Investigation of the impact of a particle foam insulation on frost buildup on the aircraft structure

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Abstract. The aircraft insulation separates the thermally comfortable cabin interior environment from the extremely cold outside condition. However, the fabrication and installation of the insulation in the aircraft is a labour intensive task. Tailored, rigid particle foam parts could be a solution to speed up installation process. The presented study investigates the feasibility of such a concept from a hygrothermal point of view. Due to the temperature difference between the cold air trapped between aircraft skin and insulation on one side and the warm cabin air on the other side, a buoyancy induced pressure difference forms. This effect drives the warmer air through leakages in the insulation system towards the cold skin. Here, moisture contained in the air condenses on the cold surfaces, increasing the risk for uncontrolled dripping (“rain in the plane”) when it melts. Therefore, this study compares the frost build-up of different installations of a rigid particle foam frame insulation with the classical glass fiber capstrip. Tests are hosted in the Fraunhofer Lining and Insulation Test Environment chamber.

1. Introduction

In an aircraft, the sidewall separates the thermally comfortable passenger cabin from the harshly cold exterior environment of approximately -50 °C during cruise. The major protection from cold is achieved by the installation of insulation blankets, ultimately leading to a sufficiently warm surface temperature of the sidewall to avoid discomfort.

The main material for insulating an aircraft is glass fiber wrapped by a moisture resistive foil. This insulation is installed in the form of blankets and covers the frames and fields (Figure 1).

While field blankets are comparably easy to install, the capstrip covering the frame requires more manual work. FAA AC No: 25.856-2A [1] depicts that the capstrip should be fixed either with so called through frame fasteners or with brackets at least every 14” (35.5 cm, Figure 2). Thus, a high amount of manual work is required to install this piece of insulation on the frame. With the use of a rigid particle foam capstrip, this installation effort shall be reduced.
In addition to the thermal protection, the insulation has a function of airflow and moisture barrier in the aircraft. Due to the temperature difference between the warm cabin and crown section and the cold exterior skin, a stack pressure forms resulting in an airflow towards the skin in the upper section of the aircraft envelope. Even though passengers often perceive the air as dry, its due point is at about -10 °C and thus above typical fuselage temperatures in cruise. As a result, frost will form on the skin behind the insulation. On ground, most of this ice is drained after melting by a suited installation of the insulation blankets similar to roof shingles. However, some water may flow in an uncontrolled way and ultimately drip into the cabin (“rain in the plane”). [5] reviews data from a survey conducted by [2] on the B757 fleet and concludes an average daily amount of 91g of water condensation per field. [3] estimates the magnitude of the driving stack pressure to 4 Pa and shows the correlation between the sizes of leakages in the insulation layer and the resulting air ingress. Thus, a careful installation of the insulation blankets helps reducing moisture related issues.

Within the research presented in this paper, it was experimentally investigated to which extent a particle foam insulation on the frame provides the same level of protection against air ingress as the conventional capstrip.

2. Method

2.1. Lining and Insulation Test Environment (LITE) Chamber

The tests of the particle foam insulation were carried out in the Lining and Insulation Test Environment (LITE) chambers of the Fraunhofer IBP in Holzkirchen, Germany. The chamber has been constructed for the experimental investigation of aircraft insulation systems. It consists of an exterior aluminum
fuselage with five frames thus resulting in four fields. The floor area is 2.89 x 1.74 m and it is 1.86 m high (Figure 3). The chamber walls are insulated to limit thermal losses. In order to condition the exterior fuselage, a second skin has been built leaving an approximately 5cm wide air gap. This gap is flushed with conditioned air in order to represent cold exterior conditions or a hot day on ground. In an airliner, the chamber section would approximately accommodate nine economy passengers.

![Figure 3: LITE chamber (aluminium fuselage)](image)

In order to represent the cabin climatic conditions, the chamber is ventilated by an HVAC system providing heating, cooling and humidity control. The air in the chamber can be considered well mixed.

2.2. Sidewall test setup

For the experimental campaign, the fuselage section was split in two subsections. On the left section, the frame was covered by the particle foam insulation while on the right section, the conventional capstrip with through-frame fasteners was used. The primary field insulation blankets were of the same type on all sections. Through this installation, three major types of leakages emerge (Figure 4):

- Between the particle foam frame insulation and the field blanket
- Between the capstrip and the field blanket
- On the upper and lower edge of the field blankets

![Figure 4: Particle foam insulation and capstrip installed in the LITE test chamber](image)
The primary insulation layer was covered with sidewall lining panels. On the rear side, state of the art secondary insulation has been fixed (Figure 5). This insulation consists of glass fiber blankets wrapped in foil. The window openings in the sidewall are plugged with Styrofoam bluff bodies to align with the field blanket and seal the opening against air ingress.

The sidewall is supported on its lower edge by a U-bar mounted on top of the reconstructed dado panel (black lower panel in Figure 5). On the upper edge, it is prolonged with a self-constructed structure and pressed against the frame using stamps attached to threaded bars that are fixed on the ceiling. The top structure leaves an overflow path between cabin air and the air gap between primary and secondary insulation. In the aircraft, this gap is not visible to the passenger but is present behind the stow bin.

![Figure 5: Fixation of sidewall in front of the primary insulation (left and middle), secondary insulation behind sidewall (right)](image)

In order to divert parts of the cabin air behind the sidewall, an extraction fan was installed with four suction ports (one per field) at the floor behind the dado panel. This fan generates a pressure difference between cabin and behind the sidewall of approximately 4 Pa. In contrast to the real aircraft, where cabin air is extracted at dado panel level, the dado panel one used in the test chamber is airtight. Therefore, any air circulating behind the sidewall results from leakages. The global ventilation pattern of the chamber is shown in Figure 6. The cocoon air only cools the fuselage structure and does not mix with cabin air. Most of the cabin ventilation air is recirculated and re-supplied after conditioning. The excess of air removed by the extraction fan behind the dado panel is compensated by leakages in the suction side of the HVAC system ducting.

![Figure 6: LITE chamber ventilation](image)
2.3. Test matrix

The test campaign was designed to answer two major questions from a hygrothermal point of view:
- Does the installation sequence of the insulation parts influence the frost buildup?
- Can the material thickness be reduced to save weight?

The first question addresses the sensitivity of frost buildup towards optimizations in the installation process. In order to address this, the installation sequence of the insulation pieces was altered (Figure 7). In the baseline trial, the field blankets were first installed and it was made sure the blankets’ edges were clamped by the particle foam insulation. This is considered a careful and high quality installation. To compare, the frame insulation was first installed and then the field blankets were put between the frames. Thus, a somewhat undefined gap prevails. As this procedure requires less careful manual work, it is considered the low quality installation. Both tests were conducted using a frame insulation of 20 mm thickness.

![Comparison of the low quality installation (top) with the high quality installation (bottom)](image)

In order to investigate the potential to reduce material, 10 mm and 20 mm thick particle foam frame insulations were tested. In both tests, the frame insulation was carefully installed.

2.4. Test conduct

The boundary conditions summarized in Table 1 were applied. Cabin humidity was exaggerated in order to receive a clearer frost buildup distinction between the test cases.

Table 1: Test boundary conditions

| Boundary condition                        | Value  |
|------------------------------------------|--------|
| Exterior fuselage temperature            | -30 °C |
| Cabin ventilation flow rate              | 368 kg/h |
| Cabin temperature                        | 24 °C |
| Cabin humidity                           | 30%    |
| Pressure difference across sidewall      | 4 Pa   |
| Exposure duration                        | 7 h    |
After the exposure, the sidewall and the insulation were removed. The frost buildup was photographed and the quantity of frost was assessed by weight difference after scratching it into a bag and wiping melted water from the structure with a sponge (Figure 8).

Figure 8: Collection of accumulated frost from the structure

3. Results

During installation, it was noted that the 20 mm thick particle foam frame insulation is more rigid than the 10 mm thick one. The latter tends to higher torsion and provides noticeably less stability. This results in a less good sealing between the frame insulation and the field blanket.

Figure 9 shows the results of the determined frost buildup. The blue bar refers to the frost amount in the left two fields with the particle foam frame insulation; the orange bar refers to the fields with a state of the art capstrip. It should be noted that the middle frame has a particle foam insulation and thus slight influence is expected on the state of the art fields, too. It is obvious, that the carefully installed 20 mm particle foam frame insulation performs equally well as the conventional capstrip, but it consists of less parts and its installation thus was quicker. Built up frost is mainly due to the upper and lower edges of the field blankets. When using a thinner particle foam frame, the amount of frost increased due to less firm sealing towards the field blanket. The uncareful installation, reflected by installing the field blanket after the particle foam frame insulation results in a major increase of frost buildup.

Figure 9: Determined amount of frost for the test settings

In Figure 10 the IR signature of the frame insulations on the sidewall surface are shown. It can be seen that the section on top of the frame insulation is noticeably warmer than the section on top of the capstrip. The reason is that the capstrip is compressed by the sidewall whereas the particle foam insulation
remains rigid. The thicker (20 mm) particle foam insulation results in higher surface temperature than the thinner one (10 mm). Even though the effect is visible, its magnitude is not considered to have a major impact on the passenger comfort due to the relatively local confinement.

4. Conclusion
This study investigated the performance of a particle foam frame insulation to prevent the frost buildup in comparison to the state of the art capstrip covering the frame with a flexible glass fiber insulation. The aim of replacing the capstrip is to reduce installation time and number of parts for the insulation system. The thermal effect of changing the frame insulation is visible by IR camera on the sidewall. However the magnitude is not considered relevant for a noticeable improvement of passenger comfort by increased sidewall temperature. Nevertheless, the study shows that a sufficiently rigid particle foam insulation achieves the same level of sealing as today’s capstrip. Even though the installation is quicker, it still remains indispensable to thoroughly consider the joint between field blanket and the particle foam frame insulation. The 20 mm thick particle foam insulation on the frame performs similar to today’s capstrip and therefore, it is worth further assessing its potential to reduce installation times in the factory. Further research would be required to ensure its compatibility with fire safety standards as e.g. set out in [6,7].

Figure 10: IR images comparing the frame insulation infrared signature on the sidewall (left) and the conventional capstrip (right)
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6. References
[1] FAA AC No: 25.856-2A: “Installation of thermal/acoustic insulation for burnthrough protection”, 29.7.2008
[2] Huber P., Schuster K., Townsend R.: Controlling Nuisance Moisture in Commercial Airplanes, Aero 05, 1999
[3] Walkinshaw, D.S. and Preston, K., "Controlling Cabin and Envelope Air Flows and Pressure Differentials to Prevent Envelope Condensation, Enable Cabin Humidification, Improve Fire Safety, and Decrease Fuel Use," SAE Int. J. Aerosp. 4(2):1243-1253, 2011, https://doi.org/10.4271/2011-01-2689
[4] Walkinshaw D.S. and Horstman R.H.: “Stack pressure-created airflows in insulation envelopes, Part 2: Passenger Aircraft”, ASHRAE Journal, May 2020
[5] Wörner M.: „Wärme- und Stofftransport in einer Flugzeugkabine unter besonderer Berücksichtigung des Feuchtettransports“, Dissertation at University of Hamburg-Harburg, 2006
[6] U.S. Department of Transportation Federal Aviation Administration. Thermal/Acoustical Insulation Flame Propagation Test Method Details; 2005; U.S. Department of Transportation, Washington, DC 20591, United States
[7] U.S. Department of Transportation Federal Aviation Administration. Installation of Thermal/Acoustic Insulation for Burnthrough Protection; 2008; U.S. Department of Transportation, Washington, DC 20591, United States