ARISTOTLE UNIVERSITY OF THESSALONIKI
SCHOOL OF CHEMISTRY

STUDY OF ISOLATED BUBBLES AND BUBBLE CLUSTERS IN CO-CURRENT UPWARD TWO-PHASE FLOW

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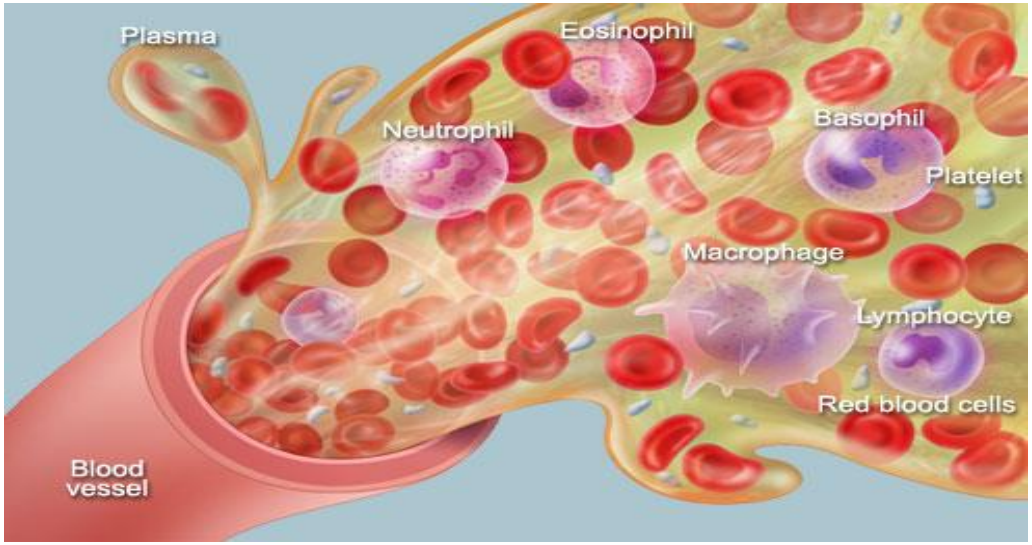

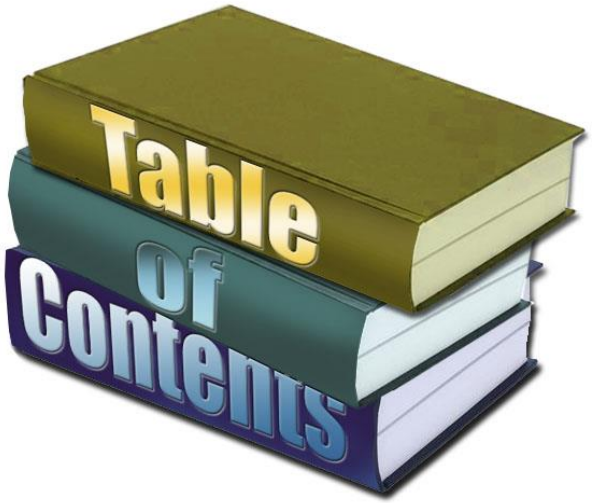

1. Introduction

2. Objective of the study

3. Preliminary tests

4. Experimental setup

5. Materials

6. Bubble size distributions

7. Electrical conductance signals

8. Statistical analysis

9. Conclusions

Materials & Methods

Results & Discussion

Decompression Sickness (DCS)

- Clinical syndrome caused by rapid reduction of environmental pressure

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- Bubble formation within body tissues

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- Decompression sickness (symptoms of variable severity: from joint pain to permanent deficits or even death)

↓

- Scuba divers, astronauts, Metro workers

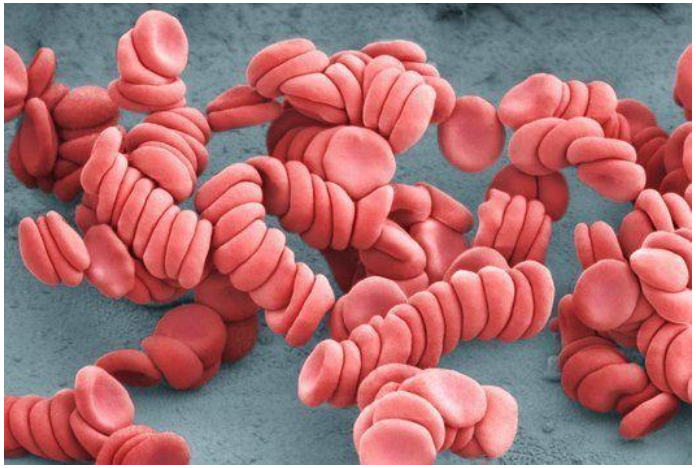
Blood's rheology

BLOOD: multiphase mixture of plasma + 3 cell types

platelets, red & white blood cells

Under low shear stress conditions:

«***rouleaux***» formation



Non-Newtonian (pseudoplastic) behaviour

2. Objective of the study

Study of vertical co-current upward bubbly flow

Use of a non-Newtonian liquid simulating human blood's rheological behaviour

Extending knowledge beyond Newtonian liquids (e.g. Evgenidis et al., 2010)

Bubbly flow in simulated human blood is studied for the first time

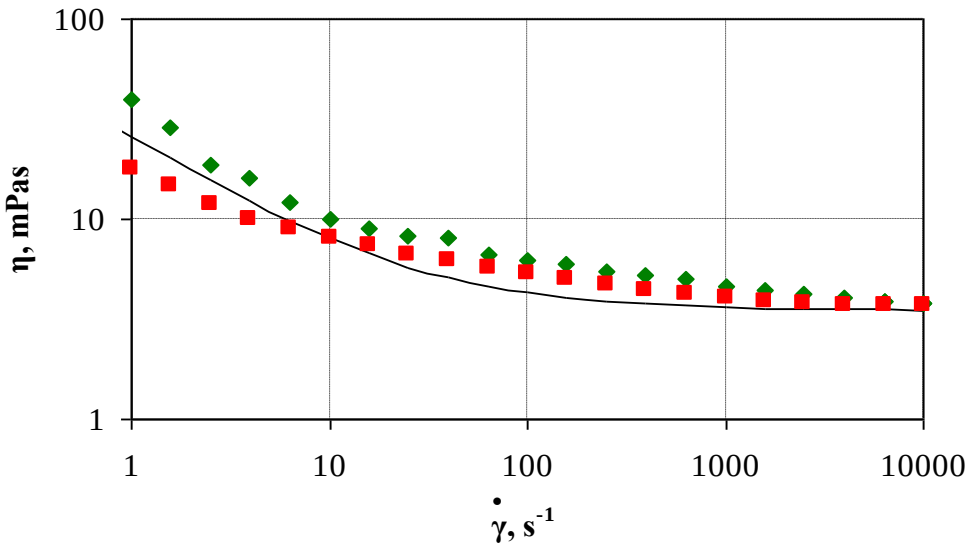
3. Preliminary tests

Non-Newtonian liquid simulating human blood's physical properties

Viscosity vs shear rate, pH, electrical conductivity

Water/Glycerol 65/35% v/v + 150ppm Xanthan gum + + NaCl 0.9% w/v

Similar composition to other blood simulants
(e.g. *Sousa et al., 2011; Anastasiou et al., 2010; Gijsen et al., 1998*)



— Carreau-Yasuda, η(inf)=3.52 mPas

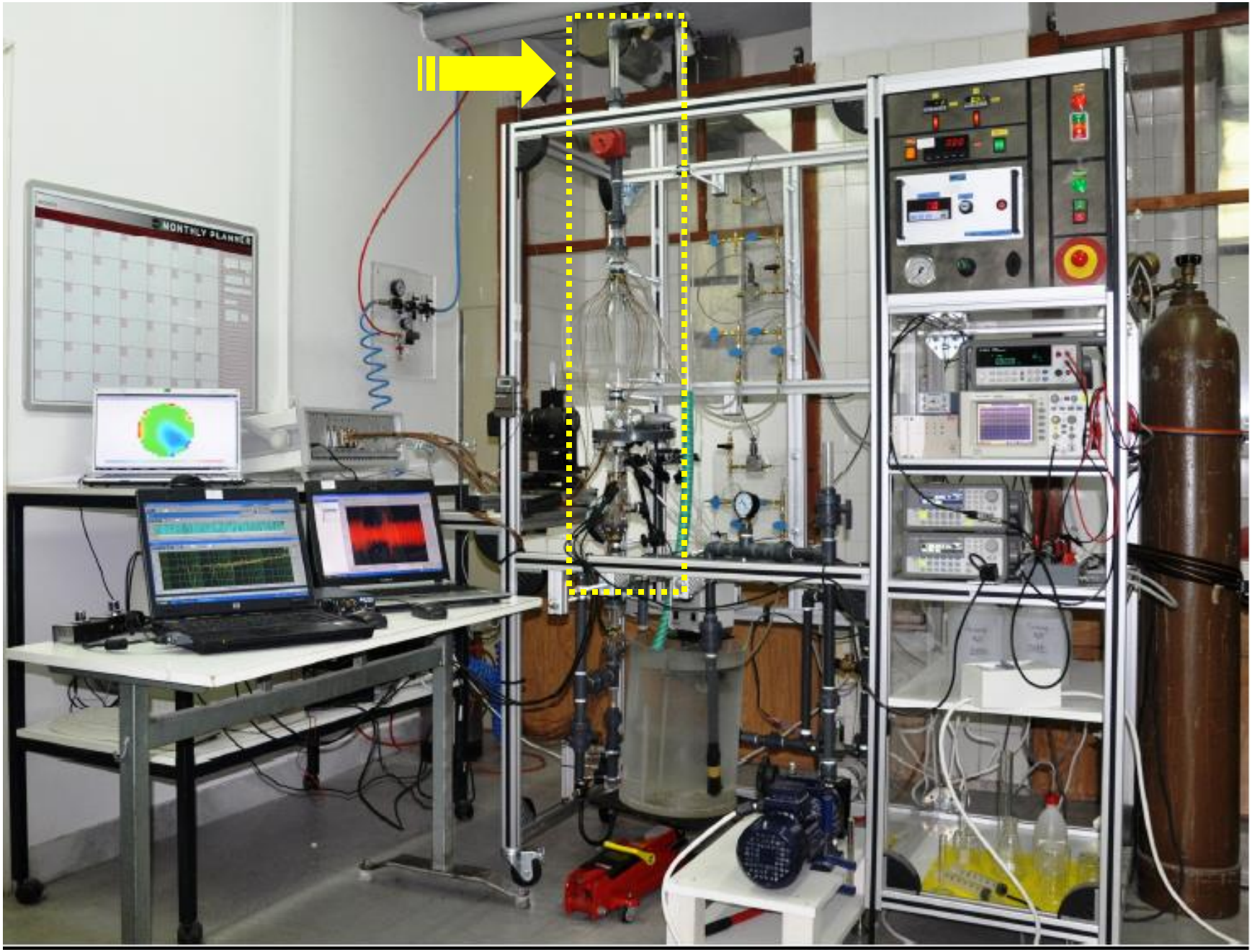
◆ Dog blood, η(inf)=3.81 mPas

■ Our solution, η(inf)=3.70 mPas

Carreau-Yasuda model:

$$\eta(\dot{\gamma}) = \eta_{\infty} + \frac{(\eta_0 - \eta_{\infty})}{[1 + (\lambda \dot{\gamma})^{\alpha}]^{\frac{(n-1)}{\alpha}}}$$

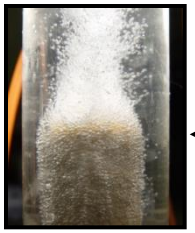
4. Experimental setup

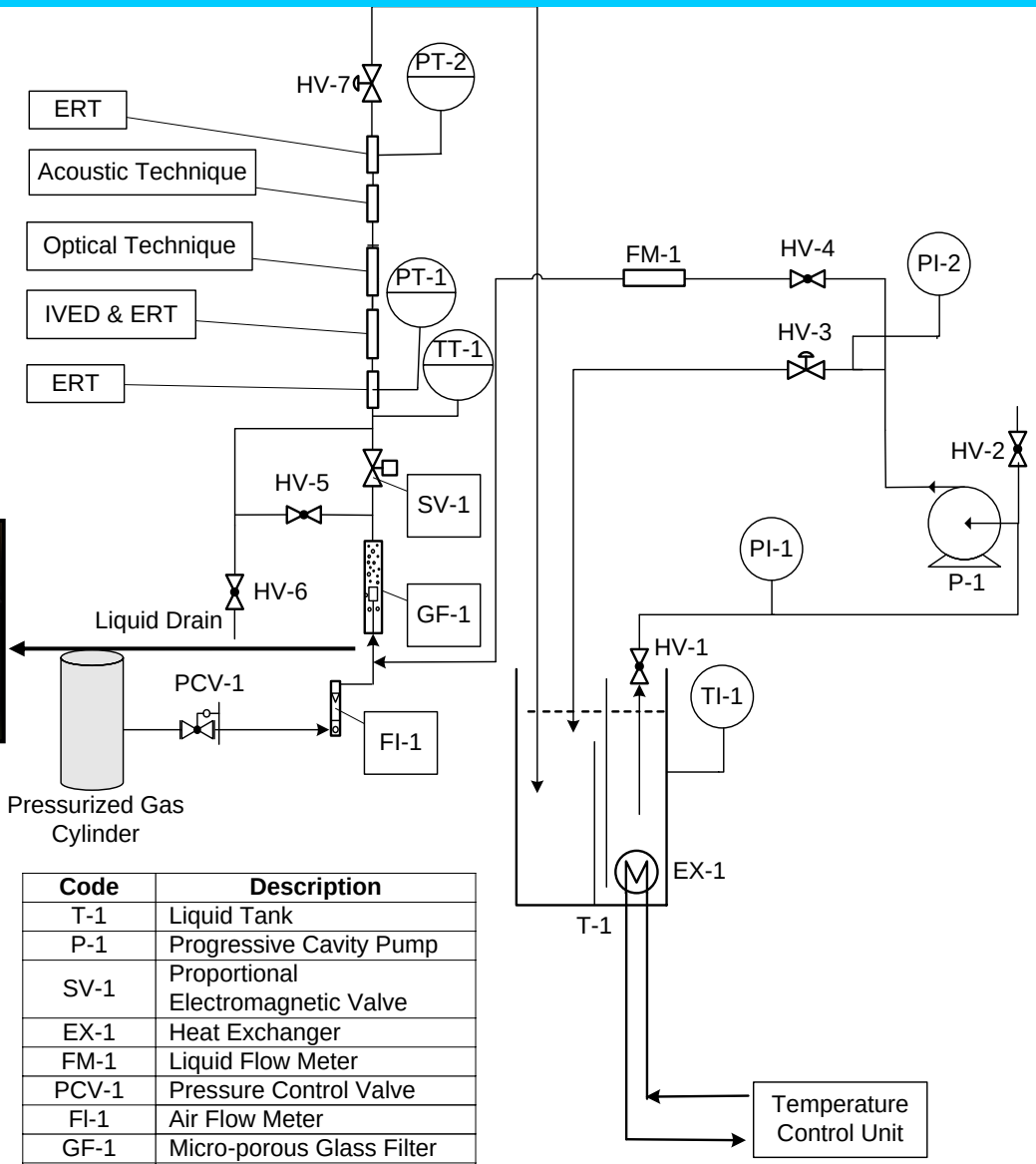


4. Experimental setup

Two-phase flow loop

- Steady & pulsatile upward co-current gas/liquid (bubbly) flow
- Various:
  1. gas/liquid flow rates
  2. main flow pulsation amplitudes
  3. gas fractions
  4. bubble sizes





Diagnostics for measuring two-phase flow characteristics:

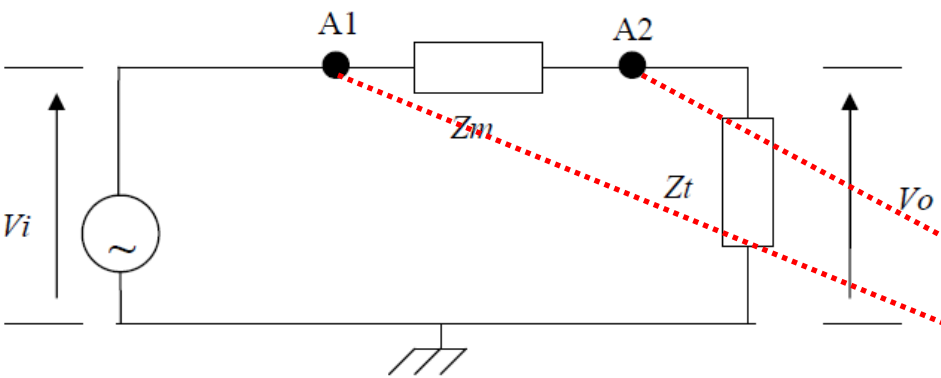
- Electrical conductance electrodes
- High Definition optical recording
- Ultra-sensitive differential pressure sensors
- Electrical Resistance Tomography (ERT, P2000, TS)
- Acoustic Bubble Spectrometer (ABS, Dynaflow)

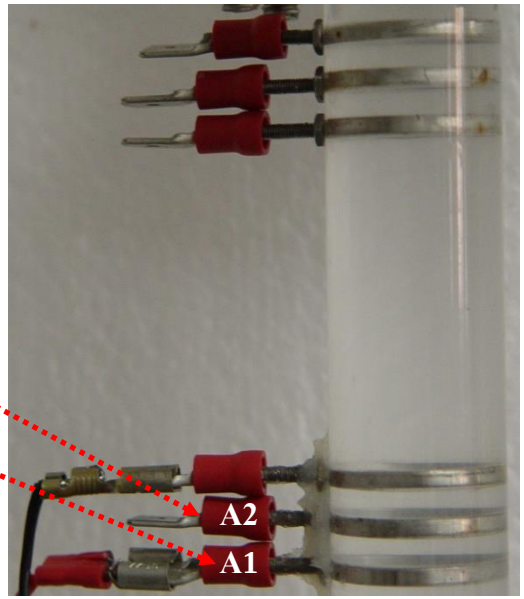
Code	Description
T-1	Liquid Tank
P-1	Progressive Cavity Pump
SV-1	Proportional Electromagnetic Valve
EX-1	Heat Exchanger
FM-1	Liquid Flow Meter
PCV-1	Pressure Control Valve
FI-1	Air Flow Meter
GF-1	Micro-porous Glass Filter
HV-1,2,3,4,5,6	On/Off Hand Valve
HV-7	Screw Down Hand Valve
TI-1	Temperature Indicator
TT-1	Temperature Transmitter
PI-1,2	Pressure Indicator
PT-1,2	Pressure Transducer

Electrical conductance technique

Operating principle: Electrical conductance measurement of a two-phase mixture

liquid (conductive phase) / gas (non-conductive phase)





A1: input electrode

A2: output electrode

V_i: input voltage

V_0: output voltage

Z_m: two-phase mixture resistance

Z_t: termination resistor

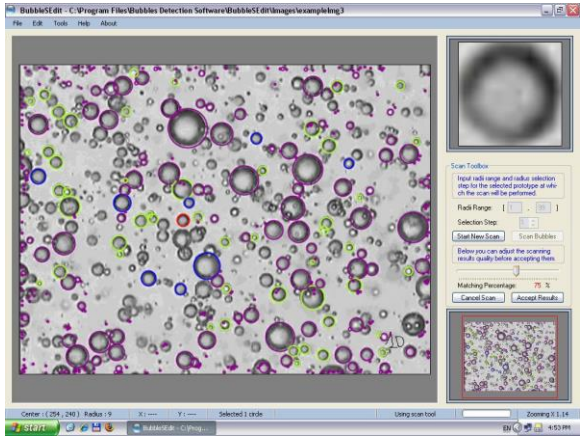
$$k = \frac{V_o}{V_i} = \frac{Z_t}{Z_m + Z_t}$$

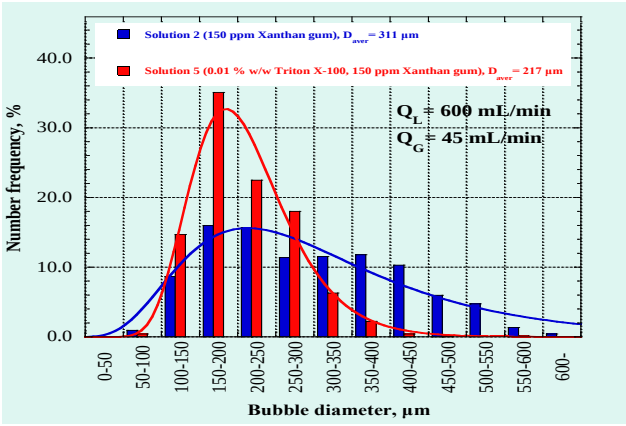
$$Z_m = (k^{-1} - 1)\, Z_t = 1/K$$

$$K/K_o = K_m = \frac{2(1-\varepsilon)}{2+\varepsilon}$$

4. Experimental setup

Optical technique





- *Detection based on a **template matching technique** (Zabulis et al., 2007)*

- Particularly effective for dense dispersions of overlapping bubbles
- Invariant to local variations of illumination

$$\text{ncc} = \frac{\sum_{x,y}\left[f_1(x,y)-\bar{f}_1\right]\left[f_2(x,y)-\bar{f}_2\right]}{\sqrt{\sum_{x,y}\left[f_1(x,y)-\bar{f}_1\right]^2\sum_{x,y}\left[f_1(x,y)-\bar{f}_2\right]^2}}$$

5. Materials

Liquid phase:

Water / Glycerol 65 / 35 % v/v + NaCl 0.9 % w/v

Gas phase

He

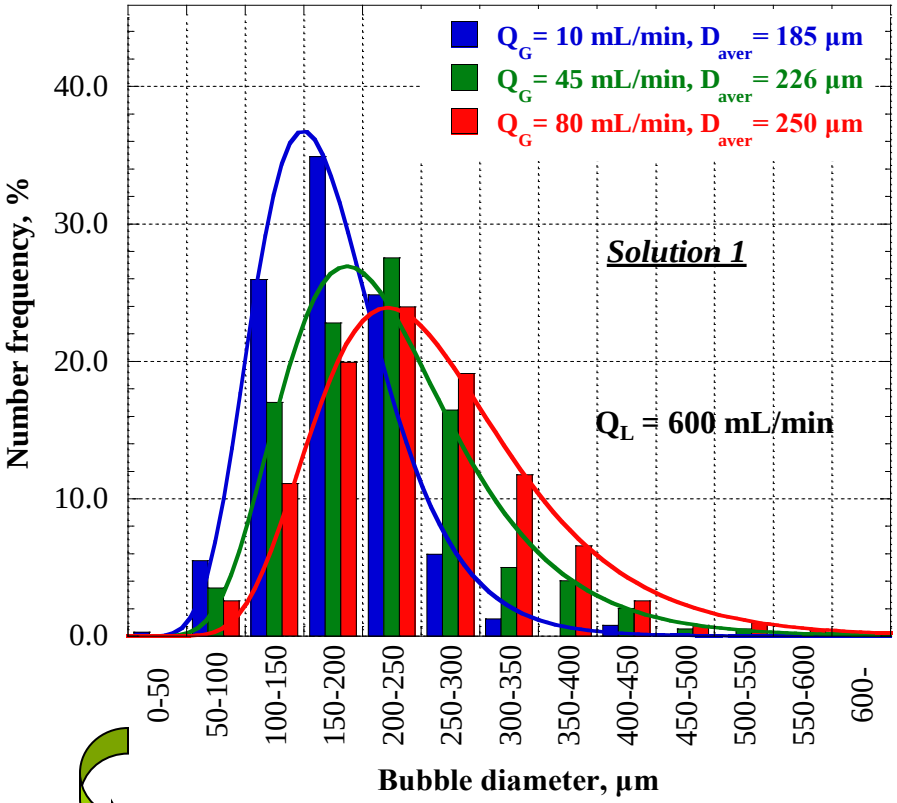
Parameters:

- Gas flow rate, Q_G (10 - 45 - 80 mL/min)
- Liquid flow rate, Q_L (600 - 3400 - 6200 mL/min)
- Triton X-100 concentration (0 & 0.01 % w/w)
- Xanthan gum concentration (0 - 150 - 1000 ppm)

#	Solution composition	Surface tension (mN/m)	Electrical conductivity (mS/cm)	Viscosity (mPa·s)	Density (kg/m^3)
1	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v	61.7	5.4	3.50	1105
2	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v + Xanthan gum 150 ppm	64.0	5.4	3.71	1108
3	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v + Xanthan gum 1000 ppm	64.4	5.4	5.18	1109
4	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v + Triton X-100 0.01 % w/w	36.1	5.4	3.01	1098
5	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v + Triton X-100 0.01 % w/w + Xanthan gum 150 ppm	37.1	5.4	3.70	1107
6	Water/Glycerol 65/35 % v/v + NaCl 0.9 % w/v + Triton X-100 0.01 % w/w + Xanthan gum 1000 ppm	33.5	5.4	5.34	1108

Effect of parameters

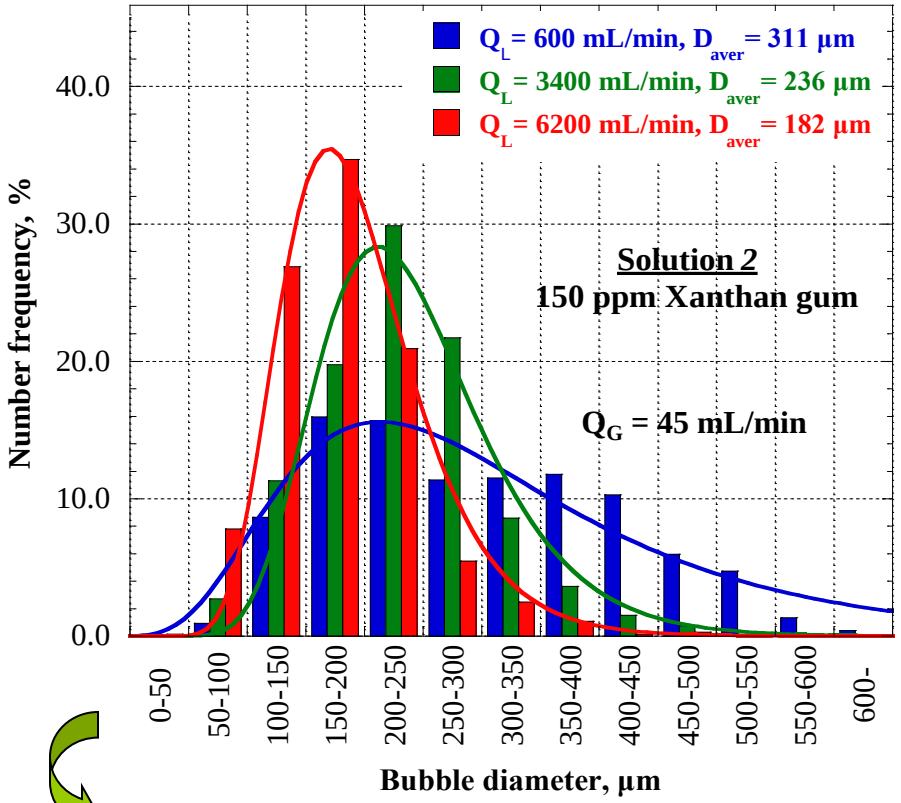
Gas flow rate



Bubble size

(Marrucci & Nicodemo, 1967; Evgenidis et al., 2010)

Liquid flow rate

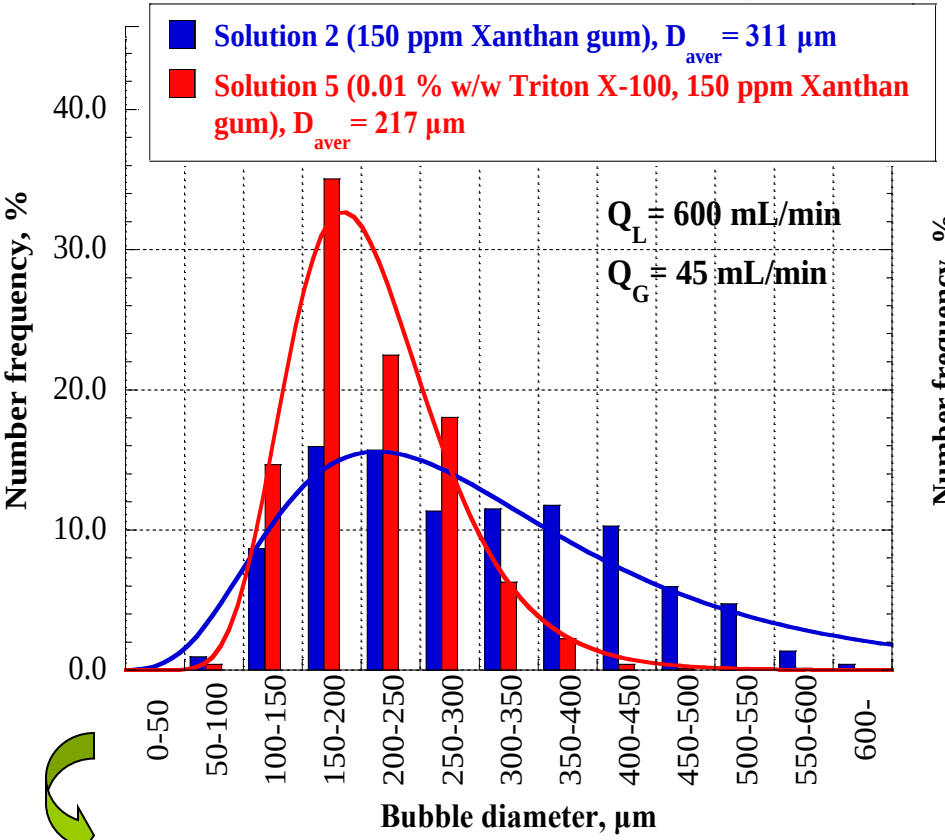


Bubble size

(Loubiere et al., 2004)

Effect of parameters

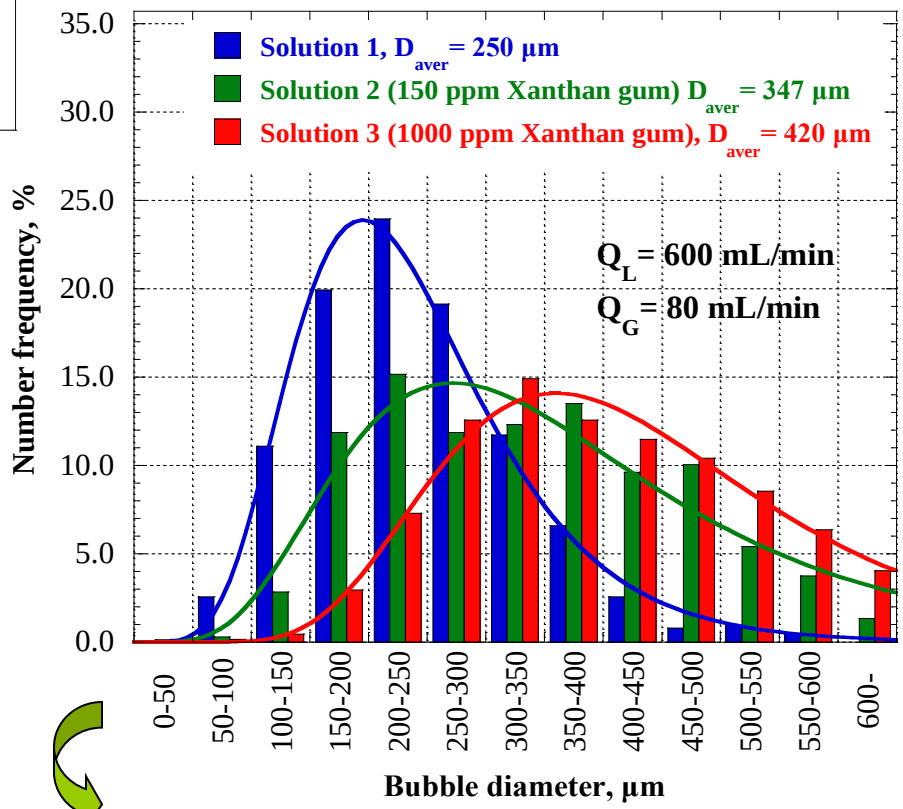
Triton X-100 concentration



Bubble size

(Xu et al., 2009; Rozenblit et al., 2006)

Xanthan gum concentration



Bubble size

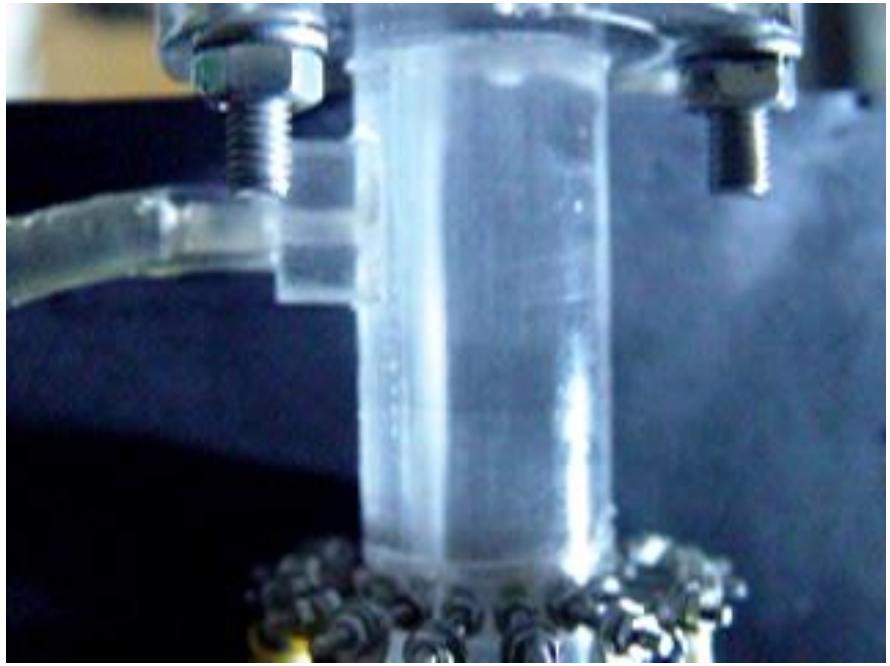
(Evgenidis et al., 2010; Wilkinson et al.,1992)

Bubble clusters

↓

- **Xanthan gum 1000 ppm**
- **Q_L= 600 mL/min (breakage in higher liquid flow rates, e.g. *Wang et al., 2011; Li et al., 2006*)**

Q_L=600 mL/min
Q_G = 45 mL/min



Q_L=3400 mL/min
Q_G = 45 mL/min

Bubble clusters

- **Xanthan gum 1000 ppm**

1) Effect of gas flow rate Q_G:

Q_G = 10 mL/min

Q_G = 45 mL/min

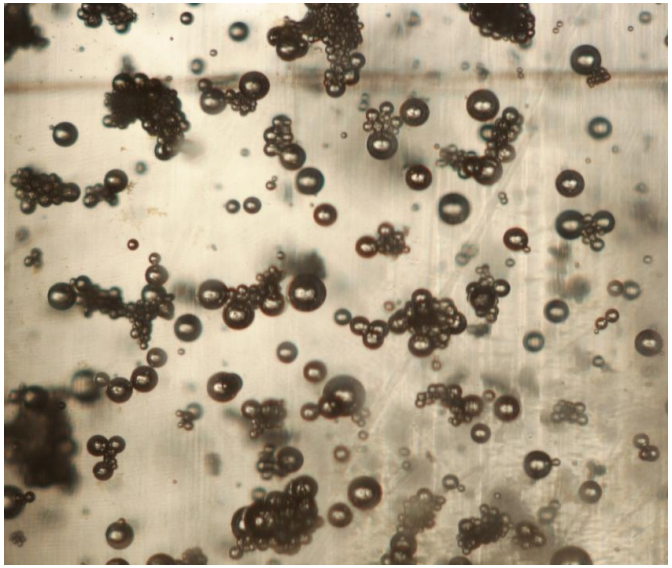
Q_G = 80 mL/min

Gas flow rate, Q_G

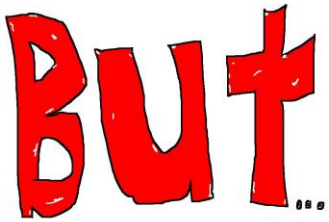
2) During the rise of clusters:

- Stable & mobile clusters for high gas flow rates
- Unstable & breaking clusters for lower gas flow rates

Several researchers attribute clusters formation mostly to non-Newtonian character
e.g. Vélez-Cordero & Zenit, 2011; Radl et al., 2007



Clusters formation in Newtonian water/glycerol solution
Evgenidis, 2010

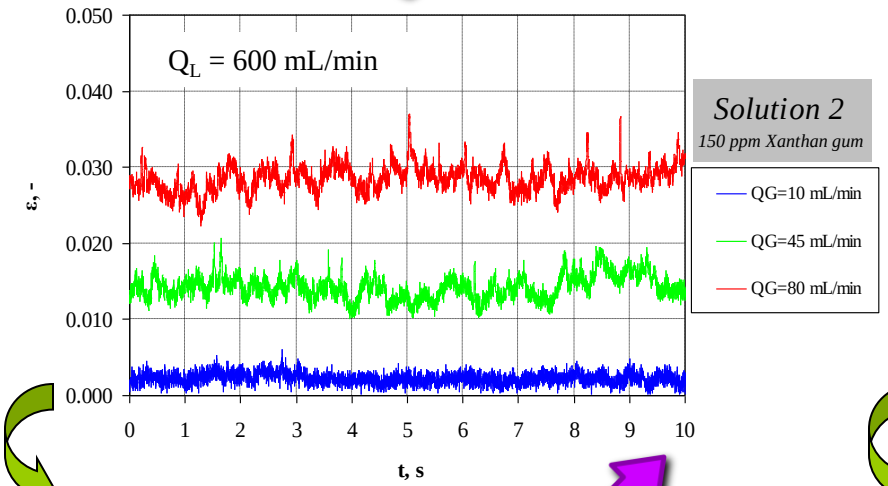


Non-Newtonian character or increased viscosity favours clustering?

7. Electrical conductance signals

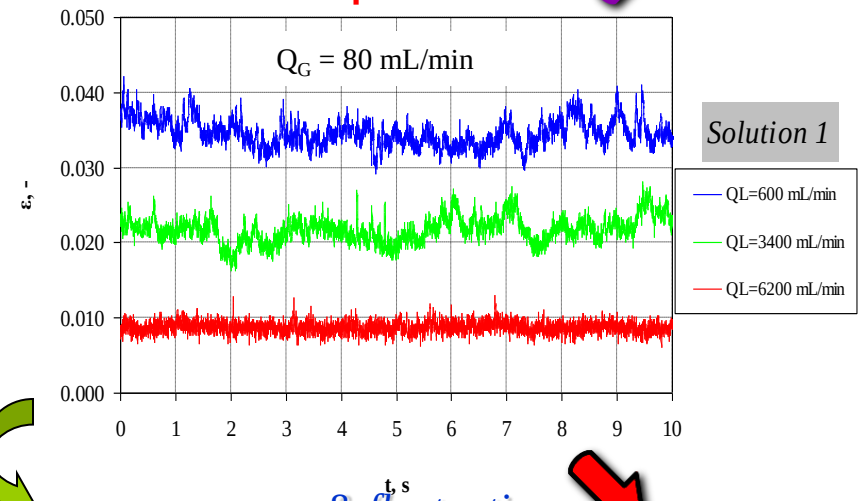
Effect of parameters

Gas flow rate



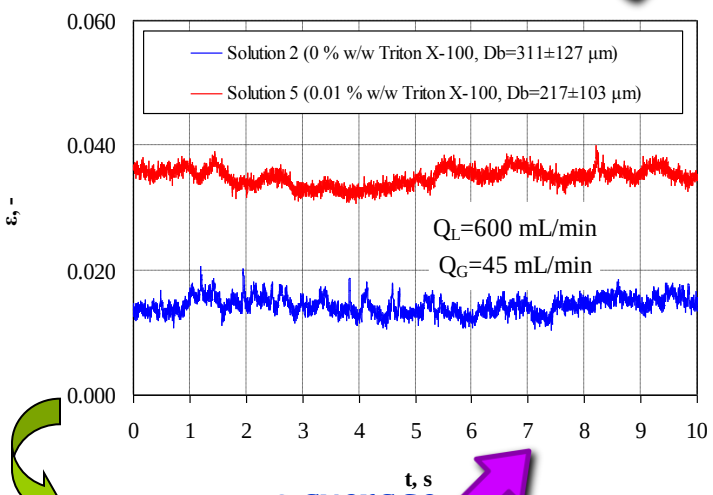
ε average & fluctuations

Liquid flow rate



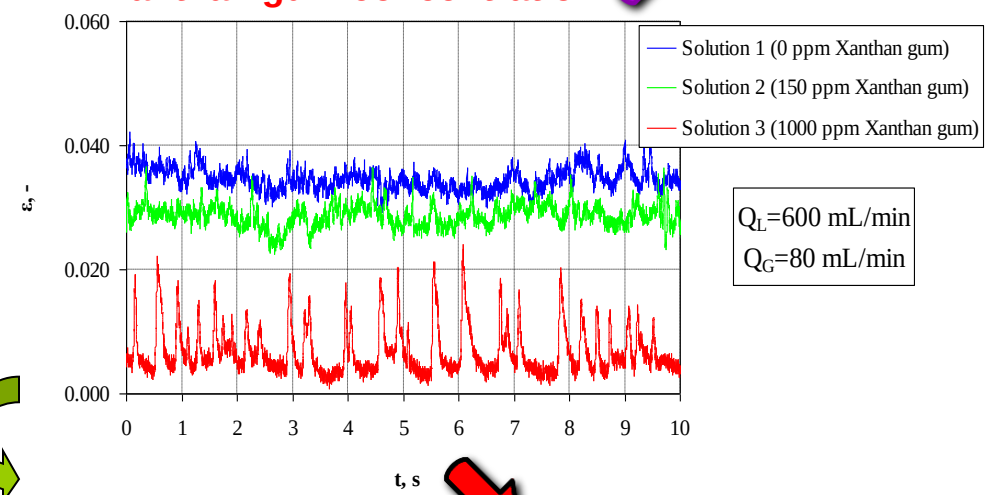
ε average & fluctuations

Triton X-100 concentration



ε average

Xanthan gum concentration



ε average

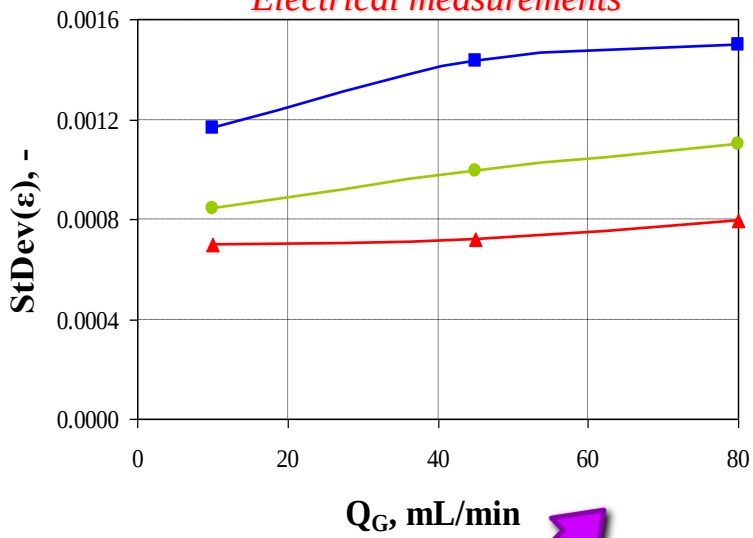
8. Statistical analysis

Gas flow rate

Solution 4
0.01 % w/w Triton X-100

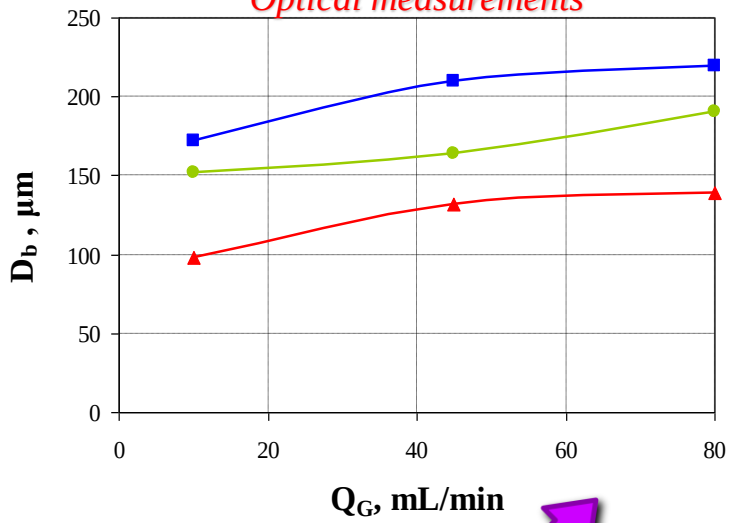
- QL=600 mL/min
- QL=3400 mL/min
- QL=6200 mL/min

Electrical measurements



ε fluctuations

Optical measurements



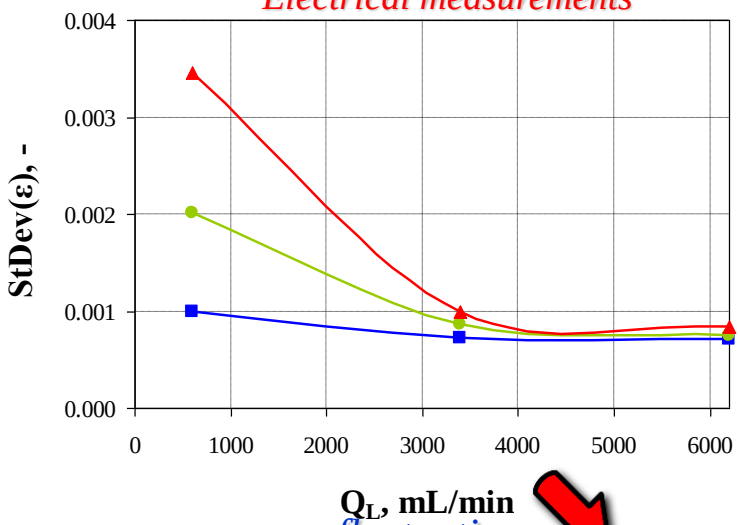
Bubble size

Liquid flow rate

Solution 2
150 ppm Xanthan gum

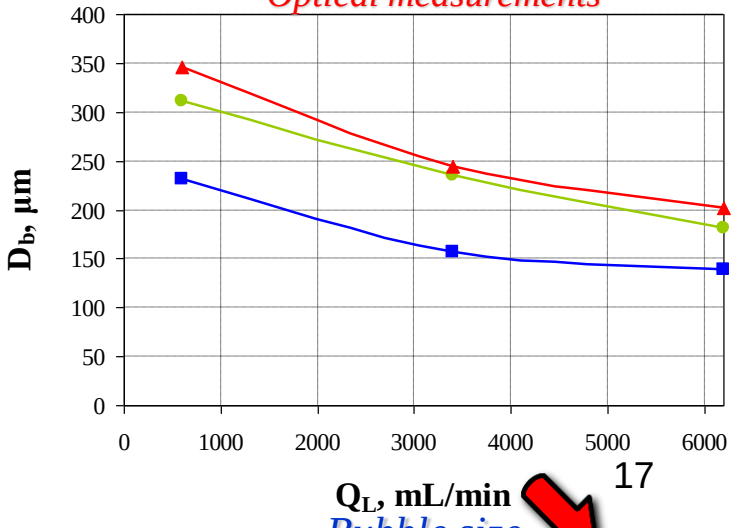
- QG=10 mL/min
- QG=45 mL/min
- QG=80 mL/min

Electrical measurements



ε fluctuations

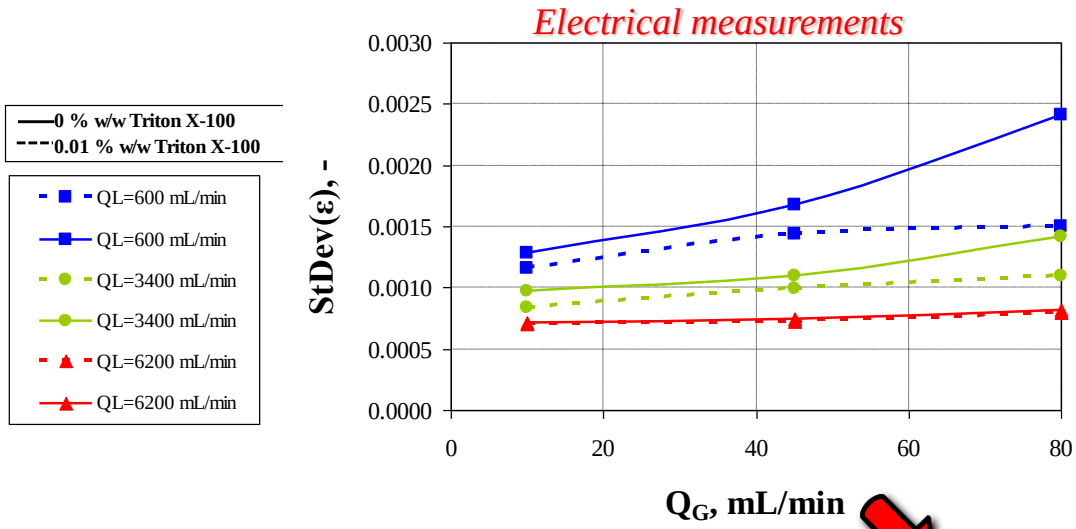
Optical measurements



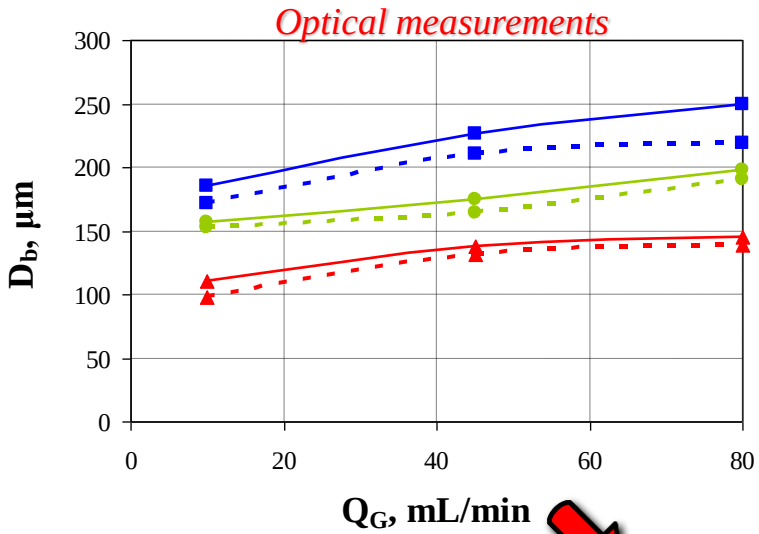
Bubble size

8. Statistical analysis

Triton X-100 concentration

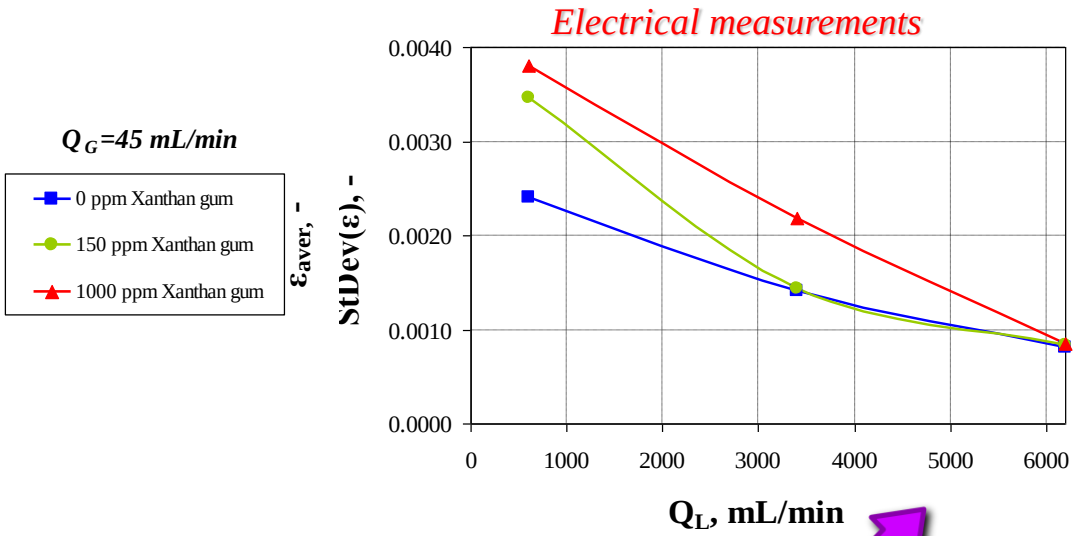


ε fluctuations

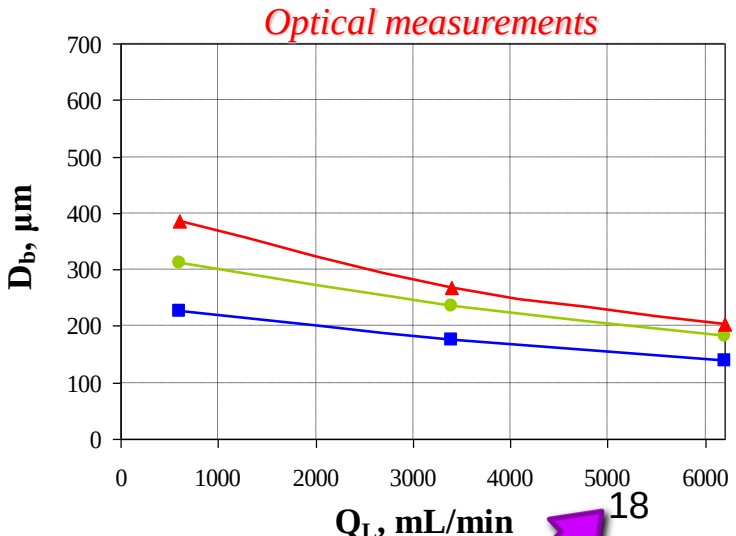


Bubble size

Xanthan gum concentration

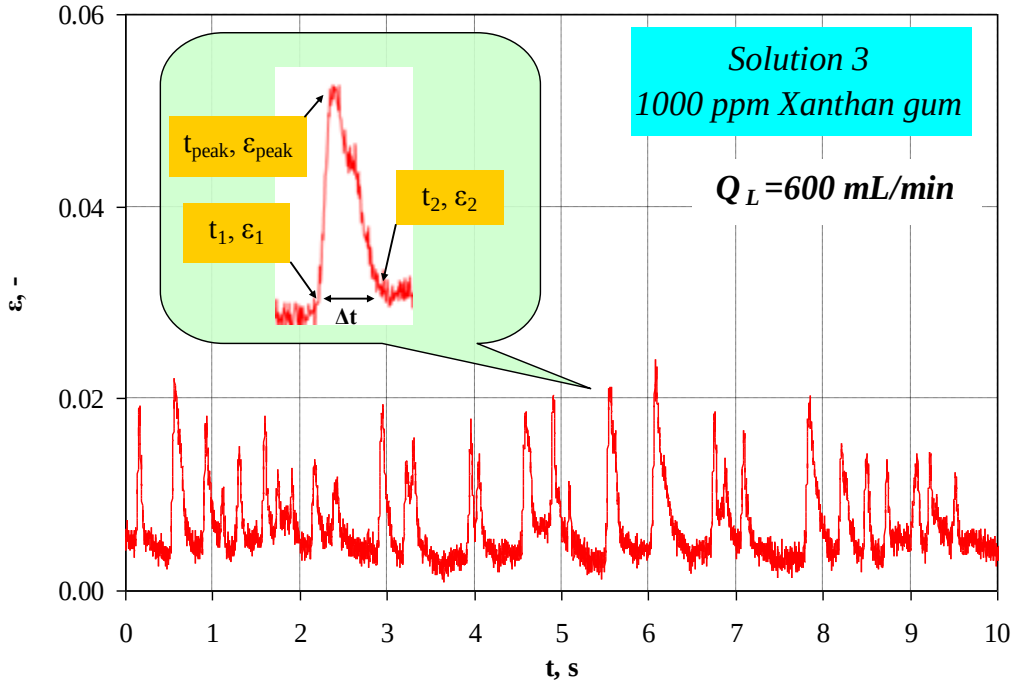


ε fluctuations



Bubble size

Analysis of peaks corresponding to bubble clusters



ε_{peak}: ε value at the top of the peak

ε_1: ε value at the time of «emergence» of the peak

ε_2: ε value at the time of «disappearance» of the peak

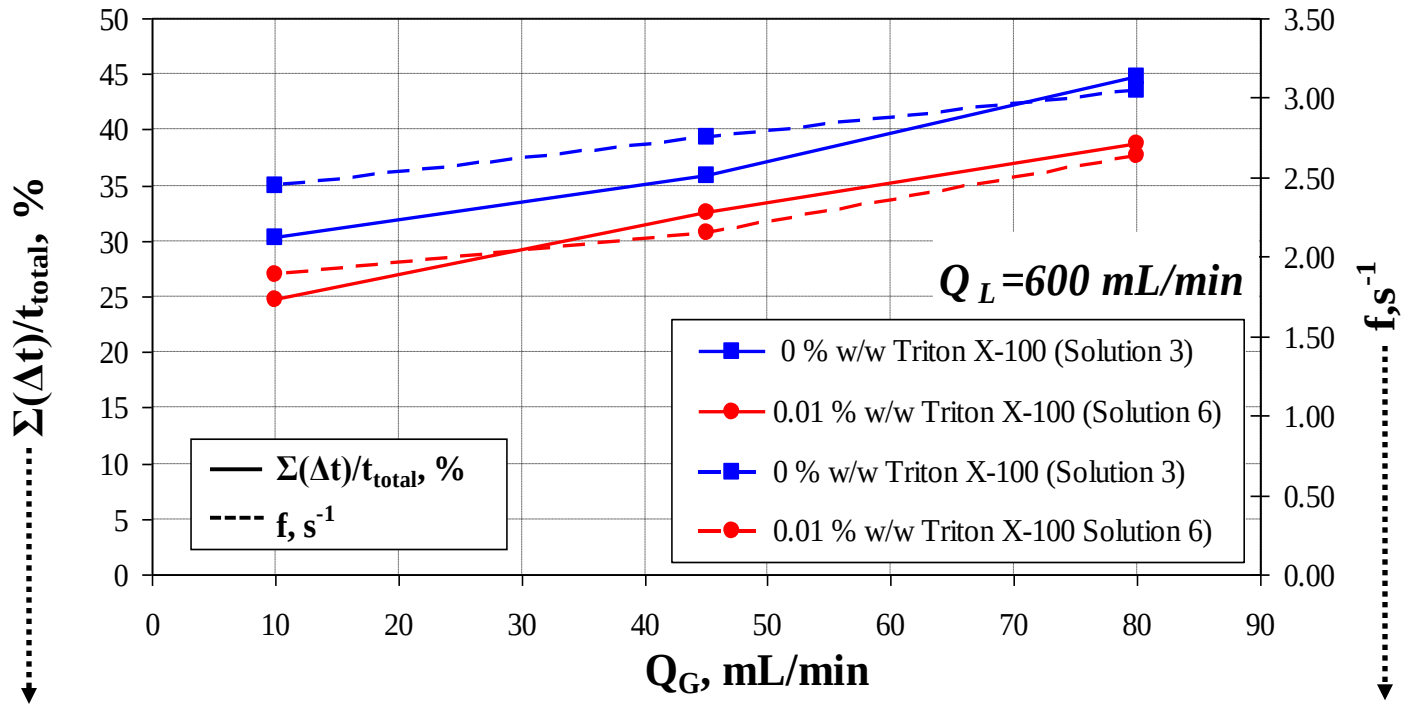
t_{peak}: time corresponding to ε_{peak}

t_1: time corresponding to ε_1

t_2: time corresponding to ε_2

$\Delta t = t_2 - t_1$

Analysis of peaks corresponding to bubble clusters



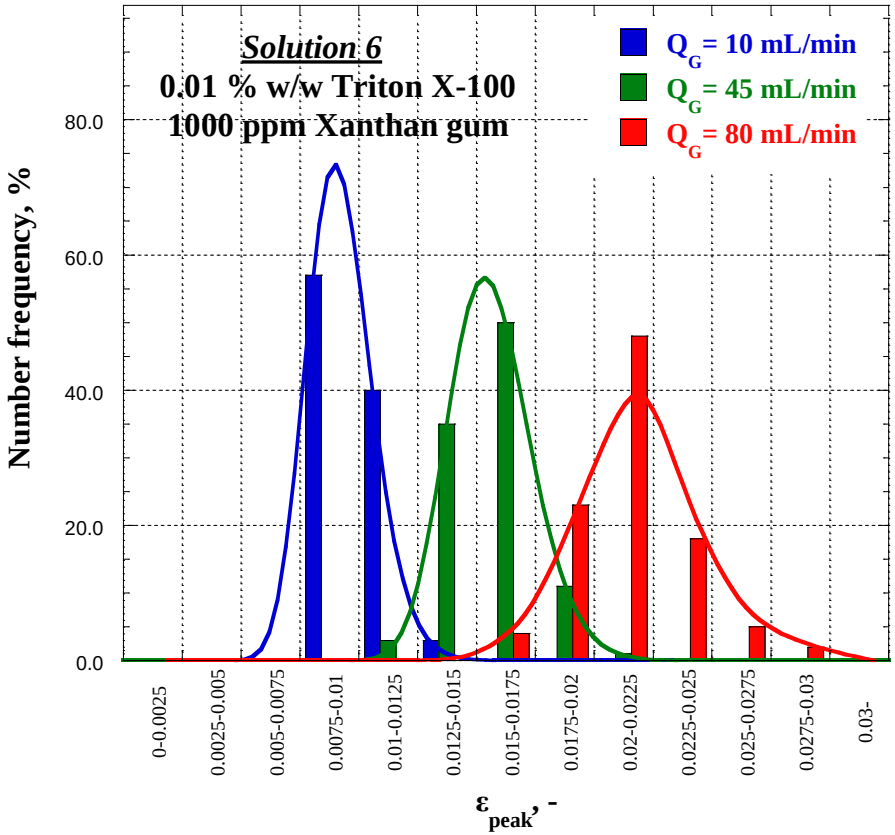
Percentage of the signal occupied by the peaks

Peaks frequency in the recorded signal

Q_G ↗ induces: $\Sigma(\Delta t)/t_{total}$ & f ↗

Triton X-100 concentration ↗ induces: $\Sigma(\Delta t)/t_{total}$ & f ↘

Analysis of peaks corresponding to bubble clusters



Q_G ↗ induces: ε_{peak} ↗

9. Conclusions

Bubble size

1. ↘ with the ↗ of Q_L & Triton X-100 concentration.
2. ↗ with the ↗ of Q_G & Xanthan gum concentration.

Gas fraction

1. ↗ with the ↗ of Q_G & Triton X-100 concentration.
2. ↘ with the ↗ of Q_L & Xanthan gum concentration.
3. Gas fraction fluctuations around its mean value depend on bubble size.

↓

Large bubbles induce more intense fluctuations

Bubble clusters

1. Breakage with the increase of Q_L.
2. Increases in size with the increase of Q_G & Triton X-100 addition.

THANK YOU FOR YOUR ATTENTION