NANOJET CONTROLLED DROPLET EMULSION IN MICROFLUIDIC CHANNELS
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ABSTRACT
A novel microfluidic system for generating water-in-oil nanojet droplet emulsions has been fabricated and analyzed. The generation of the controlled size emulsion is achieved through the shearing and the relaxation of the dispersed water phase in between the continuous oil phase. The size of the emulsion is controlled by the flow rates and is capable of generating droplets as small as a few microns in diameters in a 30μm by 40μm cross sectional area channel without the use of surfactants.

INTRODUCTION
The developments of droplet emulsions have been of great interest, first as models for studying surface tension phenomena and then as drug delivery vehicles. This extensive research has resulted in numerous publications that uncover the fundamental physics of droplet break-up [1-3] and methods for generating microemulsions [1-3]. The first analysis of droplet break-up in flow fields was published in 1934 by Taylor [4] to consider the distortion of droplets caused by viscous stress exerted by the continuous phase. Subsequent works by numerous authors have concluded that droplet breakup occurs when the viscous stress is greater than the effect of surface tension of the droplet [4]. Summarizing these factors, the criteria for droplet breakup is determined by the critical capillary number, expressed as $Ca = \frac{\eta_c G_0}{\sigma}$ where $\eta_c$ is the viscosity of the continuous phase, $G$ is the critical shear rate, $r$ is the radius of the droplet, and $\sigma$ is the interfacial tension between the continuous and dispersed phases. The current formulation of emulsions, commonly used in manufacturing liposomes, relies on spontaneous formation through bulk agitation [3] or extrusion through nano/micro pores [5]. These methods do not lend themselves to dynamic control of individual droplet size. Recently, T-section microfluidic channels were demonstrated to produce droplet emulsions [6-8]. However, as opposed to asymmetric T-sections, our method employs a symmetric co-
flow design to generate nanojet droplet emulsions. This novel design first induces instability of the dispersed phase for controlled spatial shearing and subsequently relaxes the viscous stress in the continuous phase. As a result, the deformed stream separates into droplets of controlled sizes at predetermined rates. We have used oleic acid as the oil for this report although other oils have also been successfully used. This method holds great promise to generate micron and submicron emulsions at desired generation rates with or without the presence of surfactants to control the precision of drug encapsulation and chemical mixing.

EXPERIMENTAL METHODS

Droplet generations

The PDMS channel is fabricated using SU-8 molds and is sealed against a microscopic glass slide through oxygen plasma binding [9]. The inlets are attached with plastic tubing connected to syringes loaded with water and oleic acids. The water is dyed with napthol green to indicate the water phase under light microscopy. The syringes inject at constant flow rates controlled by Harvard 2000 pumps. The outlet of the PDMS channel is connected to the atmosphere. To avoid the surface complications caused by water adhesion to PDMS, the oleic acid is injected first to completely fill the channel before water is injected. The variation in flow rates of water and oleic acids is changed in steps using the digital control pad built onto the pumps. Video microscopy is used to measure both the speed of droplet generation and the drop dimensions.

RESULTS AND DISCUSSIONS

Effects of channel geometry

Figure 1(left). Sequential mapping of the droplet generation process. Starting from (A), due to the excessive shear stress developed at the contraction point, the droplet elongates into a nanojet (B). At (C) the stream expands due to the decrease in shear stress. Finally in (D) the droplet separates due to surface relaxation.
Figure 2(right). Droplets generated at various (water / oleic acid) flow rates. The speed of generation increases and the droplet size decreases from (A) to (C) as the flow rates of the continuous phase increases.

Figure 1 is an image of the droplet generation process. Since the injected fluids will be in an equilibrated state inside the channel, the fluids in the disperse and the continuous phases are dictated by the location of the inlet channels. The fluid injected into the top inlet will become the dispersed phase, and the fluid injected into the bottom inlet will become the continuous phase. The mechanism of droplet formation is caused by shearing and subsequent relaxation of the deformed droplet. In figure 1 the dispersion phase first undergoes a maximum deformation at the contraction point and then relaxes as it goes through the expansion channel. During deformation if the conditions becomes critical (capillary number exceeds the critical) then the stream deforms and stays in the highly elongated shape until it pasts the necking section. Once inside the expansion channel, the viscous stress exerted by the continuous phase quickly decreases as the channel expands, allowing droplet to separate as the surface tension and the pressure inside the dispersed phase relaxes the drop back to spherical shape.

Control of emulsion sizes
The viscous stress exerted on the dispersed phase is evident experimentally. The magnitude of the viscous stress exerted by the oleic acid is reflected by the increase in flow rate as shown in figure 2 that the geometry of the tip becomes sharper as the increasing viscous stress stretches the water surface. This indicates an increase in shear force and causes a decrease in droplet sizes as shown in figure 3.

Figure 3. Flow rates vs. sizes of droplets

Figure 4. Droplet size in (μm) vs. formation time at water flow rate of 1 μl/min

Generation speed
The speed of the droplet generation from the nanojet is controlled primarily by the flow rate of the dispersed phase. In figure 3 it is shown that as the droplet sizes increases, the time it takes to form the droplet also increases. In several different flow rates studies it
was shown that the flow rate of the dispersed phase has a much greater impact on the 
droplet generation rate than on the emulsion sizes. As the water flow rate decreases, the 
droplet sizes remained unchanged at the given continuous phase flow rates, but the speed 
of the droplet generation decreases by several order of magnitude. The control of droplet 
generation speeds becomes crucial in controlling the dynamic arrangements and the 
fusion of diversity of chemical solution for biochemical assays.

![Droplet generation speeds](image)

**Figure 5.** Droplets of same sizes are generated at different speeds by controlling the 
water flow rates.

**CONCLUSION**

The results presented here have demonstrated the ability to rectify and control the 
generation of various droplet sizes through actively controlling the inlet flow rates of the 
nanojet. Furthermore, the small size and disposability makes this PDMS based MEMS 
device a real bargain to be used for industrial and biomedical purposes. The system 
presented here is easy to setup, modify, but yet provides precise control over the size and 
the speed for the generation of microemulsions. Its simplicity makes the system an 
advanced platform for 1) combinatorial chemistry based on droplets, 2) synthesis of 
molecular drugs (genes, proteins, etc.) and food products, 3) new tools for analyzing 
biocolical reactions, and 4) innovative and efficient ways to synthesize various 
artificial cells (e.g. liposomes) with specified biological functions.

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