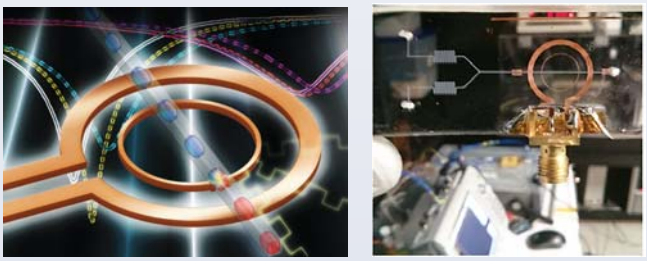
A Microwave/Microfluidics Integrated Label-Free Detection and Content Sensing System for Point-of-Care Applications

Gurkan Yesiloz[a], Muhammed Said Boybay[a,b], Carolyn L. Ren*[a]

Introduction

This study presents a sensitive, low-cost, portable microwave-microfluidics integrated system suitable for detection of droplet presence and label-free sensing of individual droplet content in microfluidic devices. Most droplet-based microfluidic studies rely on high speed imaging to provide details of droplet generation and transport, which require expensive and bulky high speed camera, and exhaustive post imaging analysis. Electrical techniques allow the miniaturization of multiple sensor arrays and their integration into one single microfluidic chip with low power requirement. Conventional capacitive and impedance detection approaches operate at low frequencies, which causes either low signal-to-noise ratio or long response time and thus limit their applications to droplet microfluidics where droplets are generated at high frequencies.

On the other hand, microwave technology, as a versatile non-optical method, has the potential to address the above issues because it eliminates the need for chemical modification or physical intrusion, and operates at high frequencies (i.e. GHz). It differentiates materials based on their electrical properties including electrical conductivity and/or dielectric constant.



Description of the microwave sensor. A capacitive region is used as the sensing and heating region. The resonator is excited by a loop and the microwave energy is transmitted to the loop by a coplanar transmission line. The excitation structure was optimized to provide highest energy coupling to the resonator.

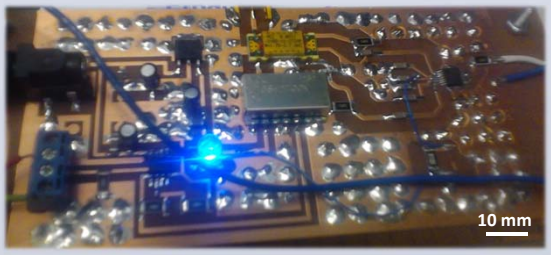
Objectives

1. Building-up miniaturized microwave/microfluidics system to realize high-throughput droplet presence detection and counting.
2. Label-free sensing of individual droplet contents in microfluidic systems.
3. Selective and rapid heating of individual droplets.
4. Developing portable and cost-effective miniaturized system by means of removing bulky and expensive off-the shelf components for point-of-care applications.

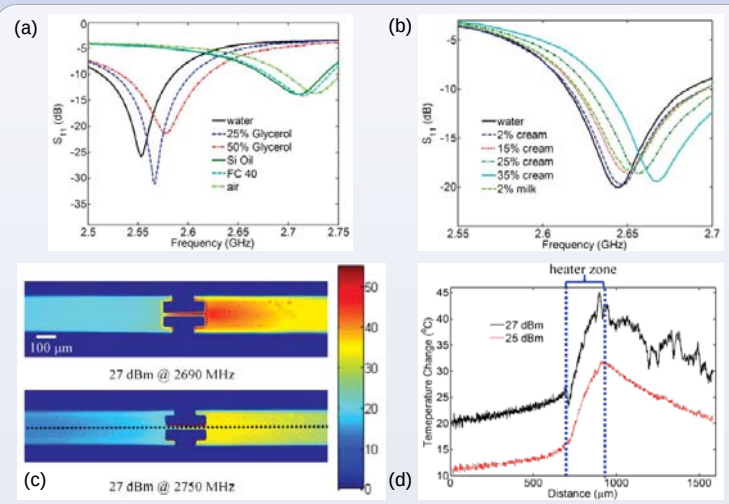
Methodology

1. Design a microwave custom circuitry
2. Design sensitive microwave resonators
3. Use inexpensive and surface mount components
4. Eliminate vector network analyzer (VNA) and signal generator
5. Implement proper fabrication protocol for fabrication and integration of microfluidic/microwave device.

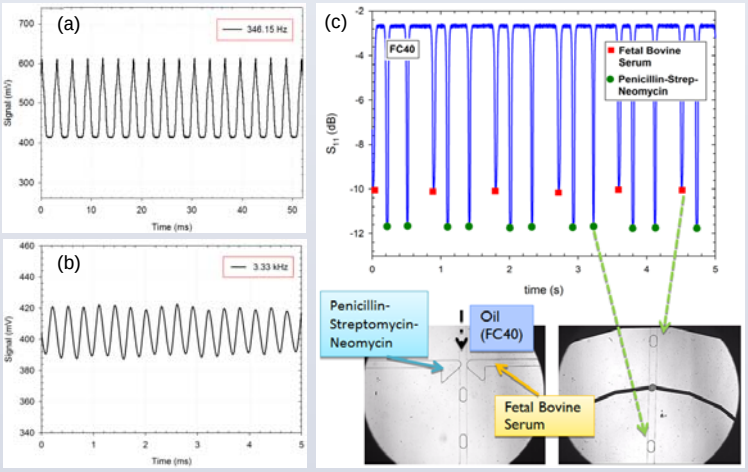
Results



The reported microwave custom circuitry is designed for label-free droplet presence detection and content sensing. The circuitry generates microwave signal as well as manipulates and correlates microwave signals into physical meaning. Surfaces mount components are used in order to make the system light-weight and portable.



(a) The reflection coefficient of the resonator was monitored to detect the changes in the channel. (b) The response of the sensor against dairy fluids, 2% milk and 35% cream diluted with different ratios were compared. (c) Showing heating feature of the sensor; temperature depends on the excitation frequency and input power. (d) The temperature distribution along the channel at 2.69 GHz is plotted for 27 dBm and 25 dBm input powers. The temperature increases with the operating frequency within the heating zone.



High-throughput droplet detection and counting (a) 346 Hz, (b) 3.33kHz. A total count of 2 million droplets was counted in ten minutes without missing any droplets. (c) Showing label-free content sensing of individual droplets; the coordinated optical imaging and microwave sensing results for Fetal Bovine Serum and Penicillin antibiotic mixture droplets.

Conclusion

- Demonstrated a system which is combination of a custom microwave circuitry and microwave-microfluidics integrated sensor for label-free detection and content sensing of individual droplets for point-of-care applications.
- The proposed system is a light-weight, cost-effective, portable, and a fast tool for on-chip droplet detection and sensing which eliminates bulky bench-top equipment.

Contact Information

[a] Department of Mechanical and Mechatronics Engineering, *University of Waterloo, 200 University Ave W., Waterloo, ON, Canada N2L 3G1,*

[b] *Department of Computer Engineering, Antalya International University, Universite Caddesi No:2, 07190 Antalya, Turkey.*

Fax: (519) 885-5862;

Tel: (519) 888-4567 x33030;

E-mail: c3ren@uwaterloo.ca

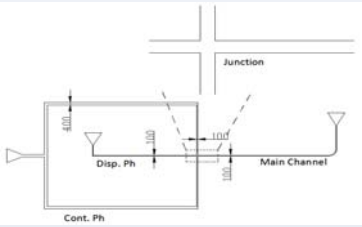
NSERC CRSNG

Model of Droplet Generation in Flow Focusing Devices Operating in the Squeezing Regime

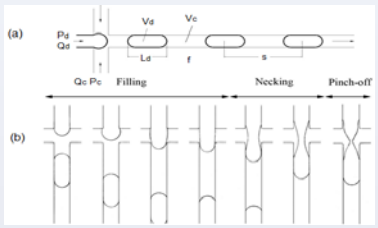
Xiaoming Chen[a], Tomasz Glawdel[a], Naiwen Cui[a], Carolyn L. Ren*[a]

Introduction

This work presents a model describing the droplet formation process in microfluidic flow focusing devices operating in the squeezing regime. The model considers the influences of channel geometry (height to width ratio), viscosity contrast, flow rate ratio and capillary number on droplet size, spacing and formation frequency. This model is validated by comparing predictions from the model with experimental results.



Sketch of chip design. The length of the main channel was set to be 2.5cm



Droplet generation cycle in the flow focusing device with three stages: (i) filling stage (ii) necking stage (iii) pinch-off stage

Objectives

1. Build a comprehensive model with minimal correlations;
2. Predict volume of droplets considering the 3D curvature of droplet shape;
3. Study all the possible influencing parameters on droplet formation process.

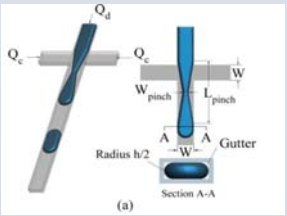
Methodology

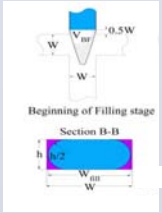
1. Droplet formation process can be estimated as a quasi-steady state.
2. Divide the droplet formation process into two sections (Filling stage, Necking stage). Pinch-off stage can be neglected compared to the other two stages.
3. Estimate the time of each section separately based on the conservation of mass for the dispersed and continuous phases.
4. Four parameters L_{fill}, W_{fill}, L_{pinch}, W_{pinch} are defined to estimate the volumes at each stage.
5. Semi-analytical models are built to estimate the four parameters.

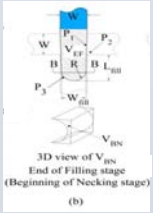
$$V_d = Q_d \cdot T = \frac{Q_d}{f} \qquad T = \Delta t_{filling} + \Delta t_{Necking}$$

$$\Delta t_{filling} = \frac{V_{EF} - V_{BF}}{Q_d} \qquad \Delta t_{Necking} = \frac{V_{EN} - V_{BN} + V_{gutter}}{Q_c}$$

$V_{BF}, V_{EF}, V_{EN}, V_{BN}, V_{gutter}$ can be estimated by the formula $V = hA - \frac{h^2}{2}(1 - \frac{\pi}{4})l$







(a) The estimated 3D shape of droplet. The out of plane curvature is approximated as h/2. (b) The 2D shapes of droplet at the transitions between each stage, where V_{BF} and V_{EF} represent the droplet volume at the beginning and end of the filling stage, respectively, V_{BN} and V_{EN} the volume of the continuous phase in the V-shape at the beginning and end of the necking stage, and V_{gutter} the volume of the continuous phase bypassing the gutter during the necking stage

➢ Determine L_{fill}

Modified the model developed by S. W. Tchikanda, et al by considering viscosity ratio effect and non-uniform cross-section

Equation of L_{fill} $$\frac{L^*_{fill}}{(1 + 0.2{L^*_{fill}}^{-1.4})^2} = \frac{2u^*_g}{w^*_{fill} g(\eta)} \frac{h^{*2}}{Ca}$$

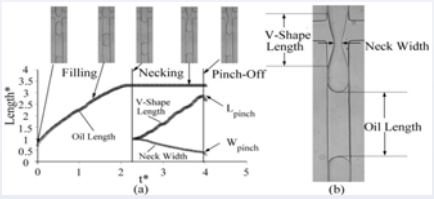
➢ Determine W_{fill}

w_{fill} is very close to the width of channel and can be estimated as 0.96w

➢ Determine W_{pinch}

$$P_{neck} - P_{tip} = \gamma\left(\frac{2}{w} + \frac{2}{h}\right) - \gamma\left(-\frac{1}{R_{neck}} + \frac{2}{w_{pinch}}\right) = 0 \Rightarrow w^*_{pinch} = \frac{h^*}{1 + h^*}$$

➢ Determine L_{pinch}



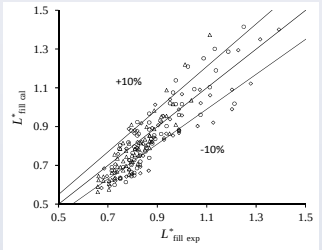
$$\frac{\Delta L^*_{pinch}}{\Delta w^*_{pinch}} = \frac{v^*_l}{v^*_w}$$

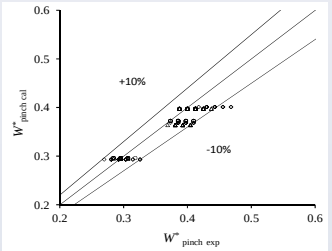
$$L^*_{pinch} = 1 + Cg(\eta)\frac{1}{1 - V^*_{gutter}}\frac{1}{1 + h^*}$$

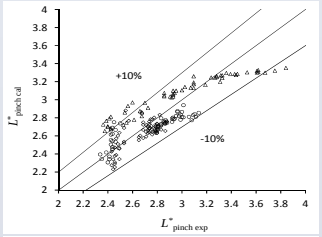
Variations of V-shape length, neck width and oil length during a droplet formation cycle

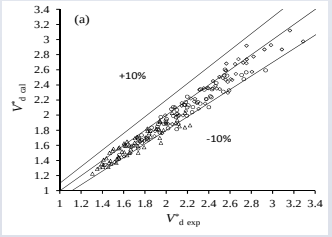
Results

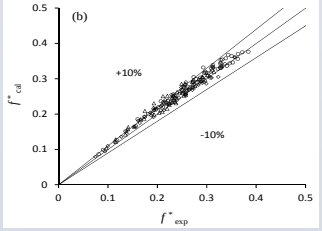
Experimental results VS. calculated results: L_{fill}, W_{pinch}, L_{pinch}, V_d, f and s

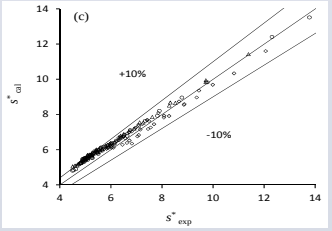












Conclusion

- The shape deformation of droplet during a formation cycle is accurately modelled based on the conservation of mass for the dispersed and continuous phases by considering the 3D curved surface of the droplet.
- Predictions from the model are in good agreement with experimental data for various conditions including different geometries, flow rate ratio, capillary number and viscosity contrast. Most of the experimental data fall within $\pm 10\%$ of the predicted values.
- The model developed here applies to the droplet formation in the squeezing regime where the droplet length is usually larger than channel width (slugs). For droplet length small than the channel width, it is not applicable.

Contact Information

[a] Department of Mechanical and Mechatronics Engineering, *University of Waterloo, 200 University Ave W., Waterloo, ON, Canada N2L 3G1,*
Fax: (519) 885-5862;
Tel: (519) 888-4567 x33030;
E-mail: c3ren@uwaterloo.ca

NSERC CRSNG