Final Technical Report

Project Title:	Distributive Distillation Enabled by Microchannel Process Technology
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Executive Summary

The application of microchannel technology for distributive distillation was studied to achieve the Grand Challenge goals of 25% energy savings and 10% return on investment. In Task 1, a detailed study was conducted and two distillation systems were identified that would meet the Grand Challenge goals if the microchannel distillation technology was used. Material and heat balance calculations were performed to develop process flow sheet designs for the two distillation systems in Task 2. The process designs were focused on two methods of integrating the microchannel technology – 1) Integrating microchannel distillation to an existing conventional column, 2) Microchannel distillation for new plants. A design concept for a modular microchannel distillation unit was developed in Task 3. In Task 4, Ultrasonic Additive Machining (UAM) was evaluated as a manufacturing method for microchannel distillation units. However, it was found that a significant development work would be required to develop process parameters to use UAM for commercial distillation manufacturing. Two alternate manufacturing methods were explored. Both manufacturing approaches were experimentally tested to confirm their validity. The conceptual design of the microchannel distillation unit (Task 3) was combined with the manufacturing methods developed in Task 4 and flowsheet designs in Task 2 to estimate the cost of the microchannel distillation unit and this was compared to a conventional distillation column. The best results were for a methanol-water separation unit for the use in a biodiesel facility. For this application microchannel distillation was found to be more cost effective than conventional system and capable of meeting the DOE Grand Challenge performance requirements.

Acknowledgment:

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Introduction

This Grand Challenge grant funded program had the overall goal of ascertaining the industrial viability and benefits of microchannel distillation, an innovative approach to liquid-liquid separations. The assessment contained herein shows that microchannel distillation can achieve (or beat) the Grand Challenge goals of 25% energy savings and 10% return on investment (ROI).

Microchannel distillation is a type of distributive distillation, an approach that uses a number of small distillation units in new configurations to greatly enhance process efficiency. Although the efficiency benefits of distributed distillation have been known for some time, the switch from the conventional single tower paradigm requires the introduction of a novel process technology that breaks the “bigger is cheaper” mold. By greatly reducing the size and cost of unit operations, microchannel process technology holds the potential to enable efficient, cost effective distributive distillation at industrial scales. The modularity of microchannel units opens up the opportunity for a multitude of configurations, which can improve efficiency by 25% or more compared to conventional single tower operations, addressing Goal 1.4 of the DOE’s 2006 Strategic Plan - Energy Productivity: Cost-effectively improve the energy efficiency of the U. S. economy.

The “Distributive Distillation Enabled by Microchannel Process Technology” project was successful in showing the energy savings possible and by setting the cost targets for microchannel distillation hardware. Manufacturing methods were explored to show a viable way of making consistently the equipment at the established cost targets.

Background

This feasibility analysis enabled by the Grand Challenge grant was intended to lead to a go/no-go decision regarding the commercialization of microchannel distillation, an innovative separation technology. Listed below are specific objectives:

1. Identify a chemical separation best poised for initial commercialization of the microchannel distillation technology.
2. Develop designs for scale up of the existing, successful single channel microchannel distillation unit to a multichannel device as a step towards the development of a full scale microchannel distillation module.
3. Improve the current fabrication process to allow cost effective manufacturing of a commercial scale microchannel distillation unit.
4. Ascertain the economic viability of commercial microchannel distillation, considering options for maximizing the economic and environmental benefits of industrial implementation.
5. Verify that microchannel distillation is a transformational industrial technology capable of reducing the energy intensity by 25% while providing a return on investment of 10% or greater.

Project Tasks

Overview

The project was divided into five tasks.

Task 1: Problem Definition

Task 1 included a systematic study to evaluate the advantages offered by the microchannel technology for different distillation systems and identify few distillation systems that have significant commercialization potential for further detailed study. Such distillation systems with significant commercial potential would be able to provide an energy savings of 25% or more and a return on investment (ROI) of 10% or more.

The study was conducted with Mid-Atlantic Technology, Research and Innovation Center (MATRIC) to evaluate energy and cost benefits of microchannel technology over conventional distillation systems. The main advantages of the microchannel technology over conventional distillation technology were demonstrated in a previous DOE Project (DE-FC36-04GO14271) and the results were utilized for cost and energy benefits that included:

1. Higher mass transfer rates resulting in shorter Height Equivalent of the Theoretical Plate (HETP).
2. Potential for lower overall pressure drop

MATRIC utilized state of the art simulation software (ChemCAD) to perform multiple simulations from varying processes under a broad range of operating circumstances and relative volatilities of binary systems.

Butane – Pentane Separation

MATRIC evaluated a vapor recompression system for a Butane-Pentane separation ($1.3<\alpha<2$) as a potential candidate for energy reduction with the use of the microchannel distillation. A typical vapor recompression system is shown in Figure 1.

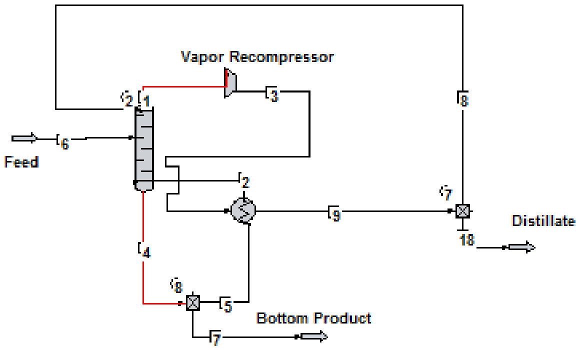
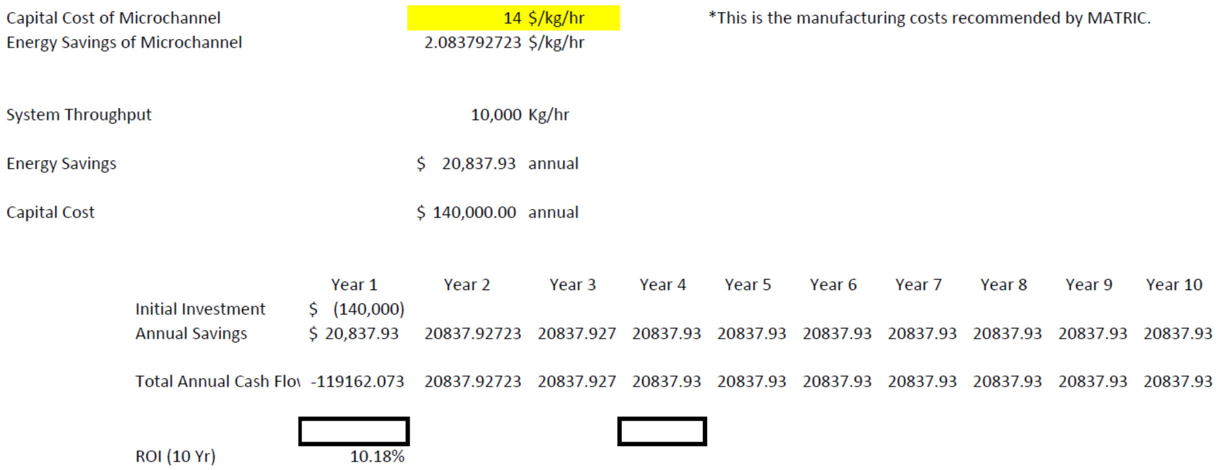


Figure 1: Typical vapor recompression system

A microchannel distillation with 50% reduction in the pressure drop over conventional recompression system and 10 times reduction in the HETP would provide an energy reduction of 38%.

The ROI estimation would require the cost of the microchannel distillation as well as feed flow rate. However, the cost of the microchannel distillation is determined by the method of manufacturing used. Task 4 is focused on the evaluation of manufacturing methods for commercial distillation columns. Therefore, the target ROI of 10% was used to estimate the installed cost of the microchannel distillation per unit feed flow rate. This estimated installed cost could later be used in the evaluation of the manufacturing method.

Assuming, total feed flow rate through the microchannel of 10,000 kg/hr, the estimated installed cost of the microchannel distillation system was estimated to be $14/(kg/hr). Figure 2 provides the details of the ROI estimations over 10 year of period.



Capital Cost of Microchannel	14	$/kg/hr	*This is the manufacturing costs recommended by MATRIC.
Energy Savings of Microchannel	2.083792723	$/kg/hr	
System Throughput	10,000	Kg/hr	
Energy Savings	$ 20,837.93	annual	
Capital Cost	$ 140,000.00	annual	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Initial Investment	$ (140,000)									
Annual Savings	$ 20,837.93	20837.92723	20837.927	20837.93	20837.93	20837.93	20837.93	20837.93	20837.93	20837.93
Total Annual Cash Flo\	-119162.073	20837.92723	20837.927	20837.93	20837.93	20837.93	20837.93	20837.93	20837.93	20837.93
ROI (10 Yr)	10.18%									

Figure 2: ROI calculations for microchannel butane-pentane system

Propylene – Propane Separation

Another distillation system identified by MATRIC where microchannel technology offers energy saving advantages was propylene-propane system. The propylene-propane separation column operates at close temperature range throughout the column and α between 1.0 and 1.5. A microchannel distillation column with reduced pressure drop in column provides proportional reduction in the mechanical horse power of the compressor. Figure 3 shows the schematic of propylene-propane distillation system.

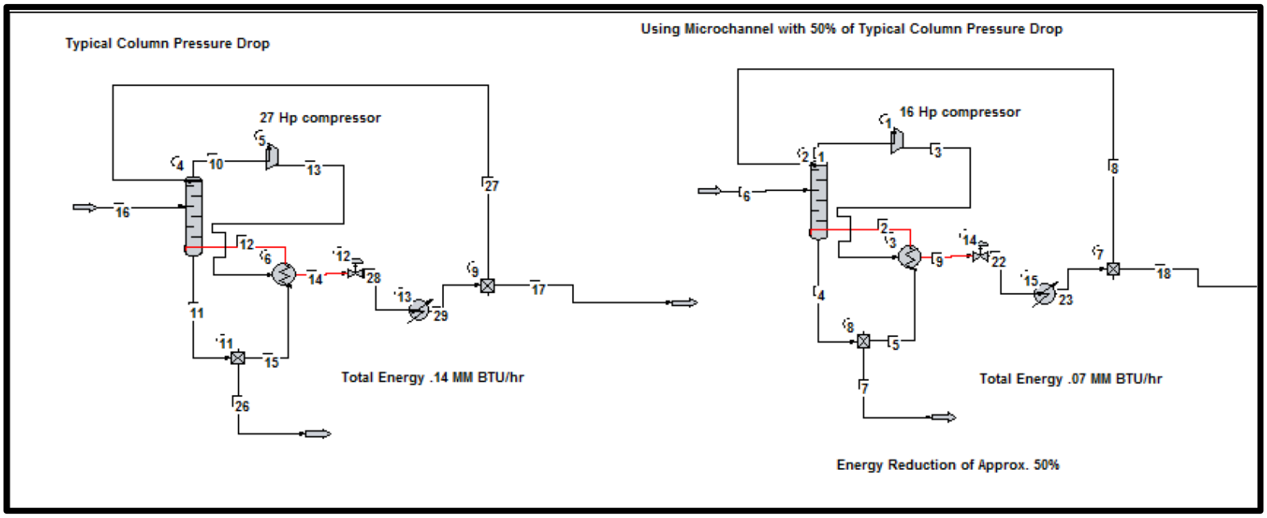
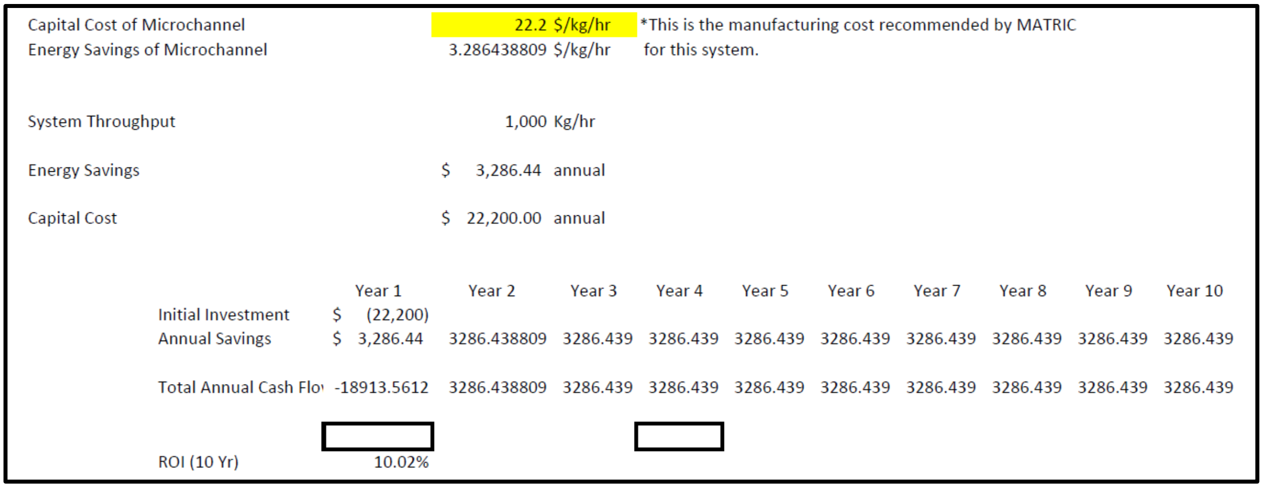


Figure 3: Schematic of propylene-propane system

With estimated pressure drop reduction of ~50% by using microchannel technology, the estimated energy saving is about 50%. Similar butane-pentane system, the ROI target of 10% was used to estimate the installed cost of the microchannel distillation column per unit feed flow rate.

Assuming, total feed flow rate through the microchannel of 10,000 kg/hr, the estimated installed cost of the microchannel distillation system was estimated to be $22.2/(kg/hr). Figure 4 provides the details of the ROI estimations over 10 year of period.



Capital Cost of Microchannel	22.2 $/kg/hr	*This is the manufacturing cost recommended by MATRIC
Energy Savings of Microchannel	3.286438809 $/kg/hr	for this system.
System Throughput	1,000 Kg/hr	
Energy Savings	$ 3,286.44 annual	
Capital Cost	$ 22,200.00 annual	

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Initial Investment	$ (22,200)									
Annual Savings	$ 3,286.44	3286.438809	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439
Total Annual Cash Flo	-18913.5612	3286.438809	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439	3286.439
ROI (10 Yr)	10.02%									

Figure 4: ROI calculations for microchannel propylene-propane system

Other Distillation Systems

The potential of integrating microchannel units with existing distillation systems was also explored. The intent of this approach was to deliver microchannel units to existing plants to incrementally increase the capacity or product purity. Typically for a conventional distillation column, an increase in capacity or purity would require redesign of the column but the modular nature of the microchannel technology can enable incremental increase in capacity or product purity. Methanol-water system was evaluated for energy savings and ROI benefits. The energy savings were projected to be in the range of 20%-25%, the ROI exceeded 10% over a period of 10 years. This is an example of potential candidate that may not meet the DOE requirements completely but is attractive from a business perspective for early stage commercialization.

Task 2: Process Flow Sheet Design

In Task 1 distillation systems were identified that showed the promise of microchannel technology in achieving DOE Grand Challenge (25% energy saving and 10% Return-on-investment). The energy savings as well as ROI can be achieved by applying microchannel technology to distillation systems by two methods:

Integrating microchannel distillation with an existing conventional column

The modular nature of Microchannel technology makes it suitable for integration with existing distillation columns. An existing conventional distillation column may require higher purity product due to change in market requirements. Instead of re-designing a new conventional column, single or multiple microchannel distillation modules can be added between the column and the condenser of the conventional column as shown in Figure 5. The vapor leaving the conventional column will become feed for the microchannel distillation column and the microchannel distillation column bottom product is used to provide reflux back into the column. The higher efficiency and smaller volume (only few stages required to achieve desired purity) of the microchannel distillation column will make it attractive for such applications. Such applications are envisioned as a potential first market for commercializing microchannel distillation technology.

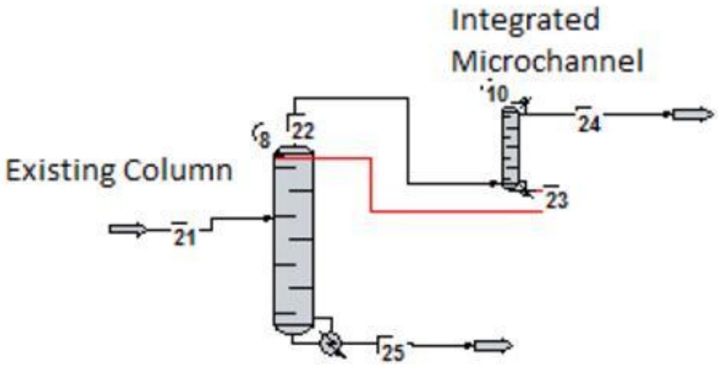


Figure 5: Integration of microchannel distillation with existing conventional column

Microchannel distillation for existing and new distillation plants

Another approach for using the microchannel distillation technology is as original equipment in new facilities and potentially even as a replacement for existing conventional distillation columns. Depending upon the capacity, the microchannel distillation column may consist of multiple microchannel modules. A schematic of a microchannel module and assembly of modules in a microchannel distillation column is shown in Figure 6. This type of application would enable a more efficient process but could result in a slower commercialization compared to integration with existing columns.

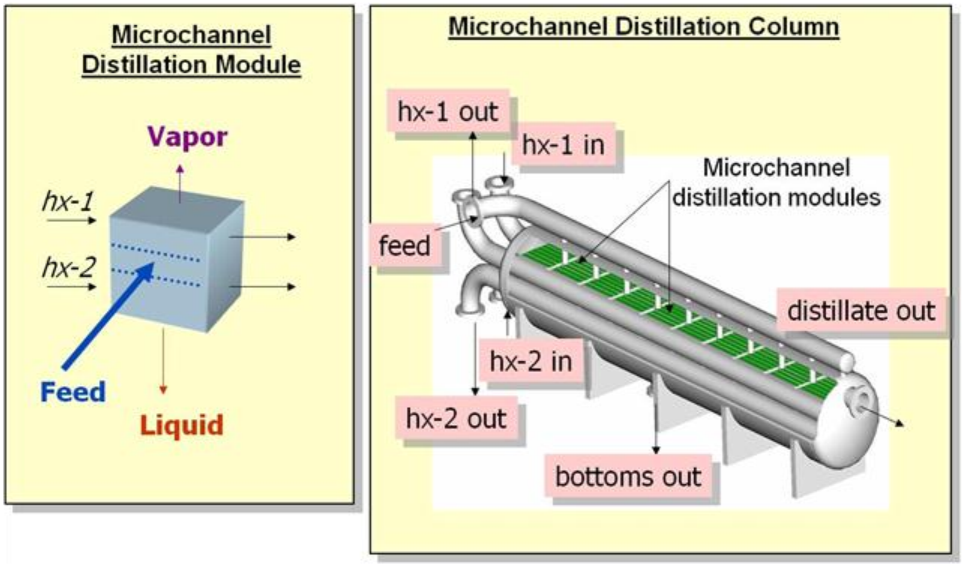


Figure 6: Microchannel distillation modules and column

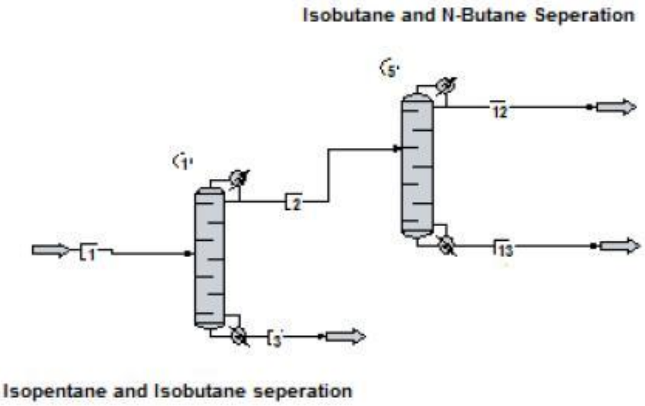
Our current focus is developing process flow sheet for method #1, integrating microchannel distillation to the existing conventional column.

Two distillation systems were chosen for detailed flow sheet design. For both systems, a commercial application was selected to compare the energy savings and return on investment with microchannel technology. Please note that the distillation system considered for detailed process flow sheet were slightly different from the distillation systems identified in Task 1. The main reason for the change was commercialization potential.

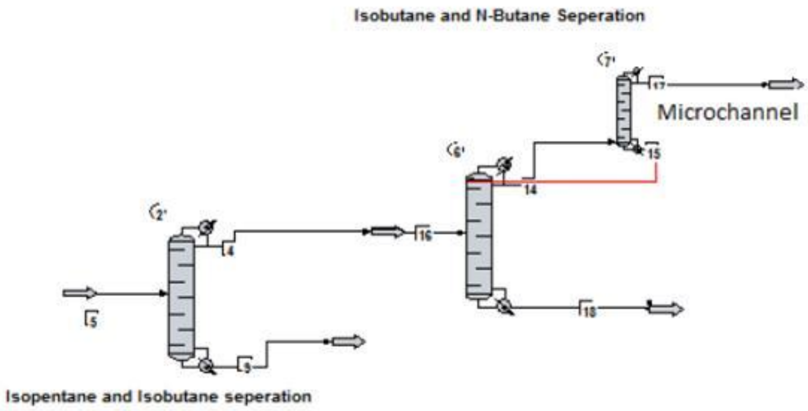
N-butanes and iso-butane separation

A vast reserve of shale gas (known as Marcellus gas) has been discovered in the area of West Virginia, Pennsylvania and neighboring states. The new discovery of the reserve will open up opportunities to increase the gas processing capacity of existing plants as well as setting up new gas plants to separate and purify valuable natural gas liquids (NGL) . Such an opportunity was explored for n-butane and iso-butanes separation using microchannel distillation technology. A schematic of conventional distillation process and integrated microchannel distillation process is shown in Figure 7.

ChemCAD, a process engineering software by Chemstations Inc, was used to simulate the n-butane and iso-butane separation. The conventional column had 74 trays. To evaluate the energy savings by integrating microchannel distillation, the feed flow rate and the product flow rates were matched between the two approaches. The condenser and re-boiler duties were compared to determine the energy savings after integrating microchannel distillation. The comparison of reflux ratio, condenser duty and the re-boiler duty between the two approaches is shown in Table 1: Comparison of energy savings with integrated microchannel distillation for n-butane/iso-butane.



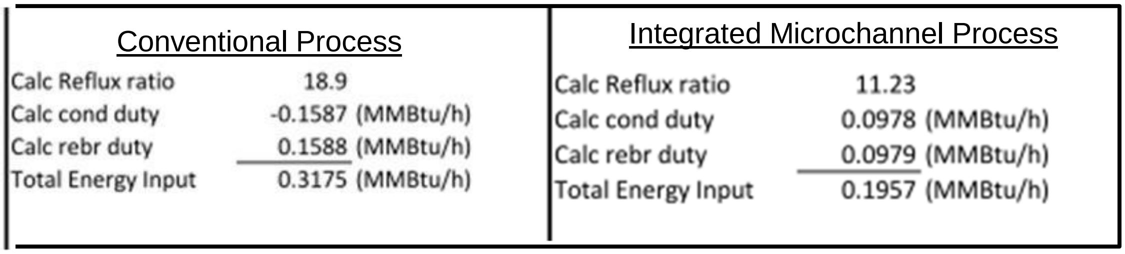
a) Conventional Separation Process Diagram



b) Integrated Microchannel Separation Process Diagram

Figure 7: Schematic of n-butane/iso-butane separation process (Conventional vs integrated microchannel)

Table 1: Comparison of energy savings with integrated microchannel distillation for n-butane/iso-butane



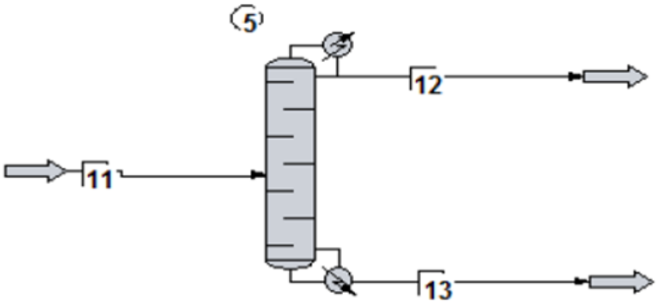
Conventional Process		Integrated Microchannel Process	
Calc Reflux ratio	18.9	Calc Reflux ratio	11.23
Calc cond duty	-0.1587 (MMBtu/h)	Calc cond duty	0.0978 (MMBtu/h)
Calc rebr duty	0.1588 (MMBtu/h)	Calc rebr duty	0.0979 (MMBtu/h)
Total Energy Input	0.3175 (MMBtu/h)	Total Energy Input	0.1957 (MMBtu/h)

Estimated Energy Savings ~47%

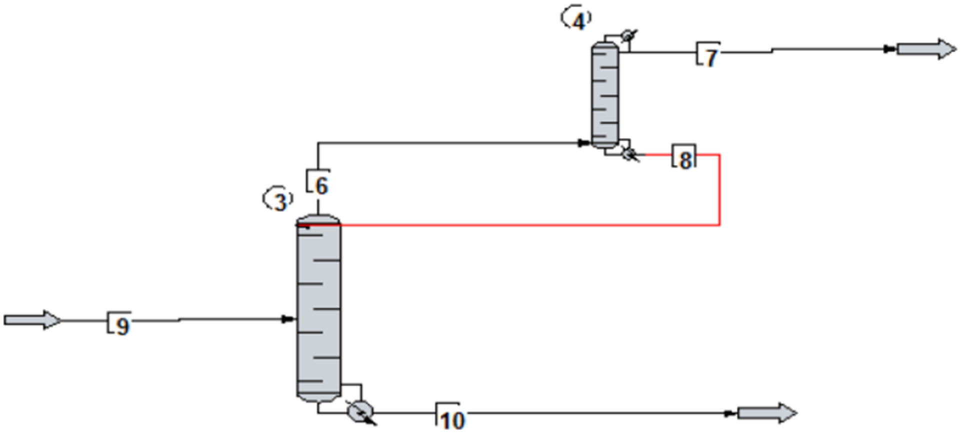
Energy savings result from improved separation by the micro-channel distillation section with reductions in the reflux ratio and corresponding reduction in condenser heat duty. The reduction in reflux also results in reducing the reboiler heat duty to maintain the thermal profile and product composition and quality.

Methanol-water separation

A conventional bio-diesel facility (10 million gal/yr) was chosen to evaluate the advantages of integrated microchannel distillation for methanol-water separation. A schematic of conventional distillation process and integrated microchannel distillation process is shown in Figure 8. Again, ChemCAD was used for the modeling the conventional as well as integrated microchannel process.



c) Conventional Separation Process Diagram



d) Integrated Microchannel Separation Process Diagram

Figure 8: Schematic of methanol-water separation process (Conventional Vs integrated microchannel)

Flexipac® structured packing by Koch-Glitsch[1] was used in the conventional system. The conventional distillation column had 20 separation stages. A comparison of the estimated energy saving with integrated microchannel distillation is shown in Table 2.

Table 2: Comparison of energy savings with integrated microchannel distillation for methanol-water

Conventional Process			Integrated Microchannel Process		
Calc Reflux ratio	2.6388		Calc Reflux ratio	1.4514	
Calc cond duty	-2.9534	(MMBtu/h)	Calc cond duty	-1.9875	(MMBtu/h)
Calc rebr duty	3.0977	(MMBtu/h)	Calc rebr duty	2.1319	(MMBtu/h)
Total Energy Input	6.0511	(MMBtu/h)	Total Energy Input	4.1194	(MMBtu/h)

Estimated Energy Savings ~38%

Task 3: Microchannel Device Design

Velocys has successfully demonstrated microchannel technology for distillation using a single microchannel device on a previous DOE project (DE-FC36-04GO14271). A picture of the single channel microchannel distillation device is shown in Figure 9. The working fluids for the device were n-pentane and cyclopentane. The HETP achieved was ~1'', significantly smaller than the HETP in a conventional distillation column.

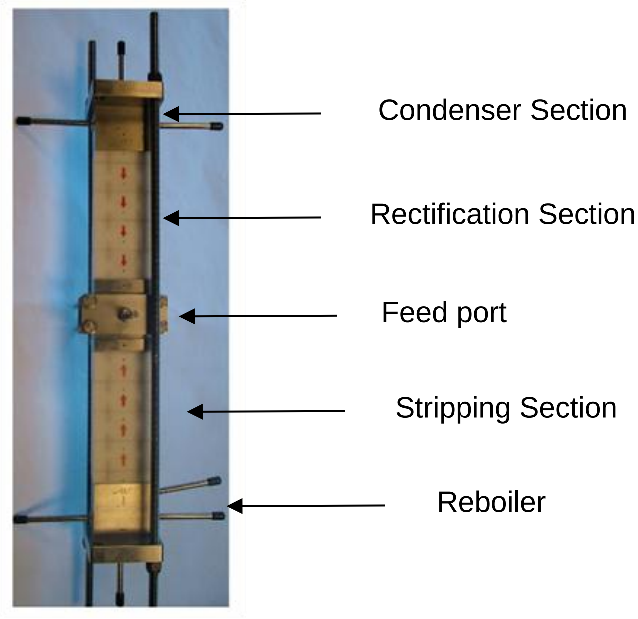


Figure 9: Photograph of a single microchannel distillation device demonstrated on DOE program DE-FC36-04GO14271

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[1] More details can be found at http://www.koch-glitsch.com/masstransfer/pages/FLEXIPAC.aspx

The principle of scaling up in the microchannel technology is to repeat the single channel multiple times. Velocys has demonstrated the same principle for a microchannel Fischer-Tropsch (FT) reactor, which has been scaled up from a single channel, laboratory scale device to a commercial reactor with a capacity of 25 bbl/day (see Figure 10). The commercial microchannel FT reactor has thousands of parallel microchannels working together to produce commercially significant quantities in equipment more than an order of magnitude smaller than conventional FT reactors.

Figure 10: Velocys commercial Fischer-Tropsch Reactor

The focus of Task 3 was to develop a concept to scale up the microchannel distillation device. The key components of the scale up device are:

1. Microchannel Core
    a. Process microchannels (or distillation microchannels)
    b. Feed distribution system
    c. Optional coolant channels
2. Condenser section
3. Re-boiler section

Microchannel Core
Figure 11 shows a schematic of the repeating unit of the microchannel core. The repeating unit consists of a single layer of process channels, feed distribution system and the coolant channels. This unit is repeated to scale up the distillation unit capacity.

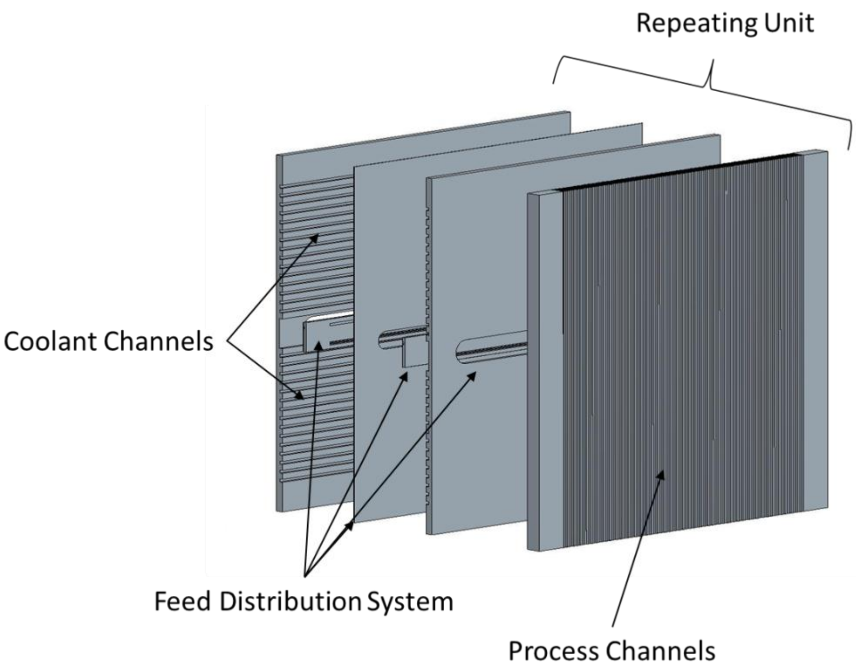


Figure 11: Schematic of the microchannel repeating unit

A layer of process microchannels contains 500 parallel channels or more. The liquid and vapor interaction for separation occurs in these tiny microchannels. The process microchannels are vertical in orientation to aid liquid and vapor flow by gravity.

The feed distribution system distributes the feed uniformly to every process microchannel. The feed distribution system incorporates the flow distribution features that were developed on a previous DOE project (DE-FC36-04GO14271).

Coolant channels are located in cross-flow orientation with respect to the process channels. The coolant channels are optional and can be used to tailor the temperature profile of the process channels in addition to the condenser and the reboiler.

Figure 12 shows a schematic of the scale up microchannel core formed by repeating units.

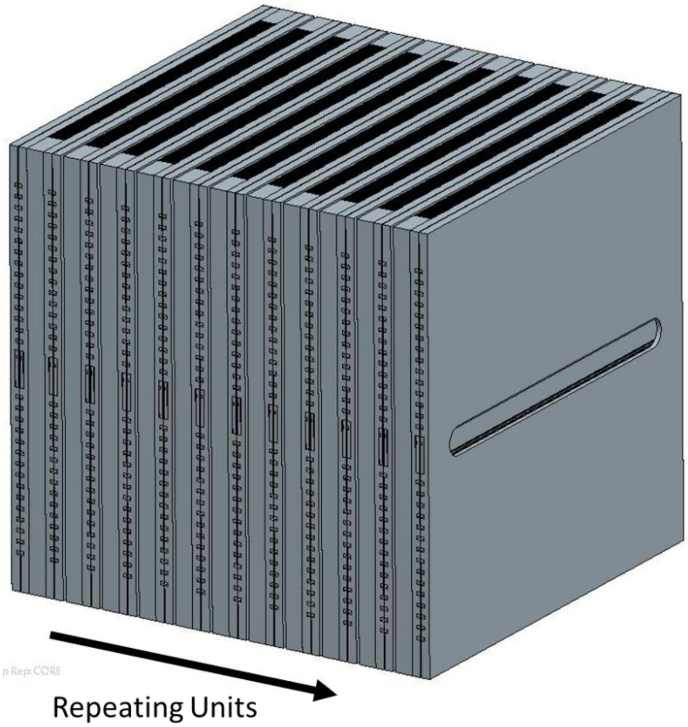


Figure 12: Schematic of scale up microchannel core

Condenser and Reboiler

The condenser and reboiler design are shown in Figure 13. The heavy component in the vapor phase exiting the top of the microchannel core is condensed in the condenser section and circulated back. A liquid pool is maintained in the reboiler section where the heat from the heating medium recycles the lighter component. The distillate is taken out from the condenser while the residue is removed from the reboiler section.

Scale up of integrated microchannel distillation device

Figure 13 shows the schematic of a single integrated microchannel device. Microchannel core is the heart of the distillation device made by repeating units. The number of repeating units as well as the overall dimensions of microchannel core depends upon the application, and capacity requirements, as well as the manufacturing method used. The modular nature of the microchannel technology enables integrating multiple microchannel distillation devices in parallel for capacity beyond what is possible in a single device. The dimensions of a single microchannel device are typically determined by the manufacturing method which can limit the size of components. Task 4 discusses the development of manufacturing method.

Figure 14 shows the assembly of microchannel distillation devices in parallel to provide commercially significant capacity. A plant could have multiple assemblies in parallel to achieve a target production rate. The production can be increased or decreased easily by adding or blocking assemblies in the plant.

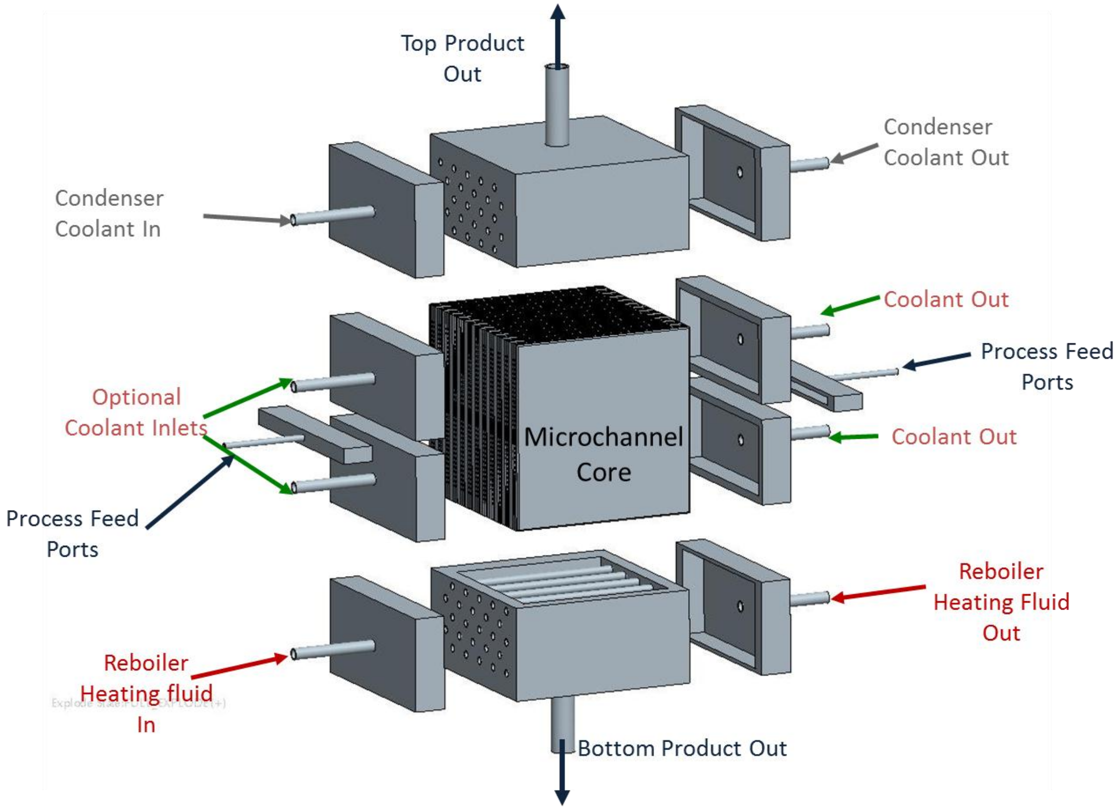


Figure 13: Schematic of scale up integrated microchannel distillation device

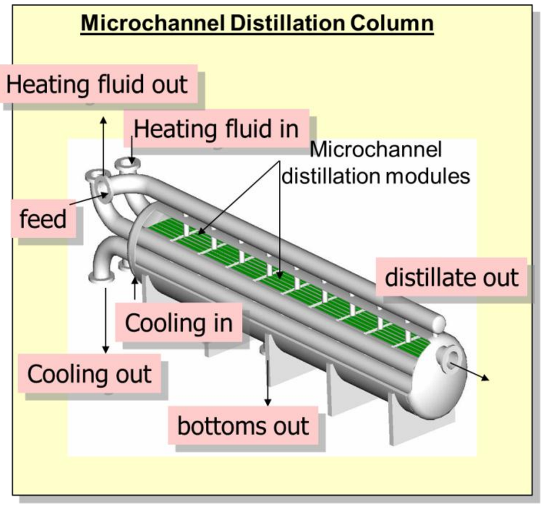


Figure 14: Schematic of microchannel distillation device assembly

Task 4: Manufacturing Development

The key focus of this task was to evaluate Ultrasonic Additive Manufacturing method and determine if it could be used for commercial manufacturing microchannel distillation units. The evaluation of Ultrasonic Additive Manufacturing method showed technical challenges which would be difficult to overcome and use it as a commercial manufacturing method. The scope of the task was then extended without requiring any additional budget to explore alternate methods for manufacturing microchannel distillation units.

Ultrasonic Additive Manufacturing (UAM)

Development of a low cost and a high precision manufacturing method is an essential requirement for the commercialization of the microchannel technology. As a part of this task, Ultrasonic Additive Manufacturing (UAM) technique was evaluated for manufacturing of the microchannels at commercial scale. UAM is a method in which thin strips of metal are bonded together using high frequency vibration to form a structure. Figure 15 shows a schematic of the UAM welding system. Typically this method is proven for softer material such as copper, however typical material of construction for distillation units is stainless steel. The key objective of the evaluation of UAM method is to determine its feasibility of using stainless steel.

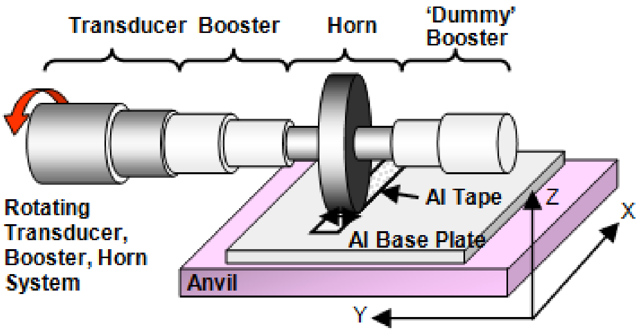


Figure 15: Schematic of UAM Welding (Graff, 2011)

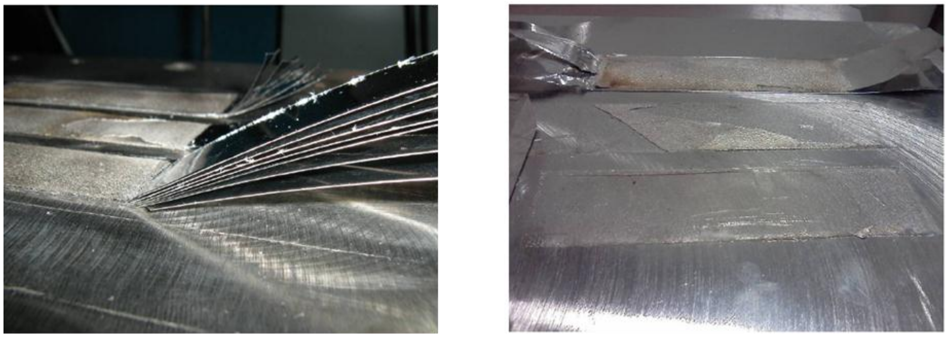
Edison Welding Institute, a pioneer institution in welding research and development, was partnered for the evaluation of the UAM method. Figure 16 shows a picture of the UAM machine at EWI.

Figure 16: Picture of UAM machine at EWI

EWI ran multiple trials to evaluate the ultrasonic parameters to join multiple stainless steel foils. Several outstanding challenges were identified with utilizing UAM to join stainless steel and it was determined that a longer than anticipated development time would be required before the process would be suitable for creating the types of parts required under the current program. The key challenges were found to be:

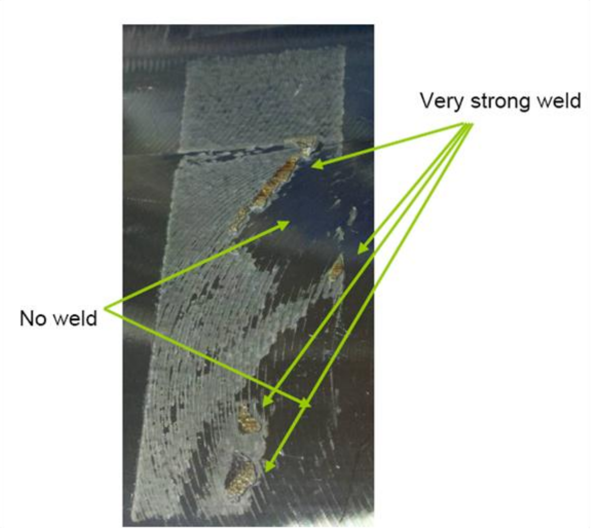
1. Excessive transfer of the stainless steel material to the ultrasonic horn resulting in a very short tool life and varying quality in the bond
2. Bond quality is not sufficient for a pressurized vessel
3. Vibration of stainless steel foils resulted in cracking at the edges of the joints
4. Edge effects were determined to be more pronounced for stainless steel than for other materials
5. De-lamination of layers occurred in multi-layer build attempts

Figure 17 shows pictures of some of the challenges encountered during the UAM evaluation for stainless steel.



Several layers of stainless steel foils joined using UAM

Delamination occurred as number of layers increased



Peel tests showed inconsistent bond results

Figure 17: Challenges during UAM evaluation

Given the technical challenges for the development of UAM method for stainless steel material, alternate manufacturing techniques were evaluated to enable manufacturing of the commercial design developed in Task 3.

Laser Welding

Laser welding is a method of using a laser beam to join multiple metal pieces. The laser energy provides the heating source to fuse the metal together. Laser welding is frequently used in high volume application including parts manufacturing in the automotive industry.

Figure 18 shows an illustration of the application of the laser welding to manufacture microchannels commercially. The microchannels are created in a bottom plate. The method of making microchannels includes high speed machining, partial chemical etching, and electro-chemical etching. The top plate and the bottom plates are joined by laser welding to create microchannels.

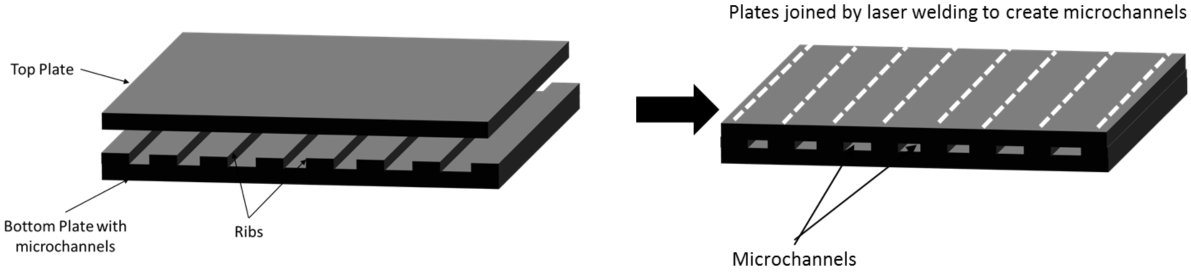


Figure 18: Illustration of manufacturing microchannels using laser welding

We worked with Edison Welding Institute (EWI) to demonstrate the feasibility of using laser welding method to manufacture microchannels. EWI has prior experience in laser welding small stainless pieces. However, when large pieces (larger than 6'' X 6'') were joined together, the heat generated along the weld induces stress to deform the welded assembly significantly, rendering it not suitable for assembly. Therefore the focus of development of the laser welding during the project was on developing a fixturing technique that would minimize the deformation in the welded part with little emphasis on optimizing laser parameters. Figure 19 shows a picture of a deformed laser welded assembly. The parts were held-down at two locations and the deformation due to the stresses induced during laser welding is shown in the figure.

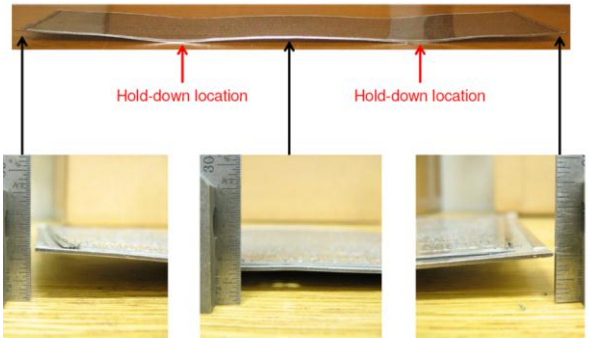


Figure 19: Deformation in laser welded assembly with current fixturing

The method of fixturing the plates for laser welding was modified and a significant reduction in the deformation of the welded assembly was achieved as shown in Figure 20.

Figure 20: Laser welded assembly with minimal deformation produced by improved manufacturing

The successful demonstration of fixture design method shows the promise of laser welding approach as a viable manufacturing method for making parts for the microchannel distillation device

Manufacturing parallel microchannels using folded fins

Another method of making parallel microchannels is forming a folded fin structure. Figure 21 illustrates an example of the folded fin structure.

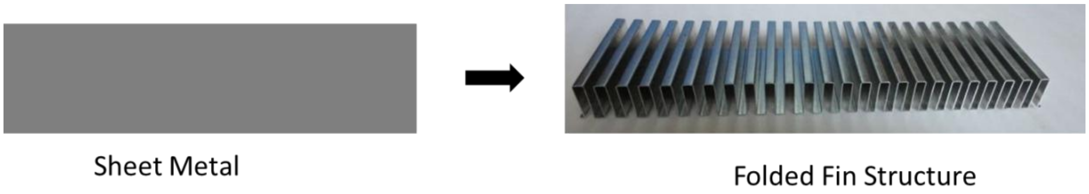


Figure 21: Illustration of folded fin structure making parallel microchannels

Multiple trials were carried out to evaluate the manufacturing method of making parallel microchannels using folded fins. Thin sheet metal, wire mesh and combination of two were used to explore the parameters such as fin height, fin length and number of fins per inch (fps). Table 3 summarizes the parameter range that was evaluated in the trials.

Table 3: Parameter space for evaluating folded fin manufacturing method

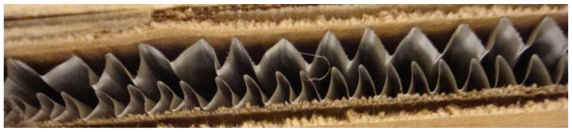
Parameter	Value/Range
Folded fin material	Copper, Stainless steel
Folded fin material type	Sheet metal, Wire mesh, Wire mesh on wire mesh, Wire mesh on sheet metal
Sheet metal thickness	0.001'' to 0.007''
Wire mesh type	80 mesh to 325 mesh
Fin height	0.125'' to 0.5''
Fins per inch	20, 30, 40
Fin length	12'' – 24''

Figure 22 illustrates examples of well-formed fin structures while Figure 23 illustrated badly formed fin structures.

120 mesh on 325 mesh, 20 FPI, 0.27'' Fin height, 18'' fin length

80 mesh on 0.006'' Cu sheet, 30 FPI, 0.27'' Fin height, 18'' fin length

Figure 22: Illustration of well-formed fin structures during the trials



120 mesh over 325 mesh, 30 FPI, 0.27'' Fin height, 18'' fin length

100 wire mesh, 30 FPI, 0.1'' Fin height, 18'' fin length

Figure 23: Illustration of poorly formed fin structure during the trials

The key conclusion was that a fin structure that was formed by sheet metal only or by sheet metal between wire mesh had better mechanical firmness than compared to mesh on mesh fin structure. The fin height affected the overall shaped of the fin. The smaller fin height resulted in repeated structure. Smaller fin length and higher fpi typically resulted in well-formed fin structure.

In summary, the evaluation of UAM method did not show manufacturing promise and required long term development. Alternate manufacturing methods (laser welding and formed fins) were evaluated and found to be reasonably applicable to the manufacturing of the conceptual design proposed in Task 3.

Task 5: Economic Analysis

Cost of Conventional distillation column

With support of MATRIC, quotations were received for the conventional distillation columns for the two potential separation systems identified in Task 2 – iso-butane/n-butane distillation column and methanol-water distillation column. Table 4 summarizes the quotation received for iso-butane/n-butane separation and Table 5 summarizes the quotation received for methanol/water system.

Table 4: Quotation summary of commercial iso-butane/n-butane separation column

Operating Parameter	Operating Condition
Quotation Vendor	Koch Modular Process Systems
Total feed flow rate	88882 lb/hr
Feed composition	60% iso-butane, 40% n-butane
Feed inlet temperature	41°C
Desired iso-butane purity	98%
Quoted installed price	$2,300,000 - $2,875,000

Table 5: Quotation summary of commercial methanol/water separation column

Operating Parameter	Operating Condition
Quotation Vendor	Koch Modular Process Systems
Total feed flow rate	3112 lb/hr
Feed composition	68% methanol, 32% water
Feed inlet temperature	92°C
Desired iso-butane purity	99.95%
Quoted installed price	$862,500 - $1,150,000

Target cost to meet ROI requirements

The target return on investment for the microchannel distillation technology is 10%. For the two potential applications identified for the microchannel technology, a target installation cost per unit flow rate was estimated that would achieve the ROI of 10%. The target installed cost for the microchannel distillation unit per unit flow rate for iso-butane/n-butane separation and methanol-water separation to meet return on investment of 10% is summarized in Table 6.

Table 6: Target installed cost for the microchannel distillation units to meet ROI requirements

Application	Target microchannel distillation cost to meet 10% ROI
iso-butane/n-butane separation	$119 / kg/hr
Methanol/water separation	$415 / kg/hr

Combining the information on the target installed cost for the microchannel based separation technology in Table 6 and the cost of conventional separation column in Table 4 and Table 5, Table 7 compares the cost of the conventional distillation column to the target cost of the microchannel distillation unit for iso-butane/n-butane and methanol/water systems. As we can see from the comparison, the target cost of the microchannel distillation unit for iso-butane/n-butane that would meet the ROI requirements could still be higher than the cost of the conventional distillation column.

Table 7: Comparison of cost of conventional distillation column to target microchannel distillation unit to meet ROI requirements

Application	Conventional Distillation Column cost	Target microchannel distillation cost to meet 10% ROI
iso-butane/n-butane separation	$2,300,000 - $2,875,000	~ $4,800,000
Methanol/water separation	$862,500 - $1,150,000	~$600,000

For the scale-up microchannel distillation concept developed in Task 3 and the manufacturing developments discussed in Tasks 4, the size of the core was estimated for methanol-water separation. The sizing calculation for the microchannel distillation core is summarized in Table 8.

Table 8: Sizing microchannel distillation core for methanol/water separation

Parameter	Value
Feed flow per process microchannel	0.68[2] g/min
Total number of microchannels required for the capacity	86675
Total number of process channels per repeating unit	426
Total number of repeating units	204
Overall size of the core	~2' X 2' X 3.5'
Total number of cores required	2
Estimated cost of cores manufacturing	$375,000
Estimated installed cost of microchannel distillation	$562,500[3]

Comparing the cost of conventional distillation column as well as target cost to meet 10% ROI requirements in Table 7 to the estimated cost of microchannel distillation in Table 8, microchannel distillation is expected to be cost competitive while providing energy savings required by DOE Grand challenge

Accomplishments

The key accomplishments of the project are:

1. Multiple distillation systems were evaluated using ChemCAD simulations. Two distillation systems were identified that could achieve the goals of DOE Grand Challenge (25% improved efficiency and 10% ROI) by applying microchannel distillation technology.
2. Detailed process flow sheets were developed to utilize the modular nature of the microchannel distillation and integrate the microchannel distillation units to an existing conventional column. The integration of the microchannel technology to the conventional technology showed 47% energy saving for butane/iso-butane separation and 38% energy saving for methanol-water separation in a bio-diesel facility.
3. A design concept to scale up microchannel distillation unit was developed. The microchannel distillation unit consisted of multiple repeating units stacked together to form core of the distillation unit. The core is then connected to condenser and reboiler sections to form a microchannel distillation unit. A concept to connect multiple microchannel distillation units in parallel to deliver commercially significant production rate was also shown.
4. Multiple manufacturing methods were evaluated for viability of manufacturing microchannel distillation units. It was shown that the available manufacturing methods such as laser welding, machining could be used for manufacturing microchannel distillation units. Ultrasonic additive manufacturing (UAM) was also explored but found to be inadequate due to lack of mechanical strength in the joined material.

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[2] Based on the experimental results achieved on previous DOE program DE-FC36-04GO14271

[3] Assumes 1.5 factor of installation

5. An economic analysis was conducted to compare the cost of conventional distillation columns to microchannel distillation. It was shown that for the conceptual microchannel distillation design and commercial manufacturing methods, microchannel technology provides a cost advantage for the methanol-water separation application in a bio-diesel plant. However, further cost reduction for the manufacturing of the microchannel distillation unit would be required to achieve cost advantages for the butane/iso-butane separation application.

Conclusions

The key conclusions from the study are:

1. Microchannel technology shows the potential to provide both energy saving and cost benefits for select distillation applications.
2. Velocys has experience in scaling up microchannel technology for commercial application and has developed design concepts and evaluated potential manufacturing methods for commercial distillation units.
3. Total projected energy saving by incorporating microchannel distillation to methanol-water separation processing ~900 kg/hr feed in a bio-diesel plant is ~38%. At 10% ROI, the energy savings translates to about $136,000 in saving per annum.

Recommendations

Current study has shown that microchannel technology can provide 25% or greater energy savings at attractive ROI (10% or higher) for distillation application. The study developed conceptual design for microchannel distillation unit and identified manufacturing methods to build the these units. The next steps for the commercialization of the microchannel distillation are proposed as follows:

1. Design, manufacture and test a lab scale microchannel distillation unit
    a. Validate performance assumptions used for cost analysis
    b. Expected feed flow rate ~5 - 50 g/min
    c. Estimated cost of the program ~$1 - 1.5MM over 2-3 years
2. Design, manufacture and test a pilot scale microchannel distillation unit
    a. Validate manufacturing method and scale-up design strategy
    b. Expected feed flow rate ~1 – 10 kg/min
    c. Estimated cost of the program ~$3 – 5MM over 3-4 years
    d. The program will require a partner for the demonstration of the pilot scale microchannel distillation unit.

Bibliography

Graff, K. F. (2011). *"Ultrasonic Additive Manufacturing," ASM Handbook, Vol.6A, Welding Fundamentals and Processes.*