Microwave flow chemistry: Faster, cleaner, greener, safer

Continuous flow microwave chemistry is now a real alternative for industry, argues **Yvonne Wharton** of **C-Tech Innovation**

Microwave chemistry has been known since the 1980s and is now widely used in academia and industry, particularly for the synthesis of small quantities of new compounds, for example in pharmaceuticals. Whilst it is widely used on milligram scale, however, not much work has been done on scaling up microwave processes to production scales.

By tradition the chemical process and manufacturing industry has relied upon batch methods of production. The limitations of these methods have become increasingly evident and companies are reporting problems with long process development times, high inventories of materials, variable product quality and increased levels of wastage.

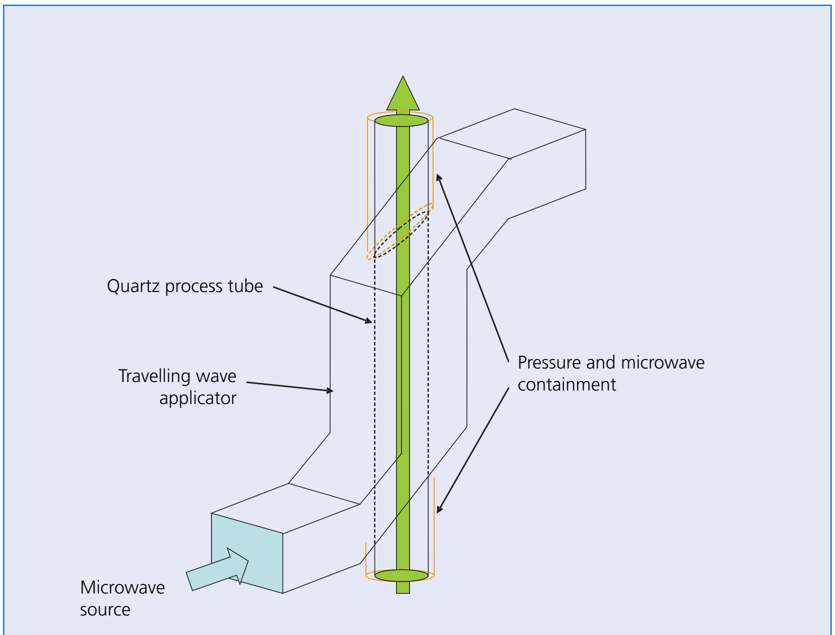
Therefore, companies are starting to look towards alternative manufacturing methods to solve these problems. Until recently, there has been very little choice of alternative methods or equipment. Continuous flow microwave chemistry overcomes these problems and goes a long way to meeting the demands that most companies set for their new processes.

Design & benefits

To date microwave chemistry has been restricted in scale to the laboratory, with equipment capable of producing milligrams or a few grams of material. Scale-up has been prevented by two major problems: the size limitations of the cavity and reactor and finding suitable materials to cope with the required pressure and temperature while being chemically compatible with the reaction mixture and transparent to the chosen microwave frequency.

C-Tech Innovation's design for a microwave flow reactor (Figure 1) overcomes these two stumbling blocks. The design is a continuous flow-through system using a travelling wave microwave applicator. This allows the use of relatively large bore process pipe-work. Large amounts of power can be coupled to the load using this design, allowing the use of high flow rates and hence high throughputs.

Figure 1 - Microwave cavity



Investigation into materials and components found that large bore quartz glass tubing is inert to most chemicals, transparent to microwaves and can be obtained in grades rated to >20 bar and >250 °C. A unique design was developed and patented for sealing the reactor tube and containing the microwave field.

Doing chemistry in flow can offer many benefits over doing reactions in a traditional batch way and combining this with microwave heating can enhance these benefits further. Some of the key advantages of carrying out chemistry in this way are that the reactions are:

- **Faster**: Microwave heating can produce substantially faster reactions than conventional heating, due to selective heating, very rapid temperature rise, the removal of wall effects or simply the ease of operating at high temperatures and pressures; there are hundreds of literature examples where the use of microwave equipment has shortened reaction times from hours to minutes. In turn, this can substantially reduce the cost of processing the required amounts of materials
- **Cleaner**: Rapid temperature rise and the absence of hot heat transfer surfaces can mean fewer undesired side reactions, resulting in higher yields and lower impurity levels. No steam or heat transfer fluids mean fewer leaks and no fouling of heat transfer surfaces
- **Greener**: There are many literature examples of solvent-free syntheses and many also show the potential for reducing catalyst use. We have shown the ability to quantify the energy-saving potential of microwave chemistry due to the shortened reaction times and reduced downstream work up as a result of the higher yields and purity that are often achieved
- **Safer**: Microwave heating is a direct heating method with no need for heating jackets or heat exchangers with large thermal mass. This means that turning off the power immediately stops energy input to the system and the temperature can be lowered quickly. Using a continuous flow system also lowers the inventory of any hazardous or unstable products and intermediates, making scale-up inherently safer than when using a batch approach

Process Improvements

A continuous flow microwave reactor was developed that was capable of producing >100 kg of product/working day and was then trialled using a range of reactions that are applicable to a variety of industrial sectors, with significant reductions in reaction times and increases in yields. Examples include the reduction in reaction time of a Suzuki coupling from two hours to one minute with no loss of yield, and a dihydropyrimidine synthesis which gave a two-fold increase in yield and a reduction in reaction time from eight hours to four minutes.[1,2]

After demonstrating that it was possible to achieve a time and materials saving with the reactor, we looked to see if it there were any other energy and environmental benefits in using microwave flow chemistry.

There is a real need to reduce energy demand in the chemicals industry as the industry contributes 4% of overall emissions of CO_2 from all industrial sectors using fossil fuel combustion. While this may not seem like a significant amount, when compared to other industries, the industry is a major industrial emitter.

The US and European chemicals industries have indicated that CO_2 emissions have stabilised while production has increased, which shows that companies are increasingly looking towards ways to make their production more efficient and more environmentally friendly.

There is cause for concern that the rapidly expanding chemicals industry in countries such as China is far more reliant on coal, which produces more CO_2 per unit energy than oil or gas. On the other hand, there has been a switch from coal to oil by the chemicals industry, which has helped to stabilise CO_2 emissions.

Most countries have programmes in place to achieve savings in energy use and governments are promoting energy efficiency in all sectors. Because of this, the overall energy efficiencies of these countries have improved. Energy savings that can be achieved easily at no cost have been estimated to be as high as 30% of the total energy use.

Once this low hanging fruit has been taken, companies will have to start looking towards new innovations to increase their energy efficiency further. The demand for chemicals is expected to increase and therefore the demand for energy by the chemical industry will increase with it. If CO_2 emissions are to continue to fall, chemicals companies will need to achieve greater efficiency gains.[3,4]

The potential energy savings from using a continuous flow microwave system approach in place of a batch process were quantified. In all cases such reactions showed significant savings in energy and reduction in CO_2 emissions, on average 58%. In some cases, the switch gave a 90% saving in energy consumption. This energy saving was brought about by the faster reaction times possible, enabling larger volumes of material to be processed per hour.

Even in the case of some reactions that did not show an increase in energy efficiency over the batch process, overall it could still be more efficient to carry out these reactions in the microwave reactor. This generally leads to an increase in yield which would save energy in the downstream work-up and reduce the volume of starting materials required.

The energy efficiency figures for the reactions carried out in the microwave reactor were between 40% and 60%. We anticipate that, when moving to a full-scale system, the energy efficiency would be around 60%, giving an even greater saving in energy over the batch process. Using electricity as the energy source also makes it possible to use 'green' energy tariffs or renewable energy sources on- or off-site.

Future developments

C-Tech is now continuing this research by embarking on a two-year collaborative Eurostars R&D project called MiFlow, in partnership with Solvionic. This aims to develop a novel microwave-assisted flow reactor to allow the scale-up of reactions with minimal process development.

The reactor should reduce energy usage in trialled chemical transformations significantly (at least 30%) and also give a large increase in energy efficiency (>50%). The ionic liquid processes being used to prove the reactor concept will be tailored from a range of end-user specific processes provided by Solvionic. The project will look to develop a highly energy-efficient microwave flow reactor and demonstrate its application using ionic liquid-based processes.

There is a real need for better controlled processes of ionic liquid synthesis, since their uses in emerging applications like electrochemical energy storage requires a high degree of purity. Because batch production is not adapted to giving colourless and high quality products, supporting solvents and washing steps have to be used. The use of organic solvents in large quantities produces waste and is not in line with the 12 Principles of Green Chemistry. In this context, the use of microwave-assisted flow reactors is a very promising alternative that will eliminate or minimise environmental damage, while also reducing waste and energy consumption.

The cost of ionic liquids is still high, mainly because their production volumes are still very low compared to molecular organic solvents. If high added value industrial applications based on ionic liquids start, the production of larger volumes will lead to costs falling. Moreover, the development of continuous flow processes for ionic liquid production will decrease production costs, thanks to better yields and reduction of waste and energy consumption associated with low investment.

Conclusions

Most of the significant reductions in energy consumption have already been achieved by the large chemicals manufacturers who can afford to invest in energy-saving equipment and to employ specialists in energy management. Even these companies, however, are finding that they cannot make further energy savings without radically changing the way they produce chemicals.

Chemicals manufacturers will have to adopt new technologies if they are going to continue to reduce their energy consumption and environmental impact in an ever growing market. Microwave flow chemistry offers one way of contributing towards this. It also presents a convenient way to scale up lab scale reactions to plant scale with less process development.

With companies and governments ever more mindful of the safety implications of chemical production, microwave flow chemistry also offers a safer way of heating large volumes of flammable materials as there is a much smaller inventory being heated at any one time when compared with batch chemistry.

Microwave flow reactor

References

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