Particuology 24 (2016) 18–31

Contents lists available at ScienceDirect

Particuology

journal homepage: www.elsevier.com/locate/partic

Review

Controllable microfluidic strategies for fabricating microparticles using emulsions as templates

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ARTICLE INFO

Article history:
Received 29 April 2015
Received in revised form 31 July 2015
Accepted 4 August 2015
Available online 26 September 2015

Keywords:
Microfluidics
Microparticle
Microreactor
Emulsion
Template synthesis

ABSTRACT

Microfluidic techniques provide flexible strategies for fabrication of uniform advanced microparticles with well-tailored sizes, shapes, structures, and functions from controllable emulsion templates. This review highlights recent progress on controllable synthesis of microparticles using versatile microfluidic emulsions as templates. First, highly controllable and scalable microfluidic techniques for the generation of defined emulsions are introduced. Versatile microfluidic strategies for fabricating microparticles from diverse controllable emulsion templates are then summarized, including solid microparticles with spherical, non-spherical, and Janus configurations, porous microparticles with flexible pore structures, and compartmental microparticles with controlled internals. Finally, the future development of microfluidic techniques for microparticle fabrication is briefly discussed.

Contents

Introduction

Microparticles are widely used in myriad fields, such as pharmaceuticals, foods, cosmetics, photonics, coating, and printing. Compared with traditional methods for synthesis of microparticles, microfluidic techniques provide very powerful platforms for creating highly controllable emulsion droplets as templates for fabricating uniform microparticles with advanced structures and functions. Microfluidic techniques can generate emulsion droplets with precisely controlled size, shape, and composition, which provide excellent templates for synthesis of functional microparticles with controllable size and shape and versatile compositions. Moreover, precise control over single emulsion droplets

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http://dx.doi.org/10.1016/j.partic.2015.08.001

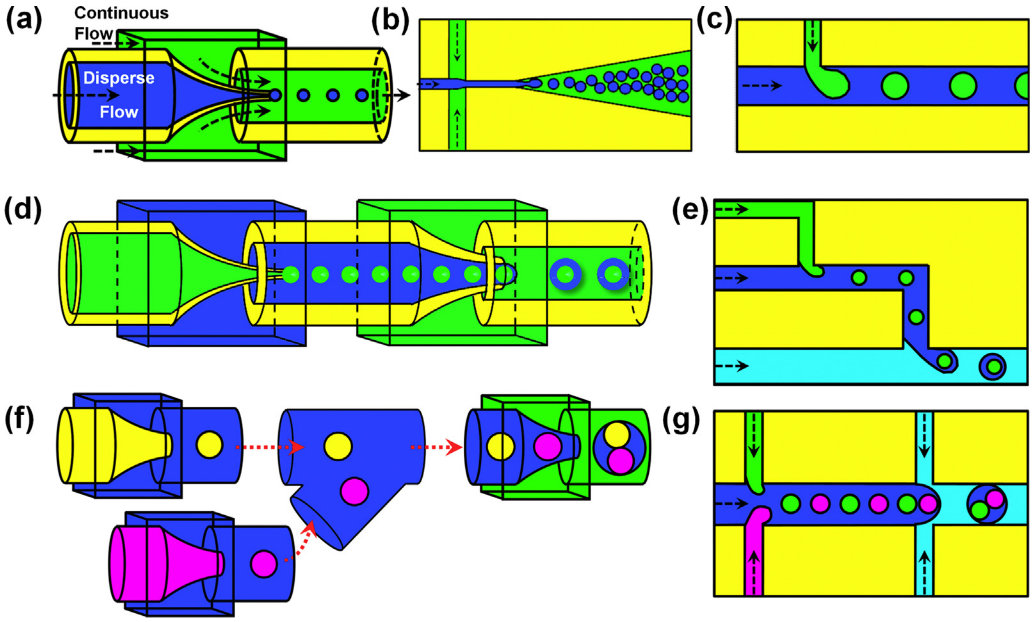

Fig. 1. Microfluidic devices for controllable generation of monodisperse emulsions. Droplet generating units with (a) co-flow, (b) flow-focusing, and (c) T-junction geometries to produce monodisperse single emulsion droplets. Microfluidic devices combining (d) two co-flow geometries and (e) two T-junction geometries to generate double emulsions. (f) Microfluidic device combining three co-flow geometries to generate controllable multicomponent double emulsions. (g) Microfluidic device combining two T-junction and one flow-focusing geometries to generate controllable multicomponent double emulsions.

by microfluidics allows further creation of multiple emulsions with highly controllable, nested, droplet-in-droplet structures, and flexible compositions (Chu, Utada, Shah, Kim, & Weitz, 2007; Shah, Shum et al., 2008). Thus, using such multiple emulsions as templates, microparticles with well-tailored internal compartments and specific functions can be fabricated with many applications.

In this review, recent progress on template synthesis of advanced microparticles from controllable microfluidic emulsions is highlighted. First, we introduce highly controllable and scalable microfluidic techniques for generating monodisperse emulsion droplets with diverse, controllable structures. Versatile microfluidic emulsion-template synthesis strategies for fabricating advanced microparticles with solid, porous, and compartmental structures are then discussed. Finally, a brief outlook on the future development of microfluidic techniques for microparticle fabrication is presented.

Microfluidic generation of controllable emulsions

Microfluidic techniques enable precise manipulation of microflows in microchannels to produce uniform pico-liter emulsion droplets with controllable sizes and structures (Wang, Zhang, & Chu, 2014). Normally, microfluidic devices that form emulsions consist of droplet-generating units and connecting units. The droplet-generating units usually contain microchannels, with co-flow (Fig. 1(a)) (Shah, Shum et al., 2008), flow-focusing (Fig. 1(b)) (Seo, Paquet, Nie, Xu, & Kumacheva, 2007), and T-junction (Fig. 1(c)) (Okushima, Nisisako, Torii, & Higuchi, 2004) geometries for droplet generation, while connecting units usually contain microchannels for droplet manipulation. Typically, microchannels can be created by coaxially inserting cylindrical glass capillaries into square glass tubes and then fixing the assembled structures on glass plates for device fabrication (Chu, Utada et al., 2007; Wang et al., 2011). The inner microchannel of the inserted capillary and the interstitial space between the inserted capillary and square tube walls create 3D microchannels for fluid flow. The wettability of the microchannels can be readily and individually modified to manipulate aqueous and organic fluids, but the device fabrication itself requires exacting manual assembly. Alternatively, 2D microchannels can be etched onto polydimethylsiloxane plates by soft lithography to fabricate devices (McDonald & Whitesides, 2002). Polydimethylsiloxane devices allow flexible creation of microchannel networks for generation and manipulation of droplets and massproduction of devices. However, the processes for modifying microchannel wettability are difficult and the devices show poor chemical resistance to organic solvents. Alternatively, microfluidic devices can be fabricated by patterning coverslips (Deng et al., 2011) on glass slides, with the gaps between the coverslips comprising the microchannel, or etching on poly(methyl methacrylate) (Xu, Li, Tan, Wang, & Luo, 2006a; Xu, Li, Tan, Wang, & Luo, 2006b) and glass (Okushima et al., 2004) plates to create microchannels. Moreover, much simpler microfluidic devices can be produced by inserting needles into plastic tubes for microchannel construction (Steinbacher, Lui, Mason, Olbricht, & McQuade, 2012).

Typically, liquid phases used respectively as the disperse and continuous fluids are injected into the microfluidic chip by constant-flow or constant-pressure pumps with flow rate control. In the droplet-generating units, droplets of single emulsions are generated using the continuous fluid to shear off the dispersed fluid (Fig. 1(a)–(c)). This leads to periodic breakup of the disperse fluid into uniform droplets (Fig. 2(a)) (Shah, Shum et al., 2008). Because the units produce one droplet at a time, accurate control over the droplet size and size distribution can be achieved. Typically, microfluidic techniques can produce monodisperse emulsion droplets with sizes ranging from millimeter – (Steinbacher et al., 2012) to micrometer – (Shah, Shum et al., 2008) or even submicrometer-scale (Jeong et al., 2012), with a coefficient of variation (*CV*) for droplet size of less than 5%. The physical properties of different fluids, geometries of the microfluidic device, and processing conditions are all important factors for controlling droplet formation. As a representative example, in co-flow-based droplet generation, the factors that influence the droplet sizes and *CV* values include the viscosity (η_c) and flow rate (u_c) of the continuous fluid, the density (ρ_d) and flow rate (u_d) of the dispersed fluid, the inner diameter (d_{tip}) of the tapered cone tip of the glass capillary (Fig. 1(a)), and the interfacial tension (γ) between the two fluids.