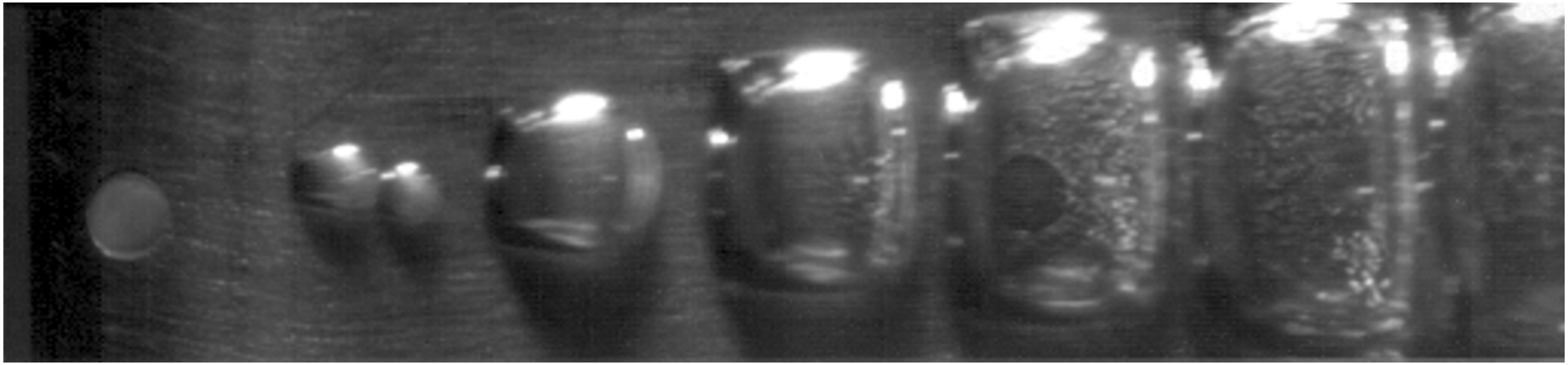
ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE
SECTION DE GENIE MECANIQUE
6th & 8th Semester, Fall 2025

CAVITATION AND INTERFACE PHENOMENA
Chapter 2: Stability and Dynamics of a Cavitation Bubble
2.1: Cavitation Inception and Nuclei Stability



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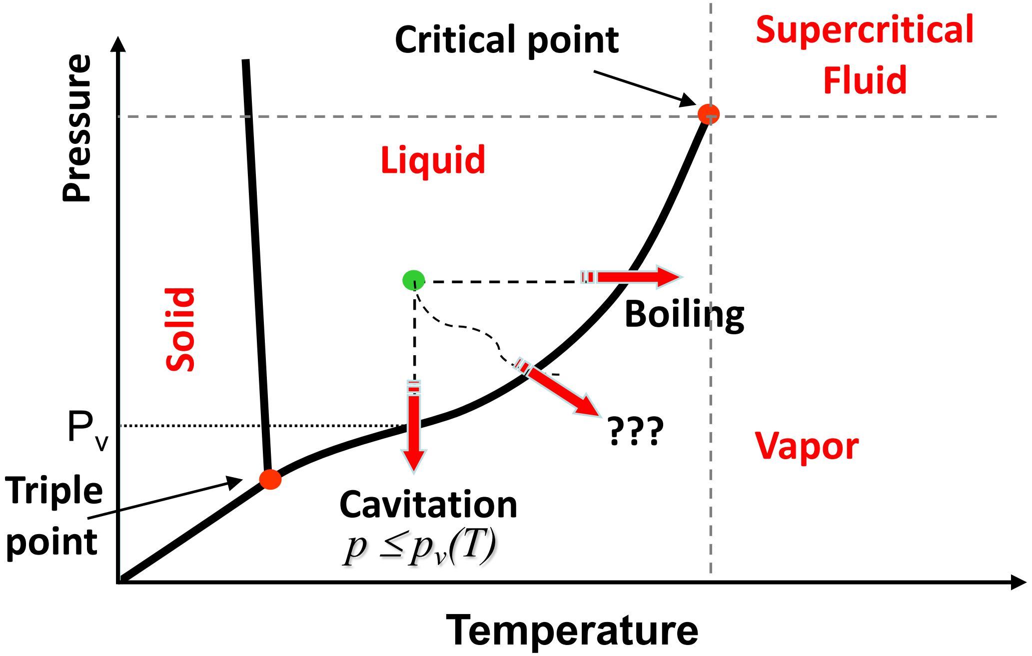
Cavitation Inception

- **Definition (?) : Cavitation is the formation of cavities filled with vapor and gas within a liquid due to a pressure decrease without heat exchange**



For water:

- **Critical point: (373.9 °C; 220.6 bar)**
- **Triple point: (0.01 °C; 6.11 mbar)**

Vacuum pump → Ice + liquid + vapor

- **This simple definition is questionable:**
  - **Vapor may be obtained following different paths !**
  - **Difference between cavitation and boiling is unclear**

Cavitation Inception

- **Cavitation inception is a particular case of the so-called “*nucleation*”**
  - ***In French: Nucléation, Germination***
- **Nucleation is used to describe the onset of the formation of a new thermodynamic phase from a parent phase.**
- **Examples of nucleation processes include the formation of vapor bubbles in a liquid phase, the formation of droplets from a vapor phase, as well as the formation of crystalline particles from vapor, liquid or even another solid.**
- **Nucleation may initiate inside or at the boundary of a homogeneous phase, made unstable because of a change of temperature, pressure or composition.**
- **Nucleation is the formation of “small sites”, called nuclei, upon which additional particles are deposited as the phase transition develops.**
- **Nucleation is a stochastic process, hardly reproducible.**

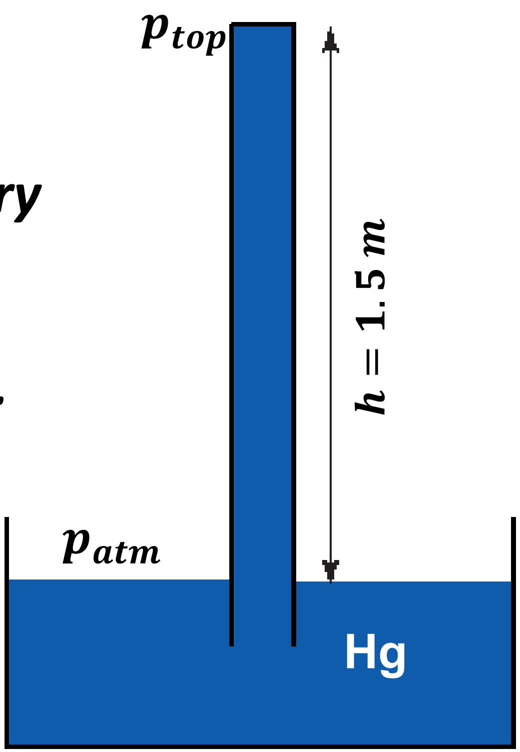
Cavitation Inception

Tensile Strength:

- **Tensile strength for solids: Maximum stress that a solid can withstand while being stretched or pulled before breaking**
- **Tensile Strength for liquids: Although pressure in liquids is widely believed to be a positive quantity, liquids can withstand negative pressure, in a metastable state, because of their molecular cohesion**
- **First experimental evidence by Huygens (1662)**
  - ***A simple experiment with a tube filled with mercury***
    - ***Top end of the tube is sealed***
    - ***Density of mercury 13.6 g/cm*** ^{3}
    - ***Pressure at the top of the tube for*** $h = 1.5\ m$:

$$p_{top} = p_{atm} - \rho g h \sim -1\ atm < 0$$

  - ***If mercury is replaced by water, a same pressure*** p_{top} $(\sim -1\ atm)$ ***is reached for*** $h = 20\ m$



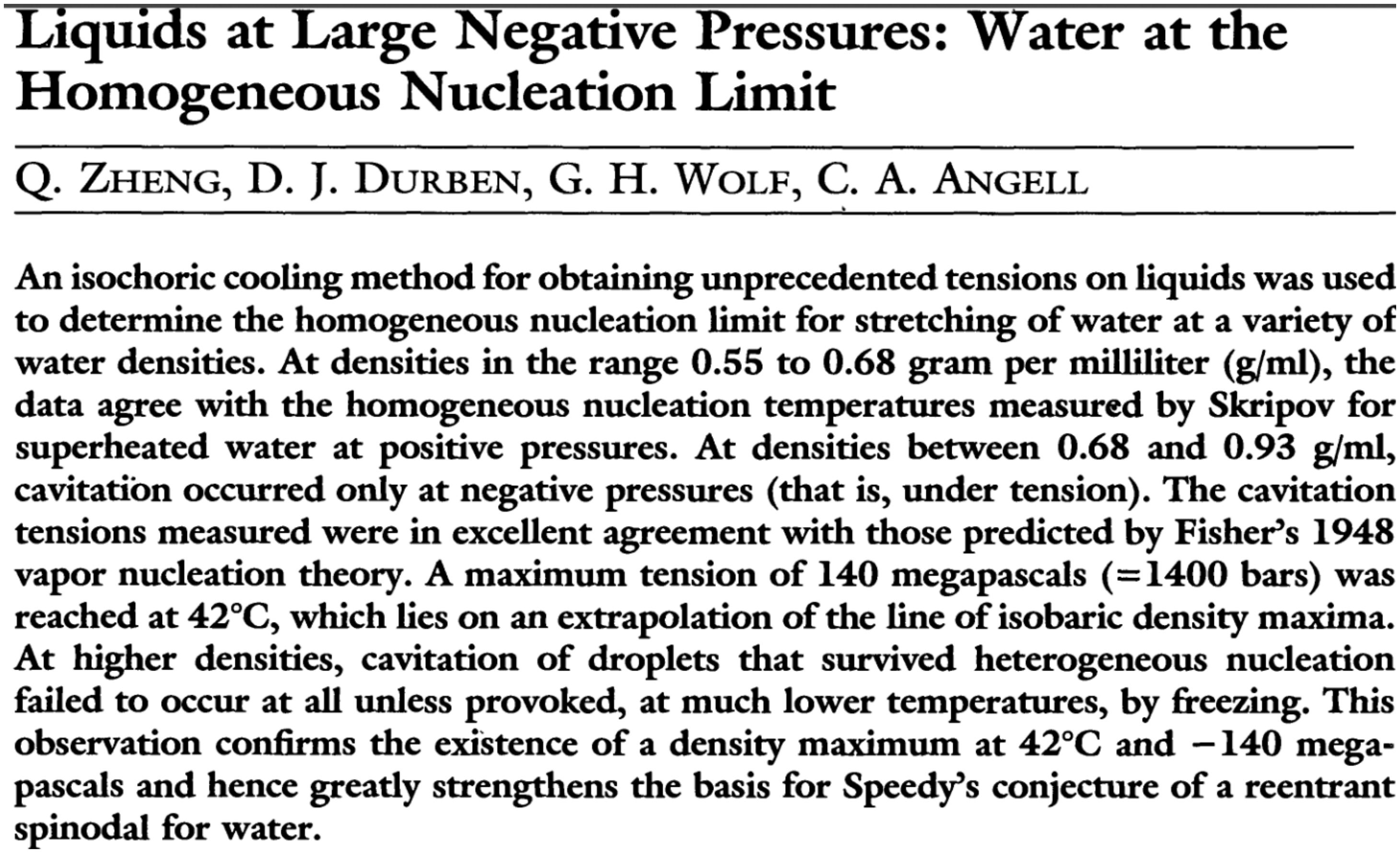
Cavitation Inception

Tensile Strength of liquids:

- Case of water: Absolute pressure threshold for vaporization?
  - Theoretical value for pure water ~ -1400 bar (tension)
  - Laboratory tests: Under specific experimental conditions, highly degassed and distilled water may withstand significant tensions (negative pressure) of ~ several hundreds bar
  - Vaporization threshold strongly depends on experimental conditions

Tensile Strength of Liquids

Tensile strength of water, record of -1400 bar achieved experimentally



Liquids at Large Negative Pressures: Water at the Homogeneous Nucleation Limit

Q. ZHENG, D. J. DURBEN, G. H. WOLF, C. A. ANGELL

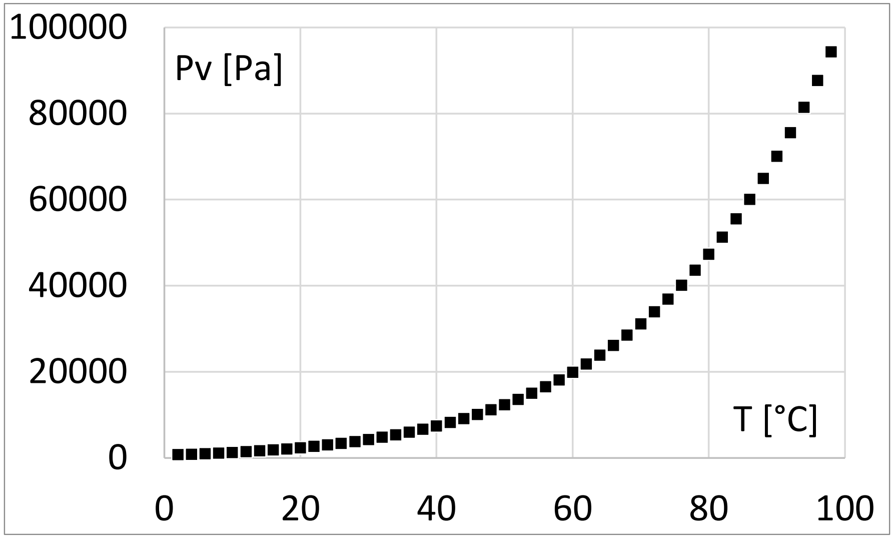
An isochoric cooling method for obtaining unprecedented tensions on liquids was used to determine the homogeneous nucleation limit for stretching of water at a variety of water densities. At densities in the range 0.55 to 0.68 gram per milliliter (g/ml), the data agree with the homogeneous nucleation temperatures measured by Skripov for superheated water at positive pressures. At densities between 0.68 and 0.93 g/ml, cavitation occurred only at negative pressures (that is, under tension). The cavitation tensions measured were in excellent agreement with those predicted by Fisher's 1948 vapor nucleation theory. A maximum tension of 140 megapascals (=1400 bars) was reached at 42°C, which lies on an extrapolation of the line of isobaric density maxima. At higher densities, cavitation of droplets that survived heterogeneous nucleation failed to occur at all unless provoked, at much lower temperatures, by freezing. This observation confirms the existence of a density maximum at 42°C and −140 megapascals and hence greatly strengthens the basis for Speedy's conjecture of a reentrant spinodal for water.

Science, 1991

Tensile Strength of Liquids

- **Case of industrial water:**
  - **Cannot withstand tensions**
  - **Empirical formula for $p_v(T)$: (Antoine's law)**

$$\log_{10}(p_v) = 8.07131 - \frac{1730.63}{233.426 + T}$$



Where, T is the temperature in °C and p_v is the vapour pressure in mmHg

Wide range for vaporization threshold:

-1400 bar for pure water and ~0.023 bar for air-saturated water at 20 °C ??

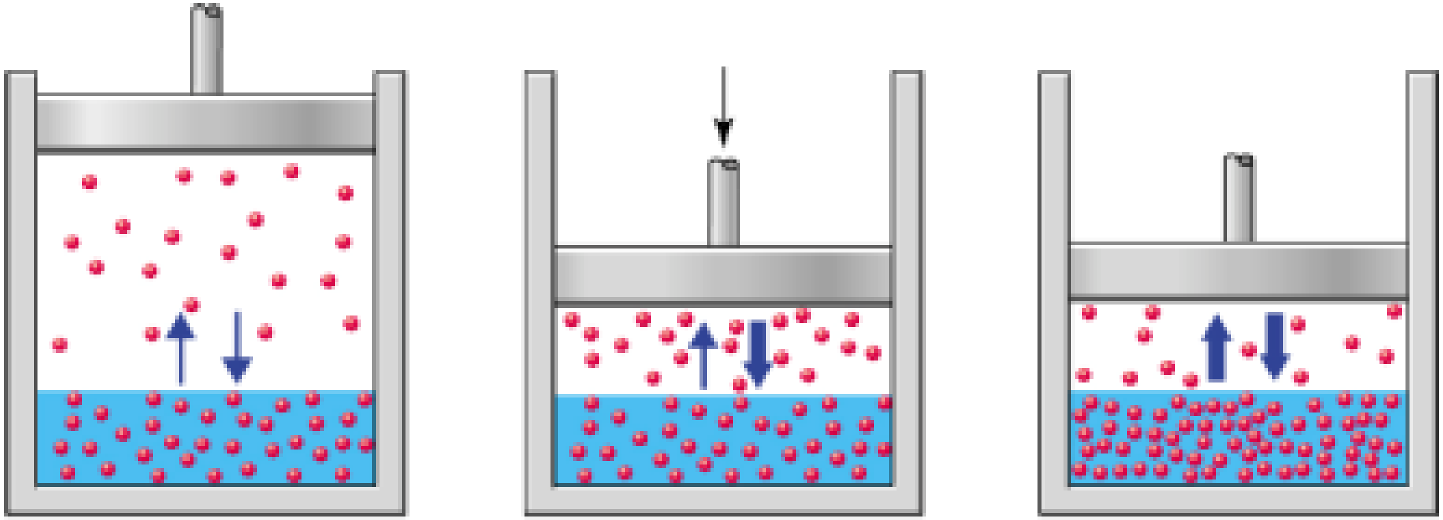
➔Existence of nucleation sites

Cavitation nuclei = Inclusions of non-condensable gas and water vapour

Stability ? Influence on cavitation ?

On the solubility of a gas in a Liquid

- Gas is always present in liquids in the following forms:
  1. ***<u>Dissolved</u>*: Isolated molecules of gas, present between the liquid molecules**
  2. ***<u>Non-dissolved (Nuclei)</u>*: Tiny bubbles filled with gas within the liquid or at the surface of a solid**
- **How much gas can dissolve in a liquid ?**
  - ***Henry's law (William Henry, 1803): At a constant temperature, the amount of a given gas that dissolves in a given liquid is proportional to the partial pressure of that gas in equilibrium with that liquid***



On the solubility of a gas in a Liquid

- **How much gas can dissolve in a liquid ?**
  - **Henry's law:**

$$c = Hp_g$$

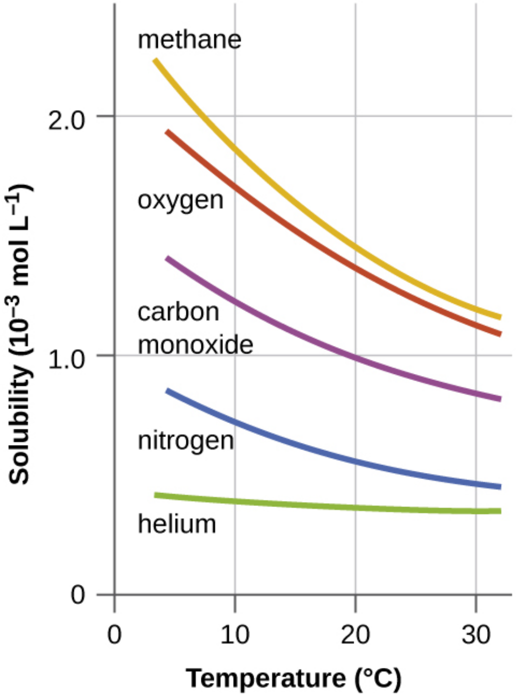
where H is the Henry's constant, which depends on the nature of the liquid and the gas as well as the temperature. c is the solubility of the gas and p_g is its partial pressure in the gas phase.

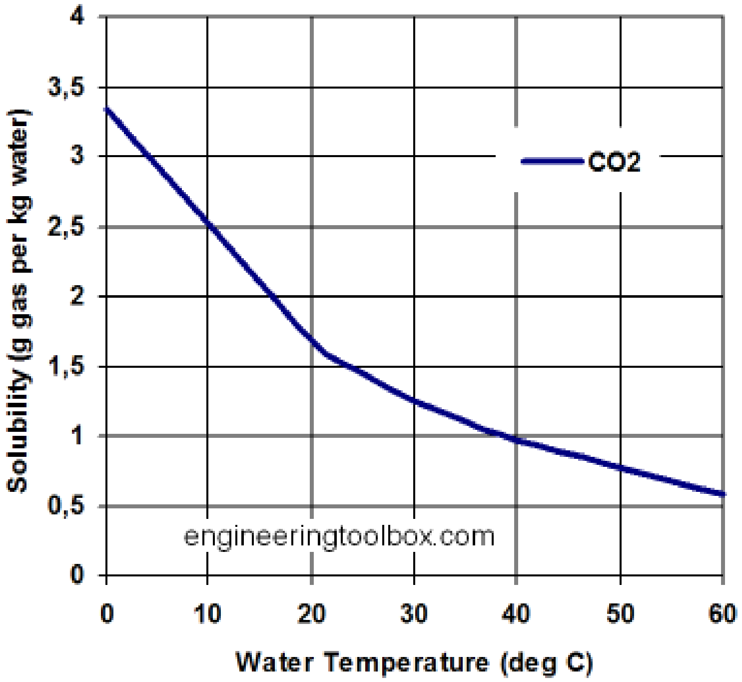
  - **Example: Solubility of selected gases in water:**

Gas	Oxygen	Nitrogen	Hydrogen	Carbon dioxide	Ammonia NH_3
Solubility in water [g/Kg] at 20°C & 1 atm	0.043	0.019	0.0016	1.69 $\sim 40 \times$ more than O_2	529

On the solubility of a gas in a Liquid

- **Effect of temperature on gas solubility**
  - **The solubility of most gases decreases as temperature increases** ***The temperature increase leads to higher kinetic energy of the gas molecules within the liquid. The resulting agitation breaks the intermolecular bonds and the dissolved gas escapes to the gas phase.***



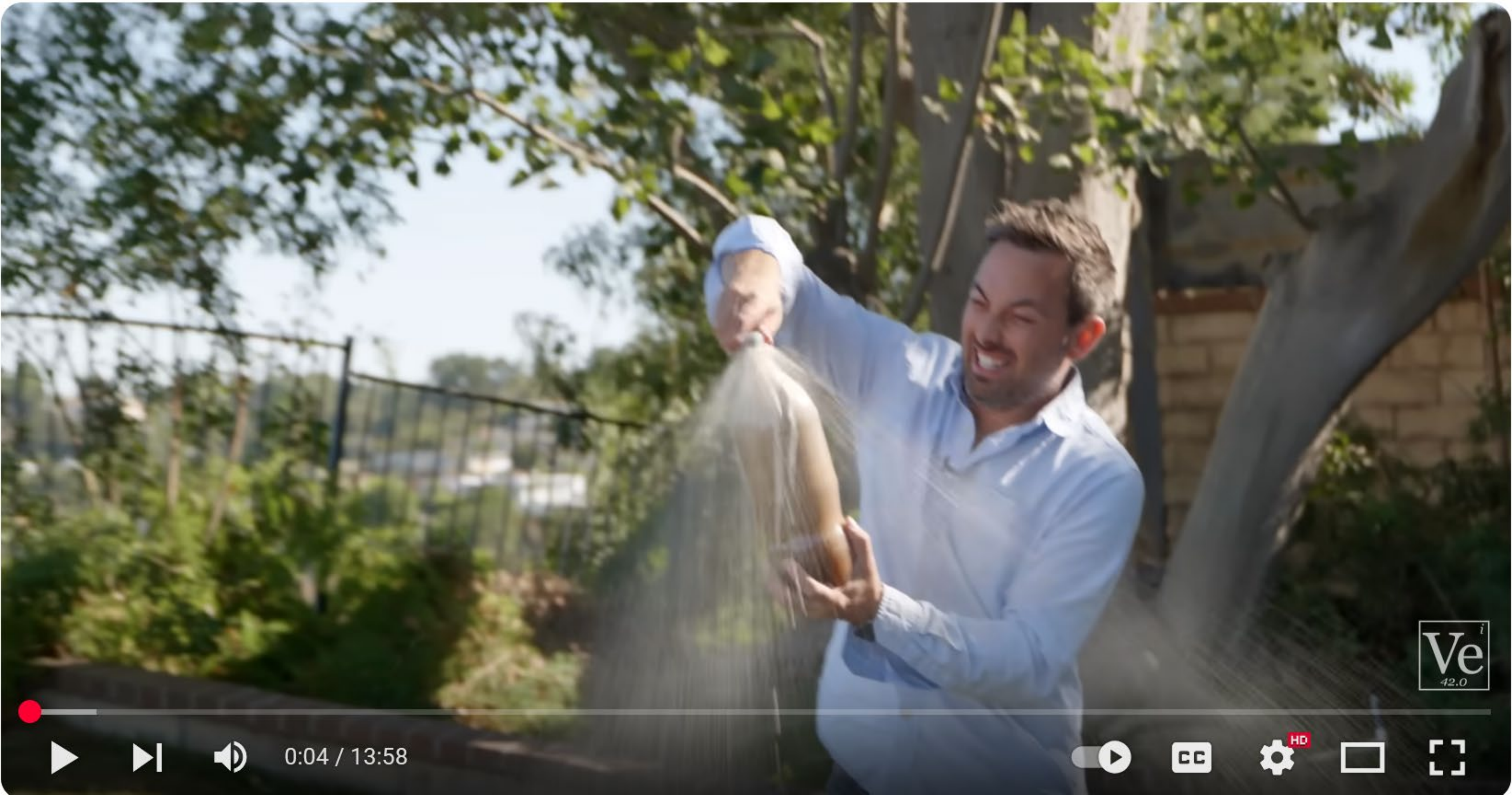


On the solubility of a gas in a Liquid
The fish kills

- **Effect of temperature on gas solubility**
  - **The fish kills: A sudden appearance of dead fish in lakes and rivers because of:**
    - **Human activity: Agricultural runoff, biotoxins, thermal pollution, …**
    - **Natural causes, such as ecological hypoxia (oxygen depletion): Long period of hot weather → Reduction of oxygen in water → Suffocating**

- ***June 2023:***
  - ***Thousands of dead fish washed up on Texas Gulf Coast (Quintana Beach County, USA)***
  - ***US officials: "the dead fish is due to a low dissolved O_2 event" in warm water***
  - ***Calm seas and cloudy skies contributed to the lack of oxygen:***
    - ***Waves are efficient in mixing & oxygenating sea water***
    - ***Photosynthesis by microscopic phytoplankton or macroalgae is another way to produce O_2, using sunlight***

On the solubility of a gas in a Liquid
The case of carbonated drinks: See video



On the solubility of a gas in a Liquid
Diving lizard's built-in "scuba tank" allows it to breath underwater

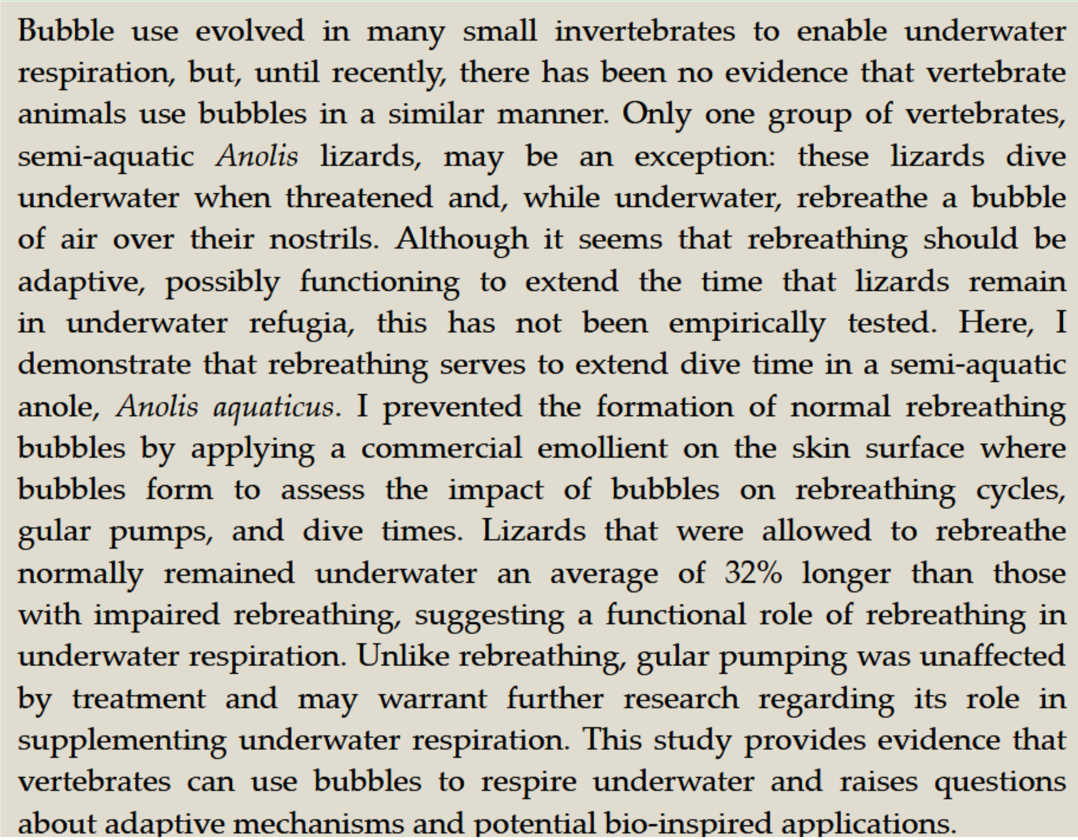
BIOLOGY
LETTERS

royalsocietypublishing.org/journal/rsbl

Novel rebreathing adaptation extends dive time in a semi-aquatic lizard

Lindsey Swierk[1,2]

Biology Letters, 2024



Bubble use evolved in many small invertebrates to enable underwater respiration, but, until recently, there has been no evidence that vertebrate animals use bubbles in a similar manner. Only one group of vertebrates, semi-aquatic *Anolis* lizards, may be an exception: these lizards dive underwater when threatened and, while underwater, rebreathe a bubble of air over their nostrils. Although it seems that rebreathing should be adaptive, possibly functioning to extend the time that lizards remain in underwater refugia, this has not been empirically tested. Here, I demonstrate that rebreathing serves to extend dive time in a semi-aquatic anole, *Anolis aquaticus*. I prevented the formation of normal rebreathing bubbles by applying a commercial emollient on the skin surface where bubbles form to assess the impact of bubbles on rebreathing cycles, gular pumps, and dive times. Lizards that were allowed to rebreathe normally remained underwater an average of 32% longer than those with impaired rebreathing, suggesting a functional role of rebreathing in underwater respiration. Unlike rebreathing, gular pumping was unaffected by treatment and may warrant further research regarding its role in supplementing underwater respiration. This study provides evidence that vertebrates can use bubbles to respire underwater and raises questions about adaptive mechanisms and potential bio-inspired applications.

Cavitation Inception

- Types of Nucleation:

  - Homogeneous nucleation:
    - Formation of isolated vapour bubbles in the liquid far from interfaces
    - Mainly due to the microscopic voids formed randomly within the liquid by thermal motion → liquid rupture and growth of macroscopic bubbles.

  - Heterogeneous nucleation:
    - Occurs on interfaces between the liquid with a solid or a gas
      - Walls, micro particles, micro bubbles
      - Due to the growth of existing and stable micro-bubbles
        - Free micro-bubbles within the liquid
        - Micro cavities attached to solid surfaces (wettability)

  - Cavitation inception is always due to heterogeneous nucleation

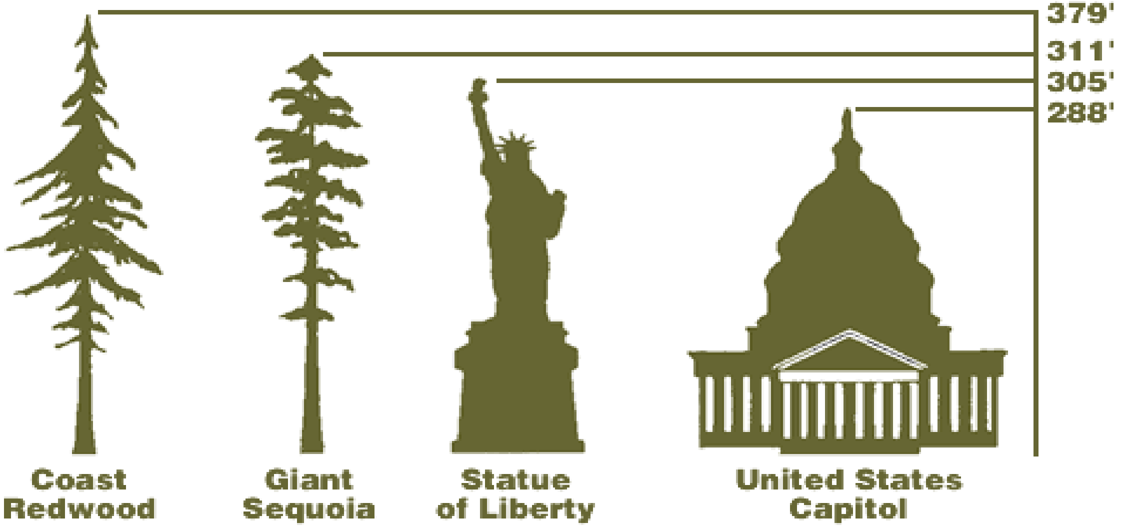
Cavitation Inception

- **Properties of cavitation nuclei**
  - **Origin: complex**
    - **Diffusion:**
      - **Gas exchange across the interfaces**
      - **Very slow process. Characteristic time: ~ seconds - hours**
  - **A little influence on liquid density:**
    - **Example:**
      Nuclei content (of ~100 μm in diameter) = 100 nuclei/cm^3
      → Void Fraction ~ 5.2 10^{-5}
  - **Negligible effects on liquid compressibility (speed of sound)**
  - **Strong influence on the cavitation incipience**

Cavitation Inception

- **Tensile Strength**
  - **Case of water ascent in giant trees**
    - **Giant Sequoia trees may be 115 m high**
    - **Historical record: 135 m (Eucalyptus)**

  - **Sap (Water + Nutrients) is pumped through tiny pipes (Xylem) from the root to the leaves.**
  - **Negative pressure ? (Open question)**



Cavitation Inception

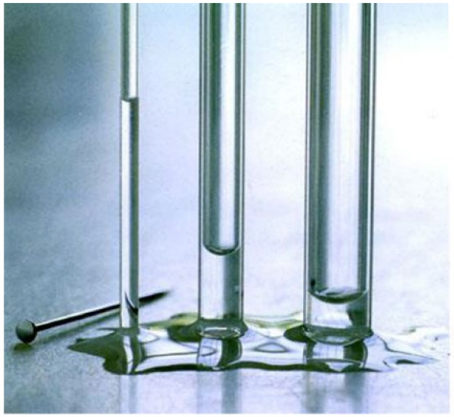
- **Tensile Strength**
  - **Extreme tensile strength of -1 MPa !**
    - **Not compatible with nuclei content of the sap**
  - **Possible explanations:**
    - **Capillarity ? Natural pumping by μ-sized tubes (Xylem):**
      - **Max ~30 m of pumping height (Not realistic)**

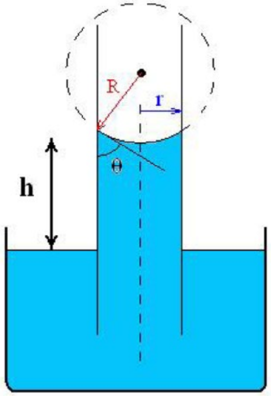
Jurin's Law: $$h = \frac{2\gamma \cos\theta}{\rho g r}$$

γ : Liquid surface tension

ρ : Liquid density

g : Gravity

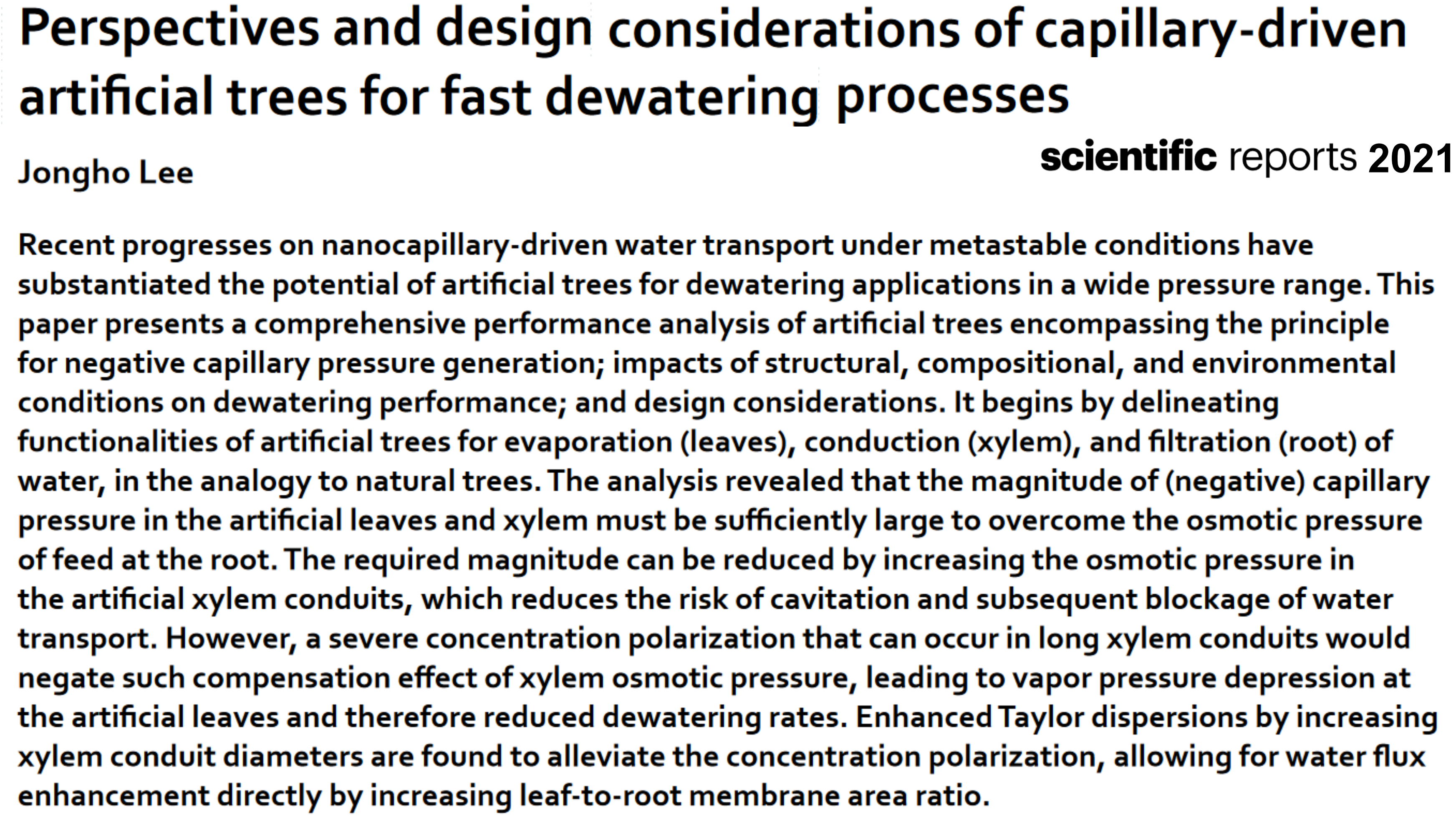




- **Cohesion-Tension theory (Transpiration)**
- **Theory of disjoining pressure (Deriagin pressure):**
  - **Xylem is partially wetted by the sap (thin wetted layer at the wall)**
- **None of these theories is fully convincing.**

Cavitation Inception

- **Application of the pumping ability of tall trees:**



Perspectives and design considerations of capillary-driven artificial trees for fast dewatering processes

scientific reports **2021**

Jongho Lee

Recent progresses on nanocapillary-driven water transport under metastable conditions have substantiated the potential of artificial trees for dewatering applications in a wide pressure range. This paper presents a comprehensive performance analysis of artificial trees encompassing the principle for negative capillary pressure generation; impacts of structural, compositional, and environmental conditions on dewatering performance; and design considerations. It begins by delineating functionalities of artificial trees for evaporation (leaves), conduction (xylem), and filtration (root) of water, in the analogy to natural trees. The analysis revealed that the magnitude of (negative) capillary pressure in the artificial leaves and xylem must be sufficiently large to overcome the osmotic pressure of feed at the root. The required magnitude can be reduced by increasing the osmotic pressure in the artificial xylem conduits, which reduces the risk of cavitation and subsequent blockage of water transport. However, a severe concentration polarization that can occur in long xylem conduits would negate such compensation effect of xylem osmotic pressure, leading to vapor pressure depression at the artificial leaves and therefore reduced dewatering rates. Enhanced Taylor dispersions by increasing xylem conduit diameters are found to alleviate the concentration polarization, allowing for water flux enhancement directly by increasing leaf-to-root membrane area ratio.

Cavitation Inception

Perspectives and design considerations of capillary-driven artificial trees for fast dewatering processes

scientific reports **2021**

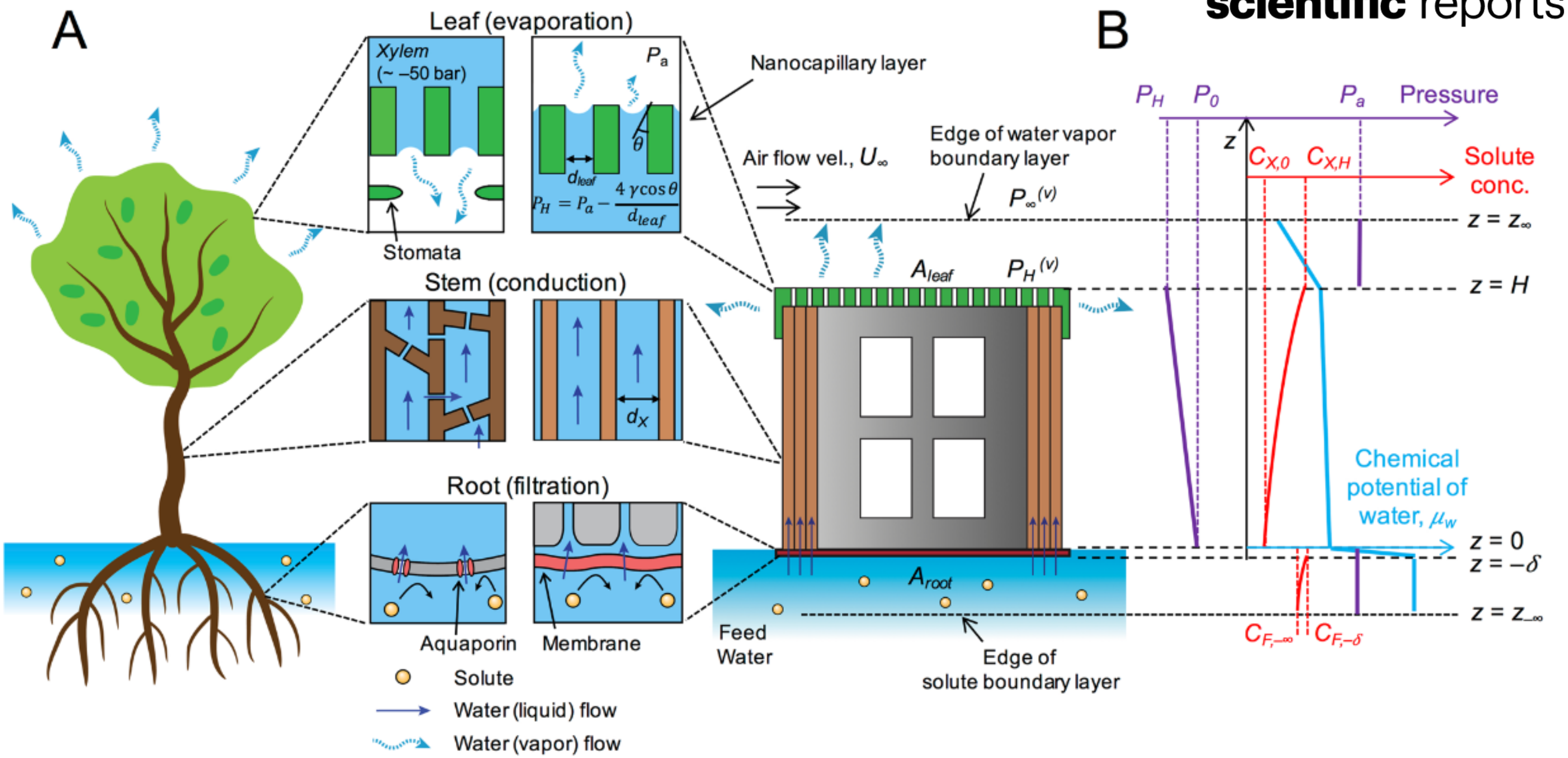
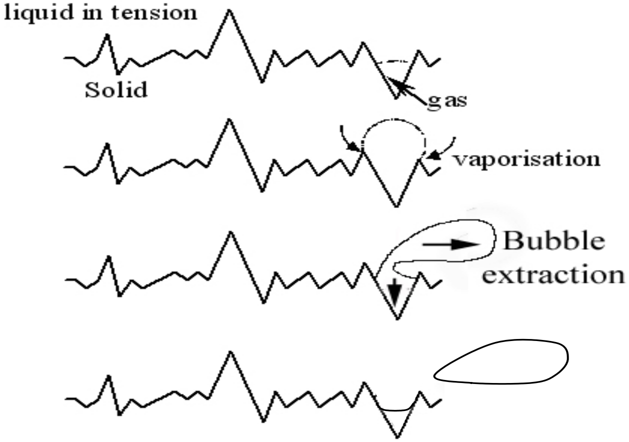


Figure 1. Overview of dewatering process by an artificial tree. (**A**) Schematic illustrations of a natural mangrove tree and an artificial tree for dewatering process, and their similarities in functions: filtration (root), conduction (stem), and evaporation (leaf) of water. (**B**) Distributions of chemical potential of water, pressure, and solute concentration through the artificial tree at different locations.

Cavitation Inception

- **Surface nucleation**
  - **A solid surface is never perfectly wetted**
  - **Illustration of the formation process of cavitation bubbles departing from a roughness element on a 2D hydrofoil**

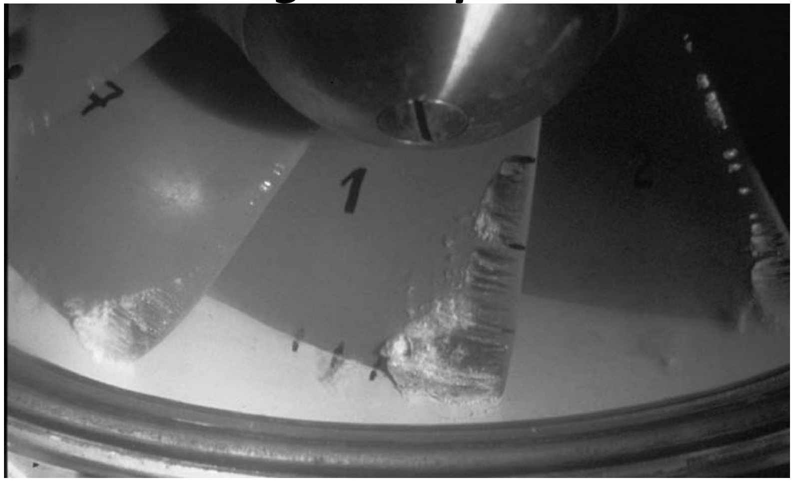


- **Similarity with boiling**

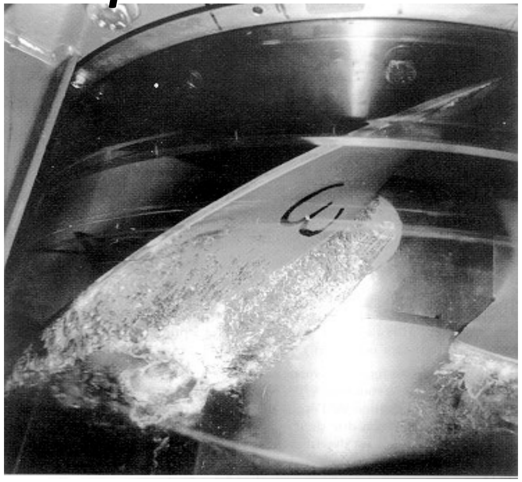
Tensile Strength

- **Surface nucleation**
  - **In industrial applications, cavitation always initiates on solid boundaries**
  - **The gas trapped in roughness elements enhances vaporization and act as nucleation site**

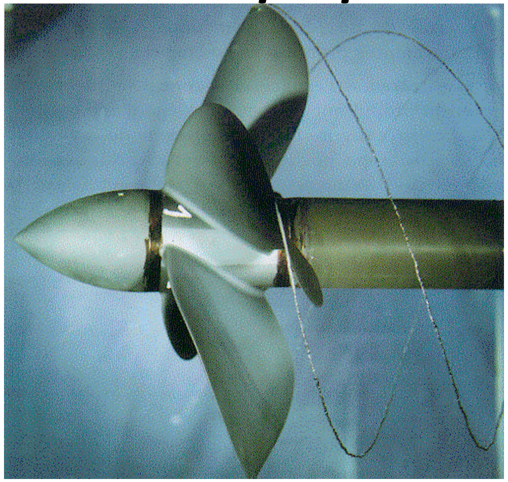
Storage Pump



Kaplan Turbine

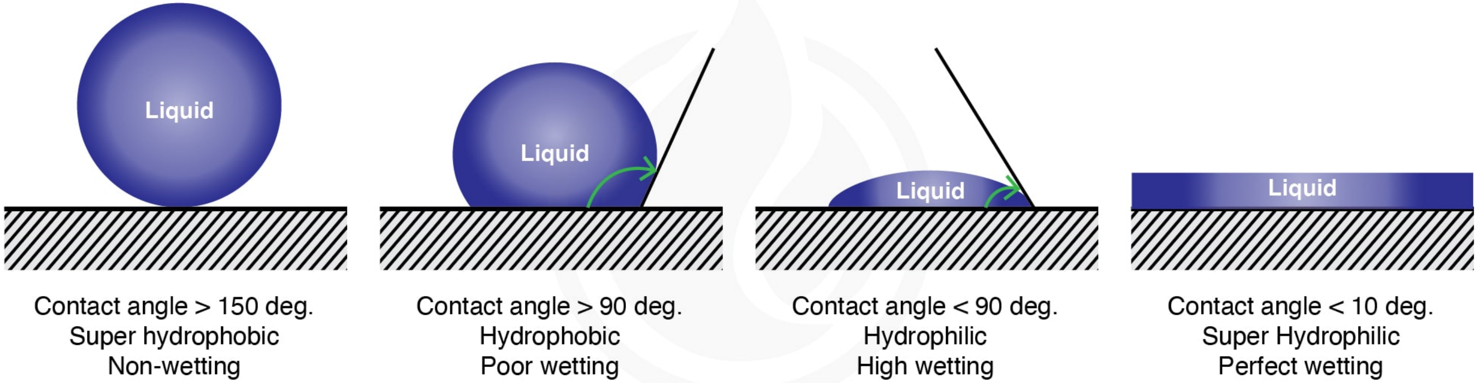


Marine propeller



Surface Tension

- **Surface tension:**
  - **Surface tension is the tendency of liquid surfaces at rest to shrink into the minimum area possible. This is due to cohesive forces between liquid molecules.**
  - **A liquid drop tends to take a spherical shape because at the liquid–air interface, surface tension results from the greater attraction of liquid molecules to each other (cohesion) than to the molecules in the air (adhesion)**
  - **When attractive forces are between unlike molecules, they are called adhesive forces:**
    - **The shape of a liquid drop on a solid surface depends on the balance between cohesive and adhesive forces:**



Contact angle > 150 deg.
Super hydrophobic
Non-wetting

Contact angle > 90 deg.
Hydrophobic
Poor wetting

Contact angle < 90 deg.
Hydrophilic
High wetting

Contact angle < 10 deg.
Super Hydrophilic
Perfect wetting

Static Equilibrium of a bubble in a liquid

- **Blake equation (also called Laplace equation)**
  - **The static equilibrium of a spherical nuclei of radius R, filled with gas and water vapour, reads:**

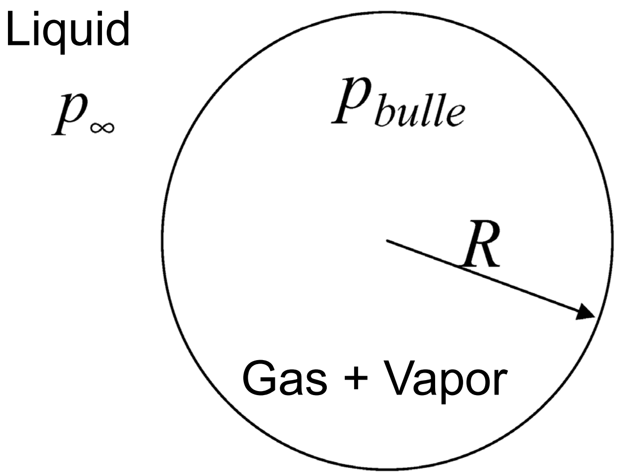
$$\boldsymbol{p_\infty = p_{bubble} - \frac{2S}{R} = p_g + p_v - \frac{2S}{R}}$$

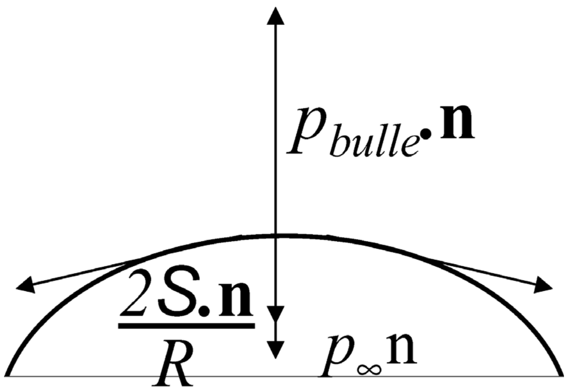
Air-Water Surface Tension:

T=0 °C : $S = 76 \cdot 10^{-3}$ N·m^{-1} ;

T=20 °C : $S = 73 \cdot 10^{-3}$ N·m^{-1} ;

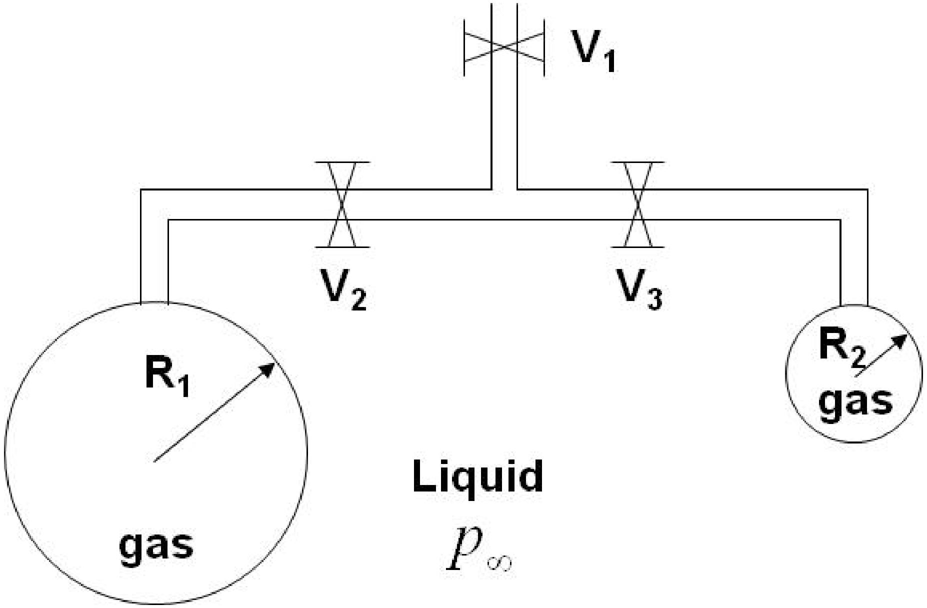
T=37 °C : $S = 70 \cdot 10^{-3}$ N·m^{-1} ;





Static Equilibrium of a bubble in a liquid

- **Exercise:**
  - **We consider 2 cavitation bubbles of radii R_1 and R_2 (with $R_1>R_2$), in a static equilibrium within a liquid at rest (all valves closed).**
  - **Describe the new state when the valves V_2 and V_3 are open (valve V_1 closed).**



Static Equilibrium of a bubble in a liquid

- **Case of a nuclei subjected to small pressure variations**
  - **Slow enough to consider the nuclei in static equilibrium**
  - **Fast enough to neglect gas transfer across the interface**

  - **The hydrostatic pressure difference seen by the nuclei:** $2\rho g R$
    May be neglected when it is small compared to surface tension term
    e.g $2\rho g R \ll \frac{2S}{R} \Rightarrow R \ll \sqrt{\frac{S}{\rho g}} \Rightarrow R \ll 2.7\,mm$
    (always verified for cavitation nuclei)

Initial state: $p_{\infty_0} = p_{g_0} + p_v - \frac{2S}{R_0}$

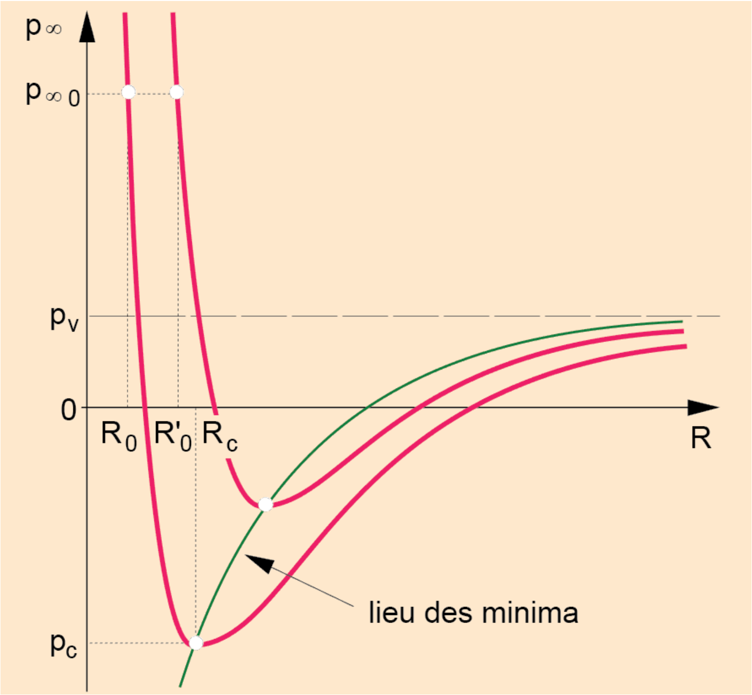
Isothermal transformation $\Rightarrow p_\infty = p_{g_0}\left(\frac{R_0}{R}\right)^3 + p_v - \frac{2S}{R}$

Static Equilibrium of a bubble in a liquid

- **Case of small pressure variations**
  - **The curve $p_\infty(R)$ presents a minimum (R_c, p_c)**

$$R_c = \sqrt{\frac{3p_{g_0}{R_0}^3}{2S}} \qquad p_c = p_v - \frac{4S}{3R_c}$$

R_c : Critical radius, p_c : Critical pressure

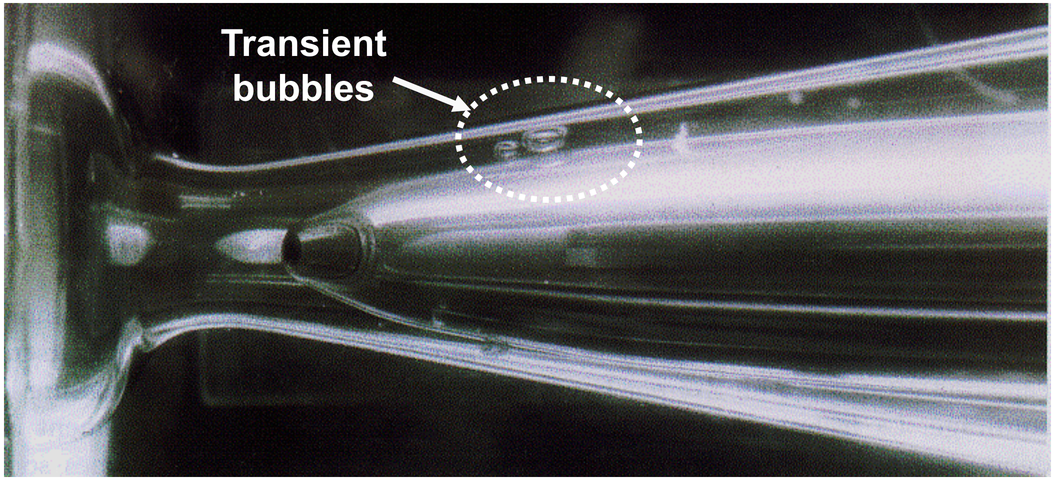


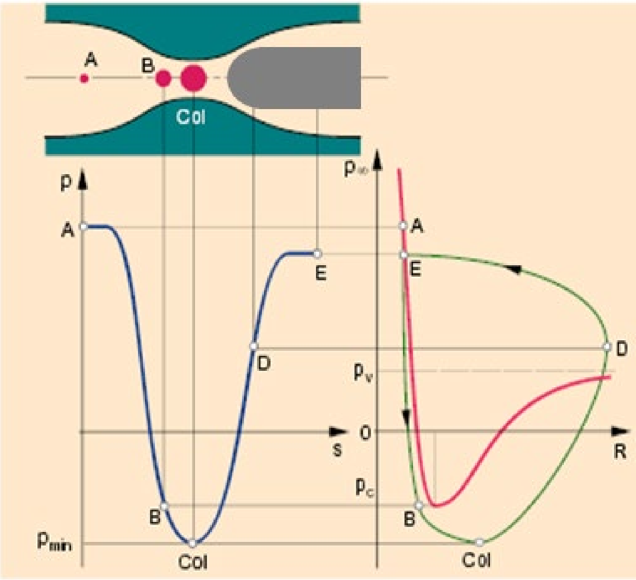
  - **For $R < R_c$, the nuclei remains stable**
  - **For $R > R_c$, the nuclei becomes unstable**

Static Equilibrium of a bubble in a liquid

Application: Measurement of nuclei content with the help of a Venturi tube

- Explosive growth of cavitation nuclei having a critical pressure > pressure in the constriction (throat)
- Pressure at the constriction adjusted with the help of a moving body
- Detection of nuclei passage with a pressure or vibration sensor
  → Histogram of nuclei size





- Drawback: Parasitic cavitation always attaches to the solid boundary (roughness)
- <u>So far, no reliable instrument is available to measure nuclei distribution in a liquid</u>

Static Equilibrium of a bubble in a liquid

Laboratory tools for cavitation nuclei generation (control of nuclei content)

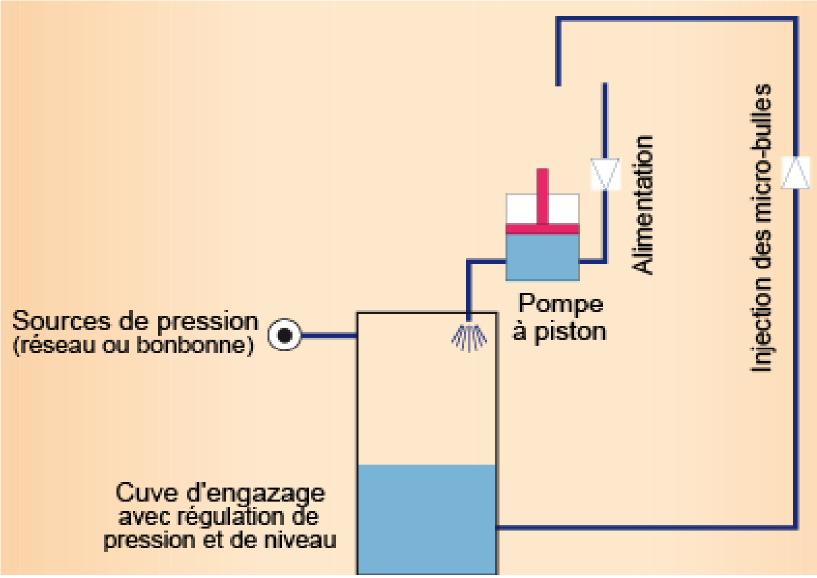
Principle :

Atomization of a liquid jet in highly pressurized tank (~ 5-10 bar)

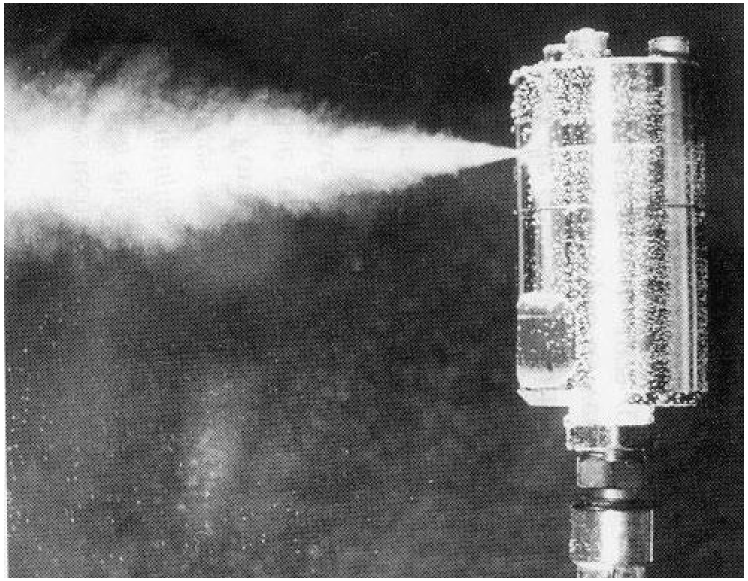
Injection of air saturated water through a thin space between 2 discs

Production of tiny bubbles (~20-50 μm diameter)

Principle of bubble generation



Injector



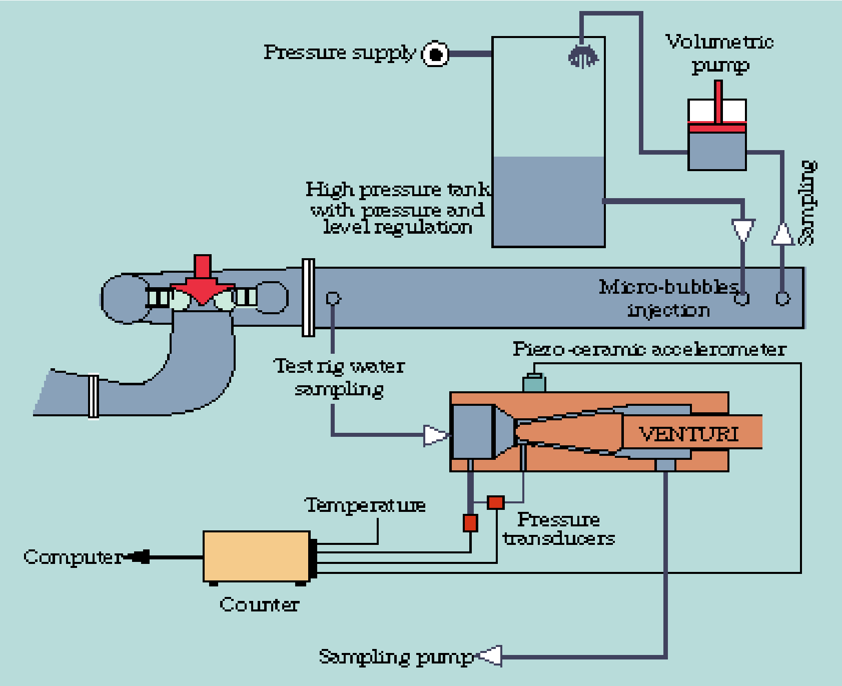
"White water"

Static Equilibrium of a bubble in a liquid

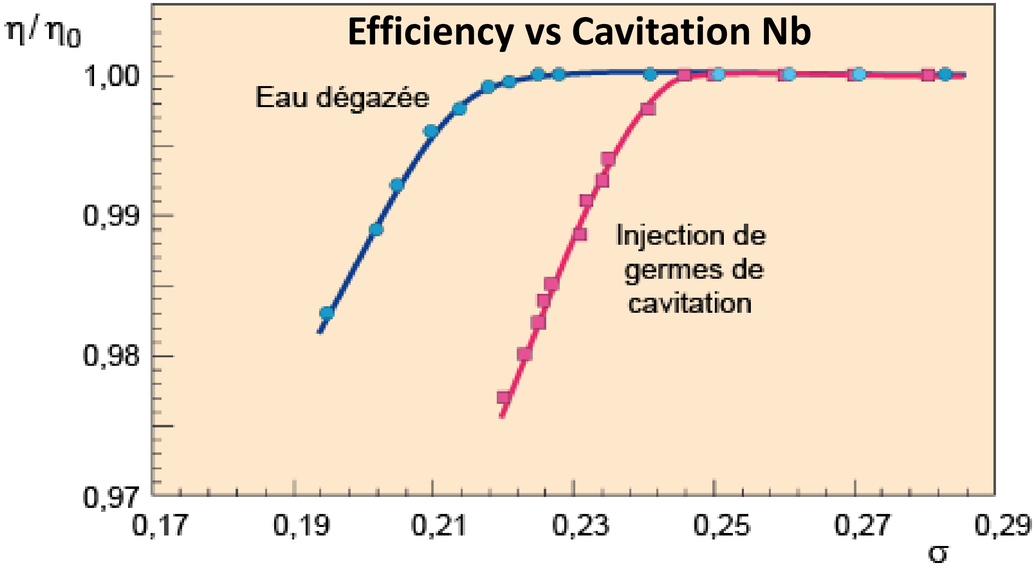
Laboratory tools for cavitation nuclei generation (control of nuclei content)

Usage:

Model tests of hydraulic turbines, pumps and marine propellers (effect on cavitation nuclei on hydrodynamic performances)



Effect of nuclei content on efficiency of a model of Francis turbine



Nevertheless, with the lack of reliable instrumentation for gas content monitoring, model tests of hydraulic machines are always performed with well degassed water