

HYDRODYNAMIC CAVITATION PILOT STUDY FOR CONTROLLING COOLING WATER QUALITY

W. A. Gaines, B. R. Kim, A. R. Drews, C. Bailey, T. Loch, S. Frenette
Sali Group, LLC
314 Pauline Blvd, Suite 100
Ann Arbor, MI 48103

ABSTRACT

A field study was conducted on a cooling-tower system at an automotive manufacturing facility to evaluate the performance of a VRTX hydrodynamic cavitation device for disinfection, scaling, corrosion, and heat-transfer efficiency.

Primary findings are:

The VRTX unit performed as well as the chemical program that it replaced in terms of bacterial control without adding any chemicals (including disinfectants). The bacterial count was maintained at $\sim 10^4$ cfu/mL over 2 months of the study.

The VRTX unit enabled the cooling system to be operated at a higher cycle of concentration (CoC) than that used during the chemical program, without adversely affecting pH, scaling, and corrosion. This increase in CoC is expected to lead to a decreased water usage.

The observed corrosion rates of copper and mild steel were either equivalent or better than those obtained during the chemical program, though corrosion of galvanized steel was appreciable.

The use of the VRTX unit did not appear to adversely affect heat-transfer efficiency.

KEYWORDS

Cooling Tower, Hydrodynamic Cavitation, Biological Control, Scale Control, Corrosion Control

INTRODUCTION

Cooling tower water must be treated to control microbial growth, prevent scale formation and limit corrosion of the system components while maintaining adequate heat transfer performance. This paper summarizes a field trial that evaluated the performance of a hydrodynamic cavitation device (HCD) to disinfect cooling tower water, the system's scaling, corrosion and heat transfer efficiency and provides an analysis of likely operating cost performance.

Conventionally, chemical disinfectants are used to control bacteria in cooling tower systems. Although automated chemical addition is used to maintain a desired level of residual, the levels must be monitored and adjusted frequently to verify control of microbial growth. In addition, some microorganisms become resistant when subjected to a single disinfectant, and periodic alternation of disinfectants is often required to mitigate this effect. Non-chemical treatment methods are a desirable alternative, but any new treatment method must be carefully tested for its long-term anti-microbial efficacy while not adversely impacting scale formation, corrosion or heat transfer efficiency of the overall system.

For information regarding this technology contact:
Steve Frenette
Sali Group, LLC
Office: (734) 929-0644 Mobile: (734) 657-1501

Hydrodynamic Cavitation

Cavitation is the formation, growth, and implosion of vapor bubbles in a liquid. It can be created by sound waves, lasers, or by fluctuations in fluid pressure (hydrodynamic cavitation). Cavitation has been reported to kill bacteria through chemical reactions, pressure pulses and micro-jets, and by localized high temperatures. In aqueous liquids, cavitation leads to the formation of hydroxyl radicals and hydrogen peroxide. These short-lived reactive radicals are capable of secondary oxidation and reduction reactions¹ in the immediate vicinity of the bubble.

Figure 1 Asymmetrically collapsing bubble producing a micro-jet.

During bubble collapse, a pressure pulse up to 1,450 psia (10 MPa) is produced in the immediate vicinity of the bubble. Shear forces and shock waves may impinge on a bacterial cell wall within a few radii and cause cell lyses. Asymmetric bubble collapse can also lead to emission of micro-jets of fluid (Figure 1). Lohse has postulated this jet formation may be responsible for cell-wall disruption².

Thermal effects become very pronounced in the final stage of collapse when the bubble contents are highly compressed by the inertia of the inrushing liquid. Local temperatures can reach 8,540°F (5,000°K) at the liquid/vapor interface but persist for only a few microseconds³. This heat may be sufficient to kill microbes located within a few bubble radii.

Cavitation appears to be effective against numerous strains of planktonic bacteria. Of particular note, Stout⁴ demonstrated the efficacy of HCD against *Legionella pneumophila* serogroup 1 in a controlled laboratory setting. Along with the rapid bacteria kill, Stout also detected some oxidants, which is consistent with the above discussion on the generation of free radicals and oxidants.

CaCO₃ is the principal component of cooling tower scales and significantly affects heat transfer efficiency. The rate of scale formation is controlled by temperature, rate of heat transfer, pH, dissolved solids, and alkalinity. Cavitation has been reported to provide favorable conditions for CaCO₃ formation by 1) stripping CO₂ from water thus increasing pH, and 2) locally increasing temperature. Elevated pH shifts carbonate equilibrium from HCO₃⁻ to CO₃⁼, leading to increased CaCO₃ precipitation. The formation of CaCO₃ is an endothermic reaction and increased temperature promotes CaCO₃ precipitation. In addition, the crystalline form of CaCO₃ may also affect the heat transfer efficiency: Calcite generally forms as a hard, tenacious scale while aragonite and vaterite are thought to form softer precipitates that do not adhere to surfaces.⁵ Koestler⁶ operated a HCD unit on a tower and found aragonite precipitates.

Corrosion is typically controlled by 1) maintaining an alkaline pH, 2) removing corrosive dissolved gases, 3) controlling bacterial activity, and 4) eliminating corrosive chemicals. Iron corrosion rates for typical tower pHs are limited by oxygen diffusion and are nearly independent of pH⁷. To the extent cavitation reduces the dissolved oxygen concentration, iron corrosion can be reduced.

SYSTEM OVERVIEW

The open cooling system used in this study continuously removes heat from a closed-loop through two plate heat exchangers and rejects heat to a two-cell, counter-flow, induced-draft galvanized cooling tower with high efficiency drift eliminators and a covered distribution deck and a PVC honeycomb fill. Each cell has a 20-HP (15 kW) fan that provides 103,000 cfm (49 kL/s) of air flow and 380 tons (1,336 kW) of cooling. At rated capacity, the tower cools water from 105°F (41°C) to 85°F (29°C) at a 78°F (26°C) wet bulb temperature and recirculation flow rate of 1,400 gpm (88 L/s). Treated city water (Detroit, MI) is used for make-up, and blowdown is regulated by a conductivity controller.

Prior to the start of testing of the HCD unit, sodium hypochlorite, isothiazolinone, and a proprietary scale inhibitor were used to control biological growth and corrosion. Each chemical was independently added with a metering pump in a side-stream loop. Conductivity, pH, temperature, product concentrations, and other system parameters were continuously monitored. Bacterial concentrations are monitored weekly by ATP bioluminescence and chemical dosages are adjusted based on these readings.

The Hydrodynamic Cavitation Device. The HCD continuously treated water at 60-gpm (3.8 L/s) via a 5-HP (3.7 kW) centrifugal pump. It was connected as a side stream treatment on the cold well tank. Water was pumped through the HCD and returned to the cold well. A separate bag filtration system was used to remove precipitated CaCO₃ and other suspended solids. It was operated off of a side stream of the cold well using a 5-HP (3.7 kW), 140-gpm (8.8 L/s) submersible pump through a 200- μ m filter. Excluding the two pumps, there are no moving parts in the system.

The HCD consists of a pressure equalizing chamber and a cavitation chamber as shown in Figure 2. Water pumped into the pressure equalizing chamber at ~94 psig (648 kPa) is channeled into two pairs of conical nozzles positioned opposite to each other in the cavitation chamber. The water flow in the nozzles follows a spiral path around the axis of the cones before exiting through the nozzles. The rotation creates a vacuum of ~13.5 psia (93 kPa) which leads to the formation of micro-sized bubbles. Upon exiting each nozzle, the opposing streams collide at the mid-point of the cavitation chamber causing a dramatic pressure increase that in turn leads to spontaneous bubble collapse.

Figure 2 Water Flow pattern inside the HCD Chamber. (1) pressure-equalizing chamber; (2) cavitation chamber; (3) nozzles; and (4) water inlet.

Testing Procedure. Baseline data were obtained by daily sampling of system performance for ten days prior to the HCD being activated. During this period, several changes in operating conditions were made in preparation for the HCD testing: isothiazolinone and corrosion inhibitor feeds were turned off; conductivity blowdown set point was reduced from 1,100 to 450 μ S/cm (approximately city water conductivity) to purge chemicals from the system; and the cold-well tank was drained by one-third of its volume. At the start of testing, the HCD and the bag filtration units were activated, the sodium hypochlorite feed was terminated, the blowdown valve

was closed and the conductivity set point was increased to 1,100 $\mu\text{S}/\text{cm}$. Free residual chlorine was below the detection limit of $<0.1 \text{ mg}/\text{L}$ two days after hypochlorite feed was terminated. After over one month of steady-state operation, the conductivity blowdown set point was increased to 1,250 $\mu\text{S}/\text{cm}$ to see if the cycle of concentration (CoC) could be further increased without adversely affecting scaling and corrosion performance.

RESULTS AND DISCUSSION

Bacterial Concentration. Heterotrophic plate counts and dip slide results taken from the bulk water during the study are shown in Figure 3. Immediately after the HCD was activated, the bacterial concentration increased by several orders of magnitude to 10^6 - 10^7 cfu/mL before declining to a stable level of $\sim 10^4$ cfu/mL, which was maintained consistently over >2 months in the absence of added disinfectants. The manufacturer indicated that similar initial increases had been observed in other pilot tests and Mason⁸ observed a similar phenomenon when using sonication on suspensions of *Bacillus subtilis* and attributed it to de-clumping of bacterial agglomerates into a greater number of individual bacteria in the suspension before appreciable disinfection had occurred.

There was a marked difference between plate and dip-slide counts at low concentrations. The data suggests that dip slides cannot accurately measure bacterial concentration when the concentration is relatively low ($<10^4$ - 10^5 cfu/mL) and did not provide a useful comparison to plate counting after the initial "de-clumping" period. In addition, the ATP-based bioluminescence data did not correlate well with either heterotrophic plate counts or dip-slide results. Therefore, no comparisons between either counting method and bioluminescence data are included in this study.

Legionella was not found above the detection limit (1 cfu/mL) throughout the study with biweekly sampling or during the previous 3 years of semiannual sampling.

Scaling. The water-usage efficiency of a cooling tower is commonly measured by computing CoC, which is the concentration of a conservative parameter in the recirculating bulk water divided by that same parameter in the make-up water (higher cycles are more water efficient). The CoC based on calcium is commonly used. Typically, the cooling tower was operated to achieve a CoC of ~ 5 . Changes in CoC, make-up water, and Langelier's Saturation Index (LSI) before and during the study are shown in Figure 4. Following system purging, the conductivity averaged 1,043 $\mu\text{S}/\text{cm}$ and CoC increased from 4.1 to 5.0. During the first half of the study, average make-up flow decreased from 3.4-gpm (0.2 L/s) to 2.5-gpm (0.16 L/s). The flow rate decreased further to ~ 1.4 gpm (0.09 L/s) after the conductivity set point was increased to 1,250 $\mu\text{S}/\text{cm}$.

System pH temporarily decreased from ~ 8.8 to about 8 following purging but soon stabilized near its initial value of 8.7-8.8. It's possible that the degree of CO_2 stripping (which shifts equilibrium away from carbonic acid thus increasing pH) was equivalent to the alkalinity that had been added by the sodium hypochlorite. LSI decreased from 1.70 under the chemical program to 1.38 after switching to the HCD.

X-ray Fluorescence (XRF) analysis of three particulate samples collected from the bag filter showed that it is dominated by calcium compounds, but with significant amounts of silicon, magnesium, aluminum, zinc, phosphorous, and iron.

X-ray diffraction (XRD) patterns were quite similar. Aragonite was not observed in any of the three samples, contrary to the manufacturer's claim that the HCD would tend to produce aragonite instead of calcite. In addition to the calcite collected in the bag filters accumulation of loose scale deposits were also observed in the tower basin, indicating that bulk water precipitation was occurring.

Corrosion Control. The results of non-passivated corrosion coupon tests before and during the study are shown below (in mils/year). Other than the galvanized steel coupon, no appreciable corrosion was observed. The observed corrosion rates of copper and mild steel were either equivalent or better than those obtained during the chemical program. Corrosion rates observed under both the chemical and HCD programs fall into the "Excellent" category set by the National Association of Corrosion Engineers (NACE) guidelines. The galvanized steel coupon appeared to suffer fairly severe corrosion during the testing period and the XRF analysis of the filtered scale indicated significant quantities of Zn. Unfortunately, no data on galvanized steel corrosion was collected prior to the start of the HCD study so no direct comparison of rates can be made.

	<u>Days Exposed</u>	<u>316L S.S.</u>	<u>Copper</u>	<u>Galvanized Steel</u>	<u>Untreated Mild Steel</u>	<u>Treated Mild Steel</u>
Chemical	23		<0.1		1.3	
Chemical	61		<0.1			0.5
HCD	65	<0.1	<0.1	4.3	0.3	
NACE	Rating:		≤0.1		<1	

The city water averaged 0.03 mg/L Zn during the study while the cooling water had 0.1 to 0.32 mg/L in solution. Since this is higher than the calculated CoC would indicate, the city water cannot be the only source. The extra Zn found in the cooling water and removed as Zn precipitates by filtration must have come from galvanized steel in the cooling tower. The high rate of galvanized steel corrosion may be indicative of inadequate tower passivation.

Heat-Transfer Efficiency. Calculated values of the overall heat-transfer coefficient for both heat exchangers appeared to show a marginal improvement during the study period. However, the number of readings collected was insufficient for a meaningful statistical analysis.

Economic Analysis. An economic analysis of the capital and variable costs associated with a conventional and HCD system at the test facility are shown below. The equipment, installation, maintenance and licensing costs are compared to operating costs of the conventional disinfectant system.

Operating Cost (\$/year)

Savings

Chemical elimination	11,936
Maintenance reduction	675
Reduced purchase water	3,710
Reduced sewerage	1,282
Reduced annual cleaning	900
Energy reduction	7,318

Additional Costs*

Electrical cost	2,878
Maintenance cost	350
Annual technology license fee	222

Net Savings \$22,371/year

Capital Cost (\$)

HCD equipment	42,700
Installation	5,750

Total \$48,450

* The cost of changing the filter daily is not included in the economic analysis because an automatic self-cleaning filter would be utilized in a full-scale system.

Based on this analysis, the anticipated payback period is ~2.2 years. However, this tower was chosen as a trial location because it has typical capacity, system volume, and operational characteristics – not for financial reasons.

Other Benefits. Using a HCD-disinfection system offers several intangible benefits:

- 1) Health and safety risks to plant personnel from chronic and acute exposure can be reduced by avoiding the use and handling of chemical disinfectants, which also reduces recording keeping and employee training associated with use of hazardous chemicals.
- 2) The use of physical disinfection eliminates the need for a technical specialist to periodically assess system efficacy. This results in a "de-skilled" labor work force.
- 3) Using chemical disinfection, microorganisms could become resistant to the disinfectant, making that particular disinfectant less effective or ineffective. This is unlikely to occur in a physical disinfection system such as HCD.
- 4) Operational requirements are reduced for the HCD system over a conventional chemical disinfectant system. The HCD has only two centrifugal pumps and a filtration system. This would eliminate three chemical storage tanks, three chemical metering pumps, pH/oxidation reduction potential/temperature probes, a process controller, and a side-stream loop for monitoring equipment for the cooling-tower system investigated in this study. In addition, the

HCD system has a smaller footprint (50 ft² or 4.6 m²) than the conventional chemical disinfection system (>150 ft² or > 13.9 m²) and does not require secondary containment.

5) Elimination of hazardous chemicals reduces regulatory report requirements (e.g., Toxics Release Inventory). In addition, reducing water usage and wastewater volume by increasing CoC supports a sustainable manufacturing philosophy.

Limitations. The HCD system is a side-stream treatment system and therefore has all the limitations associated with such a system. All side-stream treatment systems treat only the circulating water and thus only the planktonic fraction of the total microbial population.

SUMMARY AND CONCLUSIONS

The HCD performed as well as the chemical program that it replaced in terms of total heterotrophic plate count without adding any chemicals. After an initial, brief increase in the count possibly due to de-clumping of bacterial colonies, the count stabilized to and maintained at ~10⁴ cfu/mL over ~2 months. No *Legionella* was found during either the chemical program or the HCD field test.

The HCD enabled the cooling system to be operated at a CoC of >5, which is higher than the average chemical program CoC of 4.1 without adversely affecting pH, LSI, or corrosion. This increase in CoC decreases both purchased water cost and sewerage costs. Loose scale particles were filtered from the system with a bag filter.

A 65-day corrosion test using metal coupons revealed no appreciable corrosion except for galvanized steel. The observed corrosion rates of copper and mild steel were either equivalent or better than those obtained during the chemical program. The impact of the poor zinc corrosion result is not known, but may indicate the tower was not properly passivated.

The high variance in the heat transfer data indicates that further study is required to fully verify a positive impact.

Preliminary economic evaluation indicates a significant yearly cost saving is possible for this facility if the HCD system was adopted, despite the fact that it was chosen for this test based on operational characteristics and not primarily for financial reasons.

Implementation of physical disinfection systems offers a number of potential benefits, including lower operating costs, elimination of hazardous chemicals, the potential to "de-skill" the labor work force, simplified equipment complexity and operation, reduced regulatory reporting requirements, and an enhanced corporate image by using a non-chemical "green" technology.

REFERENCES

1. Suslick, K.S., Mdleleni, M.M., and Ries, J.T., "Chemistry Induced by Hydrodynamic Cavitation", *J. Am. Chem. Soc.*, **119**, 9303-9304 (1997)
2. Lohse, L., "Bubble Puzzles," *Physics Today*, **56**, 36-41 (2003)
3. Brennen, C.E., *Cavitation and Bubble Dynamics*, Oxford University Press, New York, New York (1995)
4. Stout, J. "New and Emerging Technologies for Legionella Control: A Multi-Step Approach to Evaluating Efficacy", IWC-02-02, 63rd International Water Conference, Pittsburgh, PA (2002)
5. Coetzee, P., Yacoby, M., Howell, S., and Mubenga, S., "Scale Reduction and Scale Modification Effects Induced by Zn and Other Metal Species in a Physical Water Treatment," *Water SA*, **24**, 77-84 (1998)
6. Koestler, P., Wang, W., and Kelsey, R., "New Technology Saves Cooling Water Demands," Industrial Water Conference 2003, Las Vegas, NV, December 9 – 11 (2003)
7. *Betz Handbook of Industrial Water Conditioning*, Betz Laboratories, Inc., Trevose, PA (1980)
8. Mason, T.J., Duckhouse, H., Joyce, E., and Lorimer, J. P., "Uses of Ultrasound in the Biological Decontamination of Water," presented at the World Congress on Ultrasonics, Paris, France (2003)