Alternating Bubbles Emerging from Two Interacting Vertical Gas Jets in a Liquid

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INTRODUCTION

Background

- Jets or plumes of gas enter liquid vertically would break off to form a train of bubbles that rises vertically in a variety of industrial and geological systems
- Air jets break into bubbles due to a Kelvin-Helmhotz like instability [1]
- These jets of bubbles locate close to one another in many of such systems
- This enables them to interact and, therefore, affecting bubble dynamics

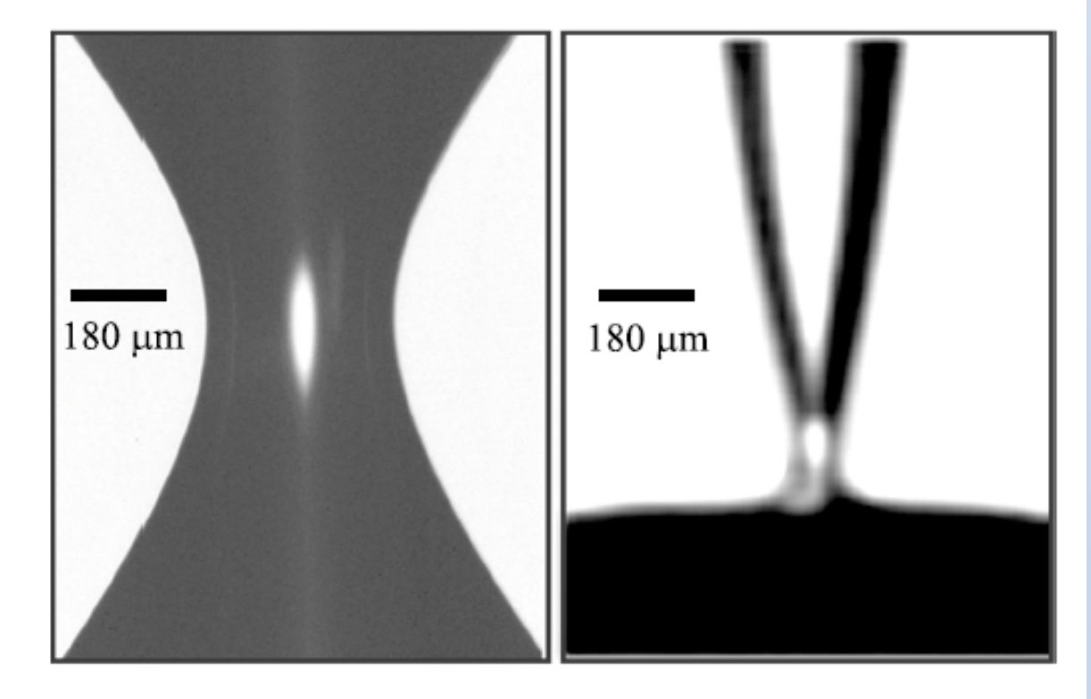


Figure 1. Bubble pinch-off. Image from [1].

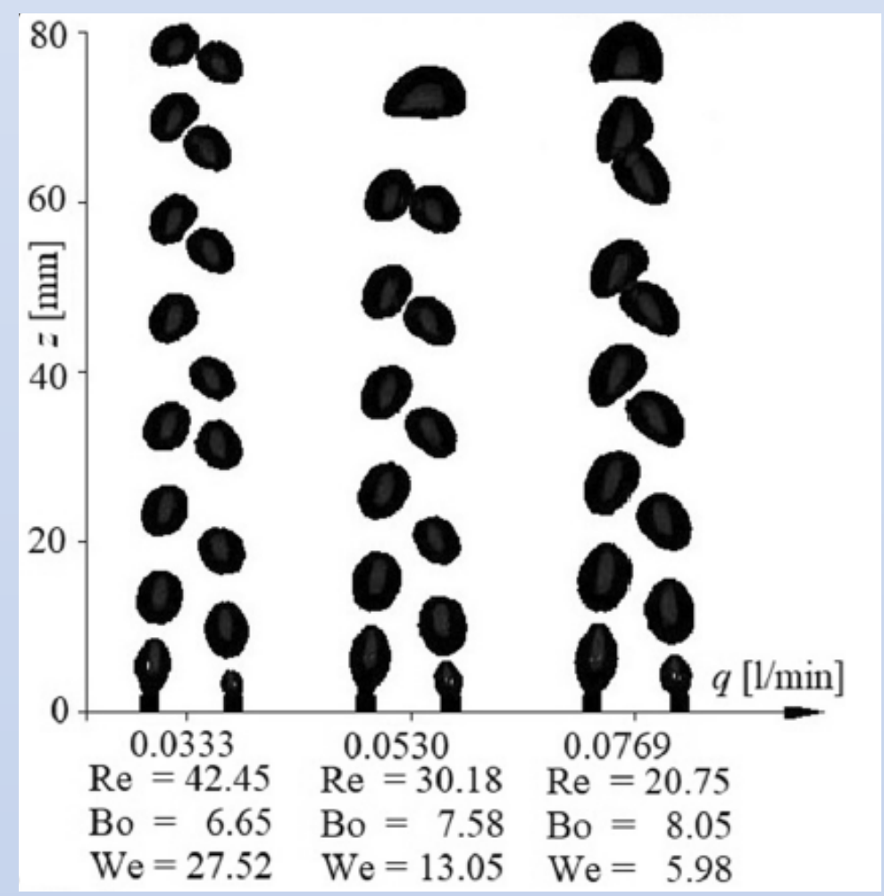


Figure 2. Asynchronous bubble formation. Image from [2].

Previous Work

- Two bubble jets, three patterns:
  - ☐ Synchronous
  - ☐ Alternating
  - ☐ Asynchronous
- The pattern depend on the air flowrate
- Higher flowrates tend to result in more asynchronous patterns [3]
- Bubble formation at one port pushes the air jet another port to break-off [4]
- The rising bubble at one port would lead to a convection that suppresses the bubble formation at a further port [5]

Research Problem

Experimental

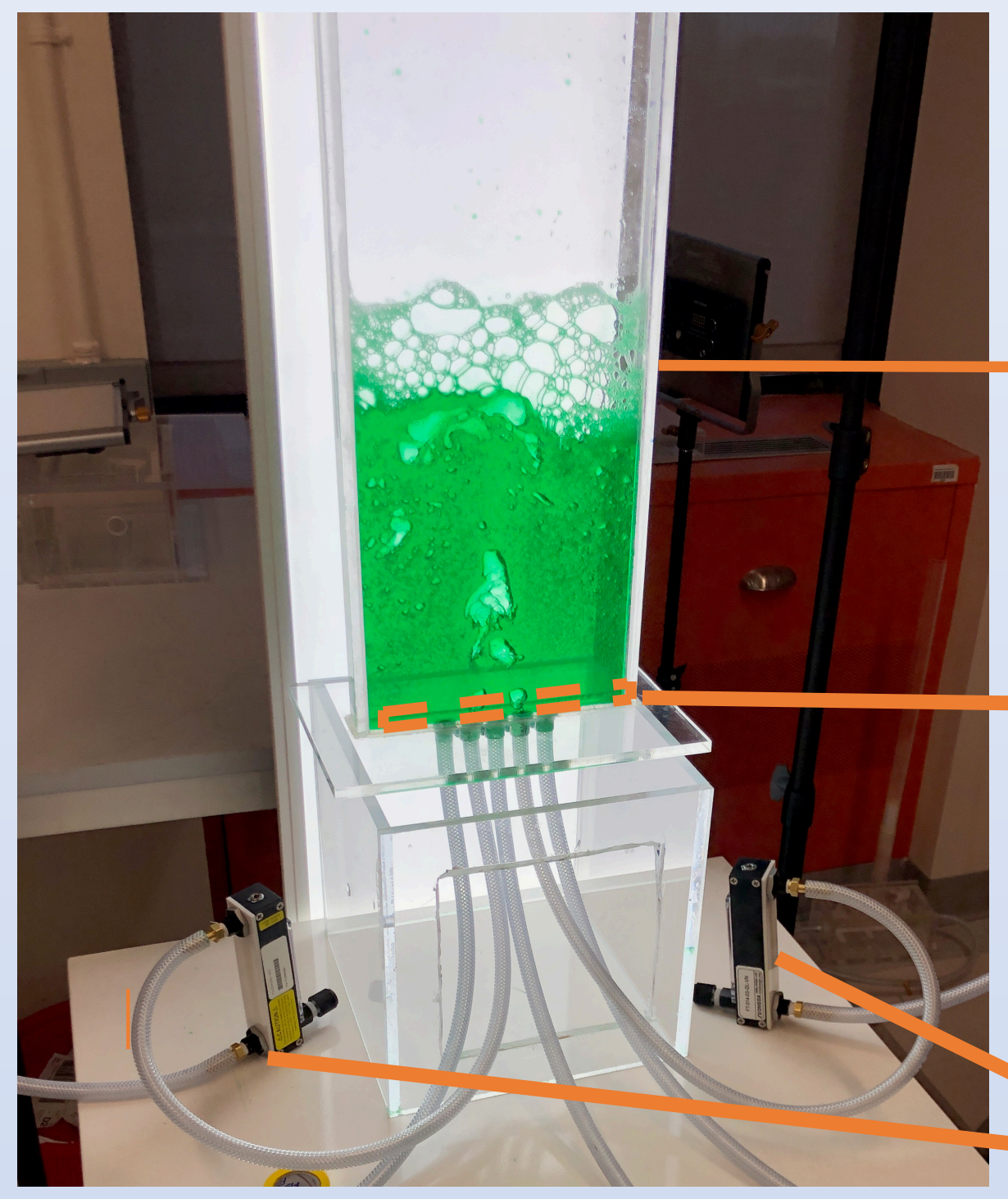
- What does the bubbling pattern look like at higher flowrate?
- How does

Theoretical

- Why do bubbling jets exhibit synchronicity at lower flowrate?
- Why do they become asynchronous at higher flowrate?
- Can we use a simplified physical model to explain the stability of these two patterns?

METHODOLOGY

Experimental Setup



Height: 100 cm
Width: 20 cm
Thickness: 1 cm

Injection ports:

Nozzle Diameter: 4.5 mm
Flowmeters: 0-5 liters per minute

Figure 3. Experimental setup.

Image Binarization

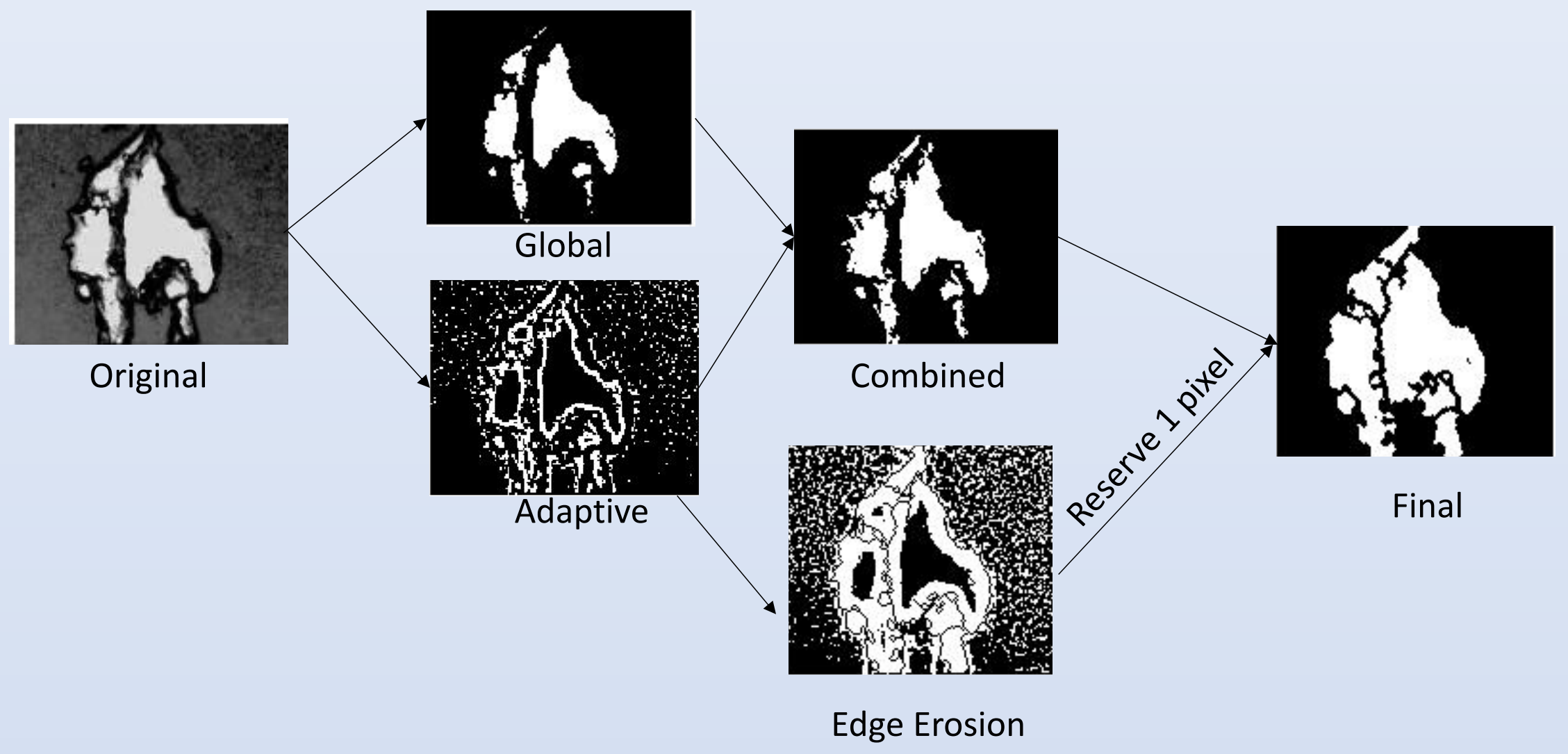


Figure 4. Binarization process

- A self-developed method to address the complex and dynamic lighting
- Ensures both recognition and accuracy

Pattern Analysis

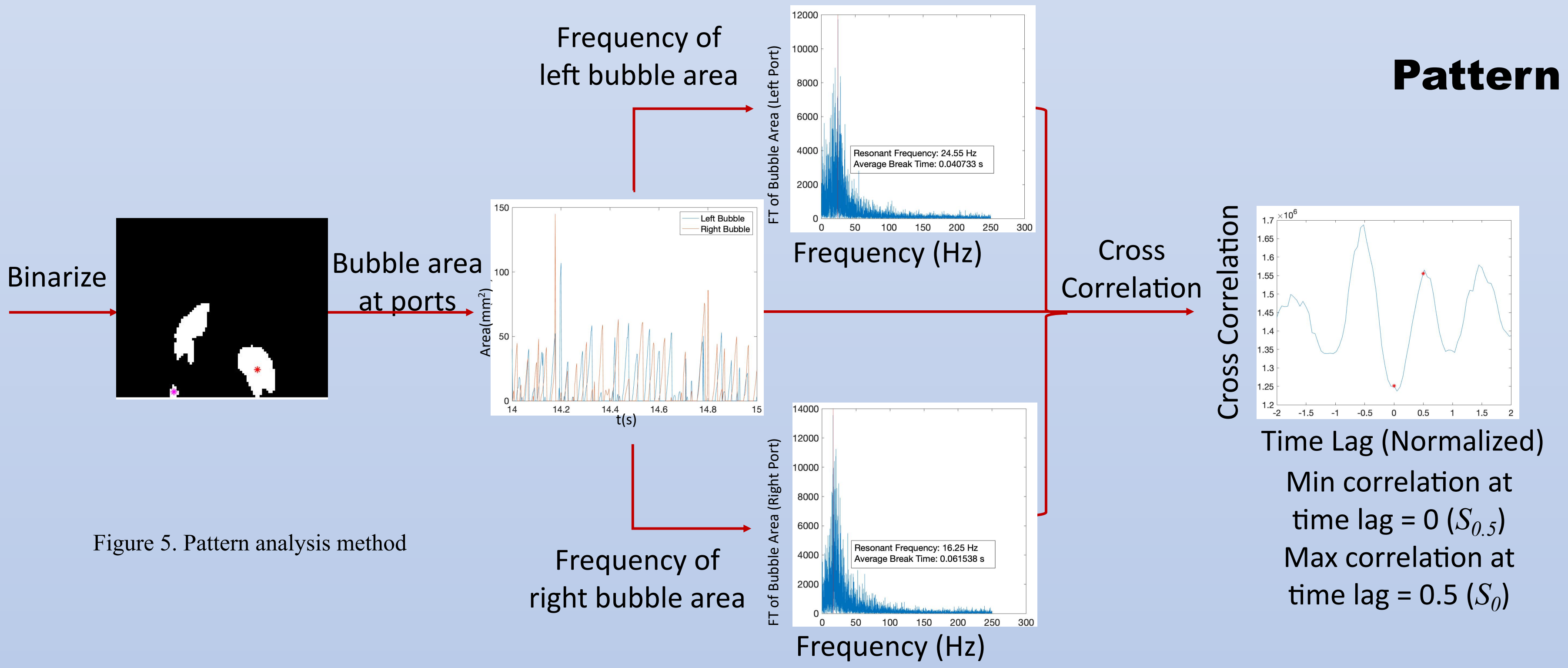


Figure 5. Pattern analysis method

- Fourier transform of bubble area to retrieve the natural frequency of bubble formation.
- Cross correlation to retrieve the relative pattern between the two injecting ports
- The greater the ratio $S_{0.5}/S_0$, the greater the percentage of alternating pattern

Result and Observations

Experimental Results

- Our results confirms that even at a higher basis, bubbles break off at an increasing flowrate exhibits a higher alternating pattern
- A smaller separation distance also increases the alternating pattern

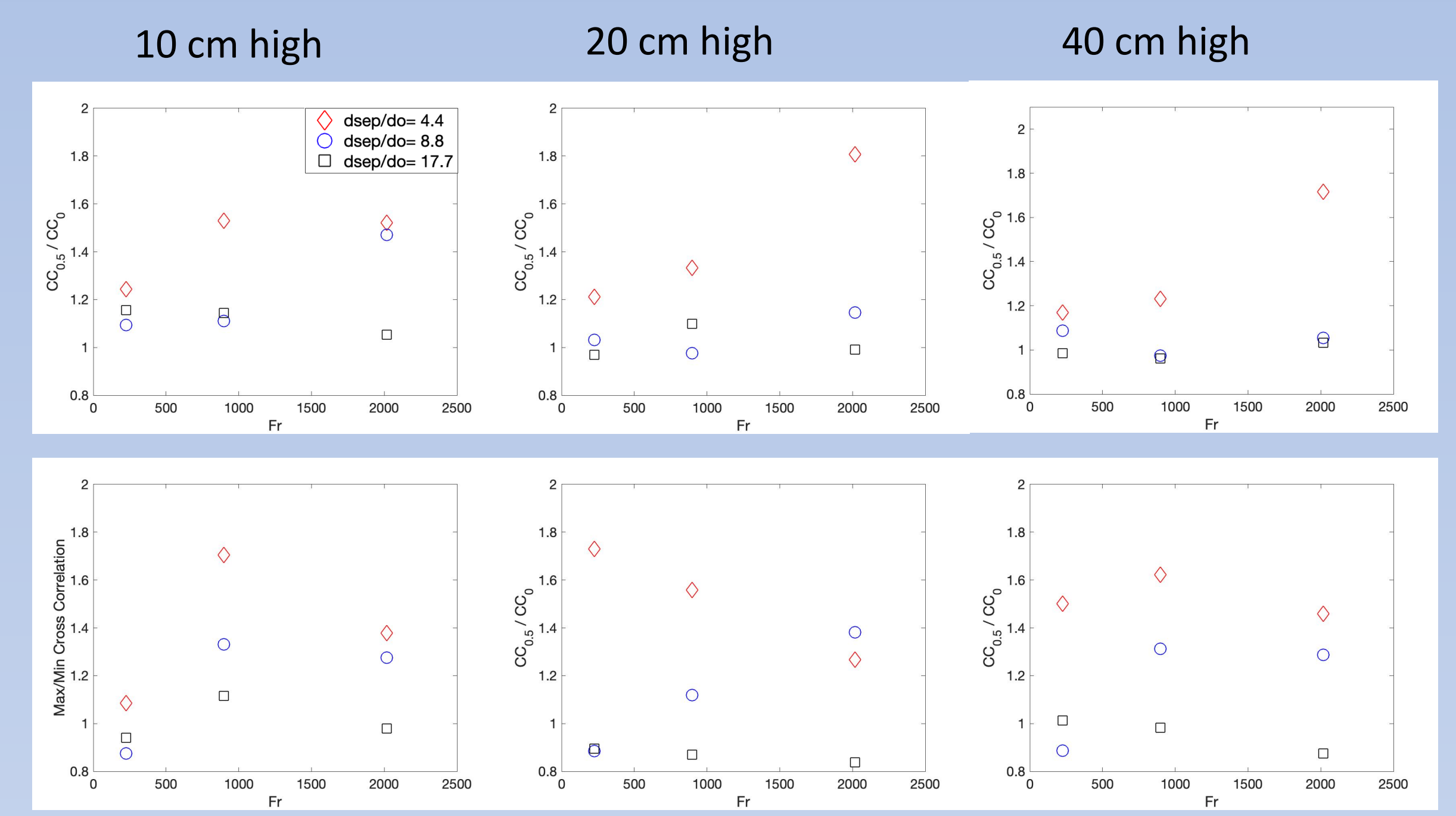


Figure 6. $S_{0.5}/S_0$ ratio of different flowrates, separation distances and water heights

Coupled Harmonic Oscillator Model

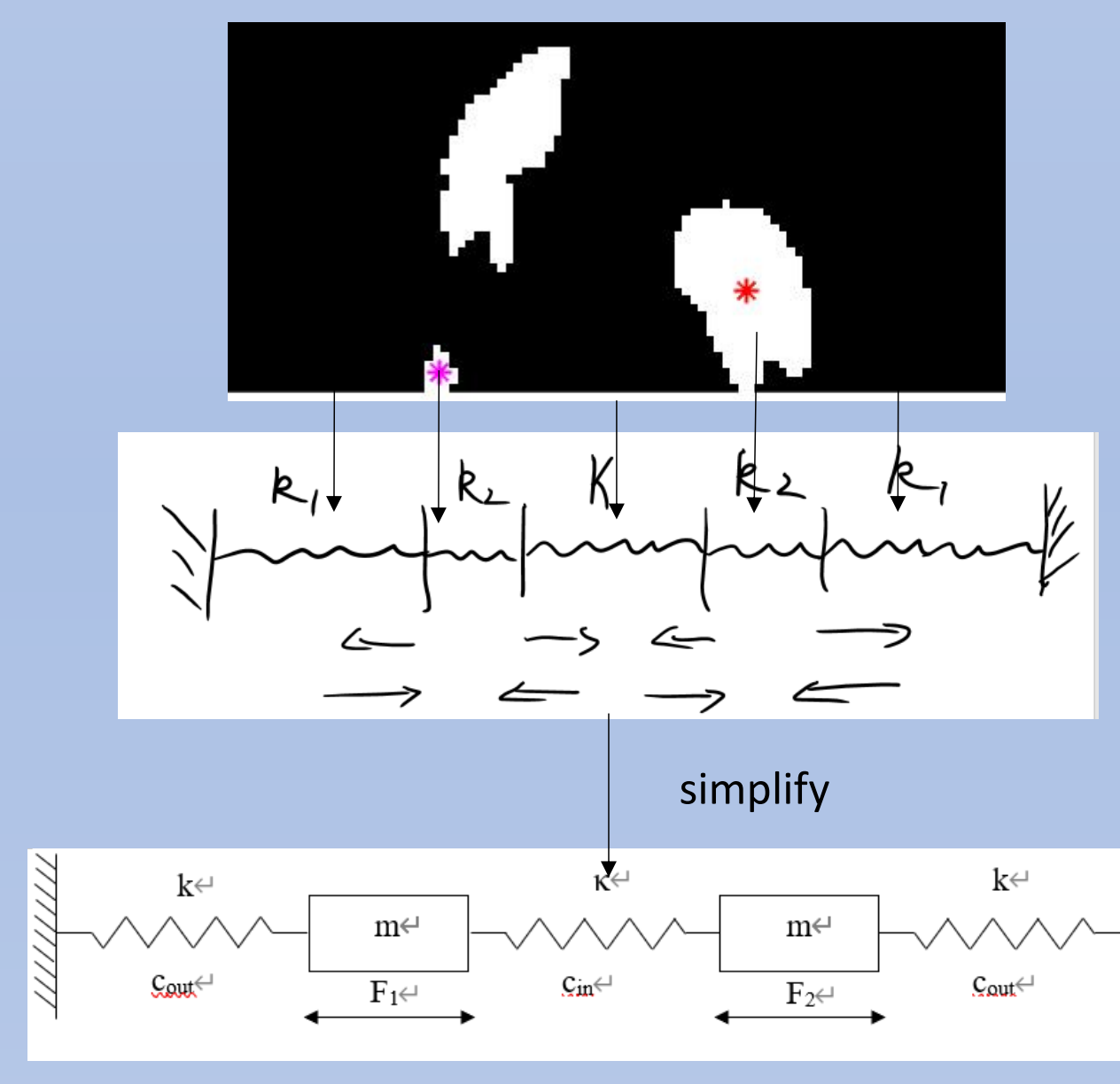


Figure 7. Harmonic oscillator model

- Coupled, dampened, forced harmonic oscillator
- The spring constants relate to compressibility of air and water
- Solved both analytically and numerically
- A long-term steady state solution and a short-term transient solution.

- Given the same initial conditions, synchronous asynchronous patterns can occur
- The key dimensionless term is k_{in} /$k_{out,}$ the ratio between effective spring constant

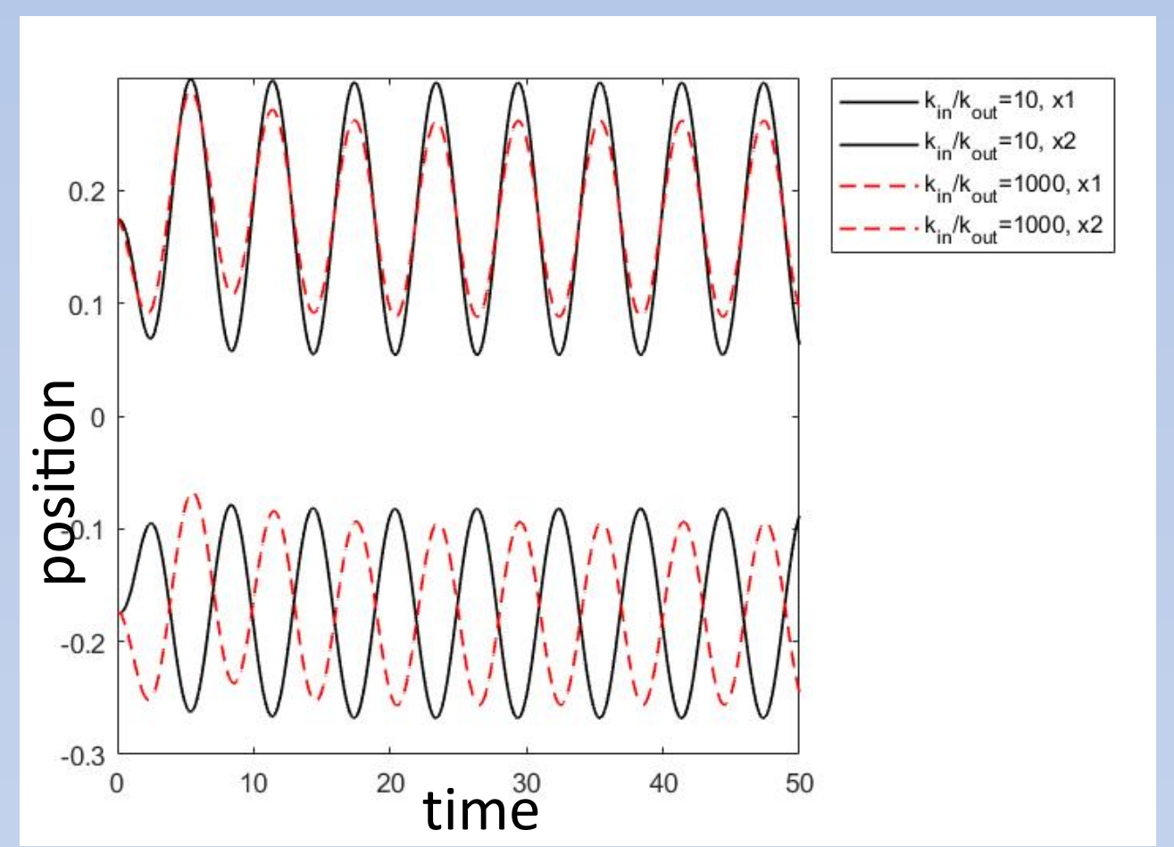


Figure 8. Synchronous vs asynchronous pattern

Result and Observations

Continued

- Since water can be seen as an incompressible fluid, k_{in} /k_{out} >>1, leading to an alternating pattern when the water between ports behaves laminarly
- An increased separation distance lowers the effective spring constant of the water between two ports, due to turbulent complications
- An increased flowrate increases the oscillatory amplitude, increasing the effectiveness of a pinch-off.
- Any difference in flowrate from the two ports offsets a more complex pattern, composed of both patterns

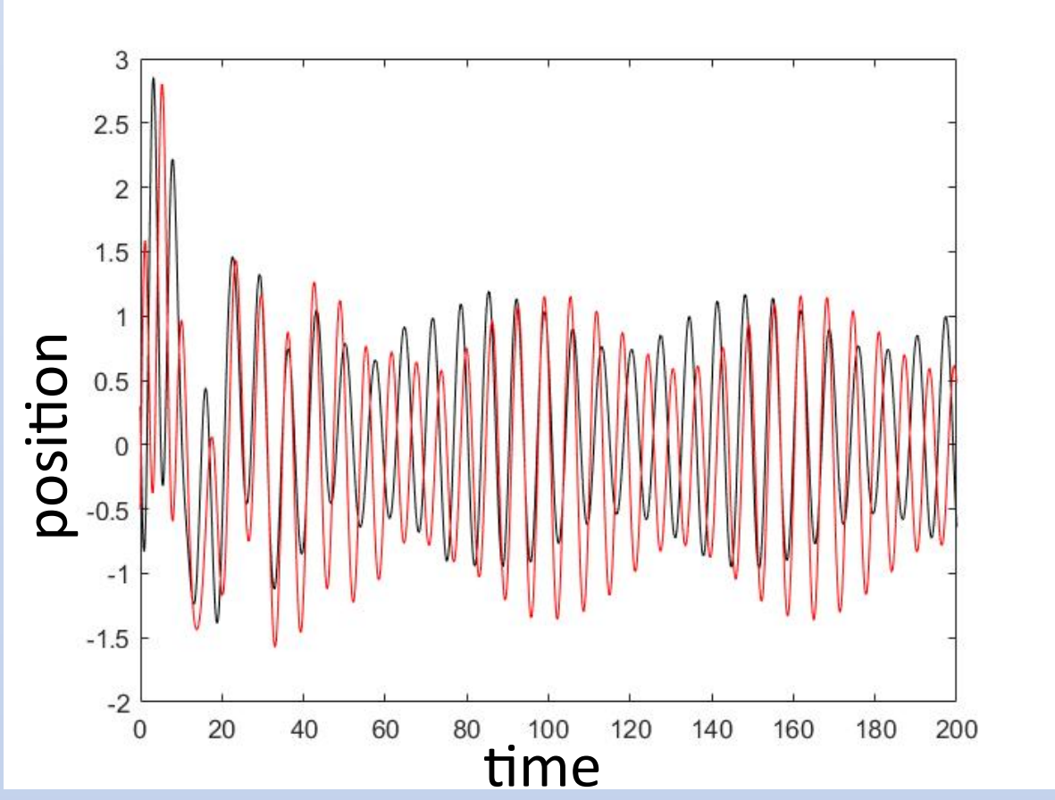


Figure 9. A more complex pattern due to a frequency difference in the driving forces

Discussion

- The growth of a bubble at one port effectively causes the pinch-off of bubbles at another port
- A coupled harmonic oscillator model can be used to model the system's behavior

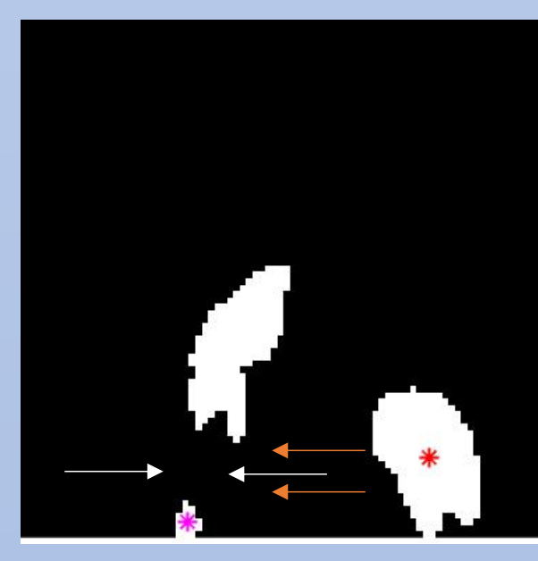


Figure 10. Diagram of a coupled pinch-off action

Acknowledgment

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References

[1] Burton, J. C.; Waldrep, R.; Taborek, P. Scaling and Instabilities in Bubble Pinch-Off. *Phys. Rev. Lett.* **2005**, *94* (18), 184502. https://doi.org/10.1103/PhysRevLett.94.184502.

[2] P. Dzienis, R. Mosdorf, T. Wyszkowski, Nonlinear dynamics of self-organising bubble departures from twin nozzles, Meccanica. 54 (2019) 2119–2130. https://doi.org/10.1007/s11012-019-01056-6.

[3] M. Ruzicka, J. Drahoš, J. Zahradník, N.H. Thomas, Structure of gas pressure signal at two-orifice bubbling from a common plenum, Chem. Eng. Sci. 55 (2000) 421–429. https://doi.org/10.1016/S0009-2509(99)00337-1.

[4] M. Ruzicka, J. Drahoš, J. Zahradník, N.H. Thomas, Natural modes of multi-orifice bubbling from a common plenum, Chem. Eng. Sci. 54 (1999) 5223–5229. https://doi.org/10.1016/S0009-2509(99)00243-2.

[5] F.A.C. Pereira, E. Colli, J.C. Sartorelli, Synchronization of two bubble trains in a viscous fluid: Experiment and numerical simulation, Phys. Rev. E. 87 (2013) 022917. https://doi.org/10.1103/PhysRevE.87.022917.

[6] S. Xie, R. B.H. Tan, Bubble formation at multiple orifices—bubbling synchronicity and frequency, Chem. Eng. Sci. 58 (2003) 4639–4647. https://doi.org/10.1016/j.ces.2003.06.002.

[7] D. Leppinen, J.R. Lister, Capillary pinch-off in inviscid fluids, Phys. Fluids. 15 (2003) 568–578. https://doi.org/10.1063/1.1537237.