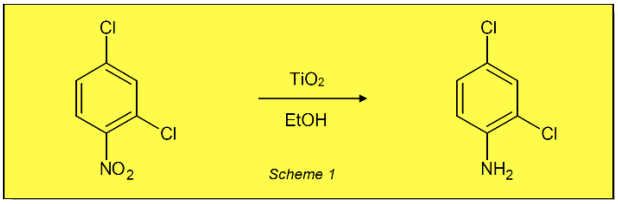
Application Note 46:

Photochemical hydrogenation with TiO_2 packed column

Produced by Vapourtec

Abstract

This application note expands on the work described in application notes 41 and 42 describing a photochemical hydrogenation using an immobilized photo catalyst. Using an immobilized catalyst allows the reactants to be free of a titanium dioxide slurry/suspension. Instead the TiO_2 is packed into a column type reactor. The versatility the of Vapourtec's systems is demonstrated and a new UV illumination system for column reactors is presented.



Scheme 1

For more details, please contact:
Vapourtec Application Support
application.support@vapourtec.com or call:
+44 (0) 1284 728659

Background

This app note continues from previous application notes 41 and 42. Using a column UV reactor shares many advantages with other photochemical reactions in flow, such as:

- Uniform light exposure
- Controlled exposure times
- Temperature control
- Any products formed are continuously removed, reducing the chance of any side products forming and products that could compete in absorbing photons

In this case, using a column UV reactor has another advantage by removing the need to have TiO_2 as a light suspension or slurry, opening up the possibility to use standard pumps, or to connect other reactors in series for a continuous reaction where previously the presence of TiO_2 could have impeded another step.

The catalyst used was a commercially available TiO_2. The catalyst is covalently bonded to the surface of hollow glass microspheres (size range 10 - 80 micron in diameter).

Method

System Setup

The flow reactor was set up using the Vapourtec E-series as shown in figure 1.

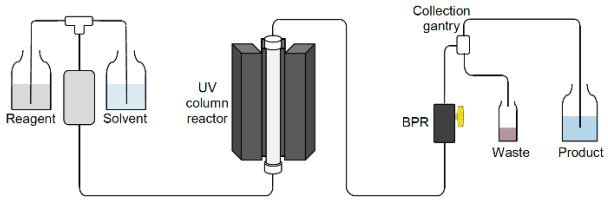


Figure 1

Pressure was controlled by a variable back pressure regulator (BPR). The elution outflow was collected via the waste/collection switching valve.

Column setup

The column used in the reactor was packed as shown in figure 2.

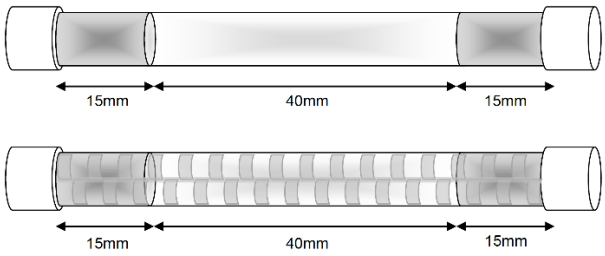


Figure 2

TiO_2 glass hollow microspheres were packed between 50-60 mesh silica. In some examples a static mixer was added to improve the uniformity of light exposure. In these cases, the length of the mixer is the total length of the column, spanning through TiO_2 and both silica sections.

Illumination of the Fixed Bed Column Reactor

The Column (6.6 mm bore) containing the catalyst was illuminated using the reactor assembly shown in Image 1. This Reactor can be attached to both the Vapourtec E-Series and the R-Series systems. The reactor provides temperature control between -20 °C and +80 °C with simultaneous illumination by LED modules positioned around the column and along the full working length. Precision LEDs are available in in the range of wavelengths 365 nm to 700 nm.

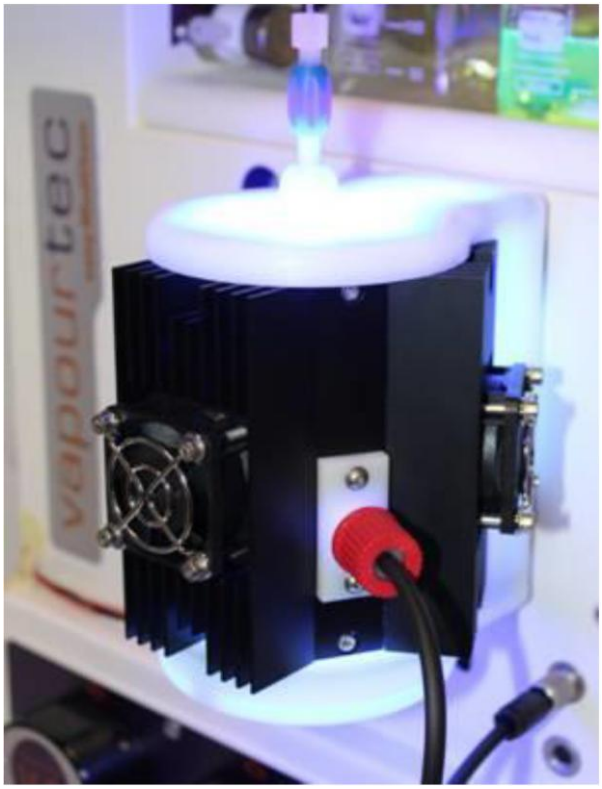


Image 1. Reactor assembly for illuminating packed bed reactors

Pump Tubing

The E-Series is fitted with three high performance V-3 peristaltic pumps and features a fluoropolymer tube as its core. The pumps feature more than one different tube type to ensure the largest range in compatibility of solvents.

Therefore the correct selection of tubing is crucial for any given reaction.

A table showing recommended tube type compatibility with a wide selection of solvents, acids and bases is available within the E-Series manual and also built into the user interface software. It is important to note, each V-3 pump can achieve a maximum of 10 mL/min. The solvent was ethanol, so either tubing can be used. For this experiment, red tubing was used.

Reagents

All reagents and solvents used were purchased from Sigma-Aldrich.

Silica was purchased from Sigma-Aldirch and the TiO_2 coated glass hollow microspheres were purchased from Cospheric.

System Parameters

System solvent:	Ethanol
Solution A:	0.005 – 0.02M 2,4-dichloronitrobenzene
UV Light Sources:	365nm LED (Gen 2)
Column materials:	50 – 6- mesh silica and TiO2 coated glass microspheres (Cospheric Inc. ID: Photospheres-0.22 10-85 um)
Flow rate A:	0.25 – 2 mL/min
Reactor volume:	approx. 1.6 ml
Reactor temperature:	37 °C
Back pressure regulator:	Atmospheric pressure

The reaction process followed the sequence of steps listed below:

1. Prepping the system
   The column was packed and assembled in the UV column reactor. The system was primed by running the system solvent through the pump and reactor and all connections were set up and checked.
2. Product pumping and collection
   The reaction was run using manual control. The reaction was run for an excess duration, to ensure the column was saturated with reactants and ensuring steady state had been reached. A small amount of product was collected using the collection gantry valve from the steady state and analysed.
3. Analysis
   A small amount of the resulting product was heavily diluted in acetonitrile and analysed by HPLC using an H_2O/ACN mobile phase. The degree of conversion was assessed by the appropriate integration peaks.

Results and discussion

Addition of static mixers to the column

Titanium dioxide even when supported on glass microspheres is an opaque white solid, which when packed into a column and placed into a reactor, it is unlikely that photons would penetrate the entire width of the column. Therefore only reactants towards the outside of the column would react and for full conversion, the flow towards the centre of the column would need to reach the outside and replace the products as it progresses.

An initial test was with a packed column with no static mixer as shown in the column set up. The results are shown below in table 1.

Table 1

Concentration of starting material (M)	Flow rate (ml/min)	Static mixer in column?	Conversion (%)	Throughput (g/h)
0.01	0.25	No	90.0	0.022
0.01	0.5	No	71.8	0.035
0.01	1	No	58.7	0.057
0.01	2	No	36.1	0.070

The results show that a lower flow rate, which equates to a longer residence time improves the conversion, but the throughput decreases. Even at a very low flow rate of 0.25ml/min, which would give an approximate residence time of 6.5 min, (assuming 1.6ml volume for liquid in a packed reactor) 100% conversion was not achieved. This is contrary to the results seen from app note 42, where the reaction with 2,4-dichloronitrobenzene, where 100% conversion was achieved at a residence time of 0.66mins.

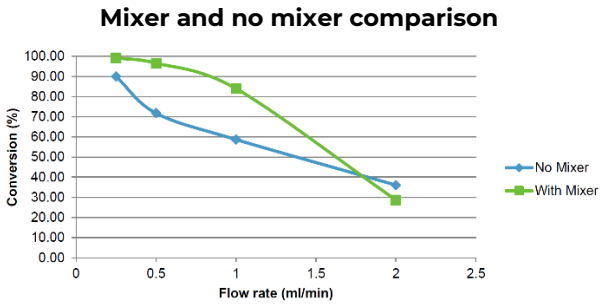
Therefore a method to improve the transfer of flow from the centre of the column to the outside and vise versa was required. This was done my adding a mixer into the column, then packing as per the column set up, ensuring each silica and TiO_2 section had been fully filled between the mixer gaps and settled.

The results with a packed column with a static mixer are shown in table 2 below.

Concentration of starting material (M)	Flow rate (ml/min)	Static mixer in column?	Conversion (%)	Throughput (g/h)
0.01	0.25	Yes	99.2	0.024
0.01	0.5	Yes	96.6	0.047
0.01	1	Yes	84.0	0.081
0.01	2	Yes	28.7	0.056

Table 2

With a mixer added, there was a significant improvement in conversions and ultimately throughput. While adding a mixer may decrease light penetration, the advantages of mixing the flow throughout the column ensures the reaction can easily go to completion. Graph 1 shows the difference in conversion with and without a static mixer.



Graph 1

The only apparent downside to a static mixer is at higher flow rates, where mixing or pushing reagents to the outside is less beneficial and the mixer blocks more light than without. This is a minor problem however, as with packed columns, flow rates need to be relatively low for high conversion to the desired product to be achieved.

Long duration

In application note 42, TiO_2 was in suspension with the reagents when being pumped. While being a catalyst, it was not used in catalytic amounts, even if TiO_2 is cheap, safe and readily available. Using a column allows a large amount of reactants to be used with a set amount of TiO_2, therefore the activity should be tested over a long duration to see if there is any change in conversion. Table 3 below shows a reaction that ran for 11 hours total.

Concentration of starting material (M)	Flow rate (ml/min)	Reaction duration (hr)	Conversion (%)	Throughput (g/h)
0.01	0.5	0	96.55	0.047
0.01	0.5	0.5	95.33	0.046
0.01	0.5	1	94.63	0.046
0.01	0.5	1.5	93.33	0.045
0.01	0.5	2	92.20	0.045
0.01	0.5	2.5	90.54	0.044
0.01	0.5	3	89.96	0.044
0.01	0.5	3.5	89.13	0.043
0.01	0.5	4	89.50*	0.043
0.01	0.5	4.5	89.12	0.043
0.01	0.5	5	89.21	0.043
0.01	0.5	5.5	88.64	0.043
0.01	0.5	6	88.08	0.043
0.01	0.5	6.5	86.97	0.042
0.01	0.5	7	86.05	0.042
0.01	0.5	7.5	85.31	0.041
0.01	0.5	8	83.54	0.041
0.01	0.5	8.5	83.19	0.040
0.01	0.5	9	82.14	0.040
0.01	0.5	9.5	80.90	0.039
0.01	0.5	10	80.42	0.039
0.01	0.5	10.5	78.77	0.038
0.01	0.5	11	77.71	0.038
0.01	0.5	11.5	84.52**	0.041

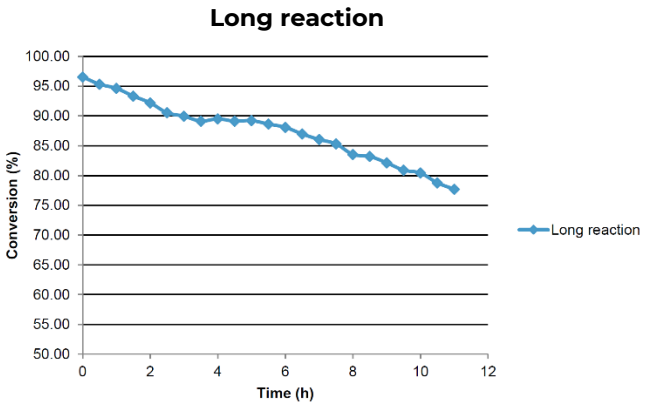
Table 2

*Column was washed by pumping just ethanol though and left overnight

**Column was given a longer wash with ethanol at increased flow rates and tested again

From the results, there is a clear and uniform decline in conversion over the course of the reaction. At 4 hours, ethanol was pumped through at the same flow rate and left overnight. The final result on the graph was at the end of the reaction, the column was pumped through with ethanol at a flow rate of 2ml/min for 10 mins and the conversion was checked again.

Due to the conversion increasing after pumping ethanol through, it is clear that the decline in conversion over time is not strictly due to the TiO_2 glass microspheres degrading/losing activity, but due to a buildup of an impurity or side product that is not readily washed out or dissolves in ethanol. Further work is currently underway to determine an effective washing regime for the packed column. The trend can be seen in graph 2.



Graph 2

One significant benefit of using glass microspheres is that they are easily reused when emptying/repacking the column as they have a lower density than water and can be easily collected from the surface.

Conclusion

This application note displays the Vapourtec's new column UV reactor, an example reaction and compares the performance when static mixers are assembled inside the column. Using the UV column reactor, this example shows that photochemical hydrogenation can achieve close to 100% conversion at reasonable flow rates using TiO_2 coated glass microspheres, which can be reused.