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# Microchannel Reactors: Applications and Use in Process Development

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# Microchannel Reactors: Applications and Use in Process Development

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## Abstract

Recent research results on microchannel reactors are reviewed with particular reference to their applications and use as a cost effective tool during process development tasks. The high surface to volume ratio, efficient heat and mass transfer characteristics, vastly improved fluid mixing etc., allow precision control of reaction with improved conversions, selectivities and yields of desired products. The reaction times are shorter as compared to the conventional reactors with less degradation and side products. Scalability and optimization are also significantly easier. The article reviews variety of applications to catalysis, polymers, advanced materials, biosystems, organic reaction etc., with emphasis on the related engineering science issues.

**KEYWORDS:** Microchannel, microfluidic, reactor chip, microlithography, nanotecnology

## 1. INTRODUCTION

It is important for a leading research and development laboratory engaged in translating processes or products from 'concept to commercialization' to keep itself abreast of the forefronts in related areas of science and engineering. For a chemical based laboratory, besides the domain knowledge in chemistry, physics, biology and engineering science, it is important to be aware of the available hardware, software, instrumentation and measurement science and analytical tools for process monitoring. This is essential to cut down lead-time for process development from what it takes normally as several years to a manageable time frame of three to four years. This is necessitated due to intense competition, saving in cost, quality considerations of the product and environment regulations.

The work elements of a general process development program consist are schematically shown in Figure 1. Clearly process experimentation is at the center stage and in the beginning the choice of reactor or contactor, the mode and scale of operation and design of experiments to maximize the process information are open questions. The type of reaction [homogeneous or heterogeneous (gas-liquid, liquid- liquid, gas-solid, liquid-solid, gas-liquid-solid), etc.] nature of downstream processing, the process intensification strategies that can be employed, etc. have a significant influence on the nature of process experiments that need to be performed. It is also important to establish analytical methods to obtain a clear measure of extent of transformation, yield of products, etc. It is equally important to identify the impurities present and their extents in the feedstock and the part they can play during the transformation process. The impurity profile of a product is reminiscent of its quality.

The initial process experimentation data so collected can be used to build preliminary relationship between the inputs, outputs and operating conditions covering a range of practical interest. The model so built can be used for arriving at optimal strategies, for operation and control. Simultaneously one can start putting the flow sheet, P and I diagram, heat and mass balances, etc. together to create a process synthesis module/environment. Additional experiments validating the optimums and transient start-up, shutdown procedures etc. can be continued. The process development program is highly interactive and as shown in Figure 1 evolves through the synergistic interactions of various work elements, until economic viability, quality of product and environmental concerns are realized.

Central to the success of process development efforts is the issue related to design of experiments in appropriate type of reactor so that the dominant length and time scales of the phenomenon involved in the process be captured. In typical process, these length and time scales can vary over a range- ($10^{-10}$ to $10^{10}$) giving rise to coexistence of interacting multiple scales. Table 1illustrates and identifies the dominant rate and transport mechanisms along with the type of models used to describe them. The interactions lead to severe nonlinearities that are difficult to handle. The recently introduced microreactors allow for adaptation of the length and time scale by manipulating the flow, channel length, width and other parameters such that the desired phenomenon leading to improved performance can be realized. From the perspective of process development this offers a major advantage that is yet to be fully realized. Thus for instance, it may be feasible to design a microreactor unit for highest possible efficiency, no or least amount of by product, maximum conversion and energy utilization. The flexible modular units can be assembled in a stack (as in fuel cell for energy) to meet the volumetric requirements giving a cleaner, cheaper and globally competitive process. In the present article we shall evaluate the microreactor technology from the perspectives of process development tasks.

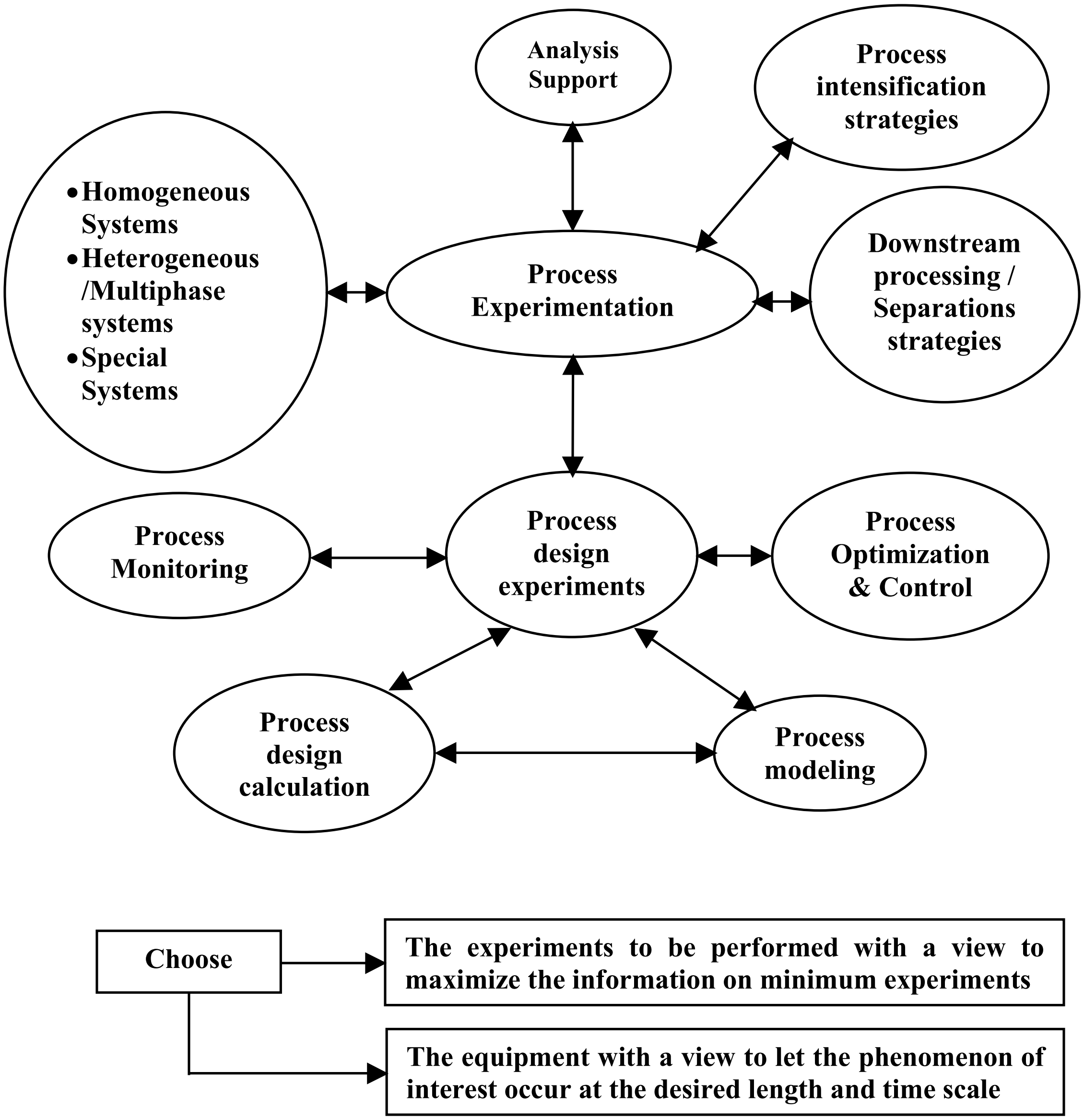
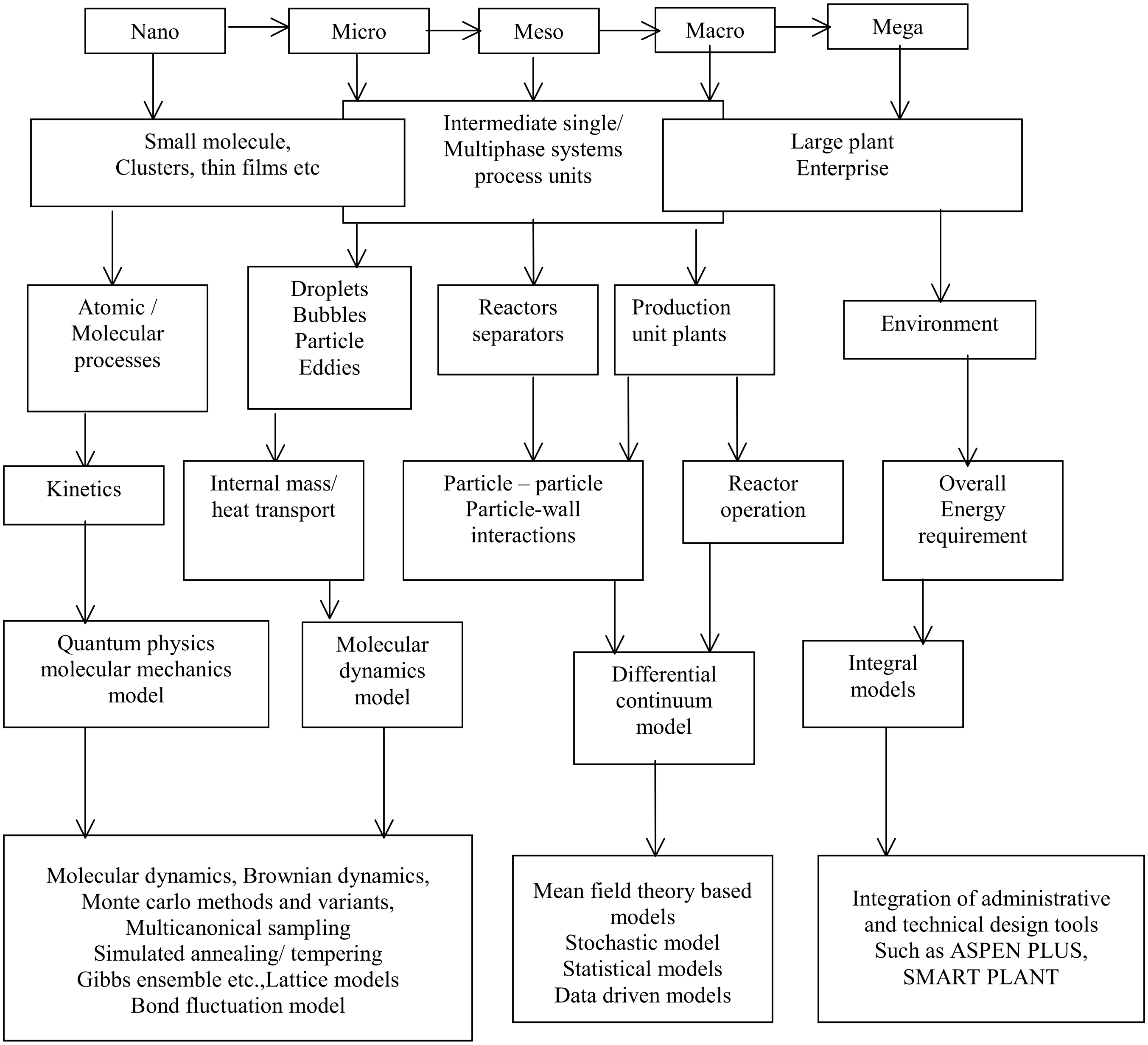


Figure 1. A general schematic showing process development strategy

Table 1. Range of length–time scales in chemical engineering processes



## 2. MICROREACTORS: GENERAL

Microreactors, as the name implies, involve reaction chamber whose dimensions are typically in the range of micrometers (μm) with volumetric capacity in the range of micro liters (μL). The notion of small volume systems is at least a few decades old and has aroused considerable interest amongst the research community since then. The possibility of reduction in dimensions with small volumes of reaction zone would allow application of high temperature or concentration with significant ease of process control and thermal management. This would therefore allow previously infeasible regimes of operation possible with improved performance. Thus for instance, among the early publications in this area we can cite the work of Harrison and Rase (1965) who describe the characteristics of an automated precision microreactor system and provide design specifications so that other research scientists can construct similar units for their need. The reactor unit was designed with a view to allow quick evaluation of a new idea, especially in catalysis research. The unit afforded a rapid and easy collection of data on reaction kinetics, catalyst activity and on stream behavior as well as comparative evaluation and testing of catalysts. In a similar instance Richardson and Rase (1978) reported a continuous stirred microreactor for liquid-liquid reactions where by adjusting inputs and operating conditions it was possible to delineate the chemical steps from intervening transport effects. (See Figure 2.) This helped in generating better understanding to solve operating problems, improved selectivity and yield and generate alternate process improvements. Attygalle and Morgan (1956) describe a versatile microreactor and extractor of extensively small volume of 5 to 10 pL for manipulation by preparation, reaction, derivatization, extraction, filtration, etc. The system could be operated under moderate pressures and temperature and can use solvents of density higher and lower than water.

Over the years the area has matured to a level where microvessels are no more just a matter of academic curiosity but have gained interest for use in industry (Hessel et al., 2000, 2003, 2004; Haswell et al., 2002, 2003,Jensen, 2001; Gavriilidis et al., 2002) and microflow devices such as mixers and heat exchangers with working throughputs in $m^3h^{-1}$ range are already a reality (Edge, 1997; Breuer, et al., 1997; Schubert et al., 2001; Haynes et al., 2002; Löb et al., 2004). A number of articles citing the relevance of microreactor technology to process development and industrial research have appeared in the literature (Rouhi, 2004). Thus for instance, Löwe and Ehrfeld (1999) report a successful application to synthesis of vitamin A precursor by a homogeneously catalyzed liquid-liquid phase reaction; other types of reactions, for example, gas phase or gas-liquid reactions have also been reported. Miniaturization offers significant advantages with respect to cost, safety, throughput, kinetics, scale-up and benefits chemical discovery and development applications.

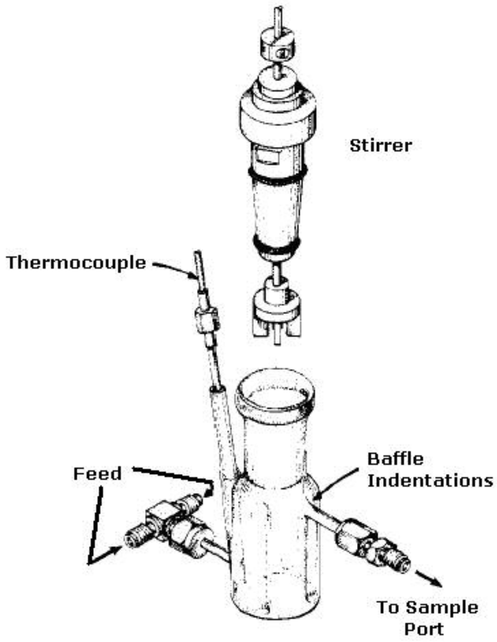


Figure 2. Continuous stirred glass microreactor (Reprinted with permission from Richardson et al., 1978. Copyright (1978) American Chemical Society)

Dewitt (1999) illustrates the utility to catalytic oxidations, heterocyclic synthesis and photochemical reactions while Jensen et al., (1999) describes processing advantages from increased heat and mass transfer to gas, liquid and multiphase systems. The benefits of integrating sensors for flow, temperature and composition with microfluidic reaction and control components are also evident in terms of ease of process development.

Not withstanding the pioneering reports and early studies on microreactors that fueled the research activities in this area, the concept of miniature total chemical analysis system began to take shape only in the early nineties. Integration and automation became an integral part of microdevice development. Thus for instance, Mainze et al., (2000) describe an integrated miniature device for sample preparation, treatment, separation and detection. The advent of microelectro mechanical systems (MEMS), Graveson et al., (1993) allowed creation of microchannel architectures in one plane on a chip or 3D microflow device for the lab scaleuse. The possibilities of full instrumentation, analysis and automation for precision control spurred on the explorations for process development, new ways of organic synthesis, material synthesis, catalyst development, testing and comparative evaluation, polymerization, biosynthesis, etc. Some of the more commonly used microreactor systems, which can be extremely useful in process development work are summarized in Table 2 along with some selected details of their operation and use.

Table 2. Some of the commonly used microreactor systems

| Microreactor assembly | Characteristics | Advantages | Figure | Reference |
|---|---|---|---|---|
| CYTOS System | • A bench top continuous reactor consisting of a series of extremely thin stainless steel plates placed on top of one another.<br>• The plates contain fine micro-channels and feed lines to allow flow of reactants, coolants, etc. | Very advantageous for<br>• Reactions with high exothermicity<br>• Reactions at elevated temperatures<br>• Reactions with unstable intermediates<br>• Hazardous & toxic systems | <br>(Reprinted with permission from Zhang et al., 2004. Copyright (2004) American Chemical Society) | Taghavi-Moghadam et al., (2001);<br>Zhang et al., (2004). |
| Instrumented shake flasks | • Cell growth culture, media screening & cell expansion studies<br>• To establish relationship between parameters and cell growth, product yield | | <br>(Reprinted from Weuster-Botz et al., 2001, Copyright (2001), with permission from Elsevier) | Anderlei et al., (2001);<br>Weuster-Botz et al., (2001). |

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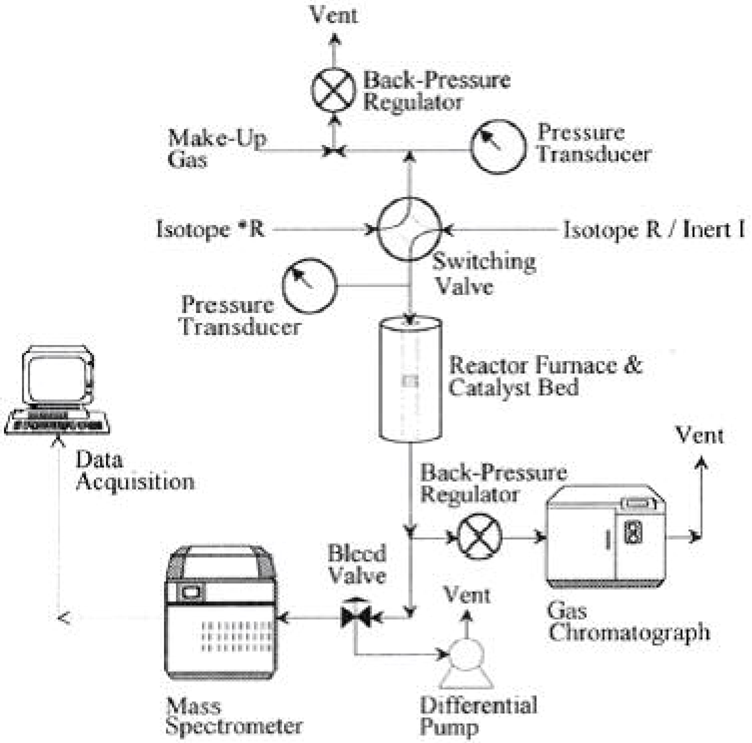
| Steady state isotopic transient kinetic analysis (SSITKA) | • Provides similar utility as TAP<br>• To measure number of active sites, mean surface residence time of the reaction intermediates, activity distribution of catalytic active sites, etc.<br>• The feed is passed over a fixed bed at required pressure, temperature, etc. The products analyzed through MS<br>• One of the components in the feed switched over to its isotopic part and the run followed to track how the old component decays | • Is much more simpler to use and maintain than TAP<br>• More reliable, steady and simple operation |  <br>(Reprinted with permission from Shannon, et al., 1995. Copyright (1995) American Chemical Society) | Shannon, et al., (1995). |

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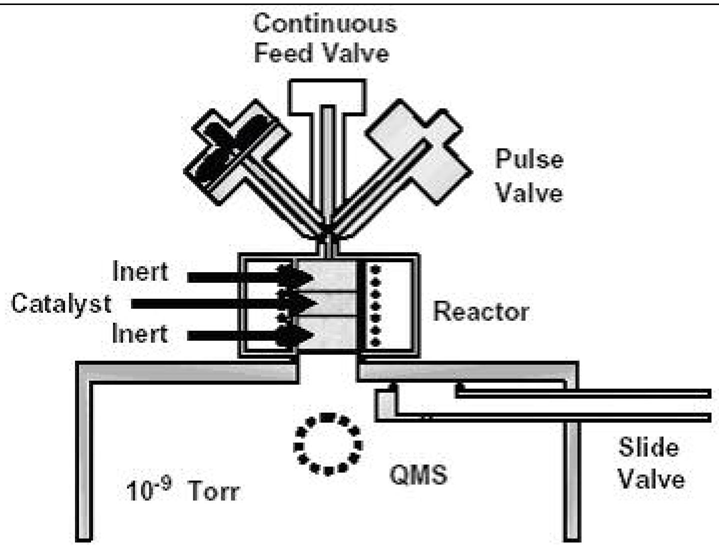
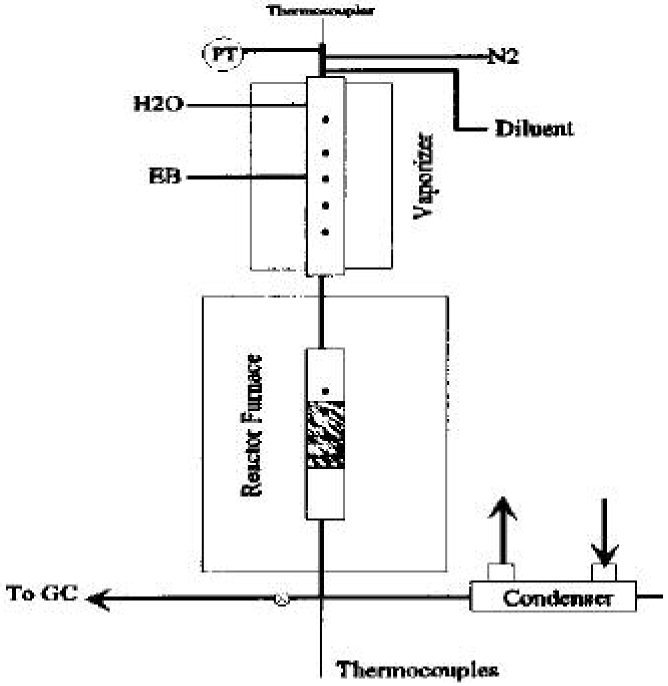
| TAP (Temporal Analysis of Product) reactor | - 0.15 $cm^3$ continuous microreactor assembly with feed valve and a set of four fast pulsing valves with response time of the order of 100 µs<br>- The outflow from reactor fed to mass spectrophotometer with a resolution better than 1 ms | - Provides accurate information about reaction intermediates, surface lifetime, kinetics, sorption behavior as well as configurational diffusivities |  (Reprinted from Gembicki et al., 2003, Copyright (2003), with permission from Elsevier) | Cleaves and Centi (1993);<br>Yablonskii et al., (1998);<br>Gembicki et al., (2003). |
| Temperature Scanning Reactor (TSR) | - A micro reactor system operated under transient conditions<br>- In TSR, we vary the LHSV and measure the conversion. Simultaneously temperature can be varied to create multi-dimensional data set, which can be numerically differentiated to directly obtain the rate | |  (Reprinted with permission from Domke et al., 2001. Copyright (2001) American Chemical Society) | Wojciechowski US Patent<br>5,340,745 (1994)<br>5,521,095 (1996)<br>5,593,892 (1997) |

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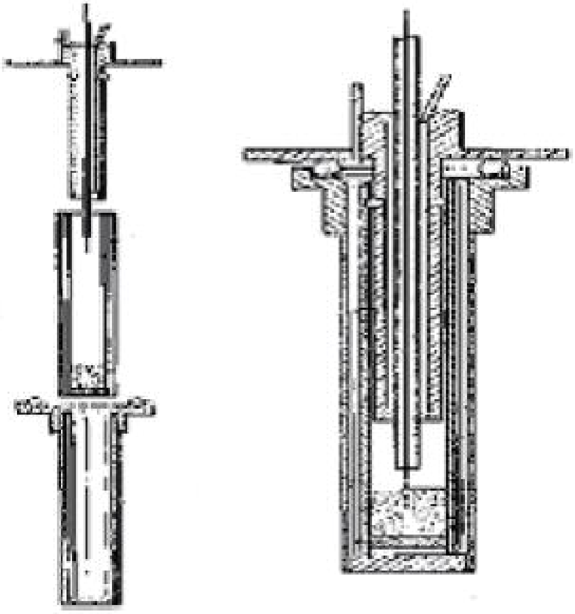
| Automated shaken microwell system | • To obtain process information on biological materials bacterial fermentation<br>• Animal cell culture<br>• Biotransformation<br>• Oxygen mass transfer | |  (Reprinted from Girard et al., 2001, Copyright (2001), with permission from Elsevier) | Duetz et al., (2001);<br>Girard et al., (2001);<br>Doig et al., (2001). |
| High Throughput Screening (HTS) | • A series of micro reactor designs that can be used in fixed or fluidized mode of operation<br>• Useful tool for catalyst discovery, optimization and data collection for kinetic models | • Allows wide range of flow rates and maintaining of desired hydrodynamic and temperature regime |  (Reprinted from Gembicki et al., 2003, Copyright (2003), with permission from Elsevier) | Gembicki et al., (2003). |

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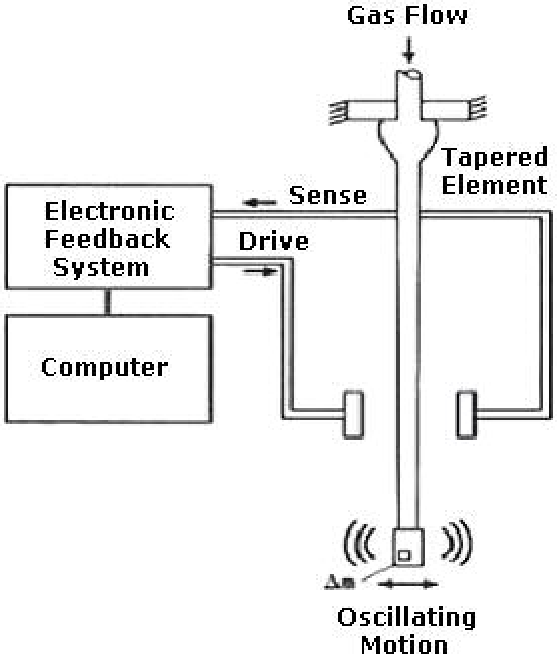
| Tapered Element Oscillating Microbalance (TEOM) | • To study catalyst deactivation rates and mechanisms<br>• A small catalyst bed mounted at the end of a tapered quartz tube, sitting on a porous metal disc of inert material<br>• The reactants passed through the bed emerge in analysis section consisting of GCMS. Conversion /selectivities can be closely monitored<br>• The mass gain of the bed is simultaneously measured using the principle of harmonic oscillator | | <br> <br>(Reprinted from Gembicki et al., 2003, Copyright (2003), with permission from Elsevier) | Gembicki et al., (2003). |

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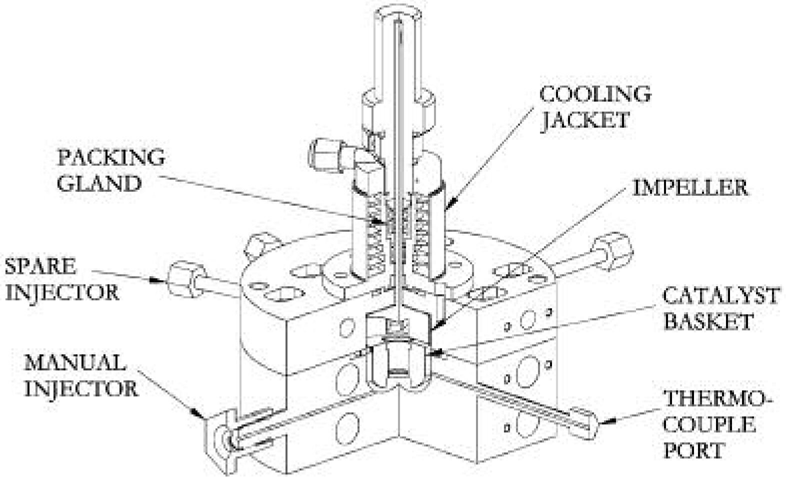
| Fluidized CREC riser simulator | • A sample of fluidizable catalyst is trapped in a basket between two grid plates.<br>• Consists of two outer shells, a lower section, and an upper section that permits the catalyst to be loaded and unloaded easily.<br>• Impeller provides a fluidized bed of catalyst particles as well as intense gas mixing inside the reactor<br>• Isothermal operation condition<br>• Series of sampling valves allow injecting hydrocarbons and withdrawing products in short periods of time. | • High gas phase circulation rates<br>• Intense catalyst mixing<br>• Better mixing with no mass-transfer limitations due to the fluidized state of small catalyst particles<br>• Mimics the conditions of FCC units matching partial pressures, reaction times, and temperature |  (Reprinted with permission from Atias et al., 2004. Copyright (2004) American Chemical Society) | De Lasa (1992)<br>De Lasa<br>US patent 5,102,628, (1992) |

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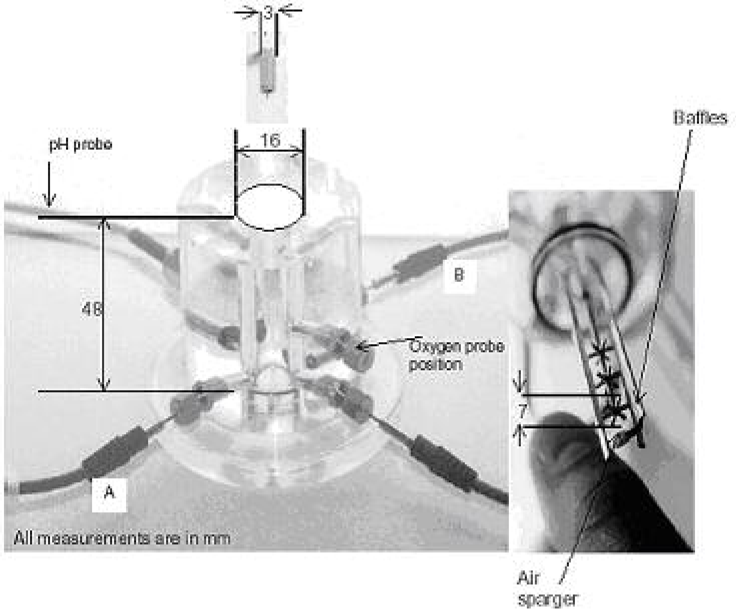
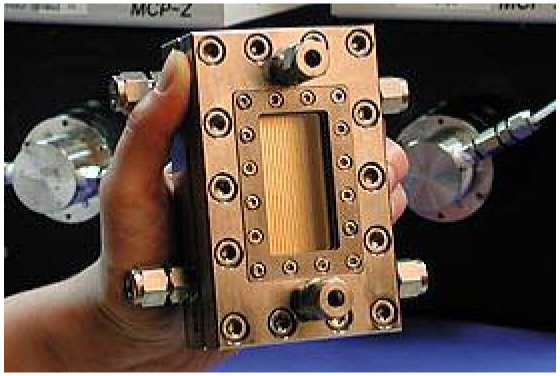
| Miniature bioreactors | • 3 ml cell culture<br>• 2 ml cell culture<br>• 24 well plate | |  <br>(Reprinted from Lamping et al., 2003, Copyright (2003), with permission from Elsevier) | Kostov et al., (2001);<br>Lamping et al., (2003). |
| Gas/liquid microreactors<br>• Falling film microreactor<br>• Micro bubble column<br>• Micromixer/tube reactor combination | • Falling film microreactor is made up of Hastelloy (a nickel based alloy).<br>• In the top and bottom plate a heat exchanger is integrated. | Advantageous for highly exothermic gas-liquid reactions. The falling film thickness depends on channel dimension. High interfacial area s & integration with heat exchangers allow isothermal operation. |  <br>(Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |

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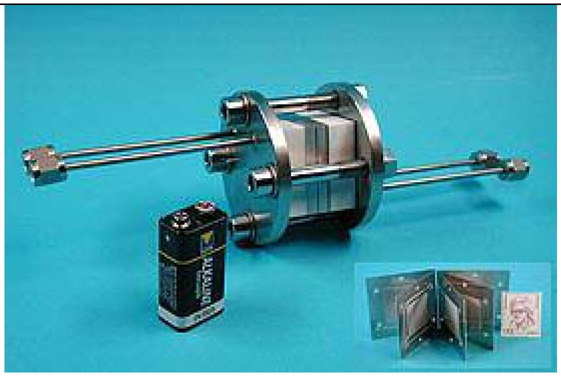
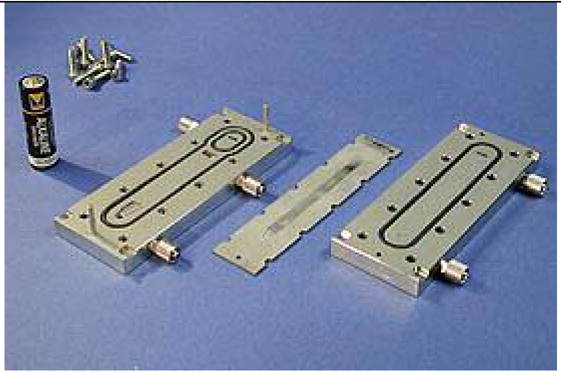
| Gas phase microreactors<br>• Monolith reactor for non-catalytic conversion<br>• Stacked multichannel reactor with mixer<br>• Stacked multichannel reactor (without mixer) | • Used for investigations of periodic operation of gas phase reactions | Microstructured plates coated with catalyst can be put together to carry out heterogeneous reactions. One unit suitably connected can be used as a counter current heat exchanger. |  (Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |
| Liquid phase microreactors<br>• Micromixer/tube reactor | • Device with large, overlapping contact surfaces for liquid/liquid reactions | Microreactor with integrated heat exchanger for liquid and liquid/liquid phase reactions made of stainless steel. |  (Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |
| Supercritical processing in microreactors<br>• Micromixer/tube reactor combination | • Combination of a micromixer with a heated tubular reactor. | • Reactions in the supercritical regime can be carried out |  (Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |

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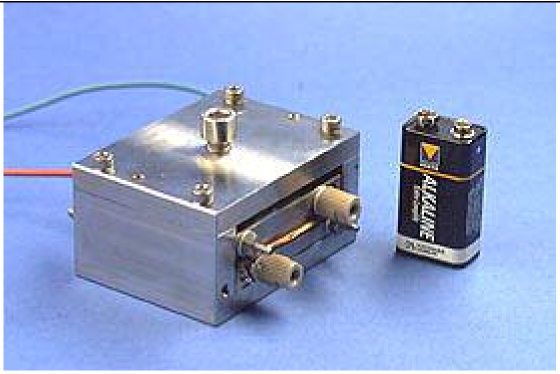
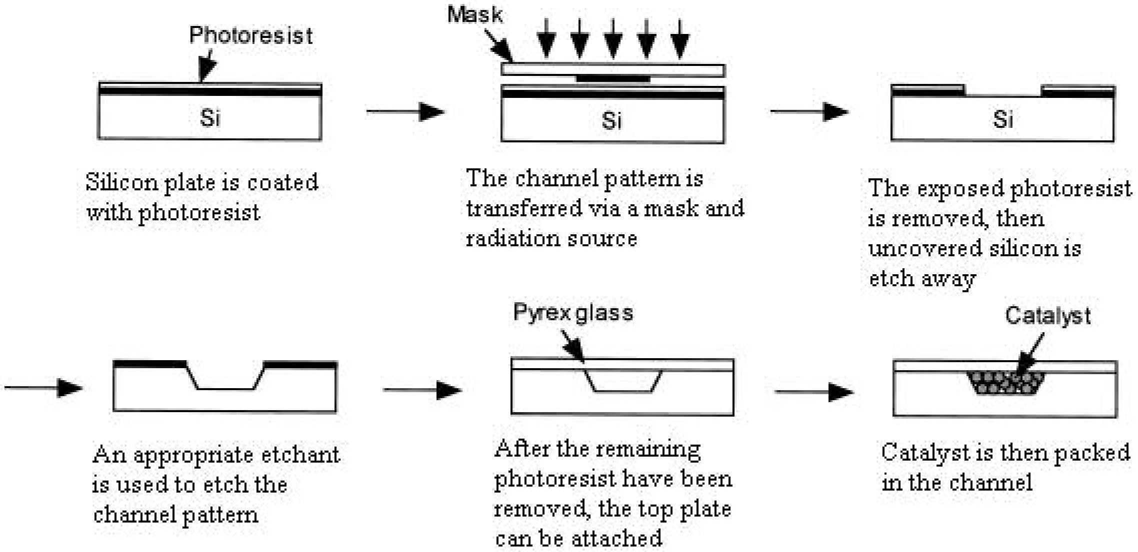
| Microreactors for catalyst/material screening<br>• Stacked plate device for fast serial screening<br>• 48-Multi-fixed bed/Titerplate reactor for parallel screening<br>• Micromixer/tube reactor operated in transient mode | • Different reactor geometries such as microstructured titerplates, parallel tube reactors | • Allows the parallel screening of 48 catalysts upon their suitability |  (Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |
| Microreactors for electrochemical applications<br>• Plate-to-plate electrochemical microreactor | • Parallel electrode plate microreactor useful for organic synthesis | |  (Reprinted from www.imm-mainz.de, Copyright (2002), with permission from IMM) | Institut für Mikrotechnik Mainz GmbH (IMM). |

## 3. FABRICATION METHODS AND NEW AND NOVEL DESIGNS

The features are fabricated onto an inorganic substance-using semiconductor processing techniques such as photolithography and etching (Harrison et al., 1992). McCreedy (2000) discusses in more details the fabrication techniques and micro total analytical system. Fluidic manipulations can be achieved with the use of either hydrostatic displacement pumps (syringe pump) or electro-osmotic flow with added advantage of electrophoretic separations. Figure 3 sketches the operational details involved during fabrication.



Silicon plate is coated with photoresist

The channel pattern is transferred via a mask and radiation source

The exposed photoresist is removed, then uncovered silicon is etch away

An appropriate etchant is used to etch the channel pattern

After the remaining photoresist have been removed, the top plate can be attached

Catalyst is then packed in the channel

Figure 3. Process for silicon chip by photolithography

For alternative substrates such as polymers, molding, embossing, a soft-lithography can be used (Goretty, 2000). Availability of commercial equipment with precise control of pressure and temperature for hot embossing of polymeric materials to create robust and reproducible microstructure has provided a low-cost alternative to silicon or glass based MEMS technologies. Microchannels for capillary electrophoresis, micro fluidic devices, micro-optical components and microreactors can be routinely produced with a degree of precision on mass scale. Thus a variety of devices fabricated using a variety of polymeric materials using different techniques like laser ablation; injection molding, silicon rubber casting, etc. are now available and reported in the literature. Becker and Gärtner (2001) review the fabrication techniques for production of polymer-based micro-fluidic devices. A number of applications such as capillary electrophoresis, micro mixers and nanoplates are described.

Cui et al., (2000) describe fabrication of a silicon wafer containing 12 reactor chips of overall dimension (20 mm long × 14 mm wide × 3 mm high), using standard processing technique. Each chip contains (a) reaction section (b) separation membrane and (c) reactor cap. The reaction section consists of 80 microchannels (50 μm wide × 400 μm deep × 8 mm long) carved on silicon <110> plane. A 20 nm Titanium adhesion layer is deposited as catalyst carrier and 20 nm platinum layer as catalyst. The separation membrane is (6 mm × 8 mm) with 80-folded rectangular 4 μm thick palladium fold structures (50 μm × 200 μm × 6 mm) to silicon. These structures enhance the separation area and are constructed using a combination of silicon <100> wet etching and dry etching. The reactor cap for inlet and outlet gas pipes is made of PDMS material.

The reaction chamber, separation membrane and reactor cap are bonded together using polyamide with good contact strength between the design. The system tested for dehydrogenation of cyclohexane to benzene shows improved performance.

Wan et al., (2001) describe the fabricated miniature zeolite based structure (silicate -1, ZSM-5, TS-1) for application as microreactors and microseparators. The devices were constructed using either (a) zeolite powder coating (b) uniform zeolite film growth (c) localized zeolite growth or (d) etching of zeolite-silicon composite film and exhibit controlled particle size, crystal morphology, layer thickness (3-16 μm) and orientation (101 and 102 films). A microreactor incorporating cross flow design with a short pass multiple flow channels geometry minimizing the pressure drop through particle bed and enhancing isothermal kinetic regime conditions (free of transport limitations) is described by Ajmera et al., (2002a). The cross flow microreactor with instrumented sensors on it provides an opportunity for high throughput testing of heterogeneous catalysts and has been used for CO oxidation as a test example. In continuation the authors (Ajmera et al., 2002b) describe a silicon macrofabricated differential packed bed reactor 25.5 mm wide with shallow catalyst bed (400 µm long × 500 µm deep) having catalyst particles with diameters 53 to 71 µm. The cross flow microreactor suppresses thermal and mass gradients in the bed with uniform flow characteristics and low-pressure drop. The catalyst bed operates differentially even at total conversion and thus allowing conventional synthesis and analytical procedures.

For the efficient screening of granular catalysts, Kusakabe et al., (2002) describe a microreactor having six channels (1 mm wide × 0.3 mm deep × 6 mm long) fabricated using silicon and glass plates by means of photolithography and wet etching. Catalyst prepared by impregnating Pt, Rh, Ru, Co, Ni, Cu, and Pd on γ-alumina support and sieved to 150-210 µm particle size was used in the channel (9 mg aliquot) to study CO oxidation reaction.

An evaporator unit for use in microreactor system was described by Sotowa et al., (2003) and consists of a micropump based on piezoelectricity driving mechanism and a microdevice serving as an evaporator heated electrically by means of platinum wire. A silicon plate having three diaphragms (7 mm in diameter) and a glass plate having a valve and pump chambers (each 7 mm in diameter) were tightly bonded and patterned using photolithography and wet-etching technique. The pump discharge rate depends on the applied voltage and frequency; the actuation pattern, the outlet back-pressure and liquid viscosity and can typically reach a level of 60 ml $min^{-1}$ for water. The unit can be assembled using epoxy adhesive or anodic bonding and showed high discharge rate or high discharge pressure in the respective cases. The micro evaporator channel was wet-etched on one side of a silicon wafer (10 mm × 40 mm) while on the other side a channel carrying a platinum heater element was fabricated. The unit encased in glass plates on either side was tested for evaporation of benzene and vapor rates of approximately 7 ml $min^{-1}$ could be easily achieved.

Hostis et al., (2000) describes a microreactor and electrochemiluminescence (ECL) detector fabricated using a silicon-wafer. A platinum or carbon interdigited electrode array was laid on top of Si Pn photodiode and the entire device was modified using SU-8 technology to form a series of shaped spacers around each device. In the case of a detector, a single channel for flow was defined while for the reactor a complex layout consisting of two chambers separated by a series of SU-8 columns was constructed. The upstream chamber was packed with glass beads carrying the immobilized enzymes whereas the downstream chamber carried the detector. The unit was tested for detection of glucose with acceptable accuracies. Such detectors can be more easily fabricated in polymers. Thus for instance, for specialty polymers such as fluorinated ethylene-propylene (FPE), the unique property of dual layer comprising of PTFE (outer layer) and FPE (inner layer) can be used to create microstructures. During heating beyond 350°C the outer layer melts to diffuse in FPE where channels are created by drawing tungsten wires. Sahlin et al., (2002) use the device and the technique to detect biurate complexes of the natively electro inactive peptide.

In sub nanolitre microreactor with volumes of 60 and 540 pL fabricated on 6 µm thick layer by dry etching, a high resolution liquid volume detection was done by aluminum electrodes which were fabricated at the bottom of the reactor and covered with silicon nitride for electrical insulation (Hjelt et al., 2000). The liquid volume in the reactor is determined by impedance measurement. The contact-less measurement device can be used to measure sub nanolitre volume for different liquid compositions and reactor size to an accuracy level of 1 pL. The device is useful for high speed screening systems to determine dispensed liquid volume.

A microreactor containing T shaped channels network (221 µm wide × 73 µm deep) was described by Fletcher et al., (2003), etched on a 0.5 mm thick bottom glass plate that is thermally bonded to another top glass plate 0.5 mm thick. The channels receive the reactants through hydrodynamic pumping where the reaction between methanol and acetic acid occurs to produce ethyl acetate. The reactant and product concentrations were determined at different spatial locations using an inverted Raman microscope spectrometer equipped with a laser source at wavelength of 780 nm and other accessories. The scattering bands for each reactant and product species were completely resolved and gave quantitative spatial evolution of the concentrations. The miniature device is extremely useful for in-situ monitoring of chemical reactions. Raman microscopy provides a complementary technique to other methods such as UV/VIS absorbance and fluorescence methods and is especially advantageous for species where the overlap of band for other reactants, products etc. render conventional methods very restrictive in their usefulness.

In another study, Yunus et al., (2002) reported voltametric sensing of chemical species contained within two immiscible liquid streams flowing through rectangular ducts (75 μm high × 500 μm wide × 3 mm long) fabricated on a Foturan glass using standard processing technique of photolithography. Microelectrode sensors were located on the inner wall of the duct. The liquid streams were pumped separately and together through the duct and linear sweep voltmeter measurements performed. The variation of transport limited current, as a function of volumetric flow was determined.

A reconfigurable microreactor consisting of substrate in which a number of overpassing channels which can be optionally interconnected with each other is described (US patent 6,599,736 (2003)). The blocking elements can be positioned or inserted so as to obtain the desirable configuration. Likewise suitable modifications such as a tightly fitting conductive core surrounding the channel and sealed to the reactor tube at both ends to confine the coolant except for inlet and outlet holes can provide close temperature control (US patent 4,585,622 (1986)). A method and apparatus for operating a microreactor at high pressure is disclosed in US patent 20,040,081,600 (2004), while organizing the plates in a stack such that the openings in adjacent plates confine a fluid path describing heat transfer area and reactor volume is described in US patent 20,020,106,311 (2002). An array of parallel fluid channels having different width and bifurcated fluid distribution channels to handle fluids with varying viscosity can provide and enhance uniform fluid flow in such a device. A simple microdevice for transporting specific amount of liquid without the use of a sophisticated actuator mechanism involves creating a configuration in a conduit where at least three microchannels intersect one another with at least two having a controlled opening/closing (US Patent 20,030,026,705 (2003)). In recent years a number of other integrated microdevices with thermal insulation from detection electrodes (US Patent 20,020,045,244 (2002)) are also described.

## 4. FUNDAMENTAL ISSUES: FLOW BEHAVIOR, MIXING PATTERN, RATE DYNAMICS, HEAT AND MASS TRANSFER, DESIGN, MODELING AND OPTIMIZATION

In the section above, we provided a brief description of an assorted set of examples involving new and novel fabrication designs with specific end applications. Many more of such examples are being presented in the literature and some of these are covered in the Tables 3-11 showing applications to different areas of interest to chemical engineers. In some of the other studies focus of research is not so much on new designs or end applications but rather on studying, using model reactions; the fundamental issues such as flow behavior, mixing pattern, rate dynamics, heat and mass transfer, design, modeling and optimization. Again considerable work covering the above aspects are reported in the literature and Tables 3-11 cover some of these in some detail. For sake of brevity we shall present only a few assorted set of examples highlighting these engineering science issues.

### 4.1 Mass Transfer Coefficient

The early comparative study of gas-liquid mass transfer coefficients in stirred autoclave, bubble column and tubing bomb microreactors clearly revealed that the latter was more efficient with interfacial areas up to 28 $cm^{-1}$ Gollakota and Guin, (1984); Bej et al., (2000) reported the results on hydro desulphurization of atmospheric gas oil. The performance of the micro trickle bed reactor was examined by studying the effects of catalyst bed height, operating liquid hold up, etc. at different liquid hourly space velocities.

In recent years the drug discovery research program has shifted towards proteomics and away from genomics. The relationship between proteins produced by each gene and the disease is attracting considerable attention. Efforts in this direction are growing exponentially as the number of targeted proteins increase. The microwell plate system provides an experimental platform for high throughput screening but the conditions for translation of results from microwell system to conventional laboratory scale unit possess considerable challenge. Understanding the scale-up information from microwell system to laboratory scale units and gathering relevant process data is proving to be very difficult. The engineering design issues of a miniature bioreactor are thus of crucial importance. Lamping et al., (2003) describe a miniature bioreactor containing a cylindrical chamber (16 mm dia. × 48 mm high) fitted with three, six-bladed flat turbine impeller (7 mm dia. × 1.5 mm wide) driven by a microelectric motor at speeds ranging up to 15,000 rpm. The chamber is fitted with four baffles (1.8 mm wide × 0.6 mm thick). Air is sparged through a nozzle of 1 mm ID at flow rates ranging from 0.2 to 100 ml $min^{-1}$. Optical fiber probes with parameter sensitive fluorophores are used to monitor dissolved oxygen tension, cell biomass concentration and pH. The experimental assembly was used to carry out all fermentation experiments with E-coli DH5α in batch mode with a view to collect basic engineering parameters for comparison with conventional scale reactors.

Computational fluid dynamics simulations were carried out to obtain energy dissipation rate, gas volume fraction and air-liquid interfacial area, which are important engineering parameters for correlating experimental mass transfer coefficients. The standard Reynolds averaged Navier-Stokes equations described the three dimensional gas-liquid turbulent flow, along with the k-ε closure scheme. The gas bubble motion and their interactions with the flowing liquid exert a drag force and couples the gas-liquid momentum equations. The impeller influence is included through additional source terms in the momentum equation while the presence of baffles treated as thin surface, is included as time-averaged sink term. No slip boundary conditions were used for both the phases while free-slip applied to bottom and sidewalls. The gas sparger was simulated as a solid body. For a fixed impeller speed and gas flow rates the CFD simulations provided on estimate of velocity field, bubble sizes, gas hold-up and energy dissipation rates. The parameters can be used in mass transfer model to predict the local as well as integral overall mass transfer coefficient.

The CFD simulations of energy dissipation rate for a single-phase system gave the power number of approximately four and for two phase gas-liquid systems as a ratio of gassed to un-gassed power of 0.8-0.9. These values are consistent and in the range reported for such systems. The conventional size reactors (~20 lit. volume) have power number ~6 for single-phase system. The average value of mass transfer coefficient of $4 \times 10^{-4}$ $ms^{-1}$ is recommended for such system whereas values of $k_La$ ~0.03 $s^{-1}$ have been obtained for actual experiments in reasonable agreement with the range reported from CFD simulations. The concept of power input per unit volume provides a scale-up relationship linking the miniature reactor to conventional size units. The experimental data of Kostov et al., (2001) on E-coli fermentation in a 2 ml minireactor that is magnetically stirred (9.8, 27.5 and 44.4 $h^{-1}$ for air velocity of vvm 1, 2 and 3) and those of Duetz et al., (2000) for air-water system, while on the lower side, confirm the range obtainable in such units. The relatively lower values of $k_La$ suggest that the miniature bioreactor systems are likely to be limited by oxygen diffusional limitations.

## 4.2 Flow Behavior

The two phase flow characteristics of a gas-liquid mixture in vertical capillary microreactor were studied by Simmons et al., (2003) covering a rage of 0.001 to 10 m $s^{-1}$ of gas flow and 0.0001 to 1 m $s^{-1}$ of liquid flow. The capillary tubes were round (2 mm) and square (3 mm) in diameter and showed flow regimes and transitions as flow changes. In the case of round tubes, annular, slug, slug-annular, bubbly and churn flow regimes were observed while the square tubes showed irregular behavior in place of annular and slug-annular flow. The understanding of flow regimes and their transitions holds importance from the point of view of rational design of such systems.

The manifold structures, for flow distribution of material inside the microchannels need to be designed properly so as to ensure uniformity of flow across the channels. This is essential to realize uniform heat and mass transfer and reaction dynamics. Amador et al., (2004) have investigated such manifold structures (consecutive and bifurcation type) for flow distribution and derived an analytical model to provide guidelines for the suitability of a manifold structure under different operating conditions, fabrication constraints and design objectives. More specifically the effects of manufacturing tolerances, channel blockages etc. are evaluated. The analysis is useful in arriving at conditions conductive to produce narrow residence time distribution in the channels.

Yamaguchi et al., (2003) report on the interface configuration of the two-layered laminar flow in a curved microchannel. Confocal fluorescence microscopy and 3-D CFD simulations were carried out to examine the fluid interface. The results indicate heavy distortion of fluid interface and increase in interfacial area. Factors affecting the behavior include flow velocity, curvature radius of microchannel and density and viscosity of liquid. The increase in flow velocity and density complicates the interface whereas the increase in curvature radius of the microchannel and liquid viscosity simplifies the interface. The interface distortion is important for microchannels whose depth is within five times its width, since diffusion and chemical reaction that occurs at the interface can get significantly affected. Okamoto et al., (2004) studied methods for increasing productivity of microreactors using (a) planar pumping or (b) alternating pumping. In planer pumping the thin liquid layers react at the interface enhancing the productivity by about 10% in comparison to standard batch reactor. In alternating type of pumping diffusive mixing through the liquid-liquid interfaces, perpendicular to flow direction, improves the yield of reaction. The yield linearly increases with increasing alternating frequencies up to a point.

Mixing by diffusion in microfluidic devices have docking time of the order of an hour. Thus, for instance, for a channel of width 200 nm and diffusivity of the order of $10^{-7}$ $cm^2$ $s^{-1}$ for typical macromolecule, the time $t = l^2/D$ works out to be 0.5 hr. In real situations involved during high throughput screening the time can even be larger. This presents a serious bottleneck for fast screening procedure and efforts to fabricate micromixing chambers that overcome the diffusional limitations continue. Use of microsplitters and microbaffles in mixing device is problematic due to inconveniences in their fabrication. Also micochips that employ electrophoresis or electro-osmosis cause high fields to occur near sharp comers. Microbaffles also cause precipitation and colloid aggregation in the stagnant regions. Micromixers and other units such as stirrers (with moving parts) are in general more difficult to fabricate. The mixing intensity of electrokinetic mechanisms is typically of the order of electro-osmotic flow (zero vorticity) unless some spurious instability exists.

Nonlinear electrokinetic flows that break the irrotational character of linear version have been predicted by Dukhin (2001) and experimentally verified by Mishchuk and Takhistov (1995). Barany et al., (1998) have measured the velocities, which are about 100 times larger than the standard electro-osmotic velocity under otherwise similar conditions. The velocity field exhibits vortices and the devices employing the principles are ideal for micromixing applications. The nonlinear electrokinetic flows exist near a conducting ions-selective granule in a uniform electric field within an electrolyte. The flux of counter ions into the granule disturbs the Boltzmann distribution and triggers a chain of events, which culminates into the nonlinear flow. Although the vortices create intense mixing, they are smaller than the granule by an order of magnitude. Introducing secondary flows to break the streamline of the vortices can cause significant improvement in mixing. Wang et al., (2000) describe a slow pH induced backflow produced with a DC field and rattling of granule electrophoretically with an ac field as means of secondary flow generation to break streamlines of the vortices and obtain a significant improvement in mixing behavior. The granule saturates in about 30 minutes in their experiments.

## 4.3 Heat Transfer

Rebrov et al., (2003) report the heat transfer characteristics of four cross flow microreactor devices using CFD for a model reaction system of ammonia oxidation on a platinum catalyst. The axial temperature gradients in the reaction channel can be decreased by appropriate flow distribution of inert gas like nitrogen. The distance between the reactant channel and coolant channel has a strong influence on temperature non-uniformity. It has been shown that by approximate design of a single periodic reactor cum heat exchanger unit, the temperature rise and non-uniformity can be reduced by adjusting inlet coolant distribution. A maximum of $4^o$ temperature difference was noticed for conditions corresponding to adiabatic temperature rise of 1400°C. The study demonstrates the reliability of microdevices for better heat management even in case of highly exothermic reactions and maintaining isothermal conditions for kinetic characterization. In a similar instance Schneider et al., (2004) report a coupled microreactor and a microcalorimeter chip. The degree of mixing in the reaction channel, especially important for fast reactions, was evaluated experimentally using a model iodate-iodide reaction and confirmed by calculations. The microcalorimeter was calibrated using neutralization reaction of $NaOH/H_2SO_4$. The sensitivity of the system to various microreactor designs was evaluated for better performance.

## 4.4 Kinetic Studies

A detailed kinetic model for ammonia oxidation reaction on supported polycrystalline platinum catalyst was derived and experimental data obtained in an aluminum microreactor (Rebrov et al., 2002). The model included extensive set of all possible reactions covering a wider range of operating conditions ($P_{NH3}$: 0.01-0.12 atm, $P_{O2}$: 0.1-0.88 atm, T: 523-673 K, contact time: 0.3-0.7 ms). The parameters of the model were evaluated using numerical algorithms and assuming the data to have come from an isothermal plug flow reactor. The flow behavior through the microstructures was described by a full set of Navier-Stokes equations and the equations coupled with reaction dynamics to simulate the various effects. The model was validated using separate experimental data obtained in the microreactor.

The hydrodesulphurization kinetics, using a commercial catalyst suitably diluted with inert solids, was reported by Bellos and Papayannakos (2003) for a straight run gas oil feed. The trickle bed microreactor performance was simulated using a model that takes into account the gas-liquid phase equilibrium and sulfur and hydrogen consumption rates are described by a first order process.

A kinetic model for methane combustion on $PdO/ZrO_2$ (10 w/w %) covering a temperature range of 400-550°C was studied in an annular microreactor. The simulation studies reveal that internal mass transfer will impede the progress unless the thickness of the active layer of catalyst is brought down under 10-15 μm. Also for combustion tests of ($CO + H_2$) mixture and $CH_4$ combustion, the model suggests near isothermal condition even up to 3% $CH_4$ mixture. The presence of $H_2O$ and CO inhibits the rate on the catalyst up to 550°C. The rate model so formulated is useful in the rational design of the reactor.

## 4.5 Design Issues

Important design issues for a microreactor requires the knowledge of the extent of the kinetic and transport rates that can be achieved and their dependence on the design choice and other parameters such as catalyst loading, operating temperature, the intrinsic conductivity of material used for fabrication and location of sensors, etc. The activity and heat transfer characteristics of a number of microstructured devices have been compared by Rebrov et al., (2001) by considering the model reaction of ammonia oxidation on Pt catalyst. The use of aluminum, a better conductor of heat, allowed to maintain temperature within 5°C at full conversion of 6% $NH_3$ stream whereas platinum based microreactor gave rise to sever temperature non-uniformity. Besides a 20% lower conversion to $N_2O$ can be obtained in aluminum reactor. The experimental data was used to redesign the microreactor/heat exchangers such that near isothermal conditions are realized. The example provides a basis to reconsider design of several other gas-solid catalytic processes involving high exothermicity. Earlier Quiram et al., (2000) considered the same model reaction and used finite element simulations to characterize the operating behavior of a microreactor and redesign the flow sensor and heat exchanger. The new design was actually fabricated and tested to yield results for conformity with the model calculations.

In an interesting study Vlachos (1998) describes the finite size effects of a microreactor assembly on ignition of $H_2$-air mixture. An exhaustive set of reactions involving nine chemical species was considered for simulation and inhibiting finite size effects on induction time was examined at atmospheric pressure and various temperatures. The studies revealed that the induction time in a 0.1 $\mu m^3$ reactor is larger by two orders of magnitudes at 1000°K as compared to conventional reactor. An analytical criterion for obtaining minimum reactor size above which the induction time remains relatively unaffected is proposed. The microreactor exhibits maximum fluctuations in the induction time and near the ignition temperature separates the slow and the fast reaction subspace. This has considerable significance in the system design for laminar as well as turbulent flows.

## 4.6 Optimization and Modeling

Mies et al., (2004) use a CFD approach to design and optimize the parameters of a high throughput Molybdenum based microreactor prior to micromachining and assembling. The reactor was to be designed to screen catalyst coatings in the temperature range of 100-800°C in gas phase reactions involving high thermal effects ($\Delta H$ = 500kJ $mol^{-1}$) and contains eight compartments ($2.28 \times 10.18 \times 40$ mm length) each of which have eight 100 μm thick molybdenum plates coated with catalytically active species at 150 μm distance from each other. The CFD analysis revealed that a uniform flow in the range of 500-1000 $cm^3$ $min^{-1}$ can be achieved by inserting a low pressure drop flow diffuser positioned upstream of the microreactor. The downstream contains a gas sampling section allowing analysis of products from any compartment without interference from others and a quench section freezing the proceedings in milliseconds.

Optimal design and operation of a microreactor and microseparator has been demonstrated by Štěpánek et al., (1999) by considering the product inhibited production of nicotinamide by immobilized nitrate hydratase. A bifurcational structured monolith is simulated and parametric dependence of solutions of a vector optimization problem is studied with reference to operational and design parameters. Considerable yield enhancement is possible by periodic operation and optimal arrangement of functional blocks.

The microreactor devices have created opportunities for development of industrially relevant chemical processes and hence their optimization, design and control issues have gained considerable importance. The general model for microreactors incorporate description of flow field along with heat and mass transfer and chemical kinetics involved in the form of coupled partial differential equations (See Figure 4.). General numeric scheme and computational fluid dynamics tools are used to obtain the internal flow patterns of fluid segments and the concentration and temperature profiles within segments and across interfaces. A number of such models addressing specific type of microreactor and chemical system under consideration have been reported in the

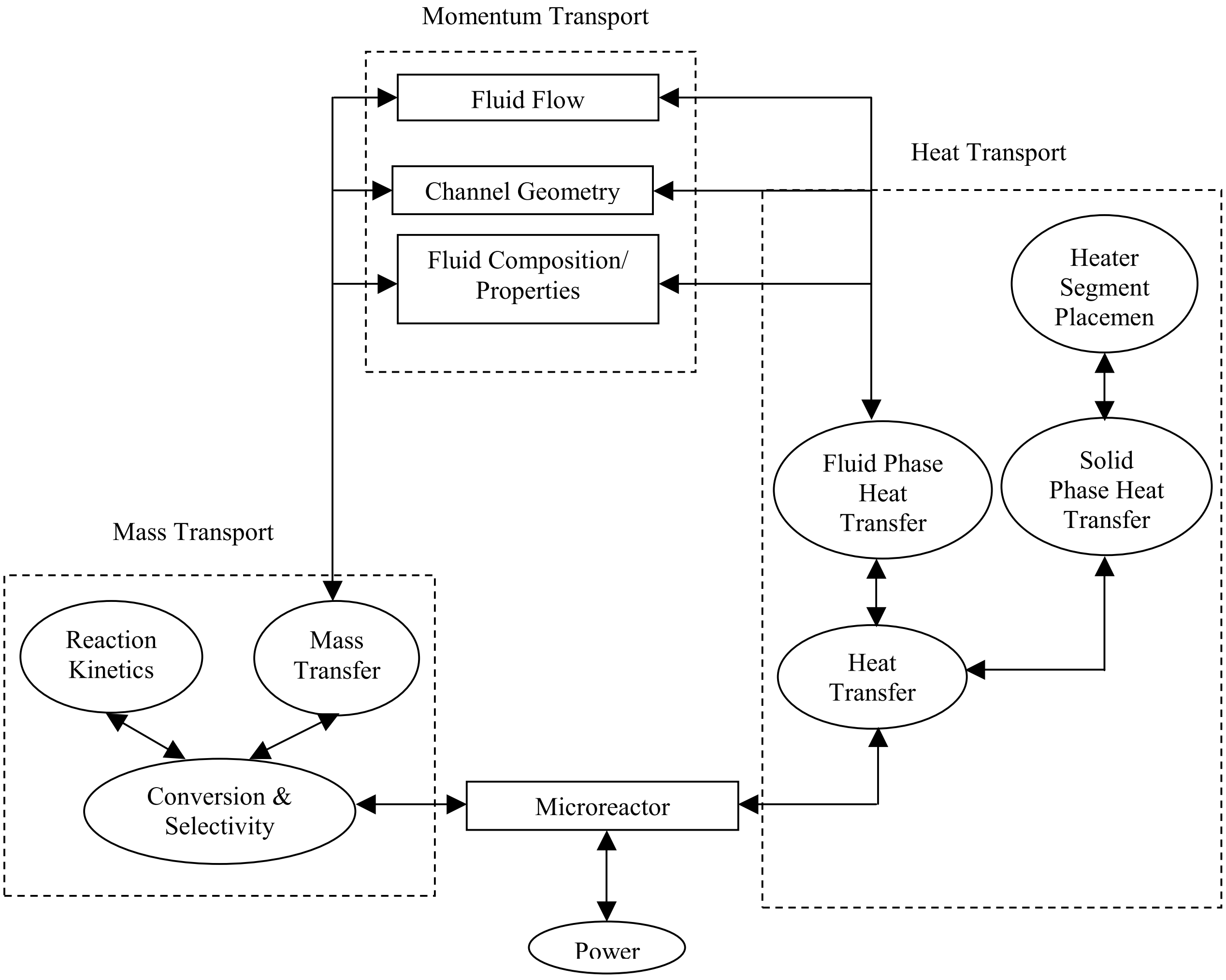


Figure 4. Interaction between the microreactor design and operating parameters
(Reprinted from Quiram et al., 2000, Copyright (2000), with permission from Elsevier)

literature. Thus Harries et al., (2003) provide a general model for segmented flow and validates the prediction with microreactor experiments. Dummann et al., (2004) developed a model for CO oxidation on Pt catalyst in hydrogen-rich reformate gas. Their analysis reveals that a detailed 2-D model is necessary to capture heat transfer processes in the reactor and that the catalyst deactivates too fast.

The complexities of a miniature reactor especially for a multiphase system preclude formulation of a model for generic use. Nevertheless, several assumptions that can often be justified can be made to provide some simplification. Thus for instance, most published work assumes the validity of Navier-Stokes equations despite some contradictory results. For microchannels (>30 μm) the flow can be described by conventional theory and laminar to turbulent transition is governed by conventional rule of $Re \leq 2500$. The momentum equations are considered to be decoupled from conservation of mass and heat equations and are separately solved. The fluid properties and composition of gas and liquid streams are independent of the chemical reactions in the temperature range. The presence of diluents or solvents helps to justify such assumptions in several systems of practical interest. The heat and mass transfer equations utilize the average velocity and it is generally believed that the laminar flow profile or the flow development does not influence heat and mass transfer.

The gas is modeled as a continuum, since the hydraulic diameter, usually in the range of 60-150 nm give rise to Knudsen number in the range of $6 \times 10^{-4}$. The liquid mean free path is smaller as compared to gases and thus rarefaction does not occur in the microchannels (>150μm). The system is considered to be thermodynamically ideal following Henry's law and Fickian diffusion mechanisms. The thermophysical properties are temperature dependent as described conventionally. The governing equations describing conservation of mass, heat and momentum subject to these assumptions need further supplementing equations describing the initial and boundary conditions. It is reasonable to assume no-slip boundary condition for the momentum equation and no flux condition for the mass balance equation. Similarly no heat-flux condition is valid for the left, right and top edges of the domain while the bottom wall of the reactor housing is assumed to be at constant temperature in equilibrium with the coolant channel. The non-uniform channel width can create non-uniform heat-flux and a temperature profile across the channel wall. A simultaneous solution of heat equation in the solid and the liquid phase is then necessary to obtain temperature and heat flux along the wall-fluid interface.

The relevance of such models and their utility to process development has been demonstrated by Schuster et al., (2003) by considering the highly exothermic reactions between fluorine and toluene. The reaction chemistry involves a number of series, parallel reactions including polymerization and radical reactions leading to decline in the selectivity towards mono-fluorinated product. Use of microchannel reactor for this gas-liquid reaction with a membrane deposited with Lewis acid catalysts is suggested as an advantageous configuration. Accordingly Schuster et al., (2003) modeled the microchannel reactor and simulated its performance and verified experimentally to show improved selectivity through better thermal management and higher production rate per channel.

In another interesting study Quiram et al., (2003) transformed the physical domain of the microreactor system into a computational domain via commercial mesh generator ICEM-CFD (1993) that used the CAD drawing of the reactor system. The boundary conditions for the reactor system are added using a preprocessor. The conservation equations for heat, mass and momentum, appropriately discretized have been solved using specially designed numerical scheme to seek the effects of operating and equipment variables such as location and type of sensors, heater segment length, gas flow composition, etc. An optimal microreactor design for a specified objective can then be obtained via simulation.

## 5. APPLICATIONS

The combination of microlithography, micromachining, microelectro mechanical systems, microfluidics and nanotechnology have synergistically led to development of microdevices of generic use that provides better understanding and scientific and technical solutions to fundamental problems. A porous silicon micro immobilized enzyme reactor is one such device extensively used in number of applications to biochemical processing and technology. For specific applications one needs to tailor the pore morphology to provide an optimal highly catalytic microfluidic component for integration in chemical microanalysis. In addition one can optimize with respect to silicon dopant type, thickness of the porous silicon layer and anodizing conditions. Laurell (2002) reviews the state-of-art on these and related aspects and cites a number of application areas. The porous silicon morphology in the microdevice is achieved by anodisation in HF-ethanol mixture. The procedure, however, often leads to non-homogeneous layer causing significant difficulties. Bengtsson et al., (2002) obtained a homogenous porous silicon layer on the channel walls (50 μm and 70 μm) by anodizing at 10 and 50 mAcm$^{-2}$ with anodisation time ranging between 0 to 50 min. The homogenous porous silicon reactor displayed improved performance with successful protein identification after only 12 s of digestion proving the importance of tailoring the device geometry and porous morphology. Laurell et al., (2001) describe an analytical toolbox containing microfluidic components that are highly adaptable for analysis of various bio-compounds. The porous silicon microreactor, suitably augmented with facilities such as a piezoelectric microdispenser, high density nanovial target plates, a matrix assisted laser desorption/ionization time-of-flight mass spectrometer for analysis, etc. can be used for applications such as rapid on line digestion (12 s), on line sample preparation of protein etc.

Another type of miniaturized reaction vessel, called nanotiter plates, is also commonly used for the synthesis of new pathways and screening of new substances. This is especially useful for synthesizing molecules, which can act as leads in drug discovery programs. Recent developments along with fabrication technologies and application of nanotiter plate are reviewed by Mayer et al., (2001) who point to further work required in characterization and specific adaptation of surface properties, evaporation of solvents and measures of prevention. The new generation of integrated microfabricated devices, also referred to as Lab-on-Chip or micro total analysis system, have been used in several biosystems. The flexibility in their use besides the advantage of reduced reagent consumption, improved performance, inter connecting channel network with multifunctional possibilities, inherent mechanical stability and possibilities of parallelization for mass production, have made them more popular. Chován and Guttman (2002) review their status.

Enzyme microreactors have been prepared on microfluidic chip or in capillaries by immobilizing enzyme on porous silicon or polymer monoliths. Different methods of immobilization have been used by different authors. Thus, for instance, Peterson et al., (2002) immobilized trypsin on polymer monolith (2 vinyl-4, 4-dimethyl azalactone, ethylene dimethyl acrylate and acrylamide or 2 hydroxy ethyl methylacrylate). The amine and thiol group of the enzyme interact with azalactone functionalities to form stable covalent bonds. The porous monoliths allow pumping of substrate or enzyme solution with very low backpressure. The effect of concentration of enzyme in the solution and its residence time determine the proteolytic activity of the enzyme. Peterson et al., (2002) used the metal chelating agent of iminodiacetic acid reacted with glycidoxy propyl trimethoxy silane and immobilized it on the inner wall of fused silicon capillary pretreated with $NH_4HF_2$. The metal ion of copper and subsequently the enzyme was adsorbed on the surface to form the capillary microreactor. The reactor was used for the peptide mapping from 0.5 pmol sample of protein in 15 min at 50°C. Even femtomol quantities could be digested and detected using the microdevice. In another study Miyazaki et al., (2004) report preparation of nanostructures (functionalized) on channel surface. They immobilized cucusimin that enabled hydrolysis of substrates in just 2 s. They also report for reversible immobilization of protein using disulfide bond and Ni complex on his-tag. The strategy could be useful for removing the denatured enzyme and its replacement with active enzyme.

An efficient, inexpensive and versatile solid phase protocol for preparation of libraries of compounds on a millimole scale has been described by Gani et al., (1997). The apparatus consisting of machined frit glass reactor with precision-engineered jacketed tubes can handle both basic and acidic conditions employed in several organic syntheses over a temperature range of (-80 to 200°C) and is suitable for the synthesis of libraries up to 600 members. The high throughput primary synthesis and screening techniques have been used by Bergh et al., (2003) to study heterogeneously catalyzed gas phase oxidation of ethane to acetic acid using mixed metal oxide catalysts. A total of 256 catalysts prepared on 3” × 3” quartz wafers were prepared and tested for their activity in parallel in a Symyx Technologies 256 microfluidic channel reactor. The unit allows processing of 3000 samples per day and the online analysis helps to identify the promising lead catalysts for further testing. The (molybdenum-vanaium-X, where X represents N, Ni or Sb) catalyst activity is enhanced considerably with Pd doping.

Senkan et al., (1999) used an eighty channels array microreactor system coupled to quadrapole spectrometer for high throughput testing of heterogeneous catalyst libraries. The kinetics, activities and selectivities of 66 ternary Pd/Pt/In catalysts were evaluated for dehydrogenation of cyclohexane to benzene over 24 hours. The entire 80-channel library can be tested in less than 10 minutes. Microreactors have also been used to screen homogeneous catalysts for hydrogenation, isomerization and asymmetric catalysis (Claude de Bellefon, 2000). Multiple microreactor system for parallel catalyst preparation and testing was used by Pantu and Gavalas (2001) for studying methane reforming with $CO_2$. The catalyst $Pt/CeO_2$ showed highest activity while mixed oxides with 25-85% samarium oxide showed stability without significant deactivation. In a similar study Ouyang and Besser (2003) studied synthesis gas conversion in a parallel microreactor system with a view to eventually apply the method to Fischer Tropsch and other synthesis related to production of non petroleum based fuels and chemicals.

The use of a novel microreactor for high throughput continuous flow organic synthesis has been described by Greenway et al., (2000). They carried out a Suzuki coupling reaction of aryl halide and an organoboron compound to synthesize 4-cynobiphenyl in a microchannel (300 μm wide × 115 μm deep) etched onto a glass plate that is subsequently sealed. The catalyst (1.8% Pd on silica) was immobilized on porous silica structure incorporated within the channel. The reactants were fed using the electro osmotic flow and product analyzed using GC-MS. The catalyst loading rate was also maintained using ICP-MS. One reactor gave 10% improved yield of 4-cynobiphenyl at room temperature in comparison to normal bulk reaction.

The efficient heat and mass transfer characteristics of the microreactors make them useful for highly exothermic reaction. Kestenbaum et al., (2001) carried out the partial oxidation of ethylene to ethylene oxide under isothermal conditions. The study reveals that even the compositions within the limits of explosion can be used to obtain space time yields up to 0.78 tons $h^{-1}$ $m^{-3}$ in comparison to 0.26 tons $h^{-1}$ $m^{-3}$ in the industrial reactor. In a similar study Wan et al., (2004) used a silicon-glass fabricated microreactor deposited with TS-1 catalyst to carry out epoxydation of pentene using hydrogen peroxide. They observed that seeding of microchannels is necessary to obtain small size crystal and zeolite thin film. The reaction rate increases with decrease in crystal size and increase in tetrahedrally coordinated Tin (IV). Catalyst deactivation and leaching of catalyst occurs in presence of organic compounds.

Maria et al., (1996) studied the dehydrogenation of methyl cyclohexane to produce hydrogen and developed a model and scale up of the kinetics of deactivation. In a similar manner, Holladay et al., (2004) studied methanol reforming in two different microreactor designs with a view to improve thermal efficiency of the fuel processor and lower the content of CO to 100ppm.

Kobayashi et al., (2004) used microchannel reactor with specific interfacial area of 10,000-15,000 $m^2$ $m^{-3}$ for gas-liquid-solid hydrogenation reactions. They immobilized the solid hydrogenation catalyst, palladium, on the glass channel walls and the gas flowed through center of the channel with liquid flowing close to the inner channel surface. Immobilization is done by forming microencapsulated Pd. Hydrogenation with several substrates like, benzalacetone, benzyl ether, etc. was found to proceed smoothly and rapidly to desired products.

Rouge et al., (2001) describe dehydration of iso-propanol to propane as a model reaction to study a microchannel reactor specially designed to operate in a periodic fashion and deposited with $\gamma$ alumina as catalyst. The catalyst coating does not change the hydrodynamics and reactor can be operated in a periodic manner with frequencies up to 1 hertz with improved performance. In addition microreactor can be used to produce nanodiameter particles with narrow size distribution as demonstrated for melamine resin (Sawada et al., 2003).

High throughput multiparameter optimization of conditions of a combinational 96 micro arrays system for polymerization type of reactions has been reported by Potyrailo et al., (2003). They use a non-destructive spectroscopic technique to directly measure chemical properties of polymers in the micro arrays and determine optimal process conditions by multivariate spectral descriptor analysis. The combinational polymerization system viz. thin film melt polymerization was optimized to obtain best processing conditions using a set of input variables (flow and concentration of reactants, catalyst loading, etc.) and processing variables (reaction time, temperature etc.). The output variables monitored are polymer characteristics, material properties etc. The methodology is generic in character and can be used for other systems.

Microreactors, suitably modified and augmented with additional facilities such as analytical tools and sensors, have been used for variety of other applications. They include photocatalytic reactions such as phenyl-phenyl acetate, photocycloaddition of antracenes (Wu et al., 2002), photocyclisation of azobenzene and stilbazole (Tung et al., 2003) and photooxidation of organic sulfides (Clennan et al., 2002). Nanosynthesis in microreactor (Xia et al., 2002), uniform sized microspheres of polyvinyl acetate (Chang et al., 2004), coating of inner walls of microreactors with nickel particles (Chang et al., 2004) and preparation of titania nanoparticles in microreactor (Jähnisch et al., 2000), oxidation of alcohols and ketones in thin film gas-liquid microreactors (Chambers et al., 2003), synthesis of fluorinated materials. (Miyake and Kitazume, 2003) and fluorinated waste gas treatment (Sichler et al., 2004) have been reported. A number of studies devoted to hydrogen generation (Kikas et al., 2003; Deshmukh et al., 2003; Ganley et al., 2004), fuel cell (Goto et al., 2003), pigments (Wille et al., 2004) also report the benefits of use of microreactors.

Of special importance from the industrial application point of view is the use of microdevices as process monitoring and process safety studies (Bou-Diab et al., 2003). Rákóczi et al., (1983) describe the detection and identification of free radicals in the gaseous phase ozonolysis of hydrocarbons. The microreactor with matrix electron spin resonance spectrometry is used. Concentration and type of radicals are shown to depend on residence time and initial concentration. Rogers and Parker (1989) modified a DTA sample holder as a catalytic microreactor for on-line analysis of products, while Licklider et al., (1995) report on-line micrometers with capillary electrophoresis and mass spectrometry for analysis of proteins and peptides. Microreactors as biosensors (Kukla and Shirshov, 1998) and tin-oxide based microreactors as air pollution monitors (Becker, 2000) are tested for their accuracy. A number of other miscellaneous applications are reported in the literature and a few of them have been included in the tables.

## 6. GENERAL DISCUSSION

Microchannels and miniature channels devices have gained considerable popularity and their widespread use in areas as diverse as catalysis, biosciences, polymers, advanced material synthesis etc. is clearly evident from the numerous example applications presented in Tables 3-11. In addition such devices have been used as specialized analytical tools for monitoring applications. Better thermal management and reconfigurable flexible design of network of microreactors make them appealing for applications to industrial scale. The robustness of their manufacturing covering a range of high performance material ranging from austenite stainless steel to copper, aluminium, titanium, and special alloys as well as speciality polymers, etc. allow the reactors to be used over a wide range of temperature from cryogenic to 1000°C as well as at high pressures (500 bar). The microchannel heat exchangers are constructed (Pua and Rumbold, 2003) by stacking and diffusion bonding of prefabricated metal plates together into a single block. A number of such bocks can be welded together to form larger units. Headers, nozzles, flanges, etc. are then welded to create the heat exchanger. The unit is more compact, about 1/5 the size of the conventional unit, for same thermal duty and pressure drop and has been commercially exploited in off shore hydrocarbon gas processing industry. Variations in the heat exchanger design to accommodate two-phase flow, such as vapour and liquid, or multiple streams in parallel or series or a combination thereof is easily possible due to reconfigurable nature. This can extensively reduce the size, piping requirement and hence the cost of product retaining the high thermal effectiveness (>99%).

Microchannels provide an opportunity to integrate heat transfer, fluid mixing and chemical reaction in the same unit and thereby reducing the number of other components. Besides, the synergy leads to accelerated reaction rate, reduced residence time and improved selectivity and yield as compared to conventional reactor set up. A number of homogeneous and heterogeneous catalytic reactions have taken advantage of this feature. The microchannel reactor walls can be coated with minimum volume of catalytic species and have the advantage of minimum pressure drop, low risk of overheating of catalyst layer, ease of maintenance of optimal temperature profile along the channel wall and low capital cost for better performance.

Careful design of microchannel network requires considerations such as the characteristics of reactants and products, their detection and analysis methods, the way they would be transported in microchannels, the extent of desirable mixing between them, the chemistry of the reactions involved, the need for separation of product from the reactants, the method of separation and analysis, the optimum conditions for conducting the reactions in terms of reactant/product residence times, temperature, etc., the heat generation/supply in terms of quantity and means and mechanism, the mass and volumetric flow in and out of the channels, the continuous or batch mode of operation, the identification of scale-up parameters, overall monitoring and control strategy to be employed, etc. Many of these issues can be specific to the system under investigation and intensive efforts to gather information as regards them are being pursued currently. It is hoped and realised in some instances that such careful designs of microchannels can lead to substantial advantages and break through in process technology.

In summary, the microchannel reactors are proving to be immensely beneficial due to their

- High surface area to volume ratio (>200), efficient heat and mass transfer and fluid mixing allow precision reaction control & quality of product. Easy optimisation and scale-up of process possible.
- Reduction in the cost of scale-up and resources to develop safe and stable processes.
- Reduction in time required accomplishing the reaction conversion. This also reduces degradation of products, side product formation and enhances the yield and selectivity.
- Easy handing of problematic chemistries such as those involving high exothermicity, unstable or toxic products or difficult to separate by-products.
- Wide options to choose high performance material of construction and reconfigurable modular flexible designs afford specificity for the system under consideration and handling of multiphase systems easier.

These features of microchannel reactors help an research and development organisation engaged in the development of new processes or products to come one step closer to the realisation of cutting down the lead time of development while ensuring quality of product, elimination of by-products, optimum use of mass and energy resources and thus the economics of the process.

Table 3. An assorted set of examples of organic reactions studied in microchannel reactors

| | Suzuki Reaction (Synthesis of 4-cyanobiphenyl) | Kumada Corriu Reaction (p-bromoanisole with phenylmagnesium bromide to give 4-methoxybiphenyl) | Aldol Reaction (silylenol ethers) | Michael Addition (enolates from a series of 1,3 diketones) | Enamine Synthesis | Hantzch reaction (Synthesis of a series of 2-aminothiazoles) | Dehydration reaction (Hexane 1-ol to hex-1-ene) | Dehydration of Ethanol | Sonogashira coupling aryl halides & monosubstituted acetylenes to disubstituted acetylenes | Addition of organometallic reagents to carbonyl compounds |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 25°C | | | | 25°C | 70°C | | 155°C | 110°C | -10°C |
| Pressure | | | | | | | | | | |
| Reactant concentration | | | | | | | | | | |
| Flow rate | | | | | | | | 3 µL/min | 1.7 µL/min | 33.3 mL/min |
| Reaction volume | | | | | | | | | 2 mmΦ x 40mm | |
| Reaction time | 25 min | 10 min | 20 min | 20 min | 20 min | 30 min | 20 min | 20 min | | |
| Residence time | 5 s | | | 2.5 s | | | | | | <10 s |
| Catalyst | 1.8% Palladium on silica, immobilized between microporous silica frits | Nickel supported on Merrifield resin | | | | | Sulfated zirconia | Sulfated zirconia | Palladium | |
| Conversion | 68% | 60% | 100% | 100% | 42% | 85% | 85-95% | <90% | | |
| Yield | 67 ± 7% | | | | | | | | 83-93% | 95% |
| Selectivity | | | | | | | | | | |
| Microreactor | Micro-channels etched into glass and sealed with a top plate. | Pressure driven polypropylene tubing microreactor | Borosilicate glass microreactor | | Borosilicate glass microreactor | T- shaped microreactor | Glass plate etched using photolithography | Glass plate etched using photolithography | T-shaped tubular reactor made of glass | Micromixer array from IMM (1 mixing units) |
| Remarks | Unlike conventional Suzuki reactions, additional base was not required | Dimensions of microreactor were solely responsible for enhanced rate of reaction | 24 hrs in batch reactor | Enhancement in conversions through stopped-flow technique | | | | | | Shorter reaction time prevent side reactions & more efficient heat management by larger surface/vol. ratio |
| Reference | Greenway, et al., (2000) | Haswell, et al., (2001) | Wiles et al., (2001) | Wiles, et al., (2002) | Sands, et al., (2001) | Garcia-Egido et al., (2002) | Wilson, et al., (2000) | Wilson, et al., (2000) | Fukuyama, et al, (2002) | Krummradt, et al., (2000) |

| | Hydrolysis of β-D-Glactopyranoside Derivatives | Transglycosylation of β-D-Glactopyranoside Derivatives | Nitration of naphthalene | Nitration of benzene & toluene | | Nitration of N, N'-dialkyl urea derivatives | Phenylboronic acid formation | | | Synthesis of phenol acetone by rearrangement of cumene hydroperoxide | Methylation of substituted aromatics | Oxidation of ethanol to acetic acid |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 37°C | 37°C | 30°C | 60-90°C | 60-120°C | 0-20°C | 22°C | 10°C | 20°C | | 0°C | 70-115°C |
| Pressure | | | | | 4 bar | | | | | | | 3-5 bar |
| Reactant concentration | | | | | | | | | | 67 wt% | | |
| Flow rate | | | 1 mL/min | | 3-36 mL/min | | | | | | | 0.2-0.9 kg/hr |
| Reaction volume | 200 x 200 µm x 400cm | 200 x 200 µm x 400cm | | | | | | | | | | 3 cc |
| Reaction time | 8 min | 11 min | | | | | | | | | | |
| Residence time | | | 15-45 s | 15-45 s | | 0.6-82 s | 8 s | 10 s | 5 s | | 6 s | 3 s |
| Reaction rate | 5 times faster than batch | 5 times faster than batch | | | | | | | | | | |
| Catalyst | E-coli | E-coli | | | | | | | | $H_2SO_4$ | | Ferric nitrate using $H_2O_2$ as oxidant |
| Heat transfer area | | | | | | | | | | 10000 $m^2/m^3$ | | |
| Conversion | 16% | 4% | | | | | | | | | | >99% |
| Yield | | | | | | | 83% | 89% | 95% | | | |
| Space-time Yield | | | | | | | | | | | | 500 $h^{-1}$ |
| Selectivity | | | | | | ~ 100% in 1st step | | | | | 95% | >99% |
| Recycle ratio | | | | | | | | | | 17 | | |
| Microreactor | Microchip reactor made of PMMA | Microchip reactor made of PMMA | PTFE capillary | PTFE capillary | Isothermal capillary reactor | PTFE capillary | Interdigital glass mixer | Caterpillar mixer | interdigital micromixer | Multichannel reactor | Micromixer array from IMM | |
| Remarks | | | | | | | | | | | Reaction temperature: increases from –70 to 0°C & residence time from 15 min to 6 s | |
| Reference | Kanno, et al., (2002) | Kanno, et al., ,(2002) | Antes, et al., (2000) | Burns, et al., (1999)(2000) | | Antes, et al., (2000) | Hessel, et al., (2000) | Hessel, et al., (2000) | Koch et al., (2001) | Weber, et al., (1999) | Wörz , (2001) | Kraut , et al., (2002) |

| | Synthesis of monochloroacetic acid | Direct fluorination of toluene | | | Fluorination of 4-nitrotoluene & 2,4 –dinitrotoluene | Fluorination of 1,3 dicarbonyl compounds, sulfur trifluoride derivatives & perfluorinatoin of alkanes | Hydrogenation of p-nitrotoluene | Hydrogenation of nitrobenzene | $CF_4$ decomposition | Knoevenagel condensation reaction between benzaldehyde and ethyl cyanoacetate (ECA), ethyl acetoacetate (EAA) and diethyl malonate |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 170-190°C | -150°C | -16°C | rt | 5°C | 5°C | 70°C | 60°C | | 373 K |
| Pressure | 4-6 bar | | | atm | | | 20 bar | 1-6 bar | 100-1000 mbar | |
| Reactant concentration | | | | | | | 10% | | | |
| Flow rate | 50 g/min | 185-327 μL/min | | | 50-100 μL/min | 42-83.3 μL/min | | 0.2-3 mL/min (0.25) | 1-200 sccm | 0.2–12 ml/h |
| Reaction volume | | 20 mL | | | | | 300 x 700 x 400 μm | 300 x 100 x 65 μm x 64 channels | $60.5mm^3$ | |
| Reaction time | | | | | | | | | | 10 h |
| Residence time | | | | | | | 280 s | | 62.5 ms. | |
| Catalyst | AgCl | | | | | | Palladium | Palladium | | $CsNaX-NH_2$ |
| Conversion | | 26% | 76% | 58% | 44% | 98% | 98% | >85% | ~94% | |
| Yield | 90% | 11% | 28% | 14% | | | | | | |
| Selectivity | | 42% | 37% | 24% | | | 100% | | | |
| Recycle Ratio | | | | | | | | 43% | | |
| Microreactor | Microreactor comprising differential microstructured plates | Microbubble column | Falling film microreactor | Silicon based microchannel reactor | | Single channel microreactor 0.5 x 0.5 mm covered by plastic plate | Aluminum structured platelets | Falling film microreactor | Microreactor based on a micro-structured electrode (MSE) system | Packed bed membrane microreactor |
| Remarks | | | | | | | | | | |
| Reference | Wehle,et at., (2000) | Jähnisch , et al., (2000, 2002) | Jähnisch , et al., (2000, 2002) | de Mas, et al. ,(2001, 2003) | Chambers , et al., (2001) | Chambers , et al., (1999) | Födisch , et al., (1999, 2001) | Yeong , et al., (2003) | Sichler, et al., (2004) | Zhang, et al., (2004),<br>Lai, et al., (2003) |

Table 4. An assorted set of examples of biochemical reactions studied in microchannel reactors

| | Peptide synthesis | DNA polymerase chain reaction | Protein digestion | Oxidation of glucose 6-phosphate to 6-phosphogluconate | Ethanol to acetaldehyde | Digestion of protein β casein |
|---|---|---|---|---|---|---|
| Temperature | | 55-95°C | | 30°C | 30°C | |
| Pressure | | | | | | |
| Reactant concentration | | | | | | |
| PH | | | | 8.3 | 8.3 | |
| Flow rate | | | 50µL/min | 8 nL/min | 8 nL/min | 50 µL/min |
| Reaction volume | | | 75µm x 25µmx 10mm x 32channels | 50µm Φ x 75cm | 50µm Φ x 75cm | 200 nL |
| Reaction time | 20 min | 62 min | 10 min | | | |
| Residence time | 2.5 s | | 12 s | 20 s | 12 s | 12 s |
| Reaction rate | | | | | | |
| Catalyst | | | | Glucose 6-phosphate dehydrogenase + NAD/NADP | Yeast alcohol dehydrogenase | |
| Conversion | 93-100% | | | | | |
| Yield | | | | | | |
| Selectivity | | | | | | |
| Microreactor | Borosilicate glass microreactor operating under electrokinetic control | Microthermal cycler composed of microreactor (silicon based microreactor) | Porous silicon micro enzyme reactor | Electrophoresis capillary | Electrophoresis capillary | Microchip immobilized enzyme reactor |
| Remarks | Application of stopped flow technique to increase conversion | | | | | |
| Reference | Watts , et al. ,(2001)(2002) | Sung ,et al. ,(2003) | Bengtsson, et al., (2002) | Avila , et al., (1993) | | |

Table 5. An assorted set of examples of polymerization reactions studied in microchannel reactors

| | Depolymerization of kraft & organosolv-derived lignins by methanol/ethanol | Bisphenol A polycarbonate by melt polymerization | Monodispersed droplet suspension of an acrylic monomer | γ ray initiated dispersion polymerization of poly (methyl acrylate) | Propylene polymerization | Formation of polyacrylate |
|---|---|---|---|---|---|---|
| Temperature | 290°C | 280°C | 293 K | 20°C | 70°C | 150°C |
| Pressure | | | | | 10 bar | 6 bar |
| Reactant concentration | | 1, 1.2, 1.4 (mol/mol) | | | | |
| Flow rate | 0.343 gm lignin + 4.4 mL 10%KOH (w/w) | 4, 6, 8 L/min | | 68 Gy/min | | 6.8 kg/hr |
| Reaction volume | | 150, 200, 250 µL | | 50µm x 50µm x 35 mm | 5 ml | |
| Reaction time | 10-15 min | 10, 20, 30 min | | 360 min | 1h | |
| Residence time | | | | | | 40 min |
| Reaction rate | | | | | $R_p=k_P C_m C^*$ =80kgpoly/gm support h | |
| Catalyst | | | | | Ziegler-Natta | |
| Conversion | 93% | | | | 26 kg poly/gm support | |
| Yield | | | | | | |
| Selectivity | | | | | | |
| Microreactor | Rapidly heated batch microreactor | 96 well microtiter plates that served as 96 microreactor arrays | T-shaped channels in quartz glass | Made up of quartz glass 120 microchannels | | Stainless steel interdigital microreactor from IMM |
| Remarks | Strong bases give more conversion | | | | | |
| Reference | Miller , et al., (1999) | Potyrailo ,. et al. (2003) | Nisisako , et al. (2004) | Chang , et al., (2004) | Weickert , et al., (1999) | Bayer , et al., (2000), Pysall , et al., (1998) |

Table 6. An assorted set of examples of petrochemical reactions studied in microchannel reactors

| | Hydrotreating of creosote oil feedstock | Coal liquefaction | Catalyzed steam methane reforming | Methanol reforming | CO removal by reaction with hydrogen to form methane | Pulverized fuel combustion | Hydrodesulfurization of dibenzothiophene | Hydrodenitrogenation of Qqinoline | Catalytic cracking of 500-600°F gas oil fraction | Catalytic cracking of hexadecane |
|---|---|---|---|---|---|---|---|---|---|---|
| Temperature | 700-830°F (750°F) | 800°F | 600-840°C | 255-320°C | 304-345°C | 1600°C | 300°C | 342°C | 850-900°F | 750-900°F |
| Pressure | 2000 psig | 2000psi | 2.5-9 bar | | | | 104 atm | 165 atm | | |
| Reactant concentration | | 50% coal | | ~60 wt% | | | | | | |
| WHSV | 1-4 (2) | 1-2 (2) | | | | | | | 325-1300 LHSV | |
| Flow rate | 10 $cm^3$/h | | 202-424 Nml/min | 0.03-0.2 cc/h | 0.05-0.15cc/h | | 1.2-7.2 $cm^3$/h | | | |
| Reaction volume | 58.9 $cm^3$ | 53 $cm^3$ | | 55.2 $mm^3$ | <0.3 $cm^3$ | | 0.31 $cm^3$ | | | 3.5 $cm^3$ |
| Reaction time | | 1.5-3 h (1.5) | 590 h total | | | | >500h | | 10 s-2 min | |
| Residence time | | | | | | | | | | 0.5-2 s |
| Reaction rate | | | | | | | | | k = 1035 | k = 6200 |
| Catalyst | CoMo / alumina | Co/alumina | Nickel oxide - alumina | | | | Sulfided cobalt molybdate | Ni-Mo | Crystalline aluminosilicate | Crystalline aluminosilicate |
| Conversion | 90% | 90% | 90% | >99% | >99% | | | | 7-28% | 14-57% |
| Yield | | | | | | | | | | |
| Selectivity | | | | | | | | | | |
| Microreactor | Fluidized bed microreactor | Fluidized bed microreactor | Microcomputer controlled reactor equipped with instantaneous response | | | Laser microreactor | Packed bed gas-liquid contactor | | Fixed bed glass reactor | Fixed bed glass reactor |
| Remarks | Accurate & convenient means of evaluating hydrotreating kinetics of lab scale (batch reactor requires more time to achieve reaction temp. & trickle bed reactor suffers from poor contacting efficiency) | Greatly reduced catalyst charge compared to bench scale reactor, keeping other parameters constant | Heat of reaction is too small to change the reactor temp. & as length is <5cm it works under practically isothermal condition | High thermal efficiencies: 15 to >30% | Significant decrease in thermal efficiency | | | | | |
| Reference | Jacobs , et al., (1992) | Haynes , et al. ,(1993, 1991) | Levent , et al. ,(2003) | | | | Eliezer , et al., (1977) | Eliezer et al., (1977) | Nace , (1969, 1970) | Nace , (1969) |

| | Isomerisation of Cyclopropane to propane | Acetylation by acetic anhydride | Dehydration of isopropanol | Dehydrogenation of Methylcyclohexane to toluene | Oxidation of ethane to acetic acid | Aromatization of propane | Pyrolysis of Ethane-Propane Mixture | Maillard reaction (2-furfurylthiol (FFT) from aqueous cysteine/furfural system.) | Synthesis of an array of 1,2-azoles |
|---|---|---|---|---|---|---|---|---|---|
| Temperature | 120°C | Room temperature | 200°C | 282-309°C | 375°C | 480°C to 550 °C (520°C) | 759-925°C (880) | 30 to 60 °C. | |
| Pressure | | | 130 kPa | 7 atm | | 1 atm | | | |
| Reactant concentration | | 140-mg/mL pea isolate solution | | | | | | | 1.0 M |
| pH | | 8 | | | 4.8-6 | | | 4-8 | |
| WHSV | | | | 15-58 1/h | | | | | |
| Flow rate | | 0.1 mL/min | 0.2-0.3 ml/s | | | | | | 1.5 µL/min |
| Reaction volume | | 100-mL | | | | | | | |
| Reaction time | | | 14 h | | 15 min | | | 8 h | 20 min |
| Residence time | | 30 min. | 0.54 s | | | | 0.038-1.1 s (0.216 s) | | 2.5 s |
| Catalyst | NaCoX Zeolites | | γ-alumina | | Aqueous metal nitrates (alkali, earth alkali, rare earth, Group IIIB, IB, IIB metals) | Gallium-loaded ZSM-5 | | | |
| Conversion | | | | | | | ~55% | 69-93% | 98-100% |
| Yield | | | | | | | 57.39 mol % | | |
| Selectivity | | | | | | 68.7 C % | | | |
| Microreactor | Pulsed Microreactor | torus microreactor (semibatch or continuous stirred tank microreactor) | Fixed bed microchannel reactor | Isothermal differential microreactor | Symyx Technologies 256-channel microfluidic reactor. | | Pulsed microreactor | Sucrose ester microemulsions | Device containing a series of interconnecting channels formed in a planar substrate, with dimensions in the range 10-400 µm. |
| Remarks | | maximum acetylation degree reached by the torus reactor is higher than with the stirred reactor. | | | | | | | |
| Reference | Benn, et al., (1978) | Legrand, et al., (1997) | Rouge, et al. ,(2001) | Maria, et al., (1996) | Bergh, et al., (2003) | Harris, et al. ,(1992) | Renjun, et al., (1986) | Fanun, et al., (2001) | Wiles, et al., (2004) |

| | Hydrogen production | Hydrogen production from ammonia decomposition | |
|---|---|---|---|
| Temperature | $T_{ign}$ = 678-900°C<br>$T_{final}$ = 28-58°C | 650°C | 650°C |
| Pressure | | | |
| Reactant concentration | | | |
| Flow rate | GHSV = 26-46 | 5/145 $cm^3$/min | 15 $cm^3$/min |
| Reaction volume | | 0.87 cm x 300µm x 1 cm | 300µm x 260 µm |
| Reaction time | | | |
| Residence time | | <0.3 s | |
| Reaction rate | | | |
| Catalyst | Pt, 13%Rh | Ruthenium | Ruthenium dispersed on alumina |
| Conversion | 55-60% | ~100% | 85% |
| Yield | 24-47% | | |
| Selectivity | 70-80% | | |
| Microreactor | Reverse flow autothermal catalytic microreactor | Aluminum framework post microreactor | 30V anodized 1100 Al microreactor |
| Remarks | 5% increase in reaction selectivity towards $H_2$; 200°C decrease in oxidation ignition temp & reactor skin temp decreases by 60°C; many hours of stable operation | | |
| Reference | Kikas , et al., (2003) | Deshmukh ,et al., (2004) | Ganley,et al.,(2004) |

Table 7. An assorted set of examples of photocatalytic reactions studied in microchannel reactors

| | Side chain alkylation of toluene 2,4 diidocyanate | photooxidations of 11 sulfides | photocycloaddition of 9-substituted anthracenes |
|---|---|---|---|
| Temperature | | | |
| Pressure | 130°C | | |
| Reactant concentration | | | |
| Flow rate | | | |
| Reaction volume | 14-56 mL/min | 0.21 mL | |
| Reaction time | | 1 h | 40 min |
| Residence time | | | |
| Reaction rate | 4.8-13.7 s | | |
| Catalyst | | methylene bluedoped Zeolite (NaMBY) | |
| Light source | | 600 W tungstenhalogen lamp | 500 W high-pressure mercury lamp |
| Conversion | 55% | 27.9-98.7% | ~100% |
| Yield | | | ~100% |
| Selectivity | 80% | | |
| Space time yield | 401 mol/Lh | | |
| Microreactor | Falling film microreactor | Zeolite as a microreactor | Water-in-oil microemulsions in a Pyrex reactor. |
| Remarks | | | |
| Reference | Ehrich , et al. ,(2002) | Edward, et al., (2002) | Da-Yang Wu, et al. ,(2003) |

Table 8. An assorted set of examples of nano particle synthesis reactions studied in microchannel reactors

| | Synthesis of titania nano particles | Synthesis of Nanosized particles of modified silica (photocycloaddition of five 9-substituted anthracences) | Synthesis of Nickel nano-particles | Preparation of micron-size monodisperse poly(vinyl acetate) microspheres | Synthesis of Gold nano-particles | Preparation of a porous structure on microchannel surface for enzyme immobilization. |
|---|---|---|---|---|---|---|
| Temperature | | 50°C | 25°C | 20°C | 25-40°C | 4°C |
| Pressure | | | | | | |
| Reactant concentration | | | | | | |
| pH | | | 10 | | | 7.4 |
| Flow rate | 0.372 and 0.075m/s in inner and outer tube | | 68 Gy/min | 68 Gy/min | | |
| Reaction volume | | | 1.6 x $10^{-7}$ ml | | | |
| Reaction time | | 72 h | 12 h | | 7 min. | 12 h |
| Residence time | 0.2 s | | | | | 0.5 s |
| Reaction rate | | | | | | |
| Particle size | 40 to 150 nm | 60-80 nm | 40–100 nm | 2.6 µm | 525-540 nm | |
| Light source | | 500 W high-pressure mercury lamp | | 1.35 x $10^{-15}$ $Bq^{60}$ Co γ-rays source | 500 W Xenon lamp | |
| Catalyst | | | | | | |
| Conversion | | | | 73 % | | |
| Yield | | | | | | |
| Selectivity | | | | | | |
| Microreactor | Same axle duel pipe microreactor | | Quartz glass microreactor | γ-ray irradiated microreactor | Water-in-oil microemulsion | Pile-up enzyme microreaction system |
| Remarks | | | | | | |
| Reference | Takagi, et al., (2004) | Da-Yong Wu, et al., (2003) | Chang, et al. ,(2004) | Chang, et al., (2004) | Harada, et al., (1999) | Miyazaki, et al., (2004) |

Table 9. An assorted set of examples of catalyst testing in microchannel reactors

| | Reactions of hydrogen with mixtures of coal and a solid, dispersed liquefaction catalyst | Methanation reaction | Hydrodesulfurization Catalyst evaluation | Carbon monoxide oxidation | Liquid-liquid isomerization of allylic alcoholes | Gas-liquid hydrogenation | Methane reforming with carbon dioxide |
|---|---|---|---|---|---|---|---|
| Temperature | 225 °C | 200-250 °C | 563 K | 520 K | 40-80°C | 40-60°C | 650 & 700°C |
| Pressure | | 1 atm | 3 MPa | 1.5-1 atm | | 1 atm | |
| Reactant concentration | | | | 1% | | | 1:1:: $CH_4$: CO |
| LHSV | | | 2-40 $h^{-1}$ | ~600 sccm | | | |
| Flow rate | | | | | 5 & 1 mL/min | 1-4 mL/min | 30 mL/min |
| Reaction volume | | | 0.1-2 $cm^3$ | ~5.1 µl | | | |
| Reaction time | | 9-25 h | 11 h | | | | 2-3 h |
| Residence time | | 200-700 ms | | | 100 s | 3-6 min | |
| Reaction rate | | | k= 2.6 x $10^{-6}$ $m^3$/kgs | | | | |
| Catalyst | | Fe, Co | Ni-Mo/γ-$Al_2O_3$ | Pd/$Al_2O_3$ | Rh/Ru/Pd/Ni & sulphonated phosphane or diphoshane ligands | Rhodium/ phosphane | Pt/$Ce_{1-x}Gd_xO_{2-0.5x}$ & Pt/$Ce_{1-x}Sm_xO_{2-0.5x}$ |
| Conversion | | 28 to 70%, | | | | | |
| Yield | | | | | | | |
| Selectivity | | | | | | | |
| Microreactor | Pulse-flow microreactor | Microreactor array system | Fully automated upflow three-phase microreactor | Cross flow short pass multiple flow channel microreactor | Dynamic sequential microreactor with pulse injection | Dynamic sequential microreactor with pulse injection | Nine catalytic microreactors for parallel preparation and testing of heterogeneous catalysts |
| Remarks | | | | Low pressure drop | | | $PtCeO_2$ has highst activity among the series of catalysts |
| Reference | Bockrath, et al., (1992) | Ouyang, et al., (2003) | Letourneur, et al., (1998) | Ajmera, et al., (2002) | Bellefon et al., (2000) | Bellefon et al., (2000) | Pantu ,et al .,(2002) |

Table 10. An assorted set of examples of reactions studied for finding the kinetics in microchannel reactors

| | Thermal cracking of a mixture of hydrocarbons (ethane, propane, isobutane and n-butane) | Catalytic cracking of gas oils | $CH_4$ combustion | Ammonia oxidation | Hydrodesulphurization of a straight run heavy gas oil |
|---|---|---|---|---|---|
| Temperature | 600 – 710 °C | 900 °F | 823 K | 523–673 K | 340°C |
| Pressure | | | 1 bar | | 54 bar |
| Reactant concentration | | | | | |
| Flow rate | | | $1.67 \times 10^{-6}$ $m^3/s$ | 2000–5500 $Ncm^3/min$ | WHSV = 2 $g_L/g_C/h$. |
| Reaction volume | | | | | |
| Reaction time | | | | 1 h | 10-12 h |
| Residence time | | 1.25 min | | 0.3–0.82 ms | |
| Reaction rate | | | $K_r = 2.326 \times 10^3$ $s^{-1}$<br>$K_{H2O} = 4.151$ $m^3/mol$ | | |
| Catalyst | | Zeolite | $PdO/ZrO_2$ | Supported polycrystalline platinum | $NiMo/Al_2O_3$ |
| Conversion | | | 60 % | | 99.6% |
| Yield | | | | | |
| Selectivity | | | | | |
| Microreactor | Quartz packed pulsed microreactor | Fixed bed microreactor | Annular flow microreactor | Aluminum-based microreactor | Trickle bed microreactor |
| Remarks | Kinetic parameters agreed well, better yields of ethylene and propylene were found with the empty pulsed microreactor | | | | Improved process safety, operability and control as well as to minimisation of waste generation, investment and energy consumption |
| Reference | Sachchida Nand, et al., (1979, 1980) | Gross , et al. ,(1974) | Ibashi, et al., (2003) | Rebrov, et al., (2002) | Bellos , et al., (2003) |

Table 11. An assorted set of examples of miscellaneous reactions studied in microchannel reactors

| | Water gas shift reactoin | Selective oxidation of CO | Hydrogen oxidation | Synthesis of azo pigments | |
|---|---|---|---|---|---|
| | | | | Red | Yellow |
| Temperature | 250-300°C | <150°C | 1000°C | | |
| Pressure | | | | | |
| Reactant concentration | | | | | |
| Flow rate | | | 0.5slpm of air | 10µL/min | |
| Reaction volume | | | 600 µm Φ x 20mm | 250µm x 100µm x 3cm | |
| Reaction time | | | | | |
| Residence time | <30ms | 14 ms | 50µs | 2.3 s | |
| Catalyst | $Ru/ZrO_2$ | $Cu/CeO_2$ | Platinum | | |
| Conversion | 95% | 99% | | ~100% | |
| Yield | | | | | |
| Selectivity | | 20% | | | |
| Colour Strength | | | | 119% | 140% |
| Brightness | | | | 5 step glossier | 6 step glossier |
| Transparency | | | | 5 step more transparent | 6 step more transparent |
| Particle size | | | | 90nm | 90nm |
| Microreactor | | | Flexible quartz glass based microreactor | | |
| Remarks | | Temp range: 60-120°C with conventional reactors increases to 60-180°C because of small dimensions & high heat transfer coefficient.<br>Temp. reaches very fast.<br>Temp. range can be controlled exactly, which maximize CO selectivity | New microreactor design has reduced heat losses substantially, well suited to high temp. some sealing problems at high flowrate | | |
| | Goerke , et al., (2004) | Goerke, et al., (2004) | Veser , (2001) | Salimi-Moonsavi, et al., (1997) | |

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