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Experimental identification of key parameters contributing to moisture accumulation in an aircraft section

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ABSTRACT

Aircraft can acquire large amounts of moisture in its insulation layers. The trapped moisture increases the aircraft's weight, degrades thermal and sound insulation performance, induces microbe growth, and causes various types of corrosion. It is known that moisture accumulation varies with flight conditions. However, the specific effects of individual parameters, such as flight altitude, cabin air pressure, cabin air temperature, and relative humidity, on moisture accumulation remain unknown. This investigation measures moisture accumulation mass in a reduced-scale mockup of an aircraft section. The mockup is composed of a metallic shell, porous insulation blankets, a ventilation system, heat and moisture generation devices, etc. The mockup is placed in a psychrometric altitude chamber in which the air pressure and psychrometric parameters can be varied in order to simulate different flight conditions. The moisture mass accumulated within the insulation blankets and on the interior skin of the shell is weighed on a digital precision balance. The results reveal that flight altitude and cabin air relative humidity have the greatest effect on moisture accumulation amounts, while cabin air pressure and temperature play relatively weak roles. Greater moisture gain is observed at a high flight altitude and a high cabin humidity level, and vice versa.

1. Introduction

Commercial airplanes can acquire large amounts of moisture in their insulation blankets during daily flights. It has been reported that the weight of trapped moisture on a conventional twinjet aircraft reaches an average maximum of 680 kg, while trijet aircraft gain an average maximum of 1089 kg [1]. Thousands of pounds can be added to a Boeing 747 airplane in just a few months of service [2]. The moisture accumulates primarily in the insulation blankets. Huber et al. [3] reported that blankets removed from a Boeing 737–300 airplane contained up to 36 kg more water than a new shipset of insulation blankets. On average, airplanes in the Boeing 757 fleet have an estimated 91 g of condensation per frame bay above the windows [3]. Accumulated moisture in the insulation blankets is very harmful, as it increases the aircraft's weight [1–3], degrades thermal and sound insulation performance [1,2,4], induces microbe growth [5], and causes various types of corrosion [4–7].

Moisture gain in insulation blankets results from net migration of water vapor into the blankets. On a cruising flight, the outer skin of the shell is exposed to extremely low temperatures. There are large temperature gradients across the insulation blankets and large partial pressure gradients in the water vapor within the blankets. Subject to the cabin humidity level and thus the dew-point temperature, the trapped water vapor may condense into liquid water or freeze directly into ice. The moisture transfer and phase change are coupled with heat transfer through the aircraft walls. The moisture transfer is further complicated by cabin air pressurization or depressurization during the ascending and descending stages of the flight. Moisture accumulation in aircraft walls is affected by cabin air pressure, humidity level and temperature gradients across insulation blanket layers. However, the available literature has not disclosed the quantitative and varying relationships between gained moisture mass and flight operating conditions.

Moisture accumulation also occurs in human clothing and building insulation in cold climates. Fan et al. [8] measured moisture absorption and condensation in fibrous insulation when one side was maintained at approximately 33 °C and the other side at −20 °C, as would be the case for a person wearing clothing in a cold ambient environment. Later, Fan and Cheng [9] measured moisture transfer through clothing assemblies, in which both moisture sorption and phase change were involved. Havenith [10] and Havenith et al. [11] measured the moisture in

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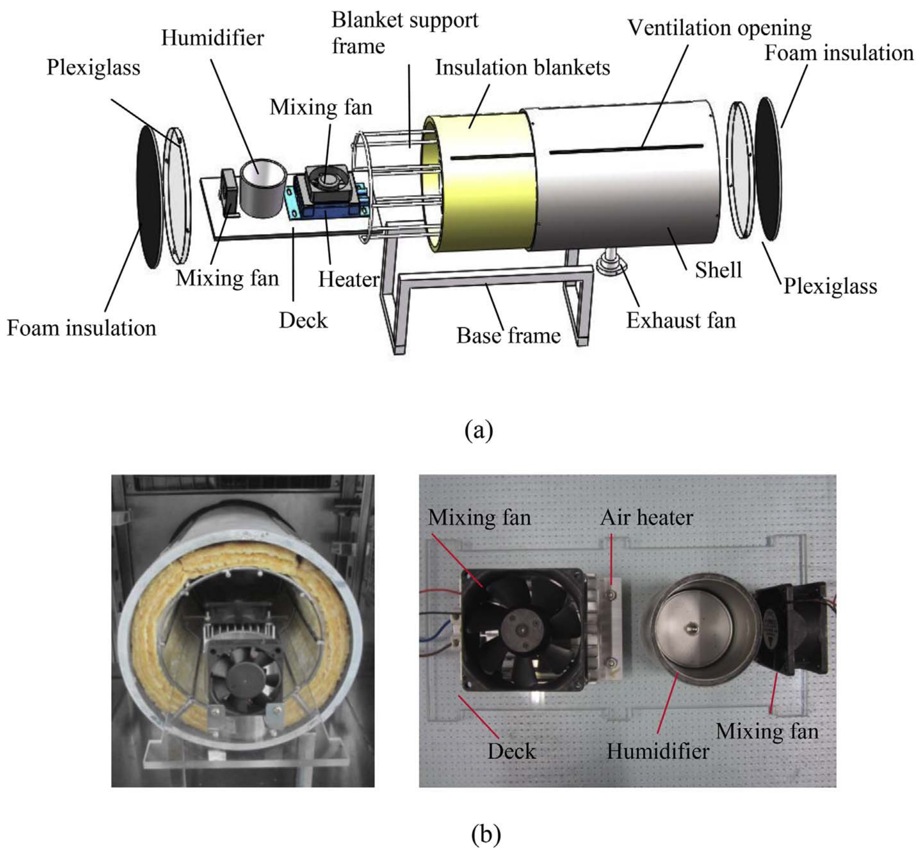

Fig. 1. Reduced-scale mockup of an aircraft section for moisture accumulation tests: (a) schematic design and (b) pictures of the mockup, where the left-hand picture is a side view and the right-hand picture a plan view of the devices on the deck.

sleeping bags exposed to −7 °C and −20 °C, respectively. Kong and Wang [12] measured moisture accumulation in a concrete slab for a period of nearly one year while the exterior surface temperature of the slab varied from less than −20 °C to approximately 30 °C. It should be noted that the outdoor temperature change for building insulation is much less extreme than that encountered by commercial airplanes. The outside air temperature during a flight can change greatly within half an hour from the start of ascent or descent. Furthermore, there is no air pressurization or depressurization process on the ground.

This investigation experimentally measured moisture accumulation in a reduced-scale mockup of an aircraft section placed inside a psychrometric altitude chamber. The onboard air pressure, temperature, and humidity, and the outside temperature variation with altitude are accurately reproduced in the laboratory. Quantitative variations in moisture accumulation with the flight operating parameters are analyzed. Parameters critical to moisture accumulation are identified.

2. Methodologies

A mockup of an aircraft section in reduced dimensions, as shown in Fig. 1, is constructed for experimental tests. The mockup contains a metallic shell, insulation blankets, ventilation slot openings and exhaust, heat and moisture generation devices, etc. A cylindrical section of aluminium alloy with a length of 35 cm serves as the mockup shell. The outer diameter of the shell is 25 cm, and the wall thickness is approximately 1 cm. The interior skin of the shell is covered by three layers of insulation blankets, with a thickness of approximately 1 cm for each layer. The insulation blankets are enclosed by water-resistant tarpaulin bags. A heater, a humidifier, and two mixing fans are placed on the deck of the aircraft mockup to maintain appropriate air temperature and humidity inside the mockup. Outside air is drawn into the mockup through two symmetrical overhead slot openings, each with a length of 32 cm and width of 0.6 cm. The internal air is exhausted by a fan below the mockup. The ventilation rate of 25 air changes per hour (ACH) is similar to that on an actual airplane. Both ends of the mockup are tightly sealed with plexiglass panels and then insulated with foam.

The mockup is placed inside a psychrometric altitude chamber in which the cabin air pressure can vary according to flight stage. The pressure inside the cabin is equal to that in the chamber because there is only a minimal pressure difference when air is drawn from the chamber into the mockup. The chamber also conditions the temperature to be the same as that encountered by the outer skin of the airplane's shell. The heater and humidifier inside the mockup raise the air temperature and humidity to appropriate values. For simplicity, no cooling or dehumidification devices are installed inside the mockup, and therefore the interior temperature and humidity cannot be lowered. To simulate the ground conditions in summer, the mockup shell is wrapped with electric pad heaters to reproduce the high outside temperature that would be encountered. The psychrometric chamber still maintains a cool internal temperature. All major parameters, except for the dimensions and the outside air pressure, are the same as those for an actual airplane. The outside air pressure has no direct impact on the moisture accumulation within aircraft walls because the aircraft shell does not permit moisture penetration.

Fig. 2 illustrates the expected variations in cabin air pressure, temperature, relative humidity, and air temperature in the psychrometric altitude chamber during simulation of a 5-h flight (from t = 0.5 h to t = 5.5 h). The ascending and descending stages of the flight are both set to half an hour, and hence the cruise time is 4 h. During the ascending and descending stages, all the operating parameters are assumed to vary linearly with time. However, the operating parameters are expected to remain fixed during the cruising stage. The solid lines in Fig. 2 represent standard reference operation, while the dashed lines denote increased parametric values and the dash-dot lines denote reduced values. The standard cabin air pressure in the cruising stage is set to 80 kPa, cabin air temperature to 25 °C, and relative humidity to 20%. The outside air temperature is maintained at −21 °C, after accounting for air friction with the outer shell skin on a cruising