Application of pulsed electrical fields for advanced cooling in coal-fired power plant

"Advanced Technologies and Concepts
to Minimize Freshwater Use in Coal-Based Thermoelectric Power Plants"
Topic 2: Advanced Cooling Technology
U.S. DEPARTMENT OF ENERGY
National Energy Technology Laboratory

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Background

Thermoelectric generation accounted for 39% (136 billion gallons per day) of all freshwater withdrawals in 2000.

→ Why so high?

Evaporation of pure water

→ High concentration of mineral ions in the circulating cooling water

→Mineral fouling problem, reducing condenser capacity

To maintain a desired calcium level in the cooling water,

→ cycle of concentration, COC = 3.5

→ continuously blowdown with fresh makeup water

Three reactions leading to mineral fouling

Reaction 1: dissociation of bicarbonate ions into hydroxyl ions and carbon dioxide

$$HCO_3^- (aq) \leftrightarrow + OH^- (aq) + CO_2(g)\uparrow$$

Reaction 2: hydroxyl ions produced further react with existing bicarbonate ions, producing carbonate ions and water

$$HCO_3^- (aq) + OH^- (aq) \leftrightarrow CO_3^{2-} (aq) + H_20 (l)$$

Reaction 3: reaction between calcium and carbonate ions, resulting in the precipitation and crystallization of calcium carbonate particles

$$Ca^{2+} (aq) + CO_3^{2-} (aq) \leftrightarrow CaCO_3 (s) \downarrow$$

Goal of the Project

To develop a scale prevention technology based on integrated system of physical water treatment (PWT) and a novel filtration method.

Specific Target

To increase COC from 3-4 to a higher COC (8-10)

How?

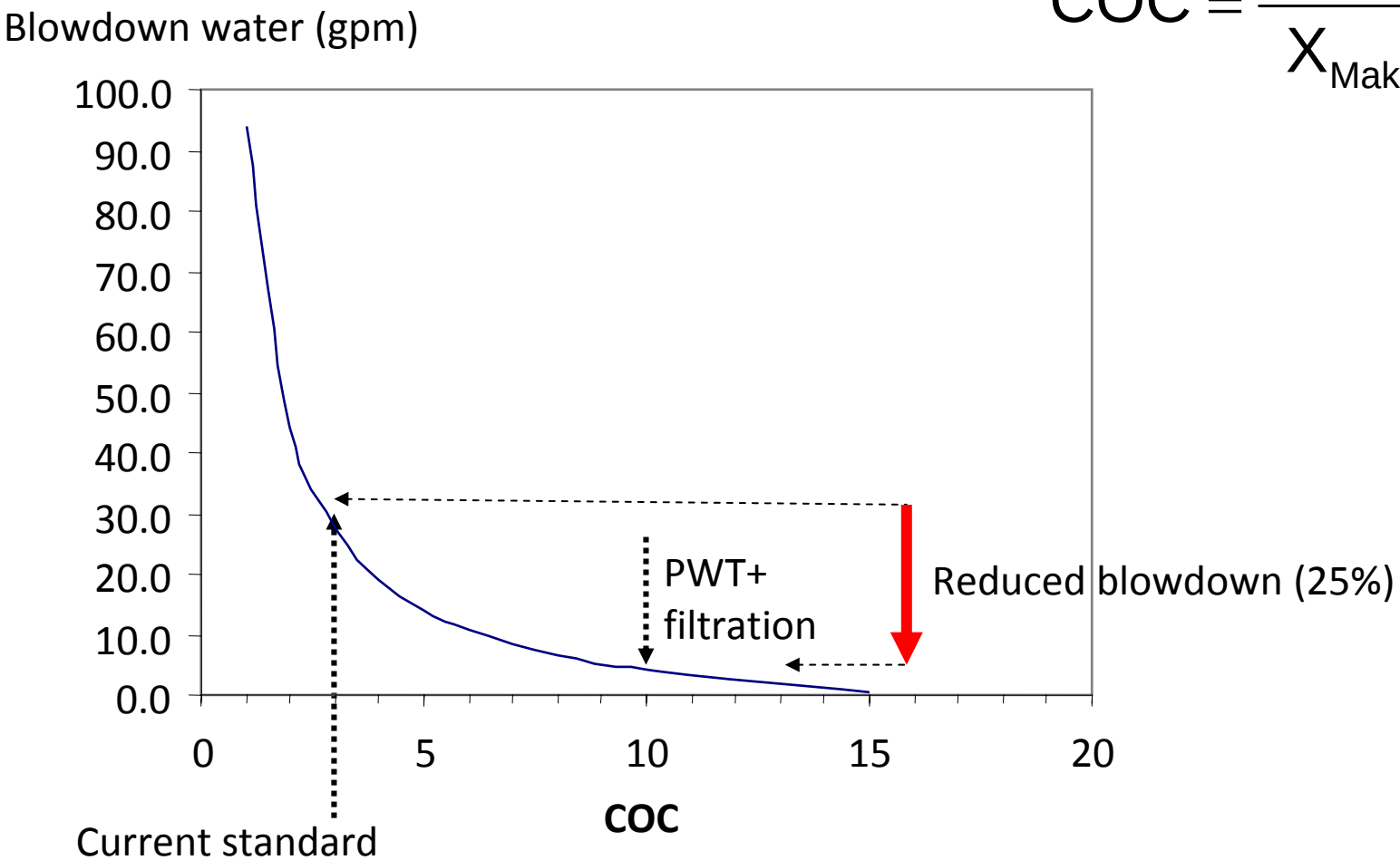
To continuously precipitate dissolved calcium ions in water to calcium particles and

To continuously remove them using a self-cleaning filter

Reduced Blowdown by Increasing COC

If Makeup water is 100 gpm,

$$COC = \frac{X_{\text{Circulating water}}}{X_{\text{Make-up water}}}$$



TASKS

Task 1
To develop a self-cleaning filtration system

Task 2
To conduct validation test using a self-cleaning filter system to prevent mineral fouling and biofouling

Development of Plasma Discharge System

Fig 2. Nanosecond pulse power supply

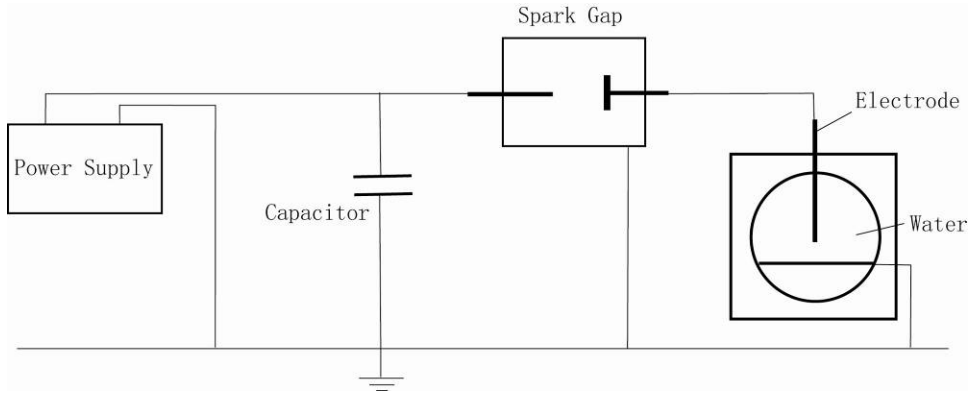


Fig 8. Circuit diagram of the plasma setup

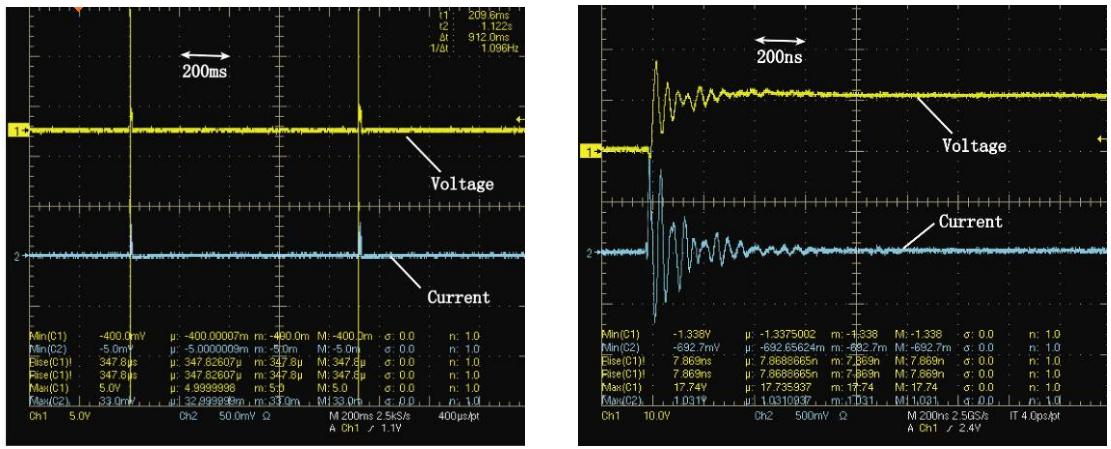


Fig 3. Voltage and current waveform of nanosecond power supply: (left) in millisecond time scale; (right) in nanosecond time scale

Use of Pin-Hole Electrode Configurations to Produce Plasma Discharge in Water

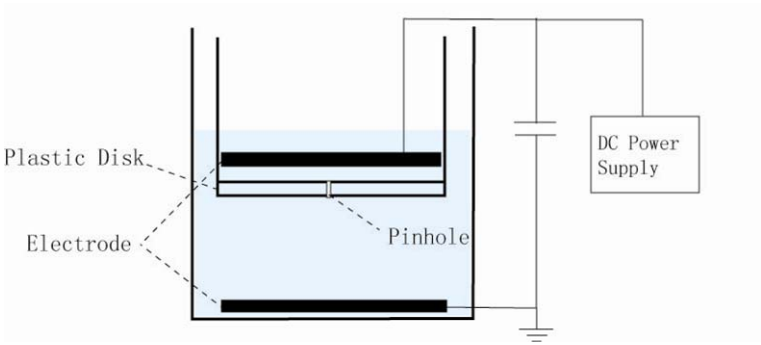


Fig 3. Schematic diagram of a discharge system with a single pinhole at the middle of an insulating sheet using a DC power supply

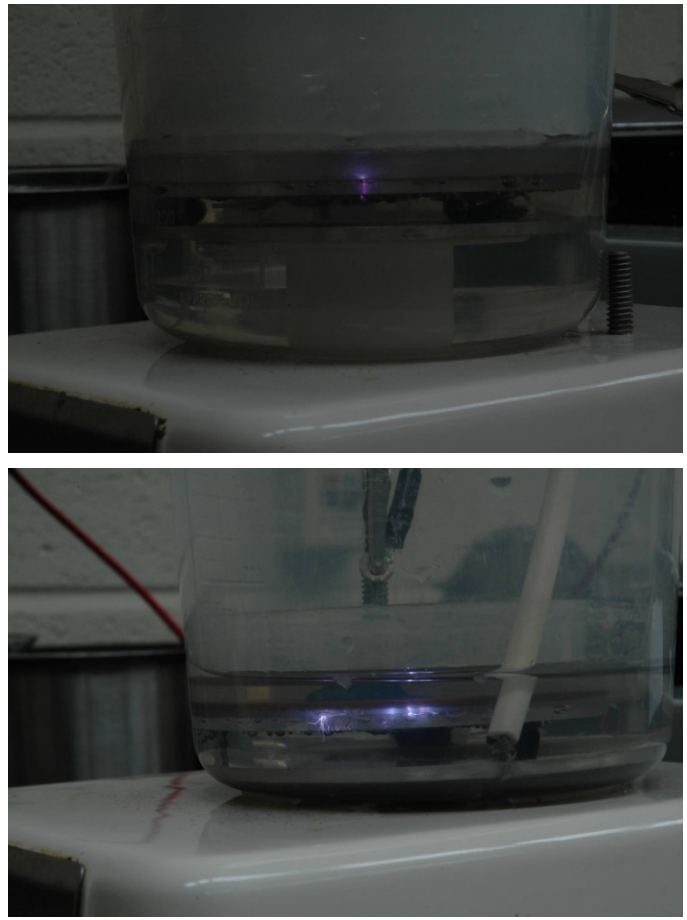


Fig 4. Corona discharge(s) produced by pinhole discharge using a DC power supply: (a) through a single hole; (b) through multiple holes

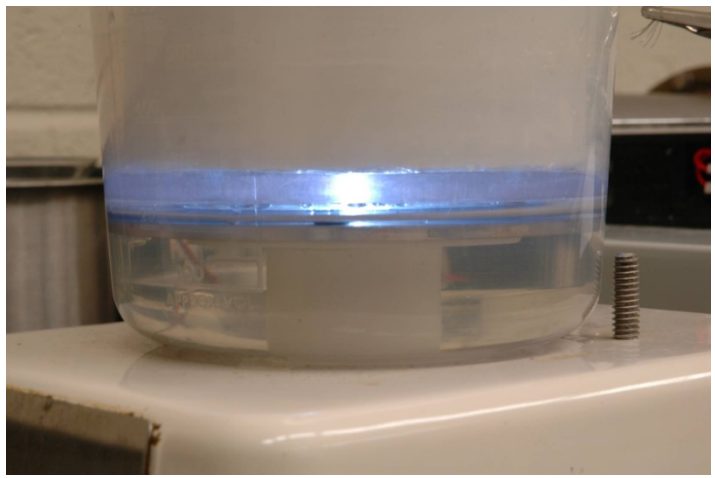
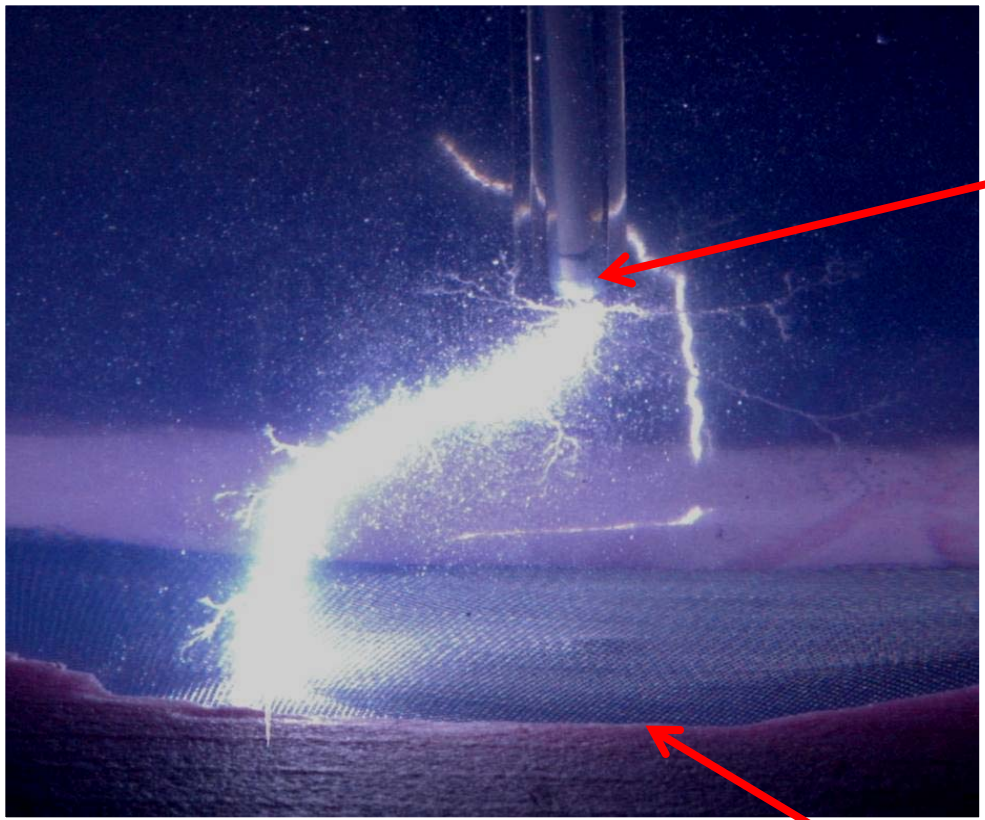


Fig 6. Spark discharge produced by pinhole discharge using a nano-second pulsed power supply

Use of Wire-Plate Electrode Configurations to Produce Plasma Discharge in Water



Wire = Tungsten Wire

Plate = Stainless Steel Filter Membrane

Scanning Electron Microscopy Photographs of Deposited Particles on Filter Membrane

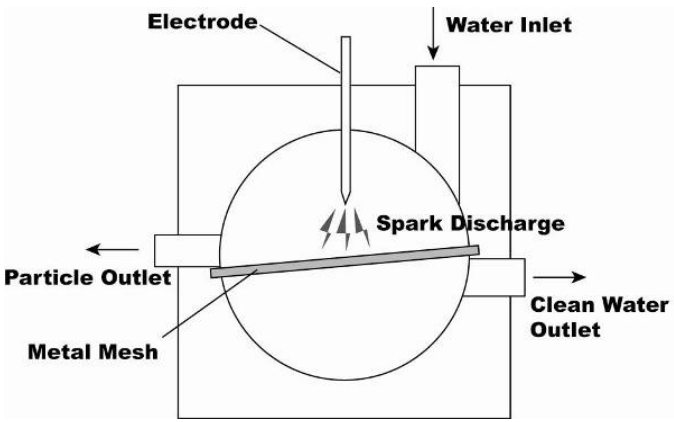
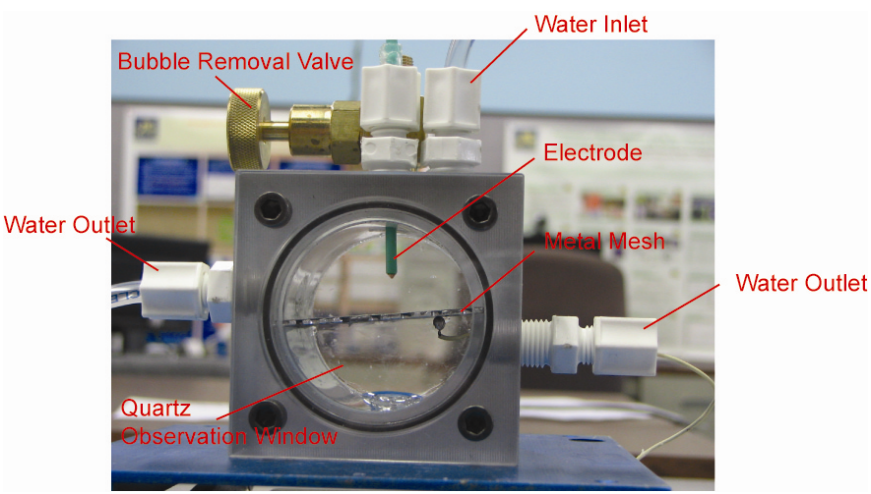
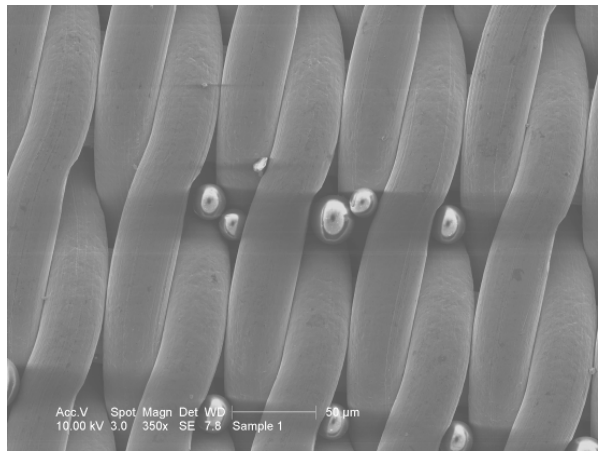
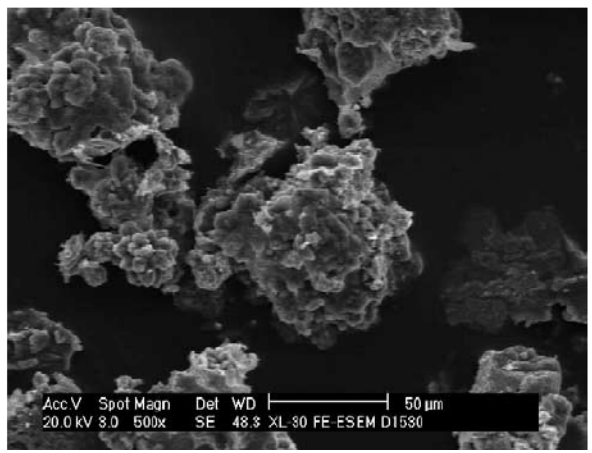


Fig 1. Schematic diagrams of a self-cleaning filter using spark discharges in water:



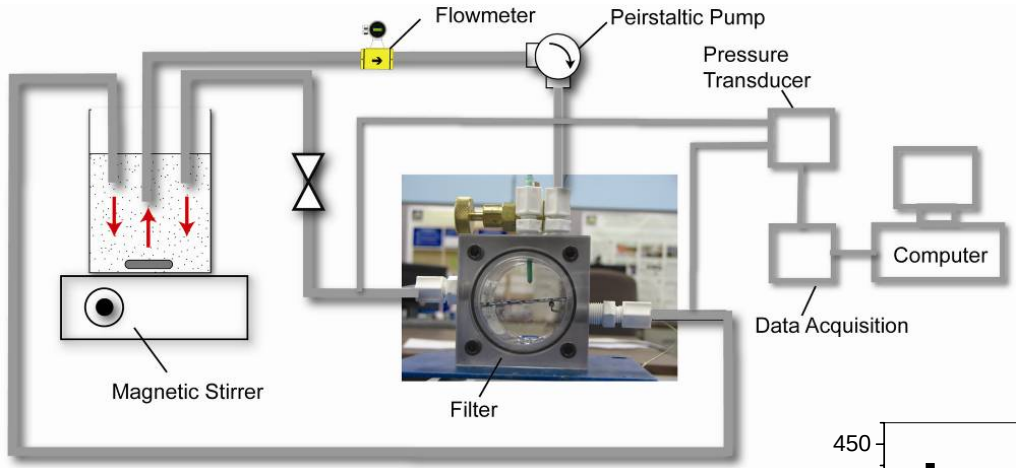


(a) glass spheres



(b) calcium carbonate particles

A Self-Cleaning Filtration System with Spark Discharge (Cooling Tower Water)



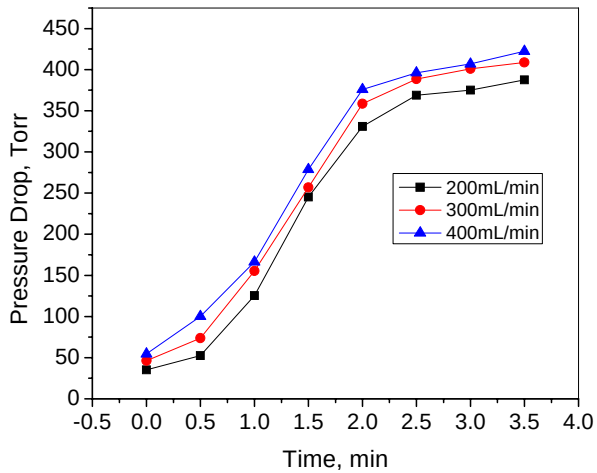


Fig. 4. Change of pressure drop under different flow rates using calcium carbonate particles produced by simulated cooling tower

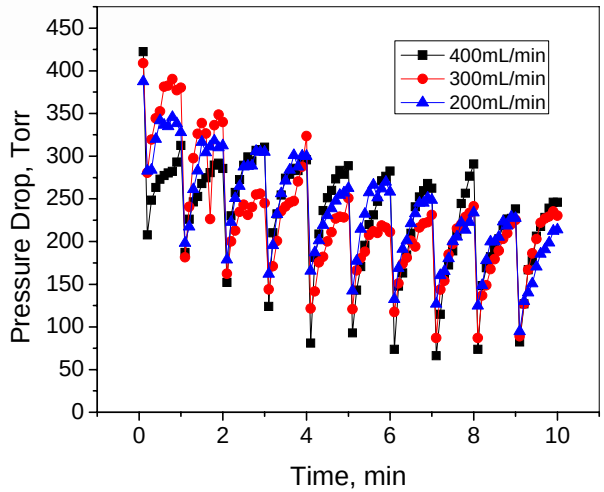
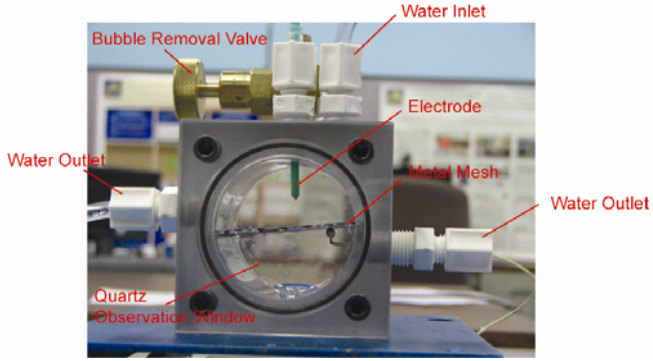
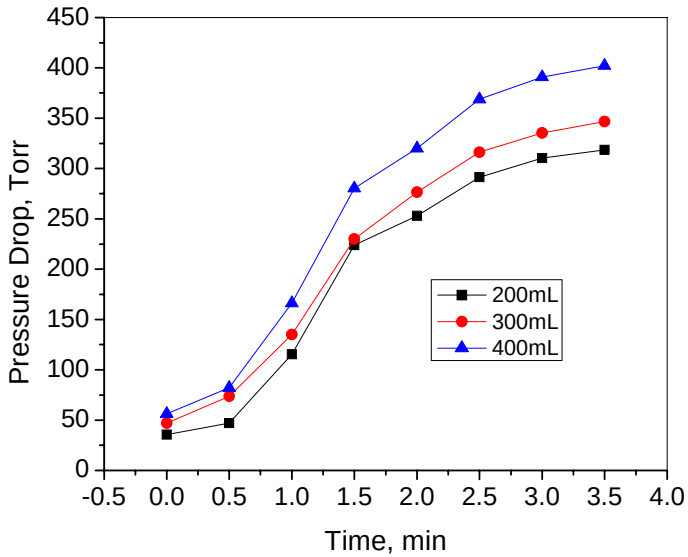


Fig. 5 Change of pressure drop under repeated pulsed spark discharges using $CaCO_3$ produced by simulated cooling tower

A Self-Cleaning Filtration System with Spark Discharge (Artificially Hardened Water)

An artificially hardened water with hardness of 1,000 mg/L of $CaCO_3$ from a mixture of calcium chloride ($CaCl_2$) and sodium carbonate (Na_2CO_3)





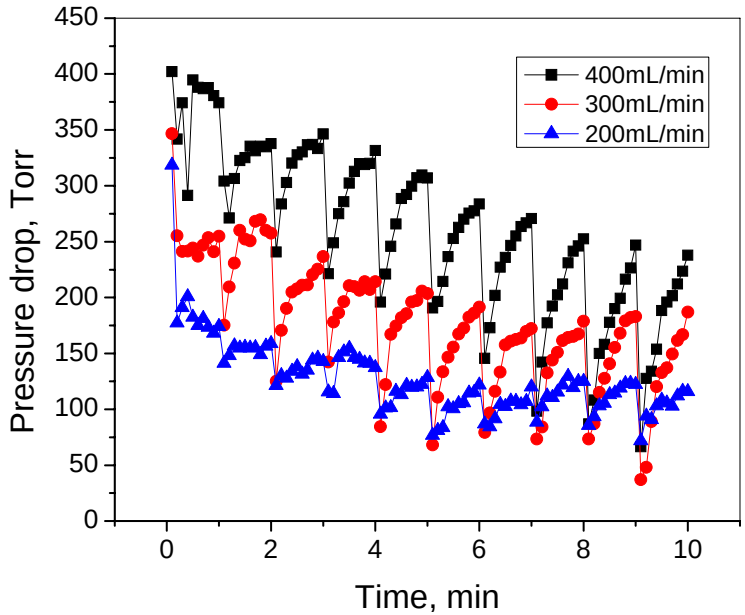
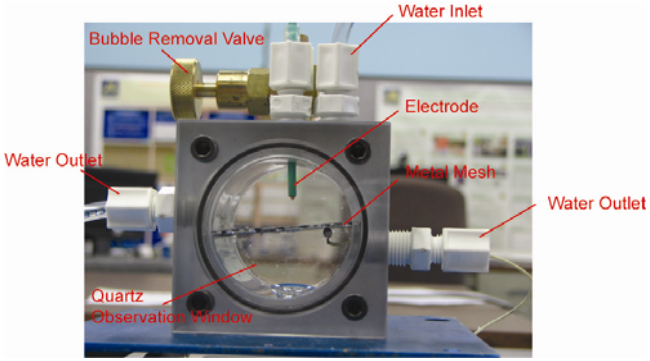
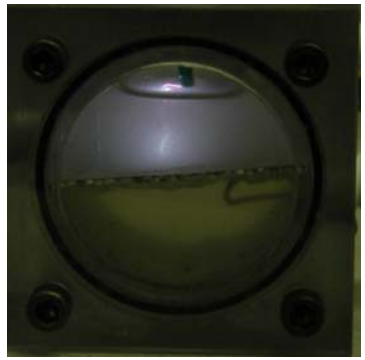


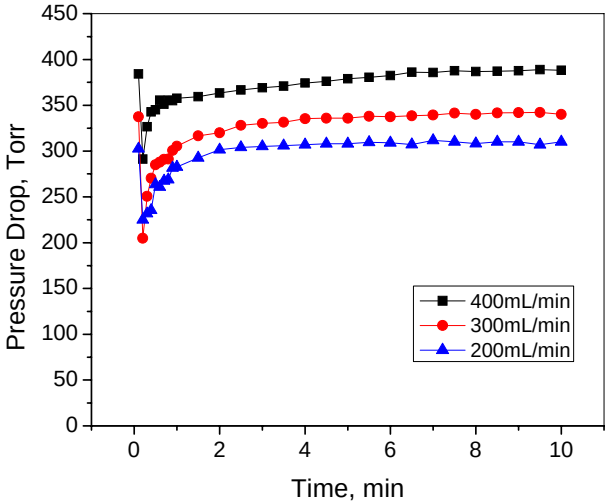
Fig. 7 Changes in pressure drop under repeated pulsed spark discharges with an artificially hardened water.

A Self-Cleaning Filtration System with Spark Discharge (Artificially Hardened Water)

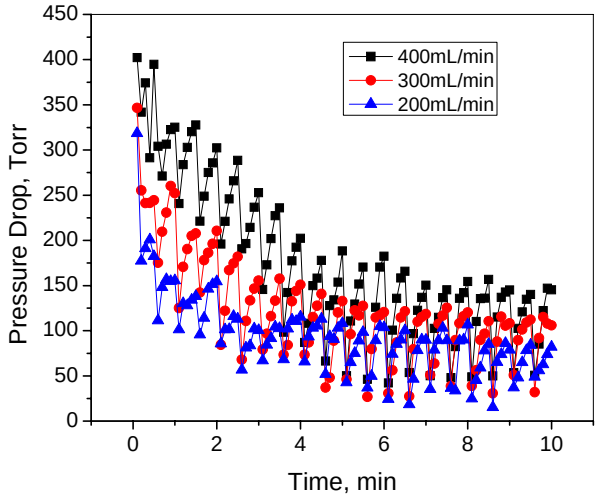




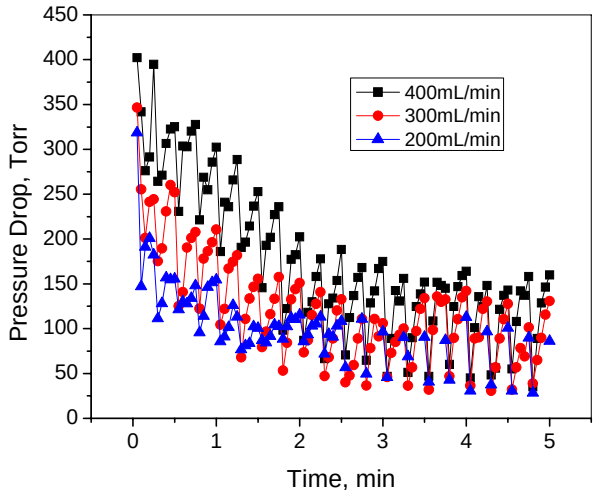
spark discharge



One single pulse only



2 pulses/min

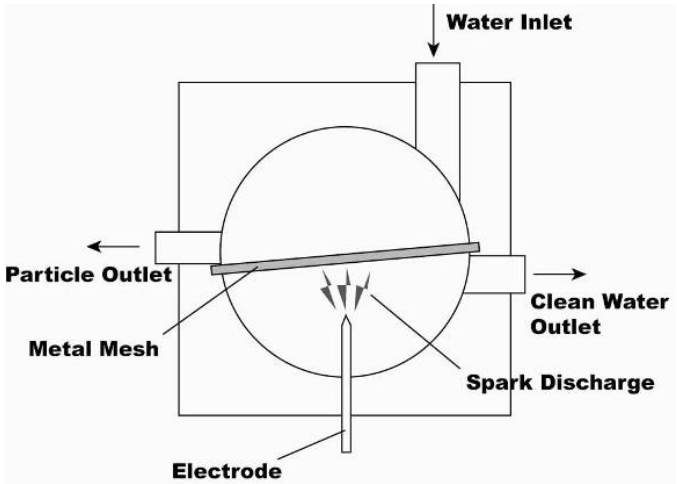


4 pulses/min

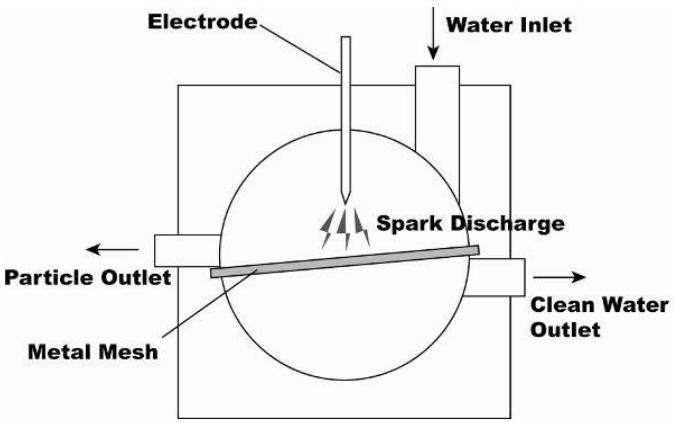
Fig. 10 Changes in pressure drop under repeated pulsed spark discharges with different frequencies with an artificially hardened water.

A Self-Cleaning Filtration System with Spark Discharge in Water

b



a



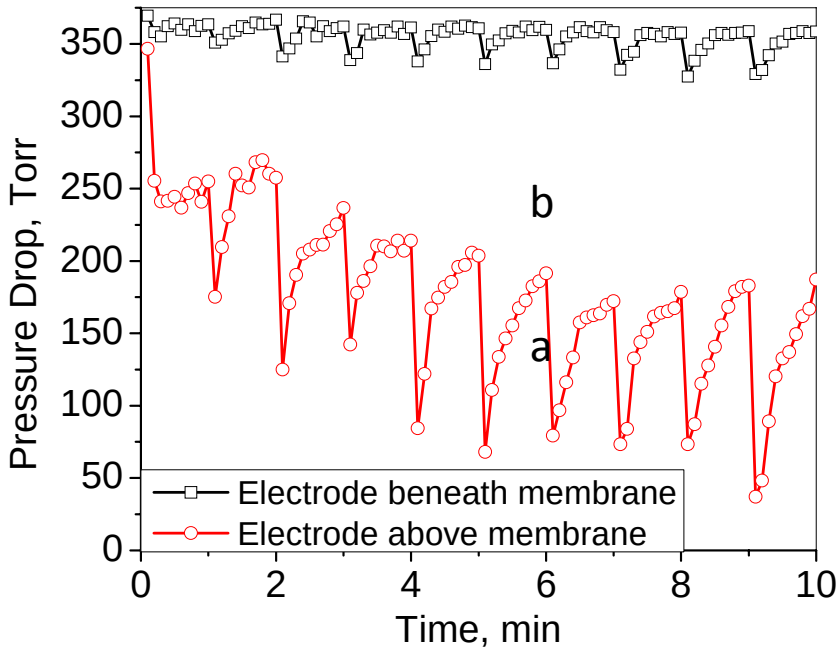


Fig 1. Schematic diagrams of a self-cleaning filter using spark discharges in water: (a) electrode on top; (b) electrode at bottom of the filter surface.

Construction of a Self-Cleaning Filter with Pulse Spark Discharge in Water

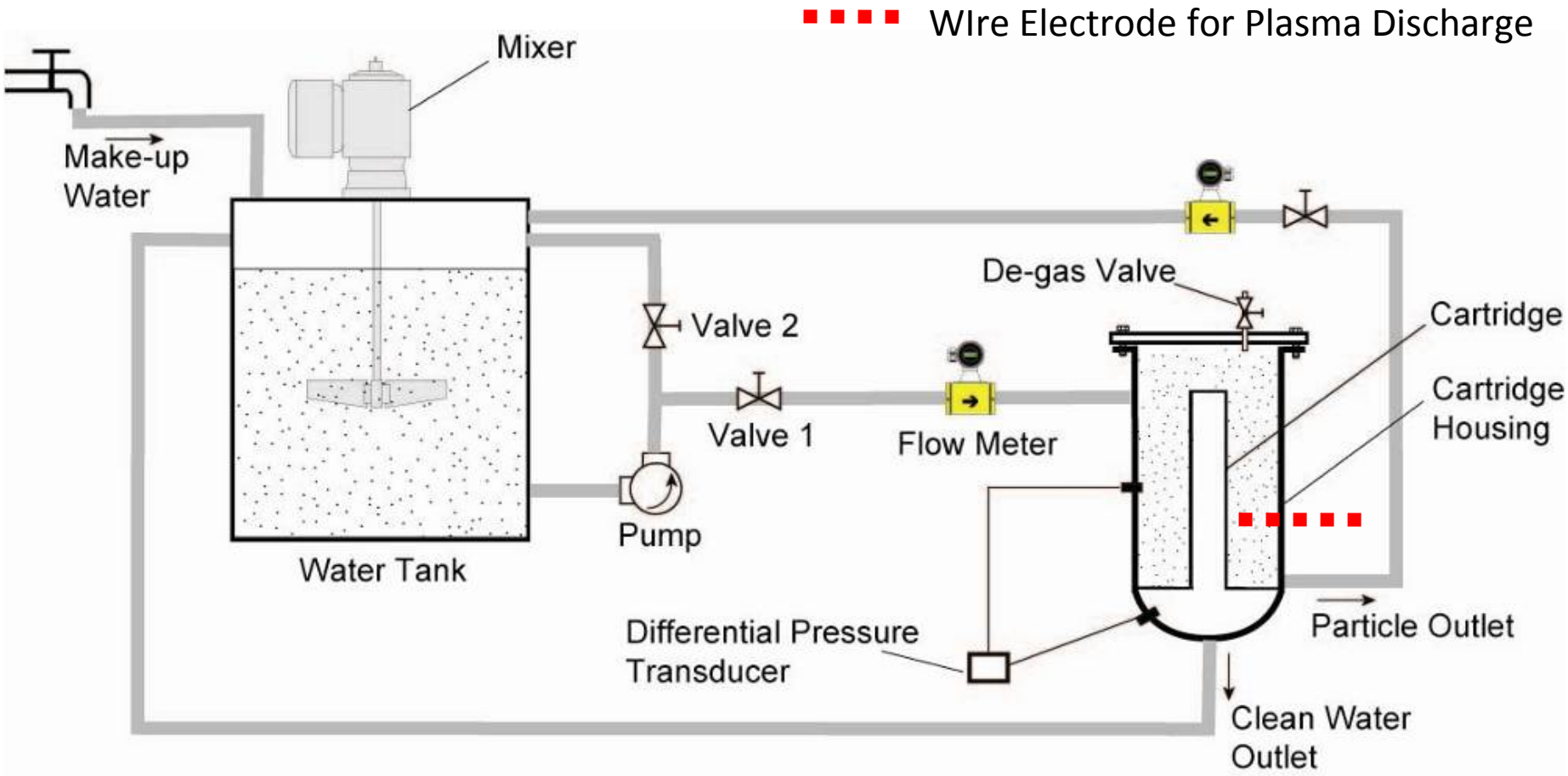


Fig. 1 Schematic diagram of the testing loop

Design Optimization of a Self-Cleaning Filter via CFD Modeling

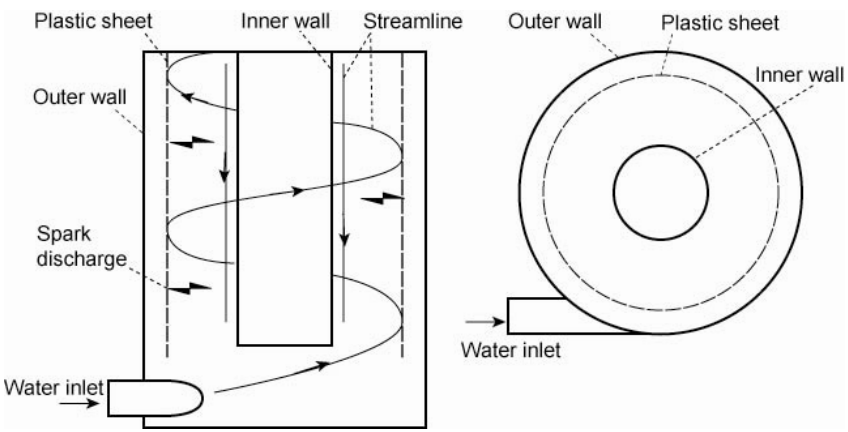


Fig. 7. Schematic diagram of new self-clean filter

Fig. 10. Velocity vector plot

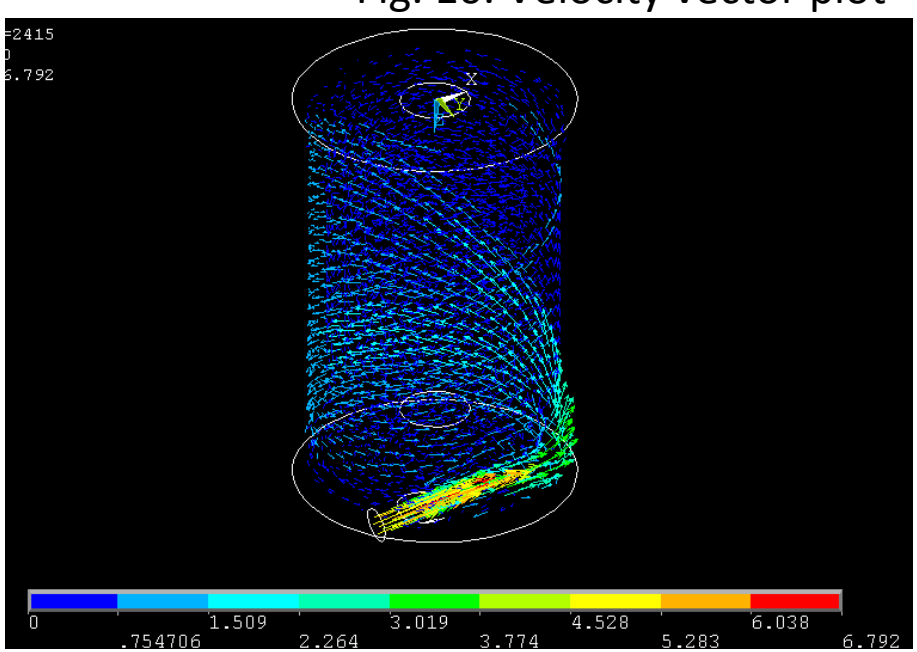
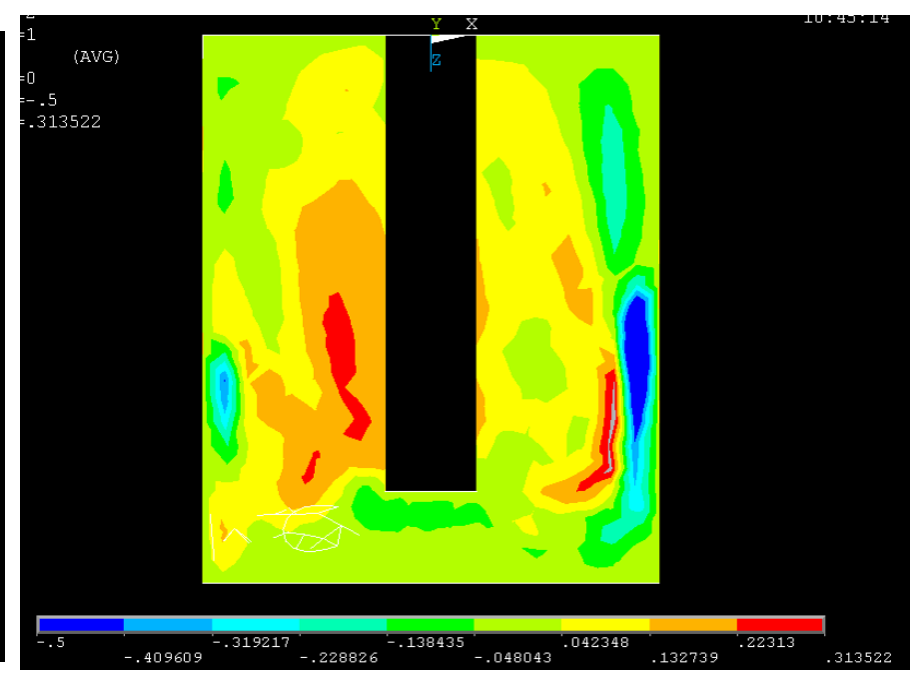


Figure 11 Velocity contour plot



Construction of a Self-Cleaning Filter and a Mini Cooling Tower

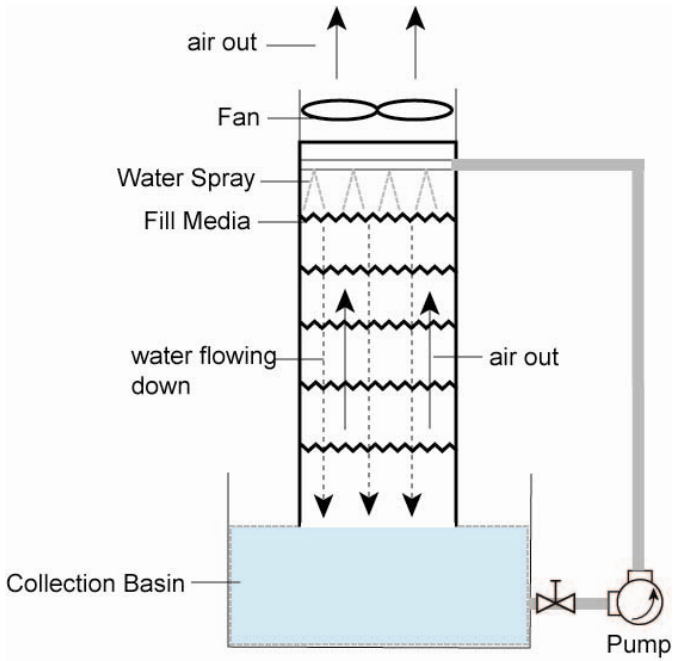


Fig. 4 Schematic diagram of the mini water cooling tower

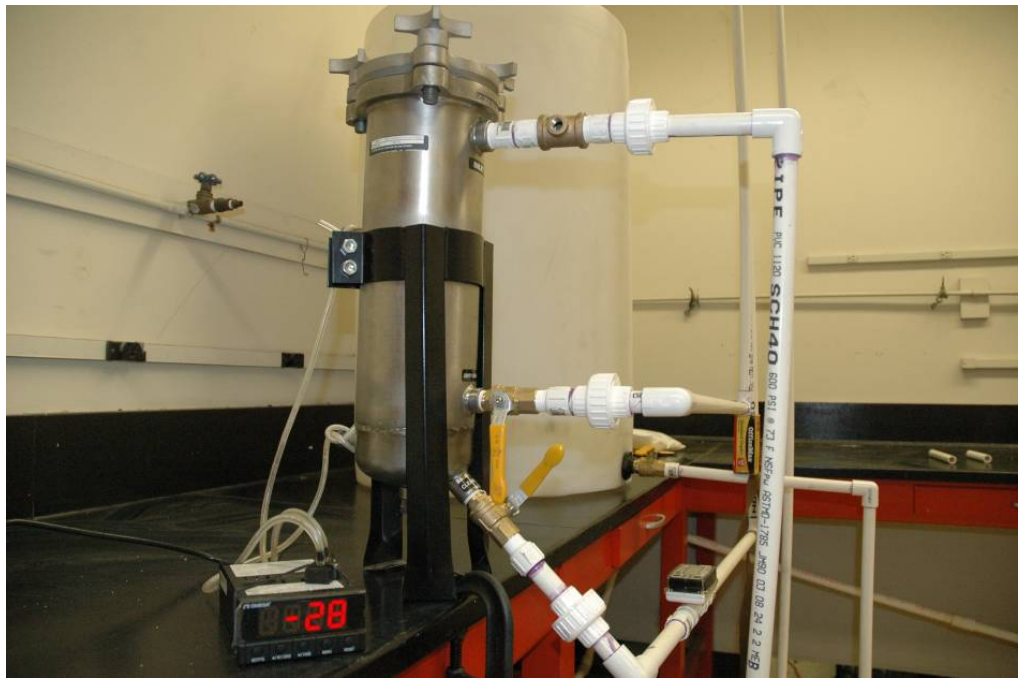


Fig. 3 Close up picture of the filter and pressure transducer

Construction of a Self-Cleaning Filter using Pulse Spark Discharge in Water

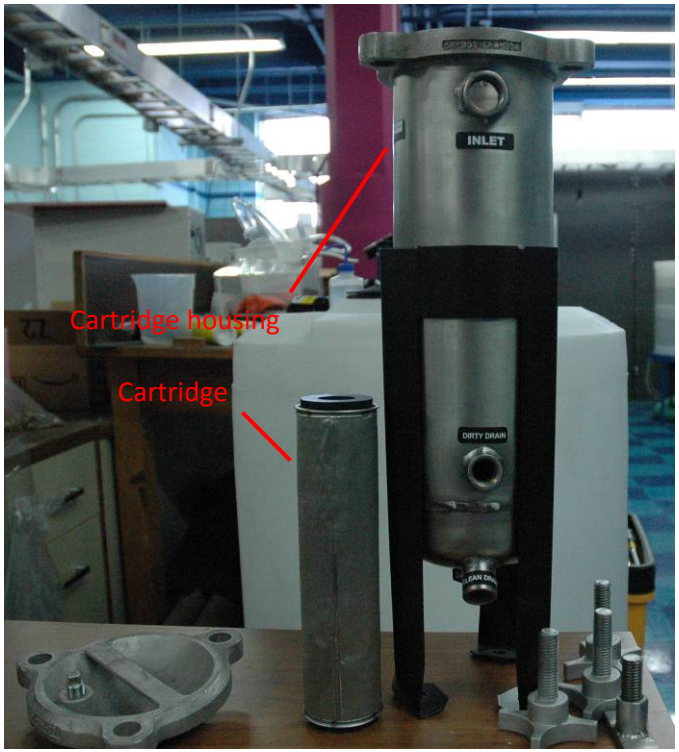


Fig. 5 Picture of a filter system with plasma generator

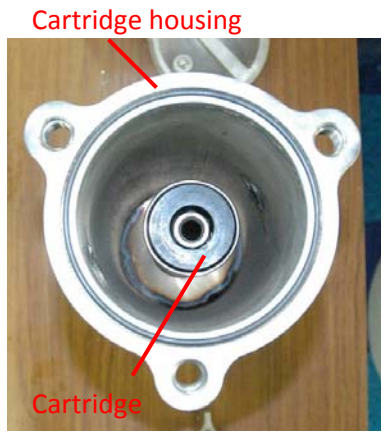


Fig. 6 Left: cartridge housing (side view). See a drain outlet at the bottom for the removal of debris; Right: cartridge housing and 10”-long cartridge (top view)

Pulse Spark Discharge inside 10-inch Long Filter using Wire-Plate Electrodes

(Top cover removed for photography)

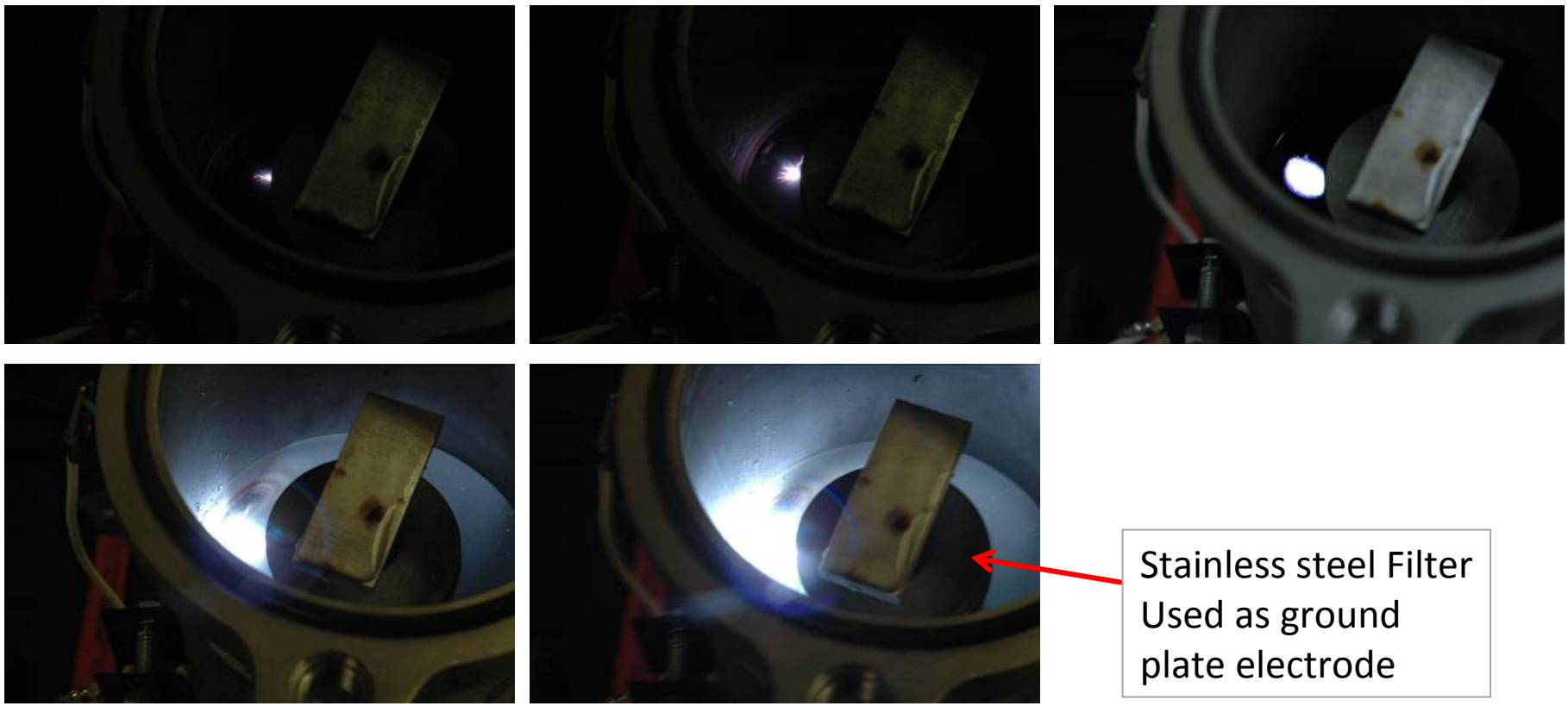


Fig. 6 Spark discharge to generate plasma inside filter case

Validation Test with a Self-Cleaning Filter

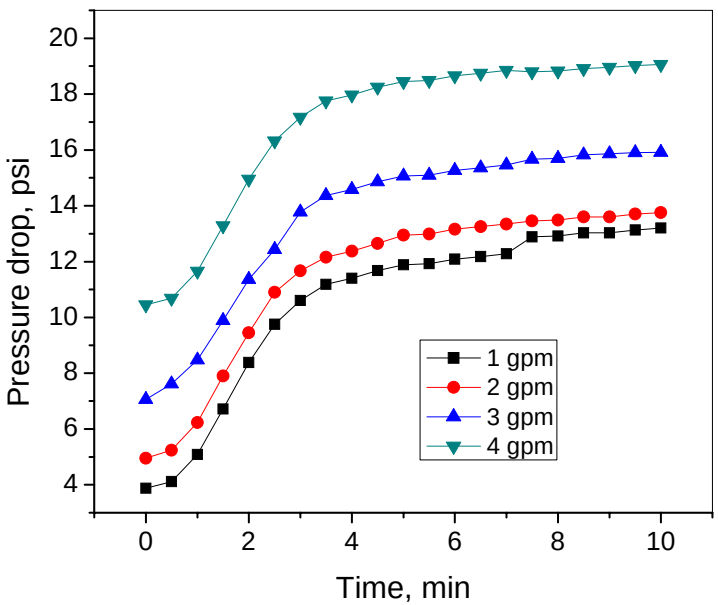


Fig. 3 Changes of pressure drop under various flow rates

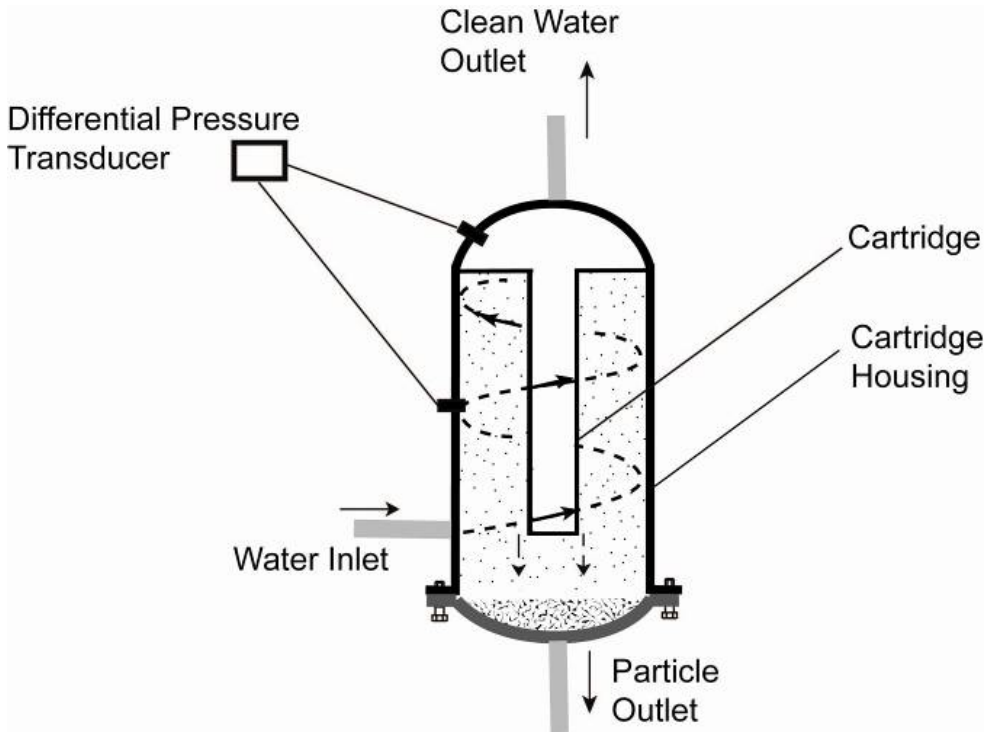


Fig. 7 Schematic diagram of the cartridge housing

Validation Test with a Self-Cleaning Filter with Pulse Spark Discharge in Water

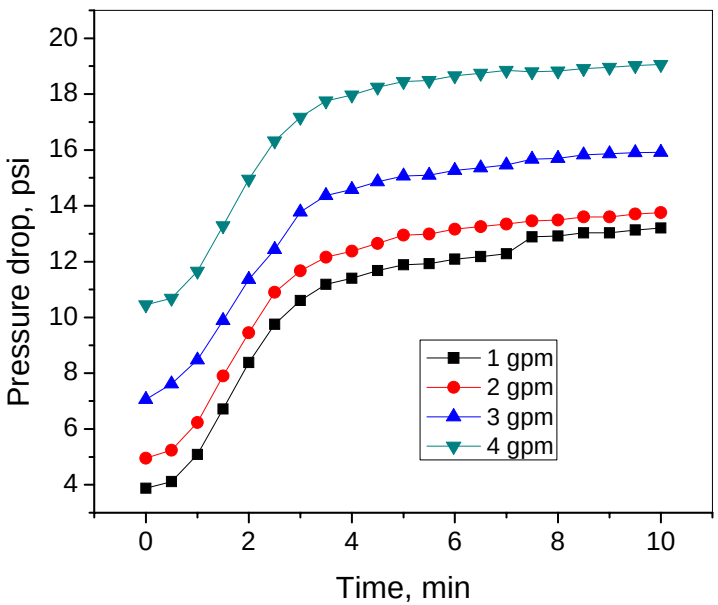
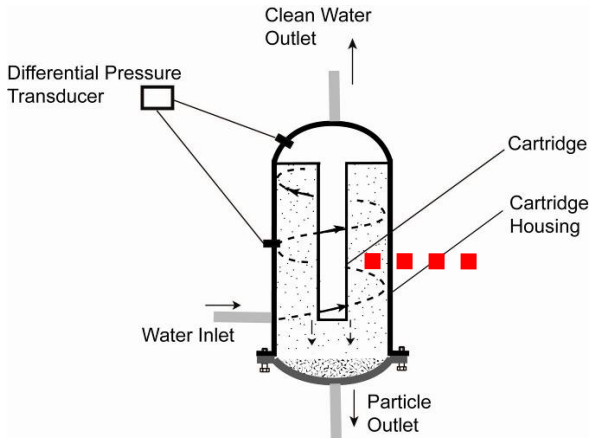


Fig. 3 Changes of pressure drop under various flow rates



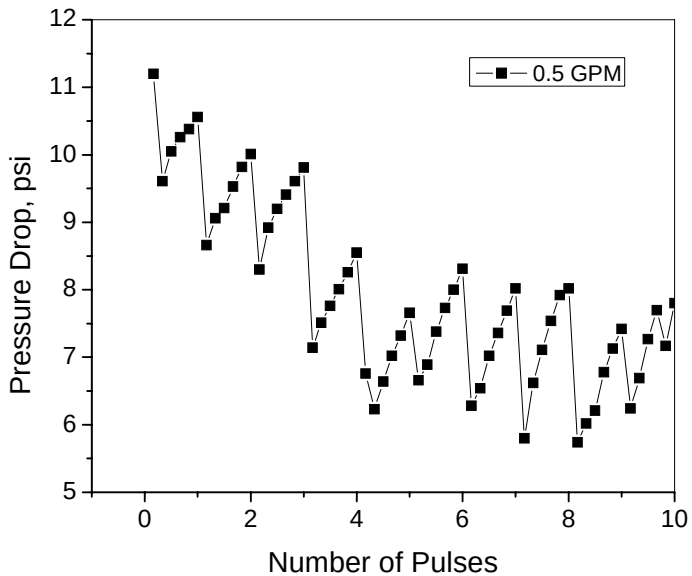
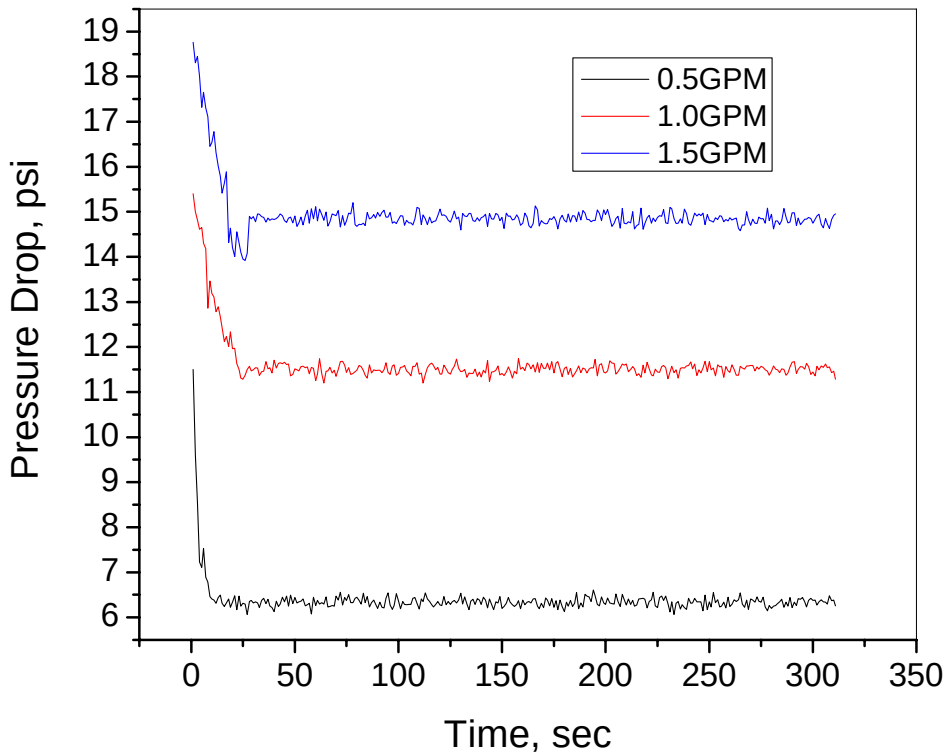


Fig. 7 Changes of pressure drop with spark discharge

Use of Spark Discharges to Maintain Constant Pressure Drop across Filter



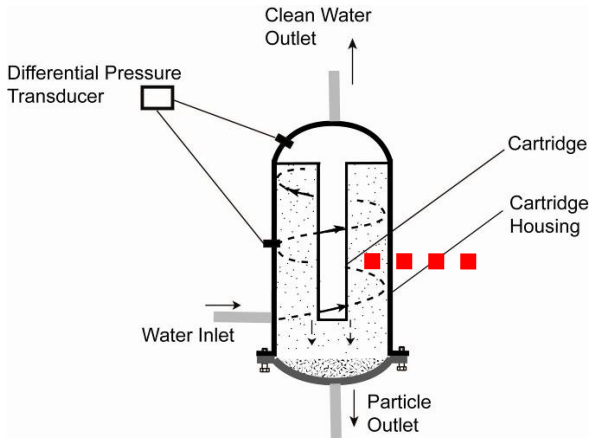


Fig. 9 Changes of pressure drop with spark discharge over an extended time period at different flow rates

Validation Test Using Spark Discharge to Prevent Bio-fouling in Cooling Water

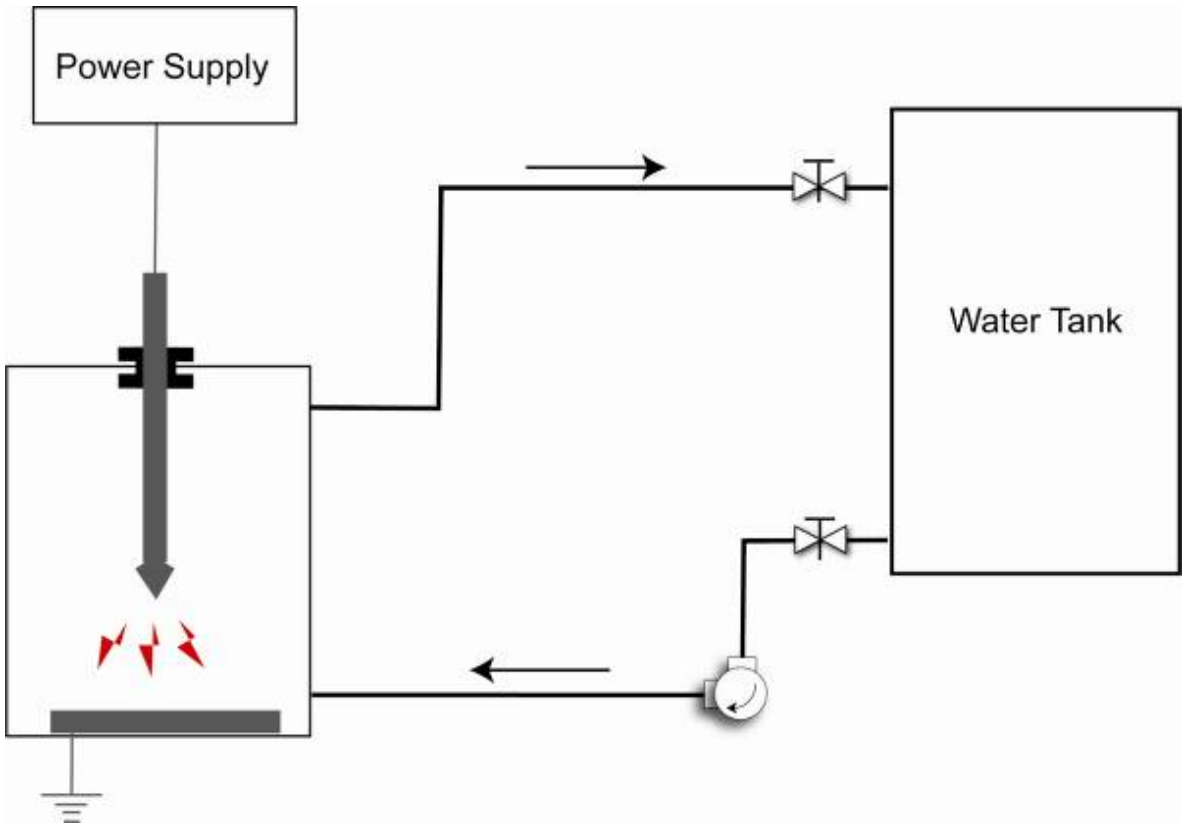


Fig. 10 Schematic diagram of the bio-fouling prevention system by spark discharge

Validation Test Using Spark Discharge to Prevent Bio-fouling in Cooling Water

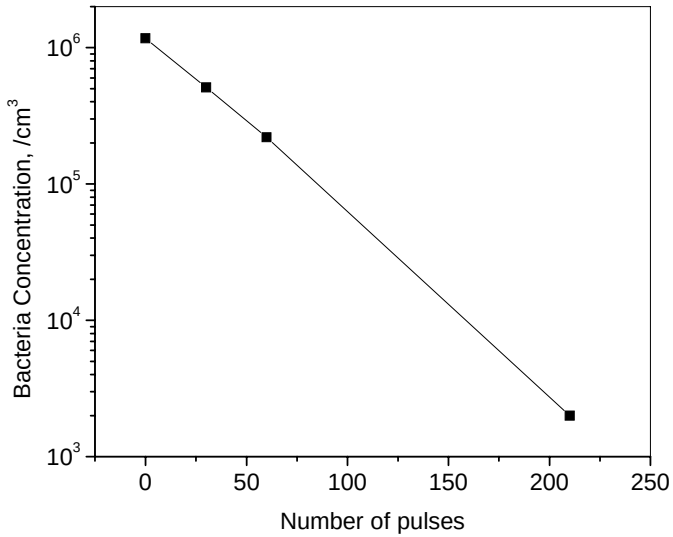


Fig. 11 *E. coli* deactivation efficiency by spark discharge in water

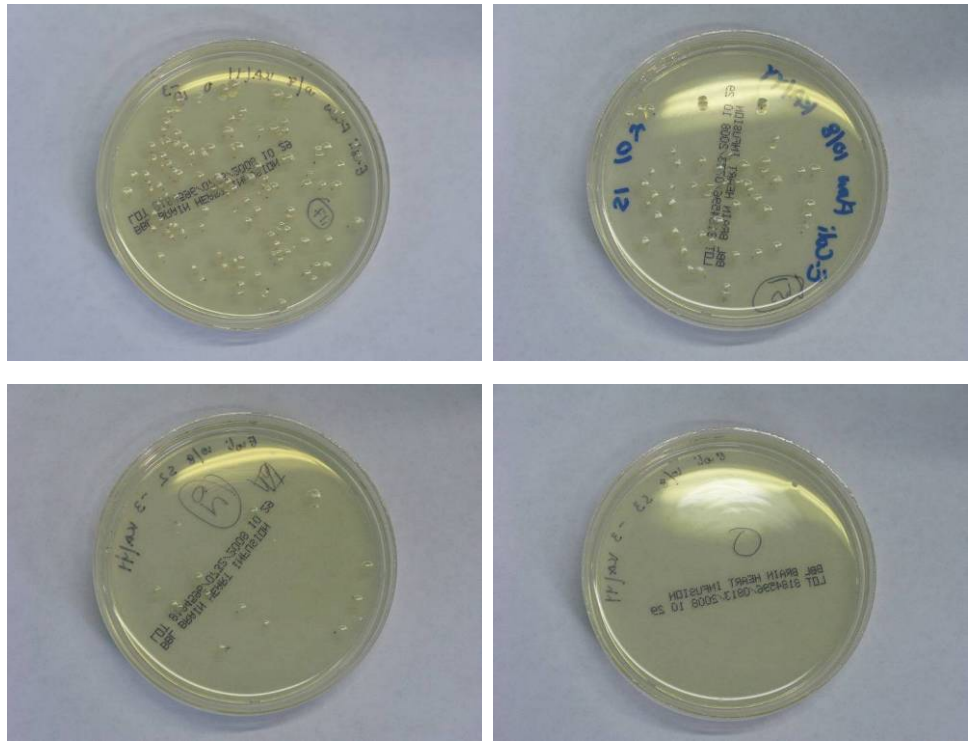


Fig. 12 Colony count of *E. coli* after spark discharge

E. coli Deactivation Efficiency by Spark Discharge in Water

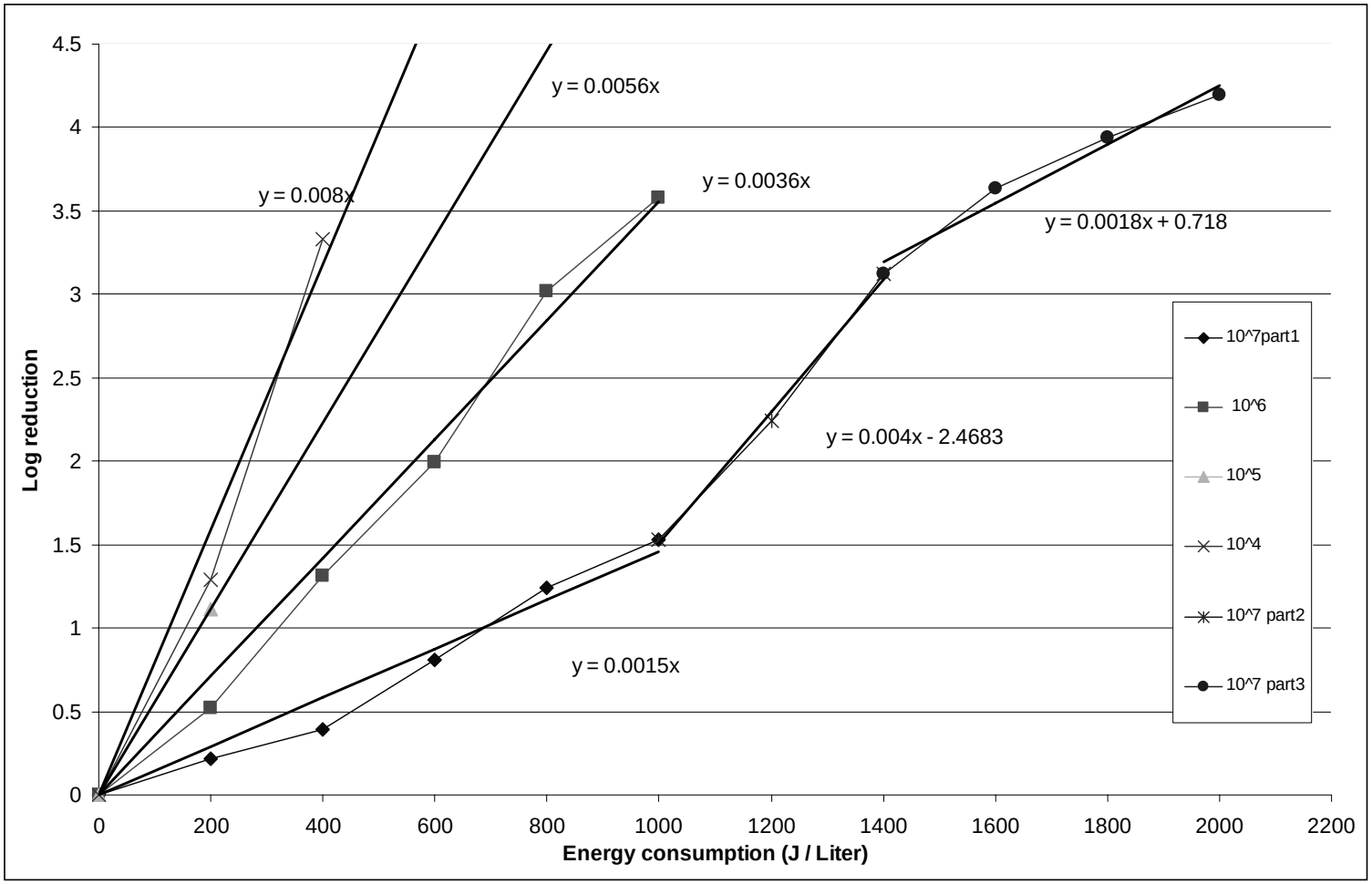


Fig. 13 E. coli deactivation efficiency by spark discharge in water depending on power input and on initial concentration of bacteria

Theoretical Modeling (Breakdown Mechanism)

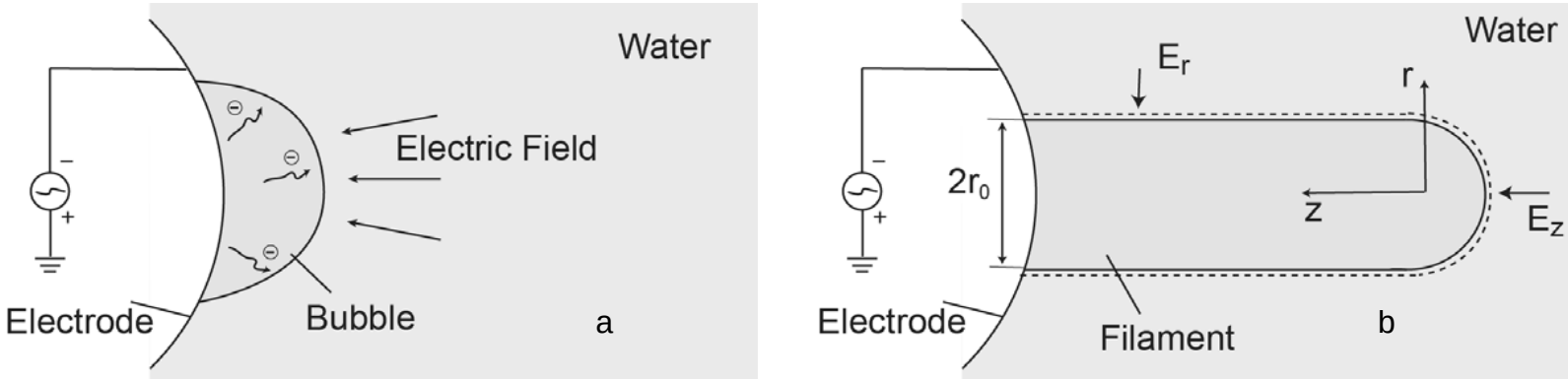


Fig. 1. (a) – initial bubble form at the moment of high voltage application; (b) – bubble elongation and gaseous plasma filament formation due to interaction of electrical forces with surface tension and external pressure forces.

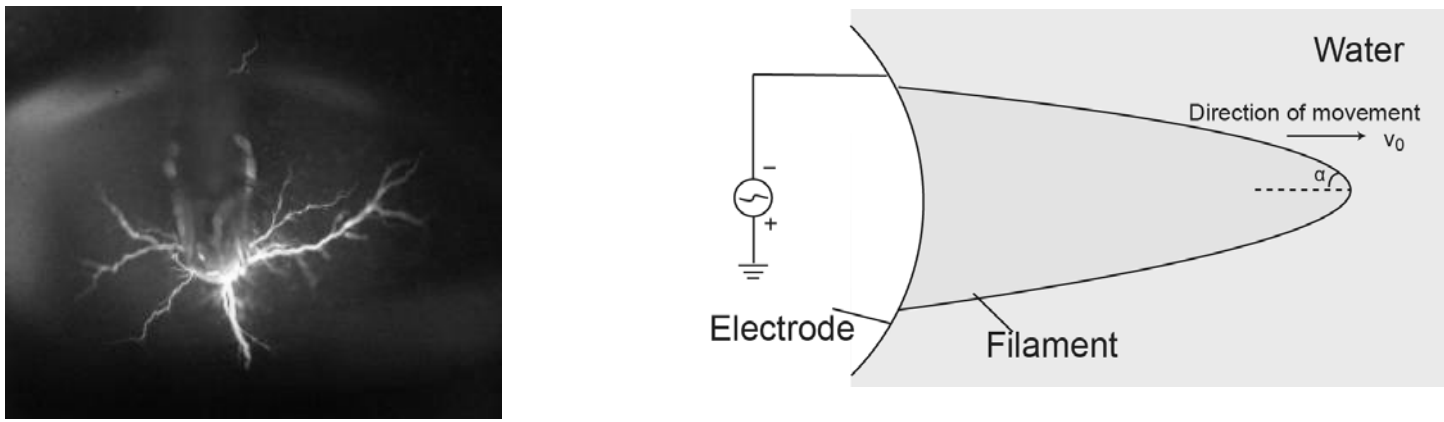


Fig. 2. (a) Photo of corona discharge in water; (b) schematic diagram of needle shape filament

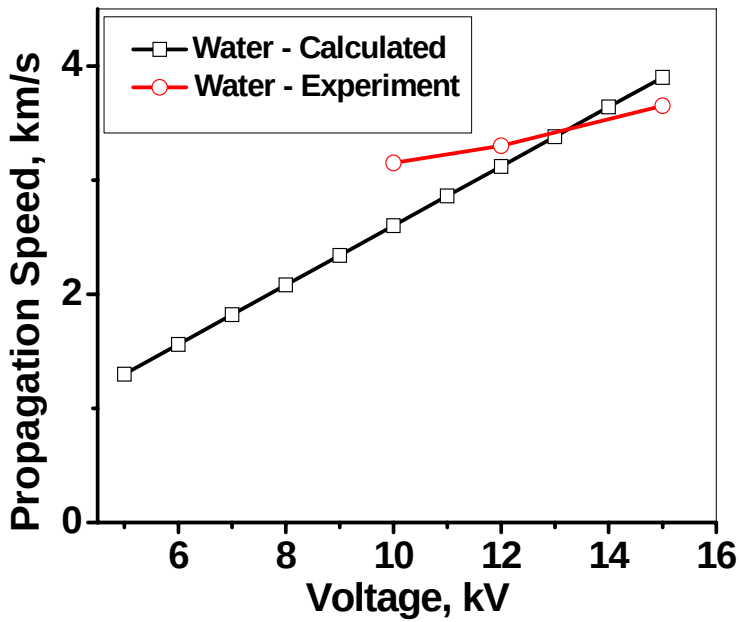
Theoretical Modeling (Breakdown Mechanism)

- Static Pressure – Surface Tension
- Hydrodynamic pressure

- Electrostatic Pressure

Balance → Max velocity of filament

$$v_0 = \frac{\Phi}{r_0}\sqrt{\frac{2\varepsilon_{water}}{\rho \tan\alpha}} \approx \frac{\Phi}{r_0}\sqrt{\frac{2\varepsilon_{water} L}{\rho r_0}}$$



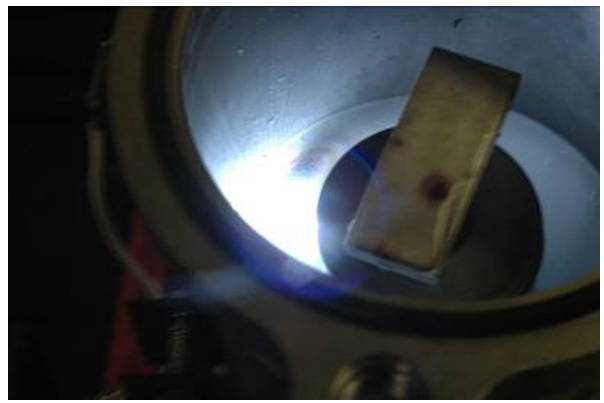


Fig. 3. Comparison of calculated and measured propagation speed of filament during breakdown of water

Theoretical Modeling (Breakdown Mechanism)

Stability Analysis

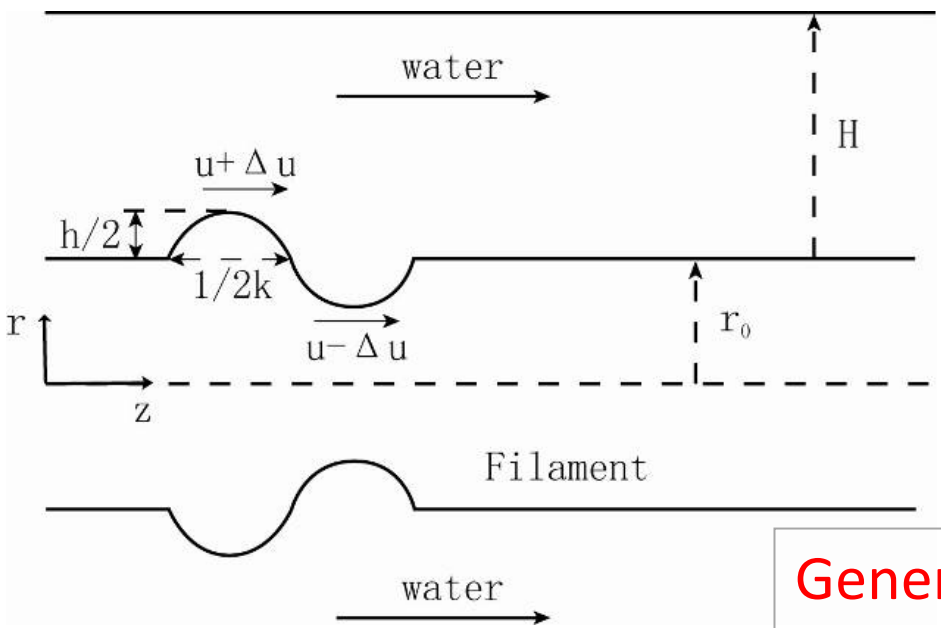


Fig. 4. Schematic diagram of disturbance at the surface of filament

Surface of the perturbation

$$r = r_0 + \frac{h}{2}\exp(ikz + iwt)$$

- Electrostatic Pressure
- Static Pressure – Surface Tension
- Hydrodynamic pressure

Generally, the surface tension tends to minimize the surface area and subsequently stabilize the disturbance, while the electrostatic force tends to push the disturbance to grow.

MILESTONE LOG

	Year 1	93006	31-Dec	3/31/2007	Year 2				Year 3			
Task Development of an integrated PWT and filtration system	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q	1Q	2Q	3Q	4Q
Task 1: Development of self-cleaning membrane filter												
Task 1.1: Review on self-cleaning filter technology	******											
Task 1.1a: Prepare a report on self-cleaning filter technology	*											
Kick-off meeting with DOE staffs		*										
Task 1.2: Theoretical modeling of dielectrophoresis	***	********										
Task 1.3a: Design of conductive filter (both lab visualization and field uses)		***	*******									
Task 1.3b: Design of pulse power supply			*****									
Task 1.3: Construction of complete filter system with pulse power system				*******								
Project review - Annual contractor review meeting				*								
Technical report - for the first year effort				*								
Task 1.4: Visualization of particle adhesion on filter medium with microscope				***	********							
Task 1.5: Visualization of particle dislodge from filter medium with microscope						*******						
Project review - semiannual						*						
Task 1.6: Optimization of filter design based on Tasks 1.4 ad 1.5						***	********					
Task 1.7: Construction of self-cleaning filters for fouling tests							***	********				
Project review - Annual contractor review meeting								*				
Technical report - for the second year effort								*				
Task 2: Validation test of an integrated PWT and self-cleaning filter system												
Task 2.1: Conduct baseline fouling tests - mineral fouling									***			
Task 2.2: Conduct baseline fouling tests - biofouling fouling										****		
Project review - semiannual										*		
Task 2.3: Conduct baseline test - combined mineral and biofouoling											******	
Task 2.4: Conduct test with integrated PWT - mineral fouling									*****			
Task 2.4: Conduct test with integrated PWT - biofouling										*****		
Task 2.4: Conduct test with integrated PWT - mineral and biofouling											*****	
Preparation of final report - draft												*****
Submission of the final report												*
Project review - Annual contractor review meeting (last)												*

Conclusions

Developed a novel self-cleaning filtration method using pulse spark discharge in cooling water.

$CaCO_3$ particles are continuously produced and removed.

The present technology can significantly reduce water blowdown, which accounts approximately 30% of water withdrawals in a cooling tower.