Electronic Supplemental Information for

Bubble Evolution in Acoustic Droplet Vaporization at Physiological Temperature via Ultra-High Speed Imaging

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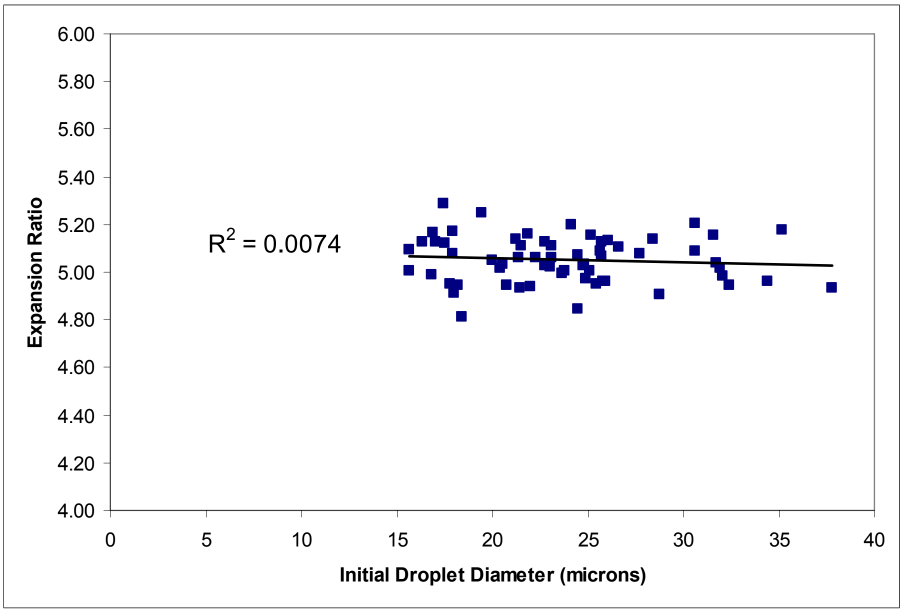
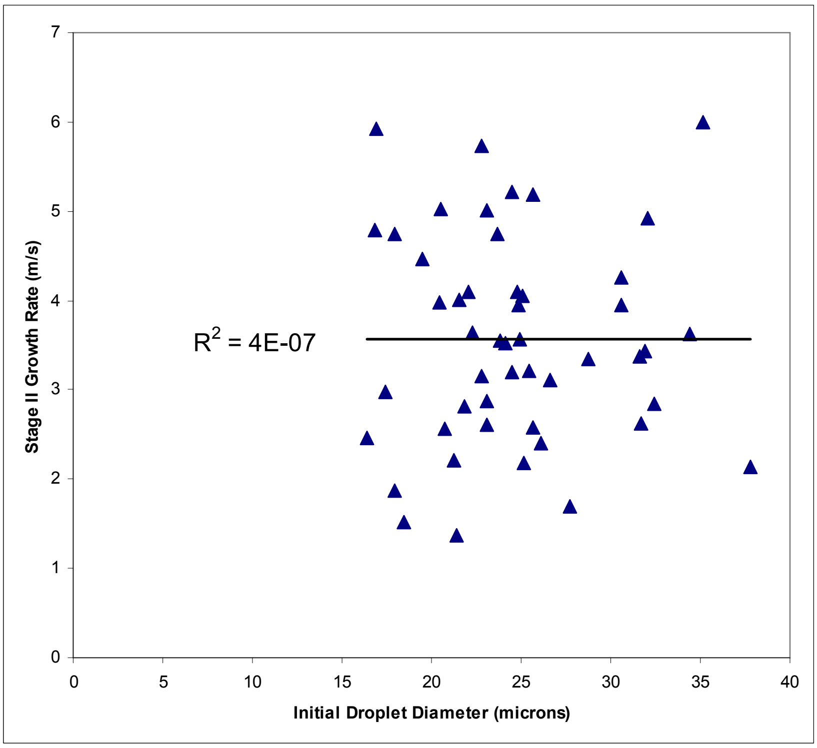
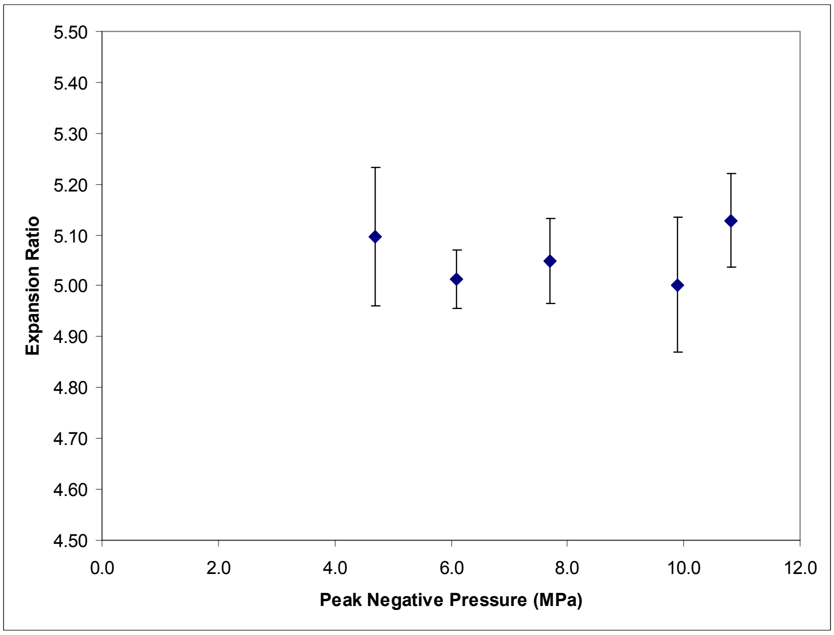
Supplementary Information (deposited electronically on journal website)



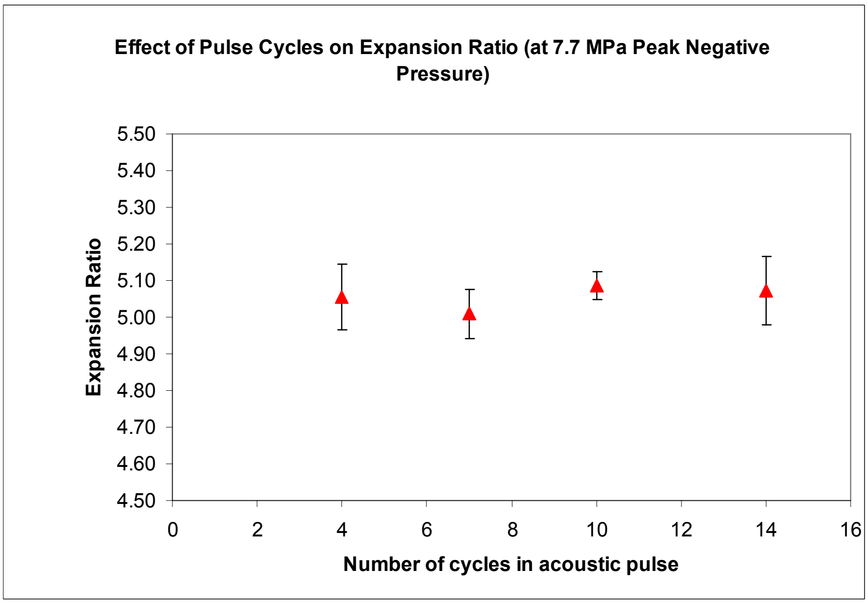
Effect of initial droplet size on the expansion ratio

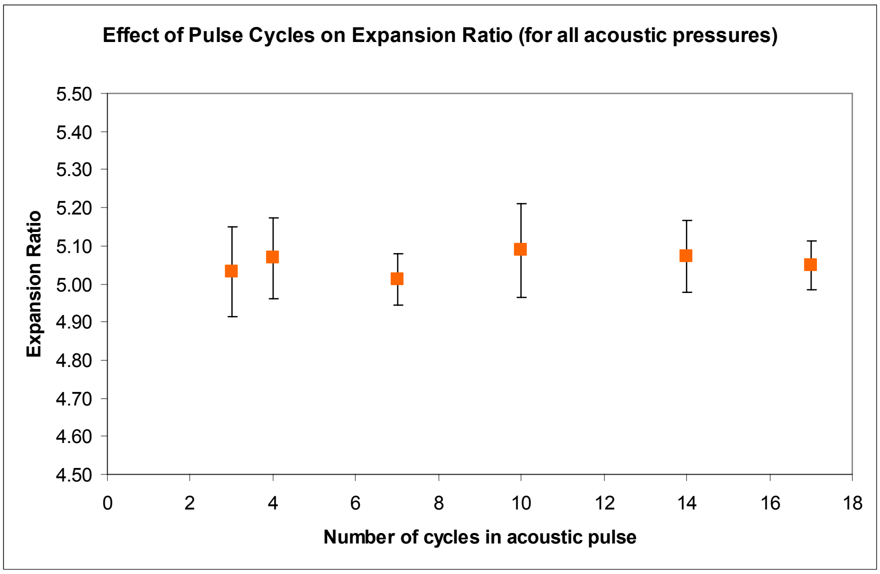


Effect of initial droplet size on Stage II linear growth rate



Effect of acoustic pressure on expansion ratio


Effect of Pulse Cycles on Expansion Ratio (at 7.7 MPa Peak Negative Pressure)
Expansion Ratio
5.50
5.40
5.30
5.20
5.10
5.00
4.90
4.80
4.70
4.60
4.50
0
2
4
6
8
10
12
14
16
Number of cycles in acoustic pulse


Effect of Pulse Cycles on Expansion Ratio (for all acoustic pressures)
Expansion Ratio
5.50
5.40
5.30
5.20
5.10
5.00
4.90
4.80
4.70
4.60
4.50
0
2
4
6
8
10
12
14
16
18
Number of cycles in acoustic pulse

At 7.7 MPa				T-Test p value					
No. Cycles	Exp Ratio	Std Dev		4	7	10	14		
4	5.06	0.088444		NA	0.180	0.437	0.762		
7	5.01	0.067961			NA	0.122	0.299		
10	5.09	0.037594				NA	0.805		
14	5.07	0.094202					NA		
All acoustic pressures				T-Test p value					
No. Cycles	Exp Ratio	Std Dev		3	4	7	10	14	17
3	5.03	0.117652		NA	0.573	0.730	0.467	0.597	0.808
4	5.07	0.105262			NA	0.047	0.708	0.924	0.649
7	5.01	0.067682				NA	0.199	0.304	0.370
10	5.09	0.121375					NA	0.823	0.525
14	5.07	0.094202						NA	0.696
17	5.05	0.064227							NA
				T-Test p value					
M-Pa	Exp Ratio	Std Dev		4.7	6.1	7.7	9.9	10.8	
4.7	5.10	0.135921		NA	0.246	0.481	0.247	0.722	
6.1	5.01	0.057512			NA	0.150	0.828	0.011	
7.7	5.05	0.08309				NA	0.361	0.055	
9.9	5.00	0.132814					NA	0.052	
10.8	5.12	0.086662						NA	

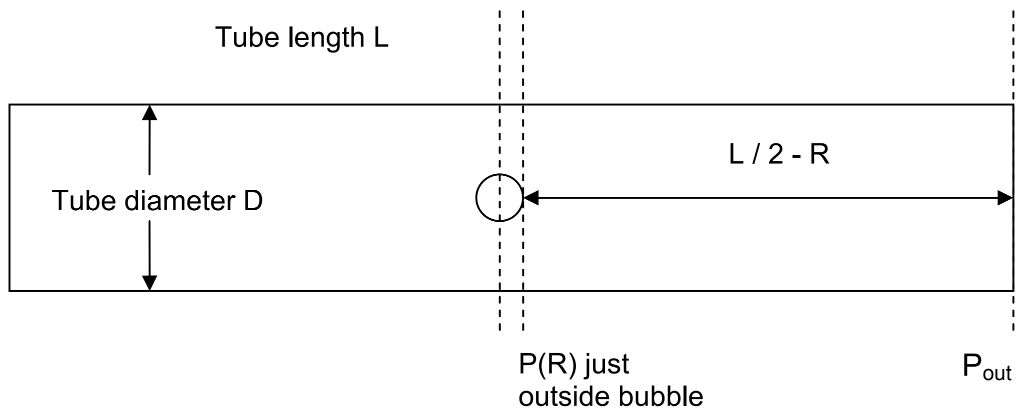
Statistical T-test (two-sided) for Independence of Means

Simplified model of bubble expansion in a tube (details of derivation)

Modified Bernoulli equation (obtain same results if start from conservation of momentum too)

$$\rho\int_{l_1}^{l_2}\frac{\partial \overline{V}}{\partial t}ds + \rho g h_L = P_1 - P_2 \qquad (1)$$

P=pressure, $\overline{V}$ = cross-sectional average velocity, s is streamline coordinate, ρ=liquid density, g=acceleration due to gravity, and h_L = head loss



Apply between point ~ at bubble surface to tube outlet, e.g. R to L/2

Assume laminar flow in liquid between bubble and tube outlet to estimate head loss term.

$$\rho g h_L = \frac{64}{\mathrm{Re}}\frac{l}{D}\frac{\rho \overline{V}^2}{2} = \frac{32\mu}{D^2}\left(\frac{L}{2} - R\right)\overline{V} \qquad (2)$$

Where D=tube diameter, R=bubble radius, L=tube length.

Conservation of mass for entire tube

$$\frac{d}{dt}\left[\frac{L\pi D^2}{4}-\frac{4\pi R^3}{3}\right]=-\beta Q=-\beta\overline{V}\frac{\pi D^2}{4} \qquad (3)$$

where β is the number of outlets (1 or 2)

Rearranging yields

$$\overline{V}=\frac{16}{\beta D^2}R^2\frac{dR}{dt} \qquad (4)$$

$$\frac{d\overline{V}}{dt}=\frac{16}{\beta D^2}\left[R^2\frac{d^2R}{dt^2}+2R\left(\frac{dR}{dt}\right)^2\right] \qquad (5)$$

Pressure jump at the bubble interface (Young-Laplace for moving interface)

$$P(R)=P_{B0}\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{4\mu}{R}\frac{dR}{dt}-\frac{2\sigma}{R} \qquad (6)$$

where P(R) is pressure in the liquid at the bubble surface, P_{B0} is initial bubble pressure, gamma = 1 for isothermal expansion (used) or close to 1 for adiabatic expansion of DDFP (1.4 for air), R_0 = initial bubble diameter

Substituting equations (2), (4), (5), and (6) into equation (1) yields

$$\frac{16\rho}{\beta D^2}\left(\frac{L}{2}-R\right)\left[R^2\frac{d^2R}{dt^2}+2R\left(\frac{dR}{dt}\right)^2\right]+\frac{512\mu}{\beta D^4}\left(\frac{L}{2}-R\right)R^2\frac{dR}{dt}=P_{B0}\left(\frac{R_0}{R}\right)^{3\gamma}-\frac{4\mu}{R}\frac{dR}{dt}-\frac{2\sigma}{R}-P_{out}$$

Solved with the following parameter values (modifications from these noted in graph):

ρ=993.3 kg/m^3
μ=6x10^{-4} Ns/m^2
σ=70x10^{-3} N/m
P_{out}=101300 Pa
P_{B0}=14.6x10^6 Pa

L=16cm

Assumptions:

- Ignores details of flow very close to bubble
- One-dimensional flow model
- Neglect “minor losses”
- Tube length approximation
- Some parameters approximated (e.g. P_{B0} , σ)