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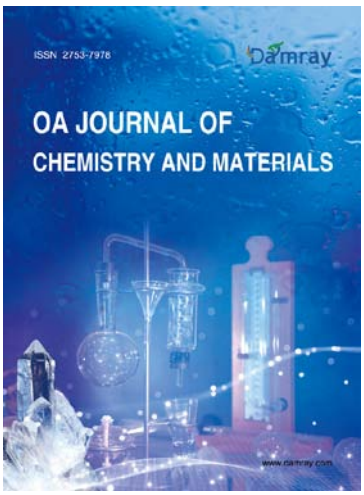
Microreactors: Emerging Alternative for Conventional Reactor Designs



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Abstract

Microreactors are reactors with continuous flow of reactants in micro channels of few hundred microns in diameter. They have large surface-to-volume ratios, which facilitates efficient heat and mass transfer rates. They have a huge scope in fine chemical industries, pharmaceutical industry due to high yield and selectivity when compared to convectional reactors. Chemists are also benefit with this technology in studying the reaction kinetics of organic compounds due to better span of control on the reaction. This report mainly focuses on providing an overview of the micro reactor technology, its advantages, design in terms of reaction types and reactor types, limitations and applications in various fields. Given the limitations of the technology, there is a lot of scope for innovation for tailoring and standardizing the micro reactor for different need. Once the limitations are overcome the microreactors can be implemented in various sectors like consumer products, health-care and in situ preparation of hazardous and explosive chemicals.

Keywords

Micro Reactors, Reactor Design, Micro Reactions, Advantages

1. Introduction

The fine chemicals and pharmaceuticals industry production typically relies on a batch reactor or a semi batch reactor. However, for the production of bulk chemicals continuous flow process have proven to be economical. In pharmaceuticals industry, due to the relatively low quantity production and the short life of the products, batch reactor was always the solution. A new technology, called the Microreactors combine the efficiency of a continuous process production and the flexibility and versatility of a batch reactor.

Microreactor is a device in which chemical reactions take place in a confinement with typical lateral dimensions below 1 mm [1]. It is typically a continuous flow reactor with channels having dimensions <1mm (typically of few hun-

dred micrometers in diameter) and a surface to volume ratio in the range of 1000-50,000m^2 /m^3. They also hold a potential in improving organic chemistry because they are inherently less wasteful than traditional methods and provide unprecedented reaction control.

The major driving force to develop this technology is large surface to volume ratio, diffusion dominated mass transfer, effective heat transfer. These characteristics are exploited for various applications such as selective reaction with highly unstable intermediates, improving heterogeneous catalysis, multistep synthesis, and process safety in highly exothermic reactions.

This report mainly focuses on providing an overview of the micro reactor technology, its advantages, design in terms of reaction types and reactor types, limitations and applications in various fields.

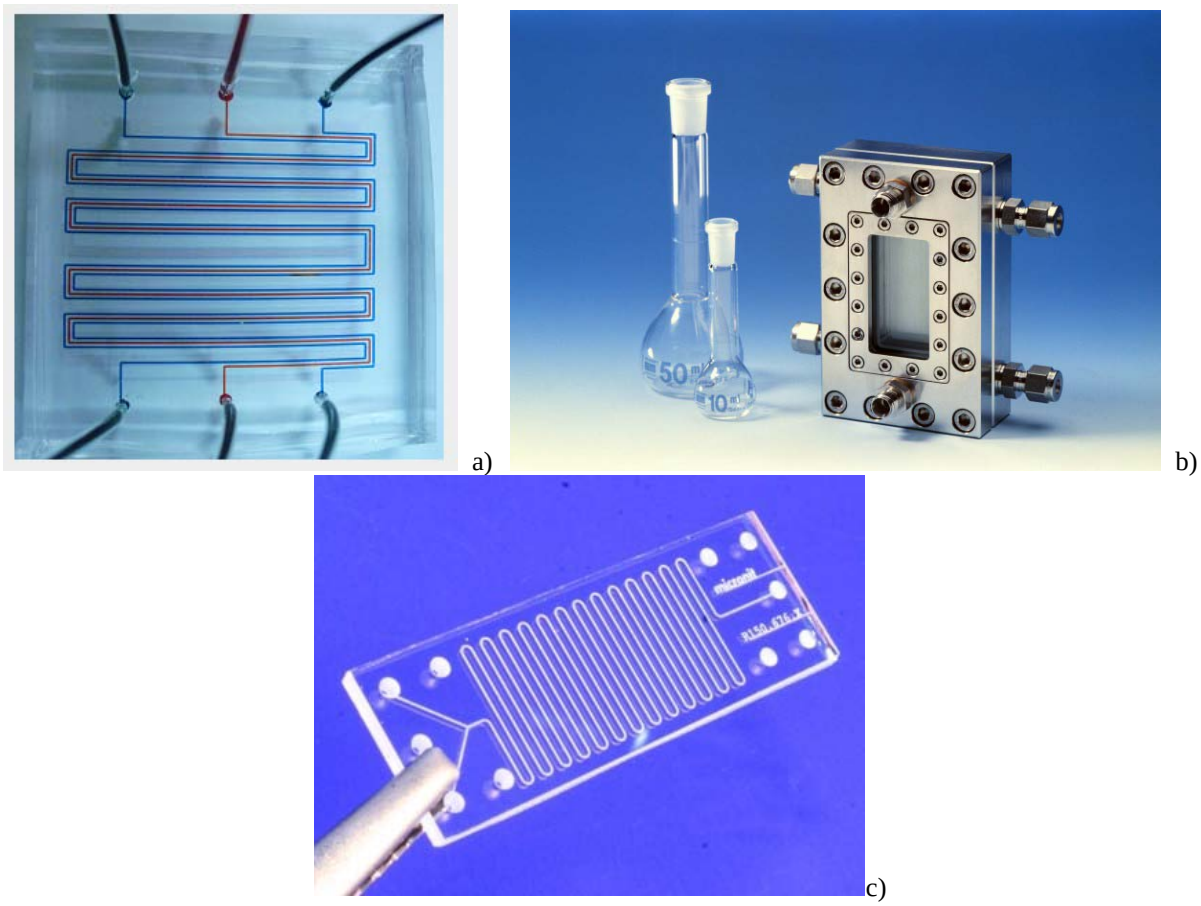


Figure 1. a) Optical image of triple channels in a microreactor b) Frame view of a microreactor c) Glass microreactor.

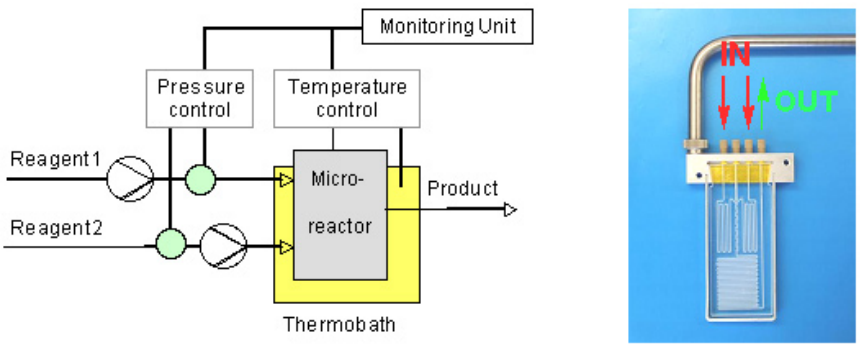


Figure 2. Schematic representation of microreactor system and a picture of reactor that is part of Sigma-Aldrich's micro reactor explorer kit.

2. Advantages

2.1. Increased yields and selectivity due to perfect mixing and thermal management.

The typical reactors use convection mode of mixing the reactants, which doesn't mix the reactants thoroughly. In this course of action, dead zones of convection mixing are created which leads to concentration gradient and "hot spots" (accumulation of heat) due to poor thermal management. This is not similar in micro reactors. Due to the small diameter of the channels, thorough mixing takes place within seconds as the reactants enter the channels. Also due to high surface to volume ratio ensures proper thermal management and no hot spots are formed which increases the selectivity and yield.

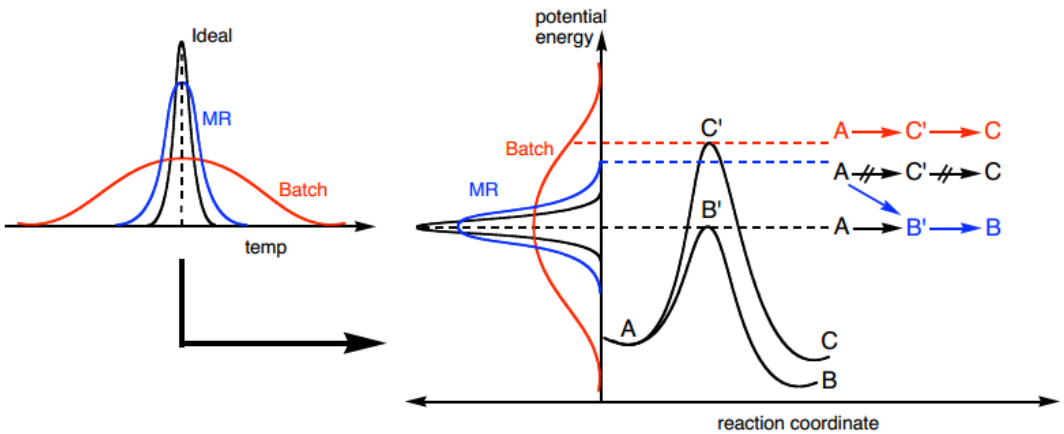


Figure 3. Comparison between ideal temperature distributions for hypothetical reaction (black) and actual temperature distribution in batch reactor (red) and micro reactor (blue). The batch reactors broad distribution allows production of undesired C, but due to narrow temperature profile, only B product forms [1].

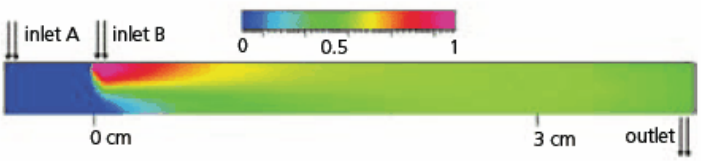


Figure 4. Efficient Mixing in a micro reactor. (Source: Sigma Aldrich-Micro reactor Technology)

Example: Grignard Addition: Micro reactor obtained an yield of 78% when compared to 49% in batch reactor. Also the selectivity of A:B was 95:5 in caparison to 65:35 A:B in batch reactor.

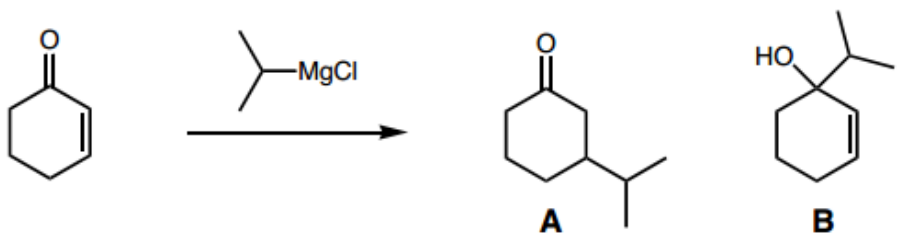


Figure 5. Grignard addition reaction [2].

2.2. Easy handling of exothermic reactions

Due to large surface to volume ratio microreactors when used with coolers can handle high exothermic reactions. This creates safe environment and a higher selectivity of product. Example: Ducry and Roberge's Nitration of Phenol. Yield increased from 55% to 75%, purity increased from 56% to 78% and the polymeric byproducts reduced by a factor of 5.

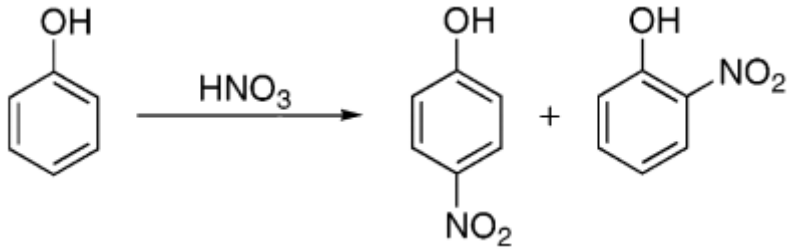


Figure 6. Nitration of Phenol [1].

In recent years, the probabilistic safety assessment (PSA) of a direct supercritical-CO_2-cooled fast reactor, called micro modular reactor (MMR), was performed [4, 5]. This reactor was developed using innovative design concepts. It adopted a modular design and passive safety systems to minimize site constraints. The S-CO_2 cooled MMR has many innovative design features including modular design and passive safety features.

2.3. Increased safety for toxic reactions

Due to small volumes and proper handling, the microreactors provide a safe environment to handle reactions which are toxic and explosive when performed in a batch reactor. The hazardous impact in the microreactor is lesser when compared to batch reactor where one needs to handle large volumes of toxic products. The reactions that require fluorination or formation of HF as by product are particularly benefitted by microreactors due to its toxicity. Also, addition of singlet oxygen reactions can be carried out safely in microreactors which otherwise are complicated due to necessity of high intensity light exposure. Oxidation of α-terpene was performed by De Mello and co workers. Yield of product acaridole increased from 67% in batch reactor to 85% in microreactor.

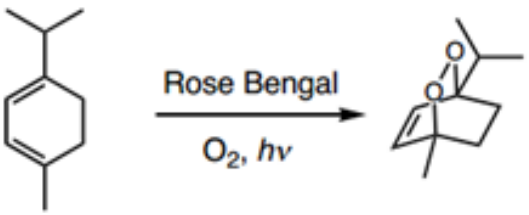


Figure 7. Oxidation of α-terpene [6].

2.4. Study of organic reaction kinetics in micro reactors

Due to better control over the reaction, the chemist are increasing using micro reactors for the study of organic compound. A variety of carbon carbon bond formation, catalytic reactions of organic compounds are studied in a micro reactor due to the better control over the reaction, feasibility to separate two compounds.

3. Types of Microreactors

With the gradual development of micro reactor investigation, it is now still challenging to classify the type of micro reactors in such an accurate way. However, we can refer to the classification criteria of conventional reactors. In terms of different application, it can be divided into two types, namely laboratory-based micro reactor and production-based micro reactor. Moreover, from chemical engineering perspective, type of micro reactor has close relationship with reactor process. The micro reactor structures vary from reactions of different phases, which offers an idea of categorizing micro reactors as gas-solid phase catalytic micro reactor, liquid-solid phase micro reactor, liquid-liquid micro reactor and gas-liquid-solid catalytic micro reactor. These four types of micro reactors are introduced as follows.

3.1. Gas-solid phase catalytic microreactor

As the gas-solid phase reactions can easily occur in this type of micro reactor, the majority of research has focused in gas-solid catalytic reactions up to now. Reactor with catalyst fixed on the wall of micro reactor consist of the easiest gas-solid catalytic reactor, while the complex micro reactors are always combined with several functions such as mixing, separation and sensor. A representative reactor of this type should be the T-shaped thin-wall micro reactor designed by Ravi Srinivasan etc [7] from MIT which applies to reactions with different amount of heat release.

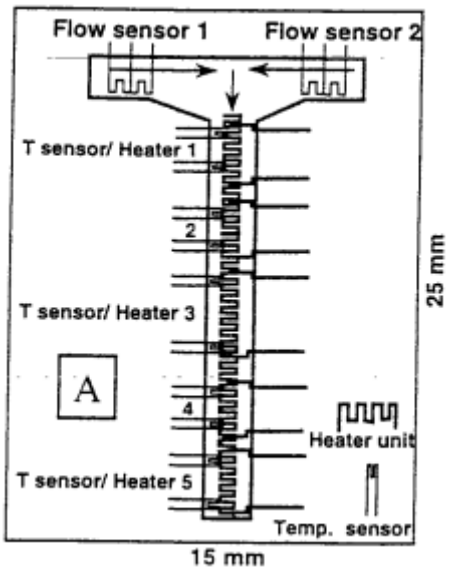


Figure 8. T-shaped thin-wall micro reactor [7].

The dynamic and diversified needs for investigating various complex materials and gas-solid reactions have led to the development of a variety of different microreactors over the years. Solid particles in microreactors are normally heated by furnaces from outside, resistive elements from inside, direct contact with bed particles, or other non-resistively methods. Solid particles can be fixed or fluidized in reactors where gas-solid contacts vary from diffusion-dominated to nearly diffusion-free conditions [8].

3.2. Gas-liquid phase micro reactor

According to the contact mode, G-L micro reactor can be divided into two types. One is called the "falling film micro reactor", from which liquid flows from top to bottom like a film for which the gas and liquid have the adequate contact area. The reaction rate of liquid and gas mainly depends on the contact area. The other type is the one in which gas and liquid enter from two channels and then combine to another channel, like a T-shaped reactor. These two types of reactors both have considerable liquid and gas contact area and the inner specific surface area is approximately 20000m^2/m^3, which is one order of magnitude larger than the conventional micro reactor.

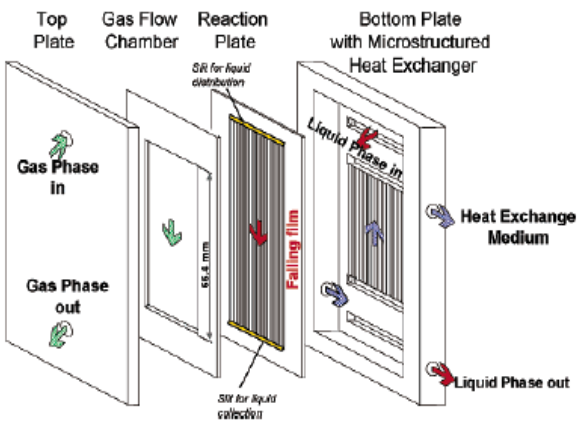


Figure 9. Falling Film Micro reactor.

3.3. Gas-liquid-solid catalytic micro reactor

These gas-liquid-solid reactions are common in chemical reactions. In most cases, catalyst stands as solid phase; reactant and product are gas and liquid. MIT designed a "packed bed micro reactor" whose structure is similar to the

fixed-bed reactor. Its major application is gas-liquid-solid catalytic reaction. MIT also tried “micro reactor scaling up” paralleling 10 packed bed micro reactors, as a result, the pressure drop of the packed bed micro reactor decreases dramatically which is in favor of scaling up.

3.4. Liquid-liquid micro reactor

This kind of reactor was utilized by BASF [9] synthesizing the precursor of vitamin. British University of Hull [10] designed a kind of T-shaped liquid-liquid micro reactor with the outstanding characteristic of transmitting liquid by means of electro-osmotic flow. The main factor that affects the reaction rate is adequate mixing.

Christian Fernandez-Maza [11] reported a holistic analysis of reactants mixing and reaction rate in liquid phase flow micro-reactors with curved geometries. In this sense, a mathematical model that accounts for momentum and mass conservation equations, together with species transport and chemical reaction rate under isothermal conditions, has been developed using computational fluid dynamics techniques (CFD). Simulated findings have been confirmed with the experimental analysis of the reaction between aqueous ammonium and hypochlorite ions. Very good agreement between simulated and experimental results has been achieved with an error lower than 10%. Therefore, the robust model herein reported is a novel and valuable tool to assist in the optimum design of micro-reactors for fluid-phase isothermal applications.

4. Types of micro reactions

A few years ago Roberge [12] et al. published a reaction classification to understand the number of reaction candidates that could fit into micro reactor / continuous processes. They classified the reactions based on their physicochemical properties namely in terms of reaction kinetics and phases (solid, liquid, or gas). The reaction kinetics were categorized in three main classes (see Figure 10).

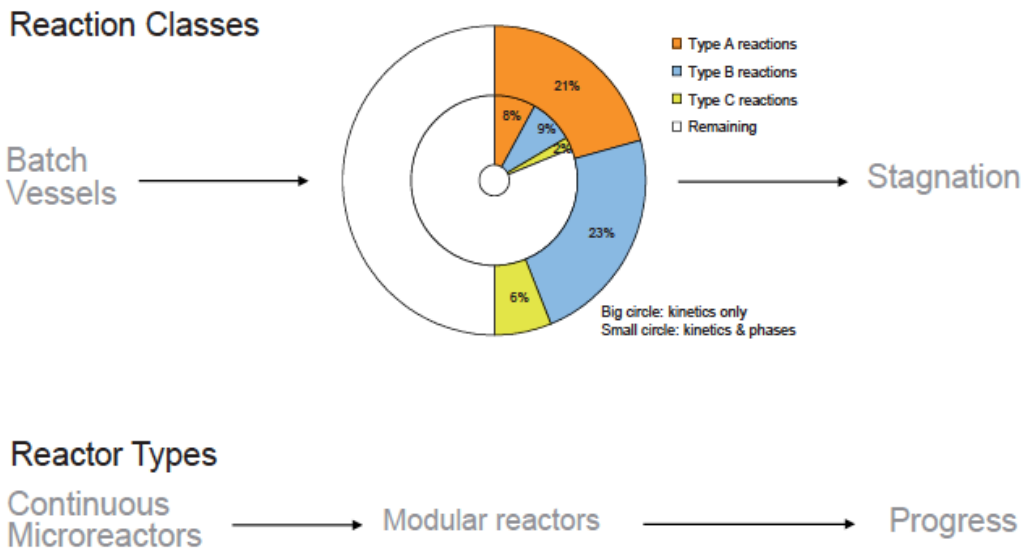


Figure 10. Reaction classes lead to the different reactor types required to operate continuous processes [13].

• Type A reactions: reactions that are very fast (< 1 s) and mainly controlled by the mixing process. In general, using a micro reactor can increase the reaction yield by rapid mixing and enhanced heat exchange performances.

• Type B reactions: reactions that are rapid (10 s to 20 min) but predominantly controlled by the kinetic. Here, the yield is increased by a precise control of the residence time (reaction time) and temperature. In other words a reaction ‘overcooking’ is avoided in a micro reactor.

• Type C reactions: reactions that are slow (> 20 min) and often operated batch wise (as opposed to semi-batch). A thermal hazard is possible that requires particular measures for such reactions where a large heat accumulation is observed (batch = 100% heat accumulation). Thus, the use of a continuous process will enhance safety with the prerequisite that process intensification has taken place when using an alternative technology. It is important to point out that the pie analysis presented in Figure 9 is not intended to predict the future use of micro reactor technology. Indeed, this reaction classification came from the fine chemical industry where most of the processes are operated batch or semi-batch

wise. Consequently, it represents the kinetic distribution of reactions and one would predict a stagnation of this distribution because it originates from historical batch reactor technology. The best example to describe this situation is to observe the rather low number of Type C reactions (6%) that poses a thermal hazard potential (reactions that required particular safety measures determined during the risk analysis). Indeed from the very beginning of process development the chemist tends to choose reaction pathways that are safe, highly diluted, and scalable. However, fine chemical manufacturing has generated plenty of waste stuff characterized by a high environmental “E factor” that is rarely lower than 25 (E = kg of waste per kg of product). The use of continuous flow processes based on micro reactor technology may change this pie distribution towards faster and more intense processes (which is the progress aspect).

5. Micro-reactor Design

Micro-reactors, "Lab-on-a-chip" device, in general, consist of micro channels, with lateral dimensions on the order of micrometers, etched on metal, glass, silicon, or other substrates via photo-lithography or other techniques.

5.1. Microfabrication Techniques

The factor to make micro-reactor superb performance is its microstructures or micro channels, so the techniques for manufacturing micro-reactors or the art of micro fabrication technology exert a great effect on development of Micro-reactors. The external length scale of a micro reactor is approximately several centimeters as the micro-channels are limited micrometers. Nowadays, there are several technologies have been preferably applied to fabrication of micro-reactor: Bulk micro machining of monocrystalline materials (Anisotropic Wet Etching);Dry Etching; LIGA Process; Injection Molding; Wet Chemical Etching of Glass; Advanced Mechanical Techniques; Isotropic Wet Chemical Etching of Metal Foils; μ-EDM; Laser Micro machining.

- Bulk micro machining of monocrystalline materials. e.g. Silicon, using anisotropic wet chemical etching [14]. Various of micro-structures like channels, filters, cantilevers or membranes can be achieved by means of patterned etch stop layers that are generated by lithographic and thin film processes on a silicon wafer.
- Dry etching processes using low-pressure plasma or ion beams. Compared with wet chemical etching, there are fewer geometrical restrictions concerning the microstructures, to a still improved structural resolution and to an extension of material choice.
- LIGA process [15]. LIGA and related techniques are based on a sequence of process steps combining lithography. Electroforming and molding. There are three steps for this: First step, a microstructure is generated by means of a lithographic process in a thick resist lay. This can be realized by utilizing a laser, a high-energy electron or ion beam as well as standard UV- or X-ray lithography with synchrotron radiation. Then a complementary metal structure is generated from the resist master by means of electroforming. In a third step, as a mold insert or embossing tool allowing replication processes to be performed such as injection molding or embossing. Using LIGA process can realized high precision, high surface quality and high aspect ratios.
- Injection molding e.g. using mold inserts machines by precision engineering techniques. Refer to the manufacture of miniaturized electrical heaters within micro-channel structures by injection molding. Mixtures of Al_2O_3/TiN turned out to be suitable materials for this purpose [16].
- Wet chemical etching of glass including anisotropic etching of photosensitive glass [17]. Glass wafers are exposed to UV light through a quartz mask with a chromium absorber pattern, well known from semiconductor processing. Silver nuclei are generated in the glass matrix by a photochemical process. Crystallization of exposed parts occurs by subsequent annealing which thereafter are removed by etching with hydrofluoric acid.
- Advanced mechanical milling, turning, sawing, embossing, punching, and drilling processes based on precision engineering. Surface cutting with diamond tools: ground-in precision diamonds makes parallel grooves of usually rectangular shape or ceramic inserts as cutting tools. Milling, turning and drilling are often used for the fabrication of larger fluidic channels in the range of several hundred micrometers. Punching is used for realization of micro-fluidic structures refers to the removal of material within platelets. Embossing techniques are used for generating micro-channels; it has been used for structuring of ceramic green tapes, composed of ceramic powder and polymeric binder material.
- Isotropic wet chemical etching. Wet chemical etching has the benefit of process costs and flexibility, however, due to the isotropic nature of etching process, only microstructures with small aspect ratios can be achieved.
- Micro electro discharge machining. μ-EDM techniques can be used in micro-scale, which is appropriate to achieved microstructures in hard or chemically resistive materials.
- Laser ablation [18]. Laser micro-machining techniques were, useful for the generation of 3-D microstructures, this technique allows micro structuring in a vertical direction, and it can realize a fast transfer from CAD design to fabrica-

tion of a microstructure is achievable without the need to use a mask.

- Additive manufacturing processes [19]. Micro-scale reactors, with high-surface-volume ratios provide a platform for reducing the size and cost of chemical reactors due to high rates of heat and mass transfer. However, widespread adoption of this technology is hampered by economics and the lack of existing supply chains. Additive manufacturing processes have the potential to overcome this roadblock. Cost modeling results indicate that for the reactor plate design, binder jetting can achieve a 40% and 56% cost savings at 1,000 and 10,000 units per year relative to laser powder bed fusion.

In general, different technologies can be combined in a process line for fabricating micro-reactors, in addition, auxiliary processes ranging from thin film technologies to mechanical surface modification play a key role in micro workshop as well as test equipment and design and simulation software.

5.2. Coating Catalyst

For most micro-reactors design, various catalysts coat inner surface of micro-channels after the channels are formed, there are several methods have been preferably used for coating catalysts.

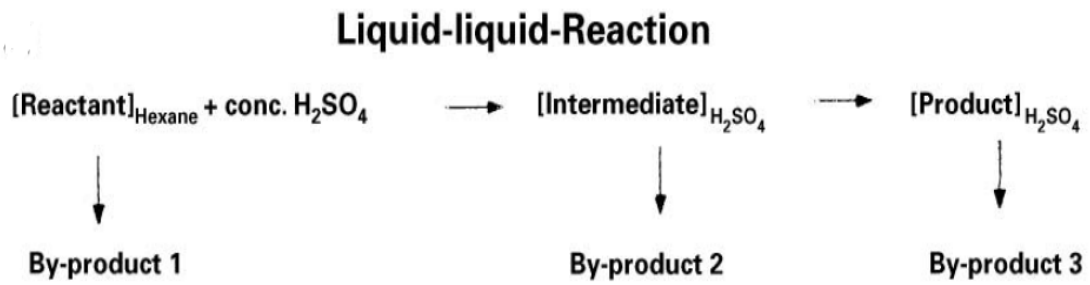
- Physical or chemical evaporation deposition technology. Catalysts are deposited on the inner surface of micro-channels by mean of spreading the catalyst on the surface as a membrane; this can be realized by physical or chemical evaporation. Evaporation deposition technology is limited to be used for simple metal modification and simple oxidants. Due to the superheated evaporation, the catalyst surface present coarse.
- Wet preparation for catalyst, catalysts can be loaded on the inner surface of micro-reactors by wet process preparation for catalyst in micro-reactor. Due to the surface tension effect, the catalysts usually get together in the corners of a chamber.
- Aerosol spray or ink-jet printing have also been used to load catalysts in micro-reactors, the best of this method is catalysts can be loaded by man's will.
- Porous substrates. The most effective method to load catalyst is to use porous substrates, by putting a porous substrate, then put the catalysts on the substrate.

6. Performance of microreactors versus conventional reactors

Microreactors are known for the fact that even very fast and very exothermic reactions can be performed isothermally and in the case of multiphase reactions the mass transfer path is minimal. The reason behind this property is its extremely large surface to volume ratio. We have chosen two examples to compare the microreactors with the conventional reactors. The first example is a fluid-fluid reaction and the second example is that of heterogeneously catalyzed gas-phase reaction.

6.1. Fluid-fluid reaction

The reaction occurring is liquid-liquid reaction and the reactant is dissolved in hexane. The product is than acidified using concentrated sulphuric acid, which acts as a catalyst for the reaction. When the reaction was carried out in a semi batch reactor the yield obtained was 70%.



In order to increase the yield the same reaction was carried out continuously in a combination of a mixer and a cooler. It was observed that the mixer has a residence time of 0.2 seconds and the cooler has a residence time of 4 seconds. There was a rise of 35^{o}C inside the mixer, which is one half of the adiabatic temperature rise. Thus, we get a conversion of 50% inside the mixer and rest of the reaction is completed in the cooler at50^{o}C. The combination of mixer and cooler gives the yield of 80-85%.

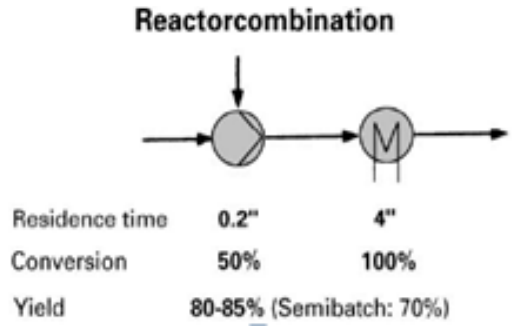


Figure 11. Technical reactor (Combination of mixer and cooler) [20].

To understand the kinetics of the reaction, conventional laboratory techniques were employed. It was found that to mix the two viscous phases, to transfer the heat of reaction, to stop the reaction by dilution with water and to separate the phases, it took 2 minutes and the yield obtained was only 25%.

This triggered the need to develop a microreactor for this reaction. The only condition was that the temperature rise was confined to about 1^{o}C with a residence time of 1 second. This implied that we use reaction channels 900µm deep and 60µm broad and surrounded by cooling channels. We have four elements of this kind as shown in Figure 12 and thus we have 8*4=32 reaction channels. The two-reactant streams are united in pairs, and then the reactants simultaneously get mixed and react. The reaction then stopped by diluting concentrated sulphuric acid with water.

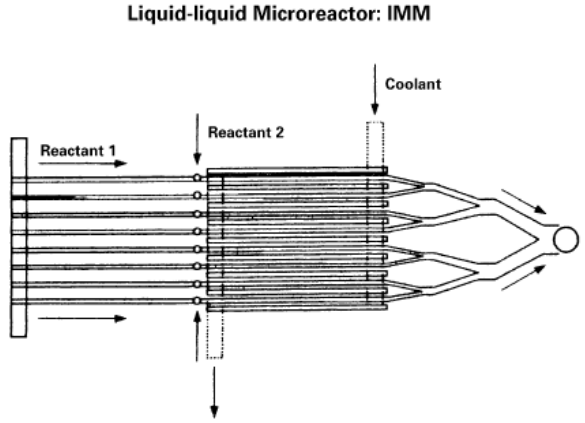


Figure 12. Structural element of liquid-liquid microreactor [20].

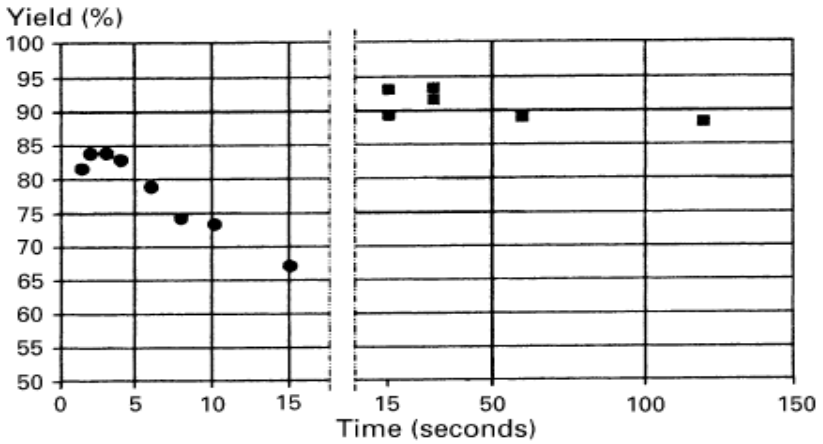


Figure 13. Yield dependence on residence-time of the liquid-liquid reaction at 50°C (●) and 20°C (■) microreactor [20].

Figure 13 shows the dependence of yield on time at 50°C. It can be seen that the yield is 80-85% at the residence time of 4 seconds. Thus, it can be concluded that the microreactor functions similar to the combination of reactors. However, as the residence time increases the yield tends to decrease. At the residence time of 15 seconds the yield is 65%. This is however much larger yield than what was obtained from conventional laboratory techniques, which were merely 25% and the residence time being 2 minutes.

If the reaction conditions are altered than the dependence of yield on residence time changes as shown in Figure 13. The temperature was lowered to 20°C and it was observed that the yield increased by 10% to 90-95% at the residence time of 30 seconds.

The common problem faced by these types of microreactors is the problem of blockage. But if these microreactors are constructed carefully so that there is no velocity gradient or temperature gradient than there will not be any problem of blockage.

6.2. Heterogeneously catalyzed gas phase reactions

This example deals with oxidative dehydrogenation of a alcohol to aldehyde. For example, the synthesis of formaldehyde is a heterogeneously catalyzed gas-phase reaction, the catalyst being silver. The production is carried out in a pan-like reactor where a 2cm thick layer of catalyst particles is placed upon a gas-permeable plate. The selectivity obtained was 95%.

$$RCH_2OH + 1/2\ O_2 \xrightarrow[Ag]{550°C} RCHO + H_2O$$

After the success of this process attempts were made to develop similar process for different compounds. In a pan-like reactor with a diameter of 5 cm the selectivity of 90% at a conversion rate of 50% was obtained. However, as the diameter was increased to 3m, the selectivity fell to 40%. Thus there was major scale up problems. The explanation provided was that in case of the laboratory pan-like reactor about 50% of the reaction heat escapes through the walls of the reactor. But a reactor of this kind with a diameter of some meters works entirely adiabatically and if the reactants and products are not stable than the selectivity goes down.

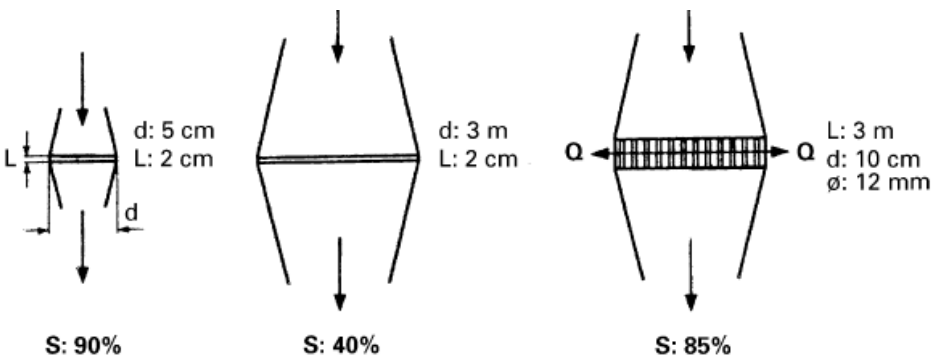


Figure 14. Oxidative dehydrogenation: scale-up problem [20].

The solution to the problem was to develop a multi-tubular reactor that operates isothermally. But experiments in a single tube gave bad selectivity. Thus it was presumed that there was a need to construct a reactor, which is the optimal compromise between a short residence time and total heat transfer. Thus a multi-short tubular reactor was constructed. These reactors gave excellent selectivity's, similar to pan-like type of reactor on laboratory scale. Thus it was concluded that this theory was true only for short-multi tubular reactors.

It was later realized that in a microreactor, it should be possible to simultaneously achieve a shorter residence time and an even better heat transfer compared with a multi-short tubular reactor. The microreactor was made of silver in order to avoid problems of how to fix the catalyst in active and stable form onto the walls of the reaction channels. The microreactor is a 1 cm^3 cube which means, the residence time is one magnitude lower. There are 200 channels for the reactants and the same number for the coolant. The rectangular cross-section of the channels 0.32*0.40mm^2 was chosen so that the cross-section is made as small as necessary in order to have excellent heat transfer, and as large as possible in order to reduce the danger of blockage.

Figure 15 shows selectivity dependence on conversion for microreactor and technical reactor. It can be seen that the selectivity has been increased from 85% to 96% from small-multi tubular reactor to microreactor.

Figure 16 gives the summary of the three types of reactors discussed till now. Large-scale pan-like reactor has a

maximum temperature of 550°C with a hot-spot of 160°C. This reactor works adiabatically and we get a selectivity of 40% at a conversion rate of 50%. The multi-short-tubular reactor of any scale, we have a maximum temperature of 450°C with a hot-spot of 60°C and a selectivity of 85%. For a microreactor, the temperature can be reduced to 390°C. We no longer have any hot-spot, the reactor works isothermally and the selectivity further improves to 96% at an even higher conversion rate.

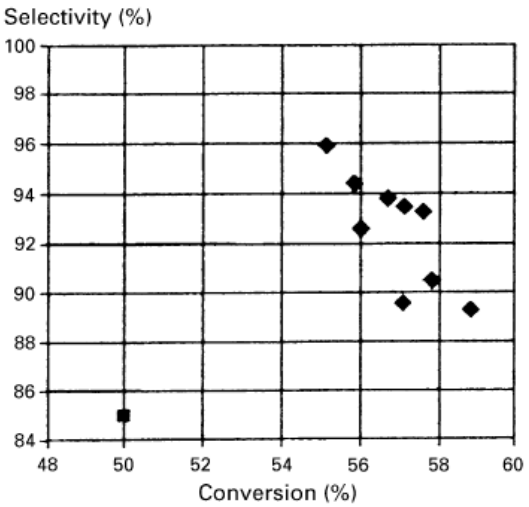
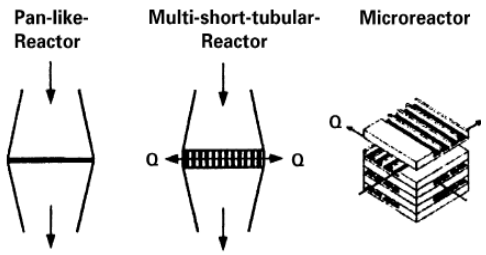


Figure 15. Selectivity dependence on conversion:(■) technical reactor, (◆) microreactor.



Max. temperature (°C)	550	450	390
Hot spot (°C)	160	60	~ 0
Selectivity (%)	40	85	96
Conversion (%)	50	50	55

Figure 16. Comparison between types of reactors: pan like, Multi short tubular & microreactor [20].

7. Application

In the early development of micro reactor, it is widely used for the laboratory research. Micro reactors are apt to undertake highly exothermic reactions, high temperature reactions, reactions with unstable intermediates and reactions involving hazardous reagents [21]. As the advantage of micro reactor has been widely known in recent years, its application to industrial process has increasingly been popular to some extent.

Due to the small volume but large surface-to-volume ratio [20] of reactor channel, micro reactors are mainly applied to the following fields: petroleum refining [22], bulk chemicals, fine chemicals, pharmaceuticals, and bio-based materials. And as for the synthesis of poisonous product (fluorinated aromatic compounds or hydrogen cyanide), micro reactor also plays an important role. It is reported that plenty of plants are now utilizing micro reactor technology, especially for some European companies and research agencies devoting themselves on cultivating and applying new micro reactor processing. For instance, Clariant and Bayer have showed great performance in developing nanoparticles. The micro reactor utilizes micro voids as dispersed medium and the dispersed phase goes through the pores mixing with the

continuous phase to be uniform. If appropriate surfactant and micro emulsion can be selected, the nanoparticle with small particle ratio and well dispersed can be obtained easily; American corporation CPS and Institute of Mainz of Germany provide enormous technical support on micro reactor; American company UOP does a good job in synthesizing hydrogen peroxide. At the Institute for Micro manufacturing (IfM) of Louisiana Tech University [23], they have been doing micro reactor research for almost 10 years including simulation, design and micro fabrication of the reactors. The conversion of cyclohexene to benzene and cyclohexane has been chosen as a model reaction.

Furthermore, micro reactor can also be used as a measuring tool in the process of micro reaction, which can further obtain the relevant parameter information, which will affect the reaction process and efficiency. Hjelt et al produced a kind of micro reactor using silicon processing, which tends to measure the volume of liquid of tiny amount by examining the resistance.

Compared with recent expensive, clumsy and complicated environmental examining devices. The environmental monitoring is also a promising application for micro reactors due to its characteristics of portability, easy manipulation and low maintenance fee. Nowadays, toxic gases such as CO, NO and NO_2 have been successfully measured in this way.

8. Limitations

Despite the advantage of micro reactor in industrial processing, some limitations still occur in the design, fabrication and application of micro reactor. Due to the variety of reaction types and reaction conditions, it is hard to design a universal micro reactor, which applies to all kinds of reactions. The limitations are summarized as follows:

(1) With the increasing number of micro reactors, the difficulty level of examining and controlling will increase significantly; therefore makes the actual cost of production much higher.

(2) Not all reaction types apply to micro reactors [13]. For example, liquid-gas phase reaction in quite a low rate, reactions without exothermic or endothermic phenomena and reactions of which the conventional processing has already had very high selectivity and yield.

(3) The tiny size of micro reactor channel makes it easier for solid particles to block the channel, so it brings obstacle to clean the channel.

(4) Many macroscopic laws will no longer apply to the microscopic regime so that it is of necessity to build microscopic theoretical system, which better applies to micro reactor technology.

(5) Design of catalyst, fabrication of sensors and controllers, and scale up of reactors.

(6) Catalyst deactivation and incompatibility with reagents and intermediates, back-pressures developed in flow, and the removal or elimination of unwanted side products.

9. Conclusion

With micro reactors, production can becomes leaner, efficient and more robust. It has the potential to reduce the size of giant micro reactors to small blocks. They provide enhanced mass and heat transfer rates, safe environment, higher yields and selectivity. Given the limitations of the technology, there is a lot of scope for innovation for tailoring and standardizing the micro reactor for different need. Once the limitations are overcome the microreactors can be implemented in various sectors like consumer products, healthcare and in situ preparation of hazardous and explosive chemicals.

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