Hydrodynamic Cavitation Technology: Industrial Applications

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Cavitation is a physical phenomenon associated with three aspects: formation, growth, and collapse of vapor or gas–vapor bubbles within the body of a liquid due to variations in local static pressure. Decreasing the pressure over a liquid and bringing it to its vapor pressure at the operating temperature generate vapor bubbles in the liquid. When the pressure is brought back to normal, these vapor bubbles collapse with a bang to generate intense pressure and temperature at the point of collapse (Fig. 1). Such intense conditions (5000 atm and 12,000 K, intense turbulence) and resulting shock wave can bring about several physical, chemical, and biological transformations, even when the bulk conditions are ambient. This release of energy can be harnessed effectively for bringing about chemical, physical, and biological transformation. Mumbai-based HyCa Technologies Pvt Ltd., along with ICT, Mumbai, has developed the technology to create and collapse precisely tailored cavitation bubbles to modulate the pressure, temperature, and turbulence conditions by means of controlled variations in the static pressure of fluid. This article describes few case studies where the company's HyCator® brand of reactor systems was gainfully employed in effluent treatment plants, cooling towers, particle size reduction, and biogas production enhancement application. The objective of this article is to make reader aware of the potential of the tailored cavitation to bring about the change most effectively.

Applications in Effluent Pretreatment

The HyCator® brand of reactor system has been used to intensify various physical, chemical, and biological processes occurring in effluent treatment plants in an energy- and cost-effective manner.

The advantage of this reactor system is listed out in Fig. 2.

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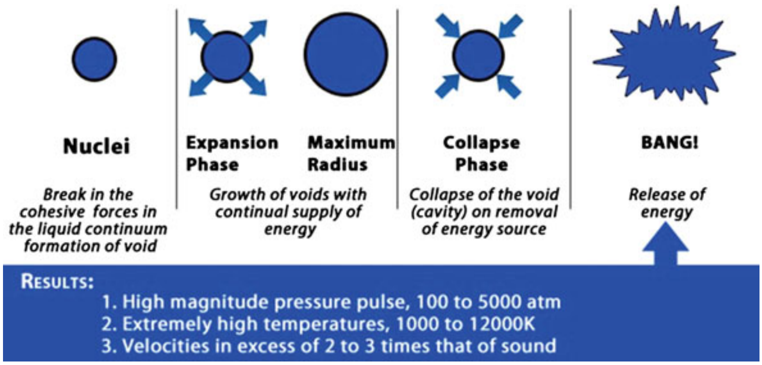

Fig. 1 Principle: hydrodynamic cavitation

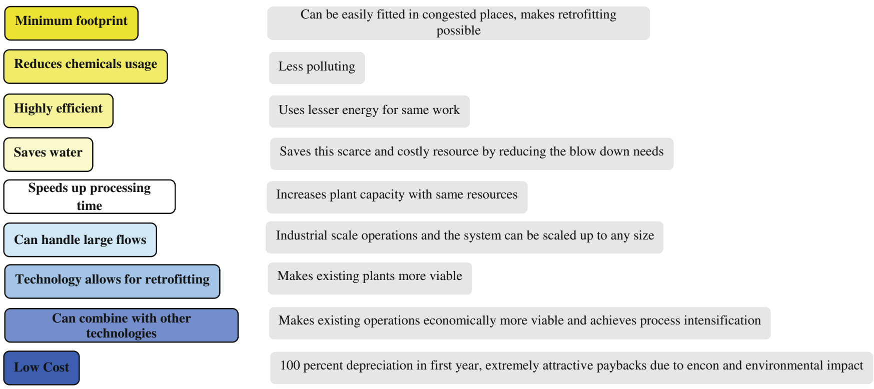

Fig. 2 Main features of HyCator® Reactor System

These reactor systems can be retrofitted to any existing effluent treatment plant to make the later more effective and efficient by reducing pretreatment time and costs, as well as by the reduction in the usage of chemicals in an environment-friendly way (Fig. 3).

The different types of reactor systems include the following:

Different reactor configurations have been developed to suit various applications, and the system can be customized to any scale of operation as targeted transformations. The HyCator®: OLM Reactor System generates tailor-made cavities for microlevel mixing. Length scales associated with cavitation are in the order of the diameter of a collapsing cavity, i.e., few nanometers to few microns, whereas in conventional mixers, the turbulent length scales are of the order of mixing element, i.e., few centimeters. Thus, cavitation is known to dissipate energy on the length scales required for micro- and molecular-level mixing which makes cavitationally induced mixing, a microlevel mixing. This makes cavitation-based HyCator®: OLM Reactor System much more energy efficient compared to conventional

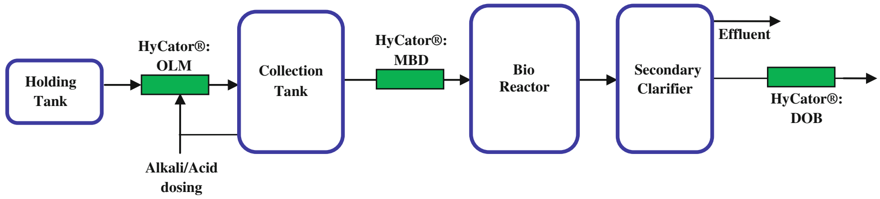

Fig. 3 Retrofitting stand-alone HyCator Reactor System into existing facility

methods of online mixing and can bring about the molecular-level mixing. Limitations do exit for highly viscous and viscoelastic fluids as the generation of cavities is more difficult in such liquids and the zone of effluence is limited.

In HyCator®: MBD Reactor System, the energy released during cavity collapse is harnessed for the breakage of the molecular bonds and generation of OH free radicals which are responsible for the oxidation of organic compounds in wastewater. The wastewater after passing through the reactor has much reduced COD levels, and biodegradability is also enhanced due to the breakdown of the larger biorefractory pollutants.

For HyCator®: MBD Reactor System used for effluent pretreatment, we first carry out multiple pilot trials on organizations' most representative effluent samples at our laboratory and set the trial protocol, and once achieving success, we request the organization to witness the trials. Conducting the trials as per the standard pilot trial protocol and conveying its analysis results will be the first step. Based on the results and observations, further course of action is decided. Without pilot trials, it is not possible to provide a full-scale solution as the effluent characteristics vary significantly.

HyCator®: DOB Reactor System helps to disintegrate (degradation and partial cell disruption) biomass in an energy- and time-efficient manner. This increases the activity of the biomass by defloccing the biomass making it accessible to oxygen and other substrates and nutrient, thereby reducing the generation of waste-activated sludge and speeding up further processing which are many times controlled by intracellular enzymes which are not easily accessible to the pollutants.

Advantages of Cavitation

Cavitation technology compares favorably with similar advanced oxidation processes (AOPs) like Fenton's process, wet air oxidation, ozonation and hydrogen peroxide treatment and ultrasonic/acoustic cavitation. These technologies require the addition of more chemicals, which in turn add to the effluent load that needs to be mineralized. Moreover, there is a requirement for higher bulk pressure and temperature as also longer processing times are needed on many occasions. Cavitation can also be combined with these conventional processes to bring about synergy between various processes.

Advantages of cavitation technology include the following:

- A greener technology that does not necessarily need additional chemicals;
- Can be coupled with other AOPs, if required;
- Bulk temperature is ambient; bulk pressure is in the range of 3–7 atm; and
- Enhances performance of existing effluent treatment facility (improves efficiency of aerobic reactor, increases biodegradability of effluent (BOD:COD ratio), reduces COD of effluent, etc.).

Similarly, cavitation-based reactor systems also compare favorably with other standard mixing technologies such as static mixing, jet mixing, and stirred tanks:

- It can operate with lower overall pressure drops and hence lower net energy consumption;
- It does not need a holding tank or static containers, since mixing is done online. Hence, it has low footprint;
- Mixing takes place on microscale, making it energy efficient;
- Can be designed and operated practically for any pressure and flow rate; and
- Can be fabricated in any material of construction for high wear and tear, corrosive resistance, and high-pressure and high-temperature applications.

Benefits of HyCator DOB Reactor System include the following:

- Increases the activity of microbes by partial disintegration and total deagglomeration of biomass resulting in high rate of reactions for acidogenesis, acetogenesis, and methanogenesis;
- Floc deagglomeration leads to better mass transfer;
- Minimum 8 % and a maximum up to 30 % increase in digester performance;
- Treatment of huge volumetric sludge streams;
- Continuous operation at varying sludge properties; and
- Stability against reactor blocking (sludge impurities).

Case Studies in Effluent Treatment

Improvement in COD Reduction Capacity of Bioreactor System

A Common Effluent Treatment Plant near Mumbai was operating two biotowers (A&B) for reducing the COD of partially treated effluent streams. COD reduction in biotower A was 40 % and in biotower B was 34 %, but even with this, the COD of the exit stream of ETP was not under the specified limits of discharge. Other alternatives to achieve this were to increase the size of the subsequent bioreactor or the residence time, i.e., reducing throughput or ozonation. All the alternatives required substantial modifications in the existing system or needed the addition of chemicals.

HyCator®: MBD Reactor System was installed in the inlet effluent stream of one of the biotowers (B) for increasing the biodegradability of the effluent. A detailed study was conducted on the biotower system to evaluate the performance of the installed device for COD reduction, biorefractory breakdown and oxidation, disintegration of biomass, and intensification of bioreactors. This was achieved by introducing air in the HyCator reactor, giving preoxygenated effluent to the biotower. The COD reduction in the biotower B increased from 34 to 54 %, at a mere additional operational cost of Rs. 0.32/m^3. The exit COD was reduced to within discharge limits. The feeding of the preaerated (preoxygenated) effluent to the bioreactor increased the biological activity of the immobilized microbes in the bioreactor without the need of the additional aeration vessel.

COD Reduction of Viscous, Partially Polymerized Glycerin Foot

A company was having trouble in treating a viscous, partially polymerized glycerin foots (distillation residue from glycerin distillation) stream. Although the stream was biodegradable, it would need extremely long hydraulic retention time (HRT) if treated in regular aerobic reactors, as it was partially polymerized and had high COD (170,000–50,000 ppm). Other options available were to use a bioreactor, but due to high viscosity and the presence of long-chain molecules, the residence time (volume) required in the bioreactor would have been very large.

HyCator®: MBD Reactor System with aeration (inside or outside) was recommended and designed for treating the same. Almost 70–95 % reduction in COD was achieved cost-effectively without any addition of chemicals such as H_2O_2, which would otherwise have been required to partially reduce the COD in a conventional ETP. The effluent stream was not required to be diluted before the subsequent aerobic treatment using the activated sludge; thus, considerable water saving was also achieved.

Conversion of Nonbiodegradable Ethylene Oxide to Biodegradable Glycols

Ethylene oxide (EO) is released during tanker unloading, which is arrested by scrubbing it with water. EO being highly soluble in water, antimicrobial, and poisonous cannot be taken to regular effluent treatment plant (ETP) as it will destroy the biomass present in the bioreactor. In this case, 2 m^3 of water containing 20,000 ppm of EO is generated and needs to be treated before it could be discharged. Conversion of EO (nonbiodegradable) to glycols (biodegradable) by conventional process requires very high temperature (>150 °C) and high pressure (30 kg/cm^2).

HyCator®: MBD Reactor System was recommended to treat this effluent stream. After successful pilot trials, a plant-scale HyCator®: MBD Reactor System was custom-made for reducing the EO content cost-effectively from 20,000 ppm to less than 3000 ppm in just 16 h. By using HyCator®: MBD Reactor System and no additional chemicals, EO was converted to a readily biodegradable material (glycols), which is further easily mineralized in a conventional bioreactor in the existing ETP.

Application in Cooling Towers

A reactor system has been developed for generating tailor-made cavities suitable for particular applications such as molecular breakdown especially useful in preventing biofouling in cooling tower water. Due to extremely high temperature and pressure and intense turbulence in the HyCator®: BFP Reactor System, shock waves are generated that are capable of destroying microbes and algae. The HyCator®: BFP Reactor System shown in Fig. 4 is a stand-alone unit, which will take its feed from cooling tower sump, and the treated cooling water will be discharged either to the line going for process or back to cooling tower sump as a closed circulation.

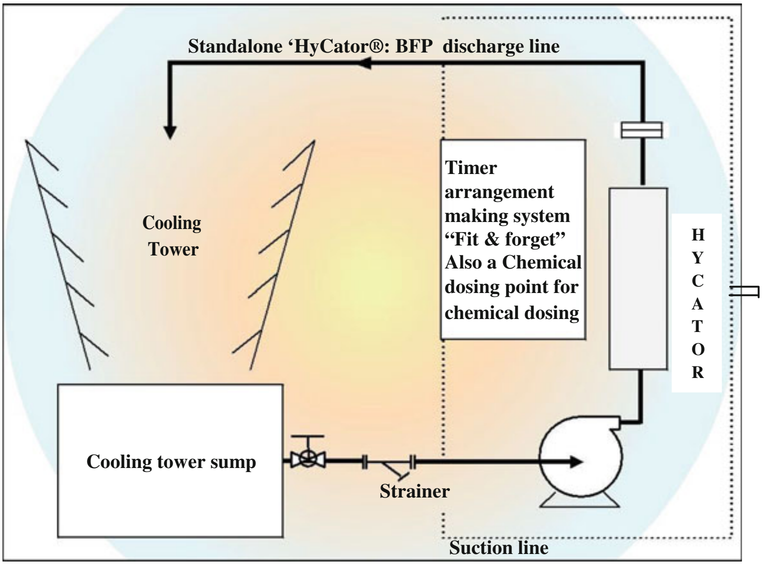

Fig. 4 Schematic of cooling tower circuit and stand-alone HyCator®: BFP Reactor System's installation

Potential Benefits

The reactor system prevents biofouling and reduces the blowdown to a very low value, which, in turn, will reduce the makeup water rearrangement. Once the frequency of makeup water is reduced, the addition of other chemicals will also reduce and other impurities due to the addition of chemicals will also reduce significantly.

In general, for normal feed water quality, the potential benefits include the following:

- Prevention of biofouling, corrosion problems, and scale formation;
- Environmentally safe: no chemicals added or unwanted residuals created by the process;
- No need of biocides;
- 40 % reduction in consumption of dispersants and corrosion inhibitors;
- Reduced blowdown of water due to operation at higher cycles of concentration, and the blowdown needs no treatment as there are no added chemicals.
- 40–80 % reduction in consumption of blowdown water.

Case Studies Involving Cooling Tower

Biofouling Prevention in Cooling Tower Water

Chemical treatment cost for biofouling and corrosion inhibition is high, and the plant management is always under pressure to reduce water usage and discharge. Cycle of concentration is also usually low. A hard scale often is formed in the summer season. The bacterial counts were 10^5 CFU/ml. HyCator®: BFP Reactor System was installed in the cooling tower circuit. A detailed study was conducted on the cooling tower system over a six-month period to evaluate the performance of the device for disinfection, scaling, corrosion, cycles of concentration, and heat transfer efficiency.

Makeup water consumption was reduced by 30 % and blowdown discharge reduced over 60 %. Bacterial microbial counts became nil, and cycles of concentration increased substantially. The results also indicated that the HyCator: BFP Reactor System treatment performed well compared to the chemical treatment without the addition of any chemicals. In this particular case, dosage of anticorrosion and scale prevention chemicals was also reduced significantly. Annual water saving exceeded 3600 m^3.

High Blowdown Water and Biofouling

The main problem with high blowdown water and biofouling is the requirement of the treatment of the blowdown water. The cooling tower is operated at low cycle of concentration. After the installation of HyCator®: BFP Reactor System, the biocides dosing was reduced to 10 % of the original and other chemicals (dispersant, corrosion inhibitor, and antiscalant) reduced to 40 % of the original. The bacterial counts came down to under the permissible limit. Blowdown was reduced by 40 %, and cycle of concentration was also marginally increased. Old scale was gradually removed, and no new scales were formed. The above cases clearly indicate the efficacy of cavitational treatment in the prevention of biofouling and reduced consumption of chemicals and makeup water due to reduced blowdown.

Application in Particle Size Reduction

In an innovative product HyCator®: PBD Reactor System, the mastered art of stimulating formation and collapse of such bubbles in the required manner and on the desired scale has been explored for size reduction. HyCator®: PBD Reactor System is fine-tuned for generating tailor-made cavities to grind the particles up to nanoscale level. Length scales associated with cavitation are of the order of a collapsing cavity, i.e., few nanometers to few microns, whereas in conventional size reduction equipments, the turbulent length scales are of the order of few mm. Thus, cavitation is known to dissipate energy on the length scales required for size reduction which makes cavitationally induced size reduction to nanoscale level. This makes cavitation-based HyCator®: PBD Reactor System much more energy efficient compared to conventional methods of size reduction.

As shown in Fig. 5, stand-alone HyCator®: PBD Reactor System can be fitted with minimal alterations in the existing system and be completely bypassed when needed. It requires minimal footprint and is ideal for place where safety issues are very stringent as an entire operation is concealed.

Comparison of Cavitation with Other Standard Size Reduction Technologies

Other similar size reduction technologies are as follows:

1. Colloid mills (e.g., ball mills, bead mills);
2. Disk mills;
3. Jet mills;
4. Rotor–stator mixers/high-pressure homogenizers.

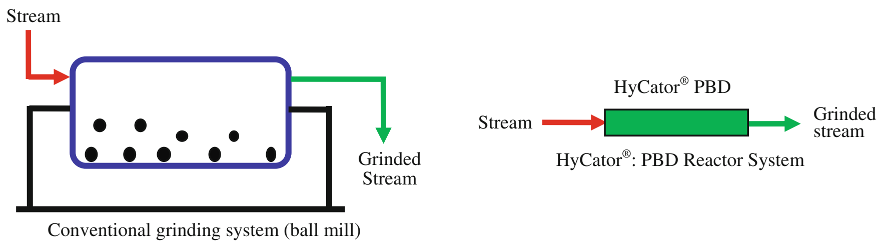

Fig. 5 Retrofitting HyCator®: PBD Reactor System into existing facility

These technologies face the following demerits such as

- Requires special equipment;
- Higher energy requirement;
- Operation is not cost-effective;
- Particle size may not be uniform.

Advantages of HyCator®: PBD Reactor System over above technologies are as follows:

- Online grinding possible;
- Can operate at lower pressure drops;
- Does not need any special equipment since size reduction is done online. Hence, it has low footprint;
- Need not have to use separate auxiliaries such as grinding media, etc., and hence, size reduction is energy efficient;
- Can be designed and operated practically for any pressure and flow rate;
- Can be fabricated in any material of construction for high wear and tear, corrosive resistance, and high-pressure and high-temperature applications.

Economic benefits of HyCator®: PBD Reactor System are as follows:

- Cost savings due to the reduction in energy consumption;
- No additional hardware requirement.

Other benefits are follows:

- Can be easily installed and needs only fitting it in bolted flanges at the required location.
- Requires no operational supervision and maintenance. But it may require slurry pump.
- Stream can be easily bypassed when required to bring in colloid/sand mill inline.
- Time saving.

Case Study of HyCator®: PBD Reactor System

Preparation of Nanosuspension Using HyCator®: PBD Reactor System

A renowned Mumbai-based FMCG company was having trouble in the process due to large nanosized (5900.0 ± 100.0 nm) suspended particles into the processing system and they wanted an absolute nanosuspension with particle size distribution as small as possible. Other alternatives to achieve this particle size distribution were to procure an extra grinding mill to decrease the size and to increase the residence time, etc. All the alternatives required substantial modifications in the existing system.

HyCator®: PBD Reactor System was installed in one of the units to prepare the nanosuspension. A detailed study was conducted on the existing system to evaluate the performance of the installed device for particle size reduction and intensification of process. By using HyCator®: PBD Reactor System, the particle size was reduced up to 300.0 ± 10.0 nm. The 90 % particle size reduction was achieved at an incremental additional operational cost and it did not need any maintenance.

Pigment Grinding Using HyCator®: PBD Reactor System

One of the Gujarat-based renowned dyes and pigment manufacturing company was using a ball mill for pigment grinding to reduce particle size from 0.66 to 0.53 μm. They were increasing substantially high manufacturing cost on account of huge power requirement for ball mill to achieve desired particle size as well as time

Table 1 HyCator®: PBD Reactor System versus bead mill for pigment grinding application

S. No.	Label	Cumulative treatment period required (h)	No. of passes	Mean dia. 90 % (μm)	Power consumed (Kw.h)	Operating cost (Rs. per liter) @ 5 Rs./kw.h
1	Sample (initial)	0	0	0.66	–	–
2	Particle size reduction using bead mill	144	9	0.53	8064	40320.00
3	Particle size reduction using HyCator®: PBD	59	20	0.53	3301	16506.00

Volume (batch size)—8844 l
Pump flow rate—300 l/h = 50 lpm
Motor power—75 Hp = 56 kW (at 60 % efficiency)

required for this unit operation was also high due to the requirement of multiple passes.

HyCator®: PBD Reactor System was proposed for grinding of pigments, and the organization achieved desired particle size reduction with 2.5 times lower power and treatment period that of previously required ball mill and substantially saved time and manufacturing cost as shown in Table 1.

Application in Biogas Generation Enhancement

HyCa Technologies has also developed HyCator®: BGG Reactor System to enhance biogas generation from anaerobic biodigesters. For an efficient utilization of feed in biodigesters, the disintegration pretreatment of digester feed process using advance technology is needed. HyCator®: BGG Reactor System has shown a positive effect on the degree and rate of digester's feed hydrolysis and ultimately on anaerobic digestion and has resulted in biogas production enhancement. By applying hydrodynamic disintegration, a controlled lysis of anaerobic digestive cells occurs in minutes instead of days. The intracellular and extracellular components are set free and are immediately available to supplement the biological degradation of the substrate which leads to an improvement in the subsequent anaerobic process. The cell of the activated sludge microorganisms ruptures and aids the digestion process leading to increased biogas production. Also, HyCator®: BGG Reactor System helps to disintegrate the larger-sized pollutant molecules into substantially smaller ones by the shear force, mechanical shock, and turbulence generated locally which help to degas the system so that pretreated feed gets easily digested further into digester, i.e., biodigestability of the feed is increased which also contributes to the enhancement in biogas production and reduction in the residual pollutant load leaving the digester.

Potential Benefits of the HyCator®: BGG Reactor System

- Increases the activity of microbes by disintegration of biomass resulting in high rate of reaction for acidogenesis, acetogenesis, and methanogenesis;
- Floc deagglomeration → better mass transfer of the substrates and the nutrients to microbes;
- Cell destruction → production of soluble chemical oxygen demand (SCOD) and proteins… → intensification of the anaerobic process;
- More biogas and less residual outlet COD;
- 8–30 % increase in the digester performance (VS degradation up from 42 to 54 %);
- Treatment of huge volumetric sludge streams;
- Continuous operation at varying sludge properties;

- Stability against reactor blocking (sludge impurities);
- Low maintenance;
- COD and color reduction in the outlet stream;
- Improvement in biodigestion and composting, etc.

Concluding Remarks

As it can be seen from the discussion and the details in the case studies, that cavitational transformation has a great future. The logic of delivering energy at the location of the transformation (be it biological, chemical, and physical) using the phenomena of cavitation has been exploited successfully. The mechanism of this energy delivery has been elucidated. The case study presented here does not limit the application of cavitation, and it has yet many more possible applications to explore.

The proposed techniques and the developed technologies have bagged the following prestigious awards:

- Gold medal at DST—Lockheed Martin Innovation Award for 2012.
- National award for the most innovative water saving product for 2011 from Govt of India/CII at the National Water Conclave, Jaipur.
- FE-EVI Green Technology Honouree from the hands of Hon Dr. A.P.J. Abdul Kalam on World Environment Day, 2011.
- Awarded the ET NOW/Bajaj Hindustan 'leap of faith' green entrepreneur of the year for 2012.
- Selected as a portfolio company of New Ventures India (a CII, USAID, UK Foreign and Commonwealth Office and World Resources Institute, Washington initiative) 2010.
- Showcased at Innovations India organized by IIT Bombay Alumni Association, Pune chapter and in Proto. in 2010.
- Showcased in the top five start-ups for the year 2009 in ET NOW.