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SciVerse ScienceDirect
Procedia Food Science 1 (2011) 123 – 130
Procedia Food Science

11th International Congress on Engineering and Food (ICEF11)

# Production characteristics of uniform large soybean oil droplets by microchannel emulsification using asymmetric through-holes

Isao Kobayashi[a], Marcos A. Neves[a,b], Kunihiko Uemura[a], Mitsutoshi Nakajima[a,b] *

[a] *National Food Research Institute, NARO, Tsukuba, 305-8642 , Japan*
[b] *Graduate School of Life and Environmental Sciences, University of Tsukuba, Tsukuba, 305-8572, Japan*

**Abstract**

The aim of this study was to investigate the production characteristics of large soybean oil droplets dispersed in an aqueous solution containing an emulsifier using newly designed microchannel emulsification (MCE) chips. The silicon MCE chips consisted of numerous asymmetric through holes with a characteristic cross-sectional size of 20 µm to 50 µm, each consisting of a microslot and a circular microchannel (MC). MCE using such chips enabled the stable production of uniform large droplets with average diameters of 75 µm and 179 µm respectively, and a coefficient of variation below 2%. The detachment behavior of the large droplets generated from the asymmetric through holes was analyzed and discussed based on results obtained by real-time optical microscopy. The size of droplets smaller than 100 µm was independent of the flow rate of the cross-flowing continuous phase ($Q_c$) applied in this study. In contrast, the size of droplets larger than 100 µm became sensitive to $Q_c$ in its range over a critical value. Large droplets with a very narrow size distribution were obtained at dispersed phase fluxes ($J_d$) of 50 L m$^{-2}$ h$^{-1}$ or less, whereas their average diameters were somewhat dependent on $J_d$.



*Keywords:* Microchannel emulsification; Fine droplet; Microchannel array; Scale up; Silicon chip

## 1. Introduction

Large droplets with sizes of 50 to 1000 µm dispersed in another immiscible liquid are thermodynamically unstable. They can be stabilized by emulsifier molecules dissolved in a continuous phase for a finite period of time. Liquid-liquid dispersions consisting of large droplets are usually used as templates for

* Corresponding author. Tel.: +81-29-853-3981; fax: +81-29-853-5776.
*E-mail address*:nakajima.m.fu@u.tsukuba.ac.jp


doi:10.1016/j.profoo.2011.09.020

producing microparticles and microcapsules through gelation, polymerization, and other secondary reactions or processes in the food and pharmaceutical industries. In particular, monodisperse microparticles and microcapsules, which require uniform large droplets as templates, are useful microcarriers for micron-scale biological materials, having a high potential for controlled release of the bioactive substances yielded inside the micromaterials. To date, uniform large droplets have been applied to produce seamless microcapsules containing lactobacilli [1] and gel microbeads containing living cells [2].

In practice, a single nozzle set in a flow channel is used to produce uniform large droplets with sizes exceeding 200 μm [1,3]. In this technique, a dispersed phase that has passed through a nozzle is injected into a coflowing continuous phase, and droplets are generated individually. The size of the generated large droplets can be uneven in a droplet production setup [3], indicating that their size is sensitive to the flow rates of both phases. It is also challenging to parallelize nozzles in a single setup. Vladisavljević and Williams recently reported that rotating-membrane emulsification is capable of producing uniform large droplets with sizes of 100 μm by injecting a dispersed phase through a rotating cylindrical membrane with laser-drilled pores into a continuous-phase region [4]. The resultant droplet size depends greatly on the rotating speed of the membrane used and is considered to be sensitive to the flow rates of both phases. It is necessary to note that the continuous phase suitable for this technique is restricted to viscous liquids with an apparent viscosity of >100 mPa s, which would be useful for cosmetic applications.

In the late 1990s, the authors' group proposed a promising technique for producing uniform droplets called microchannel emulsification (MCE) [5]. Droplet production for MCE is performed by injecting a dispersed phase through an MC array consisting of parallel microgrooves and a slit-like terrace into a well filled with a continuous phase. MCE has a unique droplet generation process based on spontaneous transformation of the dispersed phase that passes through the MCs in the absence of a cross-flowing continuous phase [6]. This spontaneous droplet generation is robust, since the resultant droplet size is basically not sensitive to the flow rate of either phase [7,8]. Kobayashi *et al*. recently developed MCE chips with microfabricated through holes, aimed at higher droplet productivity [9,10]. These novel MCE chips have demonstrated the production of uniform droplets of vegetable oil at a maximum flux of 60 L $m^{-2}$ $h^{-1}$ [9]. Kobayashi *et al*. also reported that an MCE chip with asymmetric through holes can stably produce uniform droplets, especially for low viscosity fluids [10]. Existing MCE chips can produce uniform large droplets with sizes of 2 to 100 μm; however, these high-performance chips with asymmetric through holes were designed for producing uniform droplets smaller than 50 μm. It is expected that uniform large droplets would be stably and efficiently produced using MCE chips with asymmetric through holes whose dimensions have been appropriately enlarged. Moreover, producing uniform large droplets by MCE chips have potential useful applications in various industries including food.

This study seeks to investigate the production characteristics of large oil droplets using newly designed MCE chips with microfabricated asymmetric through holes. A model oil-in-water system consisting of refined soybean oil and an aqueous solution containing an emulsifier was chosen for this study. The effects of the size of the asymmetric through holes and the flow rates of the two phases were investigated to demonstrate the production of uniform large droplets, controllable in size and quantity. The droplet-generation and droplet-detachment characteristics were also analyzed and discussed.

## 2. Materials and Methods

The 24×24-mm MCE chip (WMS3) used in this study is depicted in Fig. 1a. Asymmetric through holes, each consisting of a microslot and a circular MC, were compactly arranged within a 10×10-mm central area of the chip (Figs. 1a and 1b). Three types of MC arrays with the dimensions presented in Table 1 were designed for this study. The WMS3 chips were made of single-crystal silicon, and the MC