Microchannel Gas-to-Liquids for Monetizing Associated and Stranded Gas Reserves

A.L. Tonkovich[1], Kai Jarosch[1], Sean Fitzgerald[1], Bin Yang[1],
David Kilanowski[1], Jeff McDaniel[1], Tad Dritz[1]

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

Monetizing natural gas associated with remote oil production and stranded gas reserves without access to distribution infrastructure presents in enormous opportunity. However, to date, existing solutions, including LNG, CNG and chemical conversion to methanol, have not been adequate to address the bulk of the opportunity. This paper describes an emerging solution that does, the application of microchannel technology to steam methane reforming and Fischer-Tropsch synthesis. When combined these processes convert natural gas into a synthetic crude that can be blended with petroleum crude and shipped via existing infrastructure. The application of microchannel technology enables both key processing steps in this gas-to-liquids (GTL) process to be economically scaled down to match associated and stranded gas resources both on and offshore. Microchannel reactors systems are entering the field demonstration phase with three projects in Austria and Brazil and being evaluated for several commercial facilities.

Introduction

Flaring natural gas is both wasteful and detrimental to the environment. Approximately 5 trillion cubic feet (TCF) of gas are flared annually[1], the equivalent of 27% of U.S. consumption. Although substantial, this quantity reflects only a portion of the natural gas associated with remote oil production; industry experts believe as much as 3 cubic feet are reinjected for every 1 cubic foot flared, putting the total at approximately 20 TCF per year. Additionally, there is a vast amount of discovered, yet unproduced stranded gas reserves, those without access to distribution infrastructure. Estimates of stranded gas top 6,000 TCF, which astoundingly is the energy equivalent to all the liquid petroleum produced to date.

This paper discusses an emerging technological solution that addresses challenge/opportunity of associated and stranded gas – small-scale gas-to-liquids (GTL) enabled by microchannel process technology. To date, GTL synthetic fuel technology has been applied only to very large natural gas resources, which warrant the construction of world-scale facilities. The challenge of monetizing smaller gas resources 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 in smaller scale facilities, such as those needed for flare abatement.

Background

Many technological solutions are currently on the market or in development that address the challenge and opportunity of natural gas without ready access to distribution infrastructure, know as stranded gas. These solutions include compressed natural gas (CNG), liquefied natural gas (LNG), and a family of chemical conversion routes to produce methanol, dimethyl ether (DME), synthetic crude via Fischer-Tropsch (FT) synthesis, or other products

CNG is the simplest approach. Large compressors are used to elevate the pressure, and decrease the volume of natural gas. This high pressure gas is loaded onto specially designed tankers and shipped to a market that has natural gas infrastructure. CNG is a good option for mid-sized, gas resources less than 1,000 miles from the market, but becomes economically unfeasible for more remote reserves.

LNG is much like CNG, but uses a higher degree of compression and cooling to transform natural gas into a liquid. Special tankers are used to ship LNG to markets as far away as 5,000 miles from the stranded gas resource. Receiving LNG requires specialized terminals that boil the gas and feed it into the local natural gas pipeline network. LNG is a proven, commercial technology but to date is only economically attractive for very large gas reserves.

The chemical conversion options typically aim to produce a fungible liquid product that can easily transported from the gas resource to the world market. (One exception is DME which is volatile at ambient conditions.) Production of synthetic crude using a FT based process is seen as the best approach due to the resulting product's energy density and ability to blend with petroleum crude. All other conversion options require establishing and maintaining a dedicated logistics system.

Gas-to-Liquids Process

Gas-to-liquids (GTL) is sometimes used as a general term for all technologies that convert natural gas into a liquid product, including methanol, dimethyl ether (DME) and others. Here, it is confined to FT-based processes that convert natural gas into synthetic fuel products. This process, diagrammed in Figure 1, has two primary processing steps: 1) methane reforming, and 2) Fischer-Tropsch synthesis.

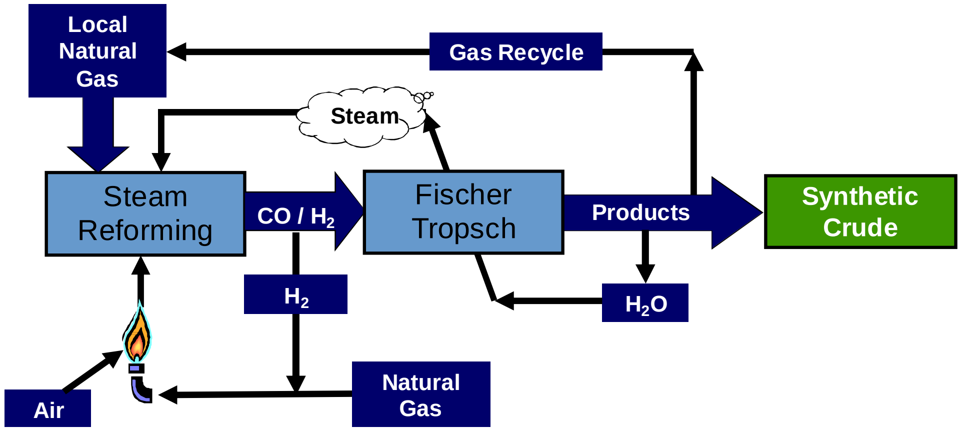

Figure 1. Both primary GTL processes, SMR and FT, can be intensified using microchannel process technology

Methane Reforming. The front end of the GTL process is the conversion of natural gas to a high energy mixture of carbon monoxide (CO) and hydrogen (H_2) known as synthesis gas, or simply syngas. Reforming technologies fall into two basic categories: partial oxidation (POX) and steam methane reforming (SMR). POX reforming encompasses a range of technology, but is essentially incomplete combustion (oxidation) of methane to yield carbon monoxide (CO) and hydrogen (H_2); complete combustion results in carbon dioxide (CO_2) and water (H_2O)

Although more complex, SMR is also a more efficient path to syngas; for this reason it is used most commonly to produce hydrogen, accounting for over 90% of this market. SMR is a high temperature (700–1100°C) catalytic process that yields syngas from methane (CH_4) and steam (H_2O). The reaction, shown in standard equation nomenclature below, is reversible in nature.

$$CH_4 + H_2O \leftrightarrow CO + 3\,H_2 \qquad (1)$$

Fischer-Tropsch Process. 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 CO and H_2 at an elevated pressure and temperature and in the presence of a catalyst. The reaction is exothermic and excess heat is typically removed by boiling water. The majority of the products from FT synthesis are paraffinic waxes based on the following chemical equation.

$$nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + H_2O \qquad (2)$$

Byproducts from the FT process are lighter hydrocarbons, including methane and naphtha. After the FT process, synthetic crude can be blended with petroleum crude oil for transportation to the world market, or be upgraded to produce distillate products, notably diesel and jet fuel.[2]

Microchannel Process Technology

Systems based on microchannel process technology have the potential to transform the energy and chemical processing industries by greatly reducing the size of chemical reactor hardware. This technology has many parallels with the microelectronics that revolutionized the computer industry because it can shrink processing hardware while improving performance. Devices using microchannel technology are characterized by parallel arrays of microchannels, with typical dimensions in the 0.1 to 5.0 mm range. Processes are accelerated 10 to 1,000 fold by reducing heat and mass transfer distances, thus decreasing transfer resistance between process fluids and channel walls as shown in Table 1. System volumes can be reduced 10-fold or more compared with conventional hardware.[3]

Table 1. Microchannel technology offers enhanced heat and mass transfer

	Units	Microchannel	Conv.
Heat Transfer			
Convective	W/cm^2	1-20	<1
Boiling	W/cm^2	1-20	<1
Mass Transfer (contact time)			
Gas Phase	Sec	0.001-0.3	1-10

Microchannel technology is ideally suited for carrying out catalytic reactions that are either highly endothermic, such as SMR, or highly exothermic, such as FT synthesis. The heat required for endothermic reactions or generated in exothermic reactions must be efficiently transferred across reactor walls to maintain an optimal and uniform temperature so as to achieve the highest catalytic activity and the longest catalyst life. Conventional reactor systems use massive hardware to manage the heat in such reactions.

Microchannel Fouling. Claims by microchannel practitioners are often met with skepticism from industry, and this commonly includes concerns about the plugging or fouling of the thousands of small channels inside each microchannel devices. While this is a legitimate worry, experiments show that two interrelated strategies help mitigate the risk of plugging: 1) high wall shear, and 2) good flow distribution.

Long duration microchannel vaporizer experiments were run with and without good flow distribution. For the devices with good flow distribution, no pressure drop increases were observed in runs ranging from 1,000 to 9,000 hours at both ambient and high pressure conditions.

The lack of pressure drop increases held true even when the feed water was intentionally doped with low levels of dissolved solids. However, higher levels did cause fouling, as is the case for plate-frame and other types of narrow passage heat exchangers. The ability of microchannel devices to handle any amount of solids is attributed to high wall shear that sweeps particles out instead of allowing them to build-up. This was verified with post operational autopsies that did show some fouling in the headers and footers, but they were sufficiently large as not to affect pressure drop or heat transfer performance.[4]

Manufacturing Techniques. Microchannel development efforts have gone well beyond the process design methodology to include the manufacturing techniques for devices that commonly operate at elevated temperatures and pressures. One of the selected processes is known as laminate fabrication. This technique provides tight tolerances, design flexibility and cost effectiveness for microchannel reactors which typically accommodate a complex suite of chemical unit operations in a single device. Laminate construction involves forming many parallel microchannels by interleaving (stacking) thin sheets of formed material (shims) with solid sheets (walls). The steps of this process are shown in Figure 2.

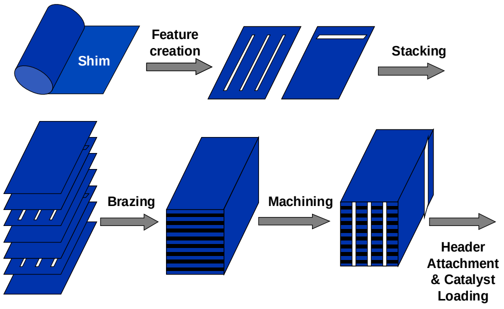

Figure 2. Laminate microchannel fabrication process

Microchannel GTL Process

Both SMR and FT can be intensified using microchannel technology, resulting in a compact process that convert commercially significant quantities of natural gas into high value synthetic crude.

Microchannel SMR

By improving both mass and heat transfer, microchannel technology intensifies SMR. Current industrial reforming box furnaces operate with contact times around 1 second. Microchannel architecture allows this to be reduced to less than 5 milliseconds, approximately 200 times faster. The graph in Figure 3 shows the results of a microchannel catalyst test device; equilibrium conversion methane (CH_4) and selectivity to carbon monoxide (CO) were both achieved at sub 6 millisecond contact times.

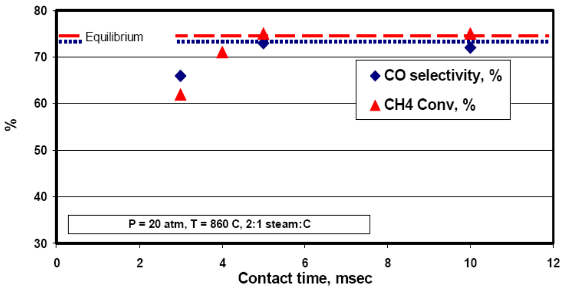

Figure 3. Microchannel SMR is capable of near equilibrium conversion at millisecond contact times

The microchannel SMR reactor incorporates multiple unit operations into one integrated device, including a recuperating heat exchanger, combustion heater, and steam reforming. An innovative M pattern, shown in Figure 4, allows for the microchannel reactor to have a hot and a cold end, which greatly simplifies installation. All manifolding and supports are attached to the cold end, allowing the hot end to float and expand freely.

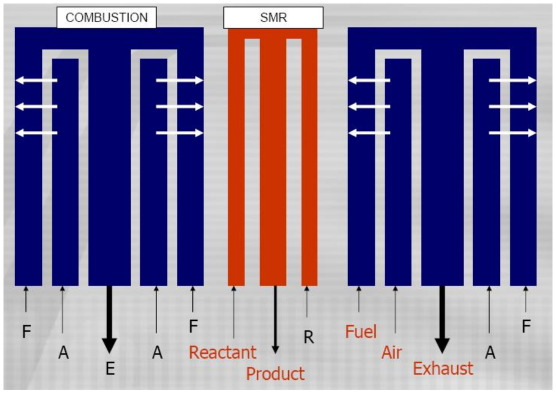

Figure 4. M design permits SMR reactor to have hot and cold ends, easing installation and operation

Microchannel SMR has been scaled up to a pilot reactor with 48 process channels, and a capacity of 9,000 SCFD. This unit operated successfully for over 500 hours with excellent performance on the process side, and no carbon build-up inside the microchannels (see micrograph in Figure 5).

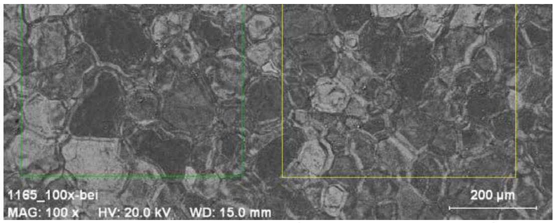

Figure 5. 100X micrograph of SMR process wall after 500+ hours of operation

Commercial scale microchannel SMR reactors will be manifolded in parallel and placed in pressure containment shells, containing up to 40 reactor blocks. A conceptual design for a 30 million standard cubic foot per day (MMSCFD) microchannel facility is shown in Figure 6. This plant has a 10m x 10m footprint. A conventional SMR with equivalent capacity would occupy a footprint of 30m x 30m.

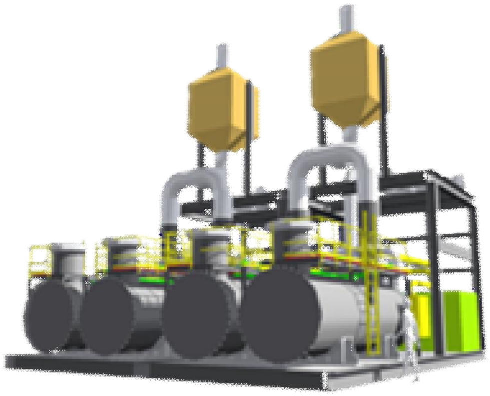

Figure 6. Conceptual 30 MMSCFD microchannel SMR

Microchannel FT

The microchannel FT reactor system is another example of process intensification, whereby the reactor volume to produce a given amount of product is reduced by an order of magnitude or more, by utilizing an advanced catalyst and the unique capabilities of microchannel architecture. For FT, this increased productivity is made possible with highly active cobalt-based catalysts [5,6] and enhanced heat transfer. Figure 7 shows a schematic of a microchannel FT reactor block, which has thousands of process channels filled with catalyst interleaved with coolant channels.

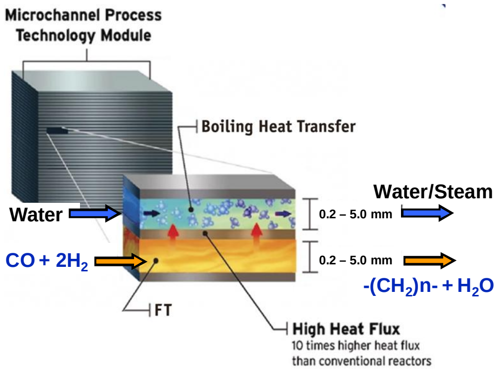

Figure 7. Microchannel FT reactor schematic

Catalyst System. An FT catalyst developed by Oxford Catalysts Group enables microchannel reactors to achieve catalyst productivities that are orders of magnitude higher than for more conventional systems (see Figure 8). A demonstration carried out in 2008 in a nominal two-gallon per day microchannel reactor operated for more than 4,000 hours and achieved productivities of more than 1500 kg/m3/h. In contrast, conventional fixed-bed reactors typically operate at 100 kg/m3/h, while slurry-bed reactors operate at 200 kg/m3/h.

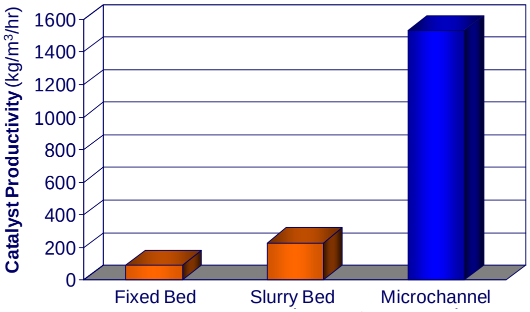

Figure 8. Microchannel FT achieves far higher catalyst productivity

Experimental Results. Microchannel FT reactors, utilizing an advanced cobalt catalyst supplied by Oxford Catalysts, have been tested at various scales ranging from small-scale laboratory devices to field tested pilots. Consistent, higher performance has been demonstrated across scales for tests, some of which have surpassed 4,000 hours time on stream. Figure 9 graphically shows results for 5 such experiments, including one with over 900 parallel process channels.

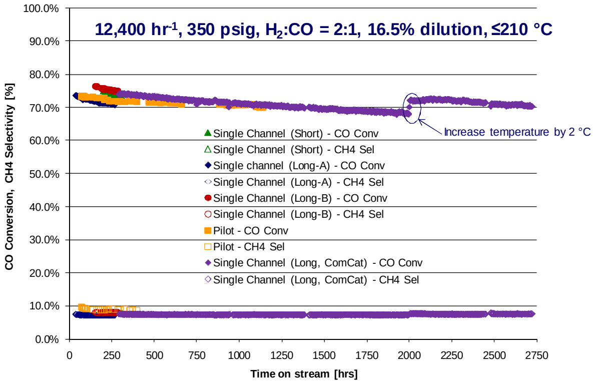

Figure 9. Microchannel FT reactor performs consistently from lab through pilot scale

The two lines on the graph above represent the conversion of CO (top), and selectivity to methane (bottom). The steady state CO conversion for these tests typically exceeded 70%, and experienced only a minimal decrease over 3,300 hours of operation. Selectivity to methane, also known as 'methane make', was under 10%. Methane production is counterproductive and should be minimized. The selectivity to methane demonstrated is on par with competing fixed bed FT technologies.

Manufacturing Scale-up

Working with a world class manufacturing supply chain, which includes Kobe Steel of Japan, Velocys has successfully scaled up microchannel process technology for industrial scale applications. This effort, begun in 1998, spanned several key scale-up steps, and recently culminated in fabricating the 6 bpd SMR and FT reactors shown in Figures 10 and 11 respectively.

Figure 10. Commercial microchannel manufacturing techniques validated for SMR reactor architecture

Figure 11. Commercial microchannel manufacturing techniques validated for FT reactor architecture

The successful fabrication of the devices shown above provides clear evidence that the techniques employed are capable of producing cost effective, high quality, commercial scale microchannel reactors.

Comparison with Competing GTL Technologies

Due to improved volumetric and catalytic productivity, microchannel SMR and FT enables lower capital and operating costs compared to competing GTL processes. This includes mini channel approaches, such as the process under development at Compact GTL, which achieves far less process intensification.

Steam Methane Reforming. Most competing syngas generation concepts use conventional processing technologies that have been scaled down from larger systems and suffer from reverse economies of scale. Microchannel SMR offers a significant cost advantage in the 5 to 30 MMSCFD range, which is appropriate for most stranded gas resources.

Fischer-Tropsch. Microchannel FT compares favorably with the following classes of conventional reactor systems: 1) tubular, fixed-bed, with a cobalt catalyst, and 2) slurry-bubble with cobalt or iron catalyst.

Tubular fixed bed reactors consist of a large number of small diameter tubes packed with catalyst. These tubes are cooled by boiling water on their outside surface. Like the microchannel FT, all reaction products (light hydrocarbon gases, naphtha, distillate, and wax) exit the reactor through one outlet, leaving the catalyst behind. The resulting products are segregated by sequential cooling.[7]

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.[9]

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

1) 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 metric ton (tonne) of reactor mass (Figure 12). It also leads to 10 times higher catalyst productivity, defined as kg/hr of synthesis gas processed per cubic meter of catalyst volume. Both capital and operating costs are thus reduced.

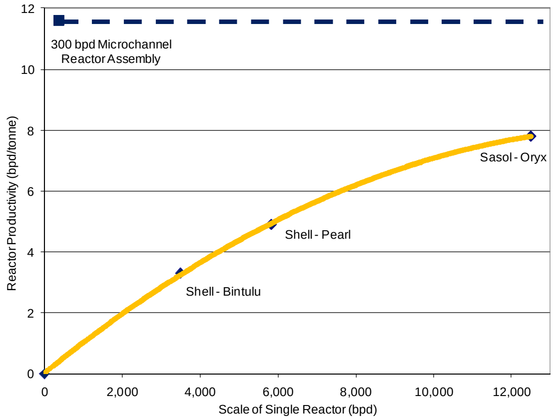

Figure 12. Microchannel FT improves reactor productivity and achieves economy of scale at far lower capacity

2) The basic building blocks of the microchannel FT reactor design are components with parallel microchannels. These reactor components, which have fixed production capabilities, can be added or removed to match throughput requirements. When this modular design approach is combined with process intensification benefits discussed in item 1 above, two advantages are realized:

a. Microchannel FT realizes economies of scale at much smaller size (200 bpd) than conventional technology (10,000 bpd). This advantage allows microchannel FT to be feasible for wellhead associated gas applications

b. 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.

3. The modular approach of microchannel FT helps minimize downtime due to individual modules needing components or catalysts to be replaced. The conventional systems require the entire system to shutdown to make changes or repairs.

4. The microchannel FT not only has a smaller footprint, it also has a lower profile. Microchannel reactor assemblies are relatively small at 1.5m in diameter and sit horizontally versus conventional FT reactors that are situated vertically and can be more than 60m tall. This is a critical advantage for mobile and offshore installations (Figure 13).

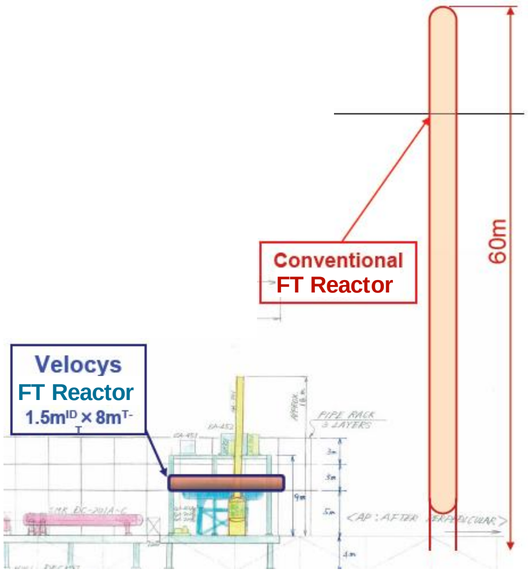

Figure 13. Small size and low profile eases installation and operation in both onshore and offshore environments

Commercial Applications

Because conventional FT technologies are not economically viable at small scale, below 10,000 bpd, the current focus for FT installation projects is large land-based natural gas fields, such as those in Qatar. However, only about 6% of the world’s gas fields are large enough to sustain a 10,000+ bpd GTL plant. Reducing the production rate to 2,000 bpd makes approximately 40% of gas fields viable sources. Microchannel technology permits economic production at this smaller scale.[10]

Associated Gas. Nearly all oil wells also produce natural gas, which is commonly known as associated gas. Based on flared gas estimates from the World Bank and information from oil field experts, an estimated 20 TCF per year of associated gas is unutilized because no local market exists. This gas is either re-injected into the reservoir, or flared. Flaring is effectively banned in many countries due to greenhouse gas emissions and other environmental issues. These practices cause more than 400 million tons of CO_2 emissions annually. Finally, reinjection currently cost up to $13 per equivalent barrel of petroleum, and these costs are highest offshore. A better solution is to convert this gas into liquids fuels in a FT process.

Microchannel GTL can be used to convert as little as 7 MMSCFD into 360 bpd of synthetic crude that can be blended with petroleum crude and transported to the market in pipelines and other existing infrastructure. The modularity of michrochannel units also permits processing facilities to be moved to new wells when production wanes.

Offshore Gas to Liquids. An advantage of microchannel technology is that it shrinks and lowers the profile of processing equipment; thus enabling facilities to be placed on offshore structures. A conceptual sketch of such a plant on a floating production, storage and offloading (FPSO) vessel is shown in Figure 14.

Figure 14. Microchannel FT concept floating production storage and offloading (FPSO)

Development Status

Microchannel FT technology has been demonstrated and is ready for commercial sales. Velocys is currently engaged in several engineering studies for facilities that will utilize biomass, coal and/or natural gas as feedstock. The first field demonstration of microchannel FT in Güssing, Austria began operations in April 2010 utilizing a slipstream of biomass derived synthesis gas. Figure 15 shows the installed microchannel FT skid.[11]

Figure 15. 25 gallon per day FT system installed in Austria

Based on the success of the facility in Austria, SGC Energia has announced that their JV will construct a fully integrated 50 bpd BTL facility in Brazil. Velocys will deliver two FT reactors for this facility in the third quarter of 2010. [12]

Microchannel SMR technology is entering the demonstration phase and will be ready for commercial sales in early 2012. An integrated GTL demonstration will begin operations in the third quarter of 2011 in Brazil in conjunction PetroBras, the Brazilian national oil company. This facility will include both microchannel FT and microchannel SMR. The capacity of this plant will be 6 bpd.[13]

Conclusion

Due to ever stricter flaring regulations, associated natural gas is typically seen as a cost of oil exploration and production because of the capital equipment and energy required to re-inject the gas back into the reservoir. The cost of associated gas is highest offshore, where drilling wells and installing equipment are more expensive, and deck space is at a premium. The opportunity lies in the ability to monetize the natural gas through a FT based GTL process enabled by microchannel technology; thereby, transforming the burden of associated gas into a valuable resource that increases revenues and stretches reserves. The process intensification possible with microchannel process technology improves volumetric productivity and efficiency, reducing capital cost and shrinking facility footprints, which is essential for economical small-scale on and offshore GTL facilities.

In addition to associated gas, microchannel GTL can also be employed to monetize vast stranded gas reserves; unlocking a vital energy resource.

Contact Information

Jeff McDaniel
Velocys, Inc.,
7950 Corporate Boulevard
Plain City, OH, 43064 US
Phone: 614-733-3319
Web Site: www.velocys.com

References

[1] World Bank, Global Gas Flaring Reduction Press Release, 2009-11-17
[2] Strange, A. M.; AIChE 2003 Spring National Meeting, New Orleans, LA, 2003.
[3] K. T. Jarosch, A. L. Tonkovich, S. T. Perry, D. Kuhlmann, Y. Wang, Reactors for Intensifying Gas-to-Liquid Technology, in Microreactor Technology and Process Intensification, ACS Symposium Series n 914, September 2005.
[4] A. Y. Tonkovich, Y. et al, Microchannel Fouling Mitigation: Flow Distribution and Wall Shear Effects, AIChE Fall 2005
[5] Y. Wang, D. P. Vanderwiel, A. Y. Tonkovich, Y. Gao E. G. Baker, US 6,451,864 2002.
[6] Y. Wang, D. P. Vanderwiel, A. Y. Tonkovich, Y. Gao, E. G. Baker, US 6,558,634 2003.
[7] B. Altemühl, Svetsaren: ESAB Welding and Cutting Journal, Vol. 63, No. 1 (2008), p. 51-55
[8] R.L. Espinoza, A.P. Steynberg, B. Jager, A.C. Vosloo, Applied Catalysis A: General 186 (1999) 13–26
[9] J. Bereznicki, Alter NRG Analyst Report, Paradigm Capital, April 15, 2007
[10] N. Jones, T. Tveitnes, “The M-flex LNG Carrier Design”
[11] Velocys, Inc. (November 2, 2009), “Microchannel reactors: Demonstrating the future for distributed biofuels production”
[12] Oxford Catalysts (May 3, 2011), “Second Order for Commercial Scale FT Reactor”
[13] Velocys, Inc. (February 9, 2010), “GTL Agreement with Petrobras and Partners”