Polydimethylsiloxane (PDMS)-based microfluidic channel with integrated commercial pressure sensors

C. M. Mackenzie Dover*, Y. Li, S. Korniliou, K. Sefiane, J. G. Terry and A. J. Walton
Department of Engineering,
The University of Edinburgh,
Edinburgh,
United Kingdom,
C.Dover@staffmail.ed.ac.uk

Abstract— The precise characterisation of boiling in microchannels is essential for the optimisation of applications requiring two phase cooling. In this paper polydimethylsiloxane (PDMS) is employed to make microchannels for characterising microboiling. In particular the material properties of PDMS facilitate rapid prototyping and its optical transparency provides the capability to directly view any fluid flow. The production of microchannels is complicated by the need to integrate custom made sensors. This paper presents a PDMS microfluidic device with integrated commercial pressure sensors, which have been used to perform a detailed characterisation of microboiling phenomena. The proposed approach of integrating commercial pressure sensors into the channel also has potential applications in a range of other microsystems.

Keywords—microfluidics, boiling, cooling, sensors

I. INTRODUCTION

Electronic circuits are continually being reduced in dimension, which is resulting in more efficient cooling being required to remove high heat densities [1]. Thus there is consequently a need for more effective and efficient cooling methods. Two-phase microfluidic flows are capable of removing heat at a high rate from a local area while requiring only a low volume of fluid [2], hence microfluidic systems represent a viable cooling solution. As a result, these devices have attracted significant attention as a complete characterisation of the relationship between their geometry and associated boiling dynamics is required to inform optimisation.

Polydimethylsiloxane (PDMS) is widely used for making devices for the characterisation of microfluidic systems [3-5]. This involves curing the polymer over a mould before bonding the moulded PDMS channel to glass following plasma-activation of its surface. PDMS is typically employed because it offers an inexpensive, straight-forward and flexible route to production. In boiling experiments, PDMS microchannels facilitate the observation of associated phenomena using both visible and infra-red optical measurements, which is important when characterising two-phase cooling phenomena. Similarly, pressure data are particularly important for the characterisation of boiling because this is essential for deducing the rate of heat transfer for a given channel geometry [6]. It is insufficient to simply measure pressure externally at the inlet and outlet reservoirs.

Hence, there are many examples of the integration of a number of different types of pressure sensors with PDMS [7-16]. In these cases the reported pressure sensors have been custom made and involve multi-step microsystem fabrication processes, adding an element of considerable complexity. A different and effective approach to producing such prototypes, is to utilise commercial miniature pressure sensors and integrate them with a PDMS microchannel. This approach to their design and fabrication has somewhat surprisingly not been previously reported in any detail in the literature. This paper demonstrates that commercial pressure sensors can monitor the subtle pressure changes associated with the individual features of two important boiling modes and is suitable for characterising boiling in microchannels. This approach can also be adapted to address other applications for which bespoke sensors have been developed; i.e cell-culture [8], DNA and cell biology studies [15], chemical mixing, reaction, extraction, separation [10], characterisation of industrial fluids such as lubricants and coatings [14] and particle sorting and separation [16].

II. FABRICATION

Figure 1 shows details of the fabricated channel with integrated Honeywell TruStability® High accuracy Silicon Ceramic (HSC) pressure sensors with a measurement range of 0-1 bar. Figure 1(a) shows the layout of the channel and reservoirs, with figure 1(b) showing the PDMS channel without the sensor (for clarity). Figure 1(c) shows the completed device with the pressure sensors integrated. As well as pressure sensing capabilities, the device was fabricated with a transparent integrated heater (ITO), which provides the heating required for the characterisation. In this design the sensors are located near the inlet and outlet of the channel. When a bubble is formed in the channel, the initial outward expansion impacts on the pressure measured at both sensors. As the bubble moves along the channel with the liquid flow the sensors can monitor the pressure as a function of time and the cameras capture the location of the vapour bubbles in the channel.

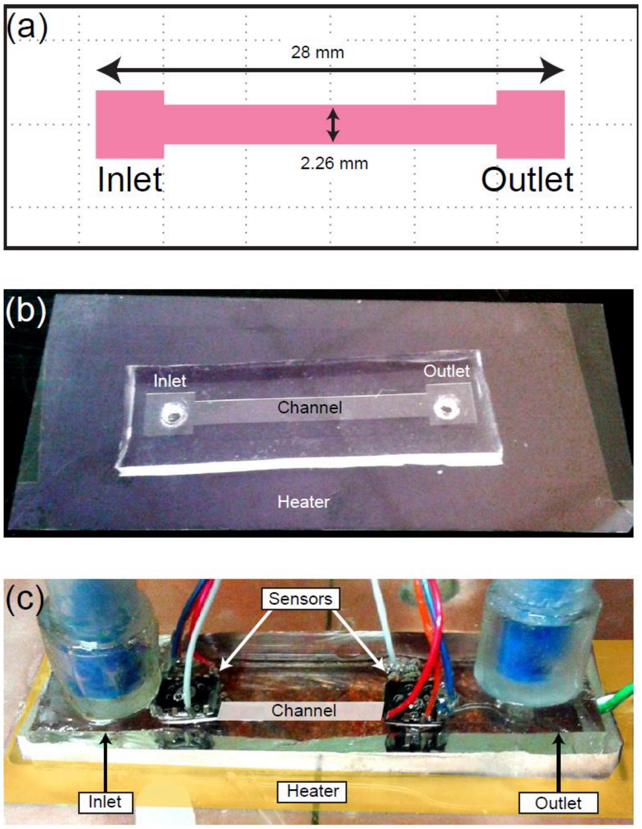

Figure 1: (a) Mask layout of channels showing lateral dimensions, (b) microchannel prototype without sensors and (c) photograph of PDMS-based microchannel with integrated pressure sensors.

The fabrication sequence for the device, including the integration of the pressure sensors, is detailed in figure 2. A mould for the channel is made by spin coating SU-8 photoresist on a Si wafer (a) and exposing the channel layout using a photomask (b). The SU-8 is developed to create a mould 100 µm in height. This height can be easily changed by altering the spin conditions, or by substituting a new resist. As well as the straight channel, presented here, the photomask also contains a multi-channel arrangement and many different layouts can be explored with varying aspect ratios and numbers of parallel channels. PDMS is then poured in to the mould (c) and dummy sensors placed in the wet PDMS (d). These dummy sensors were used to provide the cavity for the location of the working sensors. The dummy sensors are then removed (e) and when the PDMS has cured they are replaced with the working sensors (f), which each have 3 wires for connecting to the power supply and a data acquisition system. A second layer of PDMS is poured (g) and cured, to create an airtight seal. The PDMS is then peeled from the mould (h) and the bottom of the channel plasma treated and bonded to a glass slide that is coated in indium tin oxide (ITO) and serves as the heater (i). This heater is deposited using magnetron sputtered ITO which is annealed at 300 °C to improve its conductivity.

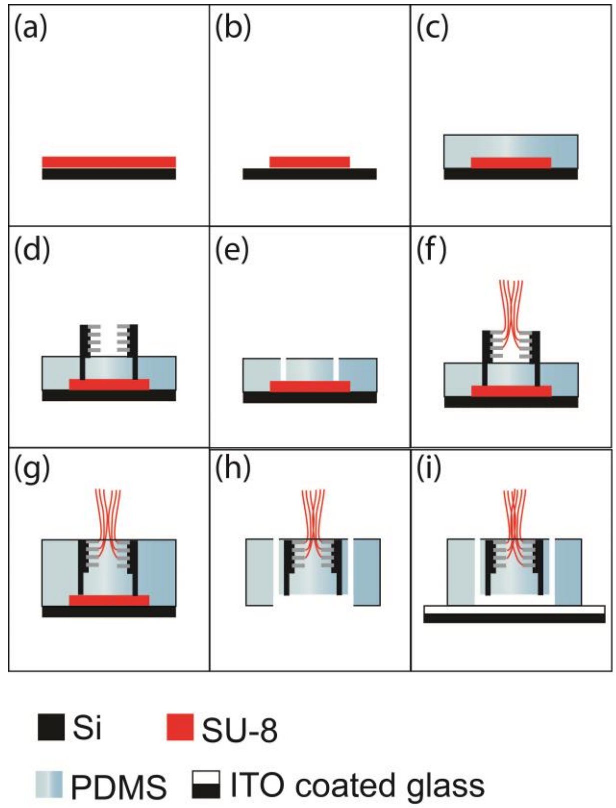

Figure 2: Cross-section of fabrication sequence associated with the production of the PDMS microchannel with integrated sensors.

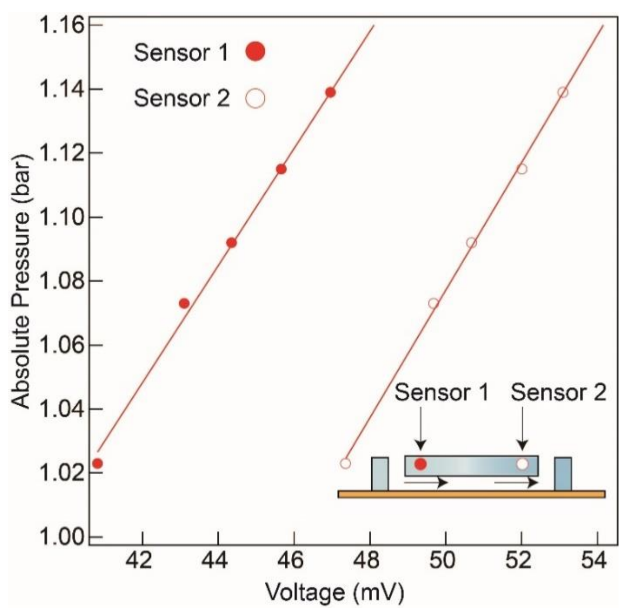

Figure 3: Calibration plot of the voltage response of the integrated pressure sensors as a function of the static pressure of FC-72 liquid at room temperature.

The HSC sensors are rated for operation between 0 °C and 50 °C and are designed for use with dry gases only and so sensors were initially protected with a Parylene coating. However, when testing them it was observed that the sensors functioned as expected when directly exposed to FC-72 (the working fluid). Hence, the sensors reported in this work were not Parylene coated and the resulting calibration curves are shown in figure 3. The observed linear response shows they are able to detect pressure in the millibar range and thus capable of detecting the acute pressure shifts associated with bubbles formed during boiling in the microchannel.

III. OPERATION

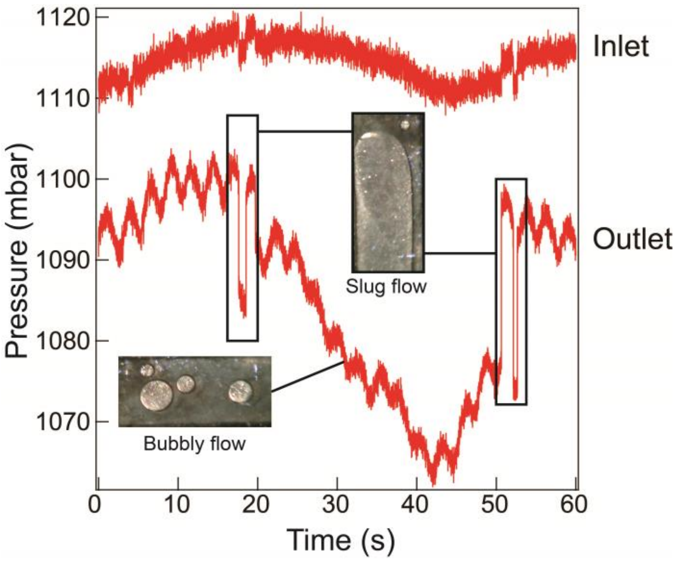

Figure 4: Example of the relationship of pressure (measured by the integrated pressure sensors) as a function of time.

Figure 4 shows an example of pressure in the channel as a function of time during microboiling. Simultaneous optical observations captured using a high speed (Nanosense Mk II, Dantec Dynamics) camera enabled boiling modes to be correlated with the output of the pressure sensors. Distinct boiling regimes can be seen quite clearly in the sensor near the outlet; high-frequency oscillations are indicative of bubbly flow and low frequency oscillations indicate the formation and expulsion of a large vapour slug from the system. Additionally, it can be observed that the pressure drops appreciably following the transition of a large vapour slug and this is due to the associated heat transfer out of the channel. With the pressure sensors located closely to the start and finish of the channel, the heat transfer at a given time can also be estimated locally with higher resolution data simply requiring additional sensors along the length of the channel. Simultaneous optical and pressure information associated with individual boiling features is at the cutting-edge of microboiling research and the reported system opens a pathway to explore a great number of different microchannel dimensions and arrangements.

IV CONCLUSION

This paper has presented a PDMS-based microfluidic device with integrated sensors to monitor microboiling with simultaneous optical measurements. The resulting device was used to characterise two-phase cooling and through its combined optical and pressure measurement capability, which can identify the unique features associated with two-phase boiling modes. The effectiveness of the device in application combined with robust and rapid fabrication facilitates the examination of microchannels with many different geometries and the approach can be easily adapted for other sensing applications.

REFERENCES

[1] A. F. Al-neama, N. Kapur, J. Summers, H. M. Thompson, "An experimental and numerical investigation of the use of liquid flow in serpentine microchannels for microelectronics cooling." App. Therm. Eng. Vol.116, 2017, pp 709–723.

[2] D. Bogojevic, K. Sefiane, A. J. Walton, H. Lin, G. Cummins, "Two-phase flow instabilities in a silicon microchannels heat sink." Int. J. Heat Fluid Fl. vol.30, 2009, pp 854-867.

[3] S. Wang, S. Yu, M. Lu, L. Zuo, "Microfabrication of plastic-PDMS microfluidic devices using polyimide release layer and selective adhesive bonding." J. Micromech. Microeng. vol.27, 2017, pp 055015.

[4] Y. Lu, F. Wang, H. Wang, "Boiling regimes in uncoated polydimethylsiloxane microchannels with a fine wire heater." Heat Mass Transfer vol.46, 2010, pp 1253–1260.

[5] D. C. Duffy, J. C. Mcdonald, O. J. A. Schueller, G. M. Whitesides, "Rapid Prototyping of Microfluidic Systems in Poly (dimethylsiloxane).", Anal. Chem. vol.70(23), 1998, pp 4974–4984.

[6] A. P. Colburn, W. J. King, "III-Relationship between heat transfer and pressure drop." Ind. Eng. Chem. vol.23(8), 1931, pp. 919-923.

[7] L. Wang, M. Zhang, M. Yang, W. Zhu, J. Wu, Gong, X., J. Wu, (2009). "Polydimethylsiloxane-integratable micropressure sensor for microfluidic chips." Biomicrofluidics vol.3, 2009, pp. 34105.

[8] C. D. Tsai, M. Kaneko, "On-chip pressure sensor using single-layer concentric chambers." Biomicrofluidics vol.3, 2016, pp. 24116.

[9] M. J. Kohl, S. M. Jeter, D. L. Sadowski, "A microfluidic experimental platform with internal pressure measurements." Sens. Actuators, A vol118, 2005, pp. 212–221.

[10] Y. Sekimori, Y. Yoshida, T. Kitamori, "Pressure sensor for micro chemical system on a chip." Proceedings of IEEE sensors 2004, 2004, pp. 516–519.

[11] J. Lichtenberg, A. Hierlemann, "Liquid-core, piezoresistive, fully polymer-based pressure sensor." The 13th international conference on solid-state actuators and microsystems, 2005. Digest of technical papers. TRANSDUCERS 2005 vol.2, 2005, pp. 10–13.

[12] C. Huang, J. W. Gregory, J. P. Sullivan, "Microchannel pressure measurements using molecular sensors." J. Microelectromech. Syst. vol.16(4), 2007, pp. 777–785.

[13] S. Foland, K. Liu, D. Macfarlane, J. Lee, "High-sensitivity microfluidic pressure sensor using a membrane-embedded resonant optical grating." Proceedings of IEEE sensors 2011, 2011, pp. 3–6.

[14] L. Pan, P. E. Arratia, "A high-shear, low Reynolds number microfluidic rheometer." Microfluid Nanofluidics vol.14(5), 2013, pp. 885–894.

[15] C. Wu, W. Liao, Y. Tung, "Integrated ionic liquid-based electrofluidic circuits for pressure sensing within polydimethylsiloxane microfluidic systems." Lab Chip vol.11, 2011, pp. 1740-1746.

[16] M. S. Cheri, J. Sadeghi, M. Salehi, (2014). "Real-time measurement of flow rate in microfluidic devices using a cantilever-based opto fluidic sensor." Analyst vol.3, 2014, pp. 431–438.