Hydrodynamic Cavitation: for Water Treatment

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Nature also utilizes cavitation!

- Use of Snapping Shrimp for actually visualizing hydrodynamic cavitation technique
- Study carried out at University of Twente, The Netherlands, indicated that the Snapping shrimp throws a cavity, which travels a certain distance and collapses.
Measurements using hydrophone indicated that the pressure pulse generated at the collapse is capable of carrying out physical or chemical transformations (Versluis et al., Science, Vo. 289, 2114-2117 (2000)).
Replicate Nature !!!

- Aim of hydrodynamic cavitation reactors will be to replicate this natural phenomena but at multiple locations simultaneously.
- Earlier investigations dealing with hydrodynamic cavitation have been mainly directed towards avoiding it e.g. cavitation erosion of propeller blades of ships.
- Concentrated efforts by few research groups worldwide have led to harnessing the positive effects of hydrodynamic cavitation.
Principle of generation

- Throttling valve
- Single hole orifice
- Multiple orifice plate

Turbulent fluctuating pressure field

Hydrodynamic cavitation

- Venturi
- High speed homogenizer
Key Effects in the Cavitating zone

- Localized intense Pressure & Temperature conditions
- Concentrated energy at the location of transformation
- High intensity turbulence, Increased transport coefficient
- highly reactive free radicals

Order of magnitude **reduction in energy requirement** for physical/chemical transformation
Engineers Job

Control the Phenomena

and

Use the Effects in Positive Way
Hydrodynamic Cavitation Reactors contd...

- Reservoir
- Centrifugal Pump
- Orifice plate (different configurations in terms of number and diameter of the holes)
- Bypass line (for controlling the inlet pressure and the flow rate into the cavitation chamber)
- Cooling water jacket

P1, P2 = Pressure Gauges; V1, V2, V3 = Control Valves

Schematic representation for experimental setup for the orifice plate hydrodynamic cavitation reactor
An orifice plate is characterized by

- Free area (flow area)
- Perimeter of the holes (shear layer)
Hydrodynamic cavitation

Applications
- Enzyme recovery, Microbial cell disruption
- Water & wastewater disinfection
- Oxidation of pollutants
Enzyme recovery

Cell Disruption

- Experiments with Invertase, Penicillin acylase and yeast Saccharomyces cerevisiae indicate
  - orifice plate setup gives order of magnitude higher yields
  - followed by High pressure homogenization &
  - least is obtained for Sonication

- For equivalent protein concentrations in liquid, Magnitudes of energy inputs:
  - Mixer-blender system = 900 J/ml
  - Ultrasonic Horn = 1500 J/ml
  - Pump setup (Hydrodynamic cavitation) = 15 - 20 J/ml
Cell Disruption

The extent of cell disruption in cavitating flow loop increases with:

- an increase in the number of passes
- an increased pressure drop across the constriction
- an increased suspension temperature and
- a decreased biomass concentration

**Location factor** is another important concept which decides the **location of the desired enzyme** in the cell and the type of **cell breakage mechanism** to be applied to get maximum results from the system.
Enzyme recovery

- Extent of enzyme release for various cavitation numbers

Balasundaram & Harrison, Biotechnology and Bioengineering, 94(2) (2006), 303-311
Microbial disinfection

Bore well water disinfection

- Pump with Power consumption of 5.5 kW; Speed of 2900 rpm.
- The cavitating valve is ball type made of SS.
- 75 L of bore well water
- Discharge pressure used - 1.72, 3.44 and 5.17 bar
- Multiple hole orifice plate placed along the flow of liquid.
- The orifice plate had 33 holes of 1 mm diameter and the effective flow area was 25.92 mm²
Bore well water disinfection

Effect of orifice plate on Total coliforms
Initial count=50-65 Total coliforms/100ml,
Vol. treated=75L
Microbial disinfection contd..

Bore well water disinfection

Hydrodynamic cavitation coupled with H₂O₂ disinfection
Microbial disinfection contd..

Bore well water disinfection

Hydrodynamic cavitation coupled with Ozone disinfection

**Hydrodynamic cavitation (5.17 bar)**

**2 mg/l O₃**

**Hydrodynamic cavitation (5.17 bar) + 2 mg/l O₃**
Sea water disinfection

Extent of killing of various microorganisms in multiple holes sharp edge orifice plate

Orifice plate
Fraction of open area = 0.75
Flow rate = 1.3 lit/s
Pressure = 3.2 kg/cm²
Hole dia. = 2 mm
Pipe dia. = 21.5 mm
Sea water disinfection

**Effect of operating parameters**

**Orifice plate**
- Fraction of open area = 0.25
- Hole Dia = 2 mm
- Pipe Dia = 21.5 mm

<table>
<thead>
<tr>
<th>Case</th>
<th>Orifice velocity (m/s)</th>
<th>Pressure (kg/cm²)</th>
<th>Number of Recirculation (cumulative)</th>
<th>Energy (kw.hr)</th>
<th>Energy per unit volume (kJ/lit)</th>
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<tr>
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<td>2</td>
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<tr>
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<td>21.6</td>
<td>4</td>
<td>525</td>
<td>0.595</td>
<td>214.42</td>
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</tbody>
</table>
Oxidation of pollutants

- Hydrodynamic cavitation for oxidation of Nitro-phenols

Oxidation of pollutants contd…

- Hydrodynamic cavitation coupled with Fenton’s process

Chakinala, Gogate, Burgess & Bremner, Ultrasonics Sonochemistry 15 (2008) 49–54
Oxidation of pollutants contd…

- Hydrodynamic cavitation for degradation of Chlorocarbons

Modeling of Cavitation
Solution to Bubble Dynamics equations

\[ C_V = \frac{P_2 - P_V}{\frac{1}{2} \rho V_O^2} \]

Pressure recovery with turbulence
Pressure fluctuations

With turbulence

\[ P = P_v + \frac{1}{2} D \left( V_o^2 - V_{td}^2 \right) - \Delta P \]

\( V_{td} \) is the actual turbulent velocity at any point estimated as:

\[ V_{td} = V_t + V' \sin (2\pi f_T t) \]

\( V_t \) is the average velocity at the point, \( V' \) is the RMS velocity, \( f_T \) is the frequency of turbulence.

\[ f_T = \frac{V'}{l} \quad l = 0.08 \left( \frac{d_O + d_P}{2} \right) \]
Pressure Profiles using CFD

Simulation of Flow field in the cavitation device gives pressure sensed by the cavity while moving through the flow domain.
Pressure Profiles using CFD contd..

Paths taken by cavities

Pressure sensed by the cavities
Single Bubble dynamics simulations

Single Cavity Approach

- Use of Rayleigh Plesset Equation (Basic approach)

\[
R \left( \frac{d^2 R}{dt^2} \right) + \frac{3}{2} \left( \frac{dR}{dt} \right)^2 = \frac{1}{\rho_l} \left[ p_i - \frac{4\mu}{R} \left( \frac{dR}{dt} \right) - \frac{2\sigma}{R} - p_\infty \right]
\]

- Estimation of collapse Pressure

\[
P_{\text{collapse}} = \left( p_o + \frac{2\sigma}{R_o} \right) \times \left( \frac{R_o}{R} \right)^{3\gamma} - \frac{2\sigma}{R} - \frac{4\mu}{R} \left( \frac{dR}{dt} \right)
\]
Bubble dynamics model gives

Instantaneous value of

- Radius
- Bubble wall velocity
- Bubble wall acceleration
- Pressure inside the bubble

as the function of Liquid physicochemical properties

Use above parameters for the Quantification of the collapse Pressure Pulse
Steady cavitation

$P_{\text{inlet}} = 11 \text{ atm}$; Gas fraction = 1.0; Orifice dia. = 0.6 mm;
Pipe dia. = 38; Number of orifice = 1;
Orifice velocity = 36 m/s; $R_o = 10 \mu m$;
Transient cavitation

\[ P_{\text{inlet}} = 3 \text{ atm}; \quad \text{Orifice dia.} = 1 \quad \text{mm}; \]
\[ \text{Pipe dia.} = 38; \quad \text{Number of orifice} = 33; \]
\[ \text{Orifice velocity} = 12 \text{ m/s}; \quad \text{Ro} = 10 \, \mu\text{m}; \]
Cavity collapses in multiple cycle

Intensity of final cavity collapse is lower than the transient cavitation but higher than stable oscillatory cavitation.
Hydrodynamic Cavitation: Transient cavitation

Pressure Recovery Profile

Cavity Dynamics Profile

Temperature profile

Collapse Pressure Profile
Typical Radicals formation profile at cavity collapse

\[ \text{Molecules} \]

\[ \begin{align*}
1.0 \times 10^0 & \quad 1.0 \times 10^2 \\
412 & \quad 413 & \quad 414 & \quad 415 & \quad 416 & \quad 417 & \quad 418 \\
H_2 & \quad H & \quad O & \quad O_2 & \quad OH & \quad H_2O & \quad N_2 & \quad N_2O
\end{align*} \]

Time (microsec)

\[ R_o = 10 \, \mu m, \quad X_g = 1.0 \]

\[ P_{in} = 4 \, \text{atm}, \quad d_o = 1 \, \text{mm}, \quad d_p = 38 \, \text{mm}, \quad C_v = 1.0 \]
Conclusion

- Strongly oxidizing OH radicals can degrade the chemical pollutants
- The high intensity shock waves are capable of disrupting a variety of aquatic microbes including pathogens
- Hydrodynamic cavitation for potable water disinfection coupled with conventional disinfection processes like chlorination, ozonation has allowed more than 2/3\textsuperscript{rd} reduction in disinfecting chemicals usage
- Hydrodynamic cavitation reactors offer immediate and realistic potential for industrial scale applications
- Scale up is comparatively easier as vast amount of information about the fluid dynamics downstream of the constriction is readily available and the operating efficiency of the circulating pumps which is the only energy dissipating device in the system is always higher at large scales of operation.
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Thank you