Hydrodynamic cavitation: Process opportunities for ice-cream formulations

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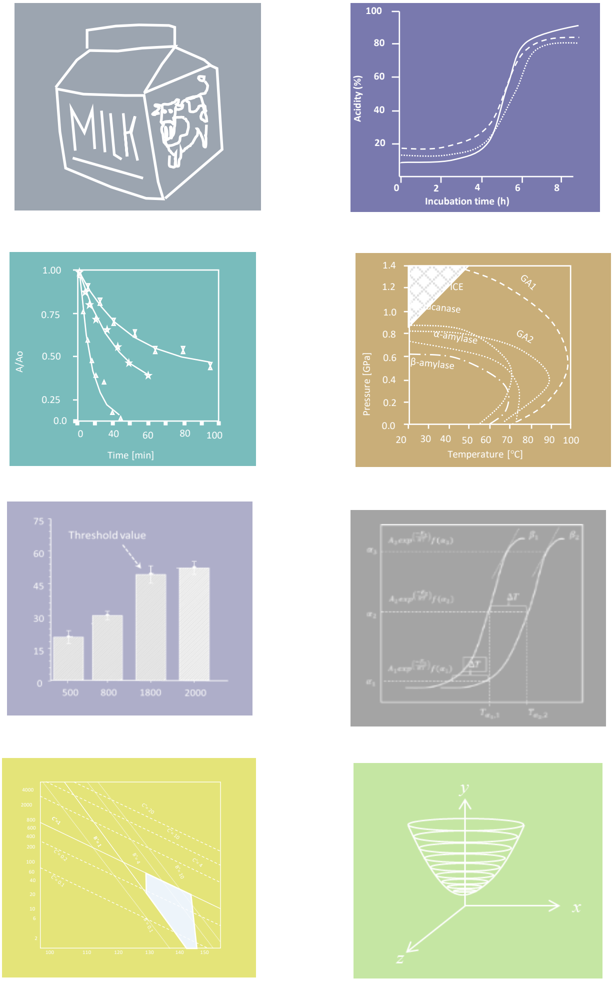
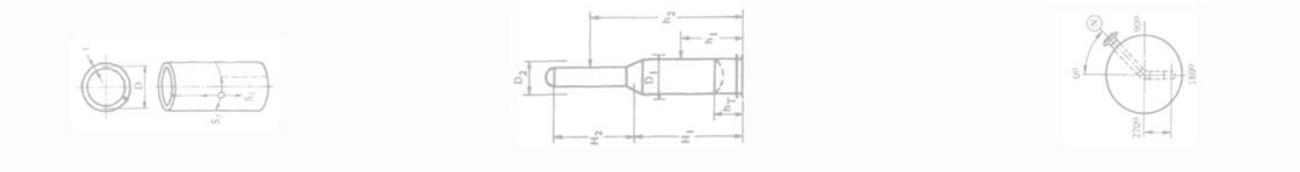




Presentation layout

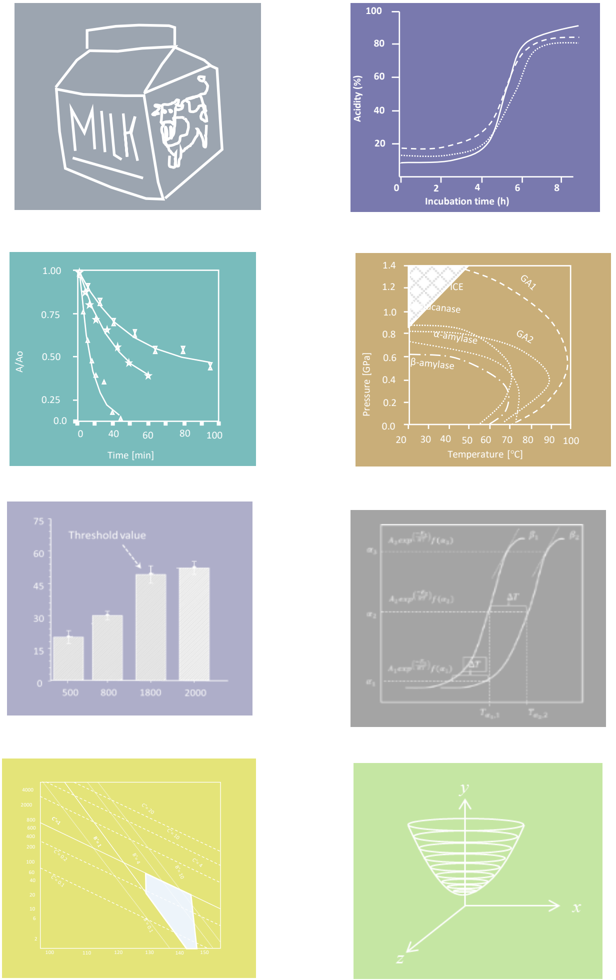
I. Significance & Challenges

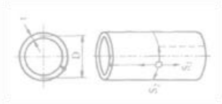
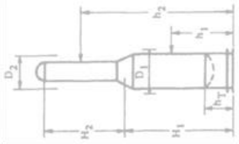
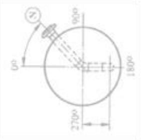
II. Current approaches

III. Hydrodynamic cavitation

IV. Manufacturing ice-cream

V. Outlook



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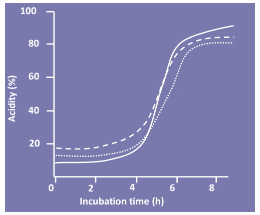

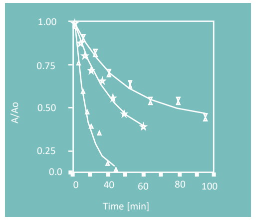

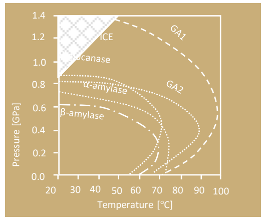

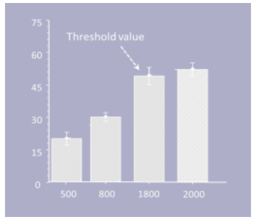

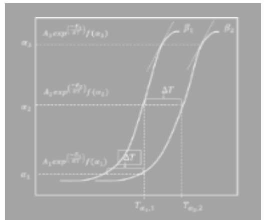


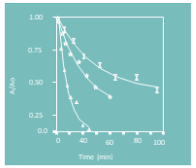
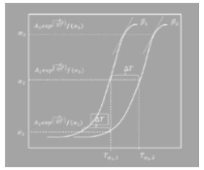

Significance of ice-cream

- Ice-cream is extremely popular dessert

  - More than 10 kg of product being consumed per person per year

  - Broad portfolio of flavors and unique ingredients

(International Dairy Federation, 2020)

- Ice-cream is highly significant in economic terms

  - Increase projected global market from $68 billion in 2016 to $97 billion by 2023

(Allied Market Research, 2020)

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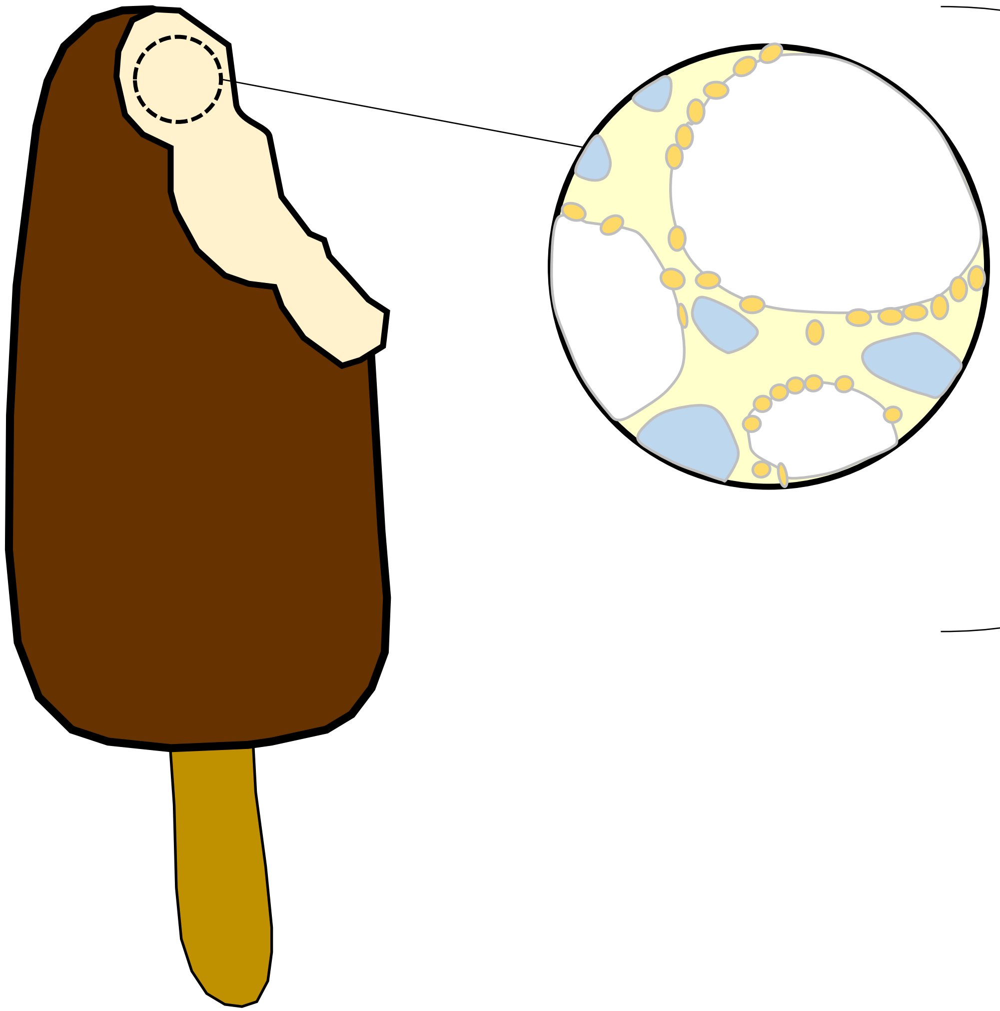
Unique material | ice-cream

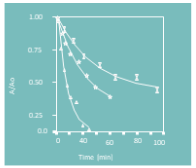


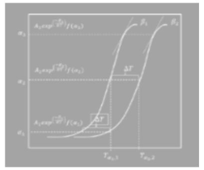
Three-phase:

- Air cells
- Ice-crystals
- Fat globules

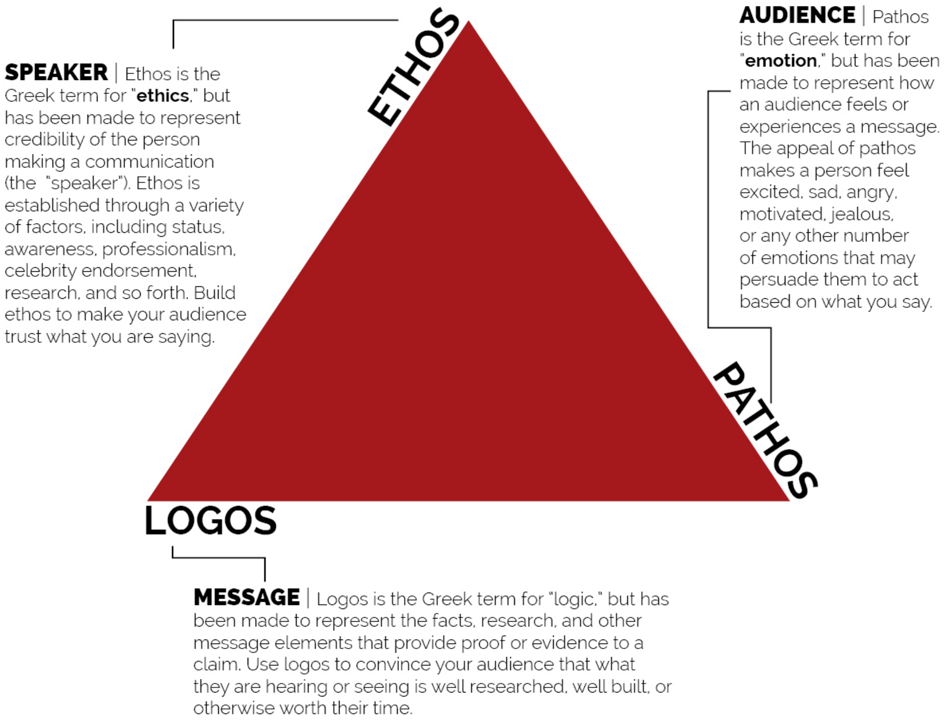
Embedded in a concentrated frozen matrix

Challenges | Clean-label



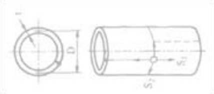
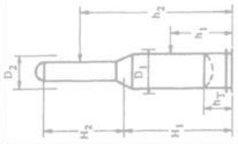
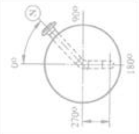


- Attitudes towards processing and ingredients
  - Driven by consumer-to-consumer persuasion
  - Perception of natural, healthy, and sustainable



Rhetorical trends:

- Clean label
- Free-type
- Gentle processing
- Natural

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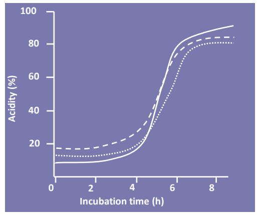
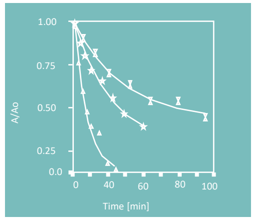
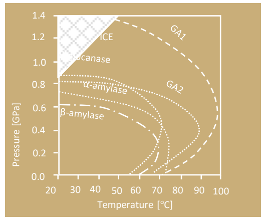
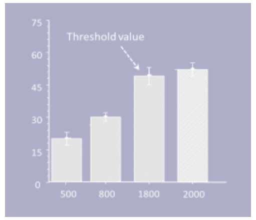
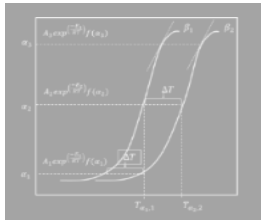
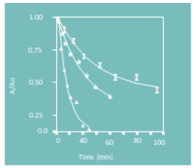
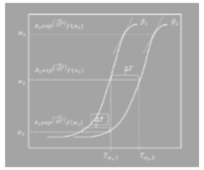










Clean-Label

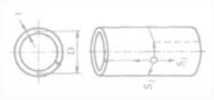
- Partial or total Removal of stabilizers

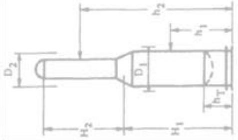
Stabilizers

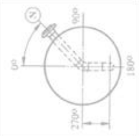
- Emulsion stability
- Stabilize air bubbles
- Reduce crystal growth
- Prevent water migration
- Impart viscosity

Current approaches for stabilizer removal

1. Optimization of existing formulations
2. Substituting with novel ingredients
3. Applying emerging technologies







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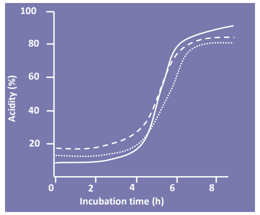
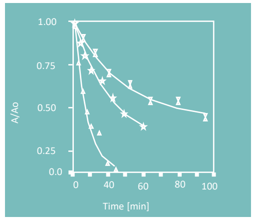
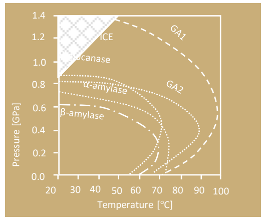
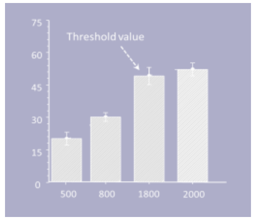
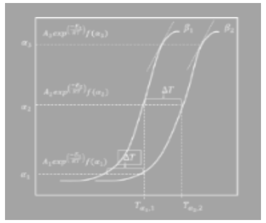




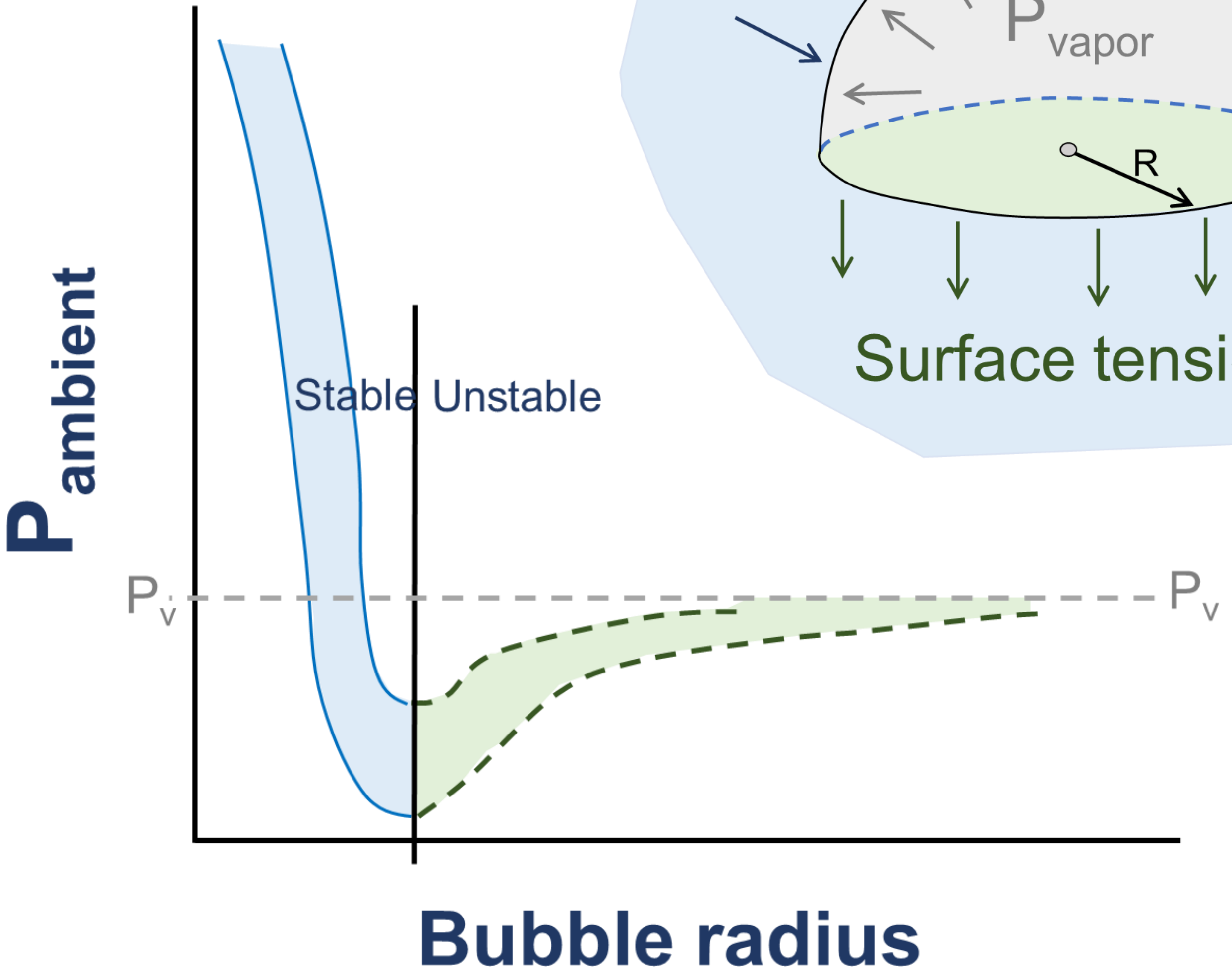


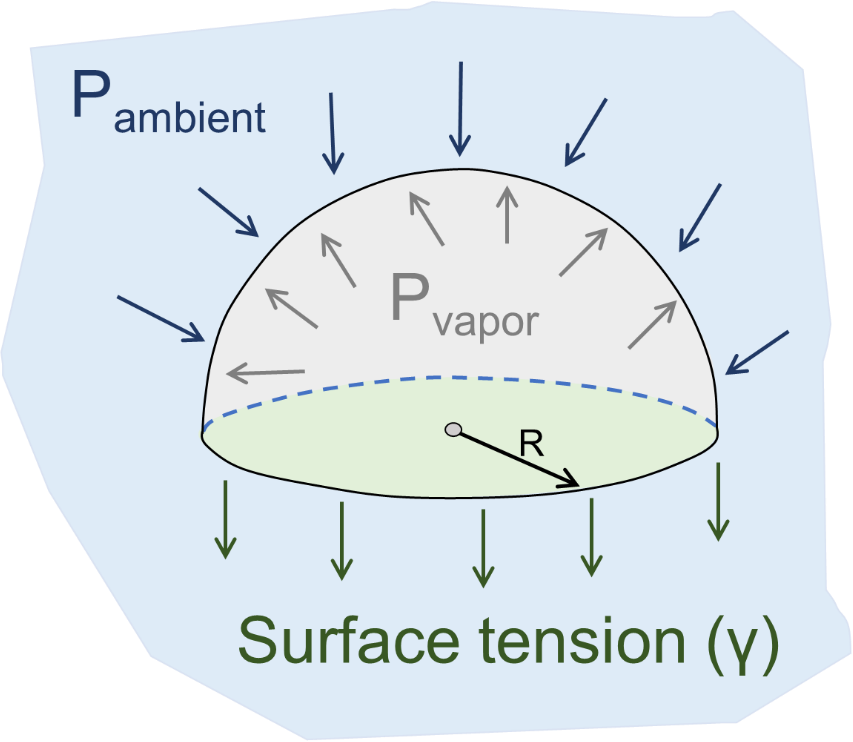


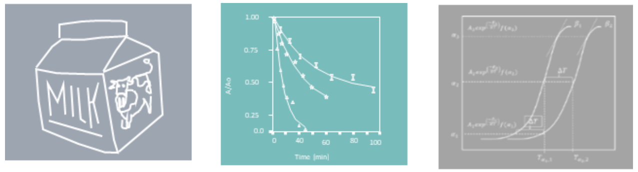


Hydrodynamic cavitation

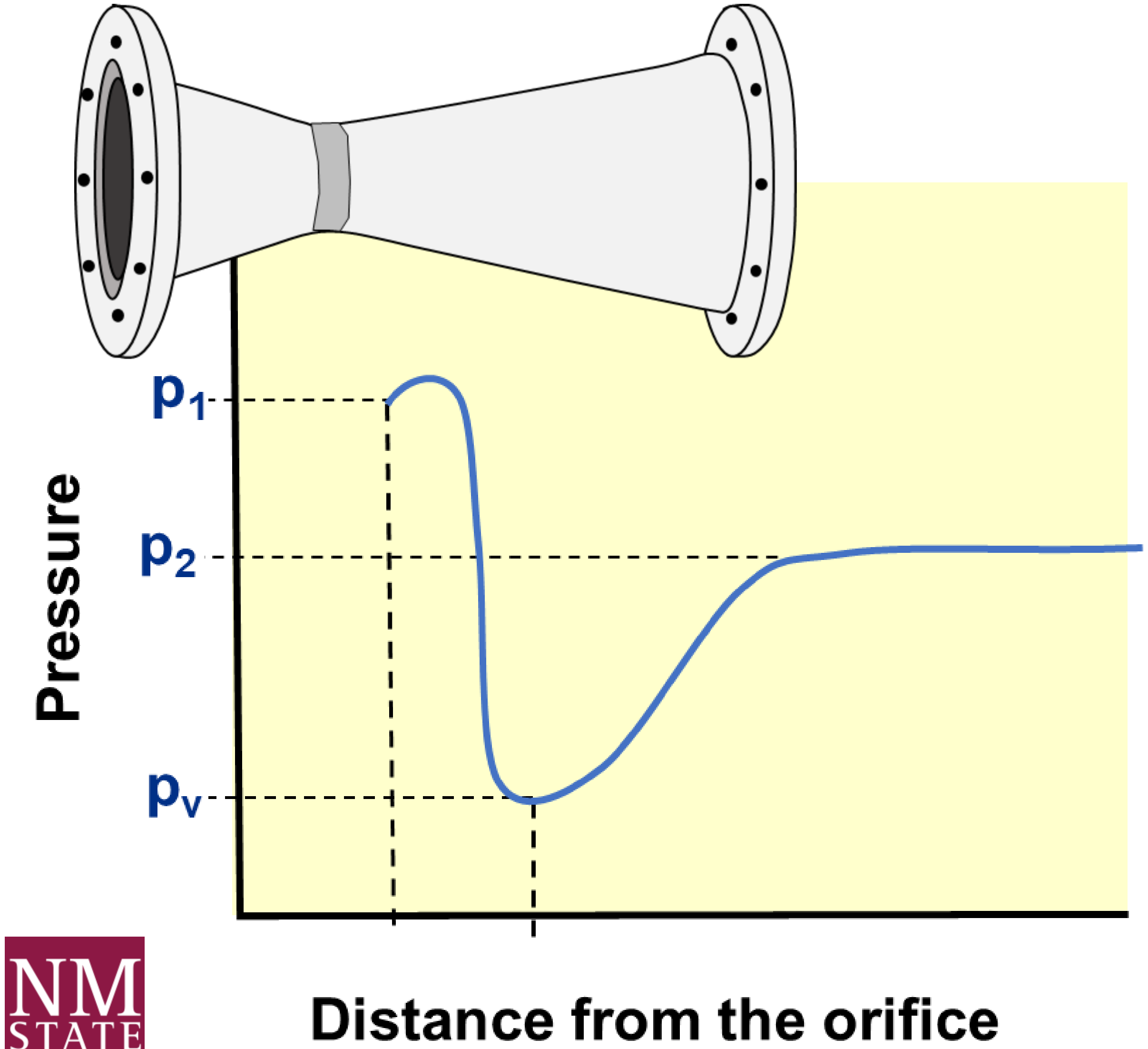
Cavitation in a propeller



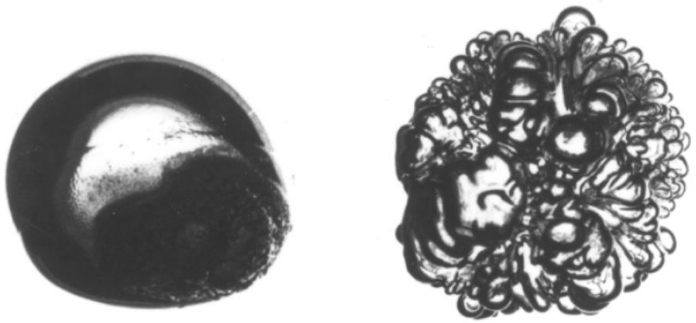




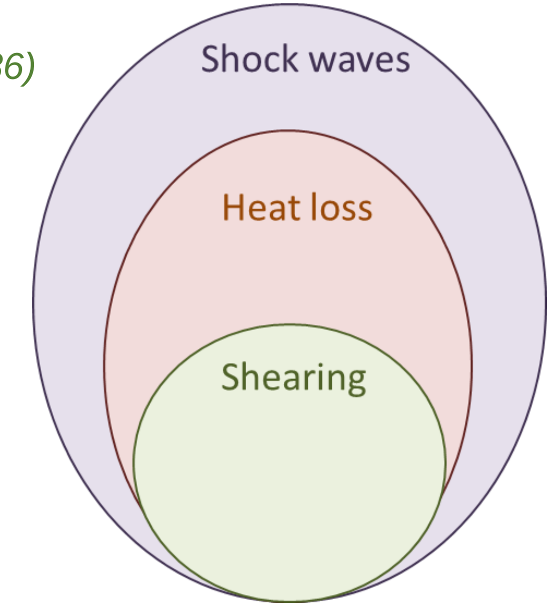
Cavitation



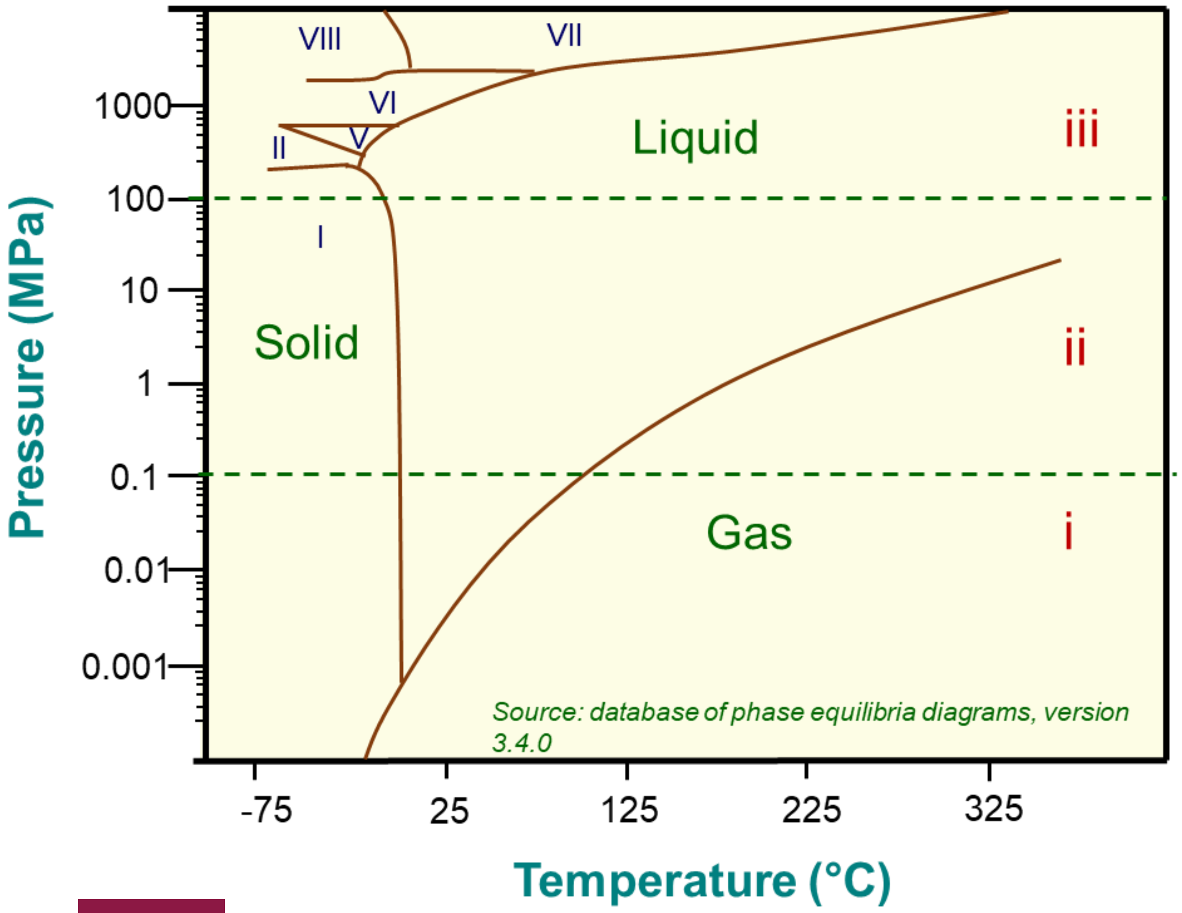
Formation, growth, and collapse



(Frost and Sturtevant, 1986)

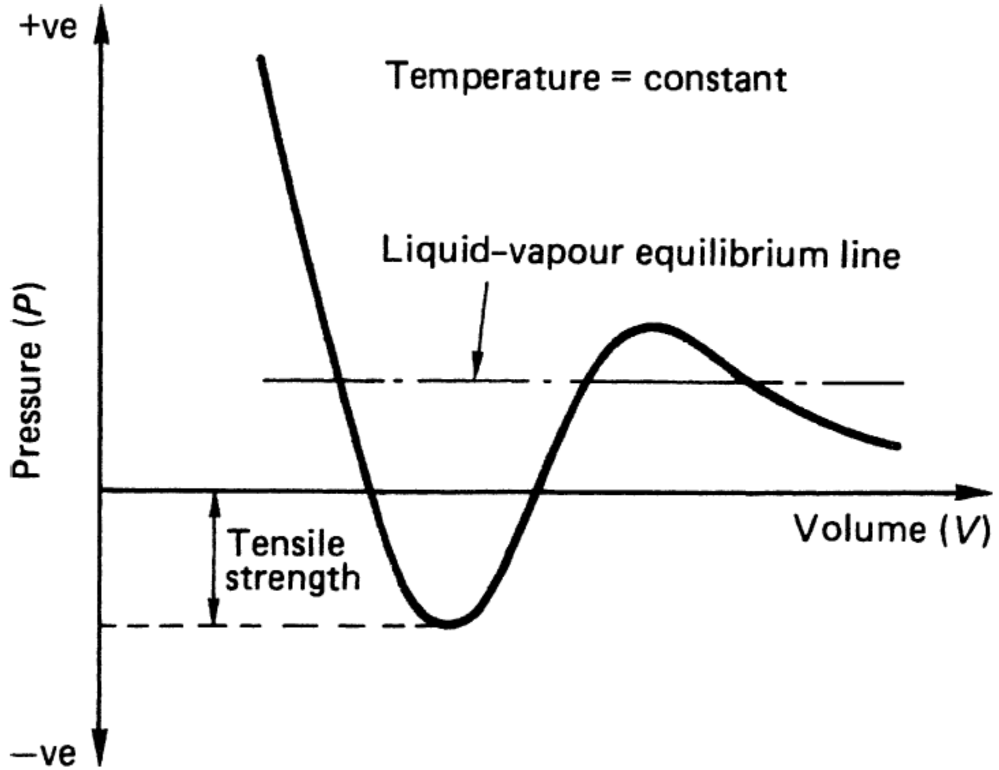


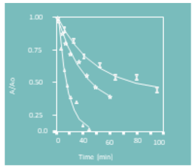
Pressure-Volume

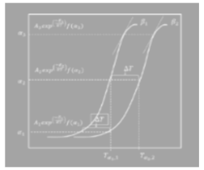


$$d(\Delta G) = \Delta V dp - \Delta S dT$$

Van der Waals' isotherm







Cavitation parameters

- Pressure coefficient (C_p)

$$C_p = \frac{p_1 - p_2}{{}^1\!/_2 \cdot \rho \cdot v_i^2}$$

- Minimum pressure coefficient (C_{pmin})

$$C_{pmin} = \frac{p_{min} - p_2}{{}^1\!/_2 \cdot \rho \cdot v_i^2}$$

- Cavitation appearance (p_{app})

$$p_{app} = p_v + {}^1\!/_2 \cdot \rho \cdot v_i^2$$

- Cavitation number (C_v)

$$C_v = \frac{p_2 - p_1}{{}^1\!/_2 \cdot \rho \cdot v_i^2}$$

- Cavitation inception (C_{in})

$$C_{in} = \frac{p_{app} - p_v}{{}^1\!/_2 \cdot \rho \cdot v_i^2}$$

- Thoma number (T_h)

$$T_h = \frac{p_1 - p_v}{p_2 - p_1}$$

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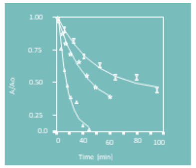
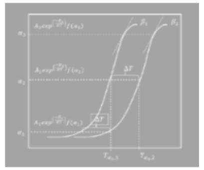
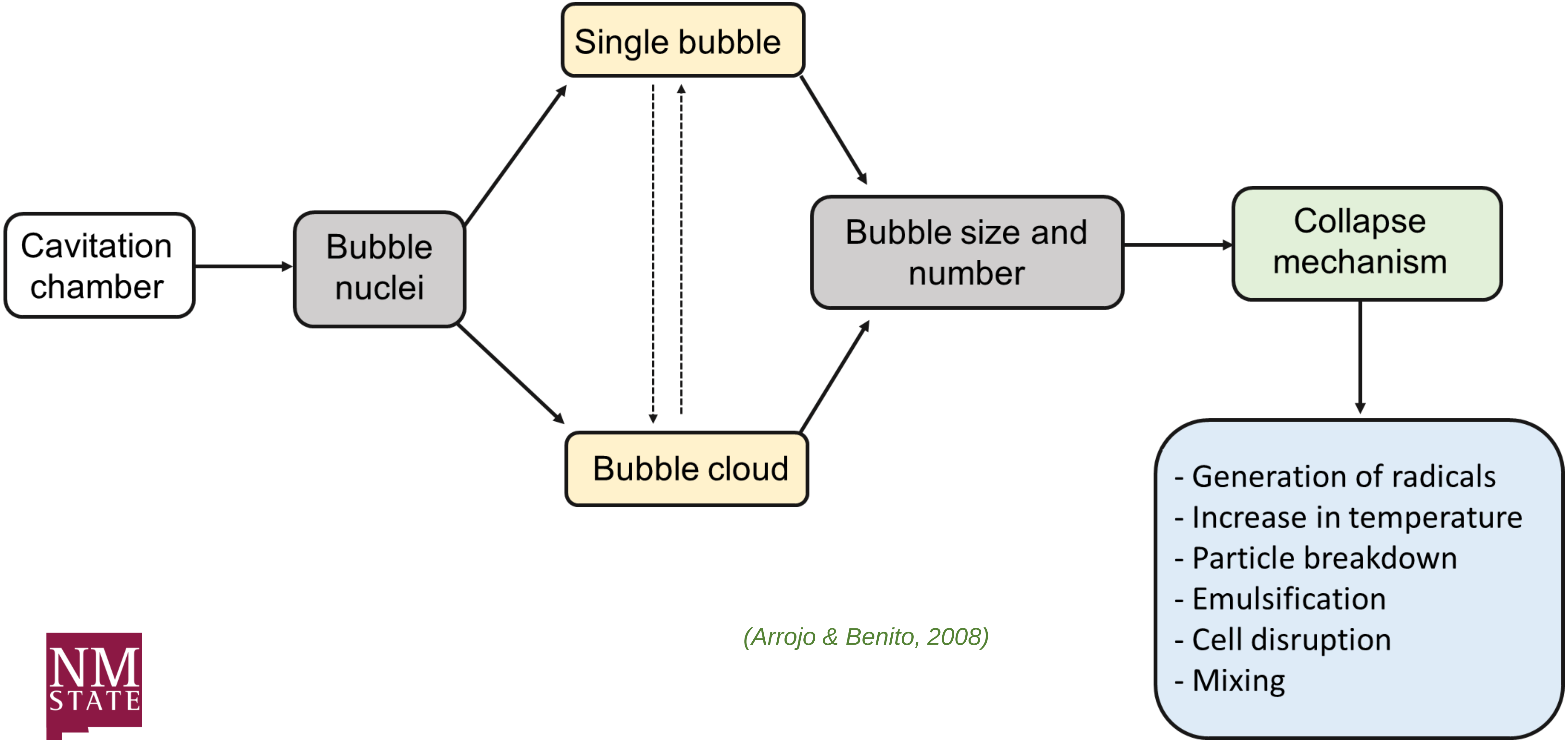
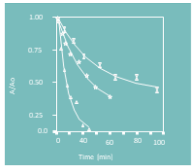
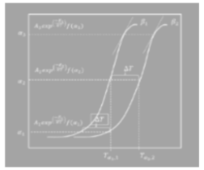



Scheme of hydrodynamic cavitation

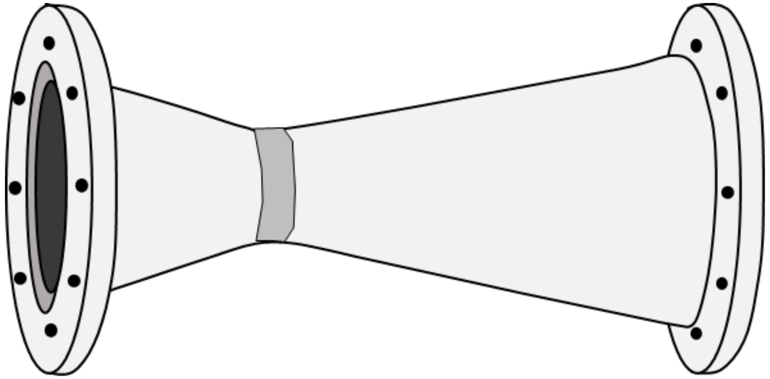


(Arrojo & Benito, 2008)

Cavitation and related technologies

Venturi effect



Geometry & arrangements

$$P_M = f(P_\infty, \alpha, \rho, \mu, V_\infty) = \frac{P_\infty - p_v}{{}^1/_2 \cdot \rho \cdot V_\infty^2}$$

- Homogenization
- Ultrasound processing
- High-shear mixing
- High-pressure jet
- High-pressure homogenization
- Hydrodynamic cavitation

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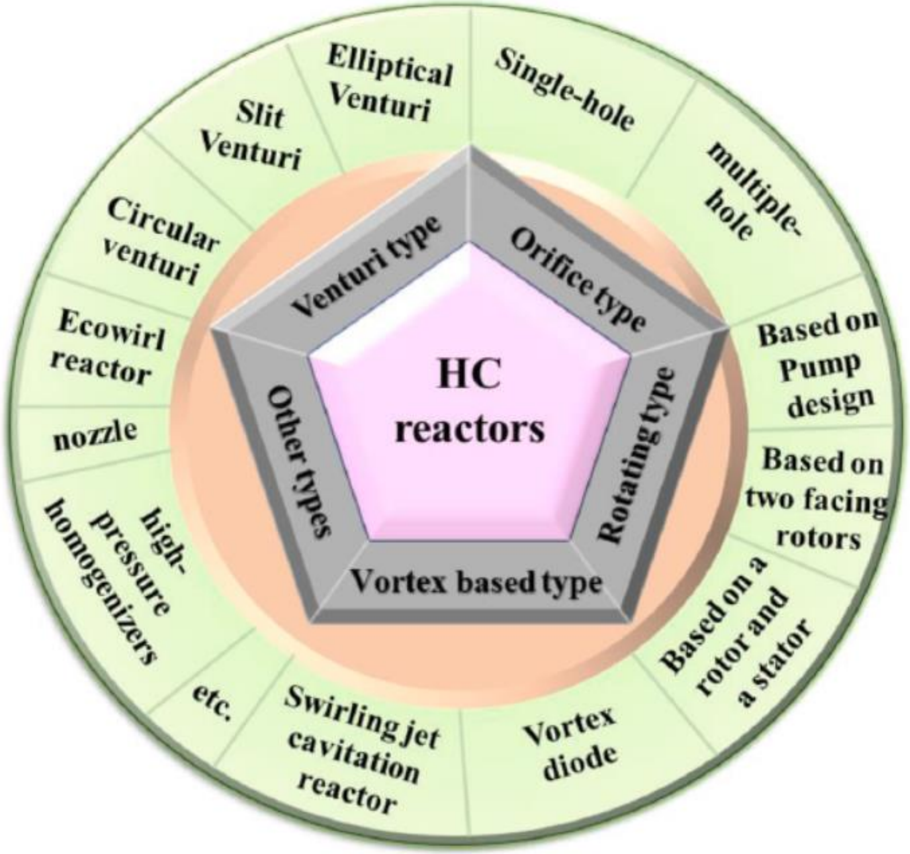
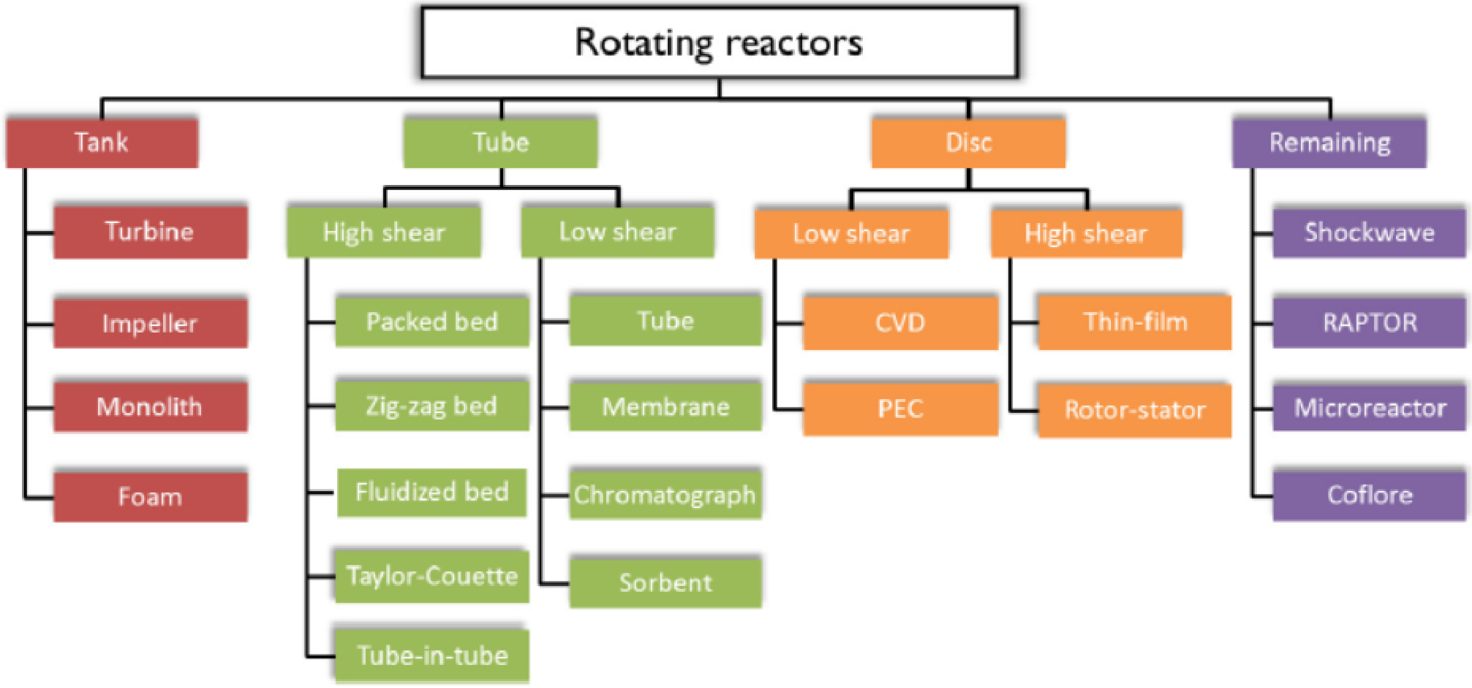
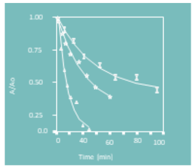
Cavitation devices | Classification

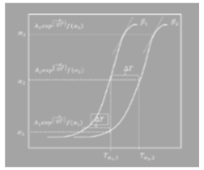


(Wang et al., 2021)



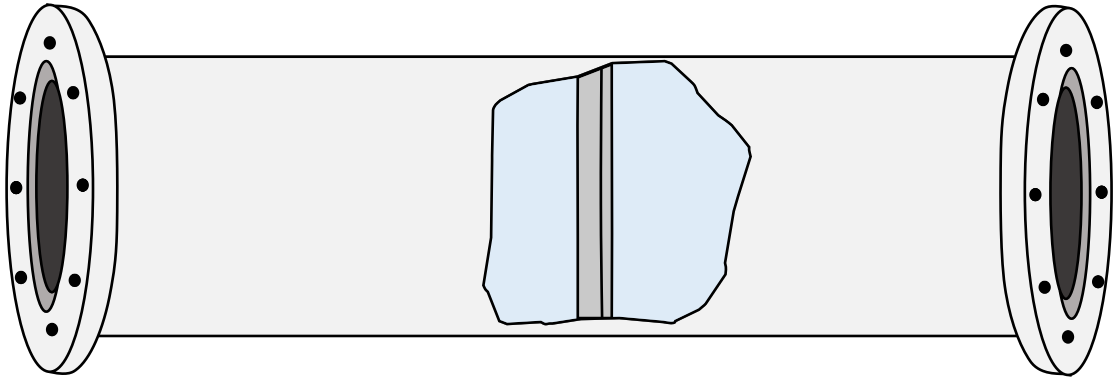
(Visscher et al., 2013)

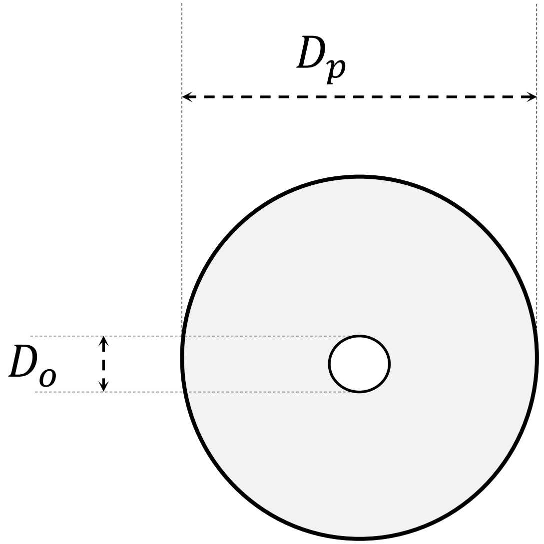




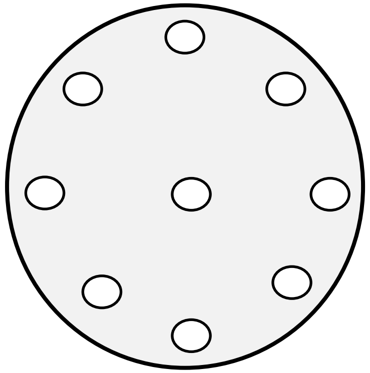
Cavitation devices | Hydrodynamic

Orifice-based

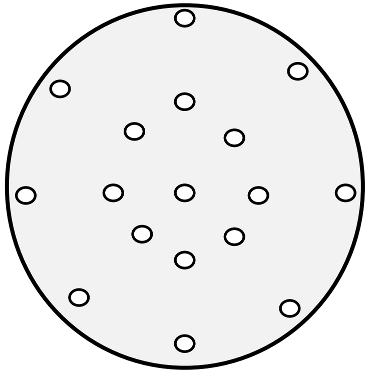




Single orifice



Multiple orifice

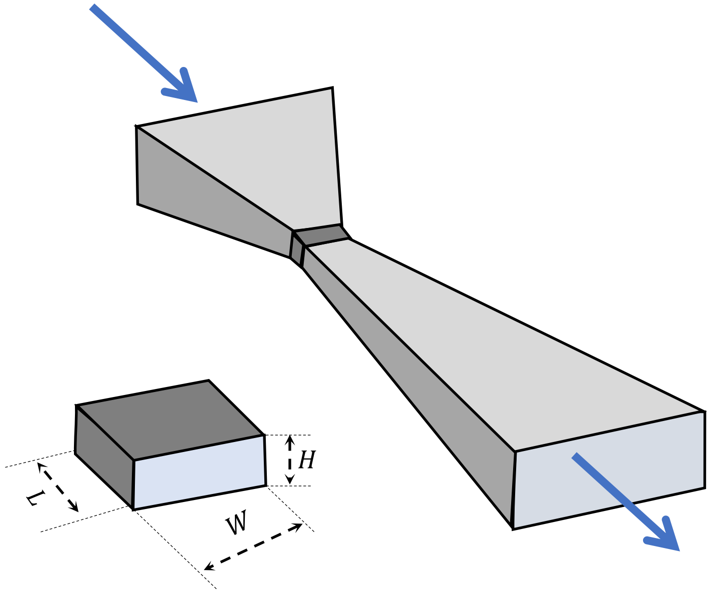


Multiple orifice

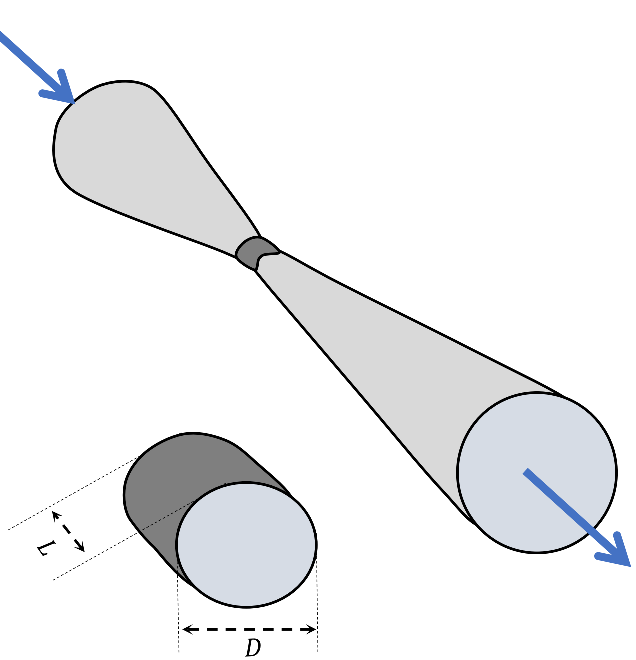
(Carpenter et al., 2016)

Cavitation devices | Hydrodynamic

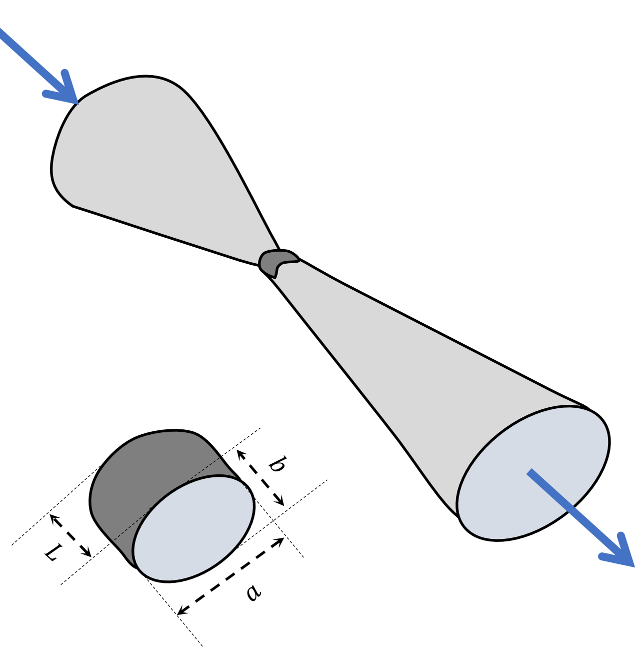
Venturi-type



Slit Venturi

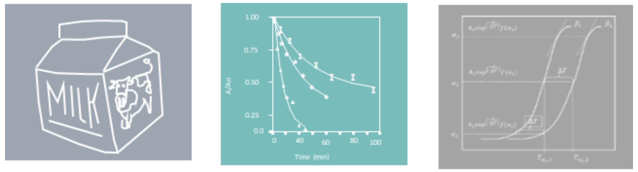


Circular Venturi



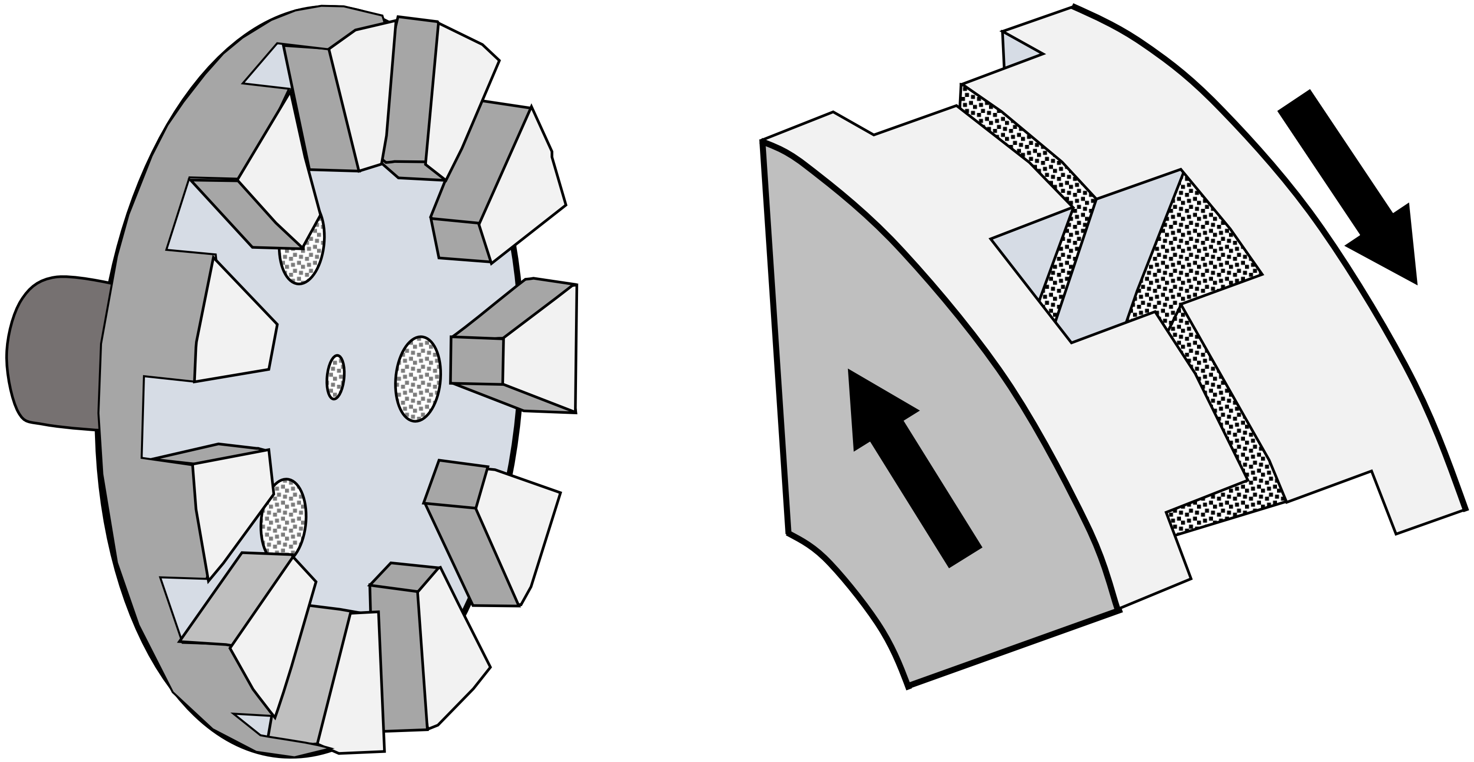
Elliptical Venturi

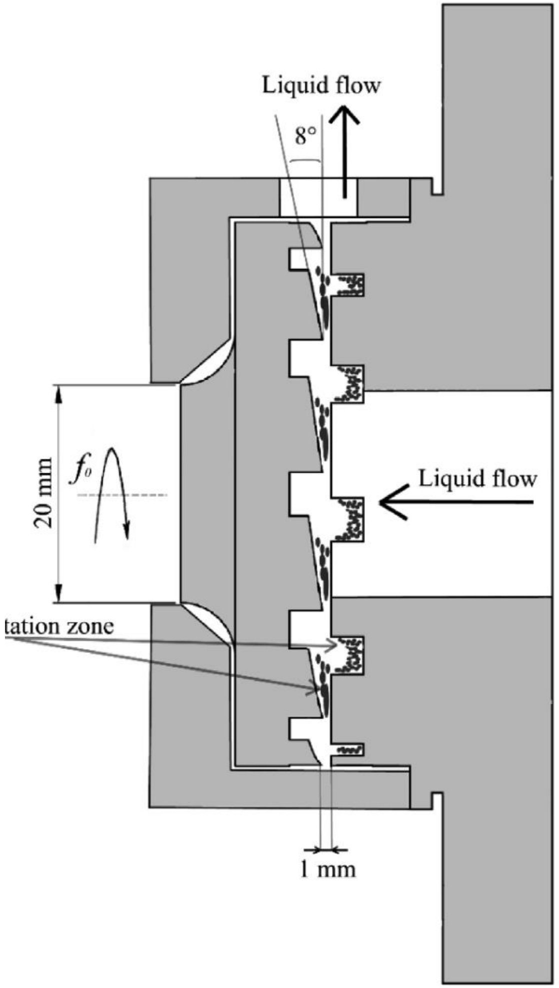
(Carpenter et al., 2016)



Cavitation devices | Rotational cavitator

Two facing rotors





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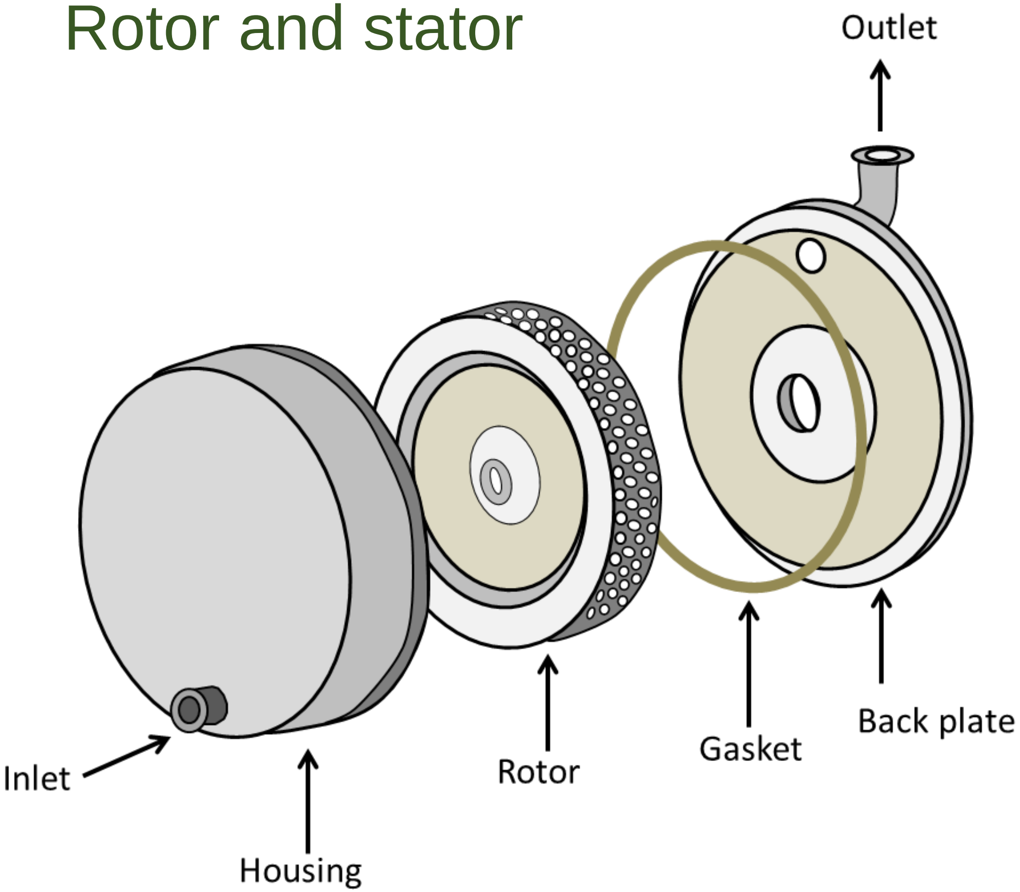
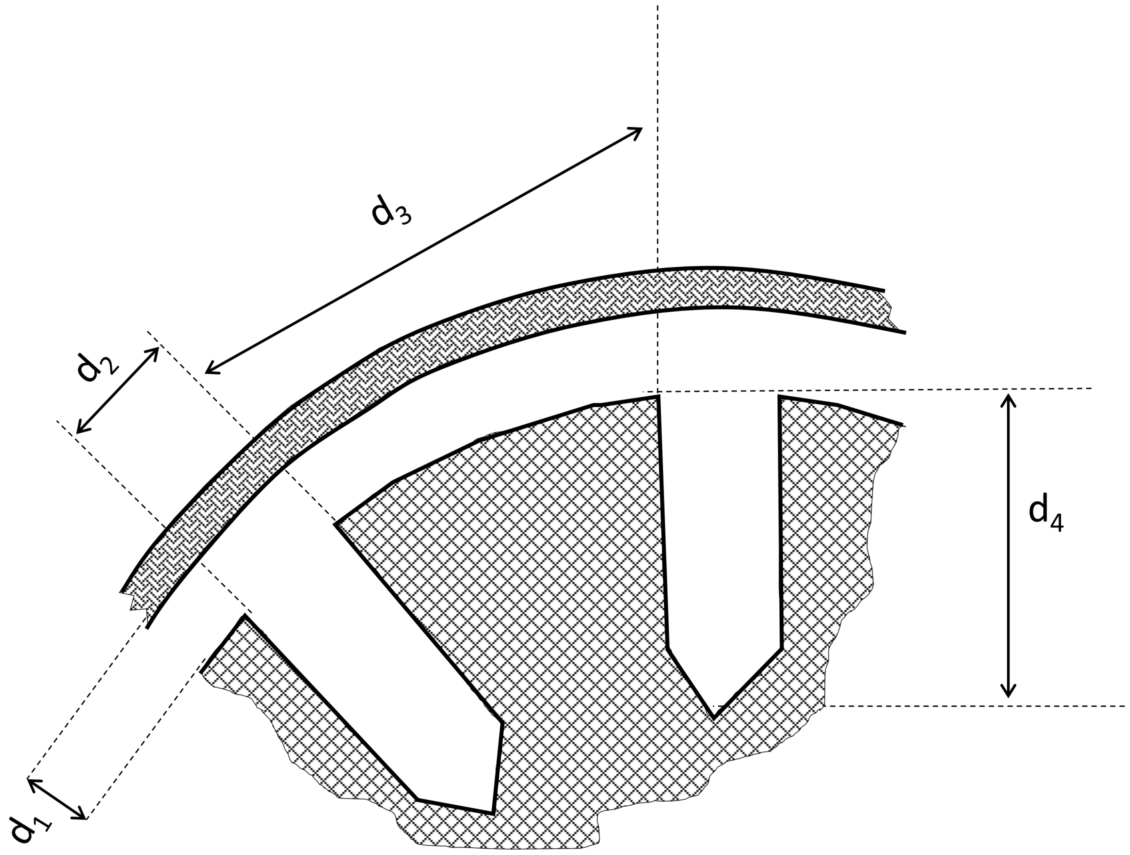
(Kosel et al., 2019)

Cavitation devices | Cavitator

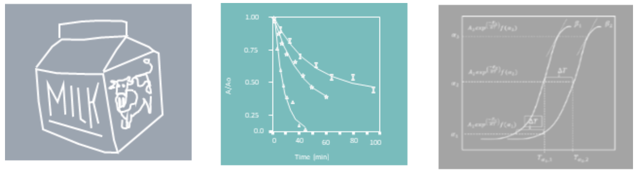
Rotor and stator

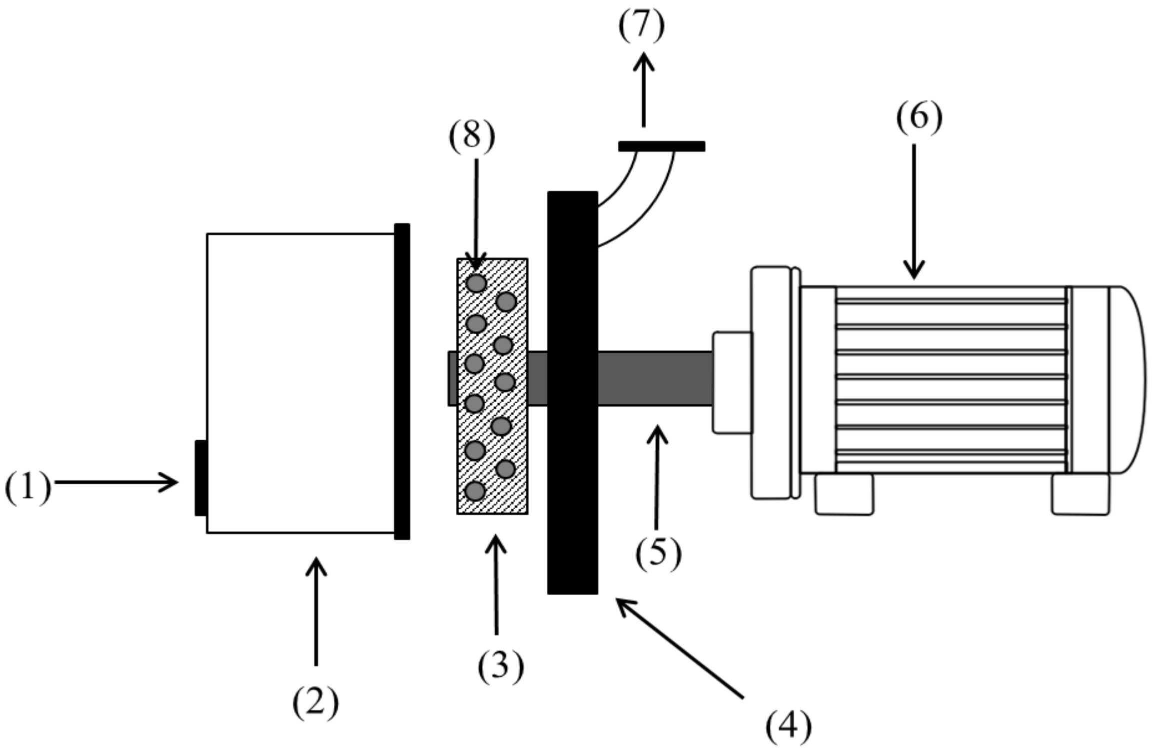


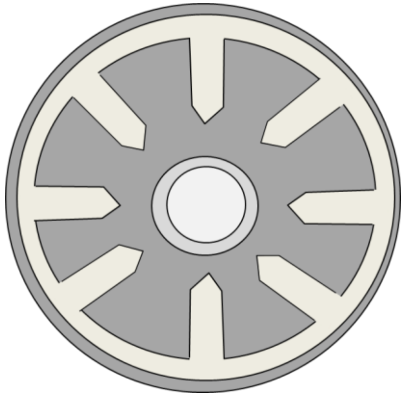


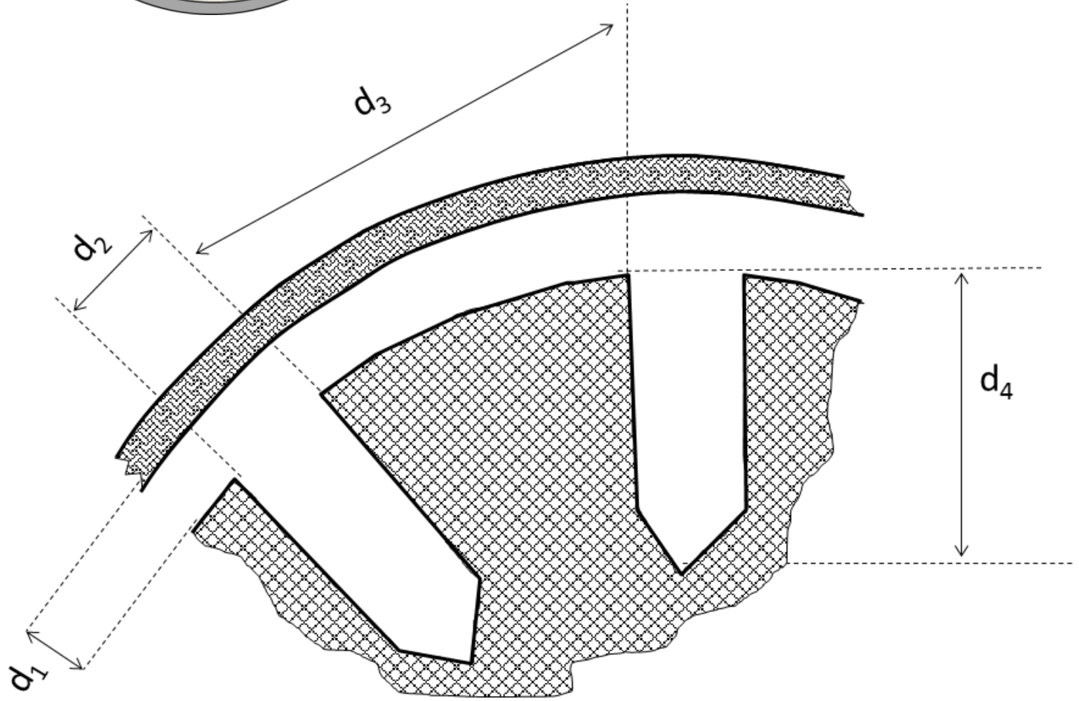
(Sim et al., 2021)

Hydrodynamic cavitation

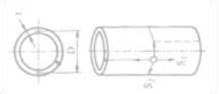
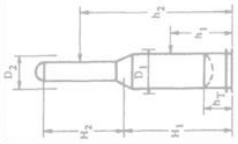
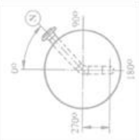




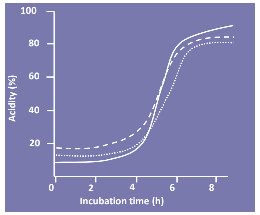




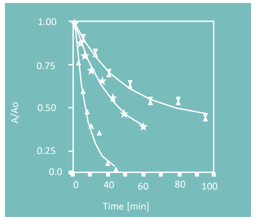
(1) product inlet; (2) housing; (3) rotor; (4) backplate; (5) shaft; (6) rotor; (7) product outlet; (8) indents; d_1 distance between rotor and housing; d_2 diameter of the indents; d_3 distance between indents; and d_4 length of indent. Drawings do not represent a real scale.

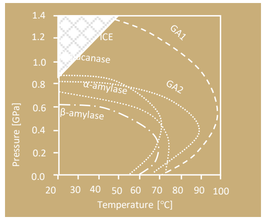




Presentation layout



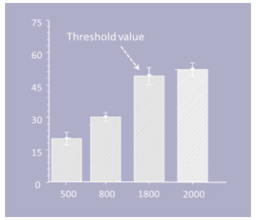
I. Significance & Challenges

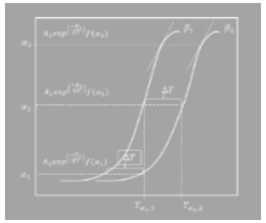




II. Current approaches

III. Hydrodynamic cavitation

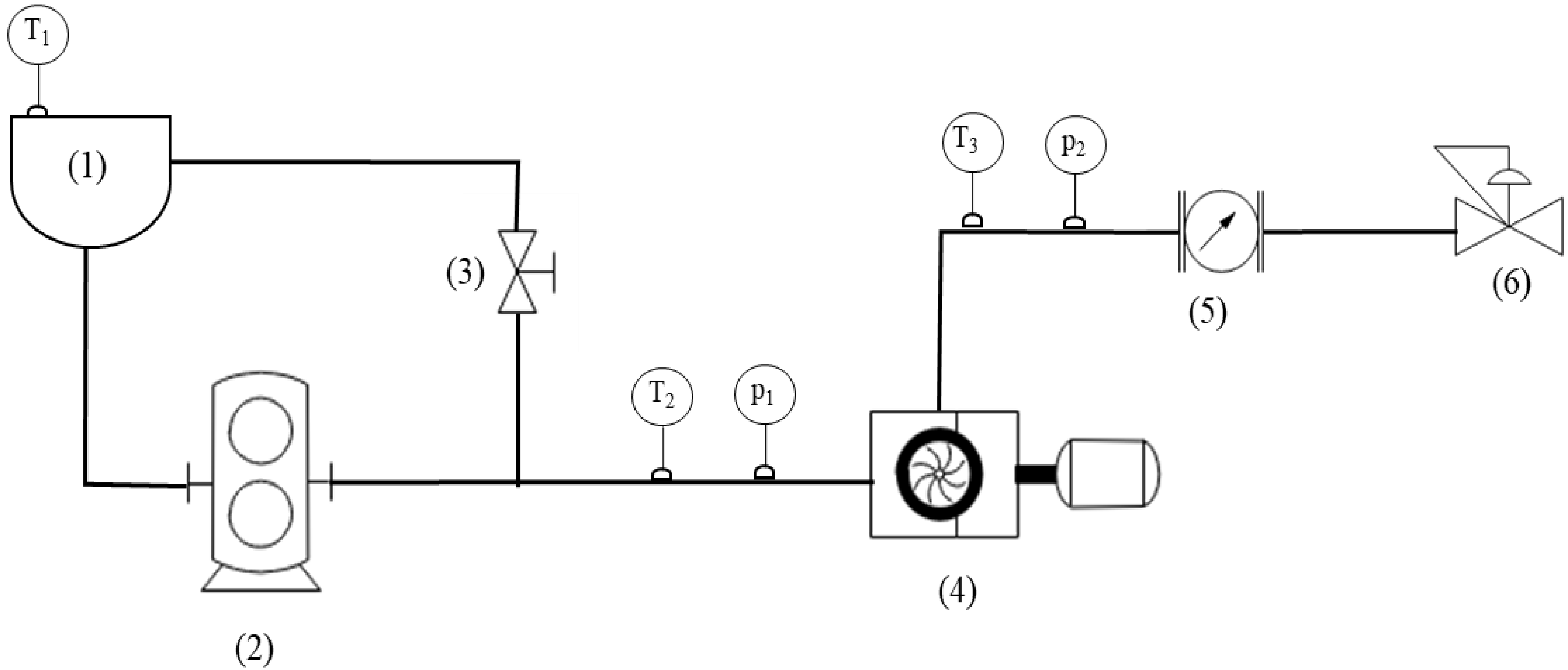




IV. Manufacturing ice-cream

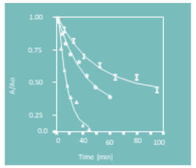
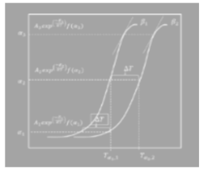
V. Outlook

Applications | Ice-cream manufacture



$$25 \leq Flow\ rate\ \leq 300\ L/h$$

$$400 \leq Speed\ of\ rotor\ \leq 3600\ RPM$$

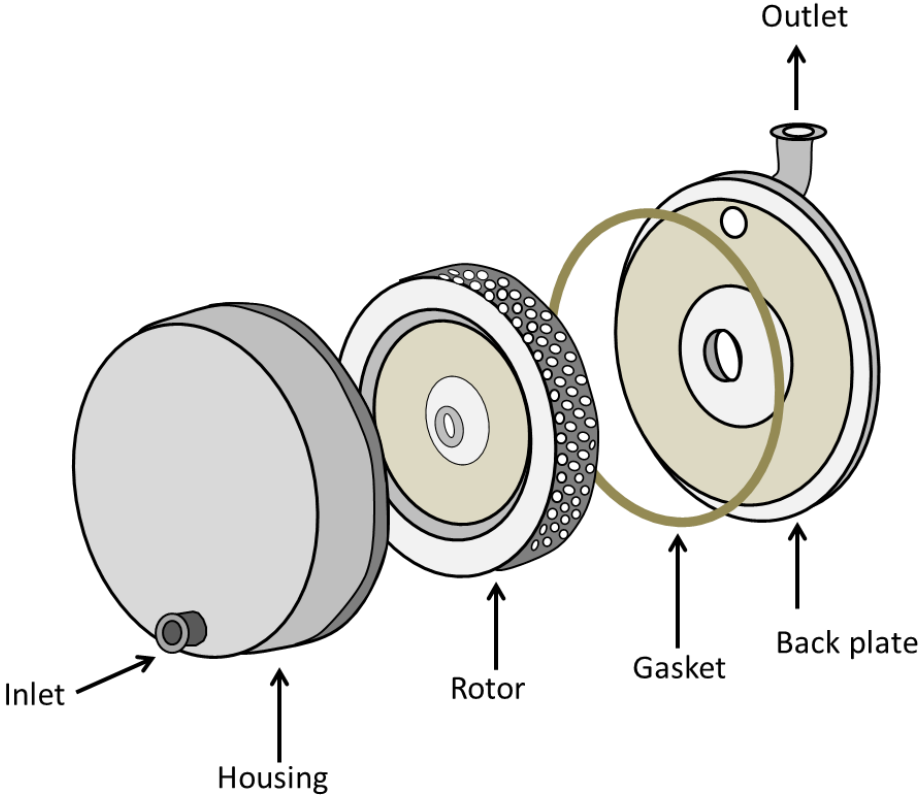
  

Applications | Ice-cream manufacture

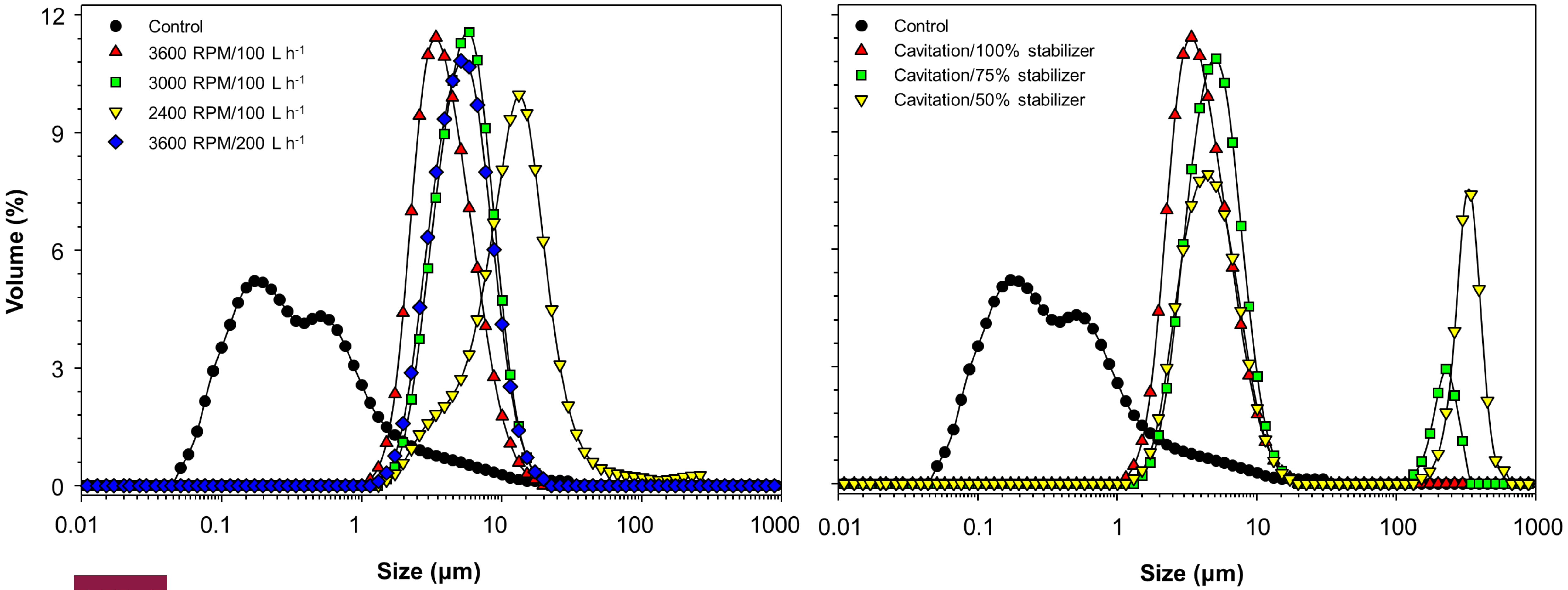
Blend of stabilizers (0.25%) and was gradually reduced

Parameter	Before cavitation	After cavitation
T.S. (%)	40.61 ± 0.04	40.23 ± 0.21
Fat (%)	13.10 ± 0.98	13.31±0.51
Protein (%)	4.21 ± 0.12	4.28 ± 0.05
Carbohydrates (%)[a]	24.36	23.46
pH	6.44 ± 0.01	6.48±0.01

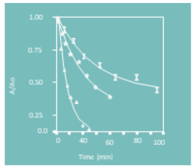
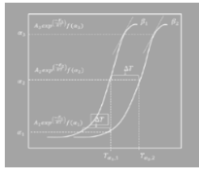
[a] Carbohydrates were calculated by difference



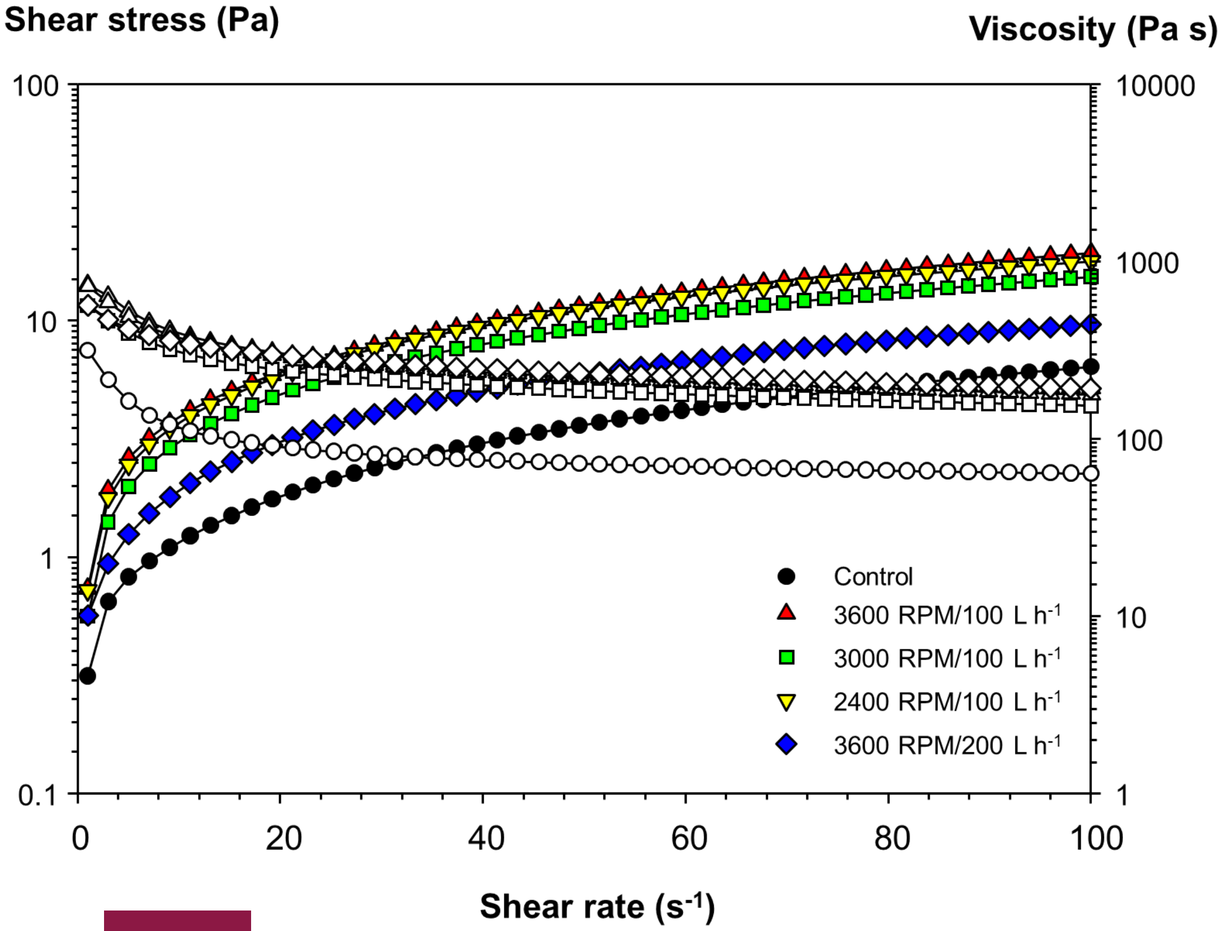
Ice-cream mix: Particle size

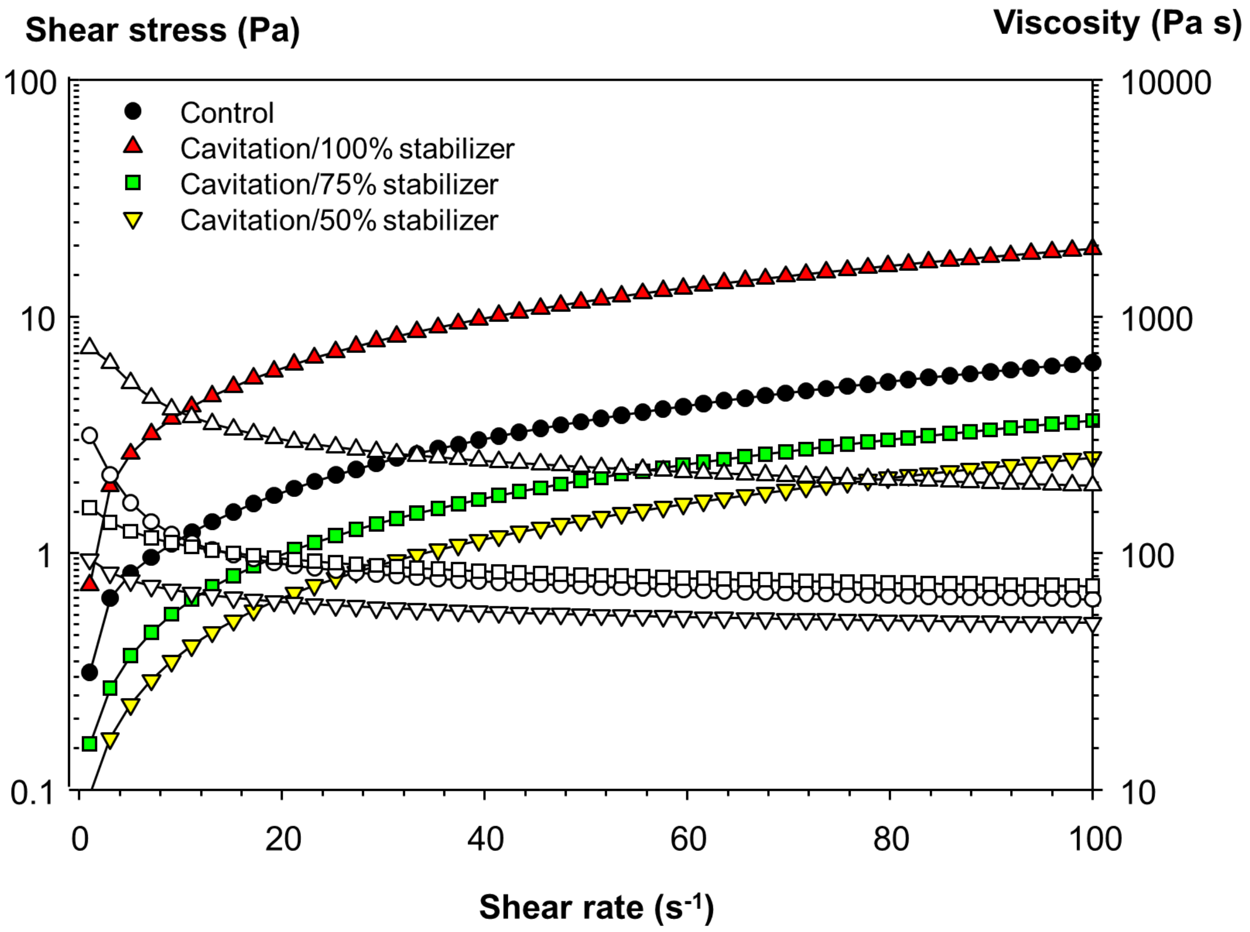


(Sim et al., 2021)

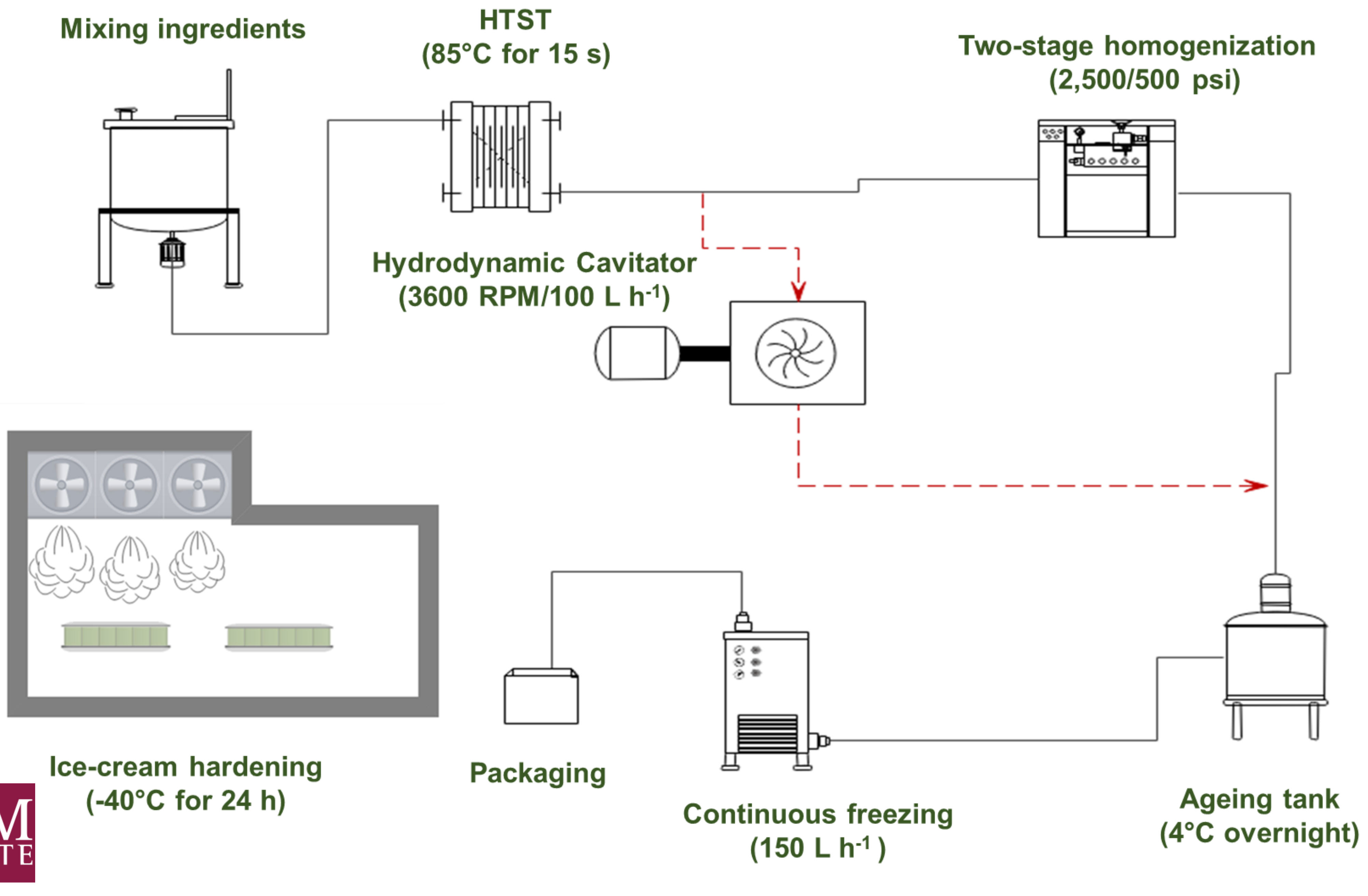




Ice-cream mix: viscosity

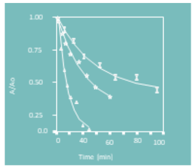
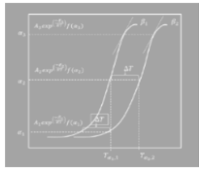


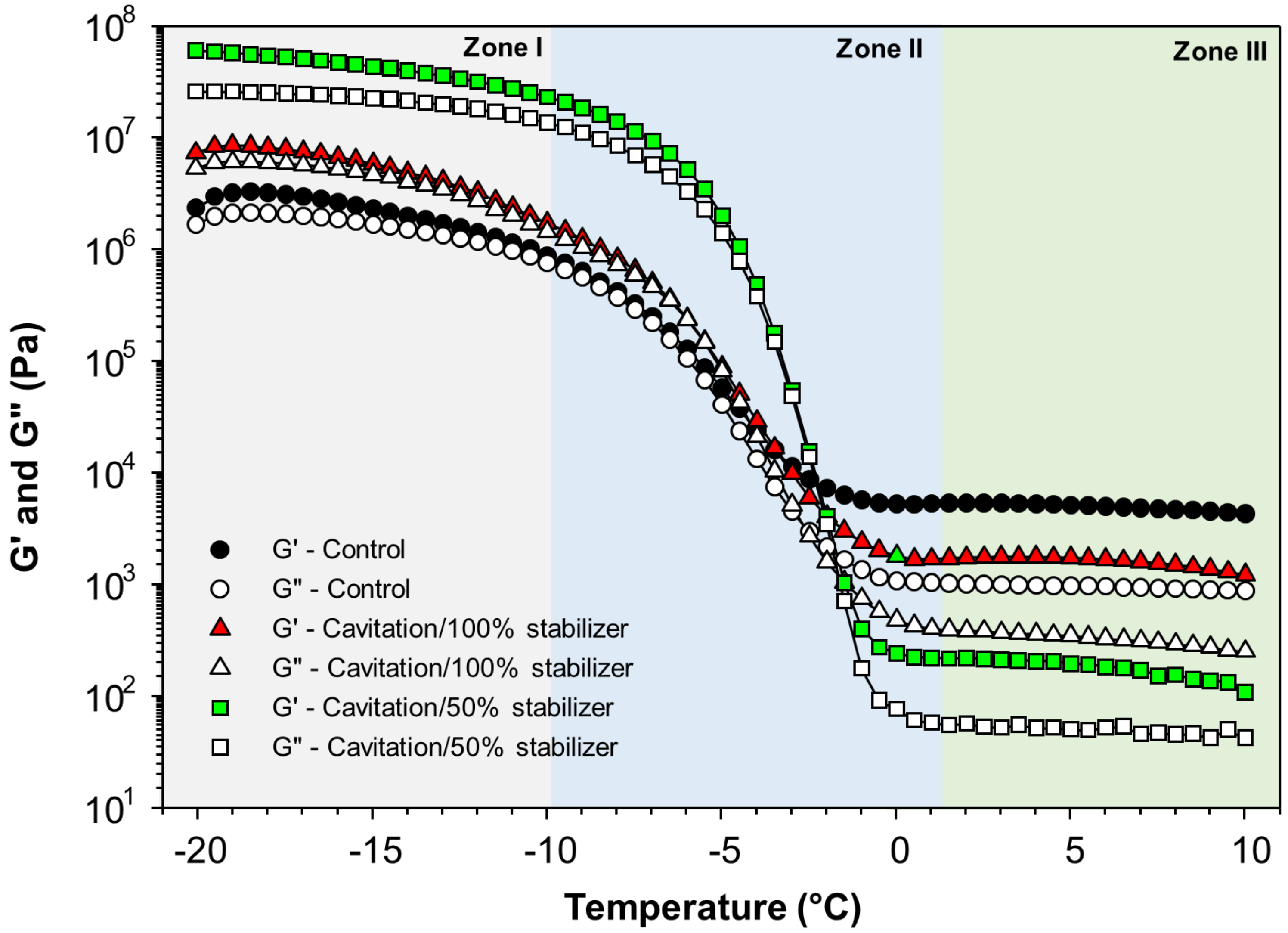


(Sim et al., 2021)


Mixing ingredients
HTST
(85°C for 15 s)
Two-stage homogenization
(2,500/500 psi)
Hydrodynamic Cavitator
(3600 RPM/100 L h-1)
Ice-cream hardening
(-40°C for 24 h)
Packaging
Continuous freezing
(150 L h-1)
Ageing tank
(4°C overnight)
NM STATE

Ice-cream: melting

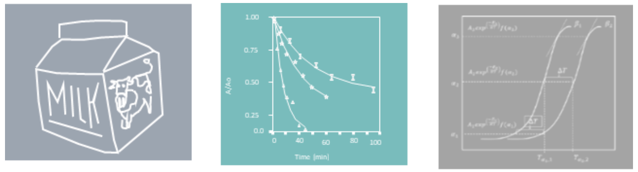


Zone I – samples exhibited some degree of scoopability

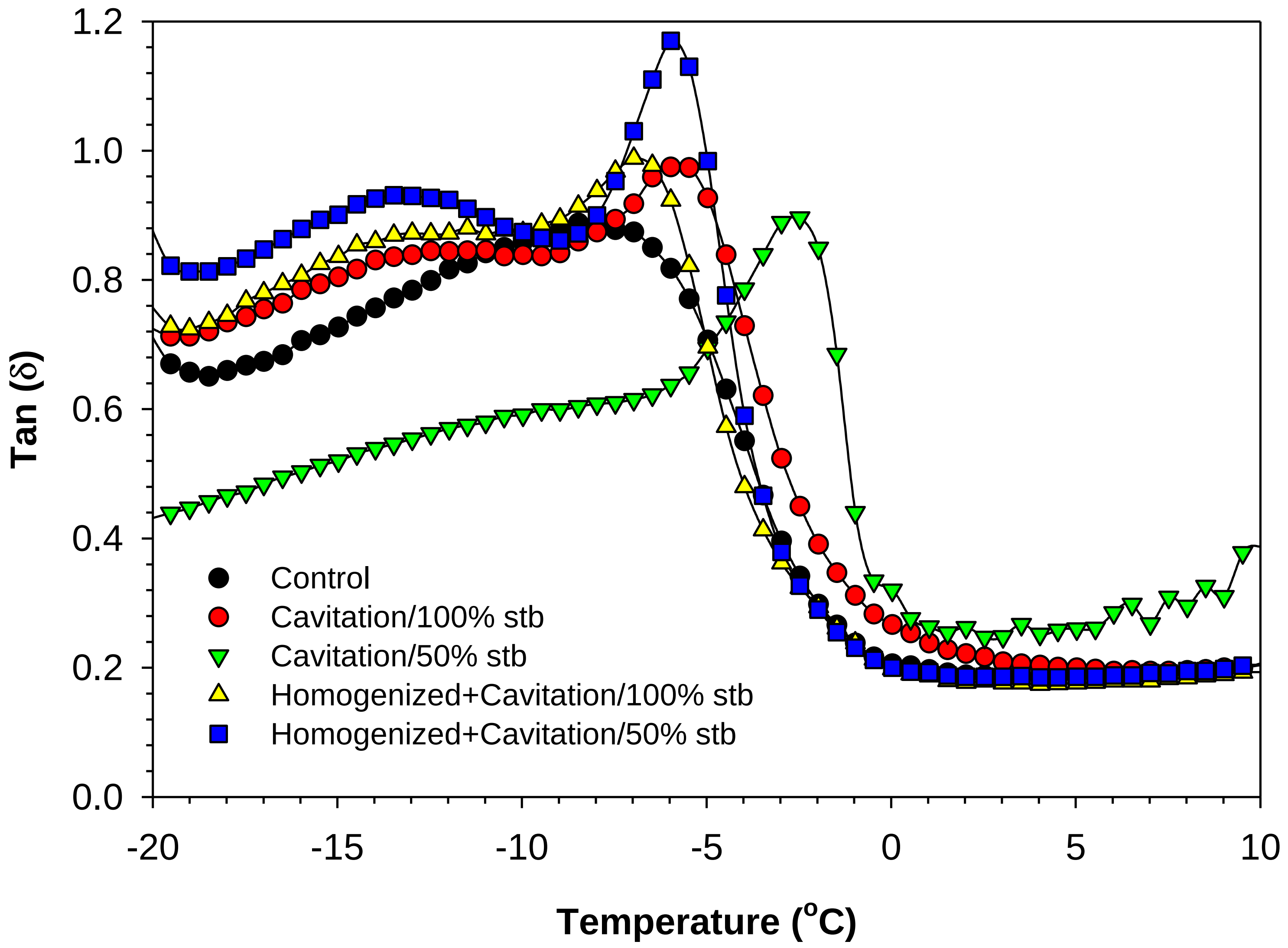
Zone II – samples produced a sharp decreased of the G′ and G"

Zone III – samples exhibited G′ values higher than G",

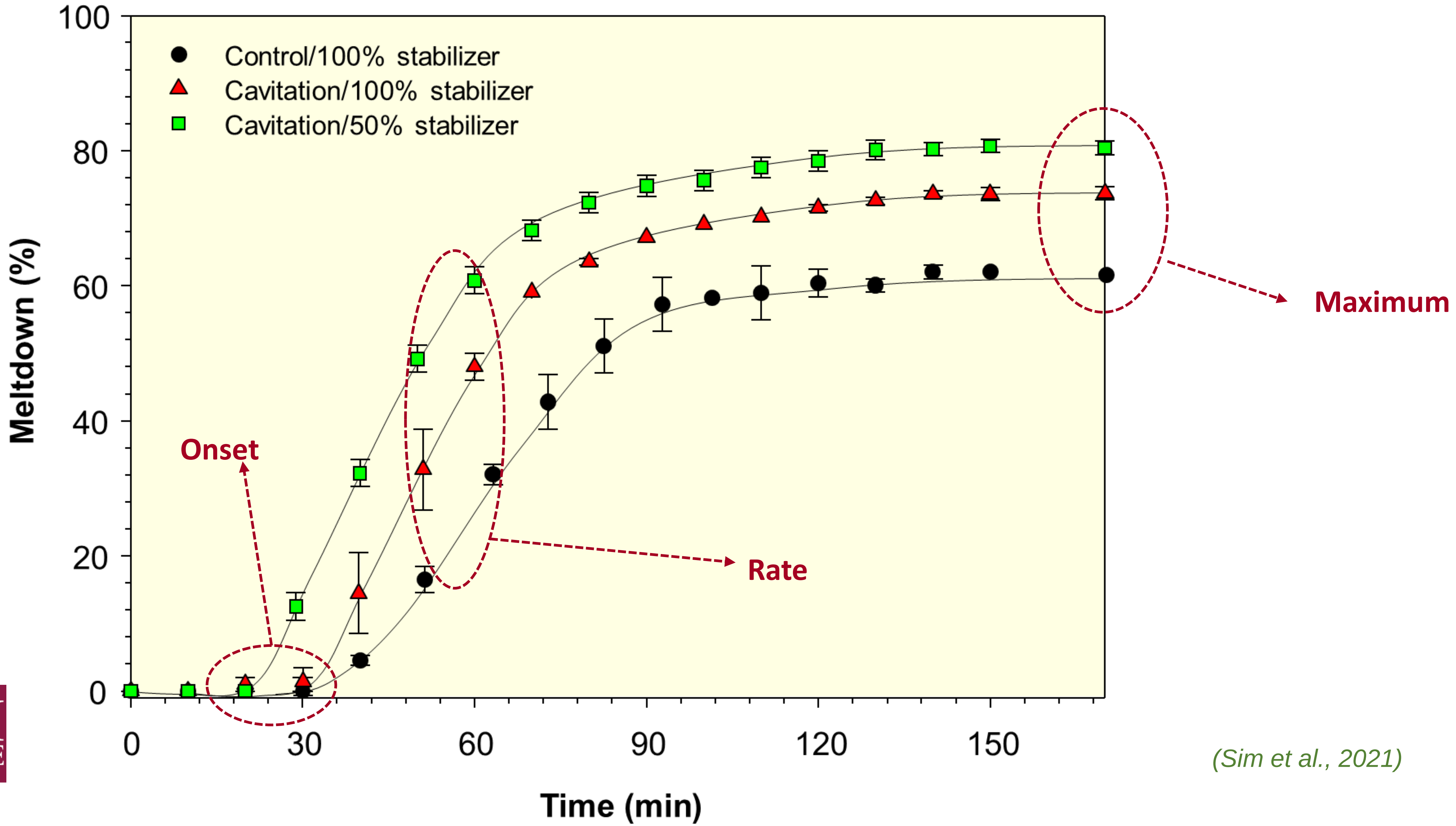
(Sim et al., 2021)



Loss tangent

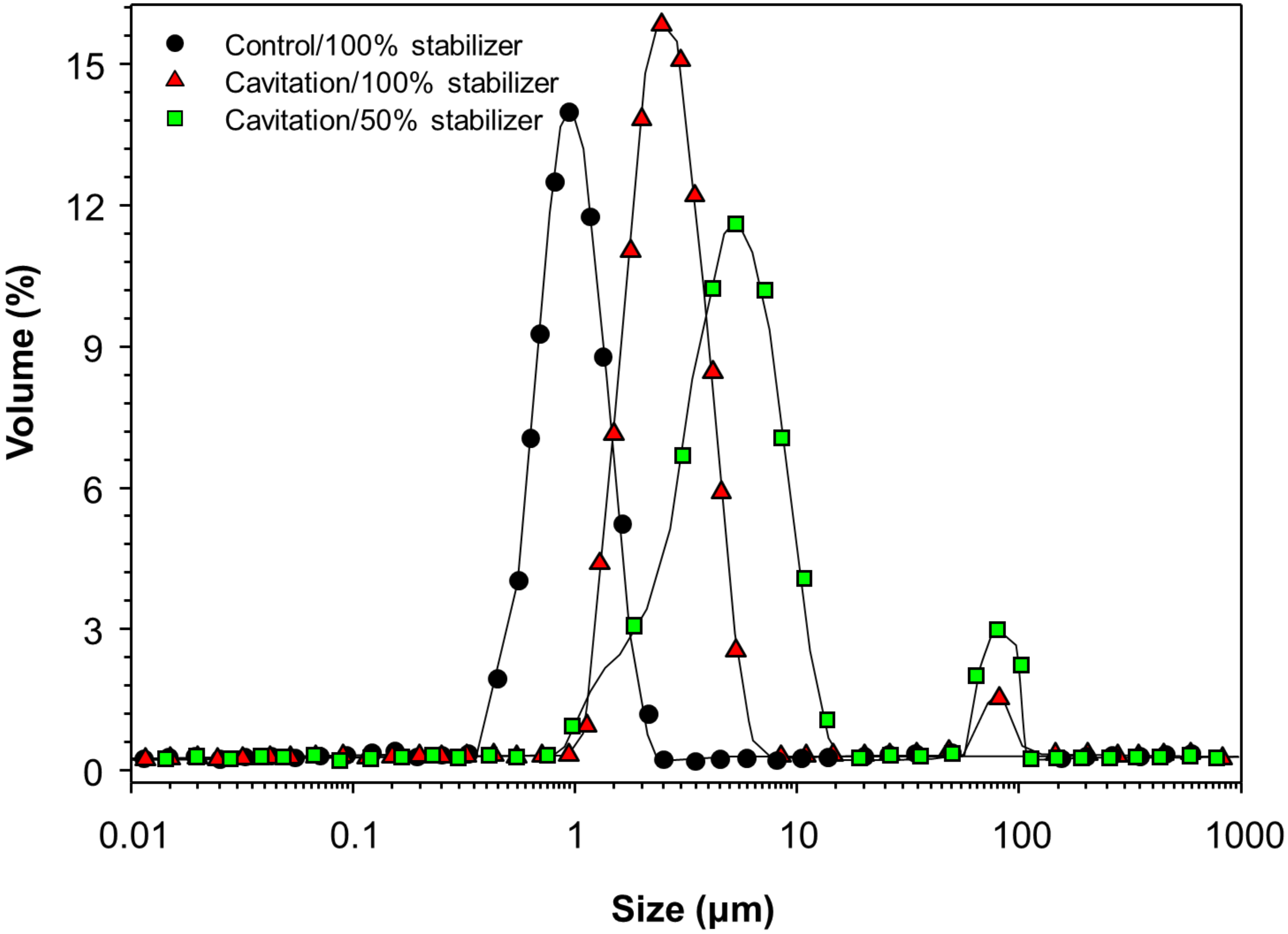


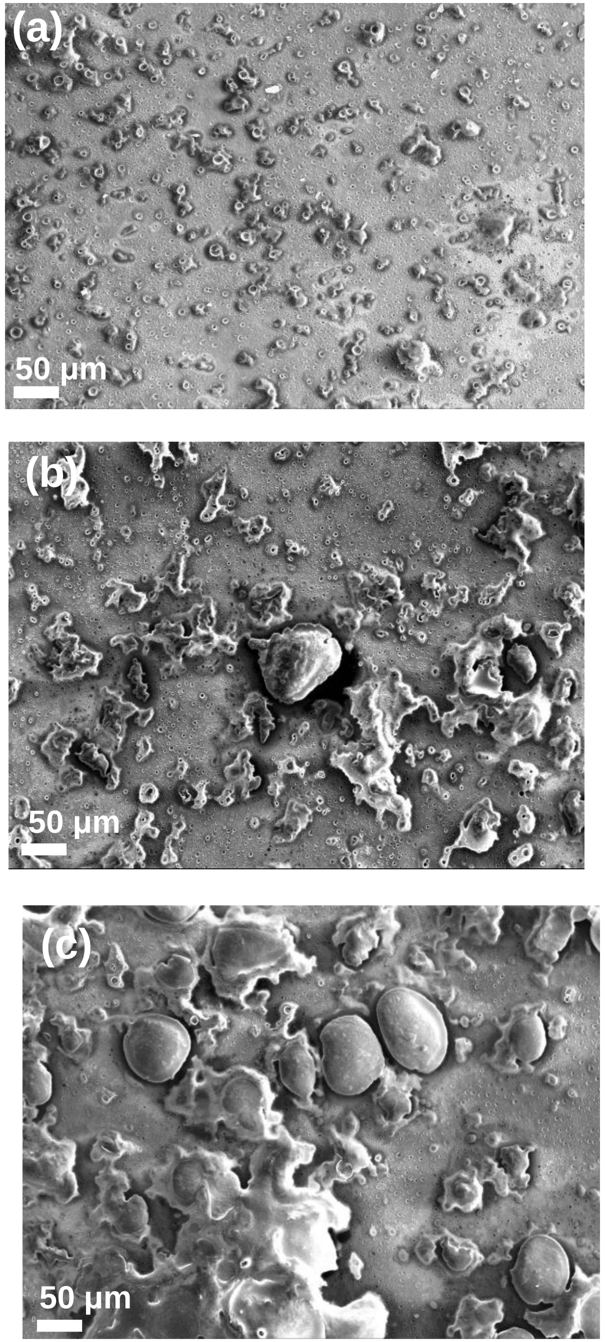
Ice-cream: meltdown

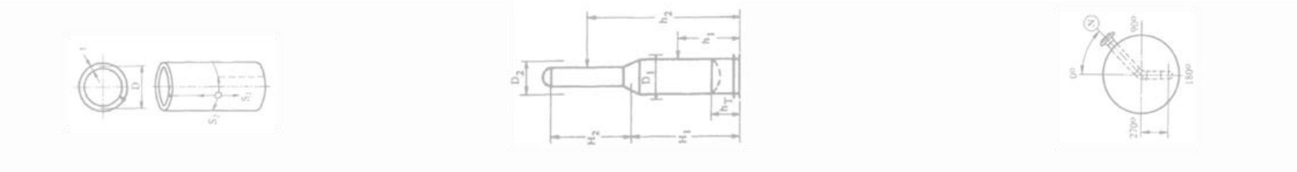


(Sim et al., 2021)

Ice-cream: dripped ice-cream







Presentation layout

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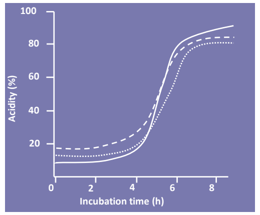
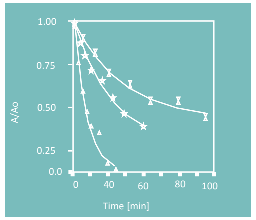
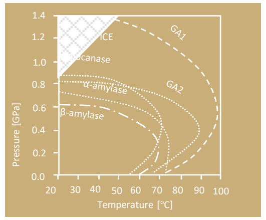
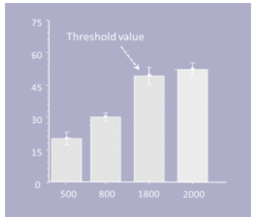
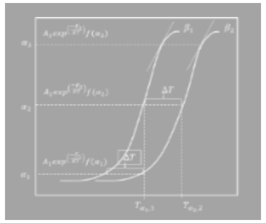
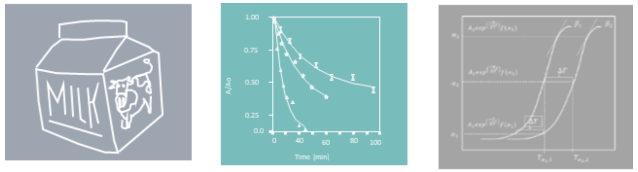






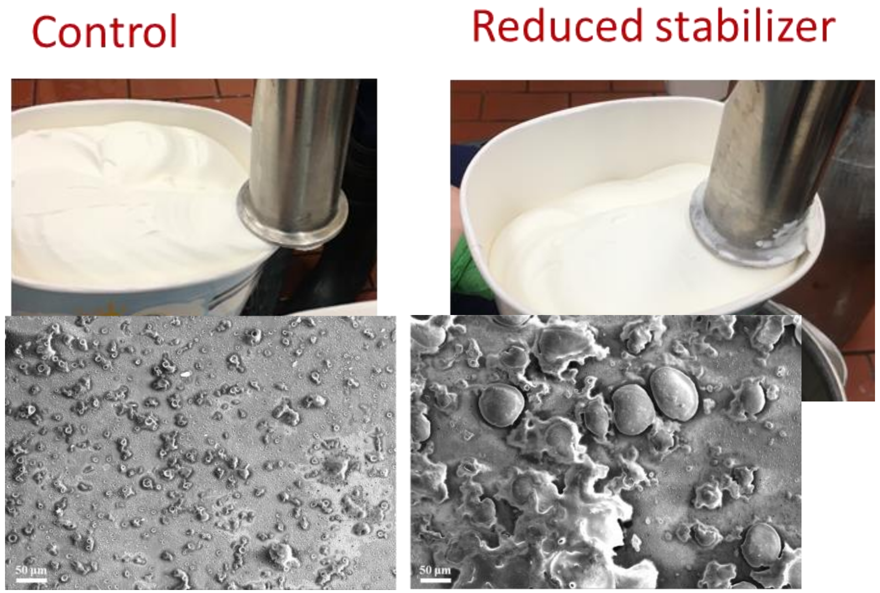


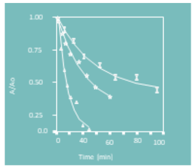
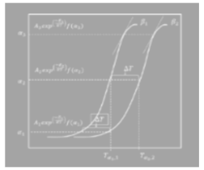




Applications | Ice-cream manufacture

- HC significantly change the flow characteristics compared to the homogenized mixes, from viscoelastic solid to viscoelastic liquid
- Such modifications have a profound effect on the melting and meltdown characteristic
- However, the impact of cavitated mixes on the HC on the crystallization and structure development will require additional research



Challenges | Hydrodynamic Cavitation

- The terminology use within the literature is rather ambiguous. Such ambiguity brings about inaccuracies and misconceptions that negatively impact the development of the technology
- More systematic studies under controlled process conditions are necessary to understand how these phenomena impact product quality and safety
- Studies and concepts of hygienic design are needed, including cleanability, drainability, compatibility, and accessibility
- The geometry and configuration of the cavitator play a major role on how the energy is dissipated

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