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RESEARCH PAPER

Production of monodisperse water-in-oil emulsions consisting of highly uniform droplets using asymmetric straight-through microchannel arrays

Isao Kobayashi · Yoichi Murayama · Takashi Kuroiwa · Kunihiko Uemura · Mitsutoshi Nakajima

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Abstract This paper reports the production of monodisperse water-in-oil (W/O) emulsions using new microchannel emulsification (MCE) devices, asymmetric straight-through MC arrays that were hydrophobically modified. The silicon asymmetric straight-through MC arrays consisted of numerous pairs of microslots and circular microholes whose cross-sectional sizes were 10 μm. This paper primarily focused on investigating the effect of the osmotic pressure of a dispersed phase (Π_d) on MCE. This paper also investigated the effects of the type of continuous-phase oils and the dispersed-phase flux (J_d) on MCE. The dispersed phases were Milli-Q water and Milli-Q water solutions containing sodium chloride. The continuous phases were decane (as control), hexane, medium chain triacylglyceride (MCT), and refined soybean oil (RSO) solutions containing tetraglycerin monolaurate condensed ricinoleic acid ester (TGCR) as a surfactant. At Π_d of exceeding threshold, highly uniform aqueous droplets with coefficients of variation of less than 3% were stably generated via hydrophobic asymmetric straight-through MCs. Monodisperse W/O emulsions with average droplet diameters between 32 and 45 μm were produced using the alkane–oil and triglyceride–oil solutions as the continuous phase. This work also demonstrated that the hydrophobic asymmetric straight-through MC array had remarkable ability to produce highly uniform aqueous droplets at very high J_d of up to 1,200 L m^{-2} h^{-1}.

Keywords Microchannel emulsification · Monodisperse water-in-oil emulsion · Asymmetric microchannel · Hydrophobic microchannel · Droplet productivity

List of symbols

CV	coefficient of variation (–)
d_{av}	average diameter (m)
$d_{eq,MC}$	MC equivalent diameter (m)
d_{hole}	diameter of circular microhole (m)
d_{pore}	pore diameter (m)
$d_{3,2}$	Sauter diameter (m)
g	acceleration due to gravity (m s^{-2})
Δh_d	height of a dispersed-phase chamber (m)
h_{hole}	depth of circular microhole (m)
h_{slot}	microslot depth (m)
$h_{terrace}$	terrace height (m)
i	van't Hoff factor (–)
J_d	dispersed-phase flux (L m^{-2} h^{-1})
l_{rows}	distance between two rows (m)
l_{MCs}	distance between two adjacent MCs (m)
$l_{terrace}$	terrace length (m)
M	molar concentration (mol L^{-1})
ΔP_d	pressure applied to a dispersed phase (Pa)
$\Delta P_{d,BT}$	breakthrough pressure of a dispersed phase (Pa)
Q_c	flow rate of a continuous phase (L h^{-1})
Q_d	flow rate of a dispersed phase (L h^{-1})
R	gas constant (Pa m^3 K^{-1} mol^{-1})
span	relative span factor of droplet size distribution (–)
T	thermodynamic temperature (K)
t_{dg}	droplet generation time (s)
$w_{l,slot}$	longer width of microslot (m)

I. Kobayashi (✉) · Y. Murayama · T. Kuroiwa · K. Uemura · M. Nakajima (✉)
Food Engineering Division, National Food Research Institute, 2-1-12 Kannondai, Tsukuba, Ibaraki 305-8642, Japan
e-mail: isaok@affrc.go.jp

M. Nakajima
e-mail: mnaka@sakura.cc.tsukuba.ac.jp

Y. Murayama · T. Kuroiwa · M. Nakajima
Graduate School of Life and Environmental Sciences, University of Tsukuba, 1-1-1 Tennoudai, Tsukuba, Ibaraki 305-8572, Japan

$w_{s,slot}$ shorter width of microslot (m)

Greek symbols

η_c continuous-phase viscosity (Pa s)
η_d dispersed-phase viscosity (Pa s)
ν_{dg} droplet generation frequency (s^{-1})
Π_d osmotic pressure of a dispersed phase (Pa)
ρ_d dispersed-phase density (kg m^{-3})
σ standard deviation (m)

1 Introduction

Water-in-oil (W/O) emulsions consisting of aqueous droplets dispersed within a continuous oil phase are frequently used in the fields of foods, pharmaceuticals, cosmetics, and chemicals. Macromolecular hydrophobic surfactants, which can form a viscoelastic adsorbed layer at an oil-water interface, are preferably used to stabilize W/O emulsions for finite periods of time (Kandori 1995). The use of monodisperse emulsions consisting of uniformly sized droplets can improve stability against droplet coalescence, and enables the simplified interpretation of experiment results and the precise control of many emulsion properties (Mason et al. 1996; McClements 2004). Monodisperse W/O emulsions have high-tech applications such as monodisperse microparticles for column chromatography (Nakashima et al. 2000; Hatate et al. 1995; Maciejewska and Osypiuk 2005) and monodisperse multiple emulsions, microparticles, and microcapsules as drug delivery carriers (Nakashima et al. 2000; Shiga et al. 1996; Nagashima et al. 1998; Wang et al. 2005; Chu et al. 2001). W/O emulsions are usually produced using mixers, colloid mills, high-pressure homogenizers, and ultrasonic homogenizers, which apply high shear and extensional stresses to break up droplets into smaller ones (McClements 2004). However, these devices generally produce W/O emulsions with wide droplet size distributions and have poor controllability in droplet size and distribution.

Membrane emulsification (ME) (Nakashima et al. 2000) and microchannel emulsification (MCE) (Kawakatsu et al. 1997; Kobayashi et al. 2002) have been developed within the past two decades as promising techniques for producing monodisperse emulsions. ME and MCE directly generate emulsion droplets by forcing a dispersed phase through membrane pores or MCs into a (cross-flowing) continuous phase (Nakashima et al. 1991; Kawakatsu et al. 1997, 1999; Kobayashi et al. 2002; Williams et al. 1998; Schröder et al. 1998; Joscelyne and Trägårdh 2000; Abrahamse et al. 2002). The droplet generation process is characterized by low shear stress due to the continuous-phase flow or no external shear stress (i.e., spontaneous droplet-breakup mechanism) and by low temperature elevation due to high energy efficiency (Schröder et al. 1998; Sugiura et al. 2001a). These characteristics are advantageous for preventing the denaturation of shear- and thermo-sensitive components (e.g., proteins and starches) during emulsification (Schröder and Schubert 1999). In addition, ME and MCE enable the precise control of the resultant droplet size by membrane pore size or MC geometry (Nakashima et al. 2000; Vladisavljevic and Schubert 2002; Kawakatsu et al. 2000; Sugiura et al. 2002). To achieve successful ME and MCE, the continuous phase must preferably wet the membrane and MC surfaces (Nakashima et al. 2000; Tong et al. 2000; Kobayashi et al. 2003); monodisperse W/O emulsions can be produced using hydrophobic membranes and MC devices. W/O emulsions have been produced by ME using silanized Shirasu porous glass (SPG) membranes (Shimizu et al. 2002; Cheng et al. 2006, 2008), polypropylene hollow fibers (Vladisavljevic et al. 2002), rotating nickel hollow membranes with circular micro-holes (Schadler and Windhab 2006), silanized silicon nitride membranes with circular micro-holes (Geerken et al. 2007), and a silanized woven stainless-steel mesh (Geerken et al. 2008). The most commonly used ME devices are SPG membranes of hydrophilic nature with narrow pore size distributions (Nakashima et al. 2000). Hydrophobic SPG membranes can produce monodisperse W/O emulsions with average droplet diameters of 0.5–70 μm and minimum coefficients of variation (CV, defined in Sect. 2.5) of approximately 10% (Shimizu et al. 2002; Cheng et al. 2008). Our group has reported the production of W/O emulsions using MCE devices, such as silanized silicon MC arrays (Kawakatsu et al. 1997, 2001; Sugiura et al. 2001b; Kobayashi et al. 2008) and poly(methyl methacrylate) (PMMA) MC arrays (Liu et al. 2004; Kobayashi et al. 2008). The current MCE devices are capable of producing W/O emulsions consisting of highly uniform droplets with average diameters of 4–100 μm and minimum CV of less than 5% (Kawakatsu et al. 2001; Sugiura et al. 2001b, 2008; Kobayashi et al. 2008; Liu et al. 2004). Moreover, MCE setups allow the optical observation of the droplet generation process, and thus help in the detailed analysis of the MCE process (Kawakatsu et al. 1997; Kobayashi et al. 2002).

Kawakatsu et al. (1997) first demonstrated the production of monodisperse W/O emulsions using hydrophobic grooved MC arrays, each consisting of highly uniform micro-grooves with a slit-like terrace and a deeply etched well. Kawakatsu et al. (2001) also clarified that MCE devices with hydrophobicity exceeding a threshold are needed for generating highly uniform water droplets. Sugiura et al. (2001b) investigated the effect of surfactants and oils on the production of W/O emulsions using hydrophobic grooved MC arrays. They discussed surfactants and

oils suitable for producing monodisperse W/O emulsions by MCE. Liu et al. (2004) fabricated PMMA grooved MC arrays through injection molding and demonstrated the generation of highly uniform water droplets into a continuous oil phase via MCs. To scale up droplet productivity in MCE, we proposed straight-through MC arrays, each consisting of highly uniform, symmetric, and deep micro-holes with an oblong section (Kobayashi et al. 2002, 2004). Straight-through MCE devices have the potential to integrate millions of MCs on a wafer. A hydrophobic symmetric straight-through MC array was used for generating highly uniform aqueous droplets several microns in size (Kobayashi et al. 2008). A PMMA symmetric straight-through MC array, which was fabricated through deep X-ray lithography using synchrotron radiation, was also developed for producing monodisperse W/O emulsions (Kobayashi et al. 2008). It should be noted that a viscous aqueous solution containing glycerol was used as a dispersed phase in the preceding cases. A major drawback of symmetric oblong straight-through MCs is poor control of the droplet generation process when using a low-viscosity dispersed phase (e.g., water). As a solution to this problem, we recently proposed an asymmetric straight-through MC array made of single-crystal silicon, each consisting of numerous pairs of microslots and circular microholes (Kobayashi et al. 2005a). The hydrophilic asymmetric straight-through MC array enabled the generation of highly uniform droplets of low viscosity oil (decane) into a continuous aqueous phase (Kobayashi et al. 2005a). Vladisavljević et al. also demonstrated high droplet-throughput of the asymmetric straight-through MC array (Vladisavljević et al. 2006).

However, the production of W/O emulsions using this asymmetric straight-through MC array has not yet been investigated. Although the osmotic pressure of a dispersed phase (Π_d), which is proportional to the salt concentration, plays an important role in W/O emulsion systems (Opawale and Burgess 1998), no investigation on the effect of Π_d was conducted in previous MCE studies. We therefore considered that it is important to investigate the production characteristics of W/O emulsion using hydrophobic asymmetric straight-through MC arrays. This work primarily focused on the effect of Π_d on the droplet generation phenomena via asymmetric straight-through MCs, the resultant droplet size, and its distribution. We also investigated the effect of the type of continuous-phase oils on the droplet generation phenomena via asymmetric straight-through MCs, the resultant droplet size, and its distribution. We further examined the droplet throughput (expressed as J_d) of a hydrophobic asymmetric straight-through MC array using a model W/O system, and the results were compared with those found in the literature for ME.

2 Materials and methods

2.1 Chemicals

Hexane, decane, and refined soybean oil (RSO) were purchased from Wako Pure Chemical Ind. (Osaka, Japan). Medium chain triacylglycerol (MCT, Sunsoft MCT-8) with a fatty acid residue composition of 75% caprylic acid and 25% capric acid was provided by Taiyo Kagaku Co., Ltd. (Mie, Japan). They were used as continuous-phase liquids. Tetraglycerin monolaurate condensed ricinoleic acid ester (TGCR, CR-310) provided by Sakamoto Yakuhin Kogyo Co., Ltd. (Osaka, Japan) was used as an oil-soluble surfactant. Milli-Q water was used to prepare all the dispersed-phase solutions. Sodium chloride (NaCl) was purchased from Wako Pure Chemical Ind. and used for adjusting the osmotic pressure of the dispersed phase. Octadecyltriethoxysilane (L-6970), which is a silane coupler reagent, was purchased from Shin-Etsu Chemical Co., Ltd. (Tokyo, Japan). All the chemicals were used as received.

2.2 Asymmetric straight-through MC array devices

A 24 × 24-mm MCE device including an asymmetric straight-through MC array (WMS1) is depicted in Fig. 1a. The fabrication process of the MCE device is described in our previous paper (Kobayashi et al. 2005a). An asymmetric straight-through MC array made of single-crystal silicon and a well on the backside of the MC array were fabricated by photolithograpy and inductively coupled plasma reactive ion etching (ICP-RIE). Compact asymmetric straight-through MCs, each consisting of a microslot and a circular microhole (Table 1) were positioned within a 10 × 10-mm central region of WMS1 devices (Fig. 1a, b). MCE devices consisting of compact MCs are needed to generate highly uniform droplets at high J_d. As illustrated in Fig. 1c, the fabricated asymmetric straight-through MCs had the high uniformity necessary for generating highly uniform emulsion droplets. Two asymmetric straight-through MC arrays (WMS1-1, and -3, EP. Tech Co., Ltd., Hitachi, Japan) were used; their dimensions and arrangements were presented in Table 1 and Fig. 1b, c.

2.3 Surface modification of asymmetric straight-through MC array devices

Surfaces of asymmetric straight-through MC array devices were modified to make them hydrophobic. WMS1 devices were silanized by the following hydrophobic modification based on the procedure described by Kawakatsu et al. (1997). WMS1 devices were first cleaned in Milli-Q water by ultrasonic vibration with a high frequency of 100 kHz

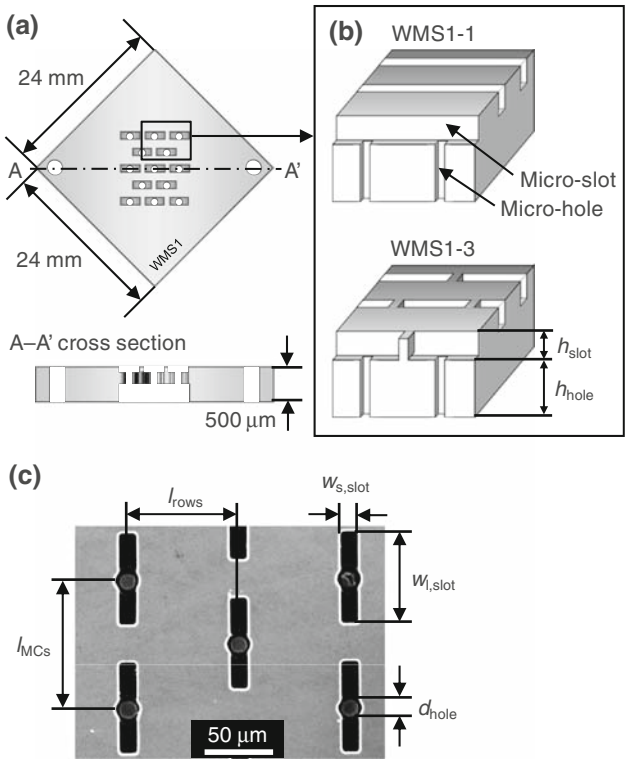

Fig. 1 **a** Schematic representation of an asymmetric straight-through MC array (WMS1) device. **b** Schematic representation of asymmetric straight-through MCs. **c** Scanning electron micrograph of the outlets of asymmetric straight-through MCs (WMS1-3)

(VS-100III, As One Co., Osaka, Japan). The cleaned WMS1 devices were surface-oxidized with an oxygen plasma reactor (PR41, Yamato Scientific Co., Ltd., Tokyo, Japan) after drying at 60°C. The WMS1 devices were then ultrasonicated in a toluene solution containing 5.0 wt% LS-6970 to remove bubbles inside the asymmetric straight-through MCs, followed by heat treatment in toluene solution at 110°C for 1 h. Their surface modification was finished by ultrasonicating first in toluene and then in hexane, and drying at 60°C. The static contact angle of a model W/O system (a water droplet containing 5.0 wt% NaCl in a decane solution with 3.0 wt% TGCR) on a surface-modified WMS1 device was 163°, indicating that the device surface was preferentially wetted by the continuous phase and was useful for preparing monodisperse W/O emulsions by MCE (Kawakastu et al. 2001).

2.4 Microchannel emulsification

2.4.1 Preparation of solutions

Continuous-phase solutions were prepared by dissolving 3.0 wt% TGCR in oil (hexane, decane, RSO, or MCT). Dispersed-phase solutions were prepared by dissolving 0.017–0.86 mol L^{-1} NaCl in Milli-Q water. The solutions were stirred with a magnetic bar and subjected to emulsification experiments.

2.4.2 Setup and procedure

The MCE setup used in this study is schematically presented in Fig. 2a. A surface-modified WMS1 device was fixed and sealed between two fluoride-rubber spacers in a module. A channel with a 1.0-mm thick for flowing the continuous phase was formed on the bottom side of the WMS1 device, and a channel with a 1.0-mm thick for flowing the dispersed phase was formed on the top side of the WMS1 device. Artificial quartz glass plates used for sealing the flow channels were surface-modified by the procedure described in Sect. 2.3 prior to use. A syringe pump (Model 11, Harvard Apparatus Inc., MA, USA) equipped with a 50 mL glass syringe was used for feeding the continuous phase, and a 10 mL water chamber was used for feeding the dispersed phase. When the effect of J_d was investigated, a 1 L plastic vessel was used to feed the continuous phase, and the syringe pump equipped with a 50 mL glass syringe was used to feed the dispersed phase. A custom-made microscope video system, the details of which are described elsewhere (Kobayashi et al. 2002), was used for visualizing and recording droplet generation.

WMS1 devices were degassed by ultrasonicating in the continuous phase for 20 min prior to each experiment. A WMS1 device was mounted into the module filled with the continuous phase. The dispersed phase was introduced into the module via the dispersed-phase feed tubing, and then injected via an asymmetric straight-through MC array into

Table 1 Geometric characteristics of asymmetric straight-through MC arrays used in this study

Device number	Size of microslot, $w_{l,slot} \times w_{s,slot}$ (μm)	Diameter of microhole, d_{hole} (μm)	Depth of microslot, h_{slot} (μm)	Depth of microhole, h_{hole} (μm)	Distance between two adjacent MCs, l_{MCs} (μm)	Distance between two rows, l_{rows} (μm)	Total number of MCs
WMS1-1	a × 10	11	27	70[b]	150	100	6,515
WMS1-3	49 × 10	12	21	70[b]	70	60	23,348

[a] A microslot with a total length of 10 mm is positioned at the outlets of MCs in each row

[b] Designed to have the described value

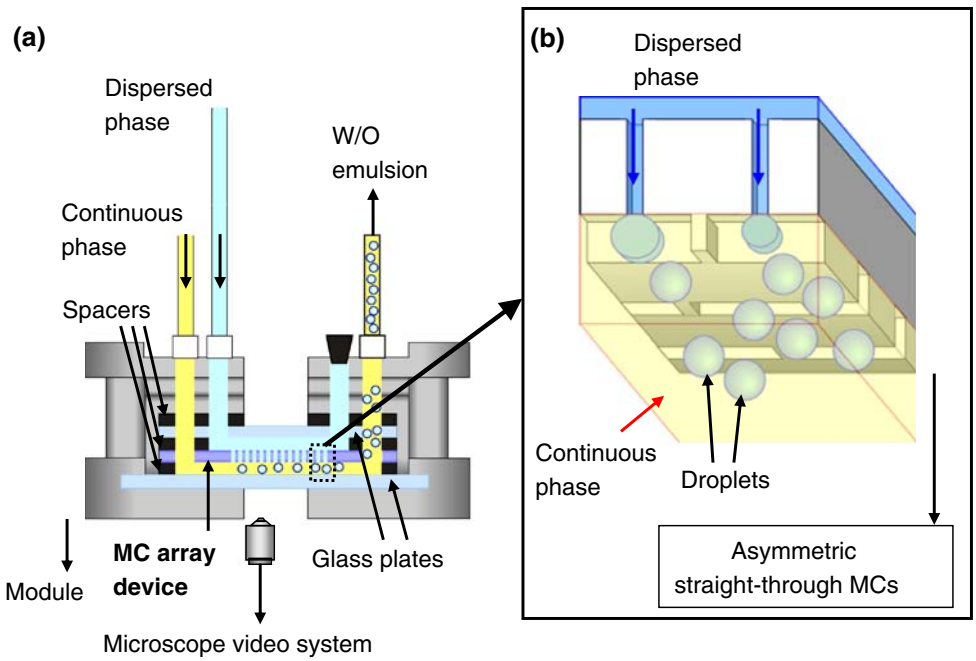

Fig. 2 **a** Simplified schematic of the MC emulsification setup used in this study. **b** Schematic view of the generation of W/O emulsion droplets via asymmetric straight-through MCs

the bottom flow channel to produce W/O emulsions (Fig. 2b). The pressure applied to the dispersed phase (ΔP_d) was increased step-wise by lifting the water chamber until the first droplet was generated at the breakthrough pressure ($\Delta P_{d,BT}$). The ΔP_d could be estimated by $\Delta P_d = \rho_d \Delta h_d g$ (Pa), where ρ_d is the dispersed-phase density (kg m^{-3}), Δh_d is the height of the water chamber (m), and g is the acceleration due to gravity (m s^{-2}). $\Delta P_{d,BT}$ ranged from 0.9 to 2.5 kPa, depending on the NaCl concentration and the type of continuous-phase oils. The flow rate of the continuous-phase velocity (Q_c) was controlled from 0 to 50 mL h^{-1} during droplet generation. For the effect of J_d, J_d was fixed at 100 L m^{-2} h^{-1} until droplet generation began, and then increased step-wise up to 1,500 L m^{-2} h^{-1}, which corresponded to the flow rate of the dispersed phase (Q_d) of 150 mL h^{-1}. In this case, Q_c was adjusted in a range of 0 to $\sim$1,000 mL h^{-1}. Droplet generation via asymmetric straight-through MCs was observed at an upstream position in the top flow channel [either in real time or using a high-speed CCD camera with a maximum recording speed of 600 fps (FASTCAM-Rabbit-mini-2, Photron Ltd., Tokyo, Japan)]. The WMS1 devices were cleaned according to the procedure in the literature (Kobayashi et al. 2008) after the module was disassembled.

2.5 Measurement and analytical methods

The density of the liquid phases used for MCE was measured with a density meter (DA-130 N, Kyoto Electronics Manufacturing Co., Ltd., Kyoto, Japan) and viscosity, with glass capillary viscometers (SO, Shibata Scientific Technology Ltd., Tokyo, Japan) at 25°C. Each measurement was repeated at least twice, and the calculated mean values were used.

Images of the resultant W/O emulsion droplets, which formed single-layer arrays in the bottom flow channel, were captured into a computer connected to the microscope video system. The droplet diameter was determined from the captured images using WinRoof version 5.6 (Mitani Co., Ltd., Fukui, Japan). The diameters of 200 droplets were measured to determine their average diameter (d_{av}) (μm) and CV (%), defined as CV = (σ/d_{av}) × 100, where σ is the standard deviation of the diameter (μm). CV was used as an index expressing the size uniformity of the droplets.

3 Results and discussion

3.1 Effect of the osmotic pressure of the dispersed phase

The effect of Π_d on the production of W/O emulsions was investigated using a hydrophobic WMS1-3 device and a decane solution with 3.0wt% CR-310 as a model continuous phase. Here, Π_d was calculated by the van't Hoff equation (Rautenbach and Albrecht 1989), $\Pi_d = iMRT$, where i is the van't Hoff factor with a value of 2 for NaCl, M is the molar concentration of NaCl (kmol m^{-3}), R is a constant with a value of 8.31 kPa m^3 K^{-1} mol^{-1}, and T is the thermodynamic temperature (K). Typical production behaviors of W/O emulsions using dispersed phases with different Π_d values are depicted in Fig. 3. Table 2 also

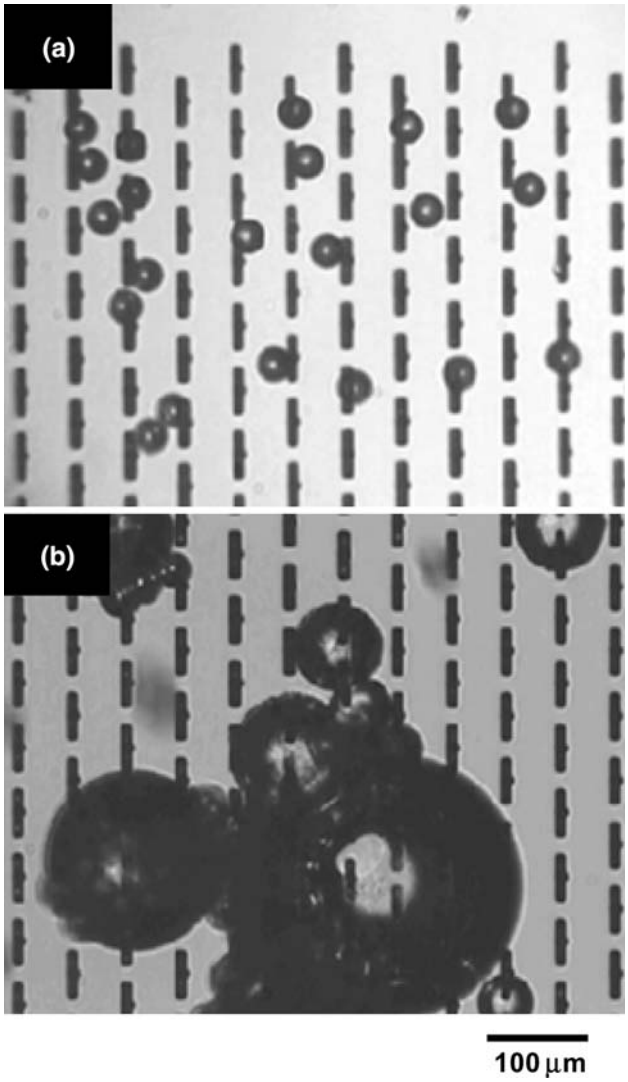

Fig. 3 Typical optical micrographs of the production of W/O emulsions with different Π_d using a hydrophobic WMS1-3 device. A decane solution with 3.0wt% CR-310 was used as the continuous phase. **a** Stable production of a monodisperse W/O emulsion at Π_d of 4.2 MPa. **b** Unstable production of a polydisperse W/O emulsion at Π_d of 0 MPa

presents the production results of the W/O emulsions and the d_{av} and CV of the generated aqueous droplets. Highly uniform aqueous droplets were periodically generated from some of the outlets of microslots at Π_d of 0.42 MPa or more (Fig. 3a). The generated aqueous droplets detached smoothly from asymmetric straight-through MCs as soon as droplet generation was completed. The resultant aqueous droplets had highly narrow size distributions with d_{av} of 32–35 μm and CV of less than 3% (Fig. 4; Table 2), demonstrating that monodisperse W/O emulsions were produced using a hydrophobic WMS1-3 device. The d_{av} of the generated aqueous droplets hardly changed at Π_d of 0.85 MPa and 4.2 MPa but decreased by 5–7% at Π_d of 0.42 MPa (Table 2). In contrast, polydisperse W/O

Table 2 Effect of Π_d on the emulsification behavior and the d_{av} and CV of the W/O emulsion droplets generated using a hydrophobic WMS1-3 device

Osmotic pressure of the dispersed phase Π_d (MPa)	Emulsification behavior	Average droplet diameter d_{av} (μm)	Coefficient of variation CV (%)
0[a]	−[b]	ND	ND
0.085	−[b]	ND	ND
0.42	++ [c]	32.2	2.2
0.85	++ [c]	34.0	2.5
4.2	++ [c]	34.6	2.0

A decane solution with 3.0wt% CR-310 was used as the continuous phase

[a] Pure Milli-Q water was used as the dispersed phase

[b] The dispersed phase greatly expanded from the outlets of microslots and transformed into droplets from the outlets of microslots, as depicted in Fig. 3b

[c] Highly uniform droplets were generated from the outlets of active microslots, as depicted in Fig. 3a

emulsions consisting of large droplets (greater than 100 μm) and small droplets (about 35 μm) were produced from the outlets of microslots at Π_d of 0.085 MPa or less (Fig. 3b). At Π_d of 0 MPa, large droplets were primarily generated from the active asymmetric straight-through MCs through which the dispersed phase passed. At Π_d of 0.085 MPa, both small and large droplets were similarly generated from the active asymmetric straight-through MCs. Microscopic observations of the droplet generation process demonstrated that a rough thin layer was formed around the expanding dispersed phase and the generated aqueous droplets at Π_d of 0 and 0.085 MPa (Fig. 3b). As illustrated in Fig. 5, the rough thin layer covering the generated small water droplets rapidly grew within 20 min after droplet generation. Shimizu et al. (2002) and Cheng et al. (2006) reported that the use of dispersed phases with Π_d over a threshold value is needed to stably produce W/O emulsions with narrow droplet size distributions by ME using surface-modified SPG membranes. Shimizu et al. (2002) also macroscopically observed the formation of a gel-like layer near the pore inlet after use with pure water as the dispersed phase. However, microfluidic devices with a T-shape junction generated highly uniform water droplets with a Π_d of 0 MPa dispersed in a hexadecane solution with Span80 (Thorsen et al. 2001; Link et al. 2004). The rough thin layer was apparently not formed around water-oil interfaces at the T-junction and around the water droplets just after generation.

As demonstrated above, Π_d is an important factor affecting the production of W/O emulsions by MCE. At high Π_d, Na and Cl ions were preferably hydrated over the surfactant molecules, apparently causing a decrease in the interaction between water molecules and the hydrophilic

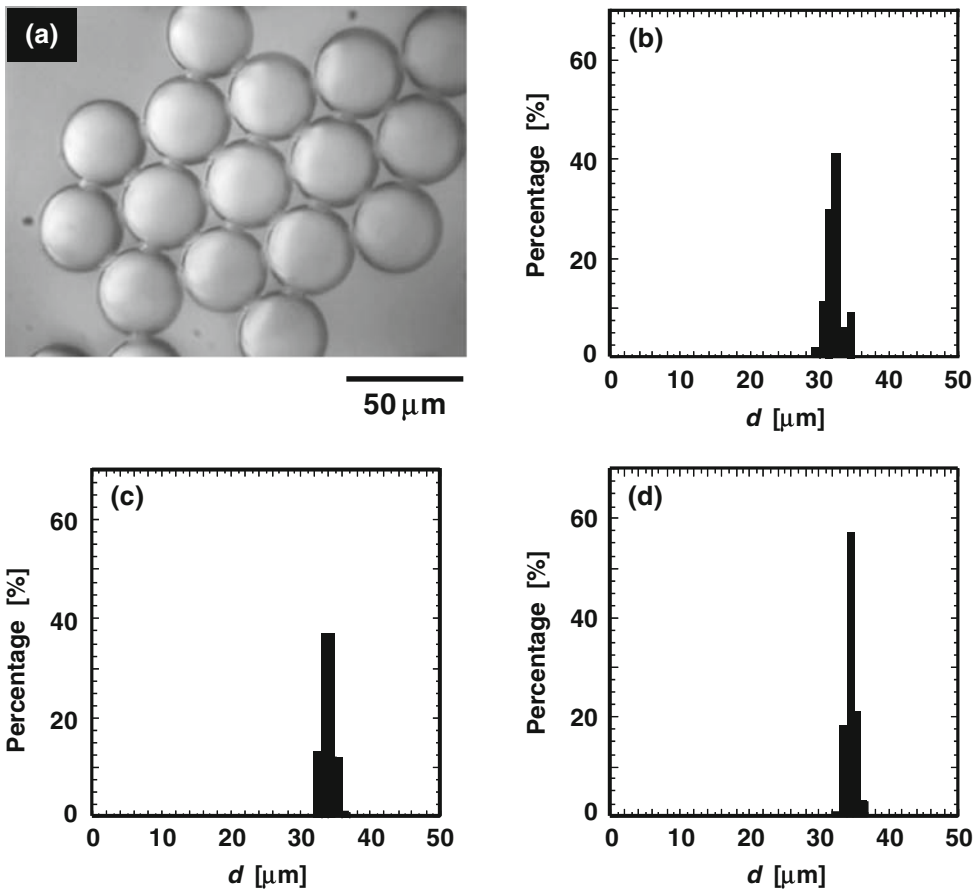

Fig. 4 **a** Optical micrograph of the highly uniform aqueous droplets generated at Π_d of 4.2 MPa. **b–d** Size distributions of the W/O emulsion droplets generated at different Π_d of 0.42 MPa (**b**), 0.85 MPa (**c**), and 4.2 MPa (**d**). The data were obtained using a hydrophobic WMS1-3 plate

group of surfactant molecules at an interface of W/O emulsion droplets (Kawashima et al. 1992; Opawale and Burgess 1998). That is, high Π_d has the ability to suppress the transport of water molecules via the water–oil interface. In addition, the static contact angle measured in Sect. 2.3 indicated that the hydrophobic asymmetric straight-through MC array was preferably wetted by the continuous phase used and repelled the dispersed phase used. We considered that the stable production of monodisperse W/O emulsions at high Π_d was primarily due to the above-mentioned reasons. Conversely, at low Π_d, the interaction between water molecules and the hydrophilic group of surfactant molecules was assumed to be strong enough to transport water molecules via the water–oil interface, causing the formation of a rough thin layer consisting of fine aqueous droplets at the water–oil interface by so-called spontaneous emulsification (Miller 1988). Uricanu et al. observed the spontaneous emulsification of a pure water drop placed in a dodecane solution with Span80, and reported that spontaneous emulsification rapidly formed a visible thin layer consisting of fine water droplets with sizes of less than 1 μm covering the water droplet within 10 min (Uricanu et al. 2006). In our experiments, a rough thin layer around the aqueous droplets was probably formed by spontaneous emulsification when water started to pass through the asymmetric straight-through MCs (several minutes after introducing water into the module). We assumed that the formed rough thin layer might prevent sufficient water intrusion into the microslots and smooth movement of the water-oil interface inside the microslots, resulting in the prolonged generation of large water droplets. In contrast, for T-junction microfluidic devices, the continuous phase flowed very rapidly around the dispersed phase at the T-junction and the generated water droplets (Thorsen et al. 2001; Link et al. 2004), possibly suppressing the formation of a visible thin layer by spontaneous emulsification.

3.2 Effect of the type of continuous-phase oils

Figure 6 depicts the typical production of W/O emulsions via a hydrophobic asymmetric straight-through MC array (WMS1-3) using different continuous-phase oils of hexane (a), MCT (b), and RSO (c), each containing 3.0wt% CR-310 (Table 3). A Mill-Q water solution with Π_d of 4.2 MPa was used as the dispersed phase. The pressurized dispersed phase was spontaneously transformed into highly uniform aqueous droplets via asymmetric straight-through MCs, independent of the type of the continuous-phase oils with a wide viscosity range. Typical examples of the generated aqueous droplets are depicted in Fig. 7. The oil type did not

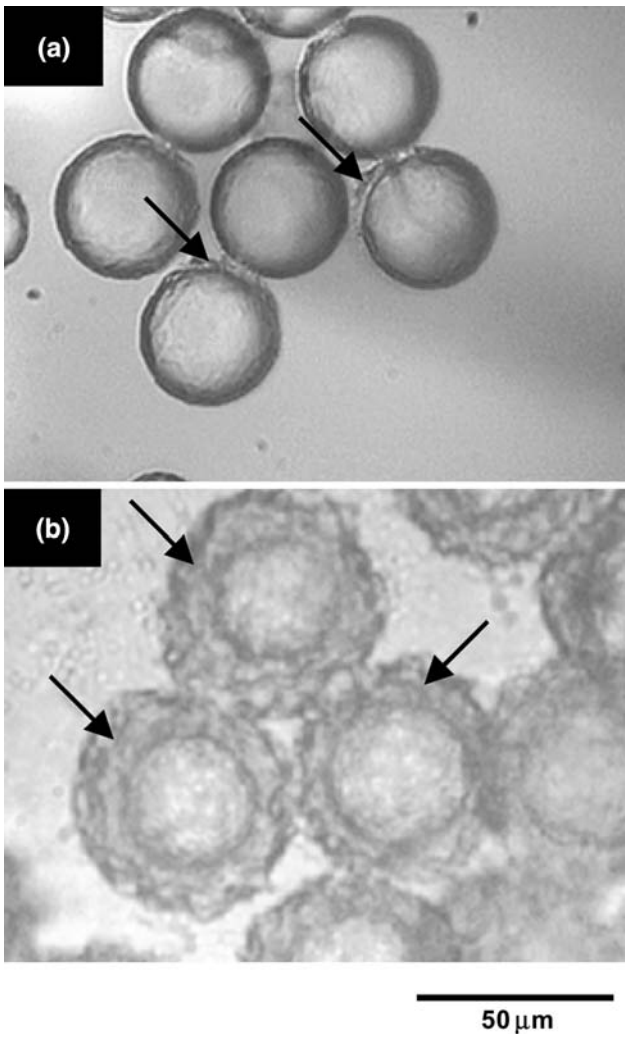

Fig. 5 Formation of aggregates around the generated Milli-Q water droplets. Optical micrographs of the generated Milli-Q water droplets just after generation (**a**), after 20 min (**b**). *Arrows* indicate the formed aggregates

affect the detachment of the aqueous droplets generated from the MC outlets. It should be mentioned that the use of hydrophobic symmetric straight-through MCs with an oblong section led to the production of polydisperse W/O emulsions containing large droplets of a Mill-Q water solution with Π_d of 4.2 MPa (data not shown). Micrographs in Fig. 6b, c also demonstrate that asymmetric straight-through MCs were capable of generating highly uniform emulsion droplets using viscous continuous-phase liquids. Viscous continuous-phase liquids had not yet been used for emulsification using straight-through MC array devices. The droplet generation time (t_{dg}) was estimated from video clips by observing at least 10 droplets for each W/O system. The starting point of droplet generation was defined as the moment when microscopic observation confirmed a portion of the dispersed phase that expanded from the outlets of microslots. The end point of droplet generation was defined

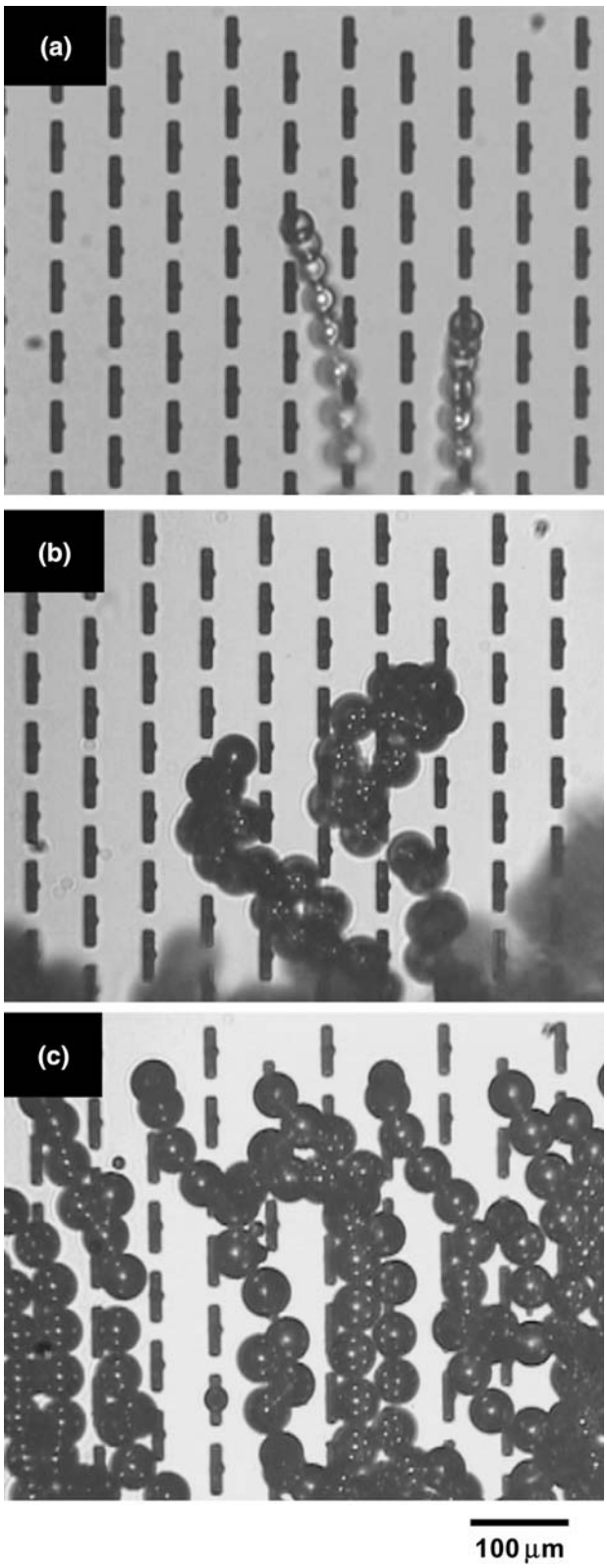

Fig. 6 Production of monodisperse W/O emulsions using different continuous-phase oils and a hydrophobic WMS1-3 device. **a** Hexane, **b** Medium chain triacylglycerol (*MCT*), **c** Refined soybean oil (*RSO*). Each of the continuous-phase oils contained 3.0wt% CR-310. A Milli-Q water solution with Π_d of 4.2 MPa was used as the dispersed phase

Table 3 Effect of continuous-phase oils on η_c and the d_{av} and CV of the W/O emulsion droplets generated using a hydrophobic WMS1-3 device

Type of continuous phase oil	Viscosity of the continuous phase[a] η_c (mPa s)	Average droplet diameter d_{av} (μm)	Coefficient of variation CV (%)
Hexane	0.36	33.5	2.9
Decane	1.00	34.6[b]	2.0[b]
MCT[c]	25.4	43.6	2.0
RSO[d]	53.0	44.6	2.2

An oil solution with 3.0wt% CR-310 was used as the continuous phase. A Milli-Q water solution with Π_d of 4.2 MPa was used as the dispersed phase

[a] Viscosity of the dispersed phase used was 1.01 mPa s

[b] The data were extracted from Table 2

[c] Medium-chain triacylglycerol

[d] Refined soybean oil

as the moment when the generated aqueous droplets started to detach from the outlets of microslots. Here, t_{dg} was on the order of a few seconds for triglyceride oil (MCT, and RSO)-containing systems and <0.03 s for alkane oil-containing systems, indicating that t_{dg} depended greatly on the continuous-phase viscosity (η_c) and increased with increasing η_c. Sugiura et al. also reported a similar trend in the effect of η_c on t_{dg} for the production of monodisperse O/W emulsions by MCE (Sugiura et al. 2004). The d_{av} and CV of the W/O emulsion droplets generated using different continuous-phase oils are listed in Table 3. As revealed in Fig. 8, all the produced W/O emulsions had very narrow size distributions with CV of less than 3%, demonstrating the ability of the asymmetric straight-through MC array device to produce monodisperse W/O emulsions consisting of aqueous droplets with a low viscosity. The d_{av} of the resultant aqueous droplets was dependent on η_c and ranged from 33 to 45 μm.

The effect of the viscosity ratio of the two phases (η_d/η_c) on the droplet/hole size (d_{av}/d_{hole}) ratio is shown in Fig. 9a. Here, η_d is the dispersed-phase viscosity and d_{hole} is the diameter of a circular micro-hole in an asymmetric straight-through MC. In this section, the d_{av}/d_{hole} ratio decreased with increasing η_d/η_c. η_d was fixed, indicating that the d_{av}/d_{hole} ratio increased with increasing η_c. Increasing η_c apparently slowed the flow of the continuous phase into the slot-like terrace, which was necessary for droplet generation by MCE (Sugiura et al. 2004). The slower flow of the continuous phase was assumed to prolong the droplet generation process, leading to the generation of larger aqueous droplets. Kawakatsu et al. reported a similar trend in the droplet/channel ($d_{av}/d_{eq,MC}$) size ratio for the production of monodisperse W/O emulsion droplets using a grooved MC array device (Fig. 9b) (Kawakatsu et al. 2001). Here, $d_{eq,MC}$ is the MC equivalent diameter, defined as four times the cross-section area divided by the wetted perimeter of the trapezoid channel. The $d_{av}/d_{eq,MC}$ ratio reported in the literature (Kawakatsu et al. 2001) was significantly greater than the d_{av}/d_{hole} ratio obtained here (Fig. 9a). In general,

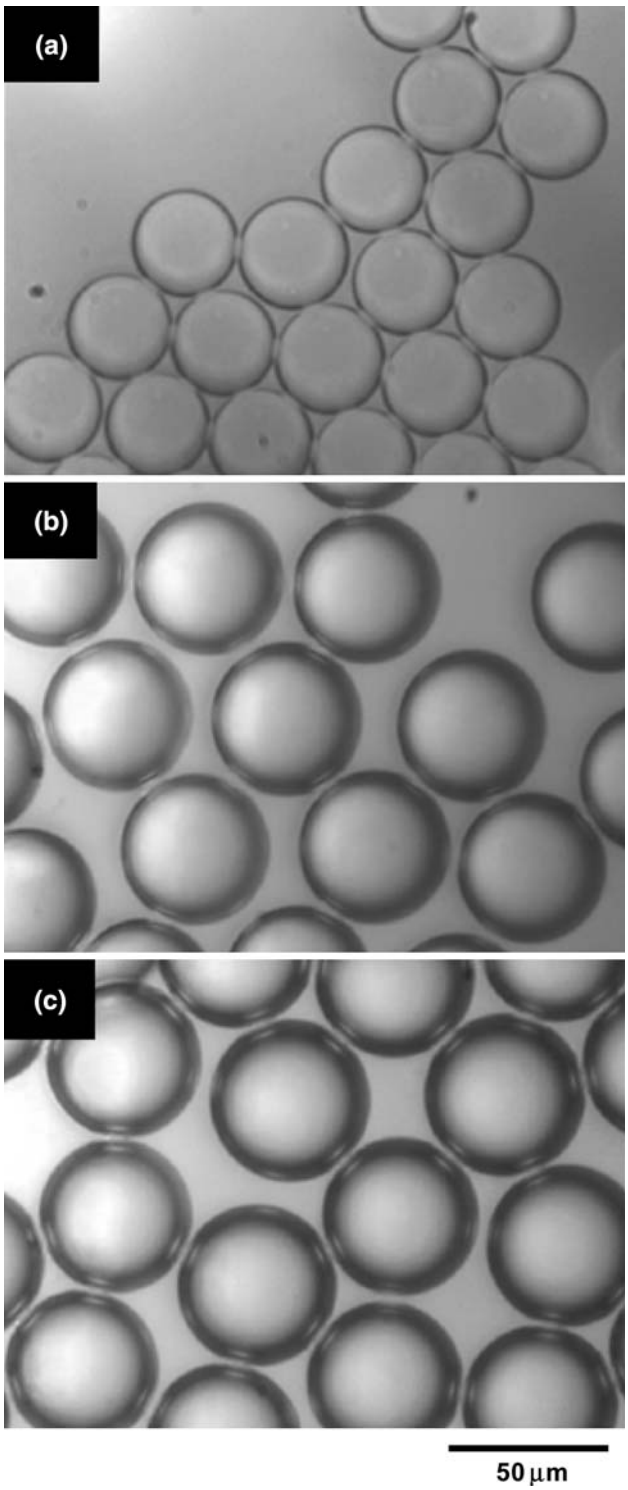

Fig. 7 Optical micrographs of the W/O emulsion droplets generated using different continuous-phase oils. **a** Hexane, **b** MCT, **c** RSO. The data were obtained using a hydrophobic WMS1-3 plate

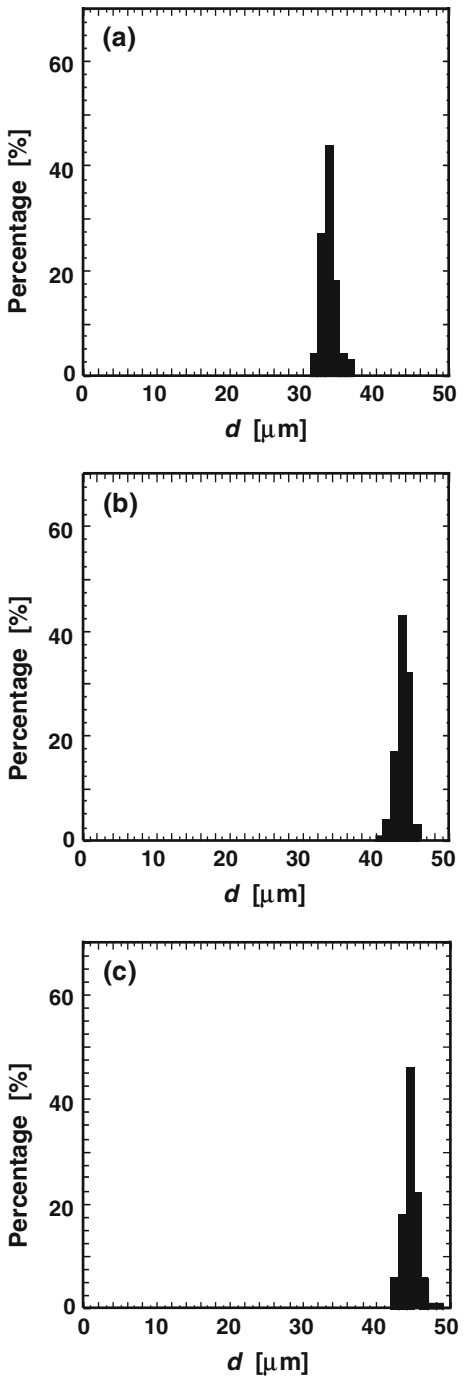

Fig. 8 Size distributions of the W/O emulsion droplets generated using different continuous-phase oils. **a** Hexane, **b** MCT, **c** RSO. The data were obtained using a hydrophobic WMS1-3 plate

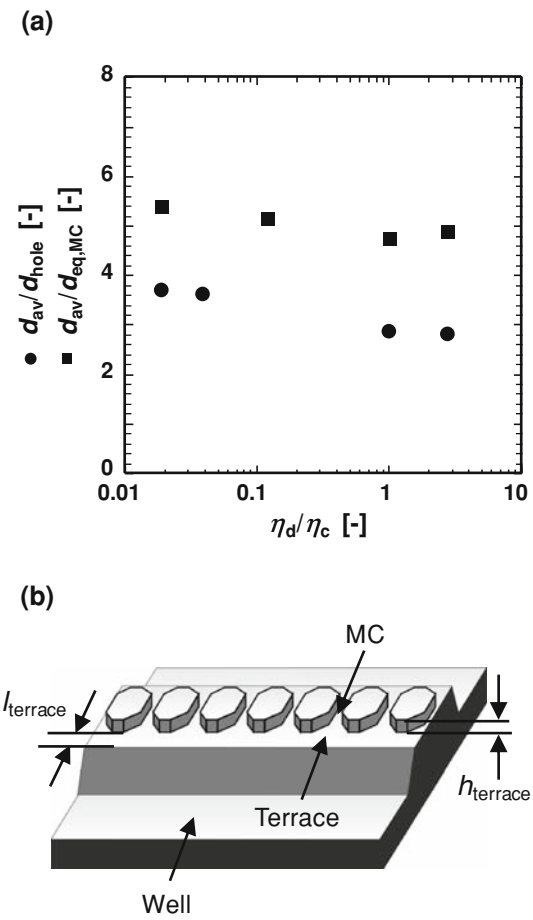

Fig. 9 **a** Effect of the viscosity ratio of the two phases (η_d/η_c) on the d_{av}/d_{hole} obtained in this study using a hydrophobic WMS1-1 plate and the $d_{av}/d_{eq,ch}$ reported by Kawakatsu et al. (2001). The droplet size data for W/O emulsions consisting of water as the dispersed phase were extracted from the literature. **b** Schematic representation of a grooved MC array

the d_{av} of emulsion droplets generated by MCE depends significantly on the $l_{terrace}/h_{terrace}$ ratio of the slot-like terrace (Sugiura et al. 2002), with $h_{terrace}$ corresponding to $w_{s,slot}$ and $l_{terrace}$ corresponding to h_{slot} (Fig. 1). The $l_{terrace}/h_{terrace}$ ratio of 4.4 in the literature (Kawakatsu et al. 2001) was significantly greater than the h_{slot}/w_{slot} ratio of 2.1 in this study. We considered that the difference between the d_{av}/d_{hole} and $d_{av}/d_{eq,MC}$ ratios was attributable to the difference between the h_{slot}/w_{slot} and $l_{terrace}/h_{terrace}$ ratios. The droplet/pore size (d_{av}/d_{pore}) ratios of the W/O emulsions produced using hydrophobic SPG membranes (Shimizu et al. 2002; Cheng et al. 2006) were analogous to the d_{av}/d_{hole} ratio obtained in this study.

3.3 Effect of the dispersed-phase flux

Figure 10a shows the effect of J_d on the d_{av} and CV of the W/O emulsion droplets generated using a hydrophobic WMS1-1 device. A decane solution with 3.0wt% CR-310 was used as the continuous phase, and a Milli-Q water solution with Π_d of 4.2 MPa was used as the dispersed phase. Monodisperse W/O emulsion droplets with d_{av} of 44.5 μm and CV of 2.5% were stably generated from the asymmetric straight-through MC array at J_d of 200 L m^{-2} h^{-1}. The d_{av} and CV of the resultant aqueous

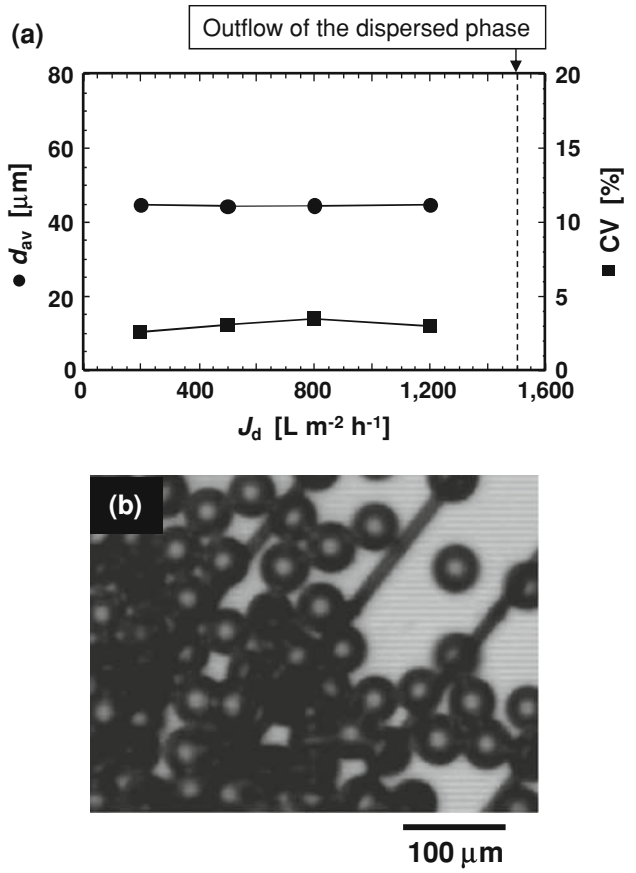

Fig. 10 **a** Effect of J_d on the d_{av} and CV of the W/O emulsion droplets produced using a hydrophobic WMS1-1 device. A decane solution with 3.0wt% CR-310 was used as the continuous phase. A Milli-Q water solution with Π_d of 4.2 MPa was used as the dispersed phase. **b** Optical micrograph of the production of highly uniform aqueous droplets at a very high J_d of 1,200 L m^{-2} h^{-1}

droplets were independent of J_d between 200 and 1,200 L m^{-2} h^{-1}. Highly uniform aqueous droplets were generated through the asymmetric straight-through MC array in the preceding J_d range. In contrast, large droplets (greater than 100 μm) and small droplets (about 45 μm) were generated from the active asymmetric straight-through MCs at J_d of 1,500 L m^{-2} h^{-1}, indicating the production of a polydisperse W/O emulsion. The maximum J_d of 1,200 L m^{-2} h^{-1} and Q_d of 120 mL h^{-1}, at which monodisperse W/O emulsions were produced using a WMS1-1 device, corresponded to a very high droplet productivity of 2.6×10^9 h^{-1} (7.1×10^5 s^{-1}). This droplet productivity suggested that each active asymmetric straight-through MC could generate highly uniform aqueous droplets with a droplet generation frequency (v_{dg}) of >100 s^{-1}. Microscopic observation (Fig. 10b) confirmed the generation of highly uniform aqueous droplets from the active asymmetric straight-through MCs (about 40% of total MCs) with a maximum v_{dg} of approximately 200 s^{-1}. It should be mention that η_c greatly affects droplet productivity for MC emulsification (Sugiura et al. 2004); the maximum J_d is assumed to increase with decreasing η_c.

The J_d for a hydrophobic WMS1-1 device was approximately 200 times greater than that for a hydrophobic SPG membrane with a d_{pore} of 0.52 μm, although the membrane was able to produce monodisperse W/O emulsions with span ($(d_{90} - d_{10})/d_{50}$) of about 0.4 (Shimizu et al. 2002). Here, d_n ($n = 10$, 50, 90) denotes the cumulative volume percentage of droplets with a diameter up to d_n, and n is the percentage. The J_d for the WMS1-1 device was also 1.5 times greater than that for a hydrophobic micro-orifice array with a d_{pore} of 3.5 μm which produced W/O emulsions with CV between 5 and 25% (Geerken et al. 2007). It is necessary to mention that the d_{av}/d_{pore} ratio for the micro-orifice array had very high values of 52 (Geerken et al. 2007).

The aforementioned results imply the high performance of asymmetric straight-through MC array devices for producing monodisperse W/O emulsions.

Emulsion production using asymmetric straight-through MC array devices can be scaled up by further increasing the number of the MCs in larger devices. We previously developed a large 40 × 40-mm MCE device (TMS3-1) consisting of 211,248 symmetric oblong straight-through MCs (Kobayashi et al. 2005b). The TMS3-1 device successfully produced monodisperse soybean oil-in-water emulsions with average droplet diameters ($d_{3,2}$, Sauter diameter) of about 30 μm. The total MC-array area of this device was nine times that of WMS1 devices. If asymmetric straight-through MC arrays (WMS1) as well as TMS3-1 are designed in a 40 × 40-mm plate, it is possible to integrate 5.9×10^4 to 2.1×10^5 MCs into a single MCE device. This scaling up could achieve the production of monodisperse W/O emulsions using an asymmetric straight-through MC array device at a droplet productivity of 1 L h^{-1}, which corresponds to a droplet-throughput capacity of several tons per year. The parallelization of MC emulsification devices is also important for practical emulsion production. The preceding improvements would enable industrial-scale production of monodisperse premium W/O emulsions. Ideally, asymmetric straight-through MC array devices could be scaled up to the size of silicon wafers (currently with a 5-in. diameter), although it is not straightforward to precisely control the flow of the two phases inside a module.

4 Conclusions

Asymmetric straight-through MC arrays, which were hydrophobically modified, had the ability to produce monodisperse W/O emulsions with CV of less than 3%, and consisting of low-viscosity aqueous droplets. Here, Π_d was a key parameter affecting the production phenomena

of W/O emulsions in MCE. A Π_d higher than a threshold that could prevent spontaneous emulsification at an oil–water interface was necessary for stably generating highly uniform aqueous droplets via hydrophobic asymmetric straight-through MCs into a continuous oil phase containing a surfactant. The use of a hydrophobic asymmetric straight-through MC array enabled producing monodisperse W/O emulsions using viscous triglyceride oils, as well as alkane oils, as the continuous-phase medium. Increasing η_c led to the generation of larger aqueous droplets and a longer t_{dg}, which indicated lower droplet productivity. A hydrophobic asymmetric straight-through MC array produced monodisperse W/O emulsions at a maximum J_d of 1,200 L m^{-2} h^{-1}, demonstrating the remarkably high emulsification performance of the MCE device. Droplet throughput of the current asymmetric straight-through MC array with a maximum Q_d of 120 mL h^{-1} is satisfactory for laboratory-scale production. We expect that further scaling up of asymmetric straight-through MC array devices by upsizing and parallelization would enable industrial-scale production of monodisperse W/O emulsions.

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