Detecting Ice in Anti-icing Fluid Films using a Polarized Light Imaging Technique

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Abstract— **De-/anti-icing fluids needs to be tested for their effectiveness (when developing new formulations), quality control during production, and certification purposes. For example, in an endurance test, were the time for freezing of the anti-icing fluid is measured after it has been spread over a specific surface (usually aluminium plates). In the case of endurance tests of aircraft de-/anti-icing fluids, their failure is evaluated by a naked-eye visual inspection and occasionally poking freezing areas (as perceived) with a toothpick to confirm visual inspection. Such visual inspection can be subjective and tedious, especially when an ice-fluid interface has low contrast in a slush state or when painted test plates are used to study fluid compatibility with a coating. Therefore, the development of more reliable ice detection tools is needed. For ice detection improvement, image processing techniques have been developed in the visible and infrared spectra. Such techniques have issues with low ice contrast or combining with the visual inspection. Here we show how to enhance ice contrast in the visible spectrum by using ice birefringence and polarized light reflection. The developed ice imaging uses the birefringence present in ice crystals compared to water and anti-icing fluids. The ice birefringence can be revealed using polarized light, as we did for a water spray endurance test. Three different types of fluids were used, i.e., Type I, Type II, and Type IV, together withthree different surfaces where anti-icing fluid was spread, i.e., polished aluminium, and two types of coated aluminium plate that were either painted with a glossy or matt acrylic paint. The method can be used for both visual inspection and automatic ice detection systems.**

Keywords— ***ice detection, aircraft anti-icing fluid, polarized light, reflection, birefringence, endurance test***

I. Introduction

Aviation de/anti-icing fluids (anti-icing fluids further in the text) are commonly used in airports to remove and prevent ground icing of aircrafts. Society of Automotive Engineers (SAE) has standards for four types of such fluids [1], [2]. Each fluid type has different composition and protection time. Anti-icing fluids shall be tested for their effectiveness (when developing new formulations), quality control during production, and certification purposes. SAE also provide methods as how to test fluids properly [3]. For example, endurance test indicates the time before fluid failure. This is an important fluid property and the focus of this work.

The endurance test procedure is as follows: tested fluid is spread over aluminium plates in a cold chamber, then water is sprayed on plates, and fluid is considered to have failed when it freezes on a certain part of the plate. Currently, the freezing is estimated only by a naked-eye visual inspection and tactile observations with a toothpick to confirm visual ones. This process can be subjective, time consuming and tedious, especially when ice-fluid interface has low contrast in a slush state or when painted test plates are used (e.g. to study fluid compatibility with a coating). Therefore, the development of more reliable ice detection tool is needed.

Non-contact optical methods for ice imaging have been developed in the visible [4] and infrared spectra [5]-[8]. Visible methods implement image processing techniques to detect ice edges, but have large error (more than 5%) compared with experienced technicians because of low ice contrast. Moreover, there is no unifying approach for digital enhancing techniques [9]. Infrared methods require cameras that are expensive and have lower resolution compared to ordinary ones. Besides, there is a challenge to combine infrared results with visual observations.

Thus, in this work we propose optical polarizing method to improve ice contrast and image processing algorithm to automate ice imaging process.

II. Methods

The detailed descriptions of the polarizing method to increase ice contrast and image processing algorithm to automatically detect ice is explained below.

A. Polarizing Method

The method is founded on crystal birefringence. Ice is a crystal, so it reflects incident light ray in two rays with different polarization states. When linearly polarized illumination is used, most of reflected light can be deleted using crossed analyzer. At the same time, light reflected from ice is saved, increasing overall ice contrast (Fig. 1).

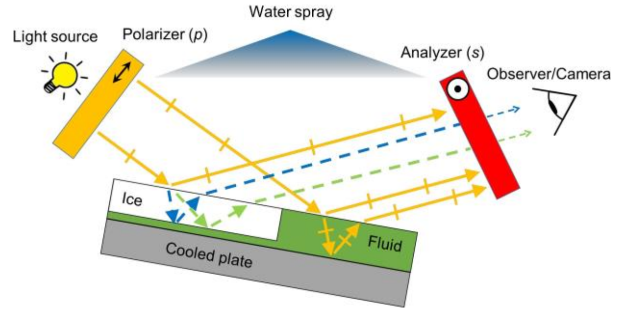

Fig. 1 Schematic of the ice imaging by polarized light reflection [10].

The ice contrast under the p-s crossed states of the polarizer and analyzer is visually better than for the opposite s-p states. This happens due to smaller reflection coefficient for incident p-polarization that drops to a minimum at a Brewster's angle [11]. Thus, the crossed polarizer and analyzer in the state p-s give the better possibility to ice imaging.

For illumination purposes three 10-W LED spotlights Yonkers 10 W (from Inspire) with a beam angle of 100° and the luminous flux of 950 lm were installed above the table where freezing tests were conducted. Three polarizing films (p-state) were affixed to the LED lights. The CPL (Circular Polarized Light) filter DHG Super Circular PL.D. 77 mm (from Marumi) was attached to the front of the lens as the crossed analyzer (s-state).

We used the CPL filter because of their ease of availability. The CPL filter is also a linear polarizer but with an attached quarter-wave plate. In this work we did not use this plate, so the filter worked as an ordinary linear analyzer.

B. *Image Processing*

The processing method required the following preparatory work. At first, a camera with a zoom lens was installed to image the test table where test plates rest. At second, an interval shooting mode began with a test start. Pictures were taken every 20 seconds.

We used the DSLR (Digital Single-Lens Reflex) camera D750, the zoom lens AF-S NIKKOR 24–120 mm (from Nikon), for the experiments. The shooting parameters were as follows: aperture – f/22; exposure – 1/2 s; sensitivity – ISO (International Organization of Standards) 640; focal length – 95 mm. The camera was in turn mounted on a tripod CROSS 628 RW30 (from Cullmann) and 2 meters from the test plates for access purposes.

A series of pictures were obtained during the tests, with the first in the series being a picture before icing starts to serve as the background (or baseline). Obtained pictures were processed using Image Processing Toolbox of MATLAB version R2021b, as follows. Pictures were transformed to a normal view (functions *fitgeotrans* and *imwarp*), and then cropped to plate's border (function *imcrop*). Next, background was deleted via subtraction of a background picture from all the following pictures. Also, the images were binarized with a manually chosen threshold to coincide output results with a visual and tactile inspection. Finally, non-zero pixels were contoured (function *bwboundaries*), relative ice area and test time were calculated.

III. RESULTS

Experiments with polished hydrophilic, coated hydrophobic aluminium plates and aviation anti-icing fluids Types I, II and IV (from Nordix) were carried. We tested two types of hydrophobic plates: one having a glossy finished coating MaxPaint (from Sila Home), and the other having a matt finish MaxPaint (from Sila Home). Results of ice detection for Type I fluid are shown in Fig. 2. Results similar to Fig. 2 were observed for all other Types II and IV fluids tested.

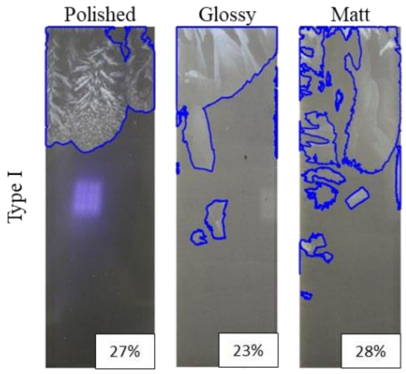

Fig. 2 Ice detection on aluminum plates coated with anti-icing fluids during water spray endurance tests and crossed polarizers. Blue lines show iced areas on polished, glossy and matt varnished aluminum plates covered by Type I anti-icing fluids. The percentages of ice covering are labeled in the right down corners of plate images.

For all tested surfaces and fluids, the crossed polarizers (*p-s*) enhanced the ice contrast substantially in contrast to the parallel polarizers (*p-p*) or without polarizers (Fig. 3). Even in slush conditions, which also refers to a fluid failure and is hard to observe, the polarizing method helped to increase ice contrast and estimate iced areas properly.

The application of polarizers also allows improving visual assessment of icing as practiced today, i.e. visual inspection. This way, the observer will take the role of the camera in the setup developed, and can look through the second polarizer (analyzer), rotate to the crossed position by finding the minimum intensity when looking at the LED light and observe icing. We observed that icing was clearly seen at viewing angles from 0° to 80° relative to the normal to the plane of the test plates. Comparative study between persons experienced or inexperienced with or without a polarizer was not performed, but certainly will be an interesting follow up study.

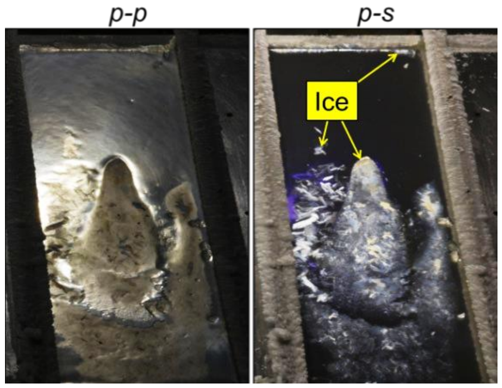

Fig. 3 Ice contrast on the same polished hydrophilic aluminum plate with Type II anti-icing fluid for parallel (*p-p*) and crossed (*p-s*) polarizers.

The processing method successfully determined the iced areas for all tested surfaces and fluids. The method worked even for cases then icing does not start from the top and happens in different parts of a plate. In such cases traditional method to determine failure found by identifying the time when ice front crosses the marked failure zone boundary (i.e., 25 mm from the top and 5 mm from the sides of the plate) is not valid. Then, according to SAE recommendations it is necessary to determine the moment when the icing area reaches 10% of the plate area [*3*]. The proposed method allowed estimating area easily and instantly, whereas it was a challenging and time consuming task for a human observer (results differ among observers).

The algorithm accuracy was the same as the accuracy of a technician present during the test. The threshold was determined from test results done by the operator/technician, and then it was set for the algorithm to meet the threshold. Given the that the optical method used provided us with high ice contrast, it was easy to visually evaluate frosted areas by the technician and further select the areas by the program; this was in contrast to what was done in [4]. Since the endurance tests are based on the human operator accuracy the proposed program considerably saves operator's time without compromising test accuracy. Additionally, the developed method evaluates the whole percentage of frozen area faster and equally or better than a human operator.

IV. Conclusions

The results obtained during endurance tests show the advantages of the proposed methods compared to ordinary visual and tactile inspection. The optical method may greatly increase ice contrast and ease a visual inspection in all endurance tests of SAE AMS 1424 and 1428 aircraft anti-icing fluids. In addition, the processing method can be used to ease fluid failure determination by instantly estimating icing area in a semi/automatic ice detection system for endurance tests.

All used materials and equipment have an affordable price and are available on the market. Also, the method highlights the structure of formed ice and may help in icing analysis for further improvements of anti-icing fluids.

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