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Fruit fly impact on an aerodynamic surface: Types of outcomes and residue components

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ABSTRACT

Leading edge contamination on aircraft wings and wind turbine blades can occur through the accumulation of insect residues, which can then increase drag by causing an earlier transition of the boundary layer from laminar to turbulence. To investigate the mechanisms of residue adherence and composition, this study focuses on the impact dynamics of insects striking an airfoil with a circular leading edge placed in a wind tunnel at a wind speed of about 100 mph. To mimic in-flight conditions, live flightless fruit flies (*Drosophila melanogaster*) were injected into the wind tunnel sufficiently upstream such that they reached the test section air-flow speed prior to impact on the airfoil. The aerodynamic surface had a leading edge radius of 3.8 cm and was tested with coatings of various surface wettability, ranging from hydrophilic to superhydrophobic. Based on previous studies and present high-speed imaging and surface imaging, five types of insect outcomes were defined (roughly in order of increasing impact speed): 1) insect bounce without rupture and no residue, 2) insect burst with release of internal fluid with adherence of full exoskeleton, 3) insect burst with release of internal fluid with little or no exoskeleton adherence, 4) disintegration of insect yielding residue of many pieces of exoskeleton, and 5) insect burst with neither fluid nor exoskeleton residue. The fifth outcome generally occurred for a superhydrophobic surface developed in this study. When insect residue did occur on a surface, it included up to three distinct components (in order of decreasing residue heights): exoskeleton pieces, yellow hemolymph from the insect abdomen and thorax, and red fluid from the insect head. Surfaces with lower surface wettability generally yielded reduced insect hemolymph residue area per insect release. In particular, a superhydrophobic coating yielded the lowest residue area and no exoskeleton residue, while the aluminum surface resulted in the highest residue area and several exoskeletons.

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. Current aircraft are designed to have a turbulent boundary layer airfoil, and thus are not highly sensitive to such residue. However, future generation aircraft may seek to employ natural laminar flow (NLF) airfoils in order to reduce skin friction drag substantially. In fact, turbulent skin friction drag represents up to 50% of the total drag for a subsonic aircraft and this number can be reduced by more than a factor of two if laminar flow can be employed. However, laminar flow wings requires smooth surfaces to prevent premature transition to turbulence. As a result, some studies estimate 6–18% increase in fuel efficiency depending on the aircraft type if laminar flow technology can be employed.

Unfortunately, leading edge contamination (which includes sand and ice, in addition to insect fouling) could lead to unwanted transition to turbulence and would eliminate much of the fuel efficiency savings that laminar flow airfoil geometries could allow [1,2]. Similar insect accretion on wind turbines are estimated to reduce wind turbine power by almost 50% [30,31]. Preventing this unwanted turbulent transition is difficult since surfaces become aerodynamically contaminated for residue heights as small as tens of microns [1,21].

Insect fouling is particularly problematic during the initial and final stages of the flight (i.e. taxi, take-off and landing), since the probability of encountering insects reduces with increasing altitude and the probability of encountering insects within 500 feet of the ground is much higher than that at greater altitudes [1,6,7]. Insect fouling occurs when the insect comes into contact with the aircraft surface at speeds higher than its rupture velocity, which fractures the exoskeleton of the insect and releases the internal fluid which

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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, turning into a solid residue that adheres to 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 $>150°$and roll-off angles $<5°$) have seen great potential in various applications in the past few years. Given their self-cleaning properties, they have been proposed to resist antifouling properties by extension, that would help prevent residues from adhering [24,26]. Furthermore, any hemolymph deposition or adhesion that solidifies on a superhydrophobic surfaces is expected to be more easily removed with aerodynamic forces as compared to those on conventional aircraft surfaces such as bare aluminum or polyurethane. Superhydrophobic coatings can thus be passive contamination inhibitors. Such coatings have the potential to be more energy-efficient and more maintenance-friendly than mechanical scrapers and sacrificial coatings.

1.1. *Previous studies*

Since insect species and location can vary widely in the atmosphere, a number of previous studies focused on characterizing the insect population as function of many conditions. The insect density, defined as the number of insects within a given volume, was found to be dependent on temperature, moisture, humidity, wind speed, altitude, and local geography and vegetation [1]. An example of this dependence was obtained for a study in Louisiana which showed that the greatest insect densities in the day time can be found in May, November, and September, and the least in January and December [3]. At nighttime, the largest numbers of insects can be found in October and May [3]. Another study in Tetney, Lincolnshire found that the most common months for insect fouling were May, June, and September [4]. Regardless of the specific months, the outside temperature is another influencing parameter of the insect density. Although studies vary in the exact temperature range limits, there is a general agreement that the temperature range for maximum insect densities is 21–27 °C.

Regarding types of insects, Refs. [3] and [4] are the first large scale attempts in characterizing aerial insect populations in terms of species and size. In Ref. [3], the vast majority of their insects were collected between 200 and 5000 feet and 39% were of the order Diptera with several other orders completing the rest. Similarly, Ref. [4] found that the aerial populations are mostly of “small or light-bodied” insects with “relatively large wing surface compared with body mass” with the most common being of the order Diptera, Aphididae, and Hymenoptera [8]. Based on these studies, the most common insect was of the order Diptera which refers to an insect with one pair of wings, that includes true flies, mosquitoes, and gnats [9]. Overall, smaller insects (1–3 mm) are more numerous than the larger ones [5]. As a result, most studies on insect fouling of aerodynamic surfaces (e.g. Refs. [2] and [5]) have focused on fruit flies (*Drosophila melanogaster*). This common choice stems arises since fruit flies are: a) common throughout the United Sates, b) in the order Diptera, c) of 2 mm in size, and d) are easily available in numerous quantity for testing.

The impact of a given insect on a surface at high-speeds is characterized by complex dynamics [10,11,32]. The outcomes depend on speed but also the relative impact angle and the insect orientation relative to the surface. In addition, they may depend on the elasticity and wettability of the surface as well as the species, size and maturation of the insect. Therefore, they are difficult to predict but some general conclusions can be made with respect to fouling as follows. For example, the rupture speed of fruit flies is dependent on the amount of body fluid and the hardness of the insect's cuticle [5]. In general, the impact location on an airfoil is important because this controls the trajectory. Ref. [10] notes that the highest residue (number of impacts) is just downstream of the stagnation point associated with the leading edge, where the insect velocity has the highest normal component [12,13]. It is noteworthy that the experiments of Coleman [5] showed that insect residue heights and concentration are not simply a function of the projected surface angle of attack, indicating that local aerodynamics can play a role.

To help reduce fouling, researchers have investigated various methods for mitigation of insect fouling such as mechanical scrapers and low wettability coatings. Of these, the coatings show the biggest potential as a passive system that requires least amount of maintenance. Several studies (Table 1) have performed experiments of insect impact on various coatings [2,14–20]. These studies employed a wide variety of setups including bug guns, wind tunnels and test flights in an attempt to better understand insect contamination on various surfaces. The antifouling performance was largely characterized in terms of residue height and area coverage. For the reasons discussed above, the ground-based tests generally employed fruit flies [1,5]. An encouraging aspect of these studies was the fact that hydrophobic and superhydrophobic surfaces have generally fared well in comparison to bare aluminum, which is typically taken as the baseline control surface for insect impact studies.

However, understanding the controlling physics for residue reduction is difficult. The effect of surface energy on insect fouling mitigation has been investigated, with some studies showing a qualitative energy and performance [2,14,17,18]. In general, materials with lower surface energy tend to result in lower insect residue, but there is not a well understood relationship between the area and height of impacted insect residue [15], e.g. a low residue height is not generally associated with a low residue area and vice–versa. Also, the quantitative correlation of the surface energy to insect fouling has not been well understood. In particular, some superhydrophobic surfaces perform extremely well while others perform worse even though they exhibit similar surface energy and water contact angle properties. The governing mechanism for such drastic differences requires further investigation, but some of the difference can be traced to surface topology. In particular, surface roughness has also been identified as influencing the residual minimization [15], whereby increased roughness generally decreases the lateral spreading of hemolymph [21]. These two studies identified low wettability and moderate coating roughness as the desired features that minimize the insect accretion. In terms of residue features themselves, Ref. [21] identified a height of 100 μm as the critical height (h_{crit}) for transition of the flow from laminar to turbulence for most commercial airliners. However, the actual height for roughness depends on the airfoil shape, angle of attack and Reynolds number [34,38].

While it would be ideal to use a single fluid instead of an actual insect for testing, it has been unfortunately difficult to identify a synthetic or natural fluid which is non-coagulating and can mimic insect residue [33]. In addition, the wide variations in performance in the available literature suggest that there may be more than one type of liquid associated with insect fouling. These issues suggest that further investigation is required onto the specific components that make up the insect residue, and no studies to date have considered such a component-based analysis, as will be investigated herein.