

Improved Fischer-Tropsch Economics Enabled by Microchannel Technology

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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 the application of microchannel technology to the exothermic Fischer-Tropsch (FT) process, which converts synthesis gas into a petroleum replacement – synthetic crude or fuels. Synthesis gas to feed the FT unit can be derived from a variety of feedstock materials, including natural gas and biomass. By greatly reducing the size and cost of chemical processing hardware, microchannel process technology enables cost effective production of synthetic fuels from smaller scale facilities, appropriate for biomass and offshore natural gas resources.

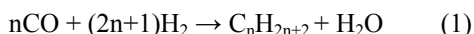
Introduction

Sustained high oil prices, concern about global climate change, and the drive for energy security have intensified attention on alternative fuels, including those produced from Fischer-Tropsch (FT) based processes. Although some very large stranded natural gas and coal resources warrant the construction of world-scale FT synthetic fuels facilities, many applications call for smaller-scale plants, including offshore gas-to-liquids (GTL), biomass-to-liquids (BTL) and waste-to-liquids opportunities. The concept of producing synthetic fuels 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 in smaller scale facilities.

Fischer-Tropsch Process and Products

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 (H₂), referred to as “synthesis gas”, at an elevated pressure and temperature and in the presence of a catalyst. The excess heat generated from the reaction has typically been removed by inserting boiler tubes that carry water. In theory, any source of carbon can be used to generate the synthesis gas.

The majority of the products from FT synthesis are paraffinic waxes based on the following chemical equation.



Typical byproducts are liquefied petroleum gas (LPG) and naphtha. After the FT process, heavier

hydrocarbons can be hydrocracked to produce distillate products, notably diesel and jet fuels.[1]

FT derived transportation fuels are typically referred to as synthetic fuels. During the 20th century, these fuels were derived from coal in situations where petroleum was not readily available, such as Germany in WWII and South Africa during Apartheid. However, since the beginning of this decade, there has been a renewed interest in synthetic fuels for four reasons.

1. World demand for petroleum is continually increasing while the world oil production has plateaued. Thus, there is a tremendous interest in alternative methods of liquid fuels production.
2. Synthetic fuels burn cleaner than petroleum-based diesel and jet fuels, because synthetics do not have soot-forming aromatics and other non-hydrocarbon contaminants.
3. There are vast natural gas reserves considered “stranded,” with no viable local uses or transportation means; these resources can be used to produce liquid fuels in an FT process.
4. Concerns about greenhouse gas emissions have increased interest in fuels derived from renewable, non-food biomass feedstocks.

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.[2]

Table 1. Microchannel technology offers enhanced heat and mass transfer

	units	Microchannel	Conventional
<i>Heat Transfer</i>			
Convective	W/cm ²	1-20	<1
Boiling	W/cm ²	1-20	<1
<i>Mass Transfer (contact time)</i>			
Gas Phase	Sec	0.001-0.3	1-10

Microchannel technology is ideally suited for carrying out catalytic reactions that are either highly exothermic, such as FT synthesis, or highly endothermic, such as methane reforming. The heat generated in exothermic reactions or required for endothermic 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. A common concern is the plugging or fouling of the thousands of small channels inside each microchannel devices. While this is an understandable concern, experiments show that two interrelated strategies mitigate the risk of microchannel 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 (20.3 bar) conditions. The lack of pressure drop increases held true even when the feed water was intentionally doped with high levels of dissolved solids. This absence of fouling within individual microchannels was verified by post operational autopsies and attributed to high wall shear. Some fouling was noted in the headers and footers, but they were sufficiently large as not to affect pressure drop or heat transfer performance.[3]

Manufacturing Techniques. Microchannel development efforts have gone beyond the process design methodology to include the manufacturing techniques for devices that commonly operate at elevated temperatures and pressures. The selected process, known as laminate fabrication, provides cost effectiveness, tight tolerances and design flexibility for

microchannel reactors which commonly 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). This process is shown in Figure 1.

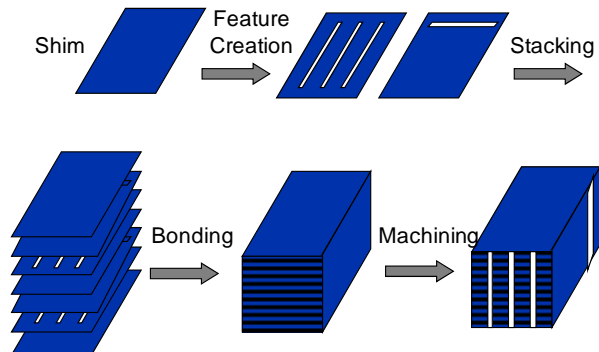


Figure 1. Laminate microchannel fabrication process

Microchannel FT Reactor Technology

The microchannel FT reactor system is an 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 enhanced heat and mass transfer capabilities of microchannel architecture. This increased productivity is made possible with highly active cobalt-based catalysts.[4,5] As shown in Figure 2, each reactor block has thousands of process channels filled with FT catalyst interleaved with water filled coolant channels.

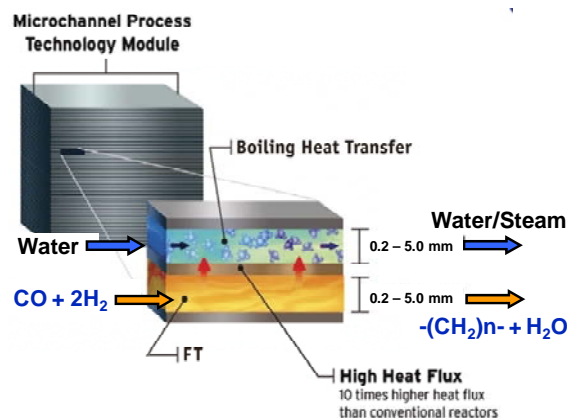


Figure 2. Microchannel FT reactor schematic

Multiple microreactors are manifolded in parallel to achieve commercially significant production volumes. Figure 3 compares a 10 reactor assembly with a conventional technology reactor. From the outside, microchannel assemblies have a low profile, with external dimensions of 1.5m diameter by 8m long. On the other hand, conventional FT reactors have a diameter of 9m or more and are over 60m tall.

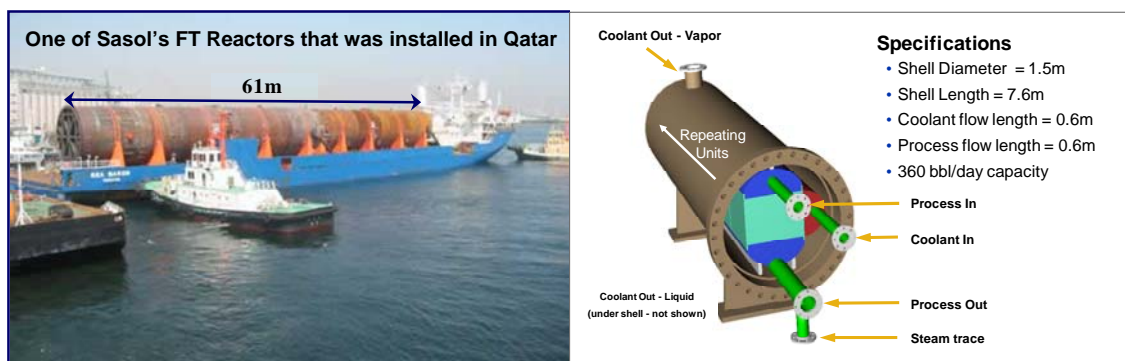


Figure 3. Microchannel FT reactor assemblies are far smaller than conventional technology FT reactors

Experimental Results. The testing of an integrated microchannel FT pilot reactor, shown in Figure 4, was first completed in January of 2007. This reactor had 40 process and 425 coolant microchannels.

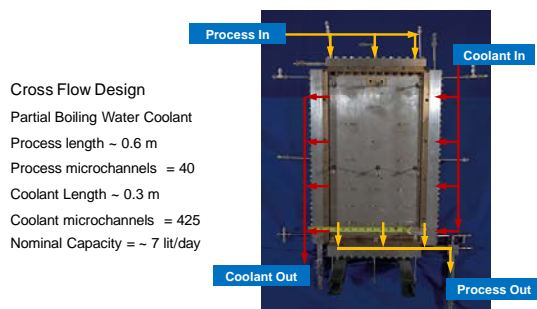


Figure 4. Pilot-scale microchannel FT reactor

The performance of a second pilot reactor is shown in Figure 5. The two key numbers are the conversion of CO, and selectivity to methane. The steady state CO conversion was over 70%. The reactor operated steadily and had minimal change in conversion level during the 1,100 hour run.

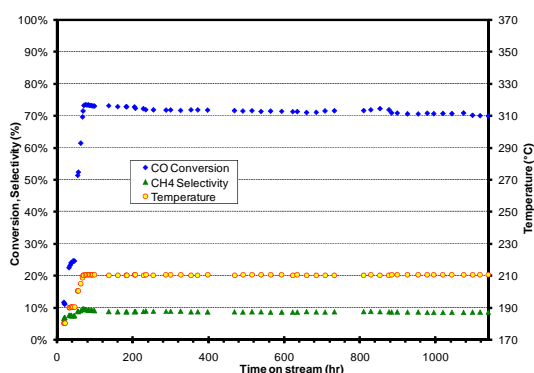


Figure 5. Microchannel FT reactor demonstrated equivalent of 28 - 44 bpd for a full-scale reactor

Selectivity to methane, also known as methane make, was approximately 9%. Methane production is counterproductive and should be minimized. The 9% methane is on par with competing fixed bed FT technologies. The reactor was operated at conditions

that correlated to a single commercial scale reactor capacity of 28 - 44 bpd. Multiple commercial reactors can operate in parallel to meet plant capacity requirements.

Process Scale-up. While several R&D groups around the world have shown the potential of microchannel reactors for process intensification, only Velocys has been successful in developing the technology for industrial scale applications. This effort, begun in 1998, spanned several key scale-up steps, and recently culminated in fabricating the manufacturing test device shown in Figure 6. If operated, this reactor would have a nominal capacity of 1,000 liters/day or 6 barrels/day (bpd). The key scale-up steps are summarized in Table 2.

Table 2. Microchannel FT process scale-up

Type	Units	Size	Year	Hours
Catalyst Development	Catalyst only	N/A	1998-2003	1,200
Commercial Length Reactor	Reaction and oil cooling	24" long	2003	600
Integrated Pilot #1	With partial boiling for cooling	12"x 24"x 0.5"	2006	1,200
Integrated Pilot #2	With partial boiling	6"x 6"x 2"	2008	3,000
Commercial Fabrication	FT with boiler	10"x 7.5" x 7.5"	2007	mfg. test
Full-scale Fabrication	FT with boiler	24"x 24"x 6"	2008	mfg. test

Limited manufacturing scale-up is required beyond this stage, as the commercial scale reactor, with a capacity to produce 36 bpd of FT products will have microchannel shims that are the same size (24"x24", 0.61x0.61m) as the device shown in Figure 6, but a stack height of 24" (0.61m).



Figure 6. Commercial microchannel manufacturing techniques validated

Catalyst Integration. Placing catalyst in packed bed reactors can be a challenge for any technology. Conventional FT reactors have as many as 29,000 small (1") diameter tubes 12m in length, which must be equally loaded and then unloaded after 2 to 5 years of operation.[6] These high aspect ratio (over 500:1 length to diameter) tubes are hung in very large, immobile reactors, but commercial integration techniques have been shown effective. Because microchannel technology has extremely small passages, many expect loading and unloading catalyst to be especially challenging, but this was found not to be the case.

Catalyst loading, regeneration and unloading for microchannel FT reactors have been successfully demonstrated. Multiple operating and non-operating reactors with commercial length microchannels (aspect ratio 385:1 length to hydraulic diameter) have been repeatedly loaded and unloaded. A mechanical loading method is employed using commercially available material handling techniques and equipment.

There are two types of catalyst deactivation in FT synthesis: 1) short-term deactivation caused by wax build-up and/or partial oxidation of the cobalt catalyst particles, and 2) longer term deactivation, which involves sintering, loss of pore structure and/or poisoning. The first is reversible; the second requires replacing the catalyst. For short-term deactivation, in situ hydrotreating was shown to be effective at restoring catalyst activity. Figure 7 displays reactor performance data at the same condition before and after regeneration.

Comparison with Competing FT Technologies

Due to improved volumetric and catalytic productivity, microchannel FT enables lower capital and operating costs compared to the following classes of conventional FT reactor systems: 1) tubular, fixed-bed, with a cobalt catalyst, and 2) slurry-bubble with cobalt or iron catalyst.

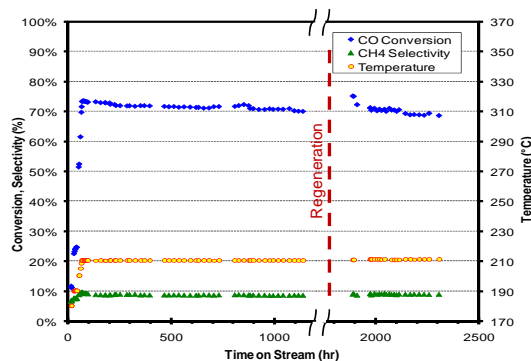


Figure 7. Microchannel FT in-situ regeneration shown effective at recovering performance

As noted above, 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.[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.[8]

Microchannel FT reactor technology has characteristics that provide substantial technoeconomic 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 ton of reactor mass (Figure 8). 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.

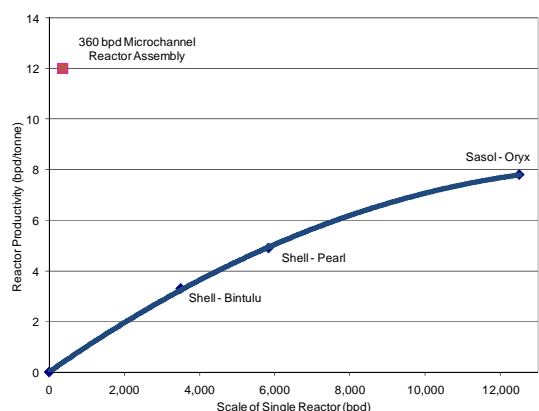


Figure 8. Microchannel FT improves reactor productivity and achieves economy of scale at far lower capacity

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 (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. The smaller economy of scale also permits feasibility for offshore GTL.

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 9).

Commercial Applications

Since conventional FT technologies are not economically viable at small scale, below 10,000 bpd, the current focus for FT planning and installation projects are coal-based facilities, in U.S. and China, or large land-based natural gas fields, such as those in Qatar.

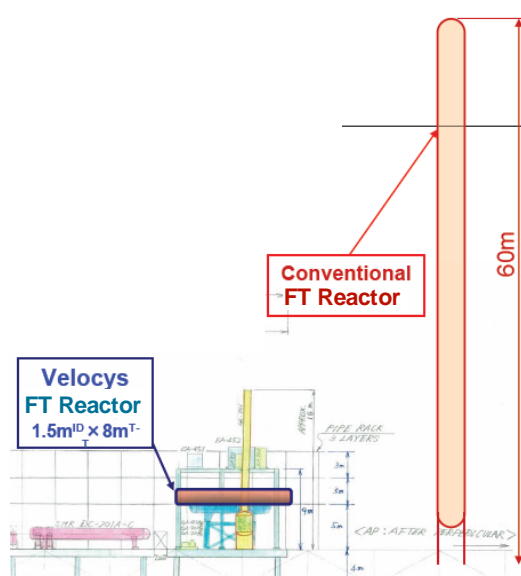


Figure 9. Small size and low profile eases installation and operation in offshore environments

Coal-to-Liquid Challenges. Several Coal-to-Liquid (CTL) projects are underway in China, but the prospects are different in the U.S. In late 2006 and early 2007, several coal-based fuel facilities were announced, ranging in size from 6,400 to 80,000 bpd, using 4,000 to 50,000 tons per day (tpd) of coal.[9] However, to date, none of the U.S. facilities have entered the construction phase and a number have been cancelled.

There are two primary hurdles for coal-to-liquid (CTL) facilities. First, the life cycle carbon (greenhouse gas) emissions for fuels from a CTL facility are 30% to 80% higher than petroleum-based fuels. This carbon footprint is clearly unacceptable to environmental groups and more importantly, key customers. The Energy Independence and Security Act of 2007 prevents federal agencies, including Department of Defense, from purchasing fuels with more greenhouse gas emissions than petroleum-derived fuels and thereby will require CTL operators to sequester the carbon dioxide (CO₂) emissions.[10] In some cases, operators will be able to capture the CO₂ and use that stream for enhanced oil recovery (EOR) projects. This approach is well proven but in many cases, EOR is not a viable option due to the location and/or size of the CTL project. Therefore, CTL promoters are evaluating the option of sequestering CO₂ in deep saline aquifers. While the Department of Energy (DOE) is funding a number of sequestration research and demonstration projects, this route has not been proven and is expected to be costly. In contrast, BTL facilities can reduce greenhouse gas (GHG) emissions by up to 90% when compared to petroleum-based fuels. For this reason, many domestic CTL developers are now planning to blend biomass to reduce carbon emissions.

Second, the proposed CTL projects have multi-billion dollar price tags and are based on processes that are not yet commercially proven in the U.S. Due to the size of these investments and the technical risk of sequestration, U.S. CTL developers have not been able to secure financing for their projects. Once the sequestration, financing and technical questions have been resolved, CTL projects will likely begin occurring at a substantial pace. However, some industry experts anticipate these questions might not be answered for a decade or more.

Biomass-to-Liquids. Biomass feedstock materials are not easily aggregated and transportation costs to large BTL plants are high. Microchannel FT can overcome these challenges by economically operating small (500-2,000 bpd) plants that require about 500-2,000 tpd of biomass. These synthesis gas generation plus FT synthesis facilities can then be located near low-cost, biomass sources. The heavy hydrocarbon products can then be economically shipped to central upgrading (refining) facilities since the FT product density is much higher than that of biomass.

The feedstock choices for FT are non-food biomass, such as forest residues, agricultural residue, municipal solid waste (MSW), and construction and demolition waste (CDW). Based on the DOE estimates and data on waste sent to landfills, the biomass supply is large enough to replace more than half of petroleum-based distillate fuel demand [11] as shown in Figure 10.

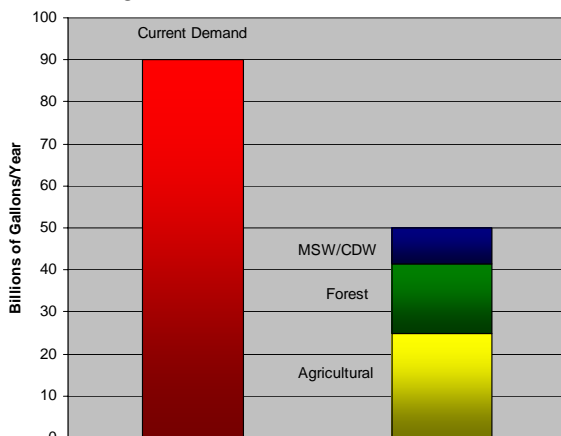


Figure 10. U.S. demand for distillate fuel versus biomass available for conversion to FT fuels

Offshore Gas to Liquids. Natural gas without access to the world market is known as “stranded gas.” This includes large reserves in remote places and associated gas that is co-produced with oil. The quantity of stranded gas is estimated to be between 900 and 9,000 trillion cubic feet in volume,[12,13] which is sufficient to supply current level of U.S. distillate fuels demand for more than 300 years.

As noted above, natural gas is either co-produced with petroleum or sits on top of petroleum reservoirs. With no local market for this gas, oil production is

not possible without venting, flaring or reinjection of this gas back into the reservoir. Venting is not allowed as the global warming potential of methane is 21 times that of CO₂. Flaring is also effectively banned in many countries due to GHG emissions and other issues. 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 liquid fuels in a FT process.

Unfortunately, GTL plants based on conventional FT technology require very large reserves. For example, 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 FT permits economic production at this smaller scale.[14]

Another advantage of microchannel FT technology is that it enables facilities to be placed on offshore structures. A conceptual sketch of such a plant is shown in Figure 11.



Figure 11. Microchannel FT concept floating production storage and offloading (FPSO)

Conclusion

Due to a number of factors, including sustained high oil prices, concern about global climate change, and the drive for energy security, alternative fuels are receiving an unprecedented level of attention. These include FT based synthetic fuel processes that can convert a wide variety of feedstock materials, such as coal, natural gas and biomass, into ultra-clean transportation fuels. Of the potential raw materials used for alternative fuels, biomass and stranded natural gas are seen as the most attractive due to their abundance and potential for low life cycle carbon emissions. Furthermore, the application of microchannel technology to FT enables cost effective production at the smaller-scales appropriate for BTL and offshore GTL facilities.

First generation biofuels, including corn ethanol and biodiesel, are prevalent today, but are seen as only an interim solution due to their use of food crops for raw material. Next generation biofuels, ones that use non-food biomass, are a more sustainable choice. Systems based on microchannel FT produce high quality, energy dense fuel from a wide variety of

resources, including waste wood, energy crops and municipal solid waste. Furthermore, they permit favorable economics for smaller-scale facilities, suitable for next generation biofuels.

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 FT improves volumetric productivity and efficiency, reducing capital cost and shrinking facility footprints, which is essential for offshore facilities.

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