Continuous formation of microbubbles during partial coalescence of bubbles from a submerged capillary nozzle

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Abstract

Bubble formation from a downward-pointing capillary nozzle was investigated in this study. The experiments were conducted at gas flow rate of 40-5400 mL/h and inner nozzle radius of 0.030-0.255 mm. Experimental results show that microbubbles were formed continuously at moderate Weber number, which was not reported in pervious investigations with injecting gas through an upward-pointing capillary nozzle. High-speed visualization indicates that the formation of microbubbles arises from the convergence of the capillary waves induced by the partial coalescence of larger bubbles. A bubbling regime map is given to identify the critical conditions for the formation of microbubbles. In the present air-water experiments, the generated microbubbles are 20-170 μm in diameter. From experimental data, a scaling law for microbubble size is proposed as a function of Weber and Bond numbers.

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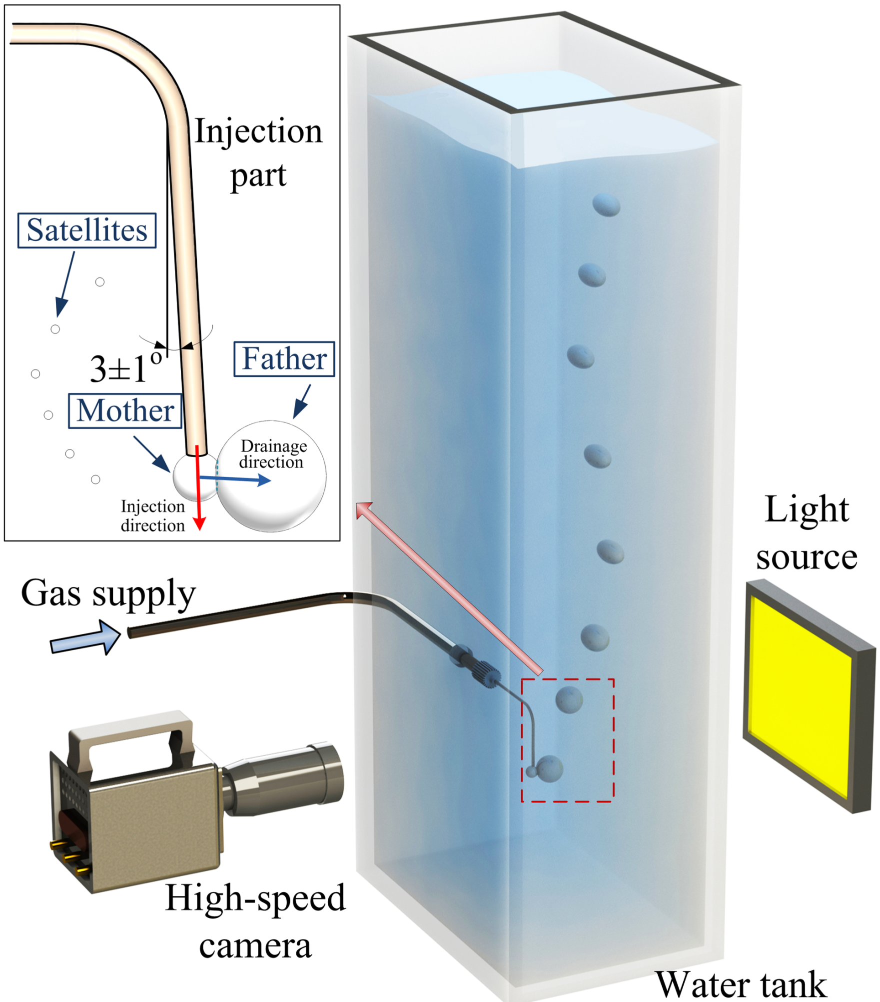
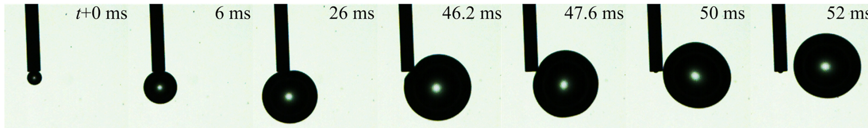
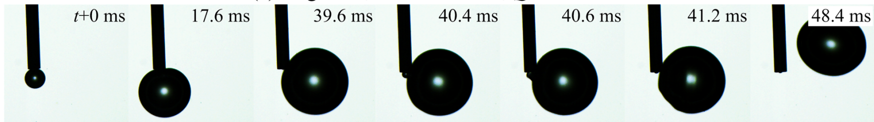
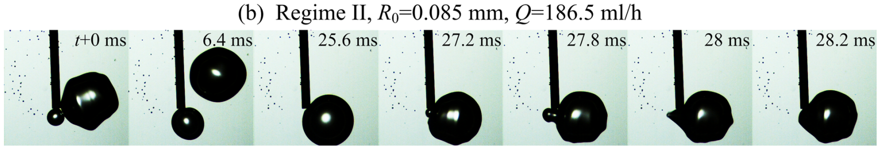

Injection part
Satellites
3±1°
Father
Mother
Drainage direction
Injection direction
Light source
Gas supply
High-speed camera
Water tank



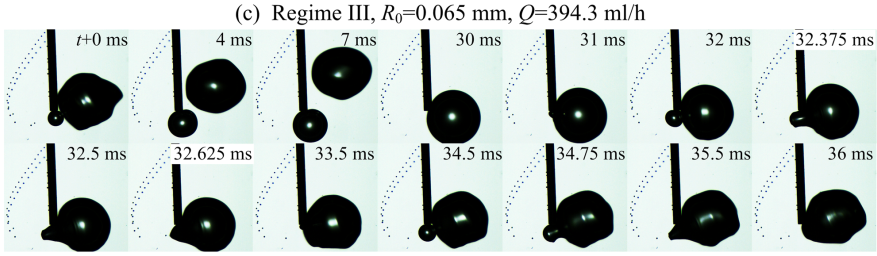
(a) Regime I, R_0=0.065 mm, Q=96.4 ml/h



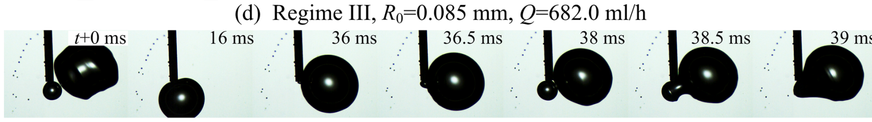
(b) Regime II, R_0=0.085 mm, Q=186.5 ml/h



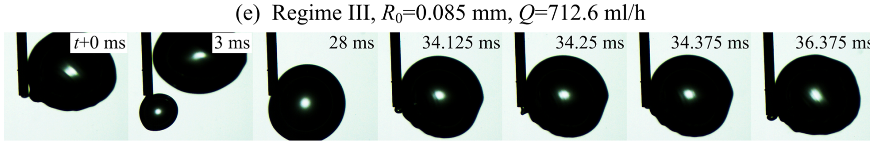
(c) Regime III, R_0=0.065 mm, Q=394.3 ml/h



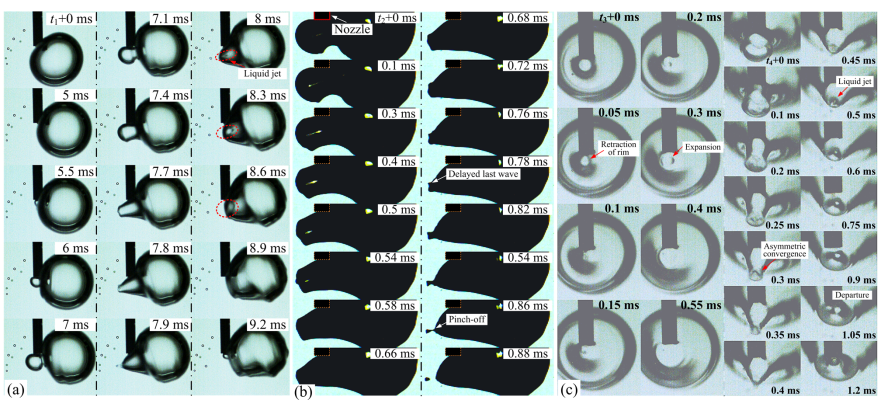
(d) Regime III, R_0=0.085 mm, Q=682.0 ml/h

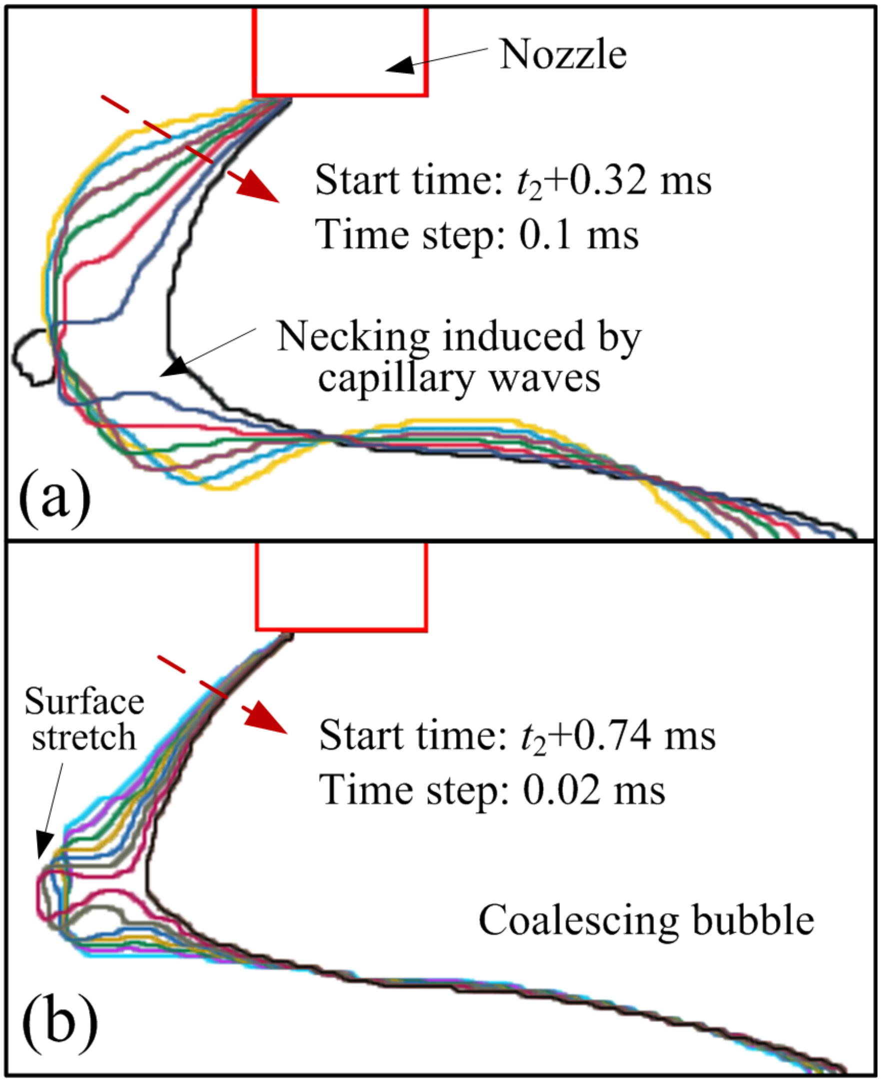


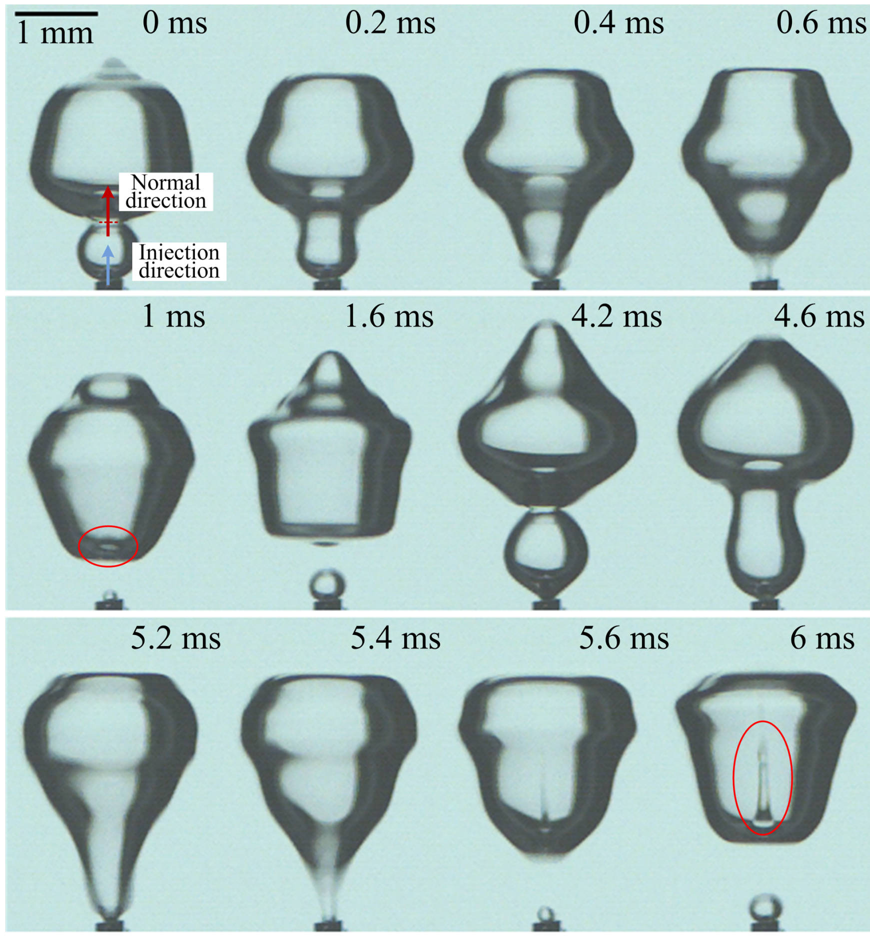
(e) Regime III, R_0=0.085 mm, Q=712.6 ml/h

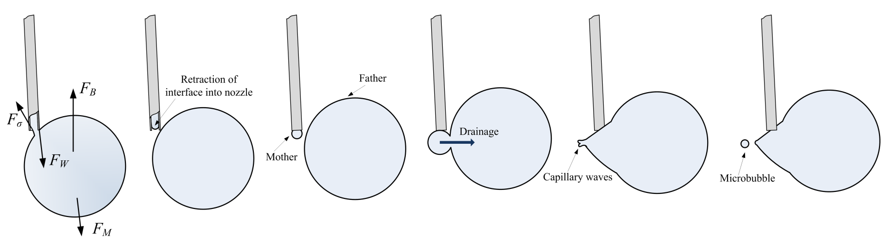


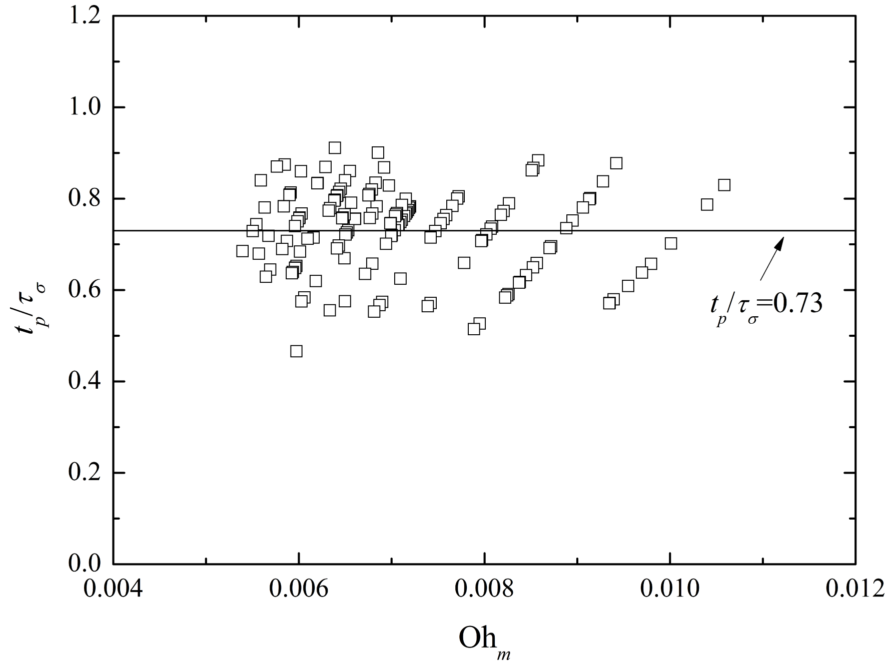
(f) Regime IV, R_0=0.085 mm, Q=1310.8 ml/h



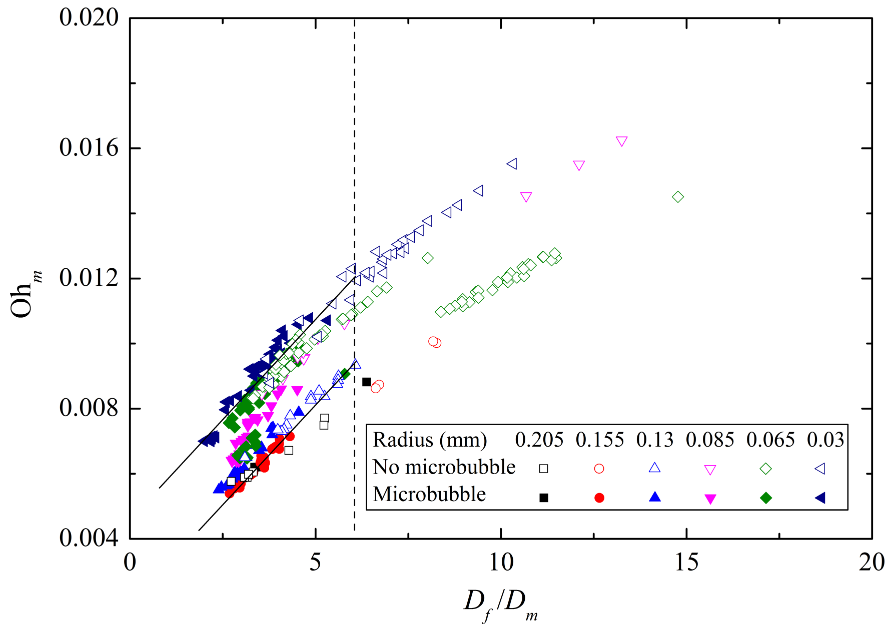

Nozzle
Start time: t_2+0.32 ms
Time step: 0.1 ms
Necking induced by capillary waves
(a)
Surface stretch
Start time: t_2+0.74 ms
Time step: 0.02 ms
Coalescing bubble
(b)


1 mm
0 ms
0.2 ms
0.4 ms
0.6 ms
Normal direction
Injection direction
1 ms
1.6 ms
4.2 ms
4.6 ms
5.2 ms
5.4 ms
5.6 ms
6 ms

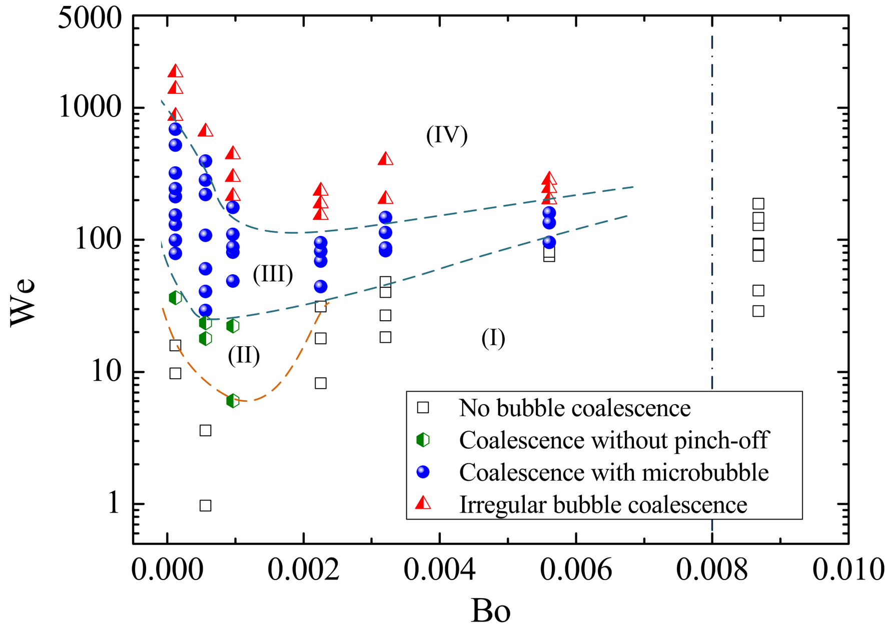

F_σ
F_B
F_W
F_M
Retraction of interface into nozzle
Father
Mother
Drainage
Capillary waves
Microbubble
(a) Just before departure of father bubble
(b) Departure of father bubble
(c) Formation of mother bubble
(d) Coalescence of parent bubbles
(e) Convergence of capillary waves
(f) Pinch-off of microbubble

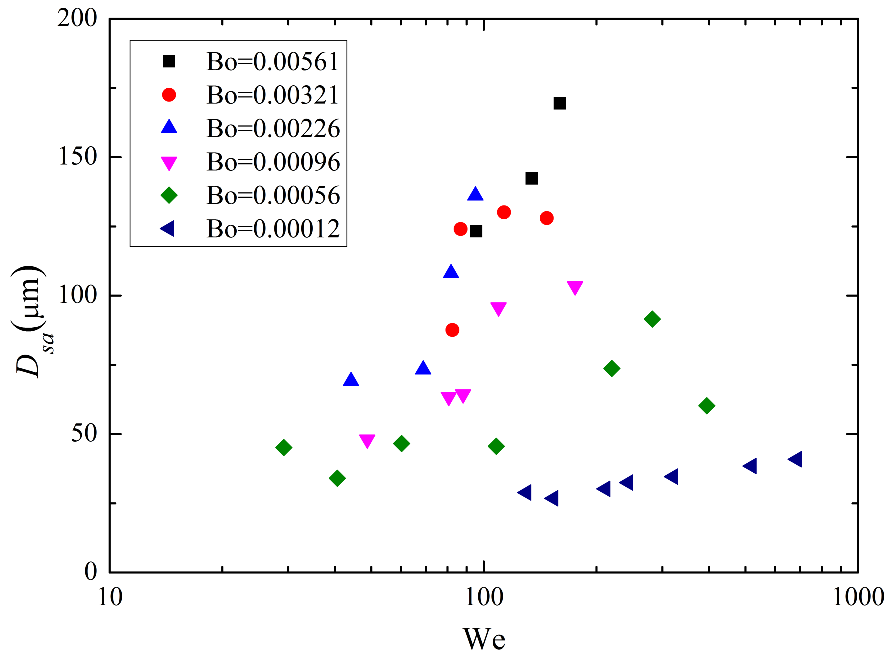


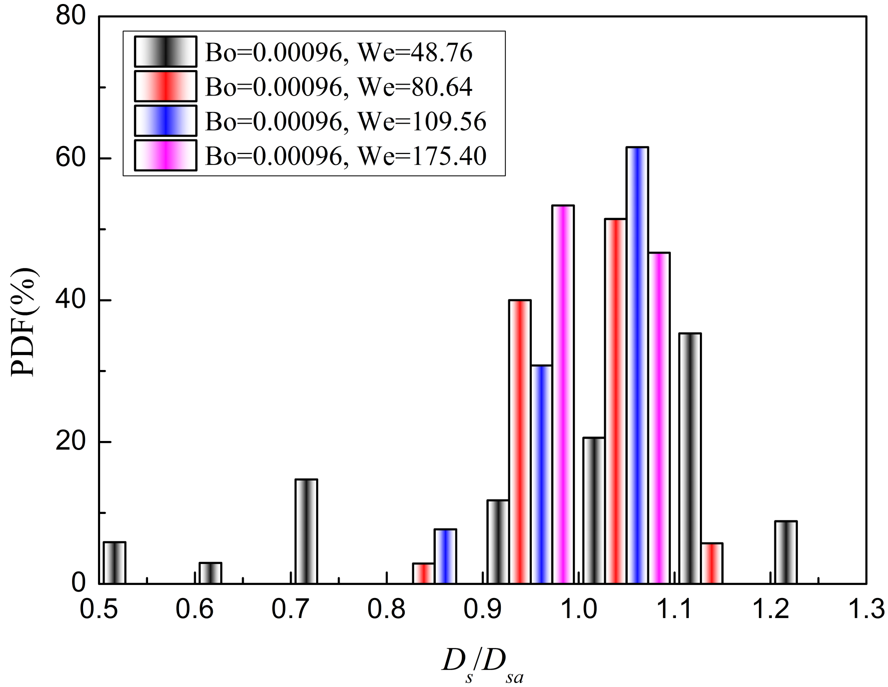
t_p/τ_σ
t_p/τ_σ=0.73
Oh_m
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.004
0.006
0.008
0.010
0.012

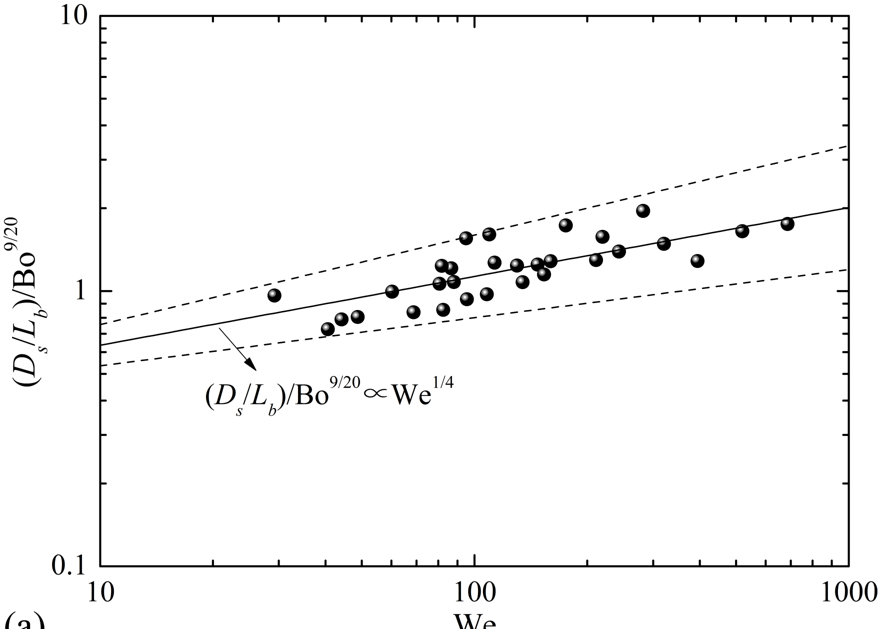


Oh_m
D_f/D_m
0.020
0.016
0.012
0.008
0.004
0
5
10
15
20
Radius (mm) 0.205 0.155 0.13 0.085 0.065 0.03
No microbubble
Microbubble

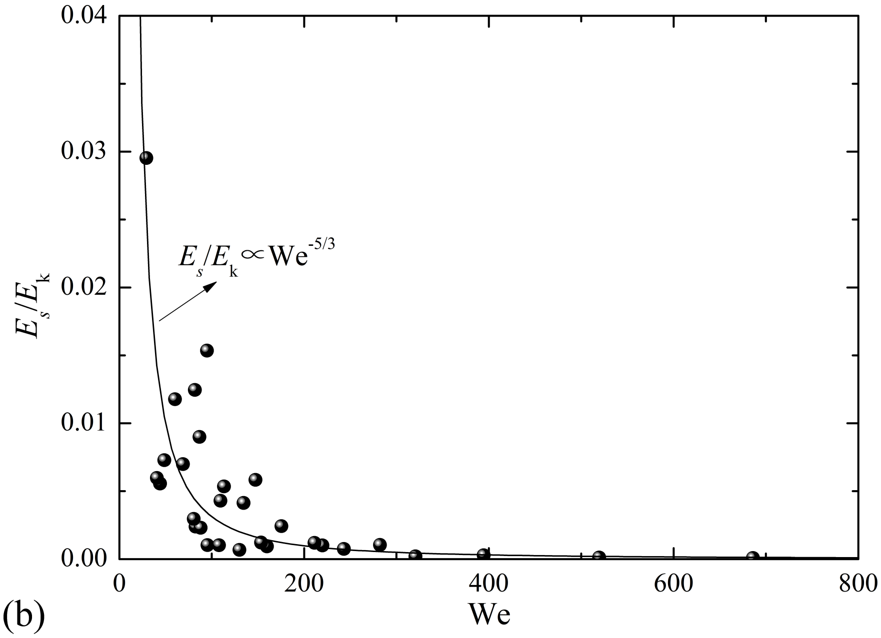

We
Bo
(I)
(II)
(III)
(IV)
No bubble coalescence
Coalescence without pinch-off
Coalescence with microbubble
Irregular bubble coalescence


D_{sa}(μm)
We
Bo=0.00561
Bo=0.00321
Bo=0.00226
Bo=0.00096
Bo=0.00056
Bo=0.00012


Bo=0.00096, We=48.76
Bo=0.00096, We=80.64
Bo=0.00096, We=109.56
Bo=0.00096, We=175.40
PDF(%)
D_s/D_{sa}


$(D_s/L_b)/Bo^{9/20}$
$(D_s/L_b)/Bo^{9/20} \propto We^{1/4}$
We

(a)


0.04
0.03
0.02
0.01
0.00
E_s/E_k
$E_s/E_k \propto \mathrm{We}^{-5/3}$
0
200
400
600
800
We
(b)