*Supplementary materials for*

# Methods to delay deactivation of zeolites on furan acylation: continuous liquid-phase technology and solvent effects

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## 1. GC-MS Analysis

GC analyses were performed on an Agilent 7890A GC (Agilent Technologies, USA) equipped with an automated split/splitless injection port and a flame ionization detector (FID). Separation was carried out on a DB-FFAP capillary column (30 m×0.25 mm×0.25 μm, Agilent Technologies, USA). The carrier gas was nitrogen (purity 99.999%) at constant flow of 0.8 ml/min. The oven temperature program was 70 °C for 3 min, 15 °C/min to 110 °C (4 min), 30 °C/min to 230 °C (3 min). The total GC analysis time was 16.667 min and the retention time was locked to 2-acetylfuran at 11.089 min. The percentages of several resultants were computed from the respective peak areas, which were calibrated by standard curves (external standard method).

The products were also identified by mass spectroscopy (MS) equipped with a mass selective detector (MSD) (5975C inert MSD with Triple-Axis Detector, Agilent). Electron ionization (EI) was used and MS was performed in scan mode (m/z=50-500) with the MS ion source at 230 °C and MS quadrupole at 150 °C. Data were acquired by the MSD ChemStation.

## 2. Experimental design

Response surface methodology (RSM) is a combination of mathematical and statistical techniques, which is useful for designing, analyzing and optimizing experiments. It can overcome the misinterpretation caused by classic empirical methods and has revealed competitive advantages for the optimization of experiments. Besides, Box-Behnken design (BBD) and central composite design (CCD) are regarded as the most suitable designs for evaluation of quadratic models, compared to other designs such as full factorial designs (FFDs). And BBD needs less experiments than CCD and FFD under the same conditions.

In this work, Response surface methodology (RSM) was used to analyze the influence of operating conditions, namely temperature [T (°C)], acetic anhydride/furan molar ratio (AA/Fu), catalyst/furan weight ratio (Catal/Fu), and reaction time [t (min)], to obtain a high molar yield of 2-acetylfuran [$Y_{2ACF}$ (mol%)]. A 4-factor and 3-level Box-Behnken design (BBD) was employed to design the experiments, consisted of 29 experiments, including 5 replicates at the center point. The independent variables ($Z_i$), levels and experiment design in terms of actual and coded variables compositions are presented in Table S1. The low, medium and high levels of variables were symbolized as -1, 0 and +1.

**Table S1.** The experimental domain

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| Factors | Symbol | Range and levels | | |
|---|---|---|---|---|
| | | -1 | 0 | 1 |
| Temperature (°C) | $Z_1$ | 50 | 60 | 70 |
| Acetic anhydride/Furan (molar ratio) | $Z_2$ | 2 | 3.5 | 5 |
| Catalyst/Furan (weight ratio) | $Z_3$ | 0.232 | 0.348 | 0.464 |
| Time (min) | $Z_4$ | 30 | 90 | 150 |

The software Design-Expert (version 8.0.6.1) was used to design and analyze the data obtained. For statistical calculation, the variables were coded according to Eq. (S1):

$$X_i = \frac{Z_i - Z_i^0}{\Delta Z_i} \tag{S1}$$

where $X_i$ is the independent variable coded value; $Z_i$ , the independent variable real value; $Z0$ i, the independent variable real value on the center point and $\Delta Z_i$ is the step change value.

The response variable was the molar yield of 2-acetylfuran. It should be pointed out that 2-acetylfuran was high selectively (approximately 100%) formed in the acylation of furan with acetic anhydride over H-beta zeolite. So the selectivity of 2-acetylfuran would not be taken as the response. The Box-Behnken design and response value are shown in Table S2.

**Table S2.** The Box-Behnken design and response value

| Trials | Variables | | | | Response |
|---|---|---|---|---|---|
| | $X_1$ | $X_2$ | $X_3$ | $X_4$ | Yield (mol%) |
| 1 | -1 | -1 | 0 | 0 | 42.5 |
| 2 | 1 | -1 | 0 | 0 | 65.2 |
| 3 | -1 | 1 | 0 | 0 | 76.8 |
| 4 | 1 | 1 | 0 | 0 | 87.6 |
| 5 | 0 | 0 | -1 | -1 | 46.1 |
| 6 | 0 | 0 | 1 | -1 | 75.3 |
| 7 | 0 | 0 | -1 | 1 | 65.5 |
| 8 | 0 | 0 | 1 | 1 | 80.9 |
| 9 | -1 | 0 | 0 | -1 | 51.9 |
| 10 | 1 | 0 | 0 | -1 | 75.6 |
| 11 | -1 | 0 | 0 | 1 | 65.5 |
| 12 | 1 | 0 | 0 | 1 | 83.3 |
| 13 | 0 | -1 | -1 | 0 | 41.0 |
| 14 | 0 | 1 | -1 | 0 | 70.4 |
| 15 | 0 | -1 | 1 | 0 | 64.0 |
| 16 | 0 | 1 | 1 | 0 | 86.8 |
| 17 | -1 | 0 | -1 | 0 | 51.4 |
| 18 | 1 | 0 | -1 | 0 | 68.9 |
| 19 | -1 | 0 | 1 | 0 | 71.9 |
| 20 | 1 | 0 | 1 | 0 | 82.6 |
| 21 | 0 | -1 | 0 | -1 | 43.1 |
| 22 | 0 | 1 | 0 | -1 | 74.7 |
| 23 | 0 | -1 | 0 | 1 | 58.5 |

| | | | | | |
|---|---|---|---|---|---|
| 24 | 0 | 1 | 0 | 1 | 86.8 |
| 25 | 0 | 0 | 0 | 0 | 72.7 |
| 26 | 0 | 0 | 0 | 0 | 72.3 |
| 27 | 0 | 0 | 0 | 0 | 79.2 |
| 28 | 0 | 0 | 0 | 0 | 73.0 |
| 29 | 0 | 0 | 0 | 0 | 74.6 |

A quadratic equation was generated to predict the response as a function of the more significant independent variables and their interactions, as shown in Eq. (S2):

$$Y = \beta_0 + \sum_{i=1}^{4} \beta_i X_i + \sum_{i=1}^{4} \beta_{ii} X_i^2 + \sum_{i=1}^{3} \sum_{j=i+1}^{4} \beta_{ij} X_i X_j \quad \text{(S2)}$$

where $Y$ is the predicted response of molar yield of 2-acetylfuran, $\beta_0$, $\beta_i$, $\beta_{ii}$ and $\beta_{ij}$ are the intercept term, the linear effect term, the squared effect term, and the interaction effect term, respectively.

## 3. Analysis of model

### 4.1 Analysis of variance (ANOVA)

The results of the analysis of variance (ANOVA) for fitting the second-degree response surface model are presented in Table S3. Values of "Prob>F" less than 0.05 indicates the model terms are significant. In this case, it indicates that the model (P<0.0001) is very significant, that is, there is only a 0.01% chance that a "Model F-Value" this large could due to noise. Besides, $X_1$, $X_2$, $X_3$, $X_4$ , $X_1X_2$, $X_3X_4$, $X2$ 2, $X2$ 3 and $X2$ 4 are significant model terms to affect the molar yield of 2-acetylfuran. The "Lack of Fit F-Value" of 0.82 (P=0.6555) implies the Lack of Fit is not significant relative to the pure error, which means there is a 65.55% chance that a "Lack of Fit F-Value" this large could occur due to noise. Non-significant lack of fit is good because the primary objective is that the model should fit the experimental data.

**Table S3.** Analysis of variance (ANOVA) for the quadratic model

| Source | SS | DF | MS | F-value | P | |
|---|---|---|---|---|---|---|
| Model | 5193.83 | 9 | 577.09 | 83.13 | **<0.0001** | **significant** |
| $X_1$ | 887.52 | 1 | 887.52 | 127.85 | <0.0001 | |
| $X_2$ | 2374.45 | 1 | 2374.45 | 342.04 | <0.0001 | |
| $X_3$ | 1164.27 | 1 | 1164.27 | 167.71 | <0.0001 | |
| $X_4$ | 453.87 | 1 | 453.87 | 65.38 | <0.0001 | |
| $X_1X_2$ | 35.40 | 1 | 35.40 | 5.10 | 0.0359 | |
| $X_3X_4$ | 47.61 | 1 | 47.61 | 6.86 | 0.0169 | |
| X2 2 | 138.86 | 1 | 138.86 | 20.00 | 0.0003 | |
| X2 3 | 88.07 | 1 | 88.07 | 12.69 | 0.0021 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| X2 4 | 74.07 | 1 | 74.07 | 10.67 | 0.0041 | |
| Residual | 131.90 | 19 | 6.94 | | | |
| *Lack of Fit* | 99.57 | 15 | 6.64 | 0.82 | **0.6555** | **not significant** |
| *Pure Error* | 32.33 | 4 | 8.08 | | | |
| Total | 5325.73 | 28 | | | | |

SS, sum of squares; DF: degrees of freedom; MS, mean square.

Statistical parameters for the quadratic model are given in Table S4. The large value of "R-squared" (0.975) shows that the model obtained is able to give a good estimate of response of the experimental design. The high "Adj R-squared" value (0.964) indicates that the model can explain 96.4% of the variability in the response, and the rest (3.6%) can be explained by the residues. The "Pred R-squared" of 0.948 is in reasonable agreement with the "Adj R-squared" of 0.964. For the proposed model, the value of 30.92 for "Adeq precison" indicates an adequate precision, thus this model can be used to navigate the design space. These results are proofs that the model is described well in the range studied.

**Table S4.** Statistical parameters for the quadratic model

| | | | |
|---|---|---|---|
| Std. dev. | 2.63 | R-squared | 0.975 |
| Mean | 68.56 | Adj R-squared | 0.964 |
| C.V.% | 3.84 | Pred R-squared | 0.948 |
| PRESS | 276.14 | Adeq precison | 30.92 |

Std. dev., standard deviation; C.V., coefficient of variation, PRESS, predicted residual sum of square

## 3.2 Model adequacy testing

The diagnostics and influence plots for model adequacy testing are shown in Figure S1. As shown in Figure S1A, the normal probability graph of internally studentized residuals resembles a straight line, indicating that the residuals follow a normal distribution. Figure S1B shows the plot of the residuals versus the ascending predicted response values, which is in accord with a random scatter. Figure S1C shows the plot of the residuals versus the experimental run order. It conforms to a random scatter, indicating that there are no lurking variables influencing the response during the experiment. The data points of predicted and actual response values are split evenly by the 45 degree line, as shown in Figure S1D, which indicate the predicted responses values are in agreement with the actual values in the range of the operating variables investigated. Figure S1E indicates there are no outliers in the data, which means that all data fit the current model well. All leverage values were less than 1 (Figure S1F), so there are no problems with the data points (unexpected errors), that is, no errors strongly influence the model. Difference of fits plot (Figure S1G) shows that all the data points lie within the limits, indicating that there are no statistics of externally studentized residuals magnified by high leverage points. Besides, difference in beta value plot (Figure S1H) indicates all the influences are suitable on any of the regression coefficients. As seen from Figure S1I, the Cook's distance values are in the determined range, which are in accord with the low leverage values (Figure S1F) and small studentized residuals (Figure S1B, C and E). These results above could strongly demonstrate the model used in this work was applicable and reliable with sufficient degree of accurancy.

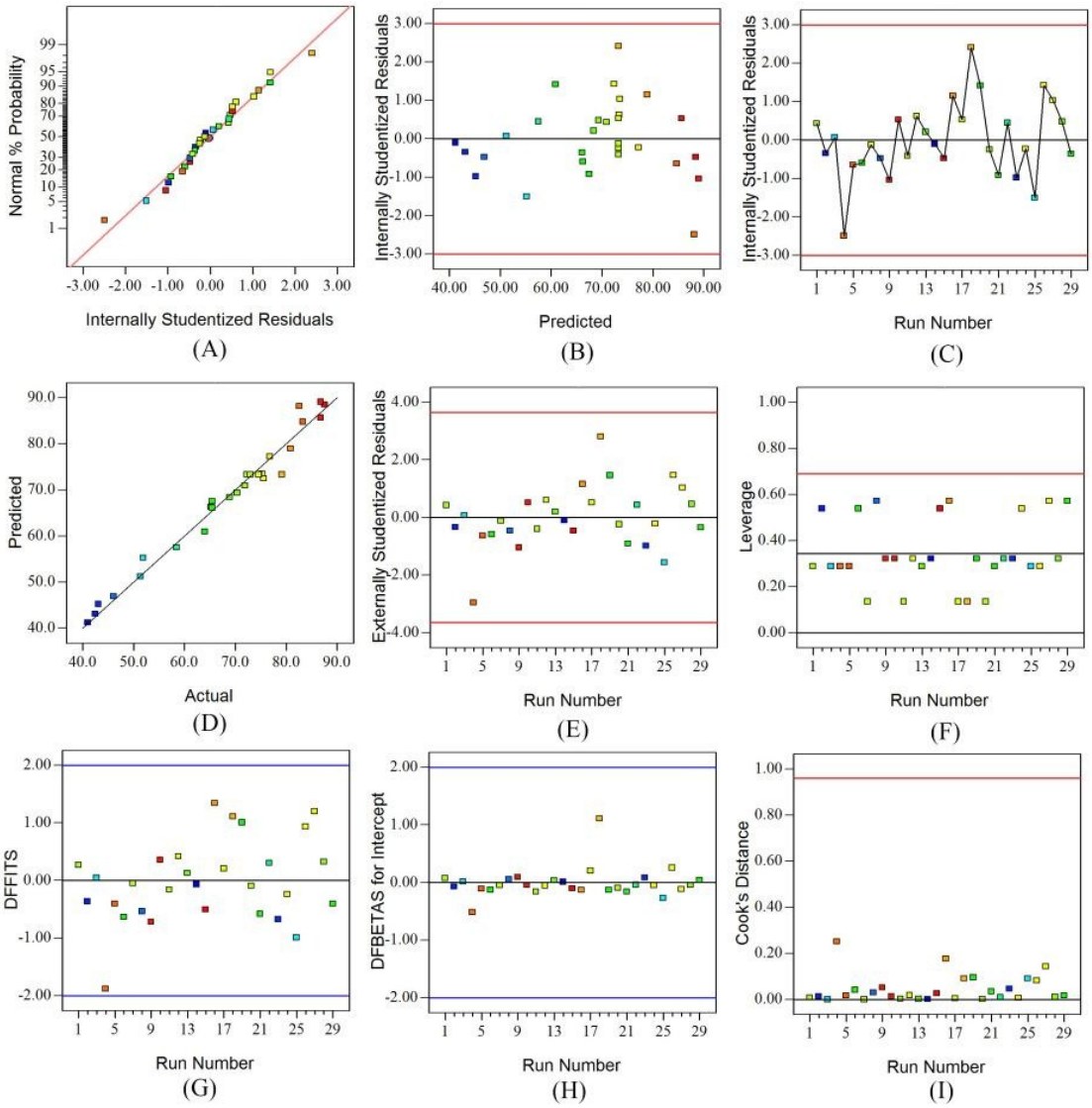


**Fig. S1.** Diagnostics and influence plots for model adequacy testing (A, normal probability graph of internally studentized residuals; B, internally studentized residual versus predicted value plot; C, internally studentized residuals versus run number; D, predicted versus actual plot; E, externally studentized residuals versus run number; F, leverage versus run number; G, DFFITS versus run number; H, DFBETAS for intercept versus run number; I, Cook's distance versus run number)

## 3.3 Model interpretation

The effects of variables and their interactions which are significant on yield of 2-acetylfuran were shown in Fig. S2, indicating that the acetic anhydride/furan molar ratio ($X_2$) was the most significant factor affecting the molar yield of 2-acetylfuran. Besides, It was suggested that the molar yield was considerably affected by independent variables of temperature ($X_1$), catalyst/furan weight ratio ($X_3$), and time ($X_4$) as well as interaction terms of temperature and acetic anhydride/furan molar ratio ($X_1X_2$), catalyst/furan weight ratio and time ($X_3X_4$). It was also worth mentioning that the regression coefficients of $X_1$, $X_2$, $X_3$ and $X_4$ were positive, it was found that a high level of $X_1$, $X_2$, $X_3$ and $X_4$ would be conductive to 2-acetylfuran yield. However, the

regression coefficients of $X_1X_2$, $X_3X_4$, $X2$ 2, $X2$ 3 and $X2$ 4 were negative, which resulted in the opposite effects.

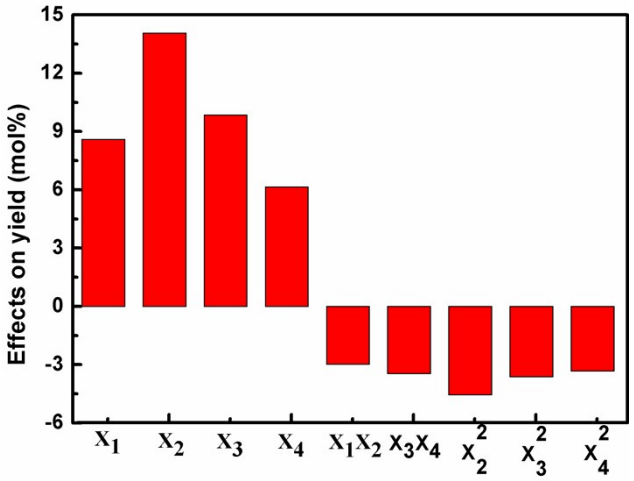


**Fig. S2.** Effect of the variables as well as their interactions on yield of 2-acetylfuran.

The response surface and contour diagrams determining the most adequate operating conditions and analyzing the process for 2-acetylfuran yield are presented in Figure S3. Figure S3A and B show the effect of temperature and acetic anhydride/furan molar ratio (AA/Fu) on 2-acetylfuran yield, in case of catalyst/furan weight ratio and time being fixed at their center points. Similarly, the effect of catalyst/furan weight ratio (Catal/Fu) and time are showed in Figure S3C and D, in case of temperature and AA/Fu being fixed at their center points. As presented in Figure S3A and B, the yield of 2-acetylfuran increased with the increasing of temperature and AA/Fu. And AA/Fu performed a remarkable effect on 2-acetylfuran yield. Adding AA/Fu enhances the accessibility of acylium ion which is the reactive intermediate. And improving the temperature promotes the activity of acid sites in H-beta zeolite, resulting in the enhancement of the reaction rate. The 2-acetylfuran yield was only 41 mol% at the lowest temperature (50 °C) and the lowest AA/Fu (2), while reached 87.6 mol% at the highest temperature (70 °C) and the highest AA/Fu (5).

From Figure S3C and D, it can be seen that higher Catal/Fu and more time lead to better yield, especially the high Catal/Fu. Since there were no elliptical nature of the contour plots being observed in Figure S3A and C, the interactions between temperature and AA/Fu (Figure S3A) or between Catal/Fu and time (Figure S3C) are weak, which is in good agreement with the outcome in Figure 2.

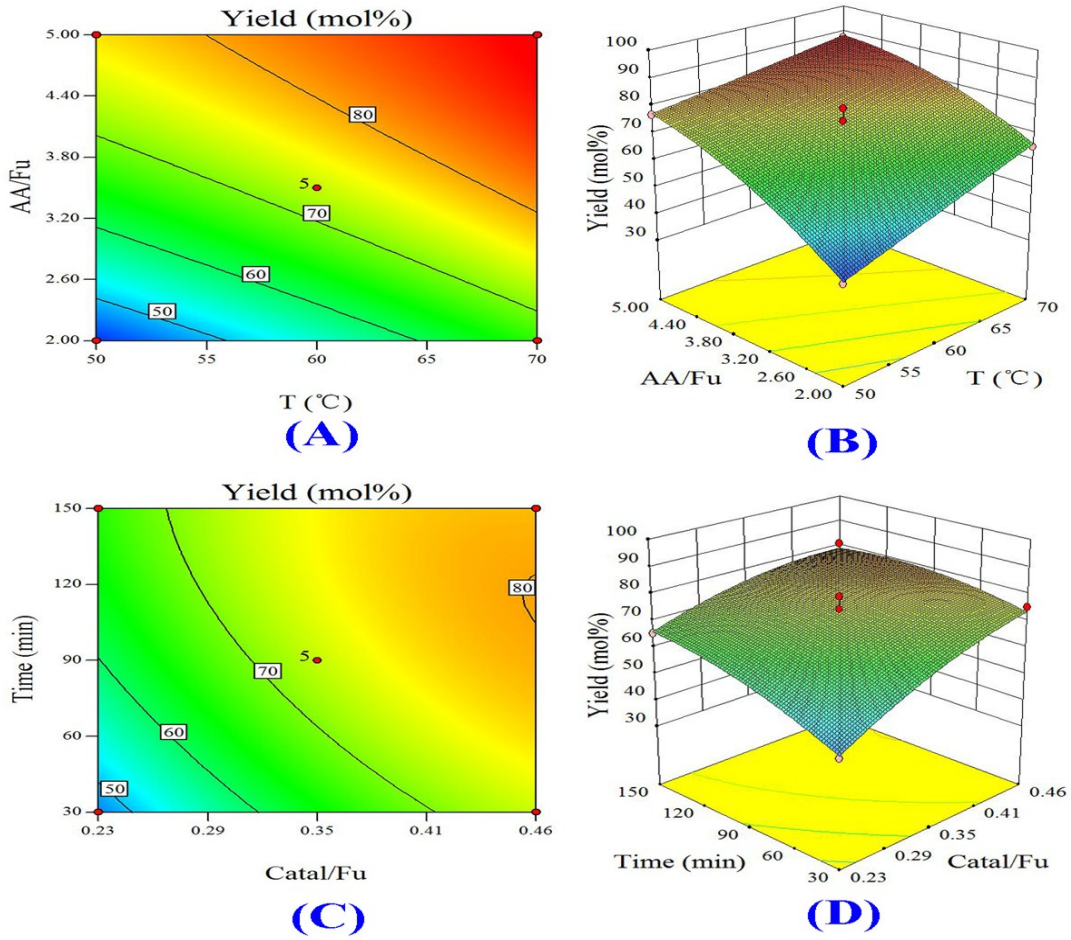


**Fig. S3.** Response surface and contour diagrams for 2-acetylfuran yield (A and B: interaction of temperature with acetic anhydride/furan molar ratio. Conditions: catalyst/furan weight ratio=0.35, 90min; C and D: interaction of catalysts/furan weight ratio with time. Conditions: 60°C; acetic anhydride/furan=3.50)

The results of optimization of model are presented in Figure S4.

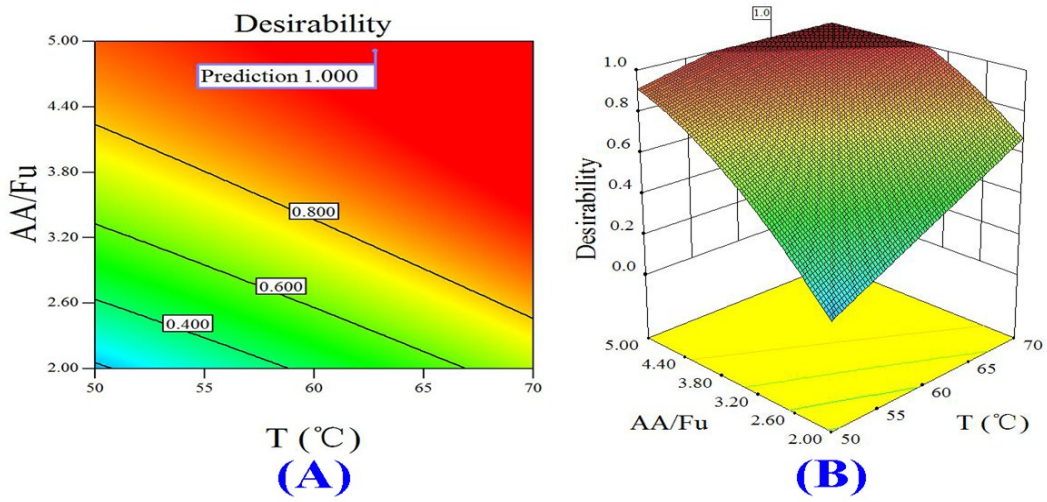


**Fig. S4.** Response surface and contour diagrams for the optimization of acylation of furan with acetic anhydride. Conditions: Catalyst/furan weight ratio=0.44; time=43min.