A Microvascular System for Chemical Reactions Using Surface Waste Heat**

*Du Thai Nguyen and Aaron P. Esser-Kahn*

ange_201306928_sm_m Lancaster Information.pdf
Supporting Information

1. Supporting Materials and Methods
   1.1. Fabrication
      1.1.1. Stripping Mug
      1.1.2. Rough Surface
      1.1.3. Stripping Unit
      1.1.4. Serpentine Microchannel
   1.2. Characterization

2. Supporting Analysis
   2.1. CO₂ MEA Reaction Mechanism
   2.2. CO₂ Release Calculation
   2.3. COMSOL Model
   2.4. High Speed Optical Analysis
   2.5. Surface Area Use Estimation

3. Supporting Figures S1-S8
4. Supporting Table S1
5. Supporting Movie S1
6. Supporting References

1. Supporting Materials and Methods:

1.1 Fabrication

1.1.1 Stripping Mug Fabrication
To form the stripping mug, the Vaporization of a Sacrificial Component (VaSC) fabrication technique was employed.[1] Poly(lactic) acid (PLA) fibers (Teijin Monofilament, Germany) were treated with tin (II) oxalate (98%, Sigma-Aldrich, USA) in order to lower the depolymerization temperature of the fiber.[2] Polydimethylsiloxane (PDMS, Sylgard 184 Silicone Elastomer, Dow Corning, USA) was prepared by mixing the base with the curing agent (10:1, wt:wt). A layer of PDMS was then poured over the surface of a coffee mug and left on aluminum foil. After 5 minutes, the mug and foil were flipped upside down as the PDMS on the mug cured at 85 °C for 30 minutes. This flipping method allowed for a more even coating of PDMS on the surface. A 300 µm PLA fiber was wrapped around the mug five times, with both ends tied to the handle of the mug. Each wrap was spaced 11 mm from the previous wrap. A second coating was poured on the mug using same method. One last coating was performed with the mug starting upside down to create a uniform layer of PDMS over the fiber. The mug was heated at 212 °C under vacuum for 3 days to remove the PLA, leaving behind a hollow microchannel (Figure S1).

1.1.2 Rough Surface Microchannel Fabrication
A 9 cm long steel gear rack (20 pitch, 1/2" face width, and 1/2" height, McMaster-Carr) was used as the rough surface. To form microchannels conforming to the rough surface, a layer of PDMS was poured over the surface of the gear rack and cured at 85 °C for 30 minutes (Figure S2). After curing, a 200 µm PLA fiber was placed over the surface. A second coating was then poured over the surface and fiber. Another gear rack was used as a complementary surface to press the fiber into the teeth of the gear rack so that it would conform to the surface. The PDMS was left to cure overnight at room temperature. The second gear rack was removed and a final coating was performed to create a uniform layer of PDMS over the fiber. The gear rack was heated to 212 °C under vacuum for 3 days to evacuate the PLA.

1.1.3 Stripping Unit Fabrication
PLA fibers with the desired diameters were placed in a rectangular 3 in. long mold box. PDMS was prepared and then poured into the mold box until a height of 5 mm was reached. The box was then placed in an oven at 85 °C for 30 min to cure the PDMS. The unit was removed from the mold box and a layer of PDMS was cured on the bottom of the sample to obtain a uniform thickness of 0.6 mm for each sample from the channel edge to the heated surface. This second layer ensured that the distance from the heated surface to the bottom edge of the channels was consistent for each unit. The PLA fiber was evacuated from the
PDMS by heating the sample to 212 °C under vacuum for 24 hours resulting in a hollow channel of the desired diameter. Last, each stripping unit was then cut to a length of 4.4 cm (Figure S3).

To fabricate the hexagonal pattern, a similar process was followed, but using a laser-cut brass patterning plate containing a hexagonal pattern. The PLA fibers were strung through a pair of plates and the plates were placed onto both ends of the mold box. The fibers were tensioned to obtain a parallel set of fibers in a hexagonal pattern. The same procedures for creating a single microchannel were then followed.

A polyether ether ketone (PEEK) tube was used to form the larger 1.59 mm diameter channel instead of a PLA fiber. Similar steps as the other fabrication procedures were then followed until the evacuation step. Instead of heating the sample under vacuum, the tube was manually removed out from the PDMS, leaving a hollow channel.

1.1.4 Serpentine Microchannel Fabrication
A process similar to the VaSC technique was followed to fabricate the serpentine microchannel. Six PLA fibers with 100 µm diameters were strung through a laser cut plate with six horizontal holes separated by 100 µm. The plates and fibers were then placed in a 2” long mold box. PDMS was poured into the mold box until the fibers were fully covered. The box was placed in an oven at 85 °C for 30 minutes to cure the PDMS. The sample was removed from the mold box and the fibers were manually pulled from the PDMS, resulting in six parallel channels. The sample was cut into a length of 2.8 mm. A single PLA fiber was threaded through the six parallel channels resulting in a single serpentine pattern. A second layer of PDMS was poured to encompass the sample and a second curing step was performed. The PLA was removed from the PDMS by heating the sample up to 212 °C under vacuum for 24 hours, resulting in a serpentine microchannel.

1.2 Characterization
CO₂ Release Measurement
To obtain monoethanolamine (MEA, Sigma-Aldrich, USA) saturated with CO₂, a 100 mL solution of 30% vol. monoethanolamine in DI water was first mixed. 30 mg of phenolphthalein (Sigma-Aldrich, USA) dye was then added to the solution. 7 mL of the MEA solution was withdrawn and placed within a scintillation vial. 100% CO₂ was flowed through the solution for 90 minutes at a rate of 20 mL/min. Further time was spent flowing CO₂ through the solution until 10 wt% of CO₂ in the solution was reached, as measured by an analytical balance. Additional aliquots of CO₂ saturated MEA were made as necessary.

A 1 mL syringe was loaded with the CO₂ saturated MEA solution. The syringe was placed onto a syringe pump (NE-1000, New Era Pump Systems Inc.), and connected to a stripping unit. For phase separation, one end of a 1/16 in. tubing (Ultra-Chemical-Resistant Clear Tygon PVC Tubing, McMaster-Carr, USA) was glued to a 1mL syringe. The other end of the tubing was connected to a mass flow meter (Cole-Palmer Low-Cost Gas Mass Flowmeter, 0-20 sccm). The flow meter was directly connected to an infrared CO₂ meter (COZIR Wide-Range 100% CO₂ Meter, CO2Meter, Inc.) to detect the concentration of CO₂ exiting the microchannel. An aluminum block (3.0 x 4.0 x 0.75 in., McMaster-Carr) was placed on a hot plate to moderate and control the temperature of the stripping unit (Figure S4). The unit was placed between the aluminum block and a 38 g PDMS weight. The weight was placed on top of the sample to ensure close contact with the heating plate and to reduce convective cooling effects on the top surface of the sample. The system was heated for 2 minutes to thermal equilibrium.

Each pumping cycle consisted of a pumping, first pause, withdrawal, and second pause phase. The pumping phase pumped the CO₂ saturated solution through the channel at the desired flow rate until 1 mL of solution was flowed through. The system then paused for 3 minutes and the sample was raised from the heating plate to cool down. This prevented unmeasured CO₂ release during the withdrawal phase. The CO₂ meter was flushed with N₂ until the CO₂ meter read a CO₂ concentration of less than 0.5%. The pump withdrew the MEA solution at a rate of 0.2 mL/min for 2 minutes. The stripping unit was placed onto the heating plate and left on for a second pause phase lasting 2 minutes. The pumping cycle was repeated for 3 hours for each experiment. After each trial, the flow meter and CO₂ meter were flushed with N₂ for 10 minutes. A new phase separating syringe was prepared for each experiment.

2. Supporting Analysis

2.1 CO₂ MEA Reaction Mechanism
The reaction between CO₂ and MEA is a two step reaction mechanism which occurs through a zwitterion intermediate (Figure S5). MEA and CO₂ react to form a zwitterion intermediate as the rate-determining step. Following this zwitterion formation, an acid-base reaction occurs between the zwitterion and another MEA to form carbamate.

2.2 CO₂ Release Calculation
The total release of CO$_2$ from the channels was calculated using a combination of the flow rate and concentration of CO$_2$ measurements (Figure S6). First, the flow rate was converted from a voltage output to a mass flow rate, compensating for the effect of CO$_2$ concentration on the mass flow meter output.

\[ f = f_{v}(V) \times 4 \left( \frac{mL}{min\ V} \right) \times \frac{1}{60} \left( \frac{min}{sec} \right) \times \left( 1 - \frac{c(\%\ CO_2)}{100} \right) \times 0.261 \]

The flow rate multiplied by the concentration was then integrated to obtain the total amount of CO$_2$ flowed through the system.

\[ T = \frac{mg\ CO_2}{mL\ CO_2} \times \int_{0}^{t_f} \left( \frac{mL}{sec} \right) \times \frac{c(\%\ CO_2)}{100} \ dt \]

To plot the total release over time, the range of integration was varied from 0 to $t_{dsat}$.

### 2.3 COMSOL Model Channel Heat Gradient

For each channel diameter and pattern, the COMSOL finite element modeling program was used to estimate the heat gradient in the vertical direction (Figure S7).\cite{note} The model was performed assuming convective cooling on the side edges of the stripping unit, but not the top edge due to the presence of the PDMS block. A surface temperature of 125 °C and a flow rate of 0.1 mL/min were used. Only single phase flow was used to estimate the temperature gradient as the exact two-phase flow transfer mechanisms are still under investigation. The model parameters were set for both CO$_2$ and water to serve as the upper and lower bound estimates of the temperature gradient (Figure S8A, S8B). From the model, we found that as the channel diameter increased, so did the temperature gradient in the vertical direction. Additionally, we observed that the temperature gradient was larger at the ends of the unit. Within the central portion of the unit, the largest temperature difference between the top and bottom of the channel was found to be only ~ 1 °C for the gas phase. For the liquid phase, the temperature difference is higher at ~8 °C due to the higher heat capacity of water. The largest temperature differences occurred in the hexagonally packed 200 µm diameter microchannels and the 1.59 mm diameter channel. A large temperature gradient was observed at the edges of the channel due to the sample boundaries. The average temperature across the entire channel was also calculated (Figure S8C). In the gas phase, the average temperatures were uniform. In the liquid phase, the average temperature decreased as the channel diameter decreased, suggesting the importance of the two-phase heat transfer enhancement on the micron scale. While the model is only an approximation to the experiment, it suggests that the vertical temperature gradient due to the change in channel size is not the only contributor to the enhanced release of CO$_2$.

### 2.4 High Speed Optical Analysis

A Vision Research Phantom v7.3 high-speed camera was used to image the flow-stripping process. MEA dyed with methyl blue (0.3 mg dye/mL solution) was saturated with CO$_2$ to reach 10 CO$_2$ wt%. The camera was mounted on a vertical camera rail with a 1.5X lens. A serpentine microchannel was mounted on a glass slide to stabilize its position and then placed on a hot plate. The hot plate temperature was adjusted until the serpentine microchannel temperature reached 125 °C. The MEA loaded with CO$_2$ was flowed through the microchannel at the desired flow rate. The camera captured 4938 frames during an exposure time of 30 µs and frame rate of 150 µs/frame. Images were processed in ImageJ.

The change in pressure was calculated using the friction factor and pressure gradient. The calculation was based on a model of slug flow in microchannels with diameters less than 1 mm.\cite{note2,note3} Using the high speed videos of the release of CO$_2$, the sum of the gas and liquid velocities for a gas bubble/liquid slug pair was measured (Movie S1, Figure S9). The change in volume of the gas bubble was also measured.

\[ \rho = \text{Liquid density (kg/m}^3) \]
\[ D = \text{Channel diameter (m)} \]
\[ U_{gl} = \text{Sum of the gas and liquid velocities} \]
\[ \mu = \text{Viscosity of the liquid (Pa}s) \]
\[ \sigma = \text{Surface tension (N/m)} \]
\[ Q_v = \text{Volumetric flow rate (m}^3$s) \]
\[ L_s = \text{Liquid slug length (m)} \]
\[ Re = \text{Reynolds number based on the liquid properties and sum of the gas and liquid velocities} \]
\[ Ca = \text{Capillary number based on the liquid properties and the sum of the gas and liquid velocities} \]
A = Channel cross-section area (m²)
Uₗ = Liquid velocity (m/s)
Cₘ = Capillary number based on the liquid properties gas velocity
Dₘ = Gas bubble diameter (m)
Aₘ = Gas bubble cross-sectional area (m²)
δ = Correction on the liquid slug length for the amount of liquid in the slug surrounding the nose and tail of a gas bubble (m)
a = Fit parameter
fₛ = Slug friction factor
P = Pressure (Pa)

\[
\operatorname{Re} = \frac{\rho D U_{gl}}{\mu}
\]
\[
Cₘ = \frac{\mu U_{gl}}{\sigma}
\]
\[
A = \pi \left( \frac{D}{2} \right)^2
\]
\[
U_i = \frac{Q_i}{A}
\]
\[
Cₘₗ = \frac{\mu (U_{gl} - U_i)}{\sigma}
\]
\[
Dₘ = D \left( 1 - \frac{0.67 Cₘₗ^{\frac{2}{3}}}{1 + 3.34 Cₘₗ^{\frac{3}{2}}} \right)
\]
\[
Aₘ = \pi \left( \frac{Dₘ}{2} \right)^2
\]
\[
δ = \frac{Dₘ}{3}
\]
\[
a = \frac{7.16 \times 3^{\frac{2}{3}}}{32} A \left( \frac{Cₘ}{\operatorname{Re}} \right)^{\frac{1}{3}} \left( Cₘ^{\frac{1}{3}} + 3.34 Cₘ^{\frac{2}{3}} \right)^{-1}
\]
\[
fₛ = \frac{16}{\operatorname{Re}} \left( 1 + a \frac{D}{Lₘ + \delta} \left( \frac{\operatorname{Re}}{Cₘ} \right)^{0.33} \right)
\]
\[
\frac{dP}{dx} = -\frac{2 \mu Uₗ}{D^2} fₛ \operatorname{Re}
\]

To estimate the pressure drop, values of \( \sigma = 0.0401 \) (N/m), \( \mu = 6.03 \times 10^{-4} \) (Pa s), \( \rho = 1010 \) (kg/m³), \( D = 100 \times 10^{-6} \) (m), \( Q_i = 1.67 \times 10^{-9} \) (m³), and \( Lₘ = 150 \times 10^{-6} \) (m) were used. The inlet pressure was measured as 75895 Pa by a differential pressure transducer (PC mountable wet/wet differential pressure sensor, Cole-Palmer). The ideal gas law was used to calculate the overall \( \text{CO}_2 \) release rate using the pressure temperature, and gas volume. Initial and final time points were measured for individual bubbles.

dt = Change in time between initial and final time points (s)
x = Distance travelled by gas bubble from inlet (m)
n = Average number of gas bubbles in the microchannel
P = Absolute pressure in gas bubble (Pa)
V = Gas bubble volume (m³)
R = Gas constant (J/mol K)
T = Temperature (K)

\[ P = P_0 - x \times \frac{dP}{dx} \]

Rate = \[ \frac{P_{\text{final}} - P_{\text{initial}}}{RT} \times \frac{1}{\text{mol CO}_2} \times 44.01 \left( \frac{\text{g CO}_2}{\text{mol CO}_2} \right) \times 1000 \left( \frac{\text{mg}}{\text{g}} \right) \times 60 \left( \frac{\text{sec}}{\text{min}} \right) \times n \]

The average number of gas bubbles in the microchannel was estimated to be 20. The results of the calculations are summarized in Table S1. The average release rate for the 100 μm diameter microchannel was 0.76 ± 0.2 mg/min.

2.5 Surface Area Use Estimation

To estimate necessary surface area to strip the CO$_2$ output of an automobile, several assumptions were used. A car is estimated to release an average of 241 g CO$_2$/km,$^{(3)}$ and was assumed to travel at 100 km/hr. A CO$_2$ stripping rate of 0.8 mg/min was used for a 100 μm diameter microchannel with a 5 cm length and 1 cm layer thickness. First, the total number of units necessary was calculated.

A$_{\text{CO2}}$ = Automotive CO$_2$ release rate (g/km)
A$_v$ = Automotive velocity (km/hr)
S = Stripping rate (mg/min)
U = number of units necessary

\[ U = 1000 \left( \frac{\text{mg}}{\text{g}} \right) \times A_{\text{CO2}} \left( \frac{\text{g}}{\text{km}} \right) \times A_v \left( \frac{\text{km}}{\text{hr}} \right) \times \frac{1}{\text{hr}} \times \frac{1}{60} \left( \frac{\text{min}}{\text{hr}} \right) \times 0.8 \left( \frac{\text{mg}}{\text{min}} \right) \]

The number of units required was multiplied by the surface area of the channels, assuming a square packed arrangement of the channels, separated by 50 μm

Cd = Channel diameter (m)
Cl = Channel length (m)
T = Structure thickness (m)
Sa = Surface Area necessary (m$^2$)

\[ Sa = \frac{U \times (Cd + 50 \times 10^{-6})(m) \times (Cl)(m)}{T(m)/(Cd + 50 \times 10^{-6})(m)} \]

3. Supporting Figures
Figure S1. Stripping mug cross-section. The first layer of PDMS applied to the stripping mug creates a 40 µm thick coating before the fiber is conformed to the surface. The additional layers create a 400 µm thick coating above the fibers.

Figure S2. Rough surface microchannel. PDMS first coats a gear rack serving as the rough surface. A PLA fiber is placed on the surface and another gear rack is used to conform the fiber to the top of the first PDMS layer. Another layer of PDMS is cured over the fiber. Lastly, the fibers are depolymerized under heat and vacuum, leaving behind an empty microchannel conformed to the surface of the gear rack. Water dyed with methyl blue was loaded into the microchannel for visual clarity.
Figure S3. Stripping unit dimensions. The dimensions of the stripping unit were largely controlled by the size of the mold box. The distance between the bottom of the unit to the channel edge was determined by the thickness of a second PDMS coating. The channel diameter “d” varied depending on the experiment.

Figure S4. CO₂ release measurement setup. A syringe pump is used to continuously pump and pull CO₂ saturated MEA through a microchannel. The microchannel is heated with an aluminum block on a hot plate. As CO₂ is released from the microchannel, the liquid and gas phases are separated by gravity in a syringe. The continuous flow of MEA forces the gas through a flow meter and then a CO₂ meter which are used to calculate release of CO₂.

Figure S5. CO₂-MEA reaction mechanism. Heating the solution drives the reverse reaction, releasing CO₂.
Figure S6. Sample CO$_2$ release data and calculation. (A) Raw data output. MEA flowed through a 100 µm diameter microchannel at a flow rate of 0.1 mL/min and a surface temperature of 125 °C. The mass flow-meter and IR CO$_2$ meter measure the flow rate and concentration of CO$_2$ simultaneously. Several peaks/plateaus appear due to the cyclic pumping of the CO$_2$ saturated MEA solution. (B) Calculated CO$_2$ release rates. Release rates are found by combining the CO$_2$ concentration and flow rate. Integrating the release rate with respect to time results in the total amount of CO$_2$ released.

Figure S7. COMSOL Heat Transfer Model. The temperatures in the channels are estimated using a single phase flow of either liquid or gas. The dimensions and flow conditions are set to match the experimental conditions. (A) Hexagonal microchannel arrangement model. (B) 1.59 mm channel diameter model.
Figure S8. COMSOL model results. (A) Liquid vertical change in temperature. As the fluid travels through the channel length, the temperature gradient decreases for all channel diameters. The high heat capacity of water results in a longer path length to reach a gradient minimum. (B) Gas vertical change in temperature. In the gas phase, the temperature gradient is more uniform due to the lower heat capacity. At the edges of the channels, a larger gradient occurs due to exposure to an outside environment. (C) Average temperatures. In the liquid phase, the average channel temperature decreases as the channel diameter decreases. In the gas phase, the average temperature is uniform with respect to channel diameters and patterns.
Figure S9. CO₂ stripping from MEA in a serpentine, 100 µm diameter microchannel. The two-phase profile was observed predominantly in the form of either slug flow or annular flow. By measuring the volume and velocities of the CO₂ gas plugs, the release rate of CO₂ can be calculated using high-speed photography. Image resolution decreases as the release of CO₂ increases flow velocity. Scale bar is 400 µm in image and 100 µm in inset.

Figure S10. Power In and Heat Transfer Coefficient vs. Initial CO₂ Release Rate. Values are plotted for each variance of the experimental parameters (channel type, temperature, and flow rate). Little correlation between the heat transfer coefficients and the initial release rates were found. A much stronger correlation was found between the power into the saturated MEA solution and the initial CO₂ release rates.
4. Supporting Tables

<table>
<thead>
<tr>
<th>Trial</th>
<th>dt (ms)</th>
<th>U_i (m/s)</th>
<th>U_f (m/s)</th>
<th>x_i (mm)</th>
<th>x_f (mm)</th>
<th>V_i × 10^{-12} (m^3)</th>
<th>V_f × 10^{-12} (m^3)</th>
<th>P_i (kPa)</th>
<th>P_f (kPa)</th>
<th>Rate (mg/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12.9</td>
<td>0.43</td>
<td>0.7</td>
<td>7.8</td>
<td>12</td>
<td>3.0</td>
<td>1.5</td>
<td>68</td>
<td>65</td>
<td>0.90</td>
</tr>
<tr>
<td>2</td>
<td>15.6</td>
<td>0.69</td>
<td>1.7</td>
<td>7.9</td>
<td>20.</td>
<td>1.0</td>
<td>1.3</td>
<td>69</td>
<td>61</td>
<td>0.74</td>
</tr>
<tr>
<td>3</td>
<td>16.2</td>
<td>0.36</td>
<td>2.0</td>
<td>9.1</td>
<td>19</td>
<td>5.2</td>
<td>7.7</td>
<td>65</td>
<td>62</td>
<td>0.43</td>
</tr>
<tr>
<td>4</td>
<td>10.2</td>
<td>0.54</td>
<td>1.5</td>
<td>11</td>
<td>19</td>
<td>1.5</td>
<td>9.2</td>
<td>65</td>
<td>61</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>10.5</td>
<td>0.56</td>
<td>1.6</td>
<td>11</td>
<td>20.</td>
<td>3.6</td>
<td>1.5</td>
<td>65</td>
<td>61</td>
<td>1.00</td>
</tr>
<tr>
<td>6</td>
<td>9.4</td>
<td>0.75</td>
<td>1.4</td>
<td>11</td>
<td>19</td>
<td>2.0</td>
<td>8.9</td>
<td>66</td>
<td>61</td>
<td>0.68</td>
</tr>
<tr>
<td>7</td>
<td>11.4</td>
<td>0.38</td>
<td>1.9</td>
<td>9.7</td>
<td>19</td>
<td>1.7</td>
<td>1.4</td>
<td>65</td>
<td>63</td>
<td>1.02</td>
</tr>
<tr>
<td>8</td>
<td>14.5</td>
<td>0.33</td>
<td>1.5</td>
<td>9.7</td>
<td>19</td>
<td>1.9</td>
<td>1.1</td>
<td>64</td>
<td>62</td>
<td>0.58</td>
</tr>
<tr>
<td>9</td>
<td>75.8</td>
<td>0.66</td>
<td>1.8</td>
<td>11</td>
<td>19</td>
<td>1.7</td>
<td>7.9</td>
<td>66</td>
<td>62</td>
<td>0.79</td>
</tr>
<tr>
<td>10</td>
<td>9.4</td>
<td>0.77</td>
<td>1.3</td>
<td>11</td>
<td>19</td>
<td>4.0</td>
<td>1.1</td>
<td>66</td>
<td>61</td>
<td>0.73</td>
</tr>
<tr>
<td>11</td>
<td>10.0</td>
<td>0.37</td>
<td>1.4</td>
<td>11</td>
<td>19</td>
<td>2.6</td>
<td>8.1</td>
<td>63</td>
<td>61</td>
<td>0.52</td>
</tr>
<tr>
<td>12</td>
<td>8.2</td>
<td>0.46</td>
<td>1.0</td>
<td>9.5</td>
<td>16</td>
<td>3.5</td>
<td>1.3</td>
<td>66</td>
<td>63</td>
<td>1.13</td>
</tr>
<tr>
<td>13</td>
<td>15.2</td>
<td>0.52</td>
<td>0.9</td>
<td>8.9</td>
<td>16</td>
<td>2.4</td>
<td>1.1</td>
<td>67</td>
<td>63</td>
<td>0.54</td>
</tr>
<tr>
<td>14</td>
<td>13.8</td>
<td>0.32</td>
<td>2.6</td>
<td>9.3</td>
<td>19</td>
<td>1.6</td>
<td>1.3</td>
<td>64</td>
<td>63</td>
<td>0.83</td>
</tr>
</tbody>
</table>

Table S1. Summary of data from high-speed optical analysis.

<table>
<thead>
<tr>
<th>Channel Type</th>
<th>Flow Rate (mL/min)</th>
<th>Temperature (°C)</th>
<th>Nusselt Number</th>
<th>Reynolds Number</th>
<th>Power In (W)</th>
<th>Heat Flux (W/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hex</td>
<td>0.05</td>
<td>125</td>
<td>0.02 ± 0.004</td>
<td>1.8</td>
<td>1.06 ± 0.16</td>
<td>200 ± 70</td>
</tr>
<tr>
<td>Hex</td>
<td>0.1</td>
<td>125</td>
<td>0.03 ± 0.01</td>
<td>3.7</td>
<td>1.30 ± 0.26</td>
<td>810 ± 260</td>
</tr>
<tr>
<td>Hex</td>
<td>0.2</td>
<td>125</td>
<td>0.06 ± 0.02</td>
<td>7.4</td>
<td>2.28 ± 0.58</td>
<td>2760 ± 590</td>
</tr>
<tr>
<td>1.59 mm</td>
<td>0.05</td>
<td>125</td>
<td>0.11 ± 0.01</td>
<td>1.6</td>
<td>0.66 ± 0.04</td>
<td>510 ± 60</td>
</tr>
<tr>
<td>1.59 mm</td>
<td>0.1</td>
<td>125</td>
<td>0.06 ± 0.01</td>
<td>3.3</td>
<td>0.42 ± 0.04</td>
<td>790 ± 130</td>
</tr>
<tr>
<td>1.59 mm</td>
<td>0.2</td>
<td>125</td>
<td>0.06 ± 0.02</td>
<td>6.5</td>
<td>0.42 ± 0.14</td>
<td>800 ± 80</td>
</tr>
<tr>
<td>100 µm</td>
<td>0.1</td>
<td>125</td>
<td>0.16 ± 0.02</td>
<td>51.8</td>
<td>0.86 ± 0.13</td>
<td>11590 ± 1250</td>
</tr>
<tr>
<td>200 µm</td>
<td>0.1</td>
<td>125</td>
<td>0.20 ± 0.03</td>
<td>25.9</td>
<td>0.78 ± 0.04</td>
<td>10910 ± 1200</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.05</td>
<td>125</td>
<td>0.17 ± 0.03</td>
<td>8.6</td>
<td>0.73 ± 0.05</td>
<td>3620 ± 490</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.1</td>
<td>125</td>
<td>0.22 ± 0.04</td>
<td>17.3</td>
<td>0.81 ± 0.04</td>
<td>8580 ± 900</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.2</td>
<td>125</td>
<td>0.45 ± 0.09</td>
<td>34.5</td>
<td>1.00 ± 0.05</td>
<td>18310 ± 980</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.1</td>
<td>105</td>
<td>0.04 ± 0.01</td>
<td>17.3</td>
<td>0.20 ± 0.05</td>
<td>3240 ± 600</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.1</td>
<td>115</td>
<td>0.16 ± 0.02</td>
<td>17.3</td>
<td>0.57 ± 0.07</td>
<td>7650 ± 360</td>
</tr>
<tr>
<td>300 µm</td>
<td>0.1</td>
<td>135</td>
<td>0.29 ± 0.07</td>
<td>17.3</td>
<td>1.20 ± 0.17</td>
<td>7750 ± 1450</td>
</tr>
</tbody>
</table>

Table S2. Additional characterization of experimental parameters. Characteristic length for the Hexagonal sizes is considered to be 200 µm.

5. Supporting Movies
Movie S1. High-speed video of CO$_2$ stripping. MEA saturated with CO$_2$ flowed through a 100 µm diameter serpentine microchannel at a flow rate of 0.1 mL/min. As CO$_2$ was released from the solution, gas bubbles formed, resulting in two-phase release.

6. Supporting References