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Controllable and high-throughput preparation of microdroplet using an ultra-high speed rotating packed bed

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ABSTRACT

Microdroplets and their dispersion, with a large specific surface area and a short diffusion distance, have been applied in various unit operations and reaction processes. However, it is still a challenge to control the size and size distribution of microdroplets, especially for high-throughput generation. In this work, a novel ultra-high speed rotating packed bed (UHS-RPB) was invented, in which rotating foam packing with a speed of 4000–12000 r·min⁻¹ provides microfluidic channels to disperse liquid into microdroplets with high throughput. Then generated microdroplets can be directly dispersed into a continuous falling film for obtaining a mixture of microdroplet dispersion. In this UHS-RPB, the effects of rotational speed, liquid initial velocity, liquid viscosity, liquid surface tension and packing pore size on the average size (d_{32}) and size distribution of microdroplets were systematically investigated. Results showed that the UHS-RPB could produce microdroplets with a d_{32} of 25–63 μm at a liquid flow rate of 1025 L·h⁻¹, and the size distribution of the microdroplets accords well with Rosin–Rammler distribution model. In addition, a correlation was established for the prediction of d_{32} , and the predicted d_{32} was in good agreement with the experimental data with a deviation within $\pm 15\%$. These results demonstrated that UHS-RPB could be a promising candidate for controllable preparation of uniform microdroplets.

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1. Introduction

Liquid flow, a typical unit operation, is common and significant in various mass transfer processes, such as extraction [1], separation [2], dissolution [3], absorption [4]. To intensify these processes, liquid is often dispersed as droplets into continuous phase. Generally, smaller droplets produce a larger specific surface area and shorter diffusion distance [5,6]. Therefore, microdroplets has been widely exploited in many chemical engineering fields like biochemical reaction [7,8], material synthesis [9–12], and microextraction [13–15].

To effectively generate microdroplets in the process system, many techniques have been explored [16], such as high-speed agitation [17,18], membrane emulsification [19,20], spinning conical frustum method [21] for liquid–liquid system, and air-blast

atomization [22,23], spinning disk atomization [24], acoustic resonator method [25] for gas–liquid system. Among these techniques, the high-speed agitation method relies on the produced shear force to break up the droplets by stirring mixture of dispersed phase and continuous phase. The membrane emulsification method generated the dispersed phase into the continuous phase by a porous membrane. In the spinning conical frustum method, near-monodisperse microdroplets are continually injected into the continuous liquid phase, and thus the mixing effects are enhanced by spinning conical. Inspired by above, an interesting idea was firstly put forward to generate microdroplets in air environment which was then directly put into continuous liquid phase for liquid–liquid system [26]. During this process, the first step is based on microdroplet generation methods for gas–liquid system which are instanced as follows: (a) The air-blast atomization method in which the flow gas is adopted to break up the liquid into microdroplets (air-blast atomization process); (b) Rotating atomization method on spinning disk, which creates centrifugal force, can split liquid into droplets and throw them away with high throughput; (c) Acoustic resonator method relies on high energy input to make huge local force on liquid, which gradually oscillates

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and breaks up into microdroplets; (d) Microfluidic chip method, using shear force and fluid interfacial tension to generate microdroplets, can produce microdroplets with controllable size distribution [27,28]. However, it is still a challenge for controllable and high-throughput generation of microdroplets.

Rotating packed bed (RPB), a typical centrifugal device for process intensification, can efficiently split and break liquid into extensive droplets owing to its high-speed rotating packing. For traditional RPB, the rotational speed is usually in the range of 0–3000 r·min⁻¹ and the droplets size is in the range of 150–900 μm [29–32]. Considering that the droplet size decreases significantly with increasing rotational speed, an ultrahigh speed RPB (UHS-RPB) packed with foam metal packing (rotational speed ranging from 4000–12000 r·min⁻¹) was developed for microdroplet generation (Fig. 1). For a better understanding, the rotational speed corresponding to the high-gravity (Higee) level is provided in Table 1. The centrifugal acceleration is defined as:

$$a = \left(2\pi \frac{N}{60}\right)^2 \left(\frac{r_o^2 + r_i^2}{2}\right)^{1/2} \quad (1)$$

where a is centrifugal acceleration; N is rotational speed; r_o is inner radius of packing; r_i is outer radius of packing.

For RPB device, the ratio of centrifugal acceleration to the gravitational acceleration g is defined as the high-gravity (Higee) level, and its expression is as follows:

$$\beta = \frac{a}{g} \quad (2)$$

In this novel equipment, a dismountable falling film generator is assembled on the shell wall for yielding continuous falling film to capture microdroplets. Foam metal packing provides plenty of microchannels to generate microdroplets under strong shear force

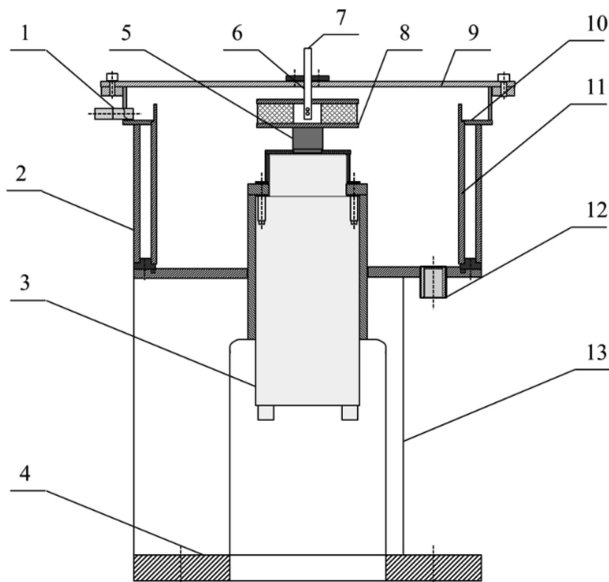


Fig. 1. Schematic diagram of the used UHS-RPB: (1) liquid inlet for continuous phase; (2) shell; (3) motor; (4) base; (5) hinge; (6) liquid distributor; (7) liquid inlet for dispersed phase; (8) packing; (9) cover; (10) overflow weir; (11) falling film board; (12) liquid outlet; (13) support.

Table 1
Comparison of the rotational speed and Higee level of traditional RPB and UHS-RPB

Items	Traditional Higee level			High Higee level							
	1000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
Rotational speed/r·min ⁻¹	1000	3000	4000	5000	6000	7000	8000	9000	10000	11000	12000
Gravity level/g	44	398	707	1105	1591	2165	2828	3579	4419	5347	6363

and centrifugal force [33,34]. Furthermore, the UHS-RPB is available for both gas–liquid system and liquid–liquid system, and has higher liquid throughput than single microfluidic chip. In addition, rotational speed of packing can be conveniently adjusted to tune the microdroplet size.

In this work, UHS-RPB was adopted to generate microdroplets. The effects of rotational speed, liquid initial velocity, liquid viscosity, liquid surface tension and packing structure on the average size (d_{32}) and diameter distribution of microdroplets were investigated. Then, a correlation of d_{32} was established using several dimensionless numbers. In addition, the comparison of dispersion effect between UHS-RPB and other analogous equipment was proposed.

2. Experimental

2.1. Materials

Water was used as dispersed liquid. Sodium dodecyl benzene sulfonate was purchased from Beijing Chemical Works (China). Glycerol was provided by Shanghai Macklin Biochemical Co., Ltd. (China). Sodium dodecyl benzene sulfonate and glycerol were all of A.R. grade, and were used without further purification.

2.2. Characterization

Here, the droplet sizes were analyzed using laser particle size analyzer (Betersize 2000S, Betersize Instruments Ltd., China) with a measuring range of 1–2000 μm and an error range of $\leq \pm 0.5\%$. The liquid viscosity was tested using rotational viscometer NDJ-1E provided by Shanghai Changji Geological Instrument Co. Ltd. (China). The liquid surface tension was determined using tensiometer Krüss 100 (Germany) provided by Kunshan Research Precision Instrument Co. Ltd. All the experiments were repeated at least 3 times.

2.3. Equipment and experimental procedure

Fig. 1 schematically displays the structure of the used UHS-RPB, which is similar to traditional RPB. One special design is the falling film generator on the shell, where continuous liquid gathers at the overflow weir and then flow across it gradually, forming the annular continuous falling film on the inner wall of shell, which can easily capture the microdroplets flying out from the rotating packing. Foam nickel with the advantages of high density and mechanical strength was packed in the rotor [35]. Detailed parameters of the used UHS-RPB are given in Table 2.

As shown in Fig. 2(a), the experimental setup contains the UHS-RPB system and microdroplet size analyzer system. In the UHS-RPB system, liquid is pumped from the storage tank and sprayed onto the inner edge of the packing via two-hole liquid distributor, and then goes through the packing by the centrifugal force. During this process, liquid is split and broken into microdroplets, and then flows into outer cavity, as shown in Fig. 2(b). Finally, liquid is collected at the bottom of the UHS-RPB and flows into the storage tank for cyclic utilization. For the liquid–liquid system, the generated microdroplets will fly into the liquid falling film on the inner wall of shell firstly and then are collected as a mixture of dispersed phase and continuous phase, respectively. The microdroplet size

Table 2
Specifications of the used UHS-RPB and operating conditions

Items	Values
Parameters of UHS-RPB	
Inner radius of packing/mm	25
Outer radius of packing/mm	50
Axial height of packing/mm	10
Outer radius of shell/mm	175
Diameter of holes on distributor/mm	1
Operating conditions	
Rotational speed/r·min ⁻¹	4000–12000
Liquid flow rate/L·h ⁻¹	10–25
Liquid initial velocity/m·s ⁻¹	1.77–4.42

analyzer system mainly includes laser generator, laser receiver and computer. As shown in Fig. 2(c), the laser beam passes through the outer cavity from the bottom hole to the cover hole. Then, the size information of microdroplets contained in the laser beam is measured and recorded in the computer. All measures were conducted at 25 °C more than 3 times in a dark environment to eliminate the influence of other lights.

2.4. Analytical method and calculation

The sizes of generated microdroplets were not uniform, and therefore, d_{32} was calculated to characterize the microdroplet size in this experiment. d_{32} is the volumetric-area ratio average diame-

ter, which based on the assumption that a droplet group with the same diameter of d_{32} and same surface area and total volume as the original droplet group. It can be calculated by the following equation:

$$d_{32} = \frac{\sum(n_i d_i^3)}{\sum(n_i d_i^2)} \quad (3)$$

where n_i is the number of droplets with diameter d_i . In addition, a smaller d_{32} means a larger specific surface area of the whole droplets group.

In order to obtain droplets with uniform size, size distribution should be controlled [5]. The Rosin-Rammler (R-R) distribution model was selected for describing size distribution of liquid droplets obtained by the UHS-RPB [36]:

$$V = 1 - \exp[-(d/c)^m] \quad (4)$$

where V is the volume fraction of the droplets with diameter below d in total volume; c is the characteristic droplet diameter defined as the diameter at the cumulative volume fraction is 63.2%, and m indicates the characteristic width of size distribution. Usually, a larger m represents a narrower distribution.

The droplet size divergence can be described by the distribution span (S_d), which is defined as follows [10]:

$$S_d = \frac{d_{0.9} - d_{0.1}}{d_{0.5}} \quad (5)$$

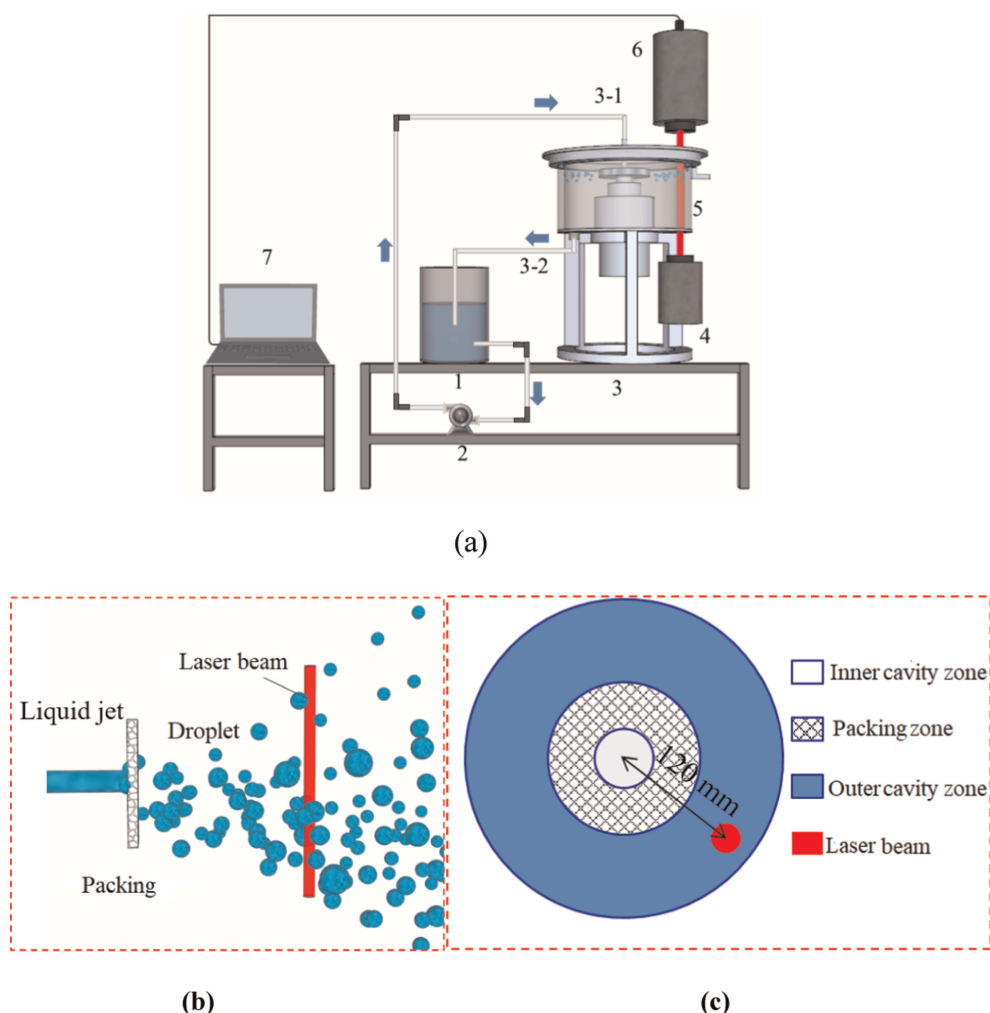


Fig. 2. (a) Experimental setup of microdroplet generator (1) liquid storage tank; (2) peristaltic pump; (3) UHS-RPB; (3-1) liquid inlet; (3-2) liquid outlet; (4) laser generator; (5) laser beam; (6) laser receiver; (7) computer), (b) schematic showing the measurement of droplet size by laser beam, and (c) top view of the microdroplet generator.

where $d_{0.1}$, $d_{0.5}$ and $d_{0.9}$ are the droplet diameter at the cumulative volume distribution probability of 10%, 50% and 90%, respectively. When S_d value is smaller, the droplet size is more uniform. Both above methods are adopted to calculate the size distribution in this experiment, and the former is used for predicting theoretical size distribution based on mathematics model and the latter is for characterizing intuitive size distribution.

3. Results and Discussion

3.1. Effects of operation conditions on microdroplets

3.1.1. Rotational speed

In this work, the packing pore size is described by the average number of pores per inch (ppi) in nickel foam packing. It is clear that the droplet size decreases with increasing rotational speed (Fig. 3). When rotational speed increases from 4000 to 12000 $\text{r}\cdot\text{min}^{-1}$, d_{32} decreases from 63 to 27 μm . This observation can be explained by two factors. On the one hand, with the increase of rotational speed, the relative velocity between the packing and the liquid increases so that the shear force on the liquid increases, resulting in the decrease of d_{32} . On the other hand, the gas turbulence is strongly enhanced by ultrahigh-speed rotating packing, leading to further atomization of liquid droplets. This results shows that the controllable preparation of microdroplets can be achieved by regulating the rotational speed of UHS-RPB technique.

Fig. 4(a) displays that the calculated data obtained by Eq. (4) agrees well with the experimental results, indicating the R-R distribution model is reliable. It can be found that with increasing rotational speed, m increases, while c decreases, suggesting that a larger rotational speed is favorable for producing more uniform droplet size distribution. This is also verified by Fig. 4(b), which shows that S_d decreases as the rotational speed increases. However, the rotational speed higher than 8000 $\text{r}\cdot\text{min}^{-1}$ has little effect on further narrowing the droplet size distribution. Considering the energy consumption, the optimal rotational speed should be kept around 9000 $\text{r}\cdot\text{min}^{-1}$.

3.1.2. Liquid initial velocity

The effect of liquid initial velocity on d_{32} is shown in Fig. 5. Compared to rotational speed, the increase of liquid initial velocity provides less energy for liquid dispersion. Therefore, the d_{32} increases slightly with increasing liquid initial velocity mainly

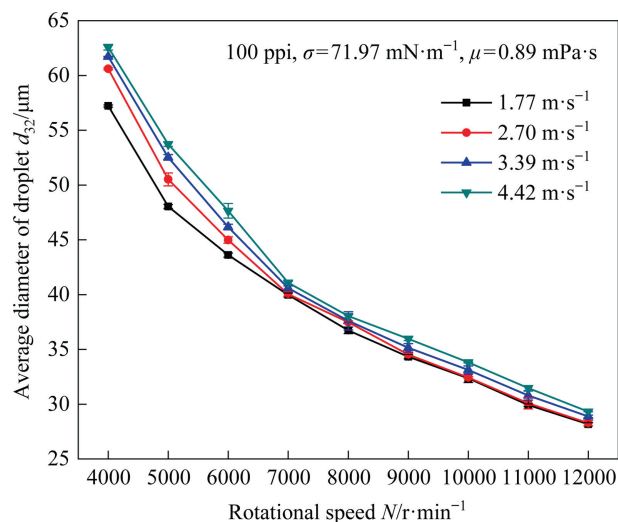


Fig. 3. Effect of rotational speed on d_{32} .

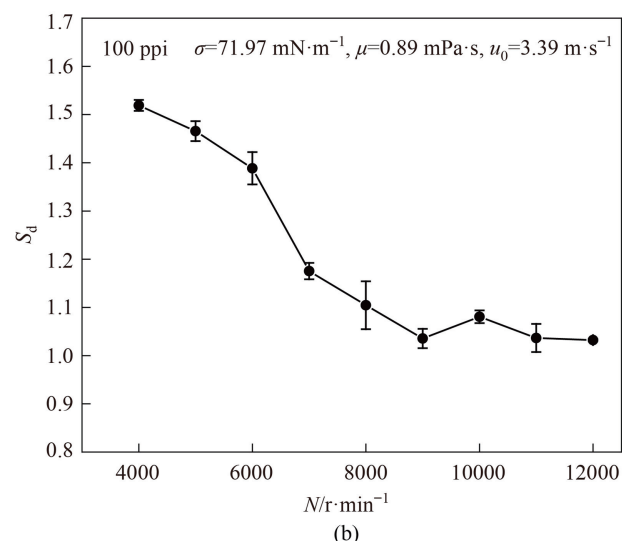
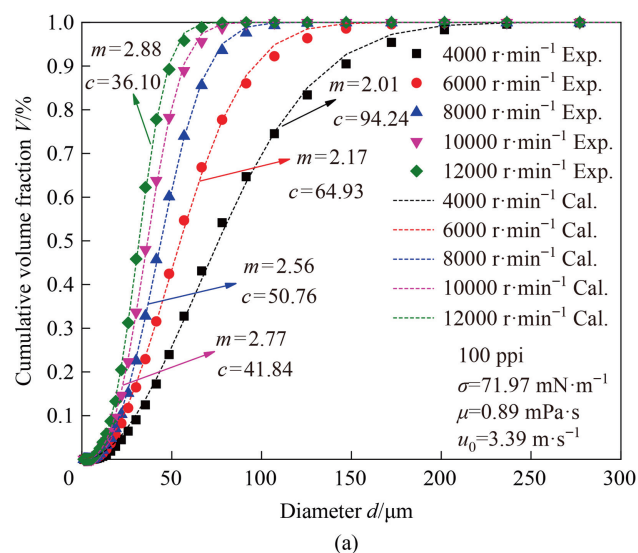


Fig. 4. Effects of rotational speed on: (a) cumulative volume distribution of droplet diameter and (b) S_d .

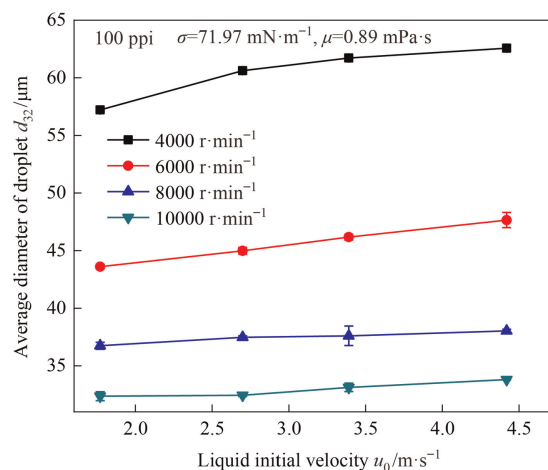


Fig. 5. Effect of liquid initial velocity on d_{32} .

because shear velocity is much higher than the radial velocity of the liquid. Especially, under high rotational speed ($N > 8000 \text{ r} \cdot \text{min}^{-1}$), d_{32} is almost unchanged with the increase of liquid initial velocity, revealing that the shearing effect produced by the rotating packing is dominant at ultrahigh speed in the process.

Fig. 6 displays the effect of liquid initial velocity on the R–R distribution of microdroplets. m and c change slightly with increasing liquid initial velocity, indicating that liquid flow rate has little effect on S_d and size distribution of microdroplets.

3.2. Effects of liquid physical properties on microdroplets

3.2.1. Liquid viscosity

In this experiment, glycerol was mixed into water for adjusting the liquid viscosity. The glycerol mass concentration was selected as 0, 30%, 40%, 50%, 60% and 70% with the viscosity of 0.89, 2.13, 3.14, 5.01, 8.85 and 18.07 mPa·s, respectively.

It is shown that the d_{32} gradually decreases with increasing the liquid viscosity (Fig. 7). Previous literature has proved that the droplets were formed due to the liquid ligament breaking at the outer edge of rotating packing [27], and the thickness of liquid ligament decreases with the increase of liquid viscosity under the high cen-

trifugal force, resulting in the decrease of d_{32} . In addition, the surface tension also decreases as the liquid viscosity increases, which is beneficial to break the droplets.

As shown in Fig. 8(a), m changes slightly with increasing liquid viscosity while c decreases with increasing liquid viscosity. Correspondingly, S_d decreases sharply when the viscosity increases from 0.89 to 2.13 mPa·s, and then almost unchanged with the viscosity increasing from 5.01 to 18.07 mPa·s (Fig. 8(b)). At relatively low viscosity, increasing the liquid viscosity decreases the number of big droplets while the number of small droplets increases, ultimately give rise to a more uniform size distribution of microdroplets. However, a high liquid viscosity could hinder the liquid breaking process.

3.2.2. Liquid surface tension

Considering that adding glycerol into water has no significant influence on the liquid surface tension, sodium dodecyl benzene sulfonate (SDBS) was added into water for adjusting liquid surface tension [37]. The selected SDBS concentration was 0 and 0.01% with liquid surface tension of 71.97 and 38.20 mN·m⁻¹, respectively.

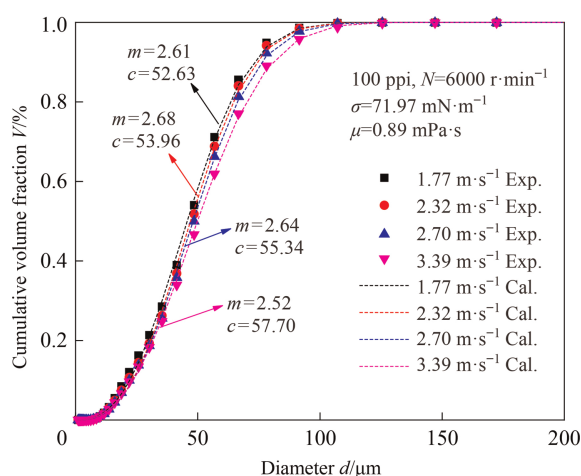


Fig. 6. Effect of liquid initial velocity on cumulative volume distribution of droplet diameter.

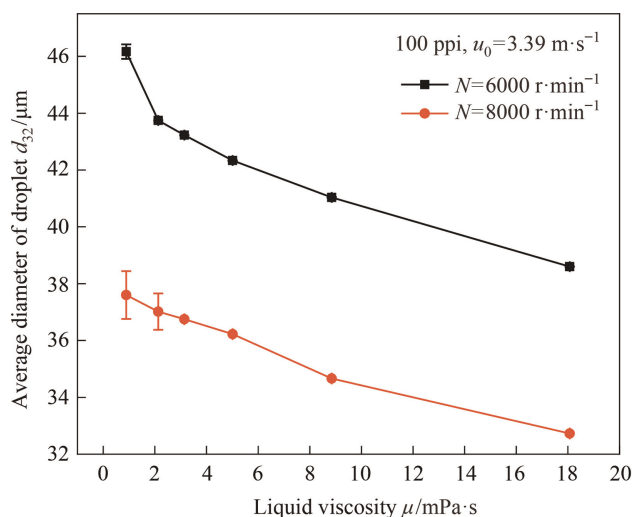


Fig. 7. Effect of viscosity on d_{32} .

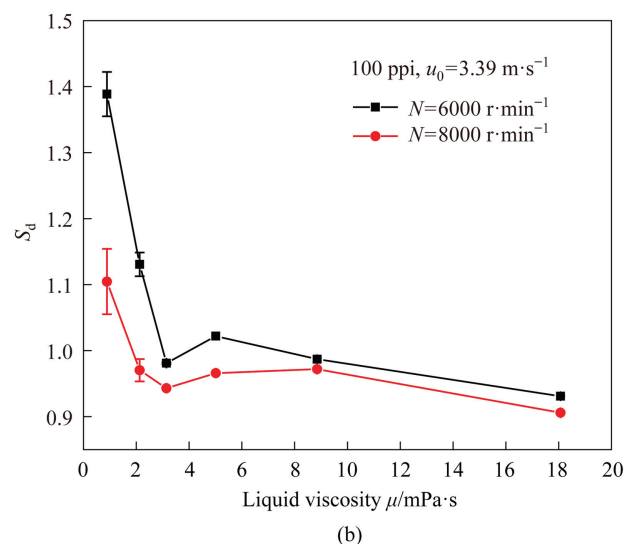
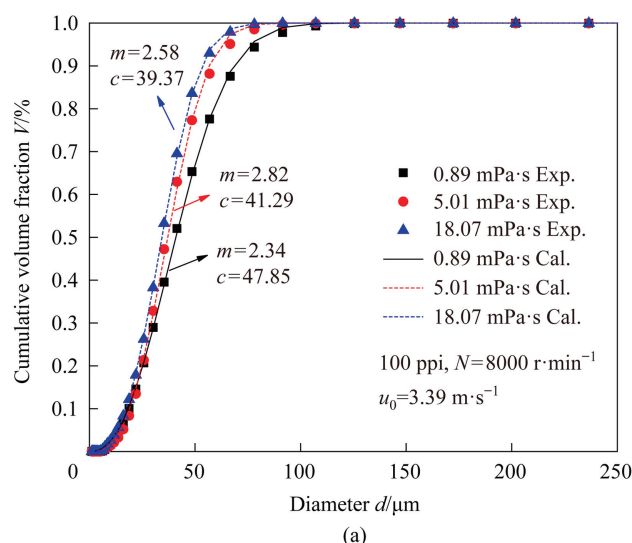


Fig. 8. Effect of liquid viscosity on: (a) cumulative volume distribution of droplet diameter and (b) S_d .

Fig. 9 shows that the microdroplets with lower liquid surface tension possesses a smaller size compared to those with higher liquid surface tension, proving that lower liquid surface tension is conducive to droplet breakup.

The effect of surface tension on the R-R distribution of microdroplets is demonstrated in Fig. 10(a). Results shows that c increases with the decrease of liquid surface tension, while m decreases with the increase of liquid surface tension, indicating that a high liquid surface tension is beneficial to generate uniform droplet size distribution. Moreover, S_d decreases with the increase of liquid surface tension, further validating that a high liquid surface tension favor the production of uniform droplet size distribution. Besides, S_d decreases with increasing rotational speed, and this trend is more evident at low surface tension than that at high area, meaning that this shear action achieved by UHS-RPB for microdroplets generation is more effective for liquid with lower surface tension.

3.3. Effect of packing pore size on microdroplets

The pore size can be reflected by the ppi of nickel foam packing and porosity of nickel foam packing. The packing pore sizes of 40 and 100 ppi correspond to porosity of 97% and 95%, respectively. Previous study has been proved that the packing porosity has important effect on liquid flow behavior [38].

It is shown that the effect of packing pore size on d_{32} (Fig. 11). The microdroplets generated by a smaller pore-size packing is smaller than that by a bigger pore-size packing. The reason is that the packing with smaller pore size has narrower microchannels, producing more tiny microdroplets.

Fig. 12(a) displays the effect of packing pore size on the R-R distribution of microdroplets. c value of microdroplets generated by a smaller pore-size packing is smaller than that by a bigger pore-size packing, while m value of microdroplets generated by smaller pore-size packing is larger.

Fig. 12(b) shows that S_d decreases with packing pore size increasing under low rotational speed ($N < 7000$ r·min⁻¹). The reason is that, when the packing pore size is bigger, more gas will enter into the pores to break up the liquid, making the d_{32} more uniform. However, when the rotational speed is above 7000 r·min⁻¹, the effect of gas flow gradually weakens relative to the effect of centrifugal force. Generally, the rotating packing with smaller pore size shears the liquid more frequently and violently, leading to a narrower S_d .

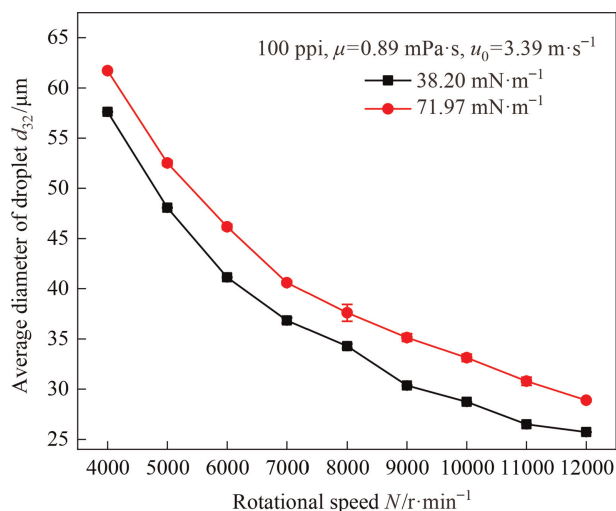


Fig. 9. Effect of surface tension on d_{32} .

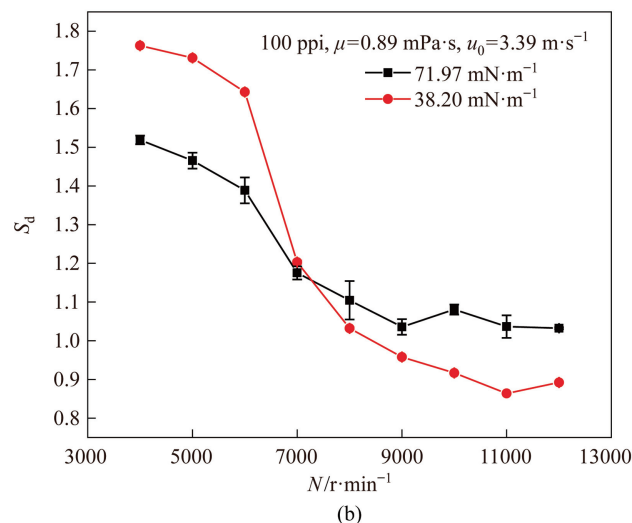
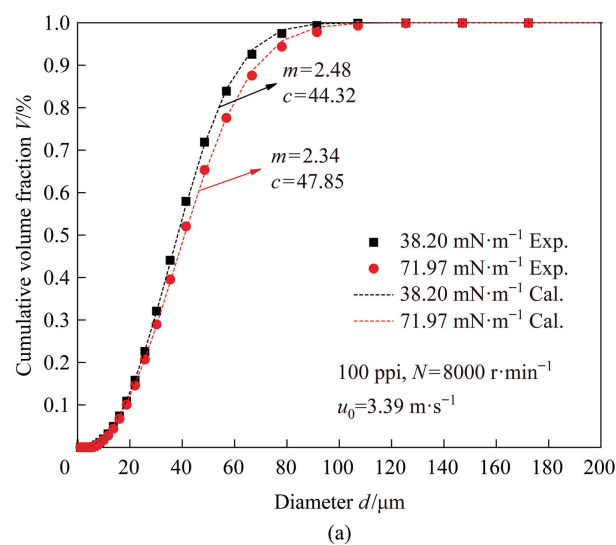


Fig. 10. Effects of surface tension on: (a) cumulative volume distribution of droplet diameter and (b) S_d .

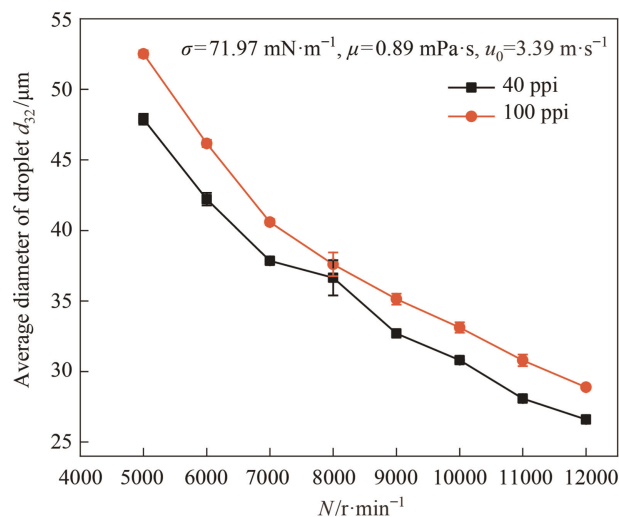


Fig. 11. Effect of packing pore size on d_{32} .

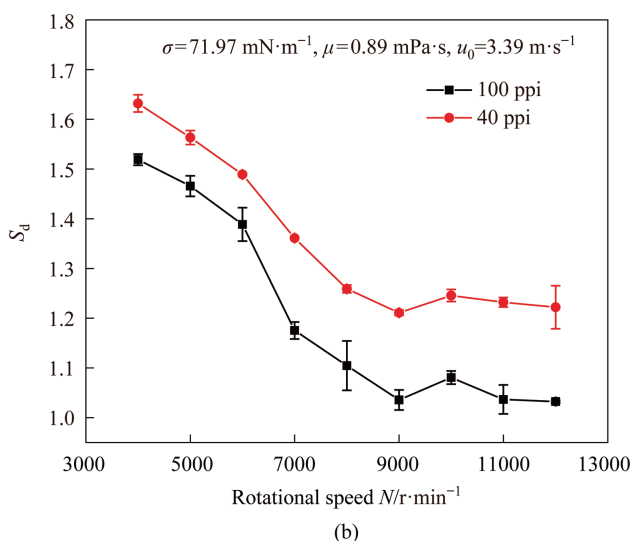
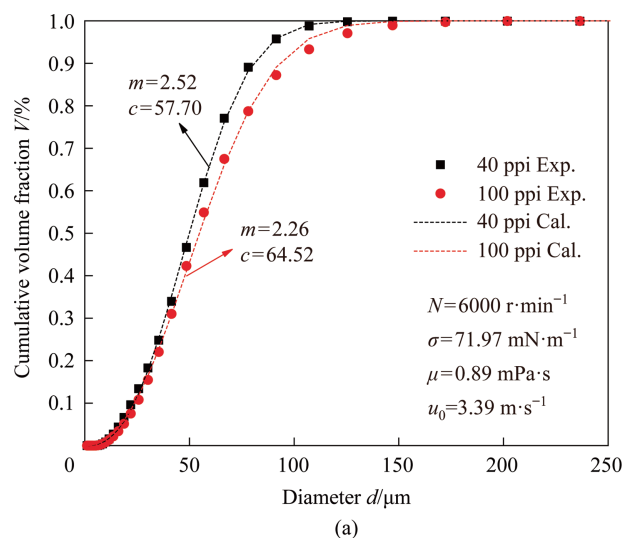


Fig. 12. Effect of packing pore size on: (a) cumulative volume distribution of droplet diameter and (b) S_d .

3.4. Correlation for droplet size

To further investigate the influence factors on the droplet sizes, dimensionless analysis was employed to establish the correlation of the ratio of d_{32} and r . The expression was obtained as follows:

$$F(\omega, u_0, r, \mu, \sigma, \rho) = 0 \quad (6)$$

where ω is angular velocity; u_0 is liquid initial velocity; r is outer radius of packing; μ is liquid viscosity; σ is liquid surface tension; ρ is liquid density.

Based on the dimensionless analysis, three non-dimensional numbers were obtained:

$$\text{Reynold number} : Re = \frac{\rho \omega r^2}{\mu} \quad (7)$$

$$\text{Weber number} : We = \frac{\rho \omega^2 r^3}{\sigma} \quad (8)$$

$$\text{Dimensionless liquid initial velocity} : q = \frac{u_0}{\omega r} \quad (9)$$

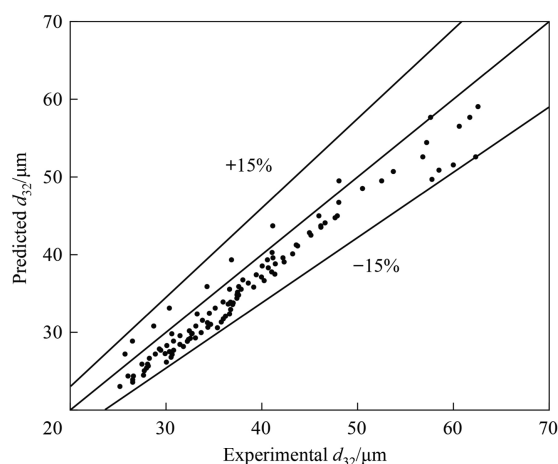


Fig. 13. Comparison of d_{32} between experimental and predicted values.

The correlation obtained by fitting d_{32}/r and Re , We , q , ε , written as follows:

$$\frac{d_{32}}{r} = 0.046 We^{-0.322} Re^{0.031} q^{0.087} \varepsilon^{-0.378} (R^2 = 0.95) \quad (10)$$

where ε is porosity of packing; We and ε are negative; Re and q are positive. The above study indicates that the higher centrifugal acceleration, liquid viscosity, liquid surface tension and packing pore size cause smaller d_{32} (Figs. 3, 7, 9 and 11). It can be found from Eq. (10) that the effects of We and ε on d_{32} are greater than Re and q . For the same packing, the centrifugal force and liquid surface tension are two significant factors for further engineering application of UHS-RPB. The diagonal graph plotted in Fig. 13 illustrates that this correlation offers relatively precise predictions of d_{32} with deviations within 15% compared to the experimental values.

3.5. Comparison UHS-RPB with other analogous equipment

In this section, analogous rotating equipment for microdroplet generation including spinning disk [24], spinning cup [39], rotary atomizer [40], rotating micro-nozzle [41] and UHS-RPB are compared in Table 3. Noting that although the present rotational speed of 4000–12000 $r \cdot \min^{-1}$ is at a relative low level compared to other analogous equipment, the microdroplet size achieved by UHS-RPB is smaller than those by others. Compared with spinning disk and

Table 3
Comparison of microdroplet generation among analogous equipment

Equipment	Operation conditions	$d_{32}/\mu\text{m}$
Spinning disk [24]	$N = 8000\text{--}16000 \text{ r} \cdot \text{min}^{-1}$; $r = 0.02\text{--}0.06 \text{ m}$; $Q = 2\text{--}10 \text{ L} \cdot \text{h}^{-1}$; $\mu = 1 \text{ mPa} \cdot \text{s}$; $\sigma = 72 \text{ mN} \cdot \text{m}^{-1}$; $\rho = 1000 \text{ kg} \cdot \text{m}^{-3}$ (water)	67–310
Spinning cup [39]	$N = 12000\text{--}18000 \text{ r} \cdot \text{min}^{-1}$; $r = 0.035 \text{ m}$; $Q = 8 \text{ L} \cdot \text{h}^{-1}$; $\mu = 1 \text{ mPa} \cdot \text{s}$; $\sigma = 72 \text{ mN} \cdot \text{m}^{-1}$; $\rho = 1000 \text{ kg} \cdot \text{m}^{-3}$ (water)	75–170
Micro-nozzle [40]	$a = 93\text{--}452 \text{ g}$; $\sigma = 63.4 \text{ mN} \cdot \text{m}^{-1}$; $\rho = 1010 \text{ kg} \cdot \text{m}^{-3}$ (2% chitosan solution)	214–372
Rotary atomizer [41]	$N = 10500\text{--}29000 \text{ r} \cdot \text{min}^{-1}$; $r = 0.055 \text{ m}$; $Q = 50\text{--}450 \text{ L} \cdot \text{h}^{-1}$; $\mu = 1 \text{ mPa} \cdot \text{s}$; $\sigma = 72 \text{ mN} \cdot \text{m}^{-1}$; $\rho = 1000 \text{ kg} \cdot \text{m}^{-3}$ (water)	35–100
UHS-RPB	$N = 4000\text{--}12000 \text{ r} \cdot \text{min}^{-1}$; $r = 0.05 \text{ m}$; $Q = 10\text{--}25 \text{ L} \cdot \text{h}^{-1}$; $\mu = 0.89 \text{ mPa} \cdot \text{s}$; $\sigma = 71.97 \text{ mN} \cdot \text{m}^{-1}$; $\rho = 1000 \text{ kg} \cdot \text{m}^{-3}$ (water)	25–63

spinning cup, UHS-RPB packed with foam nickel not only has a higher throughput, but also can shear liquid more violently. Compared with rotating micro-nozzle, UHS-RPB is equipped with foam packing that provides ideal microchannels to produce microdroplets more uniform. While compared with rotary atomizer, the d_{32} generated by UHS-RPB is 2 times smaller and the size distribution is narrower.

In general, there are two main features of UHS-RPB for microdroplets generation: (a) UHS-RPB has numerous microchannels in foam packing which can generate smaller microdroplets; (b) UHS-RPB can create stable centrifugal environment, which is beneficial for generating uniform microdroplets with high throughput. In particular, for liquid–liquid system, the UHS-RPB assembles with falling film generator can efficiently produce mixture of microdroplets dispersion, avoiding demulsification.

4. Conclusions

In this work, a novel UHS-RPB is firstly created for microdroplets generation. The effects law of the operation condition, liquid physical property and packing pore size on d_{32} and size distribution of microdroplets were explored. R–R distribution model and S_d value were both adopted to evaluate the size distribution of microdroplets. In addition, the correlation for prediction d_{32} were established based on several dimensionless numbers, and the prediction results have acceptable deviations of $\pm 15\%$. Compared to other analogous equipment, the UHS-RPB can generate smaller microdroplets in size of 25–63 μm at liquid flow rate of 10–25 $\text{L}\cdot\text{h}^{-1}$. This novel microdroplets generation technique shows a promising application in both gas–liquid system and liquid–liquid system.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclatures

c	the characteristic droplet diameter, μm
d	droplets diameter, μm
d_{32}	sauter mean diameter, μm
m	value of the distribution width
N	rotational speed, $\text{r}\cdot\text{min}^{-1}$
n	total number of droplets with same diameter
n_i	the number of droplets with diameter d_i in droplet groups with different diameters
Q	liquid flow rate, $\text{L}\cdot\text{h}^{-1}$
R	square root of coefficient of multiple determination
r	outer radius of packing, mm
u_0	liquid initial velocity, $\text{m}\cdot\text{s}^{-1}$
V	fraction of the total volume contained in droplets of diameter below d , %
ε	porosity of packing, %
ρ	liquid density, $\text{kg}\cdot\text{m}^{-3}$
σ	liquid surface tension, $\text{mN}\cdot\text{m}^{-1}$
μ	liquid viscosity, $\text{mPa}\cdot\text{s}$

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