

Kinetic and thermodynamic study of the synthesis of 5-hydroxymethylfurfural from biomass in high pressure/high temperature CO₂-water system

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ABSTRACT

Furan compounds obtained from sugars derived from lignocellulosic biomass are nowadays promising platform molecules for the production of fuels and bulk chemicals. In this work, synthesis of 5-hydroxymethylfurfural (5-HMF) from lignocellulosic biomass-derived hexoses was developed in two-phase supercritical CO₂-water systems. Conditions of reactions were above 10 MPa and 120°C, *i.e.*, the biphasic reacting mixture can be regarded as subcritical water-supercritical CO₂ system. Use of CO₂ as a potential reversible acid catalyst was studied from kinetic experiments and their modeling. 5-HMF yield improved with increasing pressure to reach a maximum of 48 mol% after 7 hours of reaction at 150 °C and under 25 MPa of CO₂. In a second part, Use of CO₂ as a solvent for extractive reaction is evaluated through experimental results of 5-HMF recovery and thermodynamic analysis.

INTRODUCTION

Since the last century the world has become tremendously dependent on oil as it is its main source of chemicals and energy. The growth in demand, combined with diminishing reserves, requires the development of new, sustainable sources for fuels and bulk chemicals. Biomass is the most attractive alternative feedstock. It mainly consists of cellulose, hemicelluloses and lignin, whose repartition depends on the plant nature. Hydrolysis of cellulose allows the production of carbohydrates which show promise because of their natural carbon content. Thanks to organic synthesis, they can provide biosourced chemical building blocks.

A typical product obtained from the conversion of sugars is 5-hydroxymethylfurfural (5-HMF, figure 1). 5-HMF is a promising platform chemical to produce fuels and renewably sourced polymers. For example, it can be oxidized in 2,5-furandicarboxylic acid (2,5-FDCA) which is a green substitute to terephthalic acid in the production of plastics. Together with levulinic acid, another platform molecule derived from 5-HMF, 2,5-FDCA has been mentioned in the top 10 biobased chemicals[1] by the U.S. Department of Energy in 2004.

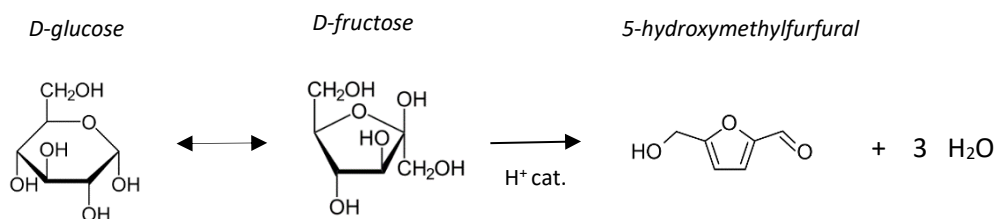


Figure 1. Reaction scheme for the synthesis of 5-HMF from hexoses.

5-HMF is produced from the acid-catalyzed dehydration of fructose and can also be synthesized from glucose through the isomerization to fructose (figure 1). Nevertheless, obtaining high yields of 5-HMF in acidic aqueous medium is limited by the partial degradation of 5-HMF into levulinic acid and formic acid in equimolar amount. Also, insoluble byproducts referred as humins are usually formed from sugars and 5-HMF polymerization. From literature, good 5-HMF yields have been obtained from fructose and glucose in different solvents and catalytic media: mineral acids [2] and solid acid catalysts [3] in high boiling point solvents, ionic liquids [4]. In contrast, few studies [5,6] have underlined the autocatalytic mechanism of the reaction which leads to interesting yields and selectivity, thanks to the action of formic acid and levulinic acid as catalysts of the reaction.

Current methods for 5-HMF synthesis suffer from non-reusable catalysts, short-term life regenerated heterogeneous catalysts and use of toxic organic solvents. As a cheap, non-toxic and easily recoverable molecule, CO₂ is ideally suited for use as a partner to water, as a solvent in this synthesis. Indeed, supercritical CO₂ (scCO₂, T_c=31 °C, P_c=7.4 MPa) in contact with water can act as a reversible catalyst liberating carbonic acid in water that can promote carbohydrates dehydration. In 2010, Wu *et al.* [7] were among the first authors to demonstrate the potential of CO₂ as the catalyst of carbohydrates dehydration. Inulin, a polymer of fructose, was converted into 5-HMF with a yield up to 53 % at 200 °C during 150 min under 6 MPa of CO₂. Six years later, three studies [8–10] showed the power of a two-phase water-CO₂ system to dehydrate fructose and glucose in 5-HMF between 90 °C and 200 °C, and up to 7 MPa of CO₂. The best 5-HMF yield (92 %) was obtained by Motokucho *et al.* in 2016 at 90 °C under 7 MPa of CO₂ for 168 hours [9].

Also, as an additional advantage, the solvent power of scCO₂ makes it possible to extract 5-HMF all along the reaction time, yielding to an extractive reaction one-pot process and which leads to enhancement of reaction yield and selectivity. The solubility of 5-HMF in scCO₂ has been studied by Jing *et al.* in 2011 for the first time [11]. They showed that 5-HMF solubility is greater at low temperature (40 °C) combined with high pressure (18 MPa). The use of a polar co-solvent like ethanol was shown to increase the solubility of 5-HMF in scCO₂ at given temperature and pressure.

Studies of kinetics about conversion of fructose to 5-HMF using homogeneous Brönsted acids, such as sulfuric acid and hydrochloric acid in water, have already been published in the literature. In 2014, Swift *et al.* published an extensive experimental study of kinetics of fructose dehydration where distribution of fructose tautomers and a direct path of fructose conversion to formic acid was considered [12]. In 2015, Fachri *et al.* developed an effective model for the dehydration of D-fructose to 5-HMF and the subsequent reaction of 5-HMF to levulinic and formic acids, including the formation of humins [13]. Yet, to the best of our knowledge, kinetic studies integrating the catalytic contribution of levulinic acid, formic acid and scCO₂ on hexoses dehydration have not been reported.

We report here the kinetics of the conversion of fructose to 5-HMF and byproducts in high pressure/high temperature CO₂-water two phase medium. A broad range of process pressure conditions (10 to 25 MPa) was applied to the system in a batch set-up at 120 to 160 °C. Experimental evolution of concentrations of reagents and products through time, enabled the development of a kinetic model including the contribution of levulinic acid, formic acid and scCO₂ as catalysts.

MATERIALS AND METHODS

Materials. D-(-)-Fructose (Sigma Aldrich, >99 % purity), D-(+)-glucose (Sigma Aldrich, >99 % purity), 5-HMF (Acros Organics, 98 %), formic acid (Acros Organics, 99 %), levulinic acid (Sigma Aldrich, 99 % purity) and sulphuric acid (PanReac, 0.01 M) were directly used without purification. Carbon dioxide was supplied by Air Liquid (99.98 % purity).

General procedure for the dehydration of D-fructose to 5-HMF. A mixture of 3.5 g of fructose and 60 mL of water was charged into a 90 mL high pressure reactor (Top Industrie, France). Then the mixture was heated at the desired temperature. When the temperature was reached, the reactor was charged with CO₂ using a syringe pump (Teledyne ISCO 260D). All the concentrations of reagents and products are known when high pressure CO₂ is injected in the reactor (time zero). The dehydration reaction was carried out under mechanical agitation (gas dispersing turbine) at 200 rpm rotation speed. Every hour, the progress of the reaction was monitored by analyzing the composition of the liquid phase using a high-pressure sampler (Top Industrie, France). 1 mL samples were then filtered through a 0.45 μm syringe filter prior to analysis. At the end of the reaction, the reactor was cooled to room temperature and the pressure was released. The solution was collected from the reactor using the sampler and filtered through a 0.45 μm filter (Milli-pore) before HPLC analysis. Each experiment was repeated twice.

Procedure for the determination of 5-HMF solubility in scCO₂. The solubility measurements were carried out in the same high-pressure reactor as the one used for the dehydration reactions. 5-HMF was charged into the reactor (in a sufficient amount to saturate the vapor phase) and heated to the desired temperature. The reactor was then charged with CO₂ with the syringe pump and the system was left to reach equilibrium under magnetic stirring. After 4 hours (the minimum equilibrium time was deduced from different experiments which yielded similar results), a sample of the vapor phase was taken thanks to the high pressure sampler. The content of the sample was recovered and diluted using deionized water before HPLC analysis for 5-HMF detection.

Analysis. The liquid samples were analyzed with a Dionex Ultimate 3000 HPLC system equipped with a Shodex RI-101 refractive index detector and an Agilent Hi-Plex H column. H₂SO₄ solution (5 mmol/L) at a flow rate of 0.55 mL/min was used as the mobile phase. The column temperature was kept at 60 °C. Internal calibration of the products was performed using ethanol as internal standard to determine sugar conversion, yields of 5-HMF, glucose, formic acid and levulinic acid. The insoluble fraction of the final solution (insoluble humins) was filtered, washed with water, dried in an oven at 50 °C for 24 hours and weighted.

RESULTS

Blank experiments. Before studying the effect of scCO₂ on the conversion of fructose to 5-HMF, blank experiments were conducted to identify a possible autocatalytic behavior. Without addition of any catalyst, 5-HMF was indeed produced from fructose in water with 17 mol% yield in two hours at 150 °C and 40 mol% yield in seven hours at 150 °C. A typical concentration versus time profile is shown in figure 2a. This result can be explained by two phenomena: i) the self-ionization of water at high temperature which releases a proton that acts as a Brönsted acid catalyst, ii) the synthesis of acid coproducts during the reaction, such as formic acid and levulinic acid, which act as catalysts for the reaction.

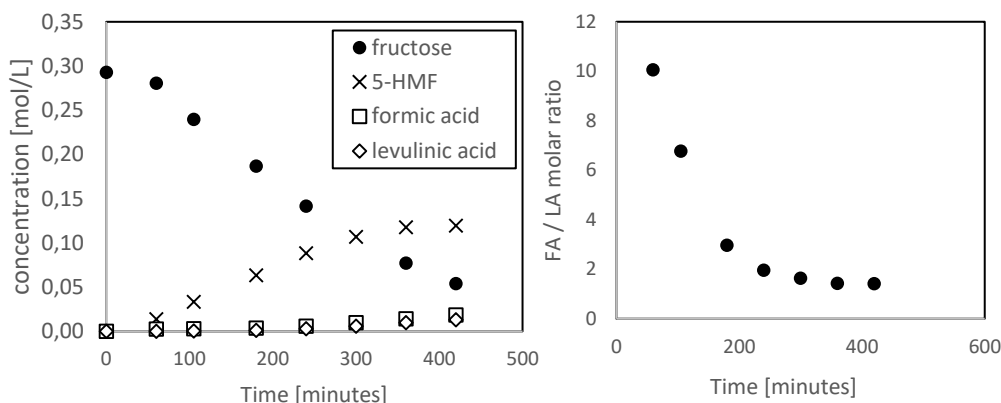


Figure 2. a-Typical concentration profile of fructose dehydration, 150 °C, no CO₂. b- Formic acid (FA) to levulinic acid (LA) molar ratio versus time, 150 °C, no CO₂.

Analyses revealed that formic acid and levulinic acid are not produced in a 1 to 1 molar ratio, as formic acid concentration detected in HPLC is higher than levulinic acid concentration. The variation of the molar ratio (formic acid/levulinic acid) versus time at 150 °C is given in figure 2b. After one hour, the amount of formic acid is 10 times greater than that of levulinic acid and molar ratio tends to reach a plateau at the value 1.4. This clearly indicates another pathway for formic acid production, which could be from fructose transformation. Levulinic acid and formic acid are both rehydration products of 5-HMF and it has been suggested that formic acid can also be a degradation product of fructose [12,14].

The production of acid coproducts is also underlined by the decrease of pH of blank experiments, from 6.8 initial value to 2.7 final value. Therefore, to develop an efficient kinetic model of 5-HMF synthesis from fructose in aqueous medium, the contribution of water, levulinic and formic acid as proton providers must be accounted for.

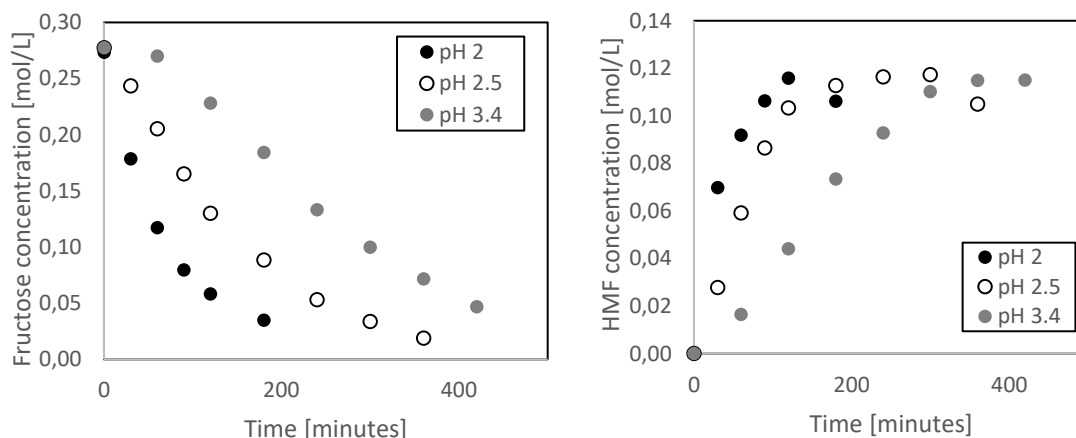
Dehydration of D-fructose in scCO₂-water system

Effect of scCO₂ on pH. To evaluate the catalytic power of scCO₂, the influence of scCO₂ pressure and temperature on the pH of scCO₂-saturated water was preliminarily examined. The dissociation of H₂CO₃ in water leads to the formation of H⁺ ions. The temperature dependence of H₂CO₃ dissociation has been correlated by Ryzhenko *et al.* in an empirical equation. In 2011, van Walsum *et al.* adopted the Ryzhenko correlation of the dissociation constant pKa in respect to temperature to develop a model predicting the pH of the binary CO₂-H₂O system. This model describes influence of temperature and pressure in the range of 100-250 °C and up to 15 MPa CO₂ partial pressure. At 150 °C, the pH decreases up to around 3.4 at 15 MPa. It is thus of interest to add scCO₂ in our system to lower the initial pH of fructose aqueous solution and check for increase of 5-HMF yield. Moreover, as pH is expected to decrease from an increase of CO₂ pressure above 15 MPa, experiments were carried out in a pressure range of 10 to 25 MPa.

Influence of initial value of pH. In 1977, Kuster *et al.* [15] studied the effect of initial pH on the formation of fructose dehydration products at 180 °C. Thanks to the addition of different amounts of formic acid as a catalyst, they found that 5-HMF formation was selectively enhanced between pH 2.5 and 3.8. More recently, de Souza *et al.* [16] reported that 5-HMF synthesis was favored between pH 1.5 and 2.15 at 150 °C. The differences in the pH range can be due to the change of temperature and catalyst, as de Souza *et al.* used hydrochloric acid instead of formic acid for their study. As a matter of fact, we decided to carry out experiments

with sulfuric acid as a strong acid catalyst to compare the effect of the initial value of pH on fructose dehydration.

Figure 3. Influence of pH on D-fructose dehydration at 150 °C, sulfuric acid as catalyst.



Three initial values of pH have been tested: 2, 2.5 and 3.4. As sulfuric acid dissociation constant is temperature dependent, an adjustment of initial pH at room temperature is needed and this has been calculated with the *PhreeqC* speciation software. Experimental results showed that decreasing pH resulted in faster fructose conversion and 5-HMF production (figure 3). Yet, at pH 3.4, the reaction was not accelerated but the rate was similar to the blank experiment. It can be suggested that the amount of H^+ in the system brought by the sulfuric acid intake was not sufficient to accelerate D-fructose conversion. Besides, the maximum 5-HMF yield was not dependent of the initial pH as it reached 42 mol% in all experiments, but at different times of reaction.

Influence of scCO₂ pressure on product yields and selectivity. The influence of pressure on the reaction is shown in figure 4. Increasing pressure from 10 to 25 MPa resulted in an increase of 44 mol% to 48 mol% 5-HMF yield at 150 °C for 7 hours. Regarding 5-HMF selectivity, high pressure lead to enhanced selectivity all along the reaction: after 3 hours, the selectivity at 25 MPa was still 80 % whereas it was 60 % without scCO₂. ScCO₂ addition in our system contributed to enhancement of 5-HMF selectivity thanks to the acidifying power of scCO₂ in the medium even if its action as a catalyst seems to be hindered by the autocatalytic character of the reaction in our conditions.

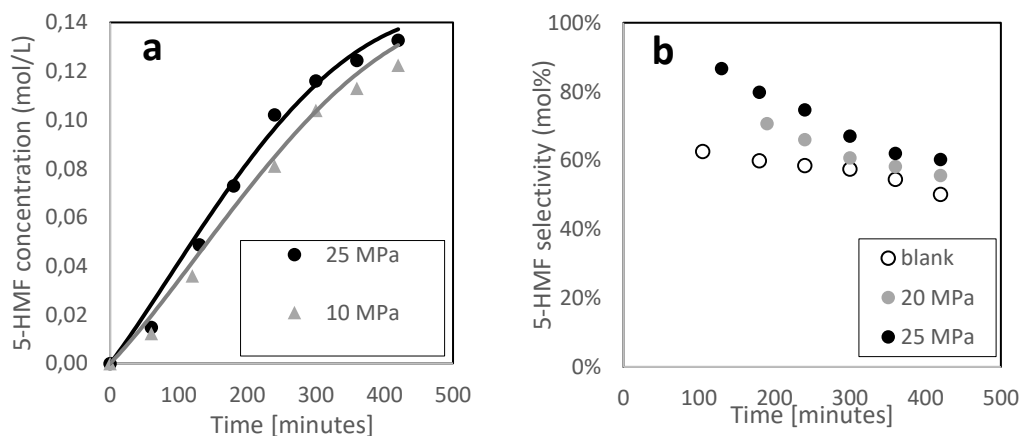


Figure 4. Influence of scCO₂ pressure on 5-HMF yield (a) and 5-HMF selectivity (b).

Kinetic Modeling. A conventional reaction pathway for fructose transformation into 5-HMF and byproducts was depicted by the literature and consists in three parallel reactions. Fructose is dehydrated into 5-HMF, which then rehydrates to form levulinic and formic acid. At the same time, fructose and 5-HMF are subjected to polymerization into solid humins. Formic acid formation from fructose was added to this scheme, in accordance with literature reports and experimental observation. The reaction network is given in figure 5.

Four acid-base equilibria were added to the network describing the formation of H^+ in the aqueous phase: self-ionization of water, dissociation of formic acid, dissociation of levulinic acid and dissolution of $scCO_2$. The system was described by four differential equations representing the evolution of concentrations of fructose, 5-HMF, formic acid (FA) and levulinic acid (LA) in respect to time. The total H^+ concentration in solution was calculated using equilibrium constants for the dissociation of water, carbonic acid, formic acid and levulinic acid and their dependence on temperature was considered. The reaction rate equations are given in figure 6.

Figure 5. Reaction network and rates used for kinetic modeling.

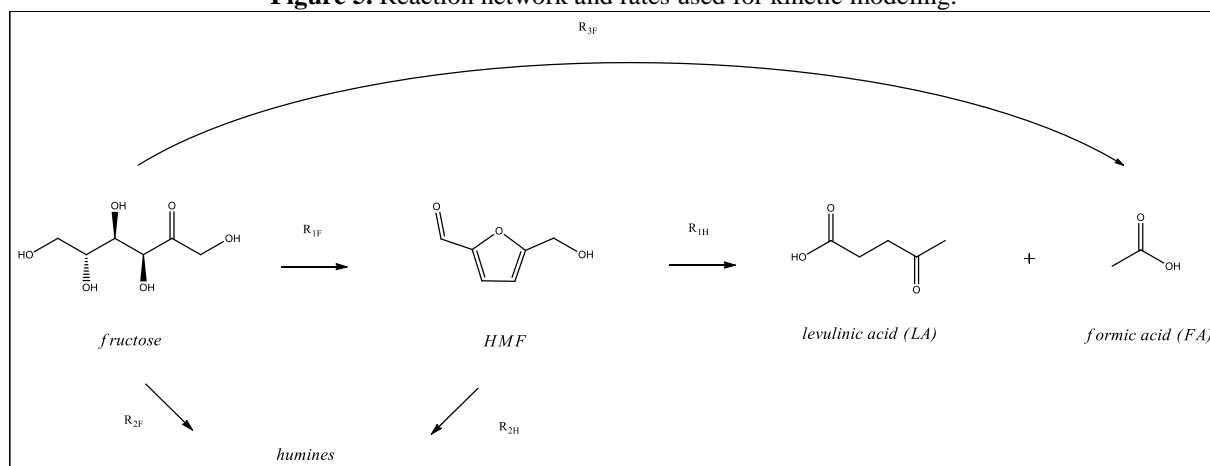


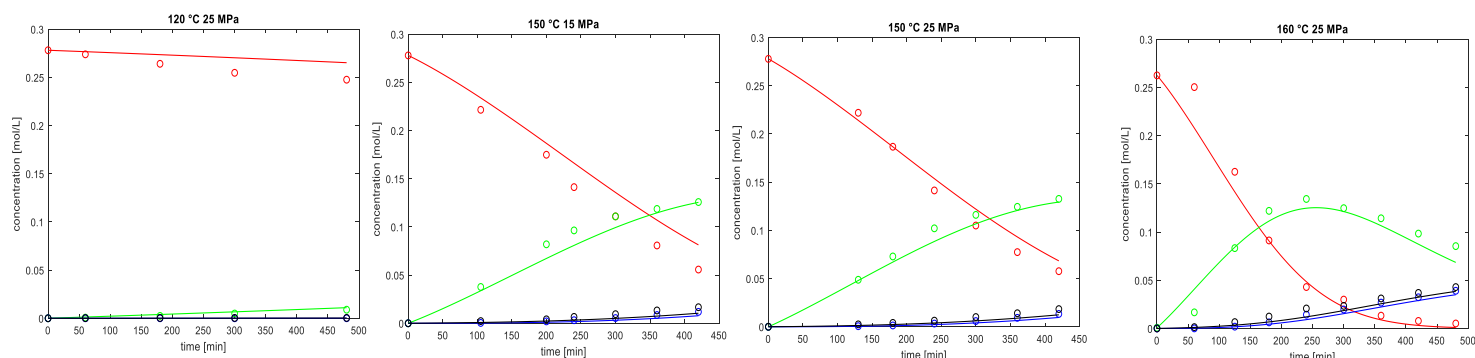
Figure 6. Reaction rate equation used for the kinetic modeling

$$\begin{array}{ll}
 \frac{dC_F}{dt} = -R_{1F} - R_{2F} - R_{3F} & R_{1F} = k_{1RF} \exp\left(-\frac{E_{1F}}{R} * \left(\frac{1}{T} - \frac{1}{T_R}\right)\right) (C_F)^{aF} (C_{H^+})^{\alpha F} \\
 \frac{dC_{HMF}}{dt} = R_{1F} - R_{1H} - R_{2H} & R_{2F} = k_{2RF} \exp\left(-\frac{E_{2F}}{R} * \left(\frac{1}{T} - \frac{1}{T_R}\right)\right) (C_F)^{bF} (C_{H^+})^{\beta F} \\
 \frac{dC_{FA}}{dt} = R_{3F} + R_{1H} & R_{3F} = k_{3RF} \exp\left(-\frac{E_{3F}}{R} * \left(\frac{1}{T} - \frac{1}{T_R}\right)\right) (C_F)^{cF} (C_{H^+})^{\gamma F} \\
 \frac{dC_{LA}}{dt} = R_{1H} & R_{1H} = k_{1RH} \exp\left(-\frac{E_{1H}}{R} * \left(\frac{1}{T} - \frac{1}{T_R}\right)\right) (C_{HMF})^{aH} (C_{H^+})^{\alpha H} \\
 & R_{2H} = k_{2RH} \exp\left(-\frac{E_{2H}}{R} * \left(\frac{1}{T} - \frac{1}{T_R}\right)\right) (C_{HMF})^{bH} (C_{H^+})^{\beta H}
 \end{array}$$

Activation energy values were taken from the literature and orders of fructose and HMF were set to 1 according to the kinetic scheme and the literature [12,13]. The other parameters (kinetic constants and orders of H^+) were determined based on minimization of errors between experimental data and the model using Matlab® software package. The results for the kinetics model of the conversion of fructose to 5-HMF and byproducts are given in figure 7 and table 1. As shown in figure 7, there is a good agreement between the model and experimental data values at the three different temperatures. The orders on H^+ are close to unity, which means

that the model predicts a first-order dependence on catalyst (an assumption already used in the literature [12]). The kinetic constants values are lower than those predicted by Fachri's model [13]. This could be explained by the use of weak acid catalyst in this study (levulinic, formic and carbonic acids), compared to the use of strong sulfuric acid in Fachri's study.

Figure 7. Comparison of experimental data (○ red : fructose, ○ green : HMF, ○ blue : levulinic acid, ○ black : formic acid) and kinetic model (solid line) for various reaction conditions



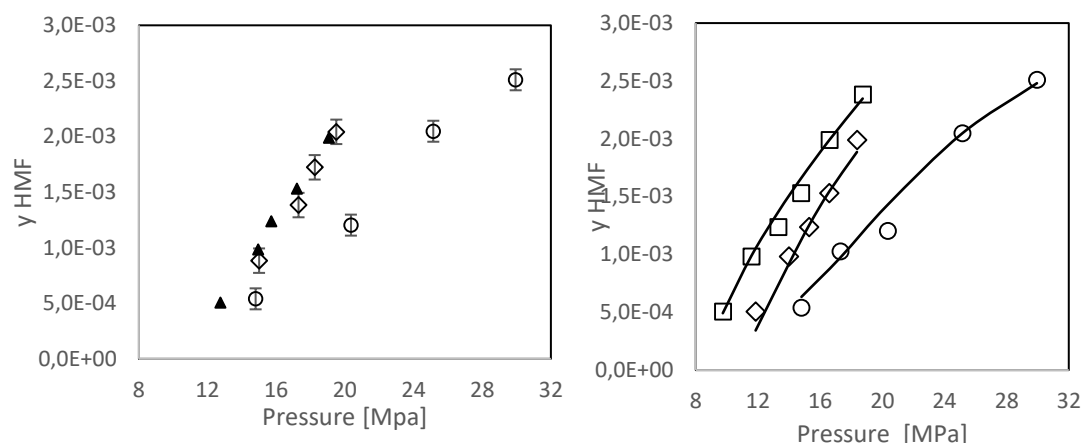
| kinetic constants (min^{-1}) | k_{1RF} | k_{2RF} | k_{3RF} | k_{1RH} | k_{2RF} |
|--|------------|-----------|------------|------------|-----------|
| | 0.66 | 0.33 | 0.0098 | 0.20 | 0.57 |
| orders on H^+ | α_F | β_F | γ_F | α_H | β_H |
| | 0.95 | 1.06 | 0.92 | 1.07 | 1.15 |

Table 1. Kinetic parameters for fructose conversion to HMF and by-products

Evaluation of scCO_2 as an extractive solvent.

To design an extractive reaction for fructose dehydration, it is of interest to evaluate the use of scCO_2 as an extractive solvent for 5-HMF. In that context, values of partition coefficients of 5-HMF between scCO_2 and water are needed in order to find, based on the concept of phase equilibria engineering, favorable operating conditions for this reaction. Up to now, no literature data have reported experimental 5-HMF partition coefficients in this system. To establish the phase ternary diagram of water-HMF- CO_2 , the three binary equilibria need to be studied. We present here our work on the measurement of vapor-liquid equilibrium in the CO_2 -HMF binary system. Moreover, the predictive performance of GC-PPC-SAFT as a group-contribution polar thermodynamic model was evaluated as group contribution approaches have already been successfully applied to predict complex phase behavior of mixtures of natural products and supercritical CO_2 [17].

Figure 6. Experimental measurement of 5-hydroxymethylfurfural solubility in scCO₂ at 40 °C (□), 70 °C (▲) Jing et al, ◇ this study), 100 °C (○) and GC-PPC-SAFT prediction (solid lines)



The solubility of 5-HMF in scCO₂ was measured at temperatures of 40 °C, 70 °C, 100 °C and pressure from 10 to 30 MPa. The experimental results were compared with the results from Jing et al [11]. Figure 6 shows the effect of temperature on 5-HMF solubility in scCO₂. 5-HMF solubility values at 70 °C are in good agreement with the study of Jing *et al.* Moreover, our experimental technique provided a new set of experimental points at high temperature (100 °C). As previously suggested by the literature, 5-HMF solubility is enhanced with high pressure and low temperature. Figure 6 also shows the prediction of 5-HMF solubility in scCO₂ with GC-PPC-SAFT at 40 °C and 100 °C. The model is able to give a good description of the system behaviour.

CONCLUSION

The conversion of fructose into 5-HMF and its degradation products was performed over a range of temperature, pH and CO₂ pressure conditions. It has been shown that fructose dehydration is catalyzed by different acid sources coming from the reaction products (levulinic acid and formic acid production) and from scCO₂ dissolution in water liberating carbonic acid. The use of scCO₂ as a reversible catalyst for the conversion of fructose to 5-HMF was shown to be effective, allowing 5-HMF yield of up to 48 mol% after 7 hours of reaction at 150 °C and under 25 MPa of CO₂. We developed a kinetic model which included for the first time the contribution of levulinic acid, formic acid and scCO₂ as catalysts for the conversion of fructose to 5-HMF. The favorable action of scCO₂ as a solvent for 5-HMF was also evaluated through experimental results of 5-HMF recovery and thermodynamic modeling. The on-going work consists in combining kinetics and thermodynamic models to develop a continuous extractive reaction process of 5-HMF from lignocellulosic hexoses.

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