

Issues in the Practical Design of a Biomolecule Separation Device Using Two-Phase Coating Flow

There are myriad methods for fabricating micro- and nano-sized devices. Most, however, will likely never achieve a small unit cost and thus will only be used in high-end products. There are, however, macro-scale processes that can achieve high-throughput and small unit cost. Additionally, there are non-cleanroom processes. By exploiting the coupled dynamics of two-phase non-Newtonian fluidics, we can fabricate micro- and sub-micro devices by following conventional injection molding techniques, which are fast and cost-effective.

Fabrication of channels through μ -Injection Molding

Injection molding of channel

Injection molding (IM) is a plastics manufacturing technique that has been around for decades. The molds that are used can be expensive, but they also can be used to produce thousands of parts, so the cost/part is minimal. Furthermore, IM has a cycle time on the order of minutes.



Figure 1a. Micro-channel design

Thus, using our mold, which was machined through a collaboration with the Micro/Nanomachining sub-group, something on the order of 100 PMMA channels (Figure 1a) can be fabricated in a day. Of course, the channels then must be sealed and interfaced to the macro-world, which is still done by hand. However, the prep, sealing and interfacing processes only add approximately 20 minutes to the process (i.e. from separate parts to completed and ready-to-use channel).

Interstitial bonding of cover slip to channel

Once the channel has been molded, the cover slip must be bonded to the channel. There are many methods of achieving this, but the goals are the same:

- Complete sealing of the channel (i.e. no leaks)
- The absence of de-bonding even at high pressures
- Chemical resistance of the bonding material

Capillary flow offers a quick and easy means of not only bonding two pieces of PMMA but also sealing the channel. Interstitial bonding, a process whereby light-sensitive glue (LOCTITE® 3301) is loaded between the channel piece and a PMMA window, is used to bond two pieces. Capillary action drives the glue through the

interstitial space but retards flow into the channel. Two major advantages of this bonding method are that no alien material is introduced into the microchannel, and the surface chemistry within the sealed channel remains after bonding. Figure 2 shows the schematic of the interstitial bonding technique.

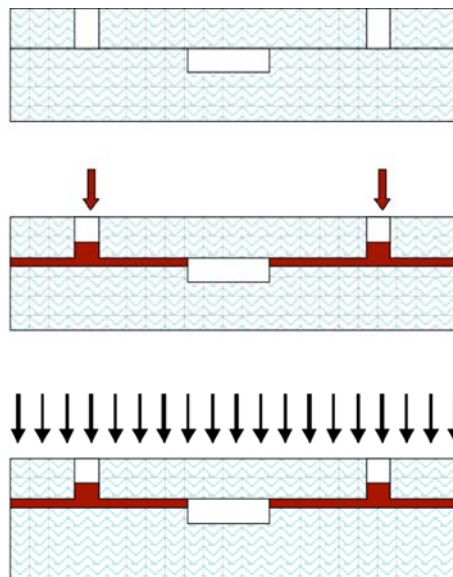


Figure 2. Schematic of the UV sealing method

Two-phase Newtonian fluidics

It is known that by flowing one material (liquid or gas) into another immiscible material, bubbles can be formed. Given the right conditions and a large enough difference in fluid viscosities, a single thread can be formed. For example, hollow plastic parts are manufactured by flowing a gas through a polymer melt prior to solidification. The same concept can be exploited on the microscale. The first step to understanding the dynamics of multi-phase flow on the microscale is to examine the Newtonian case. This allows for the study of surface tension effects without the added complexity of rheology. Figure 3 shows coring results for the Newtonian case in a 90 μ m wide by 90 μ m tall channel, and Figure 3b shows coring results within a circular capillary 100 microns in diameter.

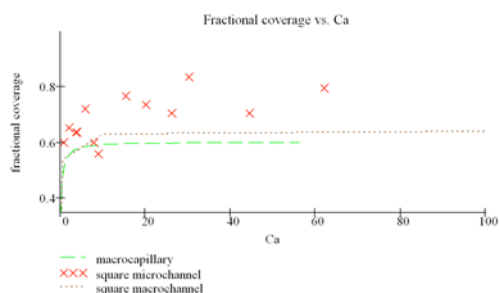


Figure 3. Coating thickness in a microchannel for a Newtonian fluid (data for square macrochannel adopted from Kolb and Cerro. Chem. Eng. Sci., v. 46 n. 9 pp. 2181-2195)

The coating thickness, referred to as fractional coverage in Figure 3, is a function of the Capillary number (Ca). The Capillary number is a dimensionless number that depends on bubble velocity, coating fluid viscosity and the interfacial tension between both fluids. The key point to notice is that at high enough Ca , the coating thickness should be (O) 60%. It is easy to see, then, how useful a curable material can be if it is used as the coating fluid. It is exactly that fact that is exploited in this research.

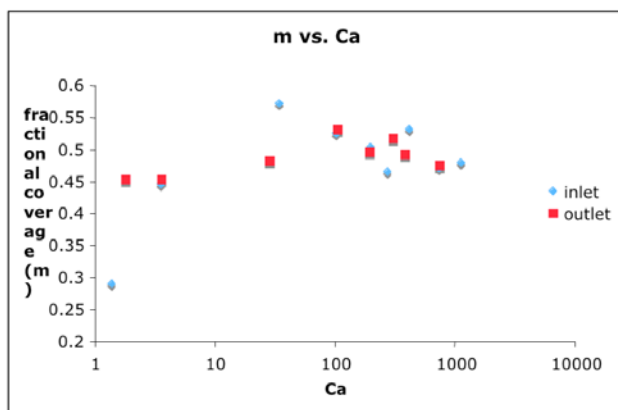


Figure 3b. Fractional coverage versus Ca for a circular microcapillary

The results for the Newtonian case should be independent of channel size. However, this research shows that the results can quickly diverge from what is expected. This is not because the physics change but rather because of a lack of control due to interfacing to the macro-world as well as the difference between transient and steady states. Because curing was begun immediately following coring, the outlet data points (in red boxes) represent a bubble shape furthest from the steady state. Due to interfacing and pressure issues, the unsteady state bubble is nearly independent of the Capillary number (i.e. flow rate). However, at longer times the bubble shape reaches a steady state, and we see a curve shape similar to that seen on the macro-scale (Fig. 3). Essentially, to fully realize the

benefits of this method, processing must either be long enough to reach a steady state throughout the entire capillary, or the pressure must be controlled in such a way that even at small times the bubble shape is close to its steady-state shape. Either case has its own difficulties, unfortunately.

Biomolecule separation

With the dynamics of two-phase flow known, the process can be used to easily and cheaply fabricate smaller channels within a pre-machined microchannel. Standard micro-injection molding will be used to make the base channel. Then, using UV-cured SU-8 (SU-8 2100), a smaller channel may be formed within the molded channel, following the details listed previously. The coating material plays multiple roles, though. Using SU-8 2100 as the coating materials allows us to take advantage of additional chemistry. Biomolecules can be separated within SU-8 channels, which is exactly what this research aims to achieve. Furthermore, if the coating is performed within glass channels (fabricated using femtosecond laser machining), an additional pyrolysis step can be added, which will form carbon on the walls of the coated channel. These also can be used for separations.

Current progress in SU-8 coated capillaries shows that electro-osmotic flow can be generated. The next step is to actually separate biomolecules. However, as with the coating process, separations involve their own difficulties. Electro-osmotic flow requires a voltage drop, but if any cracks are present in the capillary/coating, the voltage drop is affected and flow does not commence. Therefore, though separations are possible in SU-8 coated capillaries, certain handling protocols must be developed if this technique is to be used for future products.

Future directions

It has been shown that by using a viscoelastic fluid instead of a Newtonian fluid, the highest achievable coating thickness is between 80-90% of the channel dimensions. The trend is expected in microchannels and, because of the extreme shear rates, should be reached at lower flow rates than are necessary on the macroscale. Thus, combining a viscoelastic fluid and multi-coating runs should offer a cheap and fast means of fabricating micro-/nanodevices.

Publications

1. Boehm, M.; Koelling, K.; Steach, J.; Olesik, S.; "Fabrication and characterization of cored SU-8 microchannels for the separation of biomolecules" (in progress)
2. Boehm, M.; Koelling, K.; "Direct calculation of fractional coverage in micro-channels", J. Non-Newt. Fl. Mech., (in progress)
3. Boehm, M.; Koelling, K.; Lu, C.; Lee, L.J.; "Coating of Newtonian fluids in microchannels", (in progress)