MICROSCALE BOILING HEAT TRANSFER NEAR THE MENISCUS

Brenda E. Haendler  David C. Walther
Dorian Liepmann  Albert P. Pisano
Berkeley Sensor & Actuator Center
University of California, Berkeley
497 Cory Hall, Berkeley, CA 94720
Phone: 510.642.4876, Fax: 510.643.6637
E-mail: brendler@eecs.berkeley.edu

ABSTRACT
Results are presented experimentally measuring the localized temperature profile due to microscale boiling of a silicon-Pyrex bonded wafer with a 100 μm deep, 500 μm wide and six mm long microchannel. Experiments were performed using an infrared camera equipped with a magnifying lens. By using a camera, the dynamic temperature profile is shown from the inside channel all the way out to where the temperature of the wafer reaches the bulk temperature of the heating source. Temperature profiles are shown for both water and methanol as the working fluid applying between five and twenty degrees Celsius of superheat to the bulk wafer. Using these results, a discussion of the relevant heat transfer modes and non-dimensional numbers is given to gain insight into the range of influence that phase change in a microchannel has on the temperature of the wafer. Additionally, discussion is given about modeling of microscale phase change using a commercial fluid dynamics software package. The importance of these results with respect to implementation into the fuel intake manifold for a micro engine based portable power system is also discussed.

INTRODUCTION
Because the energy density of batteries is increasing at a rate insufficient to meet the power demands of handheld electronics, research is focused on the development of a micro internal combustion engine that will use high energy density liquid hydrocarbon fuel to generate electrical power [1]. The results presented here are critical to understanding how the requirements of the engine will affect the design of the fuel injection and vaporization sub-systems.

In order for a MEMS internal combustion engine based system to be feasible, all the sub-systems which support the engine must be zero or low power draw, be compact and easily fabricated, and produce consistent, repeatable, and predictable results. One of the challenges when creating a packaged micro engine is the fuel delivery and vaporization sub-systems. The fuel must enter the combustion chamber in vapor form so as to not cool down the housing too much and quench the combustion reaction. Any localized cooling of the surrounding walls of the microchannels that make up the fuel vaporization system must be quantified, characterized and minimized if necessary.

Results presented in this paper are in the form of thermal images from an infrared camera. By using an external camera to take pictures of the microchannel, the silicon, and the surrounding Pyrex, a complete picture of temperature changes in the wafer can be studied in a non-invasive manner. This gives a much more complete picture of the transient temperature profiles in the wafer than can be obtained using a series of thermocouples.

NOMENCLATURE

- Bi  Biot number
- \( cp \)  Specific heat  [J/kgK]
- \( g \)  Gravitational acceleration  [m/s²]
- \( h \)  Heat transfer coefficient  [W/m²K]
- \( h_v \)  Heat of vaporization  [J/kg]
- \( k \)  Thermal conductivity  [W/mK]
- \( L \)  Length scale  [m]
- \( Re \)  Reynolds number
- \( Ra \)  Rayleigh Number
- \( Ja \)  Jakob number
- Nu  Nusselt Number
- \( T \)  Temperature  [K]
- \( V \)  Characteristic flow velocity  [m/s]
- \( \alpha \)  Thermal diffusivity  [m²/s]
- \( \beta \)  Volumetric thermal expansion coefficient  [1/K]
- \( \varepsilon \)  Emissivity
The term coined for the abrupt transition from liquid to vapor that is seen when evaporating pure fluids in micro channels is flow eruption [2]. This transition is seen in channels where the hydraulic diameter is on the same scale or smaller than the radius needed for the first bubbles to survive and grow in a macro scale system, namely the critical bubble radius [3]. For most flow conditions this diameter is on the order of 100 μm. Therefore, in micro scale boiling systems there is not a distinct bubbly or plug flow region as is shown in Figure 1; rather the system goes directly from single-phase liquid to entrained droplet annular flow as is shown in Figure 2.

The work presented in this paper investigates the temperature profile in and around the phase change interface for a channel with a diameter close to the critical diameter of 100 μm. This study focuses on a channel where the hydraulic diameter is larger than 100 μm but smaller than a macro sized channel with would have a diameter measured in millimeters or larger.

In order to observe the evaporation behavior of various fluids it was necessary to incorporate a design that would allow the channel to be heated uniformly while still being able to observe the fluid dynamics. The microchannel was fabricated from a single polished 500 μm thick silicon wafer that was anodically bonded to a Pyrex wafer. The silicon wafer was initially coated with 1.2 μm of thermally deposited oxide to serve as a lithographic layer. For this application, oxide was used due to its good lithographic resolution resistance to undercutting during SF6 dry plasma etching. The oxide was then coated with 2 μm of Microposit I-line photoresist, exposed, and developed. The oxide was etched with the design of the microchannels using a Lam© oxide etcher and the photoresist removed using heated PRS 3000 photoresist remover. The wafer was next cleaned using a piranha sulfuric acid bath, dehydrated, and coated with 9 μm of G-line thick resist. This layer was then aligned, exposed, and developed with the pattern for the silicon through holes and hard baked for 40 minutes at 120°C. The photoresist layer was etched in Advanced Silicon Etch (ASE) deep reactive ion etching (DRIE) process at a rate of 6 μm a minute until the through holes were completely through the wafer. The photoresist was removed in PRS 3000 and cleaned using piranha. Once cleaned the wafer was placed back in the DRIE using the underlying oxide layer as the mask. The channels were then created using DRIE to the appropriate depth. Last, the remaining oxide was removed using 49% HF solution.

The tubing was attached to the wafer using Nanoports by Upchurch Scientific. The tubing diameter for the Nanoport was 1/16 of an inch outer diameter which was scaled up to 1/8 of an inch by the use of a Swagelok junction. Teflon tubing was used in all experiments.

The glass cover of the channels is a 500 μm thick Pyrex wafer. The glass and silicon wafers were then cleaned using clean room piranha bath, rinsed in ultra-pure deionized water, spin dried and anodically bonded under vacuum using a Karl Suss anodic bonder at a voltage of 1000 V and a temperature of 450°C.

The silicon wafer with the anodically bonded Pyrex wafer was heated uniformly from below using a mineral oil bath. The...
bath was placed on a hot plate which was controlled with a Watlow Series 96 pulse width temperature controller. Due to the large thermal capacitance of the mineral oil bath, the pulsing of the hot plate did not create transient temperature changes in the wafer. Figure 4 shows the experimental set-up used for these tests.

The working fluid was driven using a Cole Parmer series 74900 syringe pump. The syringes used were glass Hamilton Company ten milliliter Gastight type. The pressure was measured simultaneously with the temperature measurements using a flow-through Honeywell pressure sensor part number 26PCFB2G.

The camera used was a Thermacam SC1000 which had an IR close-up lens, FLIR Systems part number 08842-2000, attached. The data was captured directly to a compact flash disk and stored as TIFF images. At the same time video was captured at 30Hz on a super-VHS tape. Both the size of the temperature scale and the range of temperatures measured were manually set.

Figure 4. The experimental set-up used to measure the temperature and pressure independently.

Before testing was begun a map of the emissivity of the silicon wafer as a function of temperature was created. Using a pair of thermocouples to measure the surface temperature of the wafer, the emissivity reading was changed in the camera until the correct temperature was measured. The map created using this method is used for further testing to insure that the temperature readings shown are corrected for the operating conditions. Further details are given in the Discussion section of this paper.

**EXPERIMENTAL RESULTS**

Two working fluids, namely water and methanol, were chosen for the series of tests presented in this paper. Pure fluids were chosen to help isolate the effect of physical properties on the temperature gradient. Water was chosen to serve as a baseline and methanol because it is a commonly used fuel. In all figures presented the fluid is being pushed using a syringe pump from left to right. The channel chosen is 100 μm deep and 500 μm wide (167 μm hydraulic diameter) and six mm long. The wafer tested incorporates many channels of varying hydraulic diameters as well as other test structures. A neighboring channel is visible below the channel in use in many pictures and holes in the silicon can be seen above as localized hot spots.

In order to better understand the gradients seen in the boiling cases, first sub-boiling temperatures were tested. Figure 5 shows a three degrees Celsius temperature difference between the wafer and the channel near the inlet when the wafer is heated to 50°C, fifty degrees below the boiling point for the working fluid. Please note that the temperature displayed in the upper left hand corner of the graphs corresponds to the temperature reading at the middle of the cross-hairs in each picture.

![Figure 5](image1.png)

**Figure 5.** Water flowing at 0.2 ml/min in a 100 μm deep and 500 μm wide microchannel. The wafer is heated to approximately 50°C.

Figure 6 shows the thermal signature of the wafer with ten degrees of superheat on the water. The level of superheat is determined by the number of degrees over the normal or macroscale boiling point for the working fluid. Therefore, for water the macroscale boiling point is 100°C and a wafer temperature of 110°C represents ten degrees of superheat. It is documented that microscale boiling often begins a few degrees above the macroscale boiling point.

Please note that the parallel line underneath the channel of interest is another channel which is unfilled and smaller in hydraulic diameter. It is also important to note the key on the left side of each picture which relates the color scale to the temperature scale. Depending on the wafer temperature and which aspect of the thermal gradient is under investigation, different scales are selected for different conditions.

![Figure 6](image2.png)

**Figure 6.** The same flow conditions as Figure 5, but with the wafer heated to ten degrees Celsius above the boiling point for water.
For this channel diameter, it is expected that there is an abrupt transition from liquid to vapor in a diameter spanning meniscus as is drawn in Figure 2. While the exact meniscus is not readily obvious, the temperature transition does appear to follow the profile expected. It appears that the water enters the channel slightly below 100°C and has a parabolic temperature profile as it increases in temperature by a few degrees Celsius. Further along in the channel the working fluid undergoes a second temperature change where the fluid temperature increases from approximately 100°C to 105°C. This result agrees with previously published results which show that the working fluid usually changes from liquid to vapor at approximately five degrees Celsius of superheat.

Both the temperature of the working fluid as well as the temperature of the wafer surrounding the channel increase with a parabolic profile, which is the expected result. However, the temperature of the surrounding silicon and Pyrex changes dynamically with time and is affected by changes in the temperature profile of the working fluid. Therefore, the pictures shown in this paper are snapshots in time of a dynamically changing system.

These results will be compared with similar superheats using methanol as the working fluid to better understand the dependence of the working fluid on the signature of the temperature change in the wafer.

Figure 7 highlights the difference in temperature of the silicon adjacent to the channel depending on the flow rate of the working fluid. The only difference in the system between Figure 6 and Figure 7 is the flow rate has been increased from 0.2 ml/min to 0.5 ml/min. Please note that the same temperature scale was used in both pictures and the crosshair measurement was taken in the same place. Comparing the two pictures it can be seen that the temperature of the wafer near the inlet has the same profile in both cases. However, for the lower flow rate case, further down the channel the temperature approaches the bulk temperature faster than for the higher flow rate case.

The implications from this thermal signature on the design of a micro engine fuel delivery system will be detailed in the Discussion section of this paper.
channel. While the fluid flows from left to right in the channel, these gradients move from right to left with time.

Figure 10. A detailed picture of the temperature change of the working fluid and surrounding channel for water flowing at 0.5 ml/min with twenty degrees of superheat on the wafer.

Looking in more detail at the cold spots in the working fluid shown in Figure 8 and Figure 9, Figure 10 was taken using the same superheat level but zooming in on the channel and surrounding area. It is interesting to note the direct correlation between the cool spots in the working fluid and the lines of localized lower temperature in the wafer. As time progresses these local cool spots in the working fluid heat up and the radial thermal gradient that is created out of the channel moves to the left and collapses in the sidewall of the channel. The movement of these gradients corresponds to an increase in the heat flow from the hotter part of the wafer near the channel exit to the cooler section near the inlet. The start of this folding of the thermal gradient in the channel can be seen in Figure 10 by the finger-like temperature gradients which are less than perpendicular to the sidewall of the channel.

Figure 11 adjusts the temperature scale on the lower end of the spectrum for the 120°C wafer temperature case to determine if the working fluid ever gets below 102.5°C. From this Figure it appears that the working fluid, which it does fluctuate in temperature and approaches 100°C, it does not ever go below the boiling temperature away from the channel inlet. It is also interesting to note from this picture that the diameter spanning parabolic shape is once again visible, which is in agreement with the results shown in Figure 8, which has the same operating conditions. Therefore, it can be assumed that no critical information about the thermal signature of the system was lost by changing temperature scale.

In order to understand how the fluid properties affect the temperature profile, the same channel and flow rates were tested using methanol as the working fluid. The same levels of superheat were applied, although the absolute temperature of the wafer was lower, since the macroscale boiling point for methanol is 65°C versus 100°C for water.

Figure 11. Water flowing at 0.2 ml/min in a channel with twenty degrees of superheat.

Figure 12. Methanol flowing at 0.2 ml/min with twenty degrees of superheat in the 167 µm hydraulic diameter channel.

Figure 12 shows the same relative operating conditions as Figure 8. The same two stage parabolic temperature profile in the working fluid is observed as well as the overall parabolic temperature gradient in the surrounding wafer. Similar temperature gradients between the water and the methanol cases are expected since in both cases pure fluids were used. The main difference between the two cases is that the temperature gradient pointed radially outward from the channel extends further with methanol as the working fluid than it did for water at the same volumetric flow rate. A discussion of the effect of the physical property differences between the two fluids and the thermal signature is detailed in the Discussion section below.

For further comparison, Figure 13 is the same flow conditions as are used for Figure 9. Once again it can be seen that a similar temperature gradient is created with methanol as the working fluid as for the water case. Additionally, the same localized cool spots in the working fluid once again cause low temperature tendrils to extend radially outward from the channel wall.

It was observed during the testing and has been recorded on video, that while the working fluid moves left to right, the
tendrils move from right to left. Therefore, as one fluid particle moves to the right it momentarily cools the one in its wake and this cooling spot travels slowly upstream in the channel. This lends insight into the amount of heat moving through the liquid relative to the amount of heat flowing into the channel. Calculations for this system are detailed in the Discussion section.

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Figure 13. Methanol flowing at 0.5 ml/min with twenty degrees of superheat.

It was stated earlier that pressure measurements were taken at the same time as the IR measurements. Figure 14 shows the pressure trace measured for methanol flowing through the 167 µm channel at 0.5 ml/min with twenty degrees Celsius of superheat. This pressure signature is consistent with previously published results for pure fluids [4]. It is important to note that while the temperature of the channel wall is changing dynamically, so is the pressure of the working fluid. It is thought that this pressure signature is due to the back and forth movement of the meniscus along the channel, as has been visually observed.

Figure 14. Sample pressure profile for methanol flowing at 0.5 ml/min with twenty degrees of superheat.

Additional testing is underway using channels with smaller hydraulic diameters as well as using other working fluids including other pure fuels and mixtures of fuels. This work is necessary before microscale boiling can be implemented into the fuel intake manifold for a micro engine.

DISCUSSION

The importance of this work is to understand the transient temperature change in the surrounding wafer due to a microchannel with filled with a liquid changing phase. It is clear from the pictures presented in the Results section that there is a temperature gradient across the face of the wafer, which will be the focus of this section. However it is important to know if there is also a temperature gradient between the top and bottom of the wafer.

When determining the how far into the silicon the temperature change will take place, an appropriate starting place is to calculate the Biot number for the system. The Biot number is the ratio of the internal conduction resistance to the external convective resistance given by:

\[ Bi = \frac{h}{l} \]

For this calculation, \( h \) is the heat transfer coefficient (W/m²K), \( l \) is the characteristic length of the wafer (m) and \( k \) is the thermal conductivity of the silicon (W/mK). If the Biot number is less then 0.1 the system can be modeled as a lumped capacitance. Therefore, before this calculation can be completed, the convective heat transfer coefficient must be calculated.

In the experimental set-up used the top of the wafer is open to the atmosphere, while the sides and bottom are covered by the mineral oil bath. Therefore, the convection from the top of the wafer will be in the form of free or natural convection and not forced convection, between the heated surface of the wafer and the open atmosphere. For natural convection coefficients, the Nusselt number is a function of the Rayleigh number [6]. The Rayleigh number is given by:

\[ Ra = \frac{\beta \Delta T g L^3}{\nu \alpha} \]

Therefore, for external free convection, the largest convection coefficient for all the cases tested in this study is 7.35 W/m²K.

The characteristic length, which is needed for the Biot number calculation is equal to the volume of the wafer divided by the surface area. Therefore, for the silicon-Pyrex bonded wafer the characteristic length is the thickness of the two 500 µm thick wafers. Using 98.9 W/mK for the thermal conductivity of silicon at 400K, the Biot number for this system is equal to 7.43x10⁻⁵ and therefore, the temperature of the wafer can be considered to be constant in depth for all the cases tested. Because there is no gradient in the wafer from top to bottom this means that the images shown in the Results section of this paper are indicative of the temperature gradient of any
slice in the wafer and not just the top, bottom or interface surface. Understanding the Biot number for this application also leads to further understanding about how the heat is moving through the wafer.

For this application, because of the highly reflective surface of the silicon wafer, it is also important to calculate the radiation heat transfer coefficient, which is given by the equation:

$$ h_r = 4\varepsilon \sigma T_m^3 $$

Where $\varepsilon$ is the emittance of the material, $\sigma$ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8}$ W/m$^2$K$^4$), and $T_m$ is the mean temperature between the emitting surface and the surrounding atmosphere.

Using the infrared camera, the measured emissivity of the bonded silicon-Pyrex wafer was determined directly by measuring the surface temperature of the wafer and adjusting the emissivity until the calculated number was correct. From this series of experiments, Table 1 was created as a map of the emissivity of the wafer versus its bulk temperature. This map is specific to the test set-up built and the camera used, and is verified during every data collection run. Slight changes in the angle of the camera or the external conditions could change this map and therefore it was checked during every run.

<table>
<thead>
<tr>
<th>Superheat [K]</th>
<th>Flow Rate [ml/min]</th>
<th>Density (water) [kg/m$^3$]</th>
<th>Dynamic Viscosity (water) [kg/s*m]</th>
<th>Velocity (water) [m/s]</th>
<th>Reynolds Number (water)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.2</td>
<td>932</td>
<td>2.77E-04</td>
<td>0.12</td>
<td>67</td>
</tr>
<tr>
<td>0</td>
<td>0.5</td>
<td>932</td>
<td>2.77E-04</td>
<td>0.30</td>
<td>168</td>
</tr>
<tr>
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<td>928</td>
<td>2.66E-04</td>
<td>0.12</td>
<td>70</td>
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<td>196</td>
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</table>

Table 2. Reynolds number calculations for the experiments detailed above.

The third non-dimensional number which was chosen to help evaluate the system is the Jakob number. This non-dimensional number represents the heat available from the surrounding liquid divided by the energy required for phase change [6].

From the Jakob number calculations, it can be seen that as the temperature increases the Jakob number increases, corresponding to an increase in the heat available from the surrounding liquid or a decrease in the energy required for phase change. From comparing the two sets of numbers in Table 3, it can be seen that the temperature gradient should be larger for water than for methanol at lower superheats but the difference will diminish at higher superheats.

$$ Ja = \frac{c_{p,l} \Delta T}{h_v} $$

<table>
<thead>
<tr>
<th>Superheat [K]</th>
<th>cp.liq. (water) [J/kgK]</th>
<th>hlv (water) [W/mK]</th>
<th>Ja (water)</th>
<th>cp.liq. (methanol) [J/kgK]</th>
<th>hlv (Methanol) [W/mK]</th>
<th>Ja (methanol)</th>
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<td>0</td>
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</tr>
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</table>

Table 3. The Jakob number for water and methanol for the superheats tested.

It is important to note from Table 2 that the density for methanol is lower at each superheat than the density of water.
and therefore, while the two tests were done at constant volumetric flow rate, they were not at the same mass flow rate. The exact difference in the mass flow rate for the two fluids is detailed in Table 4.

<table>
<thead>
<tr>
<th>Superheat [K]</th>
<th>Volumetric Flow Rate [ml/min]</th>
<th>Mass Flow Rate (water) [kg/s]</th>
<th>Mass Flow Rate (methanol) [kg/s]</th>
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<td>5.31E-09</td>
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<td>3.08E-06</td>
<td>6.27E-09</td>
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<tr>
<td>20</td>
<td>0.2</td>
<td>3.05E-06</td>
<td>8.72E-09</td>
</tr>
</tbody>
</table>

Table 4. The volumetric flow rate to mass flow rate conversion as a function of superheat for water and methanol.

From the results shown and the calculations detailed, it can be seen that there is significant conduction across the face of the wafer. The calculated losses due to radiation and convection are small and do not account for the thermal gradients detailed in the Experimental Results section of this paper.

In order to model this dynamic temperature gradient, work is currently underway modeling the system detailed in this paper using CFDRC, a commercial off the shelf computational fluid dynamics software package. Using this software package, the transient change in the temperature of the surrounding wafer as a liquid-vapor interface moved back and forth at 105°C in a 120°C microchannel is being modeled. The calculated radiation and convection heat transfer coefficients are input to account for the other modes of heat transfer present. However, the focus of this simulation is to understand how the conduction currents move in the wafer. It is important to understand this movement of heat for application into a micro fuel vaporization and delivery system.

For small engines it is important to keep a large fraction of the heat produced near the combustion chamber. Unlike large engines where cooling is critical, the challenge for many small engines is to keep them warm enough to sustain combustion. For this reason it is important to understand how the heat will conduct away from the microchannel. It will likely be necessary, once the conduction heat transfer is well understood, to create thermal blocks in the wafer to limit or direct the heat transfer in order to insulate the engine as needed for combustion. The exact geometry will be governed by further testing as well as results from the CFDRC simulations.

CONCLUSIONS

In this paper the temperature profile for microscale boiling is presented using both water and methanol as the working fluid. Previously published results have shown that there is a dynamic pressure profile in the microchannel during microscale boiling. Experiments conducted for this paper have shown that the dynamic pressure change in the channel is accompanied by a dynamic temperature profile in the wafer adjacent to the channel. However, while the pressure in the channel consists of a few clear frequencies which can have been determined using a discrete Fourier transform, the temperature response does not have clear corresponding discrete fluctuations. Rather the temperature profile of the surrounding wafer is overall parabolic in shape and changes by means of low temperature finger shaped waves that are aligned radially outward from the channel and are gradually damped out by conduction from the hotter parts of the wafer.

Evaluating the heat transfer modes for a bonded silicon-Pyrex wafer in a heating bath open to the atmosphere, the natural convection and radiation heat transfer coefficients are found to be on the same order of magnitude. From a Biot number analysis, it is shown that there is no temperature gradient between the top and bottom of the wafer and therefore, the temperature profiles detailed in this paper are due to conduction across the face of the wafer. Further testing and modeling of the system using CFDRC are underway to better understand how the conduction gradients movement through the wafer is related to the movement of the microscale boiling phase change meniscus in the microchannel.

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