The present study, on the optimisation of the scale-up of a Friedel-Crafts acylation, joined together experimental calorimetric techniques and simulation techniques. The adopted methodology involved the execution of isothermal tests at different temperatures, using the Reaction Calorimeter RC1, to obtain the heat flow data versus time. These data were used to perform a kinetic study of the above reaction by using the simulation software BatchCAD. The kinetic model was confirmed comparing the experimental data obtained operating the desired reaction in adiabatic mode (Phi-Tec II), with the data obtained by simulation in the same conditions. Using this kinetic equation it was possible to simulate the process by the software, at first in the pilot plant conditions: the good agreement between the calculated and the experimental data confirmed the accuracy of the kinetic equations. Finally several large scale production plant simulations were run in order to maximise the yield and minimise the thermal risks varying both dosing time and reaction temperature. At the end of the study a high quality and safer reaction was obtained, saving the time (and the money) usually spent in traditional scale-up procedures.

**Keywords:** thermal runaway, Batch Reactor simulation, process optimization, Friedel-Crafts acylation, kinetic modelling

**Introduction**

The Fine Chemical Industries are ever more under huge pressure because of increasing R&D costs, growing competition and pricing pressure; therefore they need to speed-up the time-to-market to achieve market leadership.

In Italy, most of the Chemical Industry is constituted by Small and Medium-sized Enterprises (SME’s) with limited number of workers in each firm, and with the strong tendency to resort to outsourcing. This situation often prevent from a correct identification of kinetic parameters related to the chemical production of new compounds, that is essential whether to assure the company’s productivity or to comply with stricter and stricter laws on health and safety for people and environment.

Both safety and economical aspects are critical points particularly for small and medium enterprises. The aim of the present study is to define a kinetic model for the studied Friedel-Crafts reaction using calorimetric data, obtained from the Mettler RC1 and other calorimetric techniques, and a commercial computer program, BatchCAD [1], in order to simulate and to optimise the existing process in terms of productivity and safety.

**Methodology**

**Study of the desired reaction**

From literature, Friedel - Crafts acylations are well known reactions [2, 3]. The production methodology of the studied reaction was developed starting from the Friedel-Crafts acylation of Toluene in homogeneous phase with Succinic Anhydride and AlCl₃ as catalyst at low temperature.
The reaction scheme of the desired reaction is:

![Reaction Scheme]

As the measured $\Delta T_{ad}$ is about 50°C, the MTSR for the reaction performed at low temperature cannot exceed 280°C. By DSC tests we can assume that the reaction mass is stable up to 280°C. From these preliminary data we can say that the reaction does not show any potential runaway risk.

Preliminary DSC runs on the final reaction mass, reagents and products show that all samples do not decompose or oxidize within the temperature range 30–280°C during a standard dynamic test (scanning rate 5°C/min, static air atmosphere, sealed steel crucible medium pressure resistant). So we can assume that the reaction mass is stable up to 280°C.

Figure 1 illustrates the DSC of the pure product: the only relevant thermal effect is endothermic, due to the melting of the product at around 120°C.

![DSC Illustration]

The kinetic behaviour of the reaction system was studied by carrying out a series of isothermal Reaction Calorimetry (RC) experiments. The tests were run in batch mode, adding all Succinic Anhydride to the organic substrate (Toluene) at the beginning of the experiment, using Toluene as solvent and Aluminium Chloride as catalyst to yield a carboxylic compound derivative (3-(4-Methyl Benzoyl) Propionic Acid).

The RC1 tests showed that the reaction is exothermic: the shape of the RC1 curves obtained is typical for a reaction that accumulates a percentage of reactant (Figure 2a). Accumulation increases when decreasing temperature. The reaction is usually performed at around 0°C. Table 1 summarises the calorimetric data at three different temperatures.

![Experimental Heat Flow]

The equations proposed to describe the system were:

$$C_4H_4O_3 + C_7H_8 + AlCl_3 \rightarrow \text{activated complex} + AlCl_3$$

$$\text{activated complex} \rightarrow C_{11}H_{12}O_3$$

The kinetic expressions proposed were the following:

$$r_1 = k_1 \cdot [C_4H_4O_3]^m$$
$$r_2 = k_2 \cdot [\text{activated complex}]^n$$

This simplified reaction scheme, according to literature [2, 3], involves at first the formation of a not-isolating substance, the so-called “activated complex”, and then the formation of the product.
The partial reaction orders with respect to the Succinic Anhydride, $m$, and to the activated complex, $n$, which give the best fit of the Heat Flow versus Time curves were determined using the “kinetic fitting environment” of the software BatchCAD from each isothermal experiment. Results are in Table 2.

<table>
<thead>
<tr>
<th>Reaction temperature [$^\circ$C]</th>
<th>$k_1$ [1/s]</th>
<th>$k_2$ [1/s]</th>
<th>$m$</th>
<th>$n$</th>
<th>$\Delta H_{r1}$ temperature [kJ/mol]</th>
<th>$\Delta H_{r2}$ temperature [kJ/mol]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.814·10$^{-3}$</td>
<td>8.286·10$^{-3}$</td>
<td>1.527</td>
<td>0.570</td>
<td>10</td>
<td>$-96.5$</td>
</tr>
<tr>
<td>20</td>
<td>4.309·10$^{-3}$</td>
<td>2.602·10$^{-2}$</td>
<td>1.048</td>
<td>0.795</td>
<td>10</td>
<td>$-101.55$</td>
</tr>
<tr>
<td>30</td>
<td>6.450·10$^{-3}$</td>
<td>7.513·10$^{-2}$</td>
<td>1.659</td>
<td>0.935</td>
<td>10</td>
<td>$-97.3$</td>
</tr>
</tbody>
</table>

Table 2: Estimate of reaction order

After the reaction orders $m$ and $n$ were determined from all isothermal experiments, they were rounded and fixed as $n=1$ and $m=1$, and the fitting procedure was repeated to determine the isothermal rate constants at three different temperatures. Results are summarised in Table 3. Figure 2b shows the regression plots for the RC1 isothermal experiment at 20°C.

The activation energy and the frequency factor for the desired reaction were determined, according to the Arrhenius equation, from temperature dependence. The calculated values are summarised in the following table 4 and represented in Figure 3.

<table>
<thead>
<tr>
<th>Reaction temperature [$^\circ$C]</th>
<th>$k_1$ [1/s]</th>
<th>$k_2$ [1/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.431·10$^{-3}$</td>
<td>3.940·10$^{-2}$</td>
</tr>
<tr>
<td>20</td>
<td>4.269·10$^{-3}$</td>
<td>4.217·10$^{-2}$</td>
</tr>
<tr>
<td>30</td>
<td>7.244·10$^{-3}$</td>
<td>6.251·10$^{-2}$</td>
</tr>
</tbody>
</table>

Table 3: Estimate of kinetic constants

<table>
<thead>
<tr>
<th>Reaction</th>
<th>$A_1$ [m$^3$·kmol$^{-1}$·s$^{-1}$]</th>
<th>$E_1$ [kJ/mol]</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleophile attack</td>
<td>2.176·10$^{-3}$</td>
<td>9.934·10$^{-2}$</td>
<td>1</td>
</tr>
<tr>
<td>Product formation</td>
<td>$-87.29$</td>
<td>1716</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4: Estimate of Arrhenius parameters for the acylation

Figure 2b: BatchCAD fitted plot for the RC1 isothermal experiment at 20°C.

Figure 3: Kinetic constants vs $1/T$
These kinetic data were assumed to model the thermal behaviour of the studied reaction. Kinetic equation was verified by simulating, using BatchCAD, the desired reaction in adiabatic conditions in a Phi-Tec II test cell and comparing the simulation results with the experimental ones. The

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Toluene</td>
<td>35</td>
<td>g</td>
</tr>
<tr>
<td>Aluminium chloride</td>
<td>10.5</td>
<td></td>
</tr>
<tr>
<td>Succinic anhydride</td>
<td>4</td>
<td>g</td>
</tr>
<tr>
<td>Conditions</td>
<td>adiabatic</td>
<td></td>
</tr>
<tr>
<td>Stirrer</td>
<td>200 rpm</td>
<td></td>
</tr>
<tr>
<td>φ</td>
<td>1.35</td>
<td></td>
</tr>
</tbody>
</table>

Table 5

At the end of the dosing, the temperature is heightened up to 25°C. Under these conditions, no accumulation of Succinic anhydride occurs in the reactor, and temperature profile could be classified as QFS (Quick onset, Fair Conversion and Smooth profile) [4].

Pilot Plant Process and Simulation

Pilot plant process is performed using a 2.5 m³ steel reactor. The heat transfer system is composed by two service fluids which are fed into a 0.21 m³ jacket on a drain/fill mode. A manual controller allows heating, by overheat steam (127°C), and cooling, by water-glycol ether mixture (–20°C), the reactor to the appropriate operation temperature. Figure 5 illustrates the described configuration. During normal operation conditions, the reactor is charged with 649.5 kg of Toluene, 199.9 kg of Aluminium chloride and, after two hours and half, dur-
Optimisation of the Pilot Plant Process by Simulation

According to DSC tests and to RC1 experimentation, the reaction does not show any thermal risk: the final reaction mass is thermally stable in the 30–280°C range temperature and the measured $\Delta T_{ad}$ of the desired reaction is 50°C which leads to a MTSR of about 50°C in the pilot plant conditions.

Several large scale production plant simulation using the BatchCAD simulation environment were run to optimise the process in terms of productivity. At first the time of Succinic anhydride addition was reduced, and the final heating was eliminated. In this case the optimal configuration, according to the results, was an addition of Succinic anhydride in half an hour. In Figure 7 it is possible to see the temperature profile simulated by BatchCAD.

A second step in the process optimisation was to pass from semi-batch to more severe batch conditions. Figure 8 shows the simulated reactor and jacket temperature profiles in a batch reactor operating in the same temperature and charge conditions of semi-batch reactor. In the batch mode the reactor temperature is under 20°C during the whole process, so the reaction can be performed in safe conditions.

Furthermore comparing the conversion of the Succinic Anhydride in the optimised semi-batch mode and in the batch mode (Figure 9) we can state that the batch mode leads to a higher conversion in a shorter time. However both cases lead to a total conversion to form the product.

The last series of simulations were run to optimise the reaction temperature in batch mode. Figure 10 shows the reactor temperature profile in a process performed in batch mode at an initial temperature of 20°C.
Conclusions

The present study shows a short-cut methodology to optimise the scale up of a chemical processes both in safety and economical terms, to save time and money.

Limited targeted experiments in the Mettler RC1 and the DSC along with the kinetic capabilities of the software BatchCAD easily allow obtaining an accurate kinetic model of the chemical system. The resulting data have been verified experimentally in an adiabatic calorimeter and confirmed by real pilot plant data. The mentioned software allows the modelling of an industrial reactor and the simulation of the whole process, leading to the identification of safe operating conditions.

The model has been used also to simulate the behaviour of the pilot plant in different conditions to optimise the whole process.

A good characterisation of the reactant system allows to perform a quicker scale-up, promptly recognising any mistakes and inadequacy. In this particular case the applied methodology allowed to drastically reduce the reaction time and to avoid the initial cooling period.

This lecture was held at the 11h RXE User Forum Europe in Pontresina (Switzerland), September 2003.

L. Gigante, A. Lunghi, S. Martinelli, P. Cardillo (Stazione Sperimentale per i Combustibili, San Donato Milanese);
L. Picello, R. Bortolaso, M. Galvagni (F.I.S. Fabbrica Italiana Sintetici, Vicenza), Italy.

References:


Mettler-Toledo GmbH. AutoChem CH-8603 Schwerzenbach, Switzerland