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Bench-Top Test Station for the Evaluation of Coalescer Filter Architectures that Remove Seawater Aerosols

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14. ABSTRACT

The intrusion of salt-water aerosols through the air intakes of turbines in surface vessels is a long-standing Navy concern, resulting in diminished performance under operation and the incursion of additional costs and delays associated with near- and long-term maintenance. To mitigate this problem, new filtration schemes must be developed that satisfy the following requirements: (1) supporting fast air-flow rates (0.1–10 m s–1) with negligible pressure drop; (2) removing seawater aerosols with high efficiency at those extreme flow rates, particularly targeting droplets/particles <20-μm in diameter; and (3) expressing mechanisms for either periodic regeneration or self-cleaning of the filter architecture with long-term use. The NRL is developing filter architectures comprising porous metal meshes whose surfaces are modified with microstructural features that interact specifically with flowing aerosols at high flow rates. The resulting "coalescer" filter captures small aerosol particles and encourages their growth to later droplets that are shed by gravity. This memorandum report details the test stand that the NRL has developed to routinely validate these coalescer filters at a bench-scale form factor, as a precursor to scale-up and testing with a room-size test apparatus at NSWC–Philadelphia Division. We detail the design of the test station and prescribe instruments and methods for the evaluation of coalescer architectures.

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INTRODUCTION

The maritime environment has long posed challenges for the operation and endurance of modern naval vessels due to the corrosive nature of seawater. One particular example is the ingestion fine seawater aerosols that traverse the air intakes of gas turbines and diesel engines of surface vessels, causing performance degradation within such systems. This problem has become more acute for low-profile ships, where the air intake must be located closer to the water line, and is thus more susceptible to aerosols generated not only by natural ocean turbulence but also from the ship's motion through the water. Mechanical separation systems can provide sufficient protection against hard particles (e.g., sand) and large aerosols, but the capture of small-particle seawater aerosols (0.1–10 µm) is more difficult, typically requiring a fiber-based filter. Civilian ships and off-shore platforms face similar operational problems with respect to corrosion from seawater aerosols,[1] but naval applications are particularly challenging due to the extreme air-flow rates that are required for high-power operation. Thus, any filters based on fiber mats or related porous structures must exhibit appropriately engineered scaffold dimensions that minimize pressure drop at high rates of flow through the air intake. Concurrently, smaller-scale features at the surface of the filter architecture are required to capture significant quantities of small-particle aerosols and molecular contaminants as they traverse the macroscale filter.

The high aerosol content of sea spray may lead to rapid saturation of the air-intake filter and the accumulation of high salt loadings that disrupt air flow, necessitating intermittent regeneration of the filter assembly. Designing new filter architectures with "self-cleaning"

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[1] "Gas Turbine Inlet Air Treatment." R.L. Loud, and A.A. Slaterpryce, General Electric, Schenectady, NY, 1991, https://powergen.gepower.com/content/dam/gepower-pgdp/global/en_US/documents/technical/ger/ger-3419a-gas-turbine-inlet-air-treatment.pdf.

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functionality would mitigate the need for frequent cleaning and maintenance as required in present filter systems. To achieve this goal, the surfaces of practical filter substrates should be redesigned with controlled hydrophobic/hydrophilic character. Fortunately, the wetting of surfaces by water has been extensively explored from a fundamental perspective, dating back to the pioneering work of Wenzel,[2] followed by Cassie and Baxter.[3] More recent research on wettability has been inspired by the recognition of self-cleaning properties exhibited by certain surfaces in nature,[4] with the lotus leaf being a notable example. The superhydrophobic behavior expressed by the lotus leaf and related natural materials arises from the combination of microtextured interfaces and controlled surface functionality, with the former amplifying the innate wetting properties of the latter.[5] These phenomena have since been mimicked in many artificial surfaces for the purpose of controlled wettability and water repulsion, taking advantage of micro/nanoscale fabrication tools that are presently available. Herein, we highlight some example filtration architectures developed at the NRL that selectively capture and shed seawater aerosols under high-flow-rate conditions, and describe a bench-scale test system to validate such filtration concepts.

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[2] "Resistance of Solid Surfaces to Wetting by Water." R. N. Wenzel, *Ind. Eng. Chem*., 28 (1936) 988-994.

[3] "Wettability of Porous Surfaces." A. B. D. Cassie and S. Baxter, *Trans. Faraday Soc*., 40 (1944) 546-551.

[4] "Bioinspired Surfaces with Special Wettability." T. L. Sun, L. Feng, X. F. Gao, and L. Jiang, *Acc. Chem. Res*., 38 (2004) 644-652.

[5] "Wetting Transition of Water Droplets on Superhydrophobic Patterned Surfaces." Y. C. Jung and B. Bhushan, *Scripta Materiala*, 57 (2007) 1057-1060.

COALESCER ARCHITECTURES The NRL design of a coalescer-type filter architecture comprises a conductive porous scaffold (e.g., copper mesh) whose surfaces have first been modified with microstructured metal features (e.g., zinc) and then further coated by a hydrophobic polymer. Electrodeposition is a readily adaptable and scalable method for creating the microstructural features at the copper substrates, and has previously been exploited to generate superhydrophobic surfaces in its own right.[6] The application of conformal, ultrathin polymer coatings to the microstructured metal surfaces further provides control over the surface energy, while also protecting against corrosion. In the following paragraphs, we briefly outline the steps in the development of surfaces and filter architectures that exhibit size-selective wetting/de-wetting properties for the capture and shedding of seawater aerosols (Figure 1). These are produced and tested at form factors suitable for fundamental, benchtop characterization.

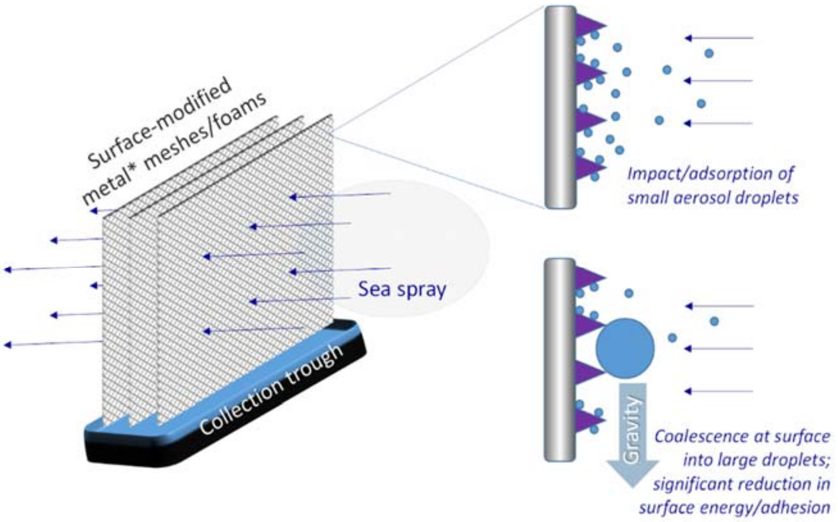

Figure 1. Schematic of coalescer filter design

Zinc metal can be electrodeposited onto conductive substrates in multiple morphologies including fractal, nodular, and/or plate-like microstructures by tuning the deposition conditions (i.e., varying current density, pulse width, and duty ratio of galvanostatic pulsed electrodeposition procedures; Figure 2). For example, high frequency, low-current-pulse reduction of Zn^{2+} from alkaline solutions generates Zn metal deposits as 1–10 μm "boulders" on an otherwise conformal

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[6] "Recent Advances in Superhydrophobic Electrodeposits." J. Tam, G. Palumbo, and U. Erb, *Materials*, 9 (2016) 151-177.

film of Zn, while high-current-pulses result in fractal “dendritic” structures. Depending on the microstructure, it has been shown that these features can play a governing role in the degree of hydrophobicity. For our coalescer-type filters, we target surfaces such that the size, aspect ratio, and spacing of the electrodeposited Zn features work in concert to yield modified meshes that readily capture small aerosol particles (0.1–10 μm), which subsequently coalesce to larger droplets. Once the droplets reach critical size, they necessarily become repelled from the microtextured surface due to the formation of air gaps beneath the porous regions.

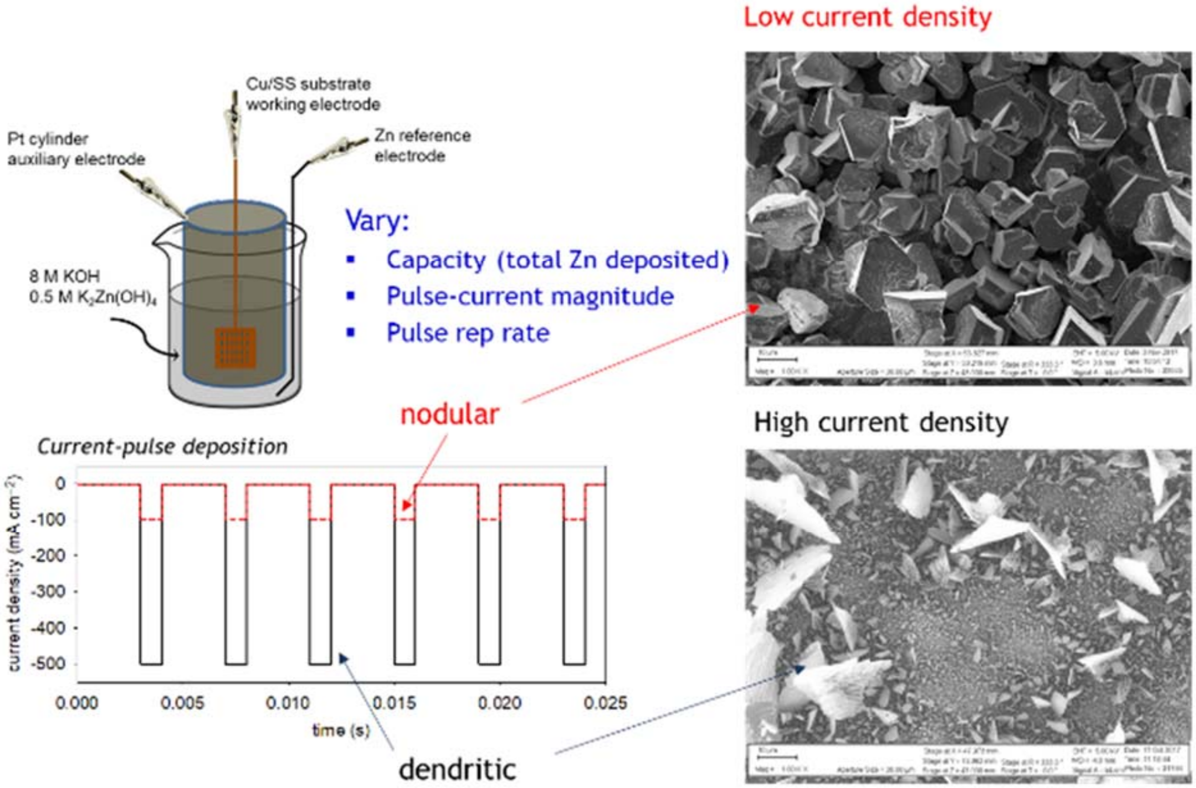

Figure 2. (left) electrodeposition protocol and example pulse duty cycle; (right) scanning electron microscopy of microstructures derived from low current density (nodular) and high current density (dendrites)

Microstructuring alone, however, may not be sufficient to achieve the desired wetting/de-wetting properties in the coalescer design, as Zn metal itself is hydrophilic. Therefore, we apply ultrathin polymer coatings at Zn-modified substrates as a means to further control surface energy. Initiated chemical vapor deposition (*i*CVD), developed by Prof. Karen Gleason at MIT in the early 2000s,[7] provides excellent control of nanoscale thickness and uniformity in vapor-deposited polymer coatings that are based on free-radical polymerization of vinyl-containing monomers at the desired surface. The NRL has established expertise and instrumentation to perform *i*CVD, having previously demonstrated the ability to conformally coat complex 3D objects with *i*CVD-derived polysiloxanes.[8] The moderately hydrophobic nature of the common *i*CVD polymers may be translated to superhydrophobic upon application to the microstructured Zn surfaces, yielding interfaces that are highly repellant to seawater droplets. The ultrathin polymer coating also serves as a protective barrier to minimize corrosion at the underlying Zn surface when exposed to salt water.

BENCH LEVEL COALESCER TESTING APPARATUS

The adsorption, coalescence, and shedding performance of the filters of interest must be evaluated on the small scale before scaling to sizes relevant to real-world air intakes, especially given the number of variations of metal microstructures and mesh sizes, and with and without the presence of the polymer coating. We designed and constructed a bench-scale test apparatus that mimics the flow dynamics of aerosol-laden air through a prospective filter/intake architecture. The dimensions of the bench-top testing apparatus is scaled down from the industrial room-size apparatus presently used at the Naval Surface Warfare Center–Philadelphia Division for validating ship-scale filter systems (Figure 3-A). Our testing platform simplifies the design of the model

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[7] "Initiated and Oxidative Chemical Vapor Deposition of Polymeric Thin Films: iCVD and oCVD." W. E. Tenhaeff and K. K. Gleason, *Adv. Func. Mater.* **18**, (2008) 979–992.

[8] "Synthesis of Poly(4-vinylpyridine) Thin Films by Initiated Chemical Vapor Deposition (iCVD) for Selective Nanotrench-Based Sensing of Nitroaromatics." W. E. Tenhaeff, L. D. McIntosh, and K. K. Gleason, *Adv. Func. Mater.* **20**, 1144–1151 (2010).

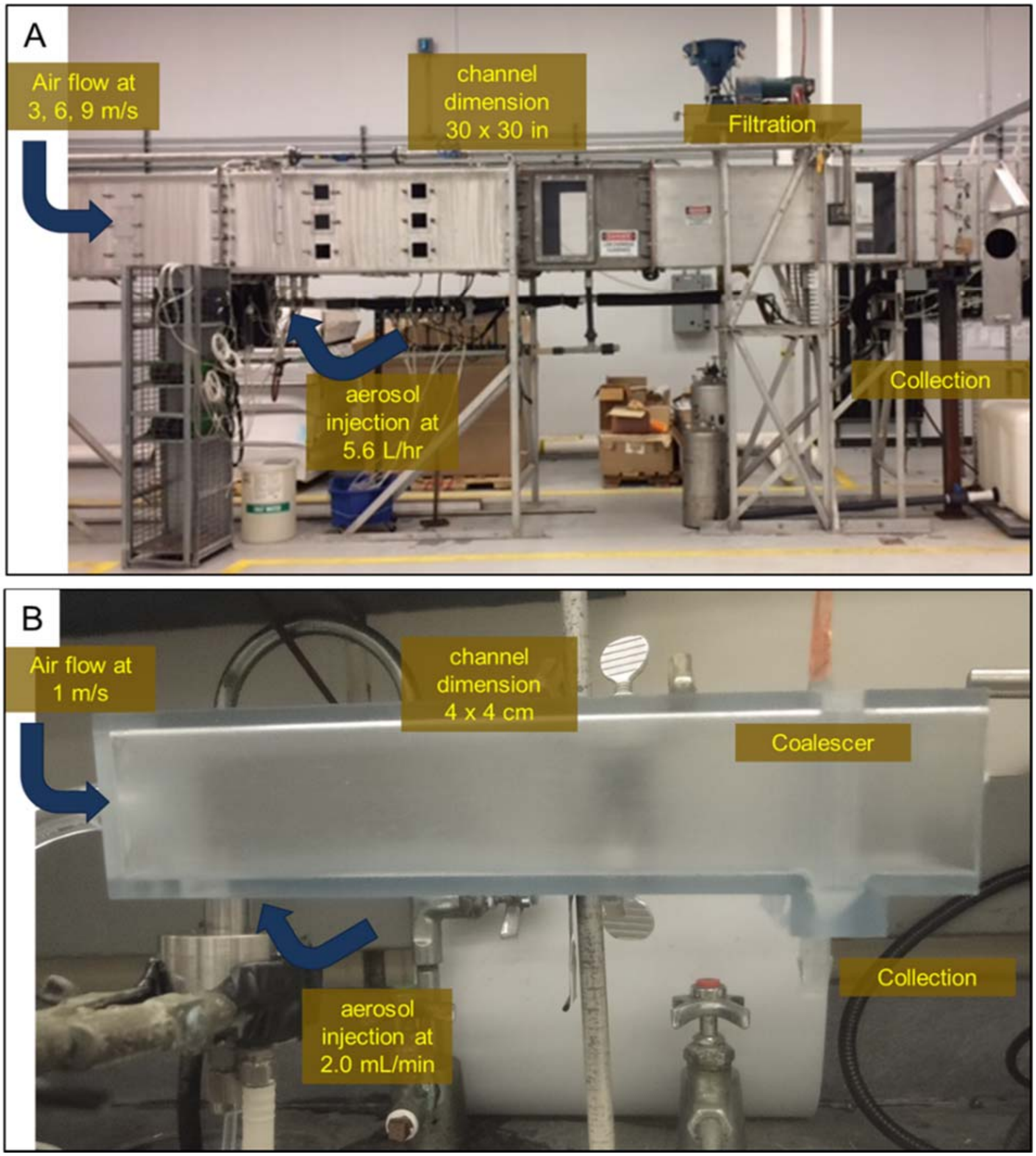

Figure 3. (A) Room-size apparatus presently used at NSWC–Philadelphia for the simulation of air-intake filtration systems, and associated dimensions, flow velocities, and aerosol injection rates. (B) Bench-top coalescer test station analog.

system by focusing solely on the channel relevant to the filter/coalescer section. The system at NSWC-PD uses a rectangular channel that is roughly 28 in × 30 in × 120 in ($a \times b \times L$), with a linear flow velocity vector, $\langle v_z \rangle$, that is typically 1–10 m/s.

We miniaturized this testing apparatus to allow high-throughput evaluation of surface-modified samples; the channel geometry is reduced to 1.5 in × 1.5 in × 10 in (Figure 3-B). This apparatus is plumbed to a larger system (Figure 4) that includes an aerosol generator and nebulizer nozzle (Sono-Tek)[9] that is fed by an artificial seawater solution (Instant Ocean) to deliver aerosol droplets of controlled diameter (1–20 μm droplet range) with concentrations of aerosols to the air stream that mirrors that at NSWC-PD. A controlled flow-rate of compressed air dictates the velocity of the sea spray (Figure 4).

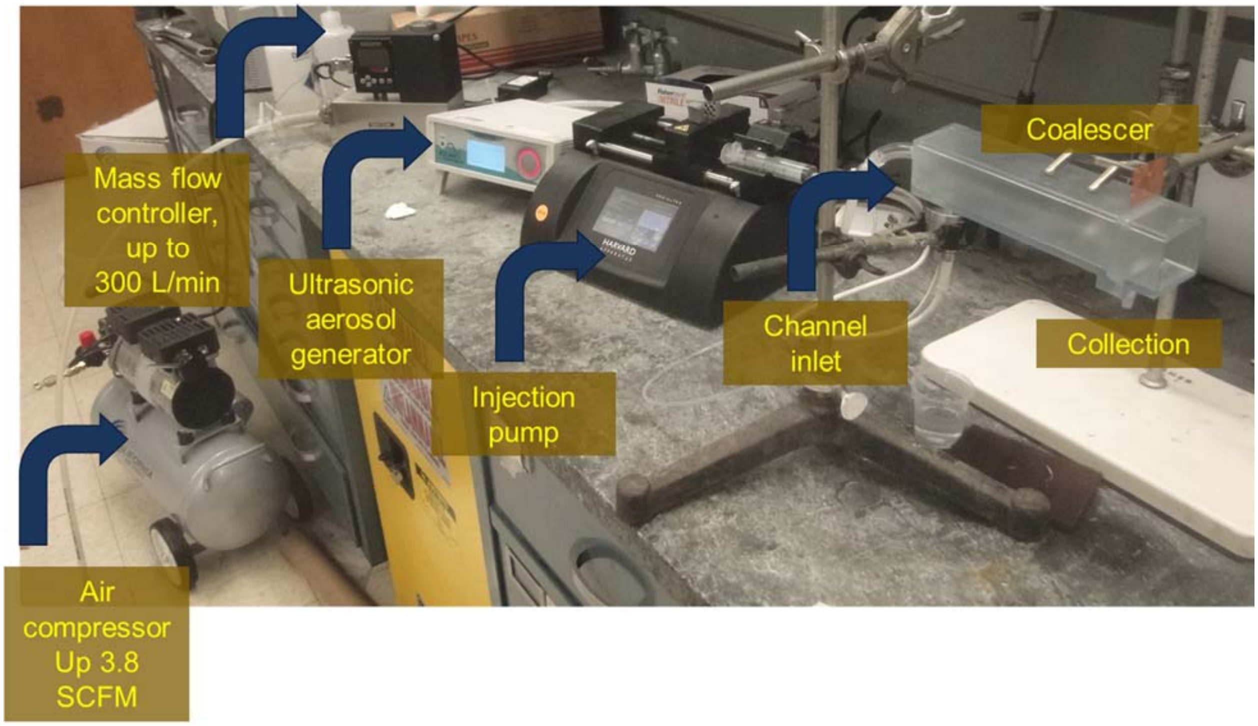

Figure 4. Full bench-top coalescer test station.

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[9] “Factors Affecting Aerosol Performance during Nebulization with Jet and Ultrasonic Nebulizers.” H. Steckel and F. Eskandar, *Eur. J. Pharm. Sci*., 19 (2003) 443.

Figure 5 shows a CAD model of NRL's bench-top coalescer evaluation cell. Multiple filters can be placed in the filter slots that allow for sea-spray collection into a graduated cylinder. The flow of salt water to the aerosol generator is also controlled and thus enables the calculation of filtration efficiency, which is defined as the volume of liquid aerosol collected in the graduated cylinder divided by the total aerosol volume sent through the evaluation cell. Any non-collected sea spray escapes to the atmosphere out of the open back of the cell.

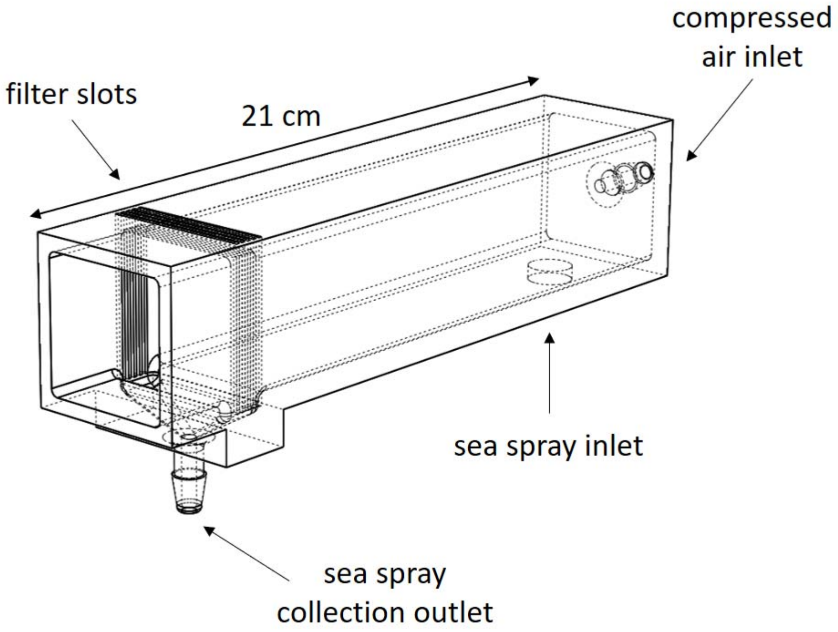


Figure 5. CAD model of NRL's bench-top coalescer evaluation cell.

A key consideration in the design of the evaluation cell is to ensure that sea spray velocity is equal to the velocity of the compressed air that is piped into the cell. The sea spray created by the aerosol generator starts out with a low velocity that is not necessarily in the direction that is perpendicular to the filters. By calculating the Reynold's number of a droplet in the apparatus, we use Stoke's law for a solid sphere in air to determine when the sea spray reaches a velocity that is equal to the velocity of the compressed air (Figure 6). Based on this calculation, we find that a sea-spray particle will reach the velocity of the compressed air after traveling a distance of only 1 cm, which means that the length of the NRL evaluation cell is sufficient and that the sea spray particles are in fact traveling at the speed of the compressed air once they reach the filtration-slot area.

EXAMPLE TESTING WITH NRL-DEVELOPED COALESCER ARCHITECTURES

The test stand described above was invaluable for evaluating a large series of coalescer filters developed at the NRL in 2017–2019, comprising copper meshes modified with electrodeposited zinc (varying amount deposited and specific morphology) and *i*CVD-derived nanoscale polymer coatings. Typical testing protocols involved: (*i*) insertion of copper screen, cut to appropriate dimensions into slots on the the test cell; (*ii*) initiation of aerosol generation and flow, typically at ~1 m/s linear velocity and a 2 mL/min aerosol delivery rate; (*iii*) collection of captured/shed water droplets in a graduated cylinder beneath the wetted copper mesh, recording volumes every 10 min; (*iv*) in some

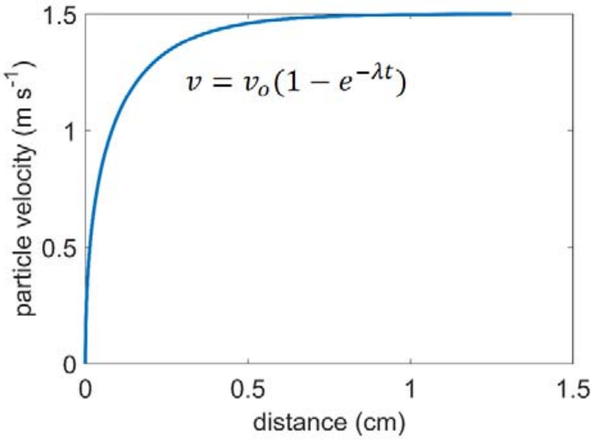


Figure 6. Sea-spray particle velocity versus distance traveled in tube.

cases, imaging the droplet formation/shedding process, as described below; and (*v*) terminating the aerosol flow, followed by removal of the copper screen, which is sometimes rinsed, dried, and retested.

Figure 7. Output of evaluation cell, highlighting a collection drop into a graduated cylinder and the escape path of the non-collected aerosol.

Our experience with using this cell for testing highlighted some nuanced considerations. For example, the cell should be slightly tilted backward (opposite the direction of flow), such that any water accumlating on the walls of the cell prior to intersecting the copper screen can be drained through a hole in the back, near the aerosol-generating nozzle. Half or more of the aerosol volume may collect and drain through this route. Subtracting this "backwash" volume provides a more accurate measure of the volume of aerosol that the copper mesh actually encounters. An important parameter that this cell design does not presently address is that of pressure drop/flow resistance.

In addition to examining the capture/shedding properties of individual copper screens, our test cell also allows up to five screens to stacked perpendicular to the aerosol flow, with spacing between screens set by the number of open slots between them. Multiple screens may increase filtration efficiency, as shown in the example in Figure 9 below, though pressure drop may also increase.

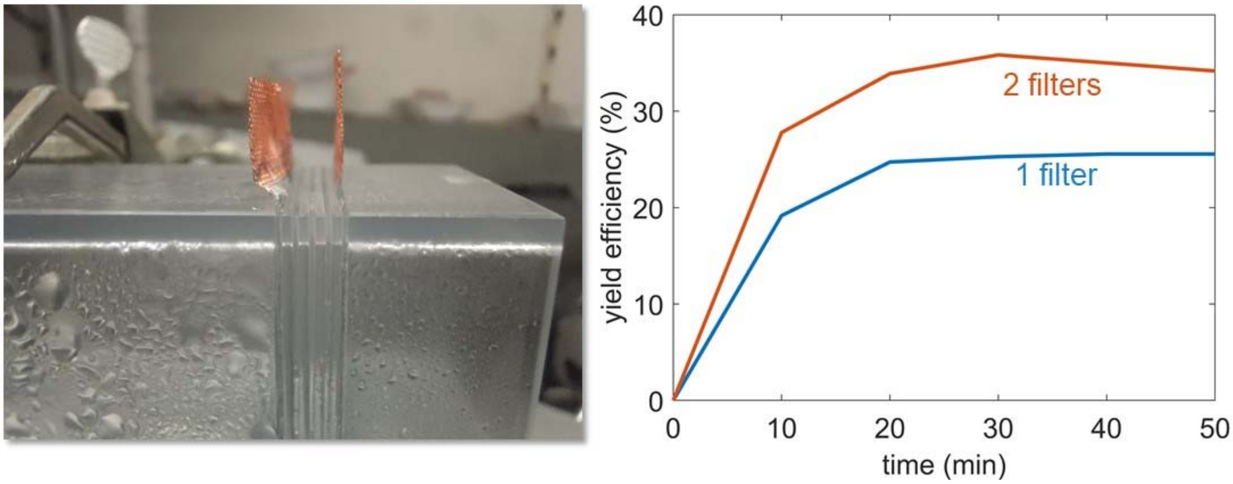
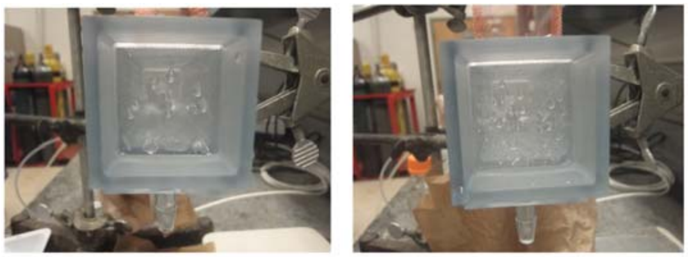


Figure 8. (left) Coalescer Filter evaluation cell with two consecutive filters in line (right) the impact of multiple filters on yield efficiency, demonstrating a 40% increase in collection efficiency with two filters over one..

The open end of the test cell permits optical microscopy and video recording of these copper screens. We image our various substrates under dynamic conditions as these surfaces are exposed to flows of aerosol-saturated air, allowing us to track the progress of initial droplet impact/adsorption, coalescence to larger droplets, and shedding. We directly observe the critical droplet size at which gravitational forces overcome adhesion forces as the droplets fall from the filter surface.

End-on images of coalesce screens under aerosol exposure



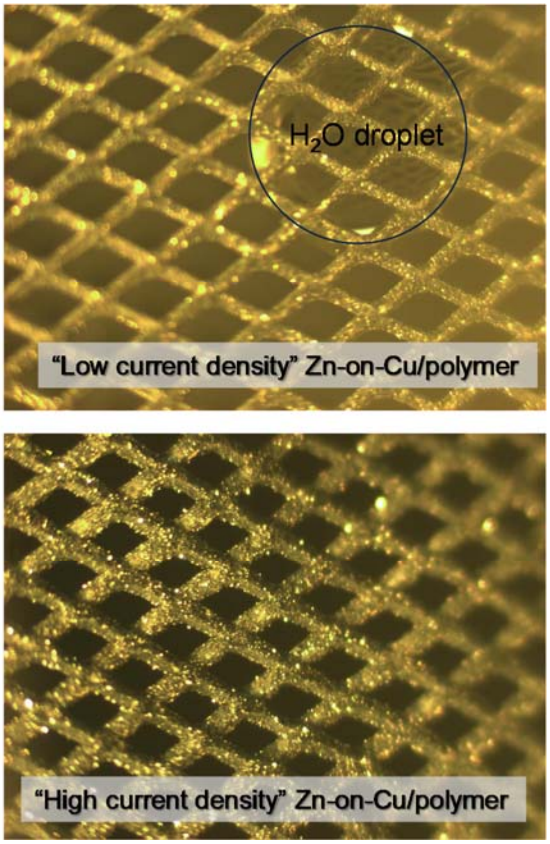


Figure 9. (left) head-on images of Zn-on-Cu substrates and the visualization of coalescence events at different microstructures (right) magnified view of Zn-on-Cu substrates

The results above provide important examples for the use of the NRL-designed test cell and aerosol-generation system, but represent only a sampling of a larger data set that has been collected. The findings of a comprehensive investigation of Zn-on-Cu screen coalescer architectures will be summarized in a forthcoming article to be submitted to a peer-reviewed scientific journal.