International Journal of Heat and Mass Transfer 86 (2015) 39–42

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Technical Note

Infrared detection of water ingress in a composite laminate crevice based on room temperature evaporation

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ARTICLE INFO

Article history:
Received 3 September 2014
Received in revised form 8 December 2014
Accepted 23 February 2015
Available online 12 March 2015

Keywords:
Thermography
Vacuum
Water ingress
Composite structures

ABSTRACT

A novel approach to detect water ingress along rivets and screws or other discontinuities is demonstrated. The approach is implemented through the generation of local vacuum. Vacuum triggers evaporation of water at room temperature. The evaporation process consumes heat energy from the surroundings, causing decrease in local temperature that can be detected using thermography. Using water droplets of different size it is shown that the measured result is a complex phenomenon that includes: (i) actual water cooling due to evaporation, (ii) heat transfer from the substrate; (iii) dynamically changing evaporation rate; (iv) finite IR absorption length of water. In application to the discontinuities, the method unambiguously allows distinguishing dry screws from screws experiencing water ingress. In the case of the wet screw, water volumes below 10 μL were sufficient to cause a temperature drop of more than 10 °C and the effect to be lasting for tens of seconds. Such changes are easily detectable by IR sensors or cameras. Although the exact estimation of water ingress volume does not seem to be feasible, the method has proven to be reliable and it is several orders of magnitude more sensitive in comparison with results reported in earlier reports.

Many industries face challenges caused by water ingress; the chief being corrosion-associated issues. In the aerospace industry, water ingress poses additional concerns due to freeze–thaw cycles during normal flight conditions [1,2]. Such cycles are equivalent to localized fatigue cycles that can eventually cause cracking. Diffusion and direct ingress are two major mechanisms of moisture ingress that have been found to have profound impact on bond degradation in composite honeycomb sandwich structures [1]. Moisture diffusion occurs due to transport through polymer matrices or by wicking along fiber–matrix interfaces. Direct ingress, on the other hand, occurs when water in bulk-liquid form enters a structure via a direct path such as leaking rivets/screws, linked voids, cracks, or improperly sealed joints. It has been found that water retention in a composite honeycomb sandwich structure was often associated with direct water ingress. Particularly, a statistical analysis of thermography data from 202 in-service rudders over 5 years clearly indicated that water ingress mainly starts at the riveted hinges [1].

The most commonly used technique for detecting water ingress is active thermography that can detect volumes in mL range [3–5]. This method is included in nondestructive testing (NDT) manuals for civil airplanes [6] due to ease of use and faster inspection process in comparison with ultrasonic and radiography techniques. The manual mandates using an air heater to warm up the field of view of an infrared camera. The areas with water under the skin will appear as darker/cooler regions in a thermal image. Cooling takes place across the surface as a whole due to heat transfer from the warmer top surface to the cooler internal surface. In case of a honeycomb structure, the internal surface is mainly in contact with air, which is a good thermal insulator. The air will trap heat and prevent the top surface from dissipating the stored heat energy. Water, on the other hand, has roughly 4000 higher volumetric heat capacity than air and, thus, it will work as a heat sink. This will allow the dissipation of heat energy stored in the honeycomb skin and lead to colder contrasts in the thermographs. An alternative approach would be to use phase change in water in order to amplify the effect. One such point is the freezing temperature of water. This method can detect water in honeycomb cells under the composite skin down to 0.2 mL volumes [5], but it might not be practical in hot climates. Another point could be the boiling temperature. However, it is too high at atmospheric pressure and can cause damage to the composite structures.

This study proposes to reduce the boiling temperature by creating a local vacuum above the area of interest [7]. When reduced pressure is achieved, water starts to evaporate consuming 2400 J per gram at pressures around 30 mbar [8]. The temperature of water can quickly drop close to zero degrees, depending on the original amount of water, flow rate of the pump and substrate

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.02.062
0017-9310/

properties [9,10]. To demonstrate this approach, a special vacuum chamber is built, as shown in Fig. 1. The chamber has a hermetically sealed IR window. The achievable pressure inside the chamber, as measured by a digital manometer, is 32 mbar. The phenomena inside the chamber can be observed using a cooled IR camera (FLIR SC7000) sensitive in wavelength range from 3.6 to 5 μm. The camera is placed in front of the window with 90% transmission for the range from 3 to 5 μm.

In the initial experiment four droplets of water were accurately placed on the surface. The volume of water in each droplet was controlled at values of 5, 10, 20 and 30 μL via syringe. The accuracy of dispensing liquid using this syringe was not better than 2.5 μL. However, all the droplets had ellipsoid shape, so the volumes where estimated using pixels in the camera and assumption that the height of each ellipsoid is equal to the smallest semi-axes in its base. Using this method the volumes are calculated to be 4.8 μL, 9.7 μL, 20.6 μL and 32.7 μL, respectively. And the heights of the droplets are 0.6 mm, 0.8 mm, 1.05 mm, and 1.25 mm, respectively. The minimum temperature was monitored on the surface of the droplet. It is worth noting that the absorption length of water in the spectral range of interest is below 100 μm [11]. Due to such high absorption the emissivity of 0.98 was chosen.

Even without vacuum, water droplets appeared to be up to 2 °C colder than the substrate and even caused noticeable cooling of the substrate itself around the droplet. The reason for this is that even at room temperature and atmospheric pressure water evaporates causing the observed temperature difference.

In Fig. 2 the lowest temperatures within each droplet were plotted vs. time. The vacuum was switched on at 4th second of the experiment. For the smallest droplet temperature dropped down to approximately 5 °C, while for larger droplets a 0 °C mark is reached. The drop in temperature was reached within 50 s, which was consistent with the results based on contact temperature measurements using thermocouples [9]. A corresponding insert in Fig. 2 shows all droplets as seen by IR camera with pseudo-color adjusted to temperatures from 5 to 13 °C for better representation. After short period at the lowest temperatures there was a gradual warming of all the droplets. The apparent warming went at different rate for different droplets but all of them heat up to approximately 10 °C. The remaining four inserts in Fig. 2 represent the conditions when within each droplet the temperature raises to 10 °C level.

It was also observed that at positions of approximately 0.5 mm away from each droplet's edge the temperature was stable at around 15 °C during this warming period, indicating that the heat exchange rate between substrate and evaporating droplet is constant. After reaching 10 °C a nearly instantaneous increase in temperature to above 20 °C was observed. This moment coincides with an emergence of a check pattern of underlying plane-woven fabric, as can be seen in inserts in Fig. 2 corresponding to final stages of evaporation for 20 and 30 μL droplet (310th s and 410th s, respectively). Hence, nearly total evaporation of the droplet can be implied. Using Eq. (1) it is possible to estimate interface temperature T_{surf} between the droplet and carbon fiber reinforced plastic (CFRP) [12]

$$T_{\mathrm{surf}} = \frac{T_{\mathrm{water}}\sqrt{e_{\mathrm{water}}} + T_{\mathrm{CFRP}}\sqrt{e_{\mathrm{CFRP}}}}{\sqrt{e_{\mathrm{water}}} + \sqrt{e_{\mathrm{CFRP}}}} \tag{1}$$

where, water temperature $T_{\mathrm{water}} = 273$ K, composite plate temperature at infinity $T_{\mathrm{CFRP}} = T_{\mathrm{room}} = 297$ K, water effusivity $e_{\mathrm{water}} = 1600\ \mathrm{Ws}^{1.2}/\mathrm{m}^2\mathrm{K}$ [13], CFRP effusivity $e_{\mathrm{CFRP}} = 950\ \mathrm{Ws}^{1.2}/\mathrm{m}^2\mathrm{K}$ [14]. After substitution of these values into Eq. (1) the resulting $T_{\mathrm{surf}} = 283.3$ K = 10.3 °C, which is in good agreement with observed value in Fig. 2. All these observations indicate that the apparent "warming up" is not related to the temperature change in the droplet but to the increased transparency of the droplet with reducing thickness. At the wavelengths of interest liquid water has averaged absorption coefficient of approximately 200 cm^{-1} [15], which will provide 50% transparency at water thicknesses below 40 μm. The origin for the different rate of "warming" is not critical for the purpose of this paper and will be explored in future work. But what is worth noting is the approximately linear dependence between evaporation time and droplet volume. Hence, the method can be potentially used for quantitative measurements.

For the demonstration of water ingress detection along the discontinuities, the system is applied to two screws (Fig. 1). One screw is dipped into dish with water. Using the weight reduction of the water dish after dipping, the amount of water trapped along the first screw is estimated to be in a range of 10 μL. The second screw is left dry. Both screws are tightly screwed onto a 3 mm-thick CFRP plate.

Fig. 3 shows the effect of applying vacuum on surface temperature around the two screws placed within the same chamber. The color gradient in all images is a fixed with temperature values varying from 20 to 25 °C for best contrast in the images. The "cold" region that appears near the center of all the images is an artifact, appearing due to self-reflection of the camera image from the IR window of the chamber, and it can be ignored in the discussion. In Fig. 3a the image is taken at atmospheric pressure and both screws appear identical, aside from the reflection artifacts. In Fig. 3b the image is taken on the 5th second after the vacuum

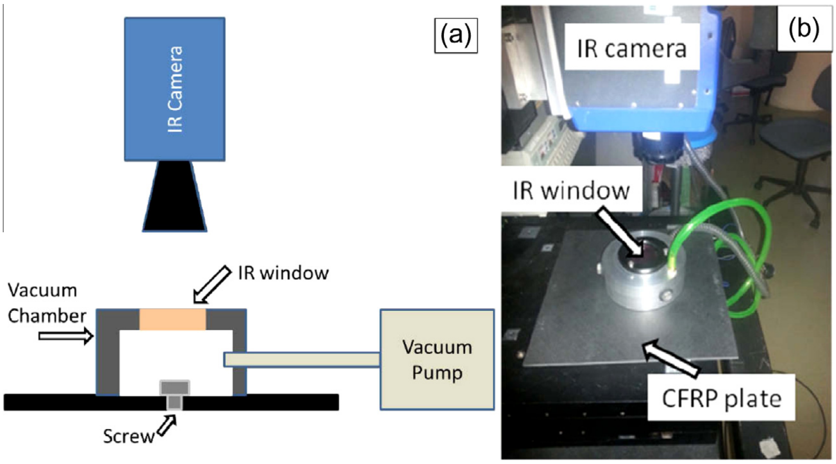

Fig. 1. Set-up for water ingress detection using local vacuum: (a) schematics; (b) photo of the set-up.