Acoustic standing wave based microsystem for low-concentration oil detection and separation

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Detection and quantification of extremely small amount of oil on site and at low cost has broad applications in environmental monitoring, both in oil spills as well as in routine marine/costal ecosystem monitoring. For example, dispersed oil, generated through the use of chemical dispersants in oil spills to break up oil slick into small droplets so that they can be rapidly diluted in 3D space are the greatest concern and poses the most challenges in detection. Fluorometry is the current standard method, however is bulky and expensive, limiting its wide deployment in the field. Here we demonstrate for the first time the development of an acoustic standing wave based microfluidic platform capable of processing large amount of liquid samples from which dispersed oil can be concentrated and separated to a detectable level by acoustophoretic force. The microfluidic platform consists of a recirculation channel structure into which dispersed oil droplets can be continuously separated from the main sample flow stream. A piezoelectric transducer attached at the bottom of the silicon-glass microfluidic channel creates the acoustic standing wave that exerts acoustophoretic force to oil droplets. An optical detector measures the presence of concentrated oil droplets by their distinct fluorescent signatures.
INTRODUCTION

Detecting and accurately quantifying extremely small amount of oil from the environment rapidly at low cost has broad applications in environmental monitoring, including oil spill monitoring in the ocean and oil leakage monitoring in water and soil. In most large-scale oil spills, chemical dispersants are commonly used to break down oil slicks into small droplets (sub 100 μm diameter) to rapidly disperse the spilled oil in the 3-D space. However the amount and extend of these oil droplets transported to coastal area is difficult to monitor, and thus the short-term and long-term effects of these oil droplets are not fully understood. Standard fluorometry method requires expensive and bulky equipment, limiting its wide deployment in the field [1]. Acoustic standing wave based particle separation has drawn significant interest due to its simple setup and highly efficient separation based on particle’s vibro-acoustic properties which include size, density and compressibility [2]. Here we present for the first time the development of a high throughput continuous flow microfluidic acoustophoretic crude oil droplet separation and detection system with integrated optical detection module.

METHODS

Principle of 1-D Acoustophoretic Force

In an aqueous straight channel where acoustic standing wave is formed, the crude oil droplet would experience a y-direction acoustic radiation force $F_a$, which is given by Equation (1) [3, 4]

$$F_a = -\left(\frac{\pi p^2 V_o \beta_w}{2\lambda}\right) \Phi(\beta, \rho) \sin(2k y)$$

where $p$ is the acoustic pressure amplitude, $V_o$ is the volume of the oil droplet, $\beta_w$ is the compressibility of water, $\lambda$ is the wavelength of the acoustic field, $k$ is the wavenumber defined by $2\pi / \lambda$, and $\Phi(\beta, \rho)$ is the so called acoustic contrast factor which is given by Equation (2) [3, 4]

$$\Phi(\beta, \rho) = \frac{5\rho_o - 2\rho_w - \beta_o}{2\rho_o + \rho_w}$$

where $\rho_o$ and $\rho_w$ are densities of oil droplet and water, $\beta_o$ and $\beta_w$ are compressibilities of oil droplet and water, respectively. Since crude oil has negative contrast factor, it would be moved to the pressure antinode in the acoustic standing wave.

FIGURE 1 shows the schematic drawing to illustrate the acoustophoretic force oil droplets experience and the direction of oil droplet motion (black). In this experiment, a 1.93 MHz sinusoidal signal was applied to the piezoelectric transducer to create half-wave resonance in the microchannel, therefore oil droplets would move towards sidewalls where the acoustic pressure antinodes form.

![FIGURE 1](image-url)
Crude Oil Droplet Separation and Detection

The developed oil droplet separation and detection system consists of a center flow through channel with waste and collection outlets (FIGURE 2). A piezoelectric transducer positioned underneath the separation region of the Si/glass chip excites the oil droplets and pushes them toward the channel sidewalls. Thus, oil droplets move to the two side channels that are then combined into a single channel for optical detection. Half-wave resonance was achieved by actuating the transducer at 1.93 MHz. For detecting the separated oil droplets, the intrinsic fluorescent property of crude oil was used. A compact and portable fluorescence detector composed of a blue LED light source and a PMT detector as well as filters and dichroic mirrors was developed and utilized here. The output voltage signal from the PMT was collected using a data acquisition module (NI 9219 DAQ, National Instruments, USA) and recorded through a LabVIEW (National Instruments, USA) program.

For system characterization, crude oil droplets suspended in water with 2% v/v Tween 20 surfactant were made by a T-junction droplet generator to obtain uniformly sized droplets and served as a mock sample. The generated droplets were then injected into the droplet separation chip with a syringe pump (Pump 11 Pico Plus, Harvard Apparatus, USA). Sinusoidal signal was supplied by a function generator (AFG3021B, Tektronix, USA) via a 40 dB power amplifier (406L, Electronic Navigation Industries, USA) to the transducer. Optical detection of crude oil droplets was evaluated by flowing the generated droplets through the compact fluorescent detector to correlate the size of the droplet to the acquired fluorescent signal intensity.

RESULTS AND DISCUSSION

FIGURE 3 shows the oil droplets (55 μm diameter) in the microchannel before and after acoustic separation. It can be seen that oil droplets successfully moved to the acoustic anti-pressure node (i.e. channel wall) and separated into the side outlets under the acoustic radiation force (flow from right to left). FIGURE 4 shows the successful detection of oil droplets using the optical detection module as the 55 μm diameter oil droplets flow through the detection region of the microchannel. The average signal intensity was 0.385 ± 0.008 V with the coefficient of variance being 2%, demonstrating the consistency and accuracy of this detection method.

FIGURE 3. Oil droplets (55 μm diameter) in the microchannel before (left) and after (right) actuating the piezoelectric transducer.
CONCLUSION

In summary, we have successfully demonstrated for the first time the separation of crude oil droplets using acoustophoretic force and the real-time detection of crude oil droplets with high sensitivity and repeatability. This result demonstrates the feasibility of an acoustophoretic crude oil droplet separation and detection system as a portable field-deployable low-concentration oil detection system.

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