Hydrodynamic Cavitation- Overview and Application in Dairy Sector

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Cavitation is a rapid phase-change event where bubbles form, develop, and burst in a liquid. It can be produced through acoustic, hydrodynamic, optical, and particle mechanisms. Cavitation has various applications in disinfection, cell disruption, sludge treatment, biodiesel synthesis, nano-emulsion production, and degradation of organic compounds. It releases high pressure and temperature, generates reactive free radicals, and enhances mass transfer. Cavitation offers energy-efficient and cost-effective operations when combined with other wastewater treatment techniques, reducing chemical usage. Optic cavitation (OC), particle cavitation (PC), acoustic cavitation (AC), and hydrodynamic cavitation (HC) are four different types of cavitation that may be categorised based on the mechanism of formation as shown in figure 1. Optical cavitation occurs when laser light converges in a liquid, causing localized energy deposit and bubble formation. Particle cavitation refers to cavitation induced by elementary particle beams. Acoustic cavitation utilizes ultrasound to induce pressure changes and chemical alterations. Hydrodynamic cavitation arises from pressure conversion to kinetic energy and flow separation in constrictive parts or irregular geometries.

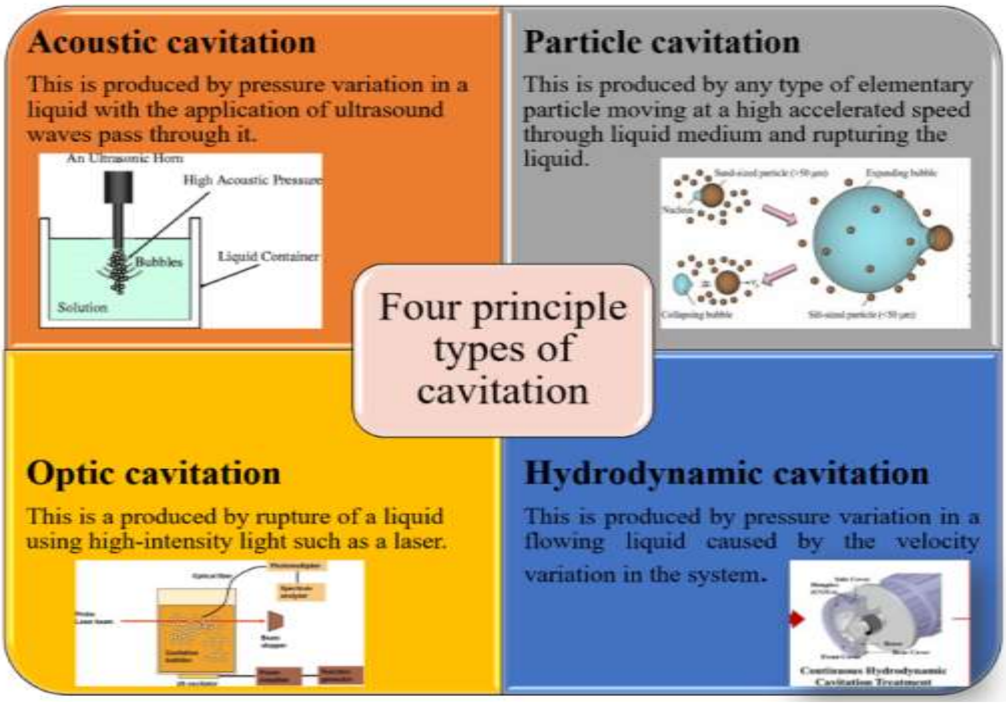
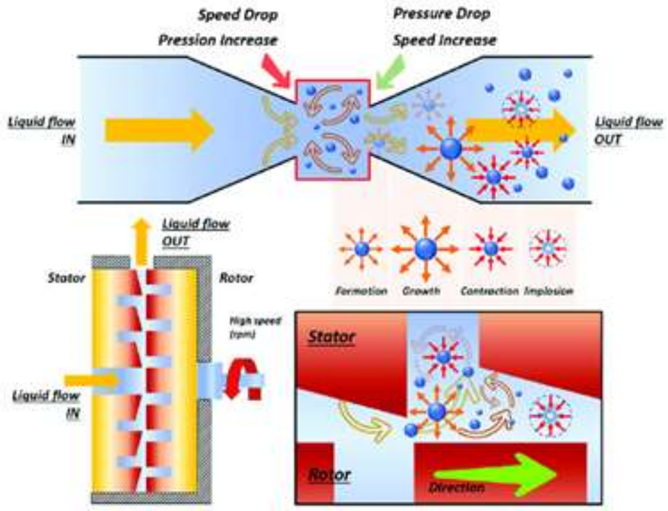


Figure 1: Four principle types of cavitation

Hydrodynamic Cavitation Mechanism

HC can be generated by pressure and flow changes using specific structures such as venturi tubes, nozzles, orifice plates, and rotating-type devices with rotor and stator designs. These structures act as throttle valves, causing an increase in flow rate or kinetic energy at the expense of pressure. Turbulence and boundary layer separation occur, resulting in energy loss. HC is produced by forcing liquid through a small orifice, increasing its kinetic energy. The process involves bubble nucleation, expansion, and implosion. At the vena contracta, the flow area is minimized, leading to a drop in liquid pressure according to the Bernoulli equation.

The flow area is minimized at the vena contracta, leading to a pressure drop as per the Bernoulli equation. Cavities form and expand when the local pressure falls below the cavitation threshold. The size of cavitation bubbles varies based on flow conditions. Throttling causes the pressure at the vena contracta to drop below the threshold, resulting in the release of numerous cavities. These cavities collapse as the pressure further decreases, releasing a sharp shock wave of energy. This shockwave helps control rotor and liquid friction, providing scale-free heating.



(Source: Verdini *et al.*, 2021)

Figure 2: Cavitation mechanism (a) Venturi system (b) Rotor-Stator system

Effect of bubble collapse

A cavitation bubble becomes unstable and starts to collapse once it reaches its maximum size or comes into contact with a significant amount of pressure. Large amounts of energy are released into the surrounding liquids during the collapse in the form of thermal, mechanical, and chemical energy, as depicted in figure 4 (Gogate *et al.*, 2006).

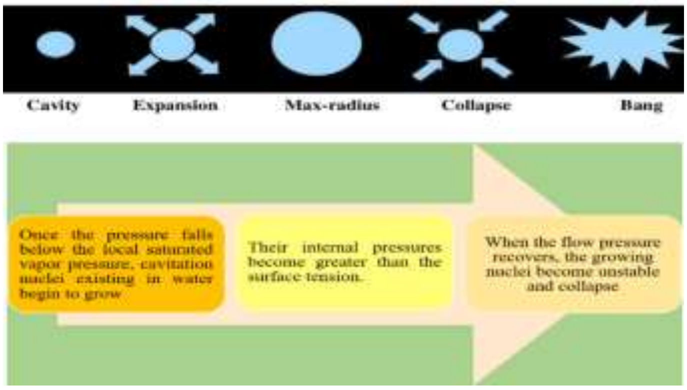


Figure 3: Phenomena of bubble formation and collapse

Mechanical Effect: High shear stress from the collapse of liquids causes shock waves, microjets, and other very damaging mechanical (physical) effects of HC. Rapid changes at the vapor-liquid interface can cause adiabatic compression of bubbles, which can result in shock waves. When the bubble wall reaches the point of maximum compression, it stops expanding and rapidly shrinks. At the start of the emission, high-pressure shock waves with significant nonlinear propagation properties are produced by contracting fluids reflecting back from the bubble interface. The velocity of a shock wave propagating in water is much faster than the speed of sound in water (roughly 1500 m/s), and it can reach pressures of up to 6000 or 7150 GPa, while travelling at speeds of almost 4000 m/s or 2000 m/s on average.

Thermal Effect: The cavitation bubble's gas and vapour are compressed by an implosion or collapse, which produces extreme heat and a local hot spot by raising the temperature of the liquid immediately around the bubble. The little hot spots raise the heating and cooling rates above 1010 K/s within milliseconds and are several thousand Kelvin in temperature. According to Suslick *et al.*, (1999), the heating effect, which is the cause of homogenous sonochemistry, is strongly dependent on the distance from the centre. There are three areas along the line: (i) inside the bubble, where the gas phase can reach its highest temperature of 4600± 200 K; (ii) at the interface, where the thin liquid layer immediately surrounding the collapsing bubble can reach a temperature of 1900 K (Suslick *et al.*, 1999); (iii) The temperature of the bulk medium is not immediately impacted by bubble collapse, though.

Chemical effect: Extreme bubble collapse conditions at the gas-liquid and gas-phase interface can break down dissolved oxygen (O_2) and water (H_2O)

molecules into reactive species such hydrogen atoms (•H), oxygen atoms (•O), hydroperoxyl radicals (HO_2•), and other species. If there is no solute, these main radicals can produce H_2O, •O, and O_2. Hydrogen peroxide (H_2O_2) is created by the recombination of •OH and HO_2• either outside of the hot bubbles or at the cooler interface. Additionally, H and OH species can interact with H_2O_2 to produce HO_2 and OH.

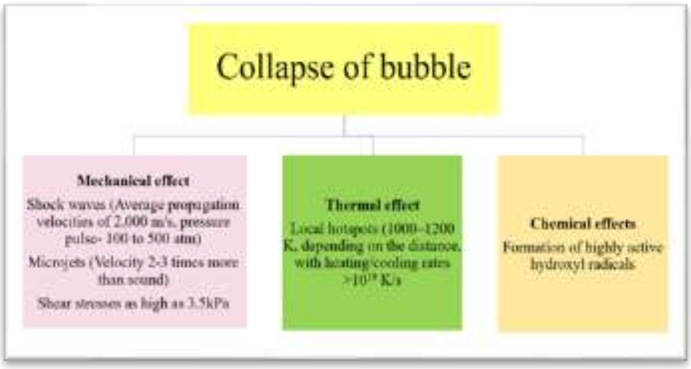


Figure 4: Effect of collapse of bubble

Applications in Dairy industry

HC was used by Milly et al. (2007) to pasteurise and sterilise liquid foods such tomato juice, apple juice, and skim milk by inactivating food spoilage microorganisms. According to their findings, HC introduced into the food chain effectively rendered yeast and lactic acid bacterium spores inactive. In the dairy processing industries, particularly in the production of milk powder, HC has various uses. The efficiency of HC in the inline application for fast rehydration of high protein milk powders for semi-industrial pilot size plant was examined by Pathania *et al.*, (2018); they made a powder dispersion of milk protein concentration and ran it through the HC reactor. The end findings showed that, in comparison to samples that had undergone conventional treatment, the milk protein powder dispersion had a particle size distribution for full rehydration with higher stability to sedimentation. Instant solubilization, wetting, dissolving, and immersion of protein milk powders dramatically reduced the apparent viscosity of the dispersion for HC samples

In the APV Cavitator, the characteristics of milk were examined, including protein interactions, heat stability, acid gelation, casein micelle particle size, and rennet coagulation of skim milk. They stated that the casein micelle particle size of the HC milk drastically changed from the control, and they also discovered that the gel strengths of the HC and conventional milk were comparable. Additionally, the impact on renneting characteristics was favourable. This demonstrated the possibility of HC as an alternative method for heating milk without forming scales in order to make yoghurt with little impact on other crucial milk qualities (Dahiya *et al.*, 2015). According study done by Li *et al.*, (2018), using HC improved the rheological and functional properties of milk protein concentrate while also having no effect on solubility. They recommended HC as an alternative to spray dying process with a positive effect on the rheological properties, such as a reduction in viscosity and elastic modulus of milk protein concentrate.

The ability of HC to recover cheese waste brines while almost eliminating the majority of natural microorganisms has also been demonstrated. The study examined how used brines from cheese production would react to (High Pressure Homogenizer Reactor) HPH at 150 MPa. There was a noticeable decrease in the microbial flora with each pass through the homogenization valve, both with and without temperature control. This lethal impact was caused by the product's exposure to the combined physical and mechanical stresses created by the homogenization valves. Five passes through the homogenization valve were sufficient to completely inactivate native pollutants, and spiked bines treated with the same method also effectively eliminated spoilage and harmful microbes. The effects of HPH on brines used in cheese production are outlined in the paper in explicit terms.

For the first time, the CHC (continuous hydrodynamic cavitation) processing technology was created and effectively used by Sun et al. (2021) to inactivate microorganisms in milk. The CHC treatment temperature was lower (70°C) and the treatment time was shorter (1-2 s) than HTST (71-74 °C, 15-40 s). For E. coli, S. aureus, and B. cereus, respectively, log reductions of 5.89 (100%), 5.53 (100%), and 2.99 0.08 (99.85%) were attained under ideal circumstances, with a production rate of 4.2 L/min and a cost of $0.00268/L. While the safety features of the CHC milk were equivalent to LTLT milk and lower than HTST and UHT milks, the effect of CHC on the nutritional content of milk was comparable to that of HTST. Milk, as well as other liquid food items with "fresh-picked" flavour, may be produced safely, healthily, and nutritionally using CHC as a viable replacement or supplementary technology. Future study is required to better understand how CHC affects bacteria, nutrient levels, and safety, as well as how to optimise CHC devices and procedures.

Conclusion

Hydrodynamic cavitation (HC) technology is an energy-efficient and cost-effective technique with practical industrial applications. It has the potential to enhance and preserve the functional properties of food and beverages in large-scale businesses, as well as in laboratories and pilot scales. However, not all types of cavitators yield favorable results, as the final product depends on the cavitator design and food composition. Further improvements are needed to achieve higher quality products with extended shelf lives. Collaborative research in the food and dairy sector can leverage HC technology for energy-efficient and rapid advancements.

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