

Results of Multifunctional Condensing Heat Exchanger for Water Recovery Applications

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ABSTRACT

Humidity control within confined spaces is of great importance for current NASA environmental control systems and future exploration applications. The engineered multifunction surfaces (MFS) developed by ORBITEC is a technology that produces hydrophilic and antimicrobial surface properties on a variety of substrate materials. These properties combined with capillary geometry create the basis for a passive condensing heat exchanger (CHX) for applications in reduced gravity environments, eliminating the need for mechanical separators and particulate-based coatings. The technology may also be used to produce hydrophilic and biocidal surface properties on a range of materials for a variety of applications where bacteria and biofilms proliferate, and surface wetting is beneficial.

INTRODUCTION

A microgravity environment presents a unique set of issues for fluid management. Phase separation is no longer automatic and two-phase flow becomes a non-trivial problem. A variety of solutions has been developed to address these issues with some success, including capillary transport of fluids, hydrophilic coatings, and phase separation using centrifugal forces.

ORBITEC has developed technologies and processes to create engineered Multifunctional Surface (MFS) properties for use in applications requiring enhanced fluid management in reduced gravity environments such as Condensing Heat Exchangers (CHX). For space-based CHX applications, desired surface properties include antimicrobial, hydrophilic, and thermal

conductivity. In addition, capillary geometry is desired for passive phase separation of the two-phase flow during condensation on the control surfaces of the CHX.

In an advanced CHX application, the MFS provides a large, thermally efficient surface area for condensation, hydrophilic surface properties to reduce contact angle, and biocidal surface properties to inhibit bacteria growth and biofilm formation. Additionally, MFS allows for the utilization of capillary channels for increased fluidic control via surface tension driven flow of condensate. Such surfaces and designs preclude the need for mechanical separators and particulate-based coatings found in current systems.

In addition, these technologies are being used to produce hydrophilic and biocidal surface properties on a range of materials for a variety of applications where bacteria and biofilms proliferate, and surface wetting is beneficial.

This paper focuses on the development of cold plasma-based technologies and processes to create hydrophilic and antimicrobial surface properties.

The effects of hydrophilic coatings on CHX performance are well documented. Published data have shown that hydrophilic coatings decrease the pressure drop through a CHX by up to 25% [Kim et al., 2002] to as much as 40% [Wang et al., 2002]. This is mainly due to the elimination of water droplets as an impediment to gas (air) flow. The pressure drop reduction results in increased air flow, which in turn leads to an increased flow velocity that tends to enhance the heat transfer coefficient by approximately the square of the flow

velocity. The pressure drop reduction can also be exploited by proportionally reducing the size of air motive hardware while keeping flow rates the same as an uncoated CHX, which results in reductions in the Equivalent System Mass (ESM) of the system and in the noise generated by the hardware proportional to pressure losses through system hardware [Minmaki, 1987].

The ability to apply a durable antimicrobial surface treatment to CHX condensing surfaces improves performance by drastically reducing the formation of biological and composite fouling on or near the condensing surface. When dealing with environmental control for human habitation, biological fouling is particularly problematic as it poses health risks in addition to deteriorating system performance. Initial contact of an untreated heat exchanger surface with bacteria can quickly result in bacterial growth, regardless of whether the surface is hydrophilic or hydrophobic [Ista et al., 1996]. The initial colony can then form a biofilm, a highly resistant layer of living matter and organic polymers, whose detrimental effects can be enhanced by the presence of other contaminants in the cabin environment [Sheikholeslami, 1999]. This biofilm is very difficult to remove once formed, hence, the crucial need for an active bactericidal heat exchanger surface, as offered by MFS.

Different substrate materials have been evaluated and selected for use in the process development steps. The primary materials selected were aluminum, stainless steel, and ULTEM. Additional materials were evaluated during later stages of the project. Aluminum was selected for its application to a CHX and due to previous work completed within the Phase I SBIR [Ma et al., 2007]. Aluminum has a high thermal conductivity and low density, is readily available and easily machined. Additionally, its ability to be easily formed is useful in creating capillary geometry at the macro scale. Stainless steel was selected because it is widely used in spaceflight applications and for its ability to withstand corrosion in wet environments such as those found within and supporting a CHX application. However, stainless steel has a high density and low thermal conductivity, which make it less desirable for use as the condensing surfaces in a CHX application. Finally, ULTEM is attractive because it is an approved polymer for spaceflight and is also widely used in spaceflight applications.

The selected materials were the basis for the development of the multi-step processes to create the antimicrobial and hydrophilic surface properties. Starting with aluminum, several investigations were conducted to study the effects of the alloy's chemistry and to evaluate a range of process parameters. Research was conducted in the laboratory to investigate potential processes. Several DOE (Design of Experiments) tests were conducted to statistically evaluate multiple variables and their interdependences. Through multiple

trials, a basic set of process steps was developed. A variety of tests was conducted on samples treated with these process parameters. An immersion test was used with condensate ersatz to simulate the water interaction with the treated surface, and to evaluate corrosion effects and changes in hydrophilic properties over an accelerated timeframe. Microbial tests were conducted to evaluate the antimicrobial properties. These parameters were then applied to additional materials with minor changes where needed, based on the substrate material properties.

A prototype subscale fin assembly was fabricated and treated for testing on a NASA C-9B aircraft. The prototype subscale fin assembly was tested within the ORBITEC Humidity Validation Payload (HVP) to investigate wetting conditions and capillary geometry in the reduced gravity environment during the C-9B parabolas. Testing was conducted with the treated fins and with untreated fins to compare MFS performance against a control.

Video data show that the simulated condensate formed a stable pattern on the treated fins. No air bubbles were ever observed once the channels were filled with water, and the water that was collected was easily contained. With the untreated fins, several cases of water bridging between fins without contacting the central vane were observed, and bubbles were noticed in the collected water. Additionally, it was observed that preferences among the channels were evident with the untreated fins. This was most evident when simulated condensate was drawn from the fin structure; some vanes were emptied, while others were not. A prototype subscale fin assembly representative of the assembly used for the C-9B testing was fabricated for the Phase II deliverable.

SURFACE MODIFICATION BY COLD PLASMAS

The method to modify material surfaces and to create hydrophilic and antimicrobial properties is based on cold plasma technology.

Plasmas are also known as "the fourth state of matter." They are ionized gases generated by electrical discharges and composed of electrons, positive/negative ions, neutrons, and other neutral species. Depending on the degree of ionization, they are classified into thermal (hot or equilibrium) plasmas and non-thermal (cold or non-equilibrium) plasmas.

One of the most important properties is the very high energy contained within plasmas (a typical cold plasma state holds electrons with energies equivalent to a temperature of 34,800-46,400 K), which is enough to break many common chemical bonds to produce highly reactive molecular fragments. Therefore, plasma technology (esp. the non-equilibrium cold plasma technology) can be used as an enabling tool to initiate a variety of chemical reactions that are otherwise very difficult to produce without the need for costly expensive

highly specialized, high-pressure and high-temperature equipment. In addition, plasma technologies are a surface-oriented approach, meaning that they will only modify the very top layer (a few tens of nanometers) of the substrate, leaving the bulk material untouched and thus maintaining the substrate's intrinsic properties such as thermal conductivity.

The chemical reactions occurring in cold plasmas are very complex, great in number, and beyond the scope of this paper. Due to the number of factors affecting the plasma reactions and the resulting complexity of plasma chemistry, it is very difficult to fully control the pathways of plasma reactions and to precisely predict the reaction products. However, by carefully studying how some external parameters, such as electric power and pressure, can affect the reaction outcomes, it has been possible to empirically select the right combination of plasma parameters to produce the desired results.

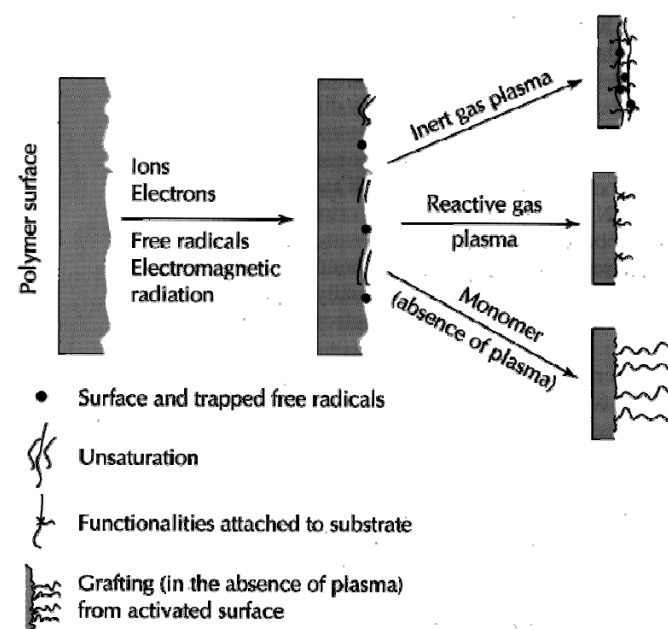


Figure 1. Schematic of several different mechanisms for plasma-induced surface modification.

Depending on the gas that is used to produce the plasma state, the surface modification mechanism can be different: (1) Most inert gases (e.g., Ar) generate non-polymer forming plasmas and their interactions with the substrate surfaces produce many highly reactive sites, which can then be utilized in a separate *in situ* or *ex situ* reaction to generate desired surface properties. (2) Plasmas produced from reactive gases generate certain volatile, gaseous species, such as carbon oxides or fluorides in CF_4/O_2 plasmas. Under a vacuum, these volatile species will leave the substrate surfaces and be removed from the system, leading to the etching of the substrate surfaces. Non-reactive gases can also cause an etching effect, e.g. Argon, if new species generated by plasmas on the substrate can recombine to form volatile molecules. (3) Finally, when certain volatile

organic or organometallic compounds, including conventional monomers, are used as plasma gases (e.g., silicon-containing monomers), they can deposit macromolecular structures onto the substrate surfaces due to fragmentation and recombination processes, resulting in *in situ* or *ex situ* polymerization reactions. These different surface modification mechanisms are illustrated in Figure 1 [Denes, 1997] using a polymer surface as an example.

PROCESS SUMMARY

The process to produce the multifunctional surfaces consists of two basic steps, which are summarized below:

ANTIMICROBIAL TREATMENT – A surface treatment is carried out prior to the cold plasma treatment. Several different approaches have been evaluated to produce antimicrobial surface properties. This includes using plasmas to initiate a Tollen's reaction (i.e., the silver mirror reaction) to embed silver nanoparticles into the substrate materials, and using selected precursors and plasma to generate antimicrobial structures on the substrate surface. Silver sputtering is also used to deposit a thin layer of silver onto the substrate surfaces.

Various silver thicknesses have been evaluated based on the (1) effect on the hydrophilic surface treatment, (2) ability to isolate the substrate from damaging environmental conditions, (3) antimicrobial effectiveness, (4) projected service lifetime, and (5) future production costs. An optimal silver thickness has been selected for further MFS development.

PLASMA TREATMENT – Several different substrate materials were treated with reactive plasma to generate the desired hydrophilic surfaces. All plasma treatments were performed in an inductively coupled plasma reactor, which is equipped with two radio frequency power supplies, one being used as primary power and the other to provide a bias voltage. The reactor offers high stability and control of all the parameters involved in the plasma process including gas flow rates, pressure, power, bias voltage, and treatment time.

A combination of the second and third reaction mechanism described earlier was used to generate the hydrophilic functionalities on the surfaces. The substrate is first exposed to a plasma that contains various energetic fragmentations with desired functionalities that become chemically attached to the substrate surfaces. After plasma treatment, the surfaces are immersed in distilled water to complete the reaction. The water bath is heated to facilitate the formation of the functionalities that eventually lead to super-hydrophilic substrate surfaces.