Corning® Advanced-Flow™ reactor technology for process intensification

D. Chamrai
Corning SNG, Corning Scientific Center, St Petersburg, Russia

Abstract

The concept of process intensification has been around for at least a decade in chemical process engineering. Conventional "batch" synthesis, with mixing and reactions done in bulky meter-scale vessels, often generates by-products and suffers from energy and material waste. Also, safety could become a concern when high-energy processes or highly toxic reagents are involved. As one of its key aspects, process intensification considers development of new equipment allowing substantially smaller, cleaner, safer and more energy-efficient and scalable methods for industrial-scale production of pharmaceutical and specialty chemical products. These needs can be addressed through the continuous-flow technology of Corning's Advanced-Flow™ glass reactors, which consist of modules with millimeter-scale channels that allow optimization of thermal and interfacial mass transfer for reducing overall heat and mass transfer resistances. This paper will describe Corning® Advanced-Flow™ reactor technology and several application cases in which these reactors demonstrated their high potential for industrial deployment and process intensification due to their ability to increase the efficiency, scalability, and quality of chemical processing – all while reducing environmental impact, performance variability and cost.
Keywords: continuous flow, advanced-flow reactor, micro-channel, process intensification, green chemistry.

1 Introduction

Increasing demand from recovering end markets and growing economies will require expansion of existing production capacities in specialty, fine, pharmaceuticals, agrochemicals and other chemical industry segments, again attracting attention to chemical processes intensification. Production of modern

doi:10.2495/CHEM110051

chemicals uses 8% of hydrocarbons worldwide - mostly as raw material, or "feedstock," but also for energy used in the manufacturing process [1]. According to DOE data the U.S. chemical industry accounts for almost 30% of all U.S. industrial energy consumption [2]. The EU chemical industry is also rather energy-intensive. Total consumption by chemical plants in EU (160Mtoe) accounts for roughly 3% of global and about 12% of EU energy demand [3]. In the chemicals industry, energy costs account for on average 10%-15% of manufacturing costs [4]. Simultaneously, changing carbon emissions laws around the world have made many chemical plants worried about their competitiveness, since the high costs associated with greener manufacturing processes cannot be passed on to consumers. Another aspect of the chemical industry's sustainability le intensification is focus is on minimization of environmental impact. Despite currently available waste treatment technologies, the problem of waste reduction is still a significant matter for many chemical plants. Thus, any technology allowing a decrease in energy consumption and minimization of waste generation may bring significant advantage for the chemicals manufacturers and contribute to higher sustainability of the chemical industry.

Several chemical industry segments, such as petrochemicals and polymers production have been utilizing continuous or semi-continuous flow production processes for a long time, benefiting from reduced process hold-ups, good residence time control, enhanced safety, high yields and selectivity and so on [5]. Today, new technologies are appearing, allowing segments of the chemical industry, such as pharmaceuticals and fine chemicals production, which traditionally employed predominantly batch process, to start switching to continuous production and thus make a step forward in chemical process evolution.

2 Corning® Advanced-Flow™ reactor

Corning's Advanced-Flow™ reactors represent one of the possible solutions which open a way for broader employment of continuous-flow production across chemical industry segments. The key principle of the technology is based on use of a continuous-flow modular system, which consists of a set of various fluidic glass modules, where reaction layer and heat exchange layers are combined in a single block, thus allowing excellent control over the reaction temperature due to elimination of hot spots. The internal space of the reactor layer is arranged as a set of continuously connected micro-channels with millimeter-scale dimensions, which allows reaching optimal surface-to-volume ratio of the reactor, (fig. 1.) Due to the small channel dimensions, such reactors are often referred as "microreactors". For multiphase reaction systems efficient mixing often becomes very critical. Geometry of channels of the Corning® Advanced-Flow™ reactor is designed in a way which allows excellent mixing at various phases [6]. Channel walls are made from materials with good resistance to chemical corrosion and smooth surfaces that enable easy cleaning. Scaling up from laboratory scale to production scale still remains an issue for many chemical reactions employed in

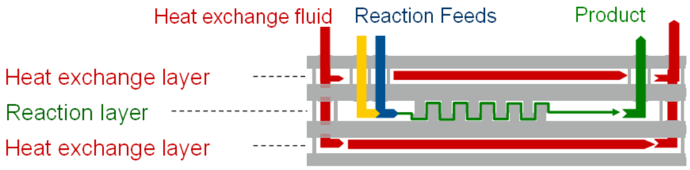

Figure 1: Construction and operation principle of a Corning® Advanced-Flow™ reactor fluidic module.

pharmaceuticals and fine products manufacturing. Corning® Advanced-Flow™ reactors deliver industrial scale capacity via both true scaling-out of the reactor volume and numbering-up principle.

Today, mass flow of a single Corning reactor on an annual basis varies between 7 and 1600 metric tons due to employment of various generations and scales of fluidic modules. Further capacity increases can be easily achieved by increase the number of reactors and their parallel use in production. Necessary to emphasize also a more general advanced feature of continuous flow processes such as an opportunity to engineer and optimize the equipment with respect to a particular reaction to be performed opposed to the traditional batch approach, when reaction is engineered in the most suitable way to fit available equipment.

3 Application examples of Corning® Advanced-Flow™ reactors

Tens of reactions have already been successfully tested with Corning® Advanced-Flow™ reactors, including reactions with miscible and immiscible liquids, gases utilization and gases release as well as reactions involving solids formation. Translating lab-scale experiments or pilot-scale tests to the industrial scale production line, we've made estimates of the economic advantage of Corning reactor-based lines over comparable traditional batch processes for several tested applications. Below, detail is provided on two examples of industrial scale operations assessment. For each case, the assessment of potential economic effect was made considering the following five process characteristics: utilities and raw materials costs, labour, capital depreciation cost, process yield and product quality as well as product throughput.

The first case covers a nitration plant with an annual capacity of 400 tons of end-product. The basis for this case is a pilot system being successfully used for selective nitration [7]. Significant benefits for this type of application can be obtained due to the ability to operate at higher concentrations, thus reducing use of solvent, while at the same time improving yield and selectivity. Other factors contributing to cost benefits include significant reduction of the size of the downstream equipment, smaller production line footprint and lower raw material inventory. Additionally, this test case demonstrated the ability to achieve significant reduction in the development cycle, moving from laboratory to production in less than 16 months. Comparison with the same using batch

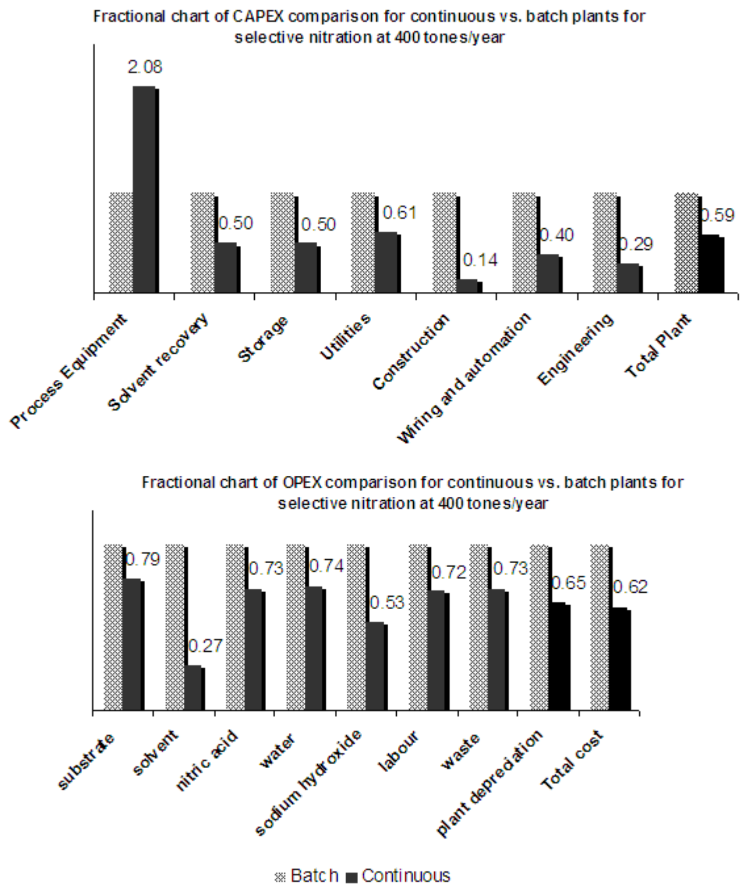

Figure 2: Fractional CAPEX and OPEX comparison of batch vs. continuous flow production plant for selective nitration.

process was made, illustrating achievable economic impacts on capital investment and operation cost, fig. 2.

Another example evaluation of Corning® Advanced-Flow™ reactor application is a hydrogenation plant with production capacity of 400 tones/year. The reaction performed is a selective highly exothermic hydrogenation, with application of a noble metal catalyst in slurry combined with hydrogen gas. This case demonstrates a different set of economic advantages of continuous-flow processes over batch production, since the optimized batch reaction demonstrated 100% yield and selectivity [8]. The advantage of continuous process in this case is related to drastic reduction of the reaction time – about 2 minutes for continuous vs. 10 hours in batch. Other benefits of continuous over batch in this case include reduction in the amount of expensive catalyst being used, smaller equipment footprint, and lower cost of the production facility due

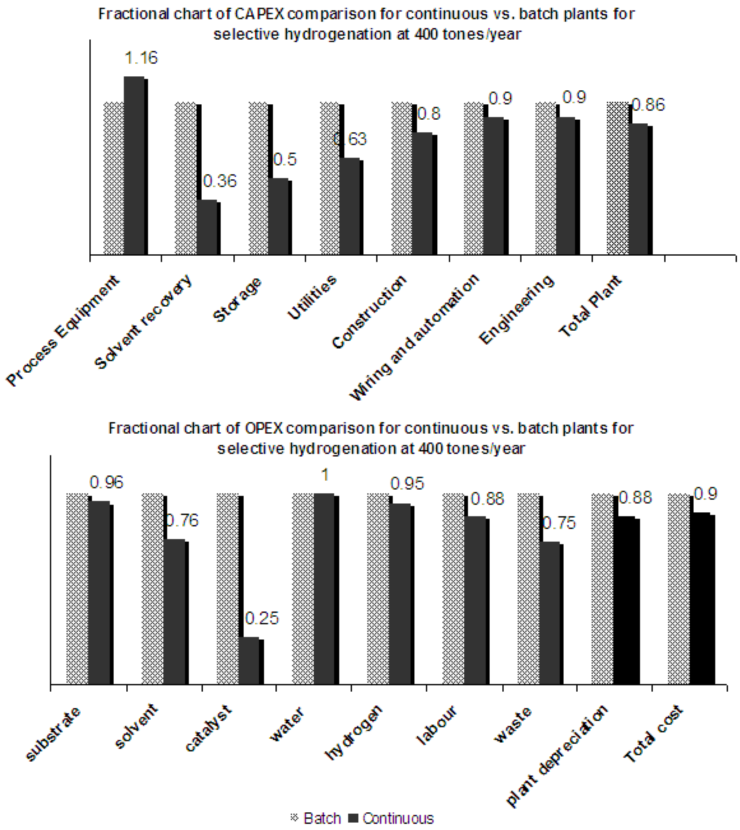

Figure 3: Fractional CAPEX and OPEX comparison of batch vs. continuous flow production plant for selective hydrogenation.

to a decrease in the level of safety requirements. The fractional cost comparisons for hydrogenation plant are presented below, fig. 3.

Significant additional advantages can also be achieved, especially in the case of a green-field plant, due to the much smaller plant footprint required. For instance, based on Corning's assessment, the batch line for nitration operating at capacity of 400 tones/year, will require a footprint of 2,927.52 m^2, whereas the same production line, employing Corning equipment can be allocated on an area of 455.84 m^2. Afterwards, maintenance and utility costs for a smaller production facility will continue to bring additional financial benefit and reduced energy consumption.

Of course, as any known technology Corning® Advanced-Flow™ reactor may have some limitations in applicability and economic benefits. Detailed analysis of applicability and estimates for potential economic benefits should be conducted on a case-by-case basis.

4 Efficient and green

It is clear that increasing the efficiency of manufacturing processes in the chemical industry could result in substantial benefit for the industry and increase its overall sustainability, lowering the negative impact on the environment. Unfortunately, the complexity of the thousands of processes being used in chemical manufacturing and significant differences between different plants' energy utilization patterns do not allow precise evaluation of the potential economic and environmental impact of specific process intensification efforts. However, in some cases applying a number of assumptions, we can try to assess potential impacts of specific technologies on the global environment. Averaging our results on the assessment of the potential benefits of Corning® Advanced-Flow™ reactors used in comparison with similar batch processes, the cumulative economic and environmental effects have been estimated and a graphical summary has been generated, fig. 4 [9]. The chart illustrates that significant improvements in process economics can be achieved due to substantial decreases in risks associated with process scale up. Also, significant reduction of solvent utilization makes a great contribution toward much greener and less expensive production of chemicals.

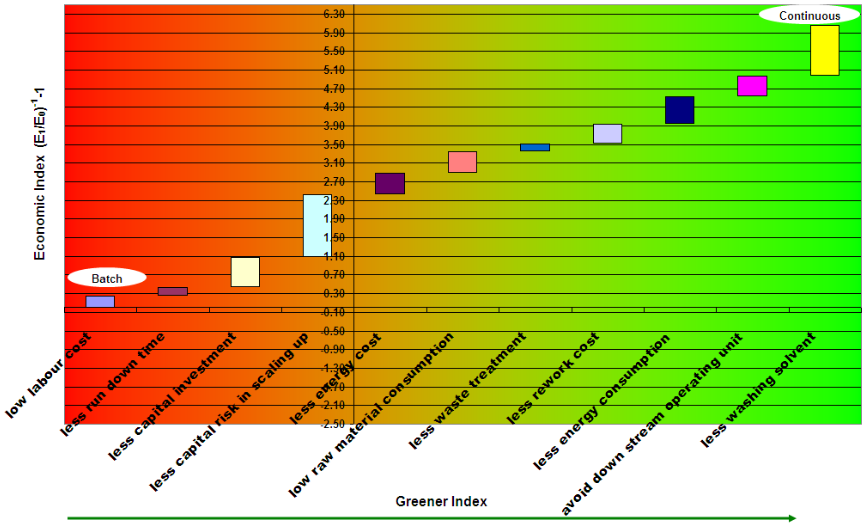

Figure 4: Economic and "green" indexes of Corning® Advanced-Flow™ reactor.

Assuming further successful development and penetration of continuous-flow technology based on employment of microchannel reactors, the potential for increased energy efficiency for chemical manufacturing processes and CO_2 emission reduction can be significant.

Internal analysis was performed in order to estimate the scale of potential environmental impact form continuous-flow microreactor-based technology penetrating pharmaceuticals and crop protection markets. The analysis utilizes results from a market forecast and technology penetration model developed internally and averaged industrial numbers on energy intensity for pharmaceuticals and crop protection segments available from various public sources. Our internal market and technology assessment revealed that it is possible that by 2015 approximately 1.7 billion tones of active ingredients (measured by mass throughput) in pharmaceuticals and crop protection segments could be produced using continuous-flow processing. The average energy intensity of pesticide active ingredients production is about 350,693 Btu (370 MJ) per kg of the final product [10]. For pharmaceuticals, energy intensity of API production on average can reach levels between 47,391 Btu/kg and 284,346 Btu/kg [11]. The calculation of the final product volumes was made with an assumption of 85:1 and 28:1 of total throughout to final product conversion ratios for pharmaceuticals and crop protection segments correspondingly. The applied conversion ratios do not consider any impact from continuous-flow process use, but represent batch process average industrial ratios in accordance with our internal estimate. Based on the National Energy Foundation, conversion rates for EU-27 grid electricity [12], from utilization of 100,000 Btu, the amount of CO_2 emitted is approximately equal to 12 kilograms. Referring to our internal energy efficiency benefit analysis and possible scenario of the future increase in use of continuous-flow production process by pharmaceuticals and crop protection segments, and assuming only electricity being used as a source of energy, by 2015 annual energy use by these two industry sectors may drop down by 118 quadrillion Btu, which is approximately equivalent to annually emitted 14.3 billion metric tones of CO_2 globally. The calculation, of course, provides a very rough estimate of the potential environmental effect of microreactor-based process intensification, but it allows getting a better idea of the scale and importance of the potential impact from the continuous flow technologies penetrating chemical industry segments, which traditionally favour batch manufacturing. Also, it allows us to mention that additional economical benefits from the employment of the continuous-flow production process can be achieved in the countries where the government imposes CO_2 taxes on the chemical producers.

5 Conclusion

Summarizing all benefits of Corning® Advanced-Flow™ reactor technology for process intensification, it is possible to conclude, that for the chemical process itself, Corning technology offers an increase of reaction rates and yields, enables new reaction paths development and simplifies downstream processes. At the same time, the technology makes a significant contribution toward chemical process safety improvement, reducing unstable intermediate acumen, and enabling in some cases “high-energy” chemistry. Taking into account all of the benefits mentioned above, it is clear that the technology has the potential to significantly increase economic efficiency of chemical production, lower operation costs due to decreased energy utilization and raw material consumption, improve safety, lower labor cost and help minimize risks associated with process scale-up. Simultaneously, the described technology can contribute to intensification of many chemical manufacturing processes while decreasing of negative environmental impact.

References

[1] Schilling C., A Balanced Diet For The Chemical Industry, 14 October 2010, www.forbes.com/2010/10/13/dupont-basf-feedstocks-technology-renewable-chemicals_2.html

[2] United Stated Department of Energy, The Industrial Technology Program (ITP), Online, www.eere.energy.gov/industry/chemicals

[3] Botschek P., Director Energy & HSE European Chemical Industry Council (Cefic), Renewable Resources – perspectives for the chemical industry, *Presentation at Renewable Resources – Sustainable Future Forum*, Helsinki region, Finland, November 2006.

[4] Bieling H.-H., Chemical reaction - an energy-intensive industry finds the solution in CHP, *Cogeneration & Onsite Power Production Magazine*, 8 (2), March 2007.

[5] Woehl P., Efficient Processing with Corning® Advanced- Flow™ Reactor Technology, *Proceedings of Industrial Green Chemistry Workshop*, Mumbai, India, December 2009.

[6] Chevalier B., Lavric E. D., Cerato-Noyerie C., Horn C. and Woehl P., Microreactors for industrial multi-phase applications. Test reactions to develop innovative glass microstructure design, *Chemistry Today*, 26, 1-4, 2008.

[7] Braune S., Poechlauer P., Reintjens R., Steinhofer S., Winter M., Olivier L., Guidat R., Woehl P., Guermeur C., Selective nitration in a microreactor for pharmaceutical production under cGMP conditions. *Chimica Oggi*, 27(1), pp. 26-29, 2009.

[8] Buisson B., Donegan S., Wray D., Parracho A., Gamble J., Caze P., Jorda J., Guermeur C., Slurry hydrogenation in a continuous flow reactor for pharmaceutical application, *Chimica Oggi*. 27(6), pp. 12–16, 2009.

[9] Pissavini S., Teaming up Chemistry and Chemical Engineering for “Greener” Processes and Improved Economics, *Presentation at 14th NIChE Conference on Micro-Reactor Technologies*, Gaithersburg, MD, USA, September 2009.

[10] Audsley E., Stacey K., Parsons D.J., Williams A.G., Estimation of the greenhouse gas emissions from agricultural pesticide manufacturing and use. Prepared for Crop Protection Association, Cranfield University, Bedford, UK, August 2009.

[11] Slater C.S., Savelski M.J., Hesketh R.P., Green Engineering Opportunities in the Pharmaceutical Industry, *Proceedings of Great Lakes Regional Pollution Prevention Roundtable Conference*, New York City, NY, USA, August 2005.
[12] National Energy Foundation, CO2 calculator, Online, www.nef.org.uk /greencompany/co2calculator.htm