Proceedings of the ASME 2009 International Mechanical Engineering Congress & Exposition
IMECE2009
November 13-19, Lake Buena Vista, Florida, USA

IMECE2009-10253

FLOW OF MICROFLUIDS IN CONVERGING MICROCHANNELS

Nelson Macken
Jong Hsien Lim
Department of Engineering
Swarthmore College
Swarthmore Pennsylvania 19081
nmacken1@swarthmore.edu
jlim3@swarthmore.edu

ABSTRACT

The interface between intersecting microfluidic multicomponent flow is investigated experimentally. Three microchannel configurations are studied. Each configuration has a main channel and an intersecting daughter channel. In two configurations, the channel cross sections are equal and square with the intersection either at 90 or 45 degrees. In the third configuration, the intersection is at 90 degrees, the cross sections are square and the daughter cross section is smaller than the main cross section. In the configurations with equal channel cross sections, microsphere solutions of 2, 4 and 7% spheres (by weight) are compared to each other as well as all water flows. Flow visualization is achieved using confocal fluorescence microscopy. A three-dimensional rendering of the location and shape of the interface is examined for a Reynolds number of approximately one. The presence of microspheres does not appear to strongly influence the location of the flow interface. For flows with equal cross section, the interface downstream of the junction is reasonably planer (two dimensional). Strong three-dimensional effects are shown for flows with unequal cross section.

INTRODUCTION

Many microfluidic applications involve the control and manipulation of flows through a series of junctions that provide flow mixing and distribution. At each junction, a separation surface appears that determines the distribution of flow. The design of the system requires knowledge of the position and shape of this surface.

These separation surfaces have been studied experimentally and, when appropriate, numerically. In dye studies, Rong and Carr [1] showed that low Reynolds numbers yielded a planar interface for circular diameters of equal diameter. Hitt and Lowe [2] and Peach *et al.* [3] used confocal microscopy in microchannels to capture three-dimensional volumetric reconstructions of the separation surface and also saw a planar tendency at low Reynolds numbers. Harris *et al.* [4] presented analytical and numerical solutions to flows in converging microchannels of various geometric cross sections. Experimental results for square microchannels with flows of varied viscosity ratios were also presented. Good agreement was achieved between the analytical and experimental results for a square channel. Reedy and Macken [5] presented results for microchannels of equal and square cross section intersecting at a right angle. They included microsphere solutions of 2 and 4% and concluded that the presence of microspheres had little effect on the shape of the interface.

In this study, we report results for three microchannel configurations. The first configuration has a main channel and an intersecting (at 90 degrees) daughter channel. The second microchannel configuration has a main channel and a daughter channel intersecting at 45 degrees. All channels in these two configurations have square and equal cross sections. In the third configuration, two channels intersect at 90 degrees but the daughter channel has a smaller square cross section than the main channel.

In the first two configurations, we compare flows of all water and water- microsphere solutions (2%, 4%, 7%). The water-microsphere flows have potential application to biological systems. Rigid microspheres can model red blood cells at particle volume fraction below 10% [5]. In the configuration with unequal channels, we illustrate the three dimensionality of the flow field. The combined flow Reynolds number (daughter plus main channel) is approximately one.

Copyright © 2009 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 07/02/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

Below we discuss our experimental methods, results and conclusions.

EXPERIMENTAL METHODS

Solution Preparation

The fluids used are either distilled water or microsphere solutions. In each test, there is a fluid with the fluorescent dye for the daughter channel and another non-fluorescing fluid for the main channel.

For the microsphere solutions, we begin with a 10% by weight beaded solution of 3.87 micron diameter polystyrene beads (microspheres) supplied by Bangs Laboratory (URL: www.bangslab.com). The microspheres have a density of 1.06 g/cc. We add enough glycerol and distilled water to have a total solution density of 1.06 g/cc and either 2%, 4% or 7% (by weight) microspheres. A few drops of surfactant, Tween ®, is added to prevent aggregation. To part of this solution, we add approximately 0.002 % fluorescent dye, fluorescence isothicyante, also known as FITC. This dye has an excitation wavelength of 488 nm. and emission wavelength of 520 nm. It glows a bright green.

Experimental Setup

The experimental setup consists of the flow module, delivery system and syringe pumps. (See Figure 1).

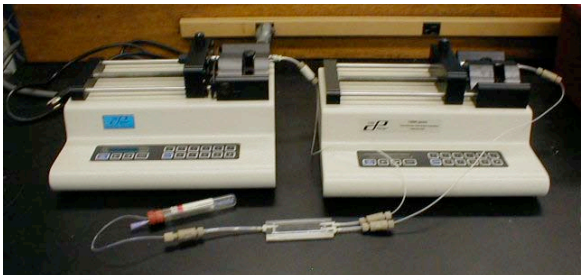

Figure 1: Experimental setup showing syringe pumps, flow module and delivery tubing.

There are three flow modules used in the investigation. Two modules have a main channel and an intersecting (at 90 degrees) daughter channel. In one of these, both channels have equal cross sections (127X127 micron). In the other, the daughter channel has a smaller cross section (127X127 micron) than the main channel (305X305 micron). The third microchannel configuration has a main channel and a daughter channel intersecting at 45 degrees. Both channels in this configuration have equal cross sections (127X127 micron). The flow modules are made from clear acrylic and are approximately 7.5 x 2.5 x 0.8 cm. The main channel and intersecting daughter channel are precision milled into the substrate. Clear tape is used to close the channels on the fourth side. Plastic fittings with sealant added to the threads are screwed into tapped fittings at the end of the channels to facilitate fluid delivery.

The delivery system consists of plumbing and attached syringes. The 0.16 cm. outside diameter polystyrene tubing is attached to the module and syringe using Luer and nylon fittings. Sealant and epoxy are used to eliminate leakage. Becton-Dickinson 1 ml plastic syringes are used. A tube assembly and syringe containing solution with dye is attached to the inlet of the daughter channel and a tube assembly and syringe with no dye is connected to the inlet of the main channel. A drainage tube assembly with test tube attached is fitted to the exit of the flow module.

The flow in each syringe is controlled by two Cole-Parmer 74900 series multichannel syringe pumps. These pumps have an accuracy of ± 0.5%. Typical flows are in the microliter per minute range.

Confocal Microscopy

Fluorescence microscopy utilizes lasers to excite individual fluorescent molecules at their characteristic wavelength. A camera connected to a computer is used to record the resulting image. Initial focusing of the flow in the module is done manually without fluorescence. All subsequent adjustments are computer controlled. In a confocal microscope, the focus is at a point. A two-dimensional image (slice) is obtained by scanning the flow field at a fixed depth perpendicular to the field of view. Subsequent slices are made at different depths, and a rendering of the data produces a three-dimensional image. The system and software allow the user to carefully specify how images are to be taken. Major adjustments include laser focus, power and wavelength range, scanning speed, pixel count and number of scans per slice. The number of slices and distance between slices is also set by the user. Our particular confocal microscope is an inverted Leica DM6000.

Experimental Procedure and Data Analysis.

The software displays the data on the computer monitor as a slice during the setup stage for each run. A run is defined as a set of slices for a fixed flow ratio, i.e., each syringe pump is set to a particular flow in the main and daughter channel respectively. The flow ratio is defined as the flow in the daughter (fluorescing) channel divided by the total flow (flow in the daughter channel plus flow entering the main channel). Steady flow must be observed before microscope adjustments can be implemented. Once the setup is complete, slices are scanned sequentially for the entire depth of the channel. This family of slices for a set flow is stored in a file and the flow is adjusted for the next run. Adjustments of microscope settings after the first run are unnecessary. A complete set of runs includes all flow ratios possible from minimal to maximum. The total flow (daughter plus main) is held constant.

The Leica computer software has the capability of displaying three-dimensional renderings of the fluoresced flow field. However, we typically do slice analysis and volume reconstruction off line. We currently use ImageJ, which is publicly available on the Internet. Two quantities are of importance in our investigation. The first is the position of the interface (separation surface) at a particular flow ratio down stream of the intersection after the flow has stabilized and is

Copyright © 2009 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 07/02/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

fully developed. The software allows for measurement of the interface location (taken from the side of the main channel with the fluorescing fluid) in pixels. A fraction is formed with this number divided by the measured channel width in pixels. The second quantity of interest is the curvature of the interface perpendicular to the flow direction. The interface position for each slice in a particular run provides this information. We typically take 20-40 slices. The error in measurement is ~ ± 5%. Data is transported from the rendering software to Excel where final data analysis and plotting occurs.

RESULTS

Results for the three flow configurations are reported below. The configuration with unequal cross section illustrates a three dimensional flow at the intersection. For the configurations with equal cross section, the effects of microspheres and angle of intersection are demonstrated.

Flow with unequal cross sections:

Results for all water flow in the module with different cross sections is shown in Figure 2. In this example, the flow ratio is 0.5. As mentioned above, the confocal microscope yields slices taken at specific depths perpendicular to the field of view at the intersection. Each slice reveals the portion of the channel that is occupied by the fluorescing fluid.

Figure 2a shows the module configuration. Note that the flow in the fluorescing smaller (daughter) channel enters at the top section of the larger channel. A two-dimensional view of the flow from the top (as shown on Figure 2a) is shown on Figure 2b. The entering flow (shown in green) appears to occupy a large portion of the main channel. Figure 2c illustrates the three dimensionality of the flow. Shown are renderings of slices produced by the confocal microscope. Near the bottom of the main channel, the entering flow field is much smaller than near the top opposite the opening in the daughter channel. This is to be expected and it illustrates the importance of three-dimensional effects for this geometry.

Flow with equal cross sections intersecting at 90 and 45 degrees:

For the modules with equal cross sections, complete sets of runs were made for 2%, 4% and 7% microsphere solutions as well as all water for comparison.

Slices taken at mid channel depth at three different flow ratios (0.2, 0.5 and 0.8) are shown in Figures 3 and 4 for a 7% microsphere solution. Other flow ratios not shown include 0.3, 0.4, 0.6 and 0.7. Slices at other depths, flow ratios and other solutions (2%, 4% and all water) show similar behavior. The interface is clear, well defined and stabilizes to a fixed position almost immediately downstream from the intersection in both the right and 45 degree intersections. The interface location at

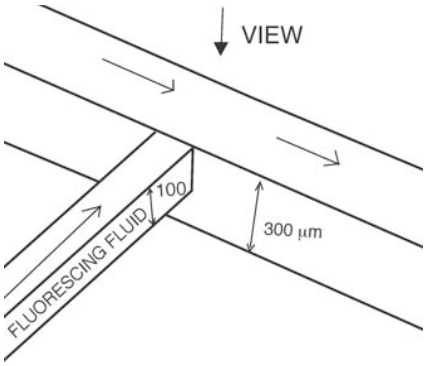

Figure 2a: Module Configuration

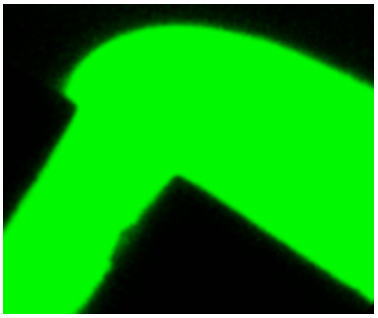

Figure 2b: Two-Dimensional View of Flow

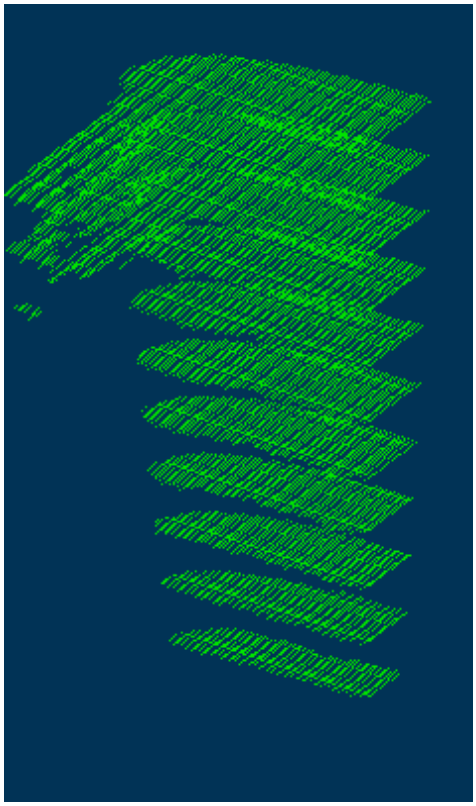

Figure 2c: Three-Dimensional Flow

Copyright © 2009 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 07/02/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

Figure 3a: Flow ratio 0.8

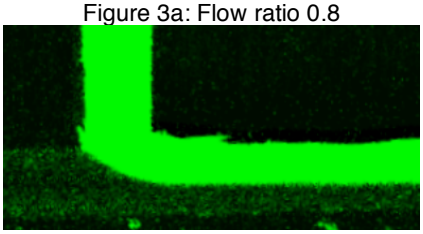

Figure 3b: Flow ratio 0.5

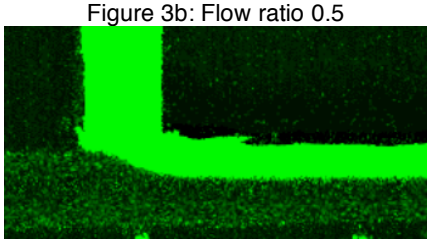

Figure 3c: Flow ratio 0.2

Figure 3: Slices at mid depth for 7% solution. Right angle flow intersection

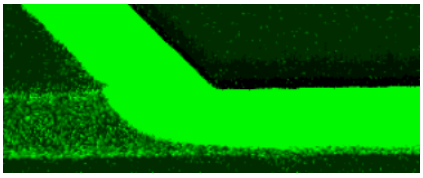

Figure 4a: Flow ratio 0.8

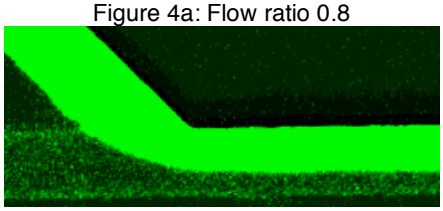

Figure 4b: Flow ratio 0.5

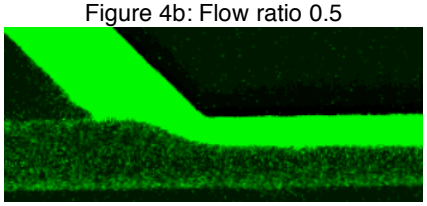

Figure 4c: Flow ratio 0.2

Figure 4: Slices at mid depth for 7% solution. 45 degree flow intersection

fixed flow ratios for the two configurations is also different. This is illustrated more dramatically in Figures 7 and 8 (discussed later). The shape of the interface at the intersections for the two configurations can be quite different as shown by comparing Figure 3c with Figure 4c at flow ratio of 0.2.

As mentioned earlier, the position of the stabilized interface at particular flow ratios is an important design parameter. Figures 5 and 6 show the interface locations of all flow ratios for 0%, 2%, 4% and 7% microsphere solutions for both configurations. Interface locations for slices at mid depth (relative to the direction of viewing) were plotted in the figures. Plots for slices at other depths show similar behavior. Note that there does not appear to be a fixed trend of the data with respect to sphere density. The data for all water flow provides a reasonable representation of the data. From this we conclude that the presence of spheres does not strongly influence the interface location.

Another important feature of the flow is the curvature of the stabilized interface. The curvature of the interface (location of the interface with depth) is shown for typical data in Figures 7 and 8. Flow ratios of 0.2, 0.5 and 0.8 for a 7% microsphere solution are illustrated. Our data for other flow ratios and other solutions show similar behavior. The figures show that the interface is reasonably planar. Previous studies for flows in intersecting microchannels report similar results. Peach *et al* [3] report modest curvature for flow in equal but non-square microchannels intersecting at right angles with fluids of unequal viscosities. Reedy and Macken [5] report reasonably planer flow for equal cross section flows intersecting at right angles and microsphere solutions of 0%, 2% and 4%. Our results imply that perhaps only two-dimensional investigations are required to adequately describe the flow downstream of intersections for channels of square and equal cross section. Figures 7 and 8 also show that the location of the interface at equal flow ratios is different for the 45 and right angle intersections. This feature is also demonstrated by data for other flow ratios and other solutions.

CONCLUSIONS

We have performed studies with microsphere solutions in intersecting microchannels of square cross section at Reynolds number approximately one. One channel configuration has a right angle intersection with unequal square cross sections. We illustrated the three dimensional features of this flow. Two channels have equal square cross sections and intersect either at a right angle or 45 degrees. The flows in these configurations include 0%, 2%, 4% and 7% solutions of water and microspheres. These flow fields immediately stabilize following the intersection for both configurations. The location of the stable interface (relative to the cross section) following the intersection is relatively insensitive to concentration of microspheres but dependent on the angle of the intersection. The interface is approximately planar regardless of the presence of microspheres or angle of intersection.

Copyright © 2009 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 07/02/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use

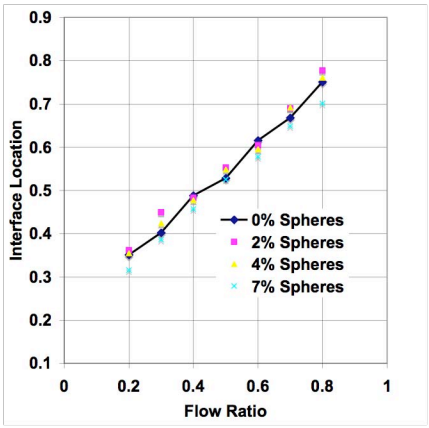

Figure 5: Right angle flow intersection. Interface location as a function of flow ratio. Data for mid depth shown.

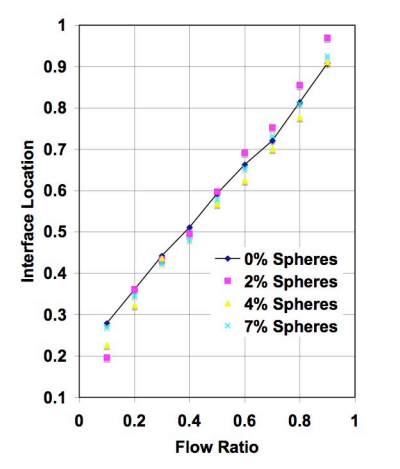

Figure 6: 45 degree flow intersection. Interface location as a function of flow ratio. Data for mid depth shown.

ACKNOWLEDGEMENTS

This work was supported by a faculty research grant from Swarthmore College. We would also like to thank faculty from the Swarthmore College biology department for their assistance with operation of the confocal microscope and the engineering support staff for their fabrication and software assistance.

REFERENCES

[1] Rong, F.W., Carr, R.T., 1990, "Dye Studies on Flow through Branching Tubes", Microvascular Research, **39**, pp 186-202.

[2] Hitt, D.L., Lowe, M.L., 1999, "Confocal Imaging of Flows in Artificial Venular Bifurcations", ASME Journal of Biomechanical Engineering, **121**, pp. 170-177.

[3] Peach, J.P., Hitt, D.L., Dunlap, C.T., 2000, "Three Dimensional Imaging of Microfluidic Mixing Surfaces Using Dual-Channel Confocal Microscopy". Proceedings of the 2000 ASME MEMS, **2**, pp. 497-503.

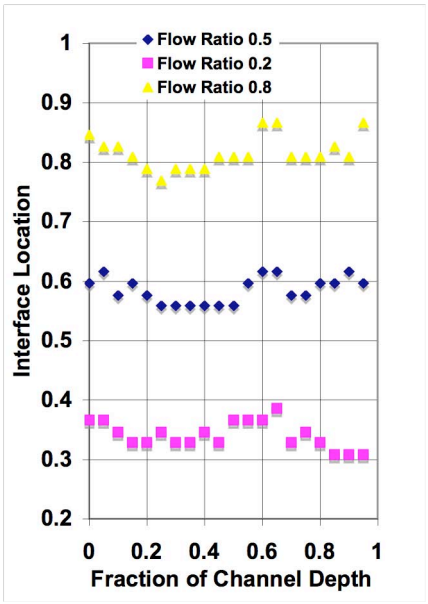

Figure 7: 45 degree flow intersection. Interface curvature for 7% microsphere solutions at selected flow ratios

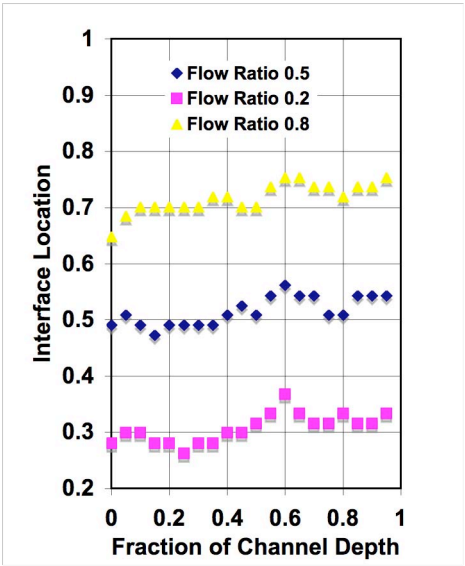

Figure 8: 45 Right angle flow intersection. Interface curvature for 7% microsphere solutions at selected flow ratios.

[4] Harris, T.R., Hitt, D.L., Macken, N., 2002, "Prediction of Interfacial Positions in Steady Converging Microchannel Flows at Low Reynolds Numbers", Proceedings of the IMECE'02 International Mechanical Engineering Congress and Exposition. IMECE2002-33776.

[5] Reedy, A.B., Macken, N., 2008, "Flow of Microsphere Solutions in Converging Microchannels", Proceedings of the IMECE'08 International Mechanical Engineering Congress and Exposition. IMECE2008-664496

Copyright © 2009 by ASME

Downloaded From: https://proceedings.asmedigitalcollection.asme.org on 07/02/2019 Terms of Use: http://www.asme.org/about-asme/terms-of-use