set at 70 °C for 2 min and programmed from 70 °C to 150 °C for 1.5 min at the rate of 45 °C.min⁻¹ and from 150 °C to 180 °C at the rate of 8 °C.min⁻¹ and from 180 to 240 °C at the rate of 35 °C.min⁻¹. The peak areas were used for quantification and the calibration curve. For every analysis, we transferred the weighted amount of the collected sample and 1 mL of 1-hexanol solution (5000 mg.L⁻¹) as an internal standard to a volumetric flask and made up to 10 mL with absolute ethanol. The identification of the obtained products, in all experiments, was carried out

by a GC-MS (Trio 1000, Fisons Instruments, model 8060). For the quantification by GC, we used the esters standard solutions in ethanol as solvent. Since the monoacetin compound is not commercialized as, it was synthesized as is reported in the literature [22].

The total conversion and the selectivity for each experiment were calculated based on the equations 1 and 2.

$$\%Conversion = \frac{[MA + DA + TA]}{[Glycerol]_0} \times 100 \quad (1)$$

$$\%Selectivity = \frac{[product]}{[MA + DA + TA]} \times 100 \quad (2)$$

MATERIALS

Carbon dioxide with purity of 99.95% was purchased from ZamZam Co. Ltd (Isfahan). Acetic acid (purity of > 99%) and Amberlyst 15[®] were purchased from Merck Co. The catalyst capacity [23] was calculated as 4.64 meq.g⁻¹. Triacetin (glycerol triacetate, purity > 99%) and diacetin (glycerol diacetate, purity = 50% verified by GC analysis) were purchased from Fluka. Absolute ethanol was purchased from Temad Co. (purity > 99%, Tehran). Glycerol was purchased from Hopkin & Williams. 1-hexanol was purchased from Riedel-deHaën (purity > 98%).

SYNTHESIS OF MONOACETIN

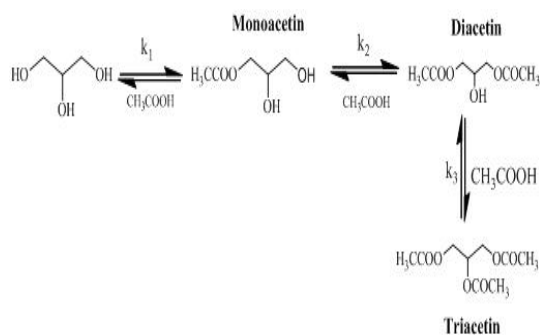
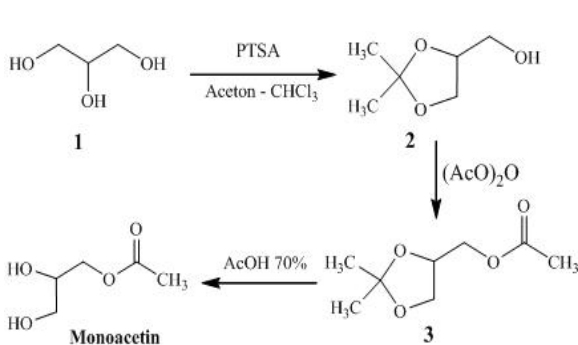
As shown in scheme 2, the protection step was carried out by reaction between acetone (36 g) and glycerol (30 g) in CHCl₃ (36 g) as solvent and *para*-toluenesulfonic acid (1.2 g) as catalyst. The mixture was refluxed for 6 h. Esterification was done using acetic anhydride in the presence of three moles of ethylamine at ambient condition with mixing time of 12 h, in this process 2 was converted to 3. Deprotection was performed in an aqueous acetic acid solution (70%); compound 3 was refluxed for 90 min at 75 °C to convert to glycerol monoacetate. At the end the residuals were removed by vacuum distillation. The final products were analyzed by GC-MS and GC-FID to verify their identity and purity (> 95%), respectively.

RESULTS

The esterification of glycerol with acetic acid could go ahead in three consecutive reversible reactions, as shown in scheme 3. The most important variables that affect the esterification of glycerol with acetic acid over a heterogeneous strong acid-catalyst, Amberlyst 15[®], under scCO₂ have been investigated. At the beginning, the operating conditions such as pressure, temperature, and molar ratio of acetic acid to glycerol were varied and the percentages of the conversion and products selectivity were measured. Also the effect of scCO₂ and the catalyst alone on the selectivity and the reaction conversion was also studied.

EFFECT OF PRESSURE

The effect of pressure on the esterification of glycerol with acetic acid over heterogeneous catalyst, Amberlyst[®] 15, at (65-300) bar was studied. All the experiments were carried out at 100 °C and the flow rate of liquid CO₂ and substrates of 1.2 mL min⁻¹ (at 0 °C) and 0.2 mL min⁻¹, respectively. As shown in Figure 2, the increase in the pressure has decreased the total conversion from 82% to 61%. This trend may mean that raising the pressure and as a result the density of scCO₂ increases the solvating power of the scCO₂ and the solubility of substrates especially acetic acid. Since the esterification reaction is a reversible reaction and takes place probably in liquid phase, less acetic acid concentration over the catalyst surface, lower the total conversion. But at low pressure most of the substrates are in liquid form and then the esterification reaction goes toward higher conversion.



As shown in Figure 2, the selectivity of triacetin synthesis increased with pressure while the selectivity of monoacetin synthesis decreased and the selectivity of diacetin synthesis remained unchanged. The solubility in $scCO_2$ is higher for triacetin compared to diacetin and monoacetin. Furthermore, the higher the solubility in $scCO_2$, the faster the evacuation of the product from the catalytic bed and the higher conversion for triacetin is expected. At the same time, when more triacetin is synthesized further water is formed and the reverse reaction competes with the triacetin production.

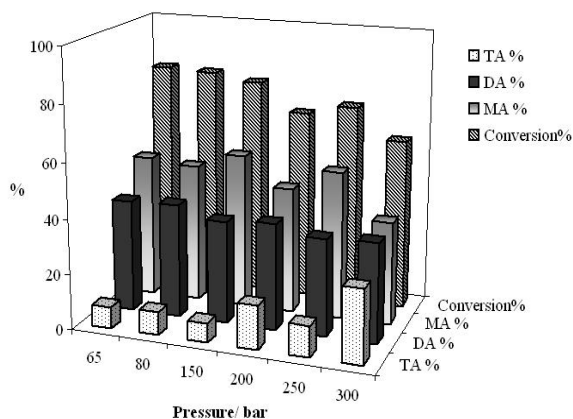


Figure 2 The effect of increasing pressure on both total conversion and products selectivity in continuous esterification of glycerol with acetic acid using Amberlyst® 15 (9.5 g) as catalyst at the temperature of 100 °C.

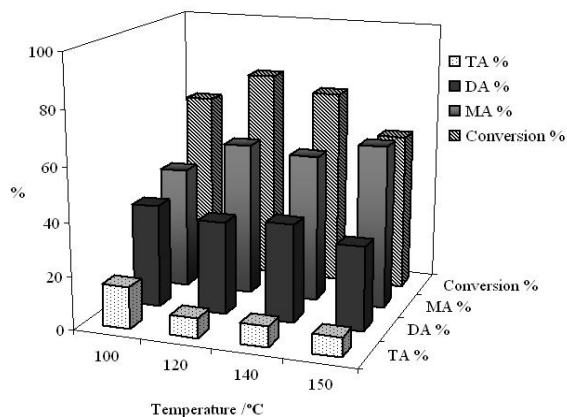


Figure 3 The effect of increasing temperature on both total conversion and products selectivity in continuous esterification of glycerol with acetic acid using Amberlyst® 15 (9.5 g) as catalyst at the temperature of 100 °C.

EFFECT OF TEMPERATURE

The effect of temperature (100–150 °C) on the esterification of glycerol with acetic acid at presence of Amberlyst® 15 was investigated as an acid catalyst in a continuous flow reactor. As shown in Figure 3, total conversion has a maximum at 120°C and further increase in temperature decreased the conversion. Decreasing of total conversion at higher temperatures might be due to loss of the catalytic activity. The trend of the selectivity variation for monoacetin is opposite of the triacetin when the temperature was increased. While for the diacetin a very smooth change is observed. An increase in the system temperature causes a decrease in $scCO_2$ density as well as a decrease in the solubility of the solutes. The more selective formation of monoacetin with increase in temperature may be explained by the higher solubility of monoacetin in contrast to di and triacetin.

THE EFFECT OF MOLAR RATIO

In order to investigate the effect of molar ratio of acetic acid to glycerol on the selectivity, their mole ratio was varied from 1.5 to 24 without changing the other variables. All experiments were carried out at 200 bars and 110 °C, as shown in Figure 4. The total conversion has decreased when the molar ratio was increased. We suggest that there is an interaction between glycerol and the catalyst active sites causing a decrease in the number of the glycerol molecules to undergo reaction with the protonated acetic acid. Moreover, selectivity of triacetin has highly risen, while it was dramatically decreased for di and monoacetin, as shown in Figure 4. The higher concentration of acetic acid leads to the higher triacetin conversion via the esterification reaction with 100% selectivity. The total conversion when the molar ratio is 1.5 is lower than in the case of 4.5. The higher concentration of glycerol could affect the reaction in two ways; the more attraction between glycerol and the catalyst diminishes the free active sites for carrying out the reaction. Furthermore, since the esterification reaction is a reversible reaction, lower concentration of the acetic acid may lead to an increase in the synthesis of monoacetin.

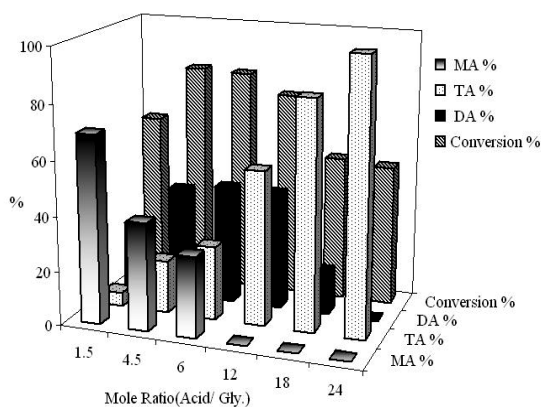


Figure 4 The effect of increasing acid to alcohol molar ratio on both total conversion (%) and products selectivity in continuous esterification of glycerol with acetic acid using Amberlyst® 15 (9.5 g) as catalyst at temperature of 110°C and pressure of 200 bar.

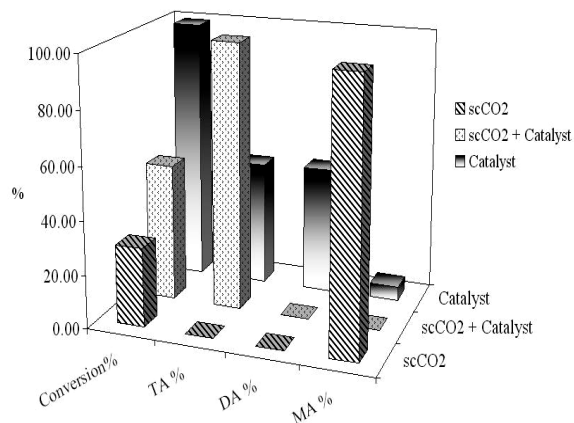


Figure 5 The effect of scCO₂, catalyst, and both on the esterification of glycerol with acetic acid using Amberlyst® 15 (9.5 g) as catalyst at temperature of 110°C and pressure of 200 bar.

THE EFFECT OF SCCO₂ AND THE CATALYST

The effect of scCO₂ and the catalyst, alone on the esterification of glycerol with acetic acid was investigated at 200 bars and 110°C when the mole ratio of the acid to the alcohol was 24. According to the results shown in Figure 5, in the presence of scCO₂ total conversion was decreased, while the selectivity was increased. The selectivity is increased to 100% when the reaction was carried out in the presence of both the catalyst and scCO₂. In contrast, the performance of the heterogeneous acid catalyst is opposite of the trend for the neat scCO₂. The presence of the catalyst has increased the total conversion, but the selectivity has been diminished. It may propose that increase in conversion, increases the water production that could lead to reverse reaction and more production of monoacetin.

CONCLUSION

The glycerol triacetate was selectively (100%) synthesized using a continuous esterification system and glycerol + acetic acid substrates under scCO₂ in the presence of a strong acid, heterogeneous catalyst namely, Amberlyst 15[®]. The results have shown that scCO₂ and the molar ratio of the substrates play a major role to tailor the selectivity in esterification reaction; however, other parameters such as pressure, temperature, and the catalyst have contributions in synthesis of the acetins. The selective synthesis is important because the boiling point of mono, di, and triacetin are very close (especially the last two) so that their separation is difficult.

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