Insect Fouling on Superhydrophobic Surfaces

K. Krishnan*, A. Milionis*, F. Tetteh*, T. Farrell**, J. Crouch**, D. Berry** and E. Loth*

*University of Virginia
122 Engineer's Way, Charlottesville,VA, USA, ghoku@virginia.edu

**The Boeing Company, Seattle, WA, USA

ABSTRACT

Leading edge contamination of aircraft wings increases drag and fuel consumption and can happen through accumulation of dirt, ice and insects. Insect fouling is particularly a problem during take-off, climb, landing and other low altitude flights. An experimental setup consisting of a wind tunnel and a method to inject live flighless fruit flies was used to the test the effectiveness of various surfaces against insect fouling. Insect fouling was analyzed based on residue area and height from multiple impacts. Superhydrophobic surfaces performed generally better than aluminum surfaces in terms of residue area. Residue height was more invariant to surface type as even a single exoskeleton that adhered to the surface on impact was enough to produce a residue height on the order of 1 mm, which is higher than the critical height to transition the flow to turbulence for most aircrafts. Two superhydrophobic coatings were particularly effective in resisting the residue in terms both area and height. However, the wettability might not be the controlling parameter of insect fouling.

Keywords: insect fouling, superhydrophobicity, insectphobic

1 INTRODUCTION

Insect residue accumulation on aircraft wings leads to increased skin friction drag through earlier transition from laminar flow to turbulent flow around the airfoil. Since, skin friction drag represents up to 50% of the total drag for a subsonic aircraft and the turbulent skin friction can be as much as 90% more than the laminar skin friction at the same Reynolds number, insect residue mitigation could lead to significant increase in fuel efficiency.[1] As much as 18% increase in fuel efficiency can be achieved if aerodynamic leading edge contamination which includes sand and ice, in addition to insect fouling is prevented completely.[2] In general, surfaces can be aerodynamically contaminated with residue heights on the order of tens of microns, as this is enough to cause transition and trip the laminar boundary layer to turbulent conditions.[1,3] However, in order to maximize the benefits of the residue free leading edges, natural laminar flow (NLF) airfoils in future aircrafts are required as most commercial airlines have a very small laminar region over wings that can currently utilize contamination free leading edge surface.

Insect fouling is particularly a problem during initial and final stages of the flight, i.e. taxi, take-off and landing, since the maximum altitude of insects is typically limited to 500 feet.[1,4,5] Insect fouling occurs when the insect comes into contact with the aircraft surface at speeds higher than its rupture velocity. This fractures the exoskeleton of the insect and releases the internal fluid which is mainly composed of hemolymph, analogous to blood and interstitial fluid in mammals. Once exposed to air and the surface, the hemolymph quickly starts to coagulate, which happens on the order of microseconds, turning into a solid residue that adheres on the surface. The hemolymph is primarily composed of water with inorganic ions (90%) while nitrogenous wastes, carbohydrates, lipids, proteins and enzymes, antifreeze proteins, pigments and hormones constitute the other 10%.

Nanotextured surfaces that are superhydrophobic with extreme water repellency (static contact angle > 150º and roll-off angles < 10º) has seen a great increase in various applications given their self-cleaning behavior.[6,7,8] Given their self-cleaning properties, they have been proposed to provide antifouling properties that would help prevent residues from adhering.[9,10] Furthermore, any hemolymph deposition or other contaminant that solidifies on a superhydrophobic surfaces is expected to be more easily removed with aerodynamic forces as compared to those on common aircraft surfaces such as bare aluminum or polyurethane. Superhydrophobic coatings are passive inhibitors and thus have the potential to be more energy-efficient compared to an active system such as air-assisted jets and more maintenance-friendly compared to mechanical scrapers and sacrificial coatings.

2 MATERIALS AND METHODS

An experimental setup consisting of a wind tunnel, airfoil, high-speed camera, light source and injection tube were used in this study as shown in Fig. 1. The symmetric modified NACA0038 airfoil had a chord length of 21 cm and leading edge radius of 3.8 cm. The wind tunnel cross section was 31 cm x 31 cm. Based on previous studies, flightless fruit flies of the order Diptera, were chosen as representative of insects.[1,11,12] The flightless fruit flies were obtained from a local pet store. They had an average mass of 0.7 mg and an average body length of 2.1 mm.

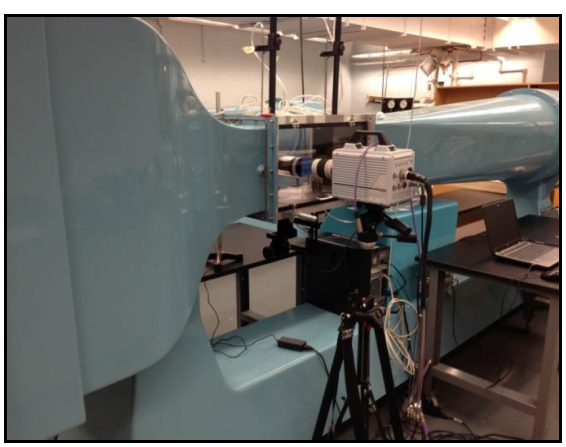
The fruit flies were accelerated in an upstream tube using compressed air such that they reached a velocity of 47 m/s before impact and matched the test section air flow speed. The injection tube exit was placed 18.5 cm away (~90 body lengths) from the stagnation point of the airfoil. This distance provided enough flight time for the insects to accelerate to the surrounding air flow, while minimizing the wake effects arising from the injection tube itself. The insect velocities were obtained through image analysis.

The fruit flies were injected into the tunnel using a clear Tygon® tube with outer diameter of 9.5 mm. The insects were released in batches of 5 at a time until a total insect release of 50 (i.e. 10 batches of 5 fruit flies) or until a congested strike zone was observed on the coating. A congested strike zone is defined as enough visible insect residues on the coating where an additional impact may have a significant likelihood of occurring on top of a pre-existing residue instead of the coating. This was done so that all impacts occured on the uncontaminated portion of the coating as opposed to a pre-existing residue since the goal of the study was to quantify the effectiveness of the coating.

The insect impacts were recorded using a Photron SA4 high speed camera at 20,000 fps. The captured videos of insect impacts were useful in classification of the impacts while ensuring that the fruit flies were intact prior to impact. The videos also aided in the calculations of insect velocity through image analysis.

Seven coatings and aluminum were selected in order to understand the effect of surface wettability on fruit fly antifouling behavior. Coatings ranged from hydrophobic - DuPont™ Capstone®, NuSil™ R-2180, Teflon®, and Rubber based coating, to superhydrophobic - Hydrobead, Hydrophobically Modified Fumed Silica (HMFS) nano-composite with Acrylonitrile butadiene styrene (NC/ABS), and nanocomposite with Capstone (NC/Capstone). The coatings were sprayed and/or applied on a 30 cm x 30 cm aluminum substrate that was then taped onto the airfoil and at least 2 similarly prepared coatings were tested in the wind tunnel for consistency in the results. Aluminum 1100, which is hydrophilic, was tested as the baseline since most aerodynamic surfaces are made out of aluminum.

a)



b)

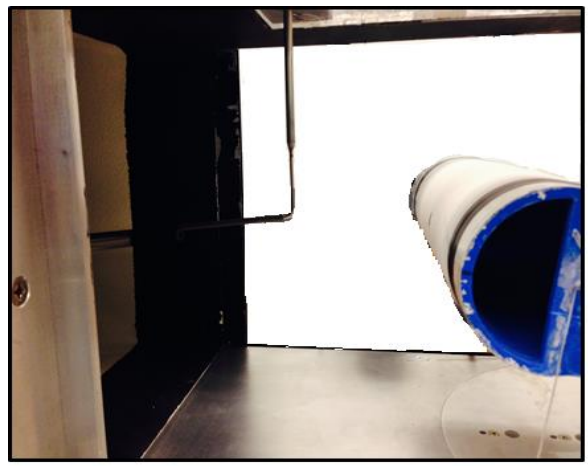


Figure 1 Experimental setup showing: a) the wind tunnel and the high speed camera and
b) close-up of the injection tube in the wind tunnel

Water contact angles were measured through the sessile drop method with a Ramé-Hart automated goniometer, 290-F4, using a 10 µl droplet size and taking at least 3 measurements. All measurements have an accuracy of ±5°. A summary of the static contact angles of the surfaces are given in Table 1. The insect residue on the surfaces were characterized using a Hirox KH-7700 digital microscope. The images from the microscope were processed using image processing software, ImageJ, in order to quantify the area of the residue. Residues were manually traced and calculated using ImageJ. The residue heights were measured using the digital microscope and were averaged from a minimum of 3 distinct residue impact locations.

Table 1 Contact Angles of Test Surfaces

Surface	Static Water Contact Angle (deg)
Aluminum	79
Capstone	113
Nusil	117
Teflon	124
Rubber	111
Hydrobead	168
NC/ABS	163
NC/Capstone	159

3 RESULTS AND DISCUSSION

3.1 Residue Area

The residue area of all surfaces were calculated based on the 3 different types of residue that was oberved: a) exoskeleton, where partial body is stuck to the surface, b) hemolymph, where only translucent yellow hemolymph was on the surface and c) red residue, where a bright red

color originating from the eyes were left as the residue. The total residue from 50 insect releases in shown in Fig. 2 bleow.

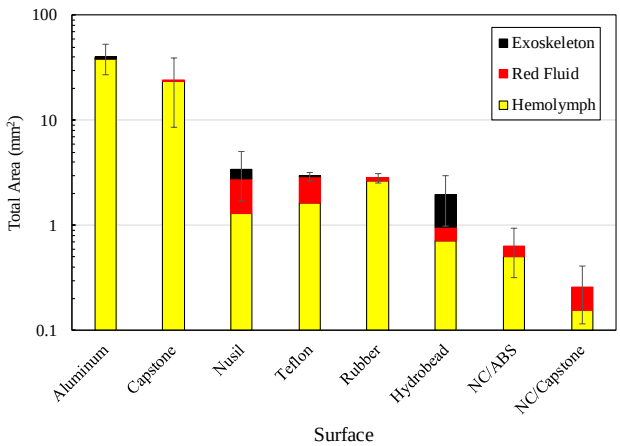


Figure 2 Total residue of different surfaces

The baseline aluminum performed the worst while pure Capstone performed second worst. The hydrophobic surfaces performed better than the aluminum and the improvement comes mainly from minimizing the hemolymph spread. As expected, the three superhydrophobic surfaces performed the best. Fig. 2 shows a significant reduction in residue area of hemolymph of hydrophobic and superhydrophobic coatings, with the exception of capstone, compared to aluminum. This suggests that the hydrophobic and superhydrophobic surfaces are effective in containing the hemolymph spread which minimized the residue area.

By counting the residue element and types, the average residue area per element was calculted as shown in Fig. 3.

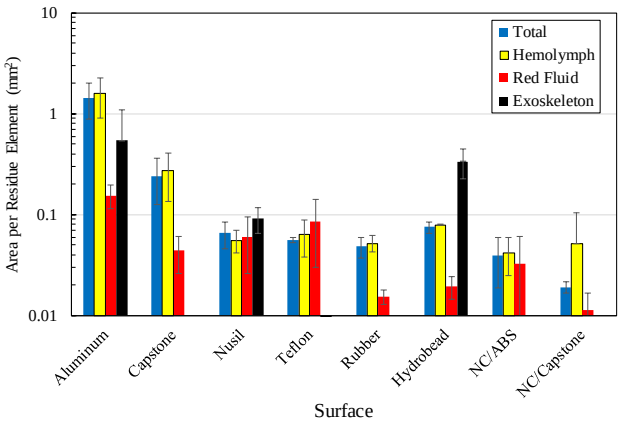


Figure 3 Average area (total and by component) per residue element on different surfaces

Figure 3 shows that the average area of hemolymph residue was an order of magnitude higher than the red residue for aluminum. The hydrophobic surfaces and superhydrophobic surfaces had hemolymph residue area on the same order as the red residue indicating the hemolymph containment mechanism discussed earlier. Also, the NC/Capstone had a very low hemolymph and red residue area per residue element.

3.2 Residue Height

The residue height was measured using the digital microscope. The average of the 3 highest measurements, which is defined as the peak residue height is shown in Fig. 4.

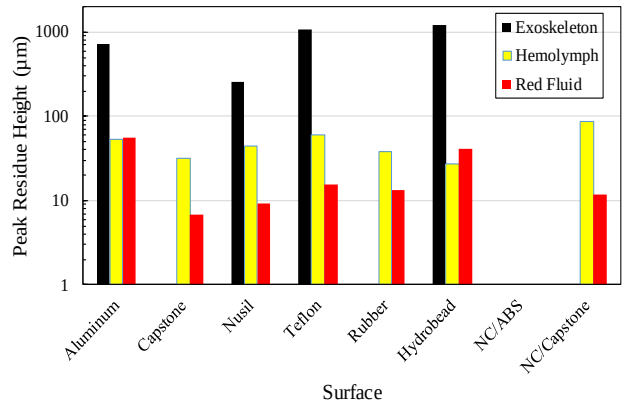


Figure 4 Residue height on different surfaces

The highest residue height arises from the exoskeleton impacts which were typically on the order of 1 mm. Nusil was an exception as although no exoskeleton impact was observed on the surface, it attracted a lot of insect legs and hairs which resulted in a residue height of around 100 µm. The hemolymph height was from 40 to 90 µm while the red residue height was on the order of 10 to 50 µm. The NC/ABS performed the best with no discernible residue height. A qualitative trend with wettability was not observed with residue height unlike the residue area. This can be seen from Nusil, Teflon, and Hydrobead having a high exoskeleton height even though their residue area was low. In fact, the exoskeleton height of aluminum is even lower than that of Hydrobead, as the exoskeleton tends to spread on the aluminum and thereby reduce the maximum height. Conversely, the Capstone which performed poorly in terms of residue area had a lower residue height than the NC/Capstone. Figure 4 indicates that the exoskeleton and hemolymph residue need to be avoided in order to minimize the residue height.

A successful coating would ideally have minimal residue area and residue height. Generally all surfaces that were tested performed better than the baseline aluminum. As shown in Fig. 5, two coatings - NC/ABS and NC/Capstone - are insectphobic, yielding low residue height and area.

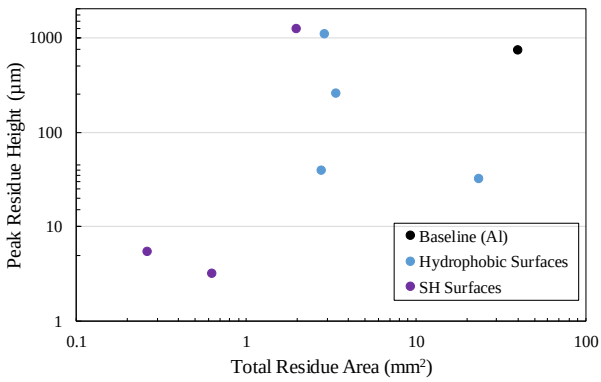


Figure 5 Peak residue height and total residue area

However, the superhydrophobic surfaces that were tested did exhibit some sacrificial aspect in order to repel the insect impact, i.e. the coatings were removed at the impact location. This indicates perhaps the sacrificial or powdery aspect of the coating is what enhances the insectphobic performance. This also suggests a closer consideration into the durability of the coatings.

4 CONCLUSIONS

The insect residue area was qualitatively dependent on the wettability of the surface with the hydrophobic and superhydrophobic surfaces performing better than the hydrophic aluminum. However, the same trend was not observed in terms of residue height, although two of the superhydrophobic coatings performed the best with respect to both residue area and height. Generally, a balance between residue area and residue height was observed with surfaces with lower height, having higher residue area.

REFERENCES

[1] R. D. Joslin, "Aircraft Laminar Flow Control." Annual Review Fluid Mechanics, 30:1-29, 1998.

[2] Wohl, C., Smith, J., Connell, J., Siochi, E., Penner, R., & Gardner, J. “Engineered Surfaces for Mitigation of Insect Residue Adhesion”, 51st AIAA Aerospace Sciences Meeting, Grapevine, TX, 1-23, 2013.

[3] Kok, M., Mertens, T., Raps, D., Young, T. “Influence of surface characteristics on insect residue adhesion to aircraft leading edge surfaces”, Progress in Organic Coatings, Vol. 76, Iss. 11, pp 1567–1575, 2013.

[4] Maresh, J. L. and Bragg, M.B. “The Role of Airfoil Geometry in Minimizing the Effect of Insect Contamination of Laminar Flow Sections,” AIAA-84-2170, 1984.

[5] Croom, C.C.; and Holmes, B.J., “Flight Evaluation of an Insect Contamination Protection System for Laminar Flow Wings,” SAE Paper 850860, 1985.

[6] B. Bhushan, Y.C. Jung and K. Koch, “Self-Cleaning Efficiancy of Artificial Superhydrophobic Surfaces”, Langmuir, 25(5), 3240-3248, 2009.

[7] R. Furstner, W. Barthlott, C. Neinhuis, P. Walzel, “ Wetting and self-cleaning properties of artificial superhydrophobic surfaces”, Langmuir, 21, 956-961, 2005.

[8] S.Nishimoto, B. Bhushan. “Bioinspired self-cleaning surfaces with superhydrophobicity, superoleo-phobicity, and superhydrophilicity”, RSC Adv., 3, 671-690, 2013.

[9] Orchard, M., Kohonen, M. & Humphries, S. “The influence of surface energy on the self-cleaning of insect adhesive devices”, The Journal of Experimental Biology, 215, 279-286, 2011.

[10] Scholz, I., Buckins, M., Dolge, L., Erlinghagen, T., Weth, A., Hischen, F., Mayer, J., Hoffman, S., Riederer, M., Riedel, M., & Baumgartner, W. “Slippery surfaces of pitcher plants: Nepenthes wax crystals minimize insect attachment via microscopic surface roughness”, The Journal of Experimental Biology, 213, 1115-1125, 2009.

[11] Coleman, W.S. “Roughness Due to Insects”, Boundary Layer and Flow Control, Volume 2, G. V. Lachmann, ed., Pergamon Press, pp. 682-747, 1961.

[12] Hardy, A.C.; and Milne, P.S. “Studies in the Distribution of Insects by Aerial Currents—Experiments in Aerial Tow-Netting From Kites” J. Anim. Ecol, vol. 7, no. 2, pp. 199-229, 1938.

[13] Milionis, A., Yeong, Y., Loth, E., Bayer, I. “Mechanically Durable Superhydrophobic Nanocomposites from Acrylonitrile Butadiene Styrene (ABS)”, TechConnect, Washington DC, 2014.