Furfural production by continuous reactive extraction in a milireactor under the Taylor Flow regime

Citation for published version (APA):

Document license:
CC BY-NC-ND

DOI:
10.1021/acs.iecr.9b00604

Document status and date:
Published: 01/04/2019

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:
• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher’s website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
• You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the “Taverne” license above, please follow below link for the End User Agreement:
www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:
openaccess@tue.nl
providing details and we will investigate your claim.

Download date: 10. Dec. 2019
Furfural Production by Continuous Reactive Extraction in a Millireactor under the Taylor Flow Regime

Myrto Papaioannou, Roel J. T. Kleijwegt, John van der Schaaf,* and Maria Fernanda Neira d’Angelo**

Laboratory of Chemical Reactor Engineering Department of Chemical Engineering and Chemistry Eindhoven University of Technology, Eindhoven 5600 MB, The Netherlands

ABSTRACT: This study demonstrates the use of a millireactor as intensified technology for the continuous production of furfural via acid dehydration of xylose in a biphasic media. Very rapid extraction of furfural, aided by fast mass transfer rates, is key to preventing furfural subsequent degradation. Thus, by operating at elevated temperatures (i.e., 150−190 °C), it is possible to maintain high furfural selectivity (ca. 70%) at high xylose conversion (ca. 80%) and very short residence times (up to 2.5 min). A reaction mechanism is proposed based on the observed conversion-selectivity trends, and on the analysis of product distribution. The contribution of humins to the carbon balance is remarkably low due to the high furfural extraction rates achieved in the millireactor. Through first-principle reactor modeling, we further demonstrate the potential of combining intensified reactor technologies with the extractive synthesis of furfural and show that solvent optimization will be crucial to boost furfural selectivity above 80%.

INTRODUCTION

Recently, the conversion of biomass into chemicals and fuels has attracted increasing attention because of the fast depletion of fossil resources and the environmental impact associated with their use. Among the existing biomass feedstocks, nonedible and abundant lignocellulose (which consists of lignin, cellulose, and hemicellulose) is one of the most attractive. One of the most important derivatives of lignocellulose is xylose, a pentose largely abundant in the hemicellulose fraction, which accounts for 25−30% of the total biomass. In an acidic environment, xylose readily dehydrates to furfural, an important building block for the production of furfuryl alcohol and other polymer precursors.

The production of furfural at industrial scale was first realized in 1921 with the Quaker Oats process, in which the dehydration of xylose was carried out batch wise in the presence of diluted sulfuric acid (ca. 2 wt %) at low temperatures (ca.153 °C) and long residence time (ca. 5 h). Severe furfural degradation under these reaction conditions resulted in low furfural yields, which triggered further attempts of process optimization in the following years. In the 1960s, Quaker Oats introduced a continuous process in which furfural is stripped using steam in order to decrease its subsequent degradation into humins. Later in 1991, the SUPRAYIELD process made use of a two-reactor approach (one operating at 240 °C, and the other at 180 °C) to reduce the residence time to 1 h, and increase product selectivity.

The renewed interest in this conversion during the past decade has given rise to significant research which aims at a more fundamental understanding of the reaction mechanism (especially that of humins formation) as a means to propose further optimization strategies. Various studies suggest possible mechanisms for the production of furfural from xylose. The most accepted mechanism (Scheme 1) suggests an initial isomerization reaction, followed by three subsequent dehydration reactions leading to furfural. Further, furfural in the acidic aqueous solution undergoes a series of undesired degradation reactions (resinification reactions) that result in...
The use of heterogeneous catalysts for furfural production has been reported that the combination of Brønsted and Lewis acid catalyst consists one of the solutions toward the optimization of furfural production. Moreover, the use of CO₂ has been reported as an alternative catalyst choice. Finally, the addition of ionic liquids has been reported to be beneficial for the furfural formation.

On the basis of the premise that an important route to humins formation starts from furfural, Weingarten et al. proposed the in situ removal of furfural from the aqueous solution by extraction to an organic solvent (e.g., methyl-isobutyl-ketone or MIBK) to increase the selectivity of furfural. In such way, the reaction can successfully be conducted at higher reaction temperatures (150–170 °C), which allow for faster reaction rates with no significant drop in selectivity of furfural due to its direct extraction to the organic solvent. To that extent, it is expected that the benefits of furfural selectivity compensate the disadvantages of cofeeding a solvent (e.g., separation costs). Still, the required residence times to achieve significant yields under these conditions remain relatively long (e.g., 50 min). Besides, from an industrial point of view, a continuous process would be in fact more advantageous. For such system, the use of micro/milli scale reactors would be advantageous as they offer enhanced mass and heat transfer rates, as well as excellent control of residence time and reaction conditions, especially if operated in the Taylor flow regime. These characteristics are important to tune product distribution and maximize the extraction efficiency, which in turn will increase furfural selectivity. Moreover, millireactor can be used for high throughput experimentation, allowing fast and safe screening of different process conditions (e.g., temperature, and residence time).

In this work, a tubular millireactor was used for the continuous conversion of xylose to furfural using sulfuric acid as catalyst and toluene as extracting medium. In the present study, xylose is used as a model compound, representative of a sugar-rich hydrolysate stream, or even other hemicellulosic waste stream like corncobs. An innovative injection system has been designed for the present study to effectively control the reaction temperature and the residence time. This work focuses on the use of very short residence times (τ = 80–396 s), which have been largely unexplored in the open literature, and yet highly beneficial to minimize degradation reactions. Moreover, the influence of several parameters (e.g., temperature) on the furfural yield has been assessed to shed light on the reaction mechanism. Finally, as the extraction performance has significant impact on furfural selectivity, a sensitivity analysis is performed in an attempt to investigate the optimum operating conditions and ultimately propose approaches of process optimization.

**EXPERIMENTAL SECTION**

**Set-up Configuration.** The biphasic dehydration of xylose is conducted in the continuous experimental setup sketched in Scheme 2. The system includes three pumps for xylose solution, acid solution, and toluene, respectively. The injection system consists of three concentric tubes. Heat tracing is placed in the outer surface of the injection system so that the system acquires the desired inlet temperature. These capillaries are 1.5 m long and have an inner diameter of 6.25 × 10⁻⁵ m, 1.7 × 10⁻³ m and 3.86 × 10⁻³ m for xylose, sulfuric acid and toluene solutions, respectively. The three streams are heated in parallel without being in contact with one another and they mix at the reactor’s entrance as illustrated in Scheme 2.

At the mixing point of toluene and xylose streams, a thermocouple is placed in order to track the temperature of the stream. The reaction section follows the triaxial injection system. The reactor is 1.5 m in length with an inner diameter of 4.1 mm. It consists of a PTFE wall and a stainless-steel mesh jacket to provide the necessary structural integrity. After the reactor, the mixture is quenched in an ice bath followed by a pressure safety relief and a filter with 20 μm pores that protects the subsequent back-pressure regulator (BPR) from any solids formed during the reaction. Samples are taken after the BPR at atmospheric pressure and RT. The reported results are reproducible within 9% error.

For the furfural degradation reactions in monophasic conditions, a series of small glass vials (1.5 mL) are used as batch reactors, since severe degradation reactions and reactor blocking were evidenced under these conditions in the flow reactor. Nevertheless, the millireactor (with a nearly ideal plug-flow behavior) and the batch reactor are expected to have similar performance when operating in monophasic conditions. The glass vials are heated in an oil bath at the desired reaction temperature. At different residence times, the glass vials are taken from the oil bath and immediately cooled in an ice bath. The collected samples were filtered using filters of 1.2 μm. The
analytics procedure is identical to the one described above using HPLC instrumentation.

The partition coefficient experiments were performed in an autoclave batch reactor from titanium. The aqueous phase (1 wt % furfural) and the organic phase were inserted in a volumetric ratio of 1:2. The reactor was pressurized with nitrogen. The temperature was set using a heating jacket. The stirring rate was 700 rpm for 30 min. The settling time was 1 h and samples were taken every 15 min from both phases. The presented distribution coefficient is the average of the four samples per temperature.

Materials and Analysis. The materials used for the experiment and for the calibration of the instrumentation were 98+% D-xylose from Alfa Aesar, furfural of 99% purity obtained by Sigma-Aldrich, 98% pure H2SO4 by Sigma-Aldrich, and 99.7% toluene purchased from Biosolve. Finally, Pelikan Blue Ink was used for the slug flow development. All chemicals were used without any further treatment. Prior to analysis, the samples were filtered using syringe filters from glass fiber and with 1.2 μm porous size obtained from ThermoScientific. The inorganic phase was analyzed with HPLC instrumentation (Shimadzu SIL-20A High-Pressure Liquid Chromatograph). Xylose and sulfuric acid were detected with a RI detector (Waters 2414). Furfural was detected with UV–vis detector (SPD-M20A) at the wavelength λ = 254 nm. The column for the HPLC was Agilent Metacarb 67C and water as mobile phase at the rate of 0.5 mL/min. The oven temperature was set at 85 °C. The organic phase was analyzed by GC instrumentation (Varian CP-3800). Toluene and furfural were detected with build-in FID detector. The column was Varian capillary FactorFour CB Sil 5 CP. Helium was used as carrier gas at the constant flow of 1.5 mL min⁻¹. The temperature ramp starts at 120 °C for 20 min and then to 250 °C for 5 min.

Modeling. The reactor model consists of a set of nonlinear ordinary differential equations (i.e., ODEs) that describe the mole balances of the main components (i.e., xylose and furfural) in the two phases (i.e., water and toluene) present in the reactor. This model assumes an ideal plug flow behavior, which is reasonable when operating under the Taylor flow regime, and that only furfural is exchanged via mass transfer between the aqueous and the organic phases. Further, the model considers the kinetics proposed by Weingarten et al.,23 as they are, among all the kinetics reported in the literature, the best to describe our experimental trends. This kinetic model includes three reactions: direct xylose dehydration to furfural (R1), xylose and furfural condensation (R2), and furfural resynthesis (R3). Different values of mass transfer coefficient (k_a) and partition coefficient (m) are considered in a sensitivity analysis. k_a ranges from 1 × 10⁻⁸ s⁻¹, a value representative of a reactor with poor mixing, to 1 s⁻¹, a value representative of an intensified reactor with enhanced mass properties like the spinning disc reactor.25 The values of m were 2 and 20 M_furf (M_xyl)⁻¹, representing solvents with poor and high affinity to furfural, respectively. The lowest value is close to those of furfural in the mixture toluene-water, whereas the highest value is closer to recently investigated solvents.26 The complete set of ODEs (supplied in the Supporting Information) were solved numerically using MATLAB.

Definitions. The following expressions were used in this study to describe the xylose conversion, furfural yield and selectivity, molar carbon balance, and furfural partition coefficient:

\[
\text{xylose conversion: } X = \frac{n_{x}^{0} - n_{x}}{n_{x}^{0}} 
\]

\[
\text{furfural yield (total): } Y_f = \frac{n_f^{org} + n_f^{inorg}}{n_x^{0}} 
\]

\[
\text{furfural selectivity: } S_f = \frac{n_f^{org} + n_f^{inorg}}{n_x^{0} - n_x} 
\]

\[
\text{molar carbon balance: } B = \frac{n_x + n_f^{org} + n_f^{inorg}}{n_x^{0}} 
\]

\[
\text{furfural partition coefficient: } m = \frac{C_f^{org}}{C_f^{inorg}} 
\]

RESULTS AND DISCUSSION

1. Biphasic Production of Furfural. 1.1. Effect of Temperature and Residence Time. Figure 1 presents the effect of temperature on the xylose conversion and the furfural selectivity at τ = 396 s. As expected, temperature has a positive effect on xylose conversion, which increases significantly above 160 °C. Simultaneously, furfural selectivity increases with temperature until it reaches a maximum of ca. 70% at 170 °C. At temperatures higher than 170 °C, furfural selectivity drops along with a visible darkening of the reaction medium, indicating that degradation reactions are enhanced under these conditions. This maximum in the selectivity to furfural with increasing conversion suggests furfural formation is a two-step reaction: initially intermediates are formed from xylose and they subsequently are converted to furfural. Once furfural is formed in quantitative amounts, degradation reactions become more significant, especially at higher temperatures.

The importance of the in situ extraction becomes evident from Figure 2, where the furfural yield in the inorganic phase (i.e., the reaction medium) and in the organic phase (i.e., the extracting medium) are presented. The yield of furfural in the inorganic phase remains relatively low, whereas that in the organic phase increases rapidly after 160 °C, when the xylose conversion begins to take off. The significant decrease of the
are comparable. The mild decrease in furfural selectivity formation from intermediates and its subsequent degradation explained by the fact that the activation energies of furfural slightly, but later it reaches a plateau at ca. 65%. This can be conversion is further increased, furfural selectivity decreases conversion of the intermediates to furfural is higher than that converted into furfural. Thus, the activation energy of the intermediate products, which seem to require moderate assumption that furfural is not the direct dehydration product of xylose, but instead, xylose is initially converted into intermediate compounds can also degrade under the reaction conditions of humins formation during the reaction. Besides increasing furfural selectivity, preventing humins formation is important to ensure long-term stable operations, as the humins have sticky, glue like properties. Figure 4 shows the carbon balance is investigated in an attempt to observe the intermediate compounds can also degrade under the reaction conditions and, as a result, furfural selectivity cannot further increase.

1.2. Carbon Balance and Reaction Mechanism. The carbon balance is investigated in an attempt to observe the conditions of humins formation during the reaction. Besides increasing furfural selectivity, preventing humins formation is important to ensure long-term stable operations, as the humins have sticky, glue like properties. Figure 4 shows the carbon...
balance as a function of conversion, temperature and residence time. Since the main components detected and quantified are xylose and furfural, the unbalance accounts for (1) soluble intermediates (i.e., furfural precursors), (2) soluble humins (precursors), and (3) nonsoluble humins. The carbon balance remains above 90% up to ca. 40% conversion and 170 °C, indicating that up to 10% intermediate products form at the very initial phase of the reaction (i.e., at low xylose conversions), which are quickly converted to furfural consecutively. Above 40% conversion and 180 °C, the carbon balance rapidly decreases until ca. 60%, likely due to very fast degradation reactions under these conditions. This is in line with a visible darkening of the reaction mixture at elevated temperatures and residence times. More specifically, as shown in Figure 4, the mole balance remains almost constant at 95% up to 25% xylose conversion. A further increase in xylose conversion shows a linear decrease in the carbon balance.

Quantification of the solid formation was performed by a gravimetric analysis of the humins deposited during ca. 80 min of operation in the filter located at the reactor outlet. As shown in Table 1, the contribution of the solids to the carbon balance is not significant.

<table>
<thead>
<tr>
<th>time on stream (min)</th>
<th>mole carbon balance w/o solids (%)</th>
<th>solids mass (mg)</th>
<th>mole carbon balance with solids (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81</td>
<td>84.2</td>
<td>56</td>
<td>85.9</td>
</tr>
</tbody>
</table>

“Total flow = 7.5 mL/min, T = 190 °C, C_{xyl} = 4 wt %, organic phase: toluene, O/I = 2:1 mL ssf (N_{ssf})−1.

Considering that solids contribution in the carbon balance is minimized by in situ furfural extraction, the remaining unbalance consists of dissolved degradation products. Additional peaks were observed in the HPLC chromatograms of the experiments. According to the observed trends in the areas of these peaks with respect to residence time, it can be speculated that they correspond either to intermediate products prior to furfural formation or to soluble degradation products, precursors of insoluble humins. However, the identification of all these compounds was not possible. One intermediate that is frequently mentioned in the literature is xylulose. However, in the present work, the results of HPLC and NMR (Figure S1 and S2) do not suggest the presence of xylulose in the reaction mixtures. Moreover, it was found that xylose isomer (i.e., xylose dimer) has similar retention time as one of the unknown peaks in the HPLC chromatogram. Its contribution to the mole balance is minor (even at lower temperatures) and negligible at higher temperatures (T > 180 °C). Nonetheless, quantification of the remaining unknown compounds is not possible without their prior identification. Therefore, LC-MS and MALDI TOF analyses (Figures S3–S4) were conducted on the reaction solutions to get further insight into the nature of the soluble reaction products, and possibly the reaction mechanism. The LC-MS analysis suggests the presence of xylose degradation reactions that render soluble high molecular weight compounds (MW ≥ 550), as well as reactions between xylose and furfural. Additionally, the last dehydration intermediate before furfural formation (MW = 114) was detected. According to the MALDI TOF analysis, xylose oligomers are present already in the stock solution, as well as in the reaction mixture. This suggests that traces of xylose oligomers might be present in the original xylose purchase mixture. Additionally, it is plausible that xylose oligomers may be formed under reaction conditions in the inorganic phase and in the presence of Bronsted catalyst. Xylose oligomers are converted rapidly to xylose in acidic environment (Figure S.5). Similar behavior has also been reported for the glucose system. On the basis of the general kinetic model of cellulose hydrolysis, glucose reacts to several products. Among them, fructose and HMF are the most significant. However, the production of disaccharides is one reaction path present in acid hydrolysis. Hence, it could be expected that comparable reaction network might be present in this system as well.

All the possible mechanisms leading to furfural production including its extraction are summarized in Scheme 3. On the basis of the analysis above, it can be concluded that apart from furfural formation, there are many other parallel reactions affecting furfural selectivity; directly via condensation reactions and indirectly through altering xylose concentration (xylose oligomerization).

2. Furfural Degradation in Monophase System. Individual batch experiments of furfural degradation with the same sulfuric acid concentration (0.1 M H₂SO₄) have been executed. The goal of these experiments is to observe the behavior of furfural degradation reactions without the presence of xylose. So far, there is no clear conclusion in the literature regarding the reaction order of furfural degradation. However, most studies assume that it is first-order reaction and the same assumption is considered in this study.

From Figure 5, it can be observed that furfural conversion increases linearly with residence. Hence, the experimental data fit the assumption of first-order kinetics and they are in agreement with the majority of literature. The comparison of furfural resification rate with furfural extraction rate is of significant importance to investigate whether extraction is fast enough to prevent furfural degradation.

3. Effect of Mass Transfer on Furfural Production. In essence, the benefits of the biphasic production of furfural lay in the effective extraction of furfural via mass transfer from the aqueous solution to an organic phase, where degradation reactions no longer take place. In turn, this results in an increase of furfural selectivity. The efficiency of this approach is determined by the relation between the mass transfer rates of furfural and the furfural degradation rates.
The extraction rate is a function of the driving force of furfural extraction, (b) the configuration of the reactor influencing the mass transfer coefficient, and (c) the temperature defining the partition coefficient. These parameters are investigated separately.

3.1. Estimation of Mass Transfer Coefficient. The millireactor used in this study was operated in the Taylor flow regime, which may be described as an alternating sequence of slugs that flow through the channel with a nearly ideal plug flow behavior (Scheme 4). In the current system, the Taylor flow development has been verified visually as depicted in Figure 6. The degradation reaction rate is calculated at 180 °C.

As presented in Figure 6, the degradation reaction rate constant is on overall comparable with the mass transfer rate. More specifically, the mass transfer rate is lower than furfural degradation reaction rate for volumetric flows lower than 0.07 mL s⁻¹. In this region, the extraction performance is expected to be limited affecting furfural selectivity. For higher volumetric flows, the mass transfer rate is higher than furfural degradation rate and the degradation reactions involving furfural are expected to be limited. On the basis of the aforementioned observations, it is expected that the mass transfer properties of the selected reaction system have significant impact on furfural selectivity.

3.2. Effect of Temperature on the Water-Toluene Partition Coefficient of Furfural. Separate experiments for the determination of furfural partition coefficient (m) at reaction temperatures were performed in an autoclave reactor. An experiment at room temperature was performed and used as the base case. In Figure 7, the partition coefficient at this temperature is ca. 4 M_{furf}^{org} (M_{furf}^{inorg})⁻¹, as presented in the literature. The furfural partition coefficient decreases with temperature, as expected, because mutual solubility between toluene and water increases with temperature.

For temperatures from 170 and 180 °C, the partition coefficient decreases to a value of ca. 2.2 M_{furf}^{org} (M_{furf}^{inorg})⁻¹. At 190 °C, the partition coefficient decreases even further to 1.4, implying that the use of toluene even at this extreme...
condition is still beneficial for the present process, although not ideal. However, the extraction performance is clearly diminished from high temperatures, which leads to a selectivity decrease.

3.3. Sensitivity Analysis of Extraction Performance on Furfural Production. As previously discussed, the extraction performance has a significant impact on furfural selectivity. The present sensitivity analysis aims to define the optimum conditions of the biphasic furfural production with respect to product yield. The main variables influencing the extraction performance, and thus the selectivity, are (1) the mass transfer coefficient \( k_L a \), (2) the partition coefficient \( m \) and (3) the volumetric ratio between the organic to aqueous phase \( O/I \). Thus, these are the three process parameters that were investigated in this section. Figure 8 shows the results of this evaluation at 170 °C. Similar analysis is performed at 190 °C (Figure S9). It should be noted that the model is based on the kinetics by Weingarten et al., which consider two main degradation routes (i.e., xylose and furfural condensation reactions, and furfural resiniification), but do not account for xylose oligomerization reactions. Nevertheless, based on experimental observations, the latter seem to have limited extent under the reaction conditions of this study. Besides, this model does not consider the formation of any intermediate species prior to furfural, which appears to be of relevance at low xylose conversions (i.e., below 10–20%). This means that the furfural yields predicted by this model at low conversions lack accuracy. Thus, the sensitivity analysis will be mostly focused on the predictions at higher conversions.
As shown in Figure 8a, the reference monophasic reaction of xylose in acidic medium leads to complete conversion in about 100 min residence time under the reaction conditions considered, while the yield does not increase beyond 45% due to significant degradation reactions. With respect to the reference case, introducing in situ product extraction to a solvent with a relatively low affinity to furfural results in a very minor effect on xylose conversion, attributed to a decrease in the extent of xylose-furfural condensation reactions, and a visible yield increase (Figure 8b). However, such increase in yield is only significant (i.e., from 45% to 75% at full conversion) when relatively fast mass transfer rates apply (i.e., \( k_l a \) above 0.01 s\(^{-1}\)). When this condition is satisfied, it is remarkable to notice that the effect of further increasing the mass transfer coefficient does not play a significant role on furfural yield, as the organic phase quickly saturates. On the other hand, when very low mass transfer coefficients apply, the rate of furfural degradation compete with that of its extraction, and the overall effect of performing the reaction in a biphasic media is limited. Figure 8c displays the model predictions using a solvent with greater affinity toward furfural (i.e., greater \( m \)). For example, greater \( m \) values may be realized when using salty aqueous solution\(^{12}\) and/or organic solvents like MBK or 2-s-butylphenol.\(^{26}\) It is evident that the beneficial effects of furfural extraction on the final yield are more significant than in the previous scenario with a lower \( m \) (i.e., 90 vs 75% yield at full conversion). There is now a larger “storage” capacity of furfural in the organic solvent and a greater driving force for its extraction. Regardless the type of solvent, we observe that the rise in furfural yield increases with the mass transfer coefficients, and it levels off for mass transfer coefficient greater than \( 1 \times 10^{-3} \) s\(^{-1}\). Although increasing the mass transfer coefficient enhances only the rate of the extraction, coupling large mass transfer coefficients with high partition coefficients (e.g., by suitable solvent selection/design) promotes both the rate and the final extent of furfural extracted, showing an even greater impact on the final yield.

Another strategy to maximize the effect of performing the reaction in a biphasic media consists of increasing the organic-to-inorganic (O/I) ratio, although this is of course not the preferred option as it will result in greater reactor volumes, downstream separation costs and overall energy demand. Still, it may be considered as an optimization value to compensate for limitations of the solvent. The predicted performance using various O/I ratios of a poor solvent (i.e., \( m = 2 M_{\text{furf}}^{\text{org}} (M_{\text{furf}}^{\text{inorg}})^{-1} \)) and a better solvent (i.e., \( m = 20 M_{\text{furf}}^{\text{org}} (M_{\text{furf}}^{\text{inorg}})^{-1} \)) are displayed in Figure 8b, e, respectively. In this analysis, an intensified reactor system (i.e., \( k_l a = 1 \) s\(^{-1}\)) is considered. Similarly, to the observed effect of \( m \), increasing the O/I ratio speeds the extraction rate (i.e., by increasing the driving force for mass transfer), and enlarges the “storage” capacity of furfural in the organic phase. Thus, it is possible to exceed 90% yield at full conversion when using O/I = 10 mL\(^{\text{org}}\) (mL\(^{\text{inorg}}\))\(^{-1}\) for a poor solvent (i.e., \( m = 2 M_{\text{furf}}^{\text{org}} (M_{\text{furf}}^{\text{inorg}})^{-1} \)), and only O/I = 1 mL\(^{\text{org}}\) (mL\(^{\text{inorg}}\))\(^{-1}\) for a better solvent (i.e., \( m = 20 M_{\text{furf}}^{\text{org}} (M_{\text{furf}}^{\text{inorg}})^{-1} \)). Logically, the former scenario would result in severe product dilution and increase in processing and energy costs. This further emphasizes the relevance of combining solvent selection and reactor design.

A further increase in the reaction temperature to 190 °C (Figure S9), it is observed a 3-fold reduction in residence time (i.e., a 3-fold reduction of reactor volume) to achieve full conversion, and a sharper decrease in furfural yield after the maximum value is achieved because of the greater activation energies for the furfural synthesis reaction with respect to those of the furfural degradation reactions.

Overall, special attention should be paid to the temperature dependence of the partition coefficients, as it may not be negligible, as observed experimentally for toluene (Figure 7). Pending the design of optimized solvents,\(^{31}\) increasing the O/I ratio could be considered as a valid strategy to optimize furfural yields.

4. Practical Considerations. As shown in this work, the principles of process intensification (e.g., in situ extraction and increased mass transfer rates) are very attractive for the synthesis of furfural, and will be key in the transition from the traditional batch to a stable flow process. Further, we have demonstrated that through a combination of solvent and reactor selection, it is possible to run the reaction continuously, extend the stable operation window for this reaction, increase furfural yields, and reduce reactor size significantly. Nevertheless, in view of the practical implementation of this process, several considerations need to be taken into account in a broader perspective, for example, considering costs and environmental impact. While the benefits of millireactor technology (e.g., fast mass transfer rates, well-defined flow distribution, small inventory) have been instrumental in our laboratory study, it is an expensive technology and not yet scalable for multiphase bulk processes. Here, other scalable intensified reactor technologies (e.g., the spinning disc reactor\(^{25}\)) will become of relevance. Concerning the solvent, we have used toluene in this study to demonstrate the concept of furfural in situ extraction. However, the partition coefficient proved to be poor, leading to large amounts of solvent to reach a significant boost in selectivity. Further, toluene is not a “green” solvent and the downstream process of furfural purification is very energy demanding. Thus, other solvents\(^{31}\) should be considered for the practical implementation of this process. In terms of feed, we believe that this process and intensification strategies will be particularly important in the valorization of sugar-rich hydrolysate streams, which will become of relevance in the future biorefinery where biomass is first separated into its fractions prior to valorization into high-value chemicals. Our initial results with this type of feeds have shown very promising results and will be reported soon.

■ CONCLUSIONS

In the present study, a millireactor operating under the Taylor flow regime was used for the production and in situ extraction of furfural using diluted sulfuric acid as catalyst and toluene as extracting medium. Because of the enhanced mass transfer properties of the millireactor and its ease of control of the residence time, we were able to maintain high furfural selectivity (ca. 70%) at high xylose conversion (ca. 80%) and extremely short residence times (less than 2.5 min). Remarkably, this process configuration rendered minimal humins formation (<2% at 190 °C), thus allowing uninterrupted continuous operation. Yet, an important knowledge gap concerning the reaction mechanism and the intermediate and degradation products remain as important bottleneck to further understand and intensify this reaction. On the basis of the observed conversion-selectivity trends, and on the analysis of the liquid samples (where various xylose-oligomers and products from condensation reaction between xylose and furfural were observed), we were able to throw some light into the reaction mechanism.
Further, through an in-depth analysis of the mass transfer effects on the process performance and a modeling-aided sensitivity analysis, we have concluded that optimizing the solvent selection and/or O/I ratio can lead to nearly 100% yield if the reactor performance guarantees a sufficiently high mass transfer coefficient. The model predictions consistently reveal that mass transfer coefficient (i.e., and thus the reactor design and the operating flow regime) is an important parameter to achieve optimal results, especially under highly reactive conditions (e.g., elevated temperatures) which increase reaction rates but are prone to rapid product degradation. Thus, based on these results we can envision that further enhancing the mass transfer properties (e.g., in a spinning disc reactor) would allow for further extending the operation windows of this reaction. Hence, the results of this study are conducive toward the development of a robust and compact continuous reactor for the selective production of furfural in biphasic media.

**ASSOCIATED CONTENT**

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.iecr.9b00604. NMR spectra for xylulose, HPLC chromatogram of aqueous phase, LCMS, MALDI TOF, xylene oligomers reaction, furfural degradation kinetics, time for mass transfer through the film and the caps of the slug, and interfacial area for the two mechanisms of mass transfer in Taylor flow regime (PDF)

**AUTHOR INFORMATION**

Corresponding Author

*E-mail: m.f.neira.dangelo@tue.nl. Phone: +3140 247 8281.

**ORCID**

John van der Schaaf: 0000-0002-2856-8592
Maria Fernanda Neira d’Angelo: 0000-0001-8599-2800

**Notes**

The authors declare no competing financial interest.

**ACKNOWLEDGMENTS**

This work was performed under the framework of Chemelot InSciTe and is supported by contributions from the European Regional Development Fund (ERDF) within the framework of OP-Zuid and with contributions from the province of Brabant and Limburg and the Dutch Ministry of Economy.

**REFERENCES**

(12) Marcatullio, G. The Chemistry and Technology of Furfural Production in Modern Lignocellulose-Fedstock Biorefineries; Delft University, 2011.
(27) Negahdar, L.; Delidovich, I.; Palkovits, R. Aqueous-Phase Hydrolysis of Cellulose and Hemicelluloses over Molecular Acidic


