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Microchannel reactor architecture enables greener processes

J.J. Lerou*, A.L. Tonkovich, L. Silva, S. Perry, J. McDaniel

Velocys, Inc., 7950 Corporate Blvd., Plain City, Ohio 43064, USA

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ABSTRACT

Green Chemistry is a design philosophy that aims to reduce or eliminate negative environmental impacts resulting from the production and use of chemicals. Microchannel process technology offers process intensification, in the form of enhanced heat and mass transfer, to a wide range of chemical reactions. This paper describes how the application of microchannel technology can help producers achieve the goals of Green Chemistry and minimize the environmental consequences of chemical and fuel production. The examples used to illustrate these advantages are Velocys' Fischer-Tropsch synthesis for biomass-to-liquids, DSM and Karlsruhe collaboration for fine chemical production, and Stevens Institute's work in applying microchannels to the production of hydrogen peroxide, as well as a detailed study of how microchannel architecture can minimize pollutant emissions from steam methane reforming.

1. Introduction

The chemical industry is facing an unprecedented challenge. To survive, a sharp reduction in pollutant and greenhouse gas emissions must occur without wrecking the markets for its products. Many see the answer coming from Green Chemistry, the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. The Green Chemistry Institute promotes this use through many mechanisms, including the 12 Principles of Green Chemistry. These are laudable goals ranging from preventing waste to use of renewable feedstock materials to improved energy efficiency. The challenge is incorporating these concepts into processes that were developed during a time of inexpensive fossil fuels, less stringent environmental regulations, and an absence of greenhouse gas emission limitations. Microchannel technology, a novel approach to chemical processing hardware, offers many salient advantages when it comes to minimizing the carbon footprint, and other environmental impacts, of a wide range of chemical processes, while also improving plant economics.

2. Background

2.1. Microchannel process technology

Microchannel process technology greatly increases the efficiency, effectiveness and productivity of chemical and energy production facilities. This technology accelerates processes by enabling reactions to occur at rates up to 1000 times faster than conventional systems. This acceleration is possible because the passages in microchannel systems are dramatically smaller than those in conventional systems. Instead of large pipes and vessels, these devices have channels with dimensions in the 0.1–0.3 mm range. As depicted in Fig. 1, the increased surface area provided by these smaller channels improves heat and mass transfer performance.

Chemical reactions are generally limited by heat and mass transfer performance. For this reason, microchannel technology has the potential to greatly improve overall system performance for range of chemical industry applications. The net result is overall system volume reduction of 10 fold or more compared to conventional hardware, increased product yield, improved energy efficiency, and the enabling of novel reaction pathways.

* Corresponding author.
E-mail address: lerou@velocys.com (J.J. Lerou).

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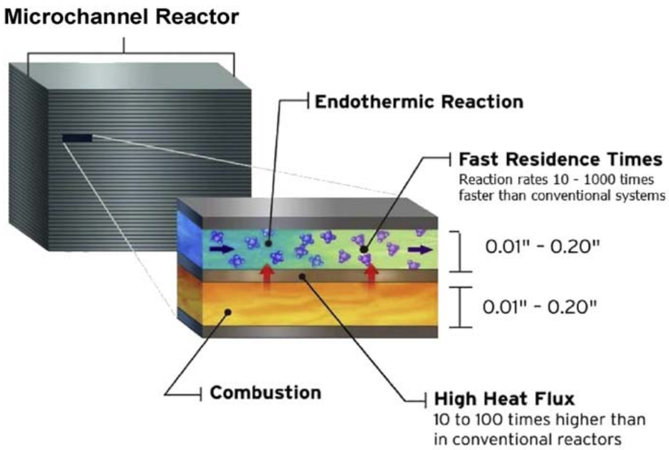

Fig. 1. Depiction of process intensification facilitating improved heat and mass transfer.

2.2. Green Chemistry

Green Chemistry is a design philosophy that aims to reduce or eliminate negative environmental impacts resulting from the production and use of chemicals. This concept is described in the 12 principles of Green Chemistry developed by Anastas and Warner (1998).

2.3. Applications of microchannel technology to Green Chemistry

As shown in Table 1, microchannel process technology addresses every Green Chemistry principle set forth by Institute for Green Chemistry and US Environmental Protection Agency. However, due to space constraints this paper will touch on only a few examples of how applications of microchannel technology are fulfilling the goals of Green Chemistry, including a detailed study of one application—reduction of pollutant emissions from high temperature steam methane reforming.

2.3.1. Prevent waste

An efficient process is one that turns raw materials into products, not by-products or pollution. This saves the plant in three ways. First, raw material costs are kept to a minimum. Second, less energy and capital intensive separation is required to produce high value products. Third, lower pollutant and waste production reduces or potentially eliminates the need for downstream abatement and treatment equipment. Velocys' work in the area of catalytic combustion to provide heat to a steam methane reformer shows that microchannel technology can reduce pollutant emission levels compared to conventional box furnaces. Technical details about this application appear in the sections below.

2.3.2. Use renewable feedstock

Renewable feedstock materials are favored over depleting one for multiple reasons, including concerns about life cycle greenhouse gas emissions. However, the switch to renewable alternatives to petroleum is challenged because biomass is not easily aggregated. This is especially challenging for fuel providers that have long achieved improved process economic by steadily increasing the size of refineries. Microchannel process technology overcomes this hurdle by achieving favorable economics at scales far smaller than conventional process technologies. Velocys, Inc. work in the field of Fischer-Tropsch (FT) synthesis for biomass-to-liquids (BTL) is an example of how microchannel technology can usher in the use of renewable feedstock.

The FT process was first developed by Franz Fischer and Hanz Tropsch in Germany in the 1920s and 1930s. The chemistry is based on making longer chain hydrocarbons from a mixture of carbon monoxide (CO) and hydrogen (H_2), referred to as "synthesis gas", at an elevated pressure and temperature and in the presence of a catalyst. In theory, any source of carbon can be used to generate the synthesis gas.

Although some very large stranded natural gas and coal resources warrant the construction of world-scale FT synthetic fuel facilities, many applications call for smaller-scale plants, including BTL opportunities. As noted above, biomass feedstock materials are not easily aggregated and transportation costs can dominate if feedstock is sourced from too far away. A reasonable plant size based on biomass logistics costs is 500–2000 tons/day, which produces approximately 500–2000 barrels/day of synthetic crude. The concept of producing fuel in compact units hinges on the ability to economically scale-down reaction hardware while maintaining sufficient capacity. By greatly reducing the size and cost of chemical processing hardware, microchannel process technology holds the potential to enable cost effective production of synthetic fuels from smaller scale facilities compared to the conventional FT reactor systems: tubular, fixed-bed, with a cobalt catalyst, and slurry-bubble with cobalt or iron catalyst.

In the tubular fixed bed reactor, the catalyst is packed in a large number of small diameter tubes with means to remove heat by boiling water outside the tubes. Like the microchannel FT, all reaction products (light hydrocarbon gases, naphtha, distillate, and wax) exit the reactor through one outlet, leaving the catalyst behind in the reactor. The resulting products are segregated by sequential cooling (Espinoza et al., 1999).

In the slurry-bubble reactors, a heavy hydrocarbon liquid is used to suspend the catalyst and the heavier products remain in the reactor while the light ones are removed from the top. A portion of the liquid mixture is continuously removed to recover the heavy hydrocarbon products, while the carrier liquid and majority of the catalyst are recycled to the reactor (Font Freide et al., 2005).

Microchannel FT reactor technology has characteristics that provide substantial techno-economic benefits over conventional FT technology. The key benefits are as follows:

a. Microchannel FT has thin (1–2 orders of magnitude smaller characteristic dimension) reaction channels which greatly improves heat and mass transfer. This allows optimal temperature control across the catalyst bed, which maximizes catalyst activity and life. This leads to far higher reactor productivity, defined as barrels/day of FT product per ton of reactor mass (Fig. 2). It also leads to 10 times higher catalyst productivity, defined as kg/h of synthesis gas processed per cubic meter of catalyst volume. Both capital and operating costs are thus reduced.
b. The basic building blocks of the microchannel FT reactor design are discrete reactors with parallel microchannels. These reactors, which have fixed production capabilities, can be added or removed to match overall plant throughput requirements. When this modular design approach is combined with process intensification benefits discussed in item 1 above, two advantages are realized:
   i. Microchannel FT realizes attractive economics at much smaller size (500 bpd) than conventional technology (10,000 bpd). This advantage allows microchannel FT to be feasible for BTL applications since it is not practical to transport the required biomass feedstock of 10,000 tons/day for a 10,000 bpd facility. These economics also permits feasibility for offshore GTL.
   ii. Since the basic reactor modules are small, reactor fabrication can take place at indoor shops, which speeds field installation. On the other hand, conventional reactors must be 'stick built' and the time to field construct these facilities is long.