Assessment of aircraft anti-icing ethylene glycol-based fluid ethylene glycol-based performance using thermography approach

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Abstract— **Protecting the aircraft surfaces from ground icing in cold weather conditions before takeoff via anti-icing fluids is crucial for flight safety. These fluids offer a specific protection time evaluated through outdoor endurance time testing. As outdoor conditions are difficult to standardize and repeat, there is interest in developing interior tests under simulated snow conditions. This study investigates the impact of snow type on snow-fluid interactions which govern fluid failure mechanisms. Natural snow is compared to fresh and aged artificial snow for ethylene glycol-based anti-icing fluids. Infrared and visual cameras are utilized to monitor a small test plate measuring six by eight centimetres, with a depth of 6 millimetres. This plate serves as the deposition site for snow at regular intervals, adjusted based on the precipitation rate at the center of the plate. The snow is distributed onto the plate via a specially designed deposition system, ensuring a consistent volume over a constant area. Thermography is used to study temperature drops and the rebalancing process under simulated snow precipitations. This work presents two test methodologies: the first considers a single snow deposition for each fluid at different concentrations. The second aims to study fluid saturation by simulating different snow intensities. The snow mass is calculated based on the density measured by the Schnee- und Lawinenforschung (SLF) snow sensor and the known deposited snow volume. The average deposited snow mass is then used to determine the time interval for snow deposition to simulate representative natural precipitation rates. Infrared (IR) thermography results for each snow type (natural, fresh artificial snow, aged artificial snow) are considered. Snow types are characterized by density and liquid water content (LWC). Results show that ethylene-based fluids experienced significant temperature drops and have a characteristic temperature rebalancing process related to the fluid's thermal and diffusion properties. Furthermore, the relationship between the deposited snow mass and the temperature gradient remains consistent irrespective of the snow type as long as the snow mass does not almost reach the saturation threshold. The impact of different snow types is studied and compared for both test procedures to evaluate possible sources of discrepancies between outdoor and indoor fluid snow precipitation endurance testing. This study revealed how the temperature changes, fluid saturation, and failure stages are reached for each studied anti-icing fluid with snow precipitation rate and snow types.**

Keywords— ***Aircraft anti-icing fluid, Endurance time, Infrared thermography, Natural snow, Artificial snow***

I. INTRODUCTION

Aircraft icing is one of the leading external causes of flight accidents [1, 2]. Several studies proved that aircraft icing has a fatal effect on flight safety [1, 3-5]. Winter operations for aircraft on the ground are based on aircraft anti-icing mechanisms that protect surfaces from precipitations such as snow and freezing rain, which is paramount as these elements can adhere to critical surfaces. Using liquid glycol products is the primary method of anti-icing the aircraft on the ground [6]. These fluids provide a specific endurance time for which they can protect the surface, beyond which the security of the surface is compromised. The industry standards SAE AS6285 and SAE ARP5485B introduced in these papers give the methods and procedures for adequate anti-icing of aircraft on the ground [7, 8]. The performance of these products is determined by their ability to postpone the formation of freezing and frozen contaminations. Their efficiency depends on their composition and meteorological conditions, such as temperature and precipitation type and intensity [9]. Studying the interaction between snow and the anti-icing fluid is crucial to deepening our understanding of failure mechanisms in evaluating the performance of anti-icing fluids. The fundamental principle of anti-icing fluids is to lower the freezing point of water, hence the interest of studying these fluids using infrared thermography. This paper will present the temperature gradient measurement after a precise snow mass deposition. Focusing on thermographic analysis, it delves into the interaction between ethylene glycol-based fluids and diverse snow types within a small-scale experimental setup. Thermography methodologies use infrared imaging technology to capture temperature variations in time within an area. This study can contribute to the field's understanding by clarifying the influencing parameters and offering valuable insights into this interaction. To fulfill this, our research team has developed a specific setup, which is presented in the following section.

II. MATERIALS AND METHODS

1) *Presentation of the experimental setup*

A small-scale experimental setup has been developed, including a newly developed snow deposition system called "snow dropper" and an aluminum test plate with a thickness of 12mm to ensure thermal stability during tests. The plate has 4 compartments of 80mm x 60mm x 6mm (L x W x H). Aluminum was chosen to prevent corrosion. A funnel with an outlet diameter of 8 mm is added to the setup to manage the deposition area. Fig. 1 presents this setup.

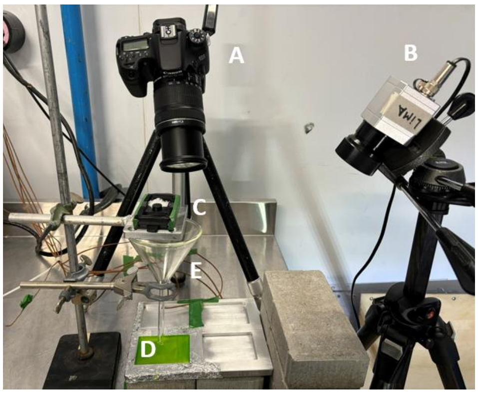

Fig. 1. Experimental setup. (A) Visual camera (B) Infrared camera (C) Snow deposition system (E) Funnel (D) Test plate.

The snow dropper allows the deposition of a precise volume of snow at a precise location. The deposited mass is estimated from the snow density measured by the snow sensor from FPGA Company GmbH (website as ref). The snow is sifted before measuring the density of the snow.

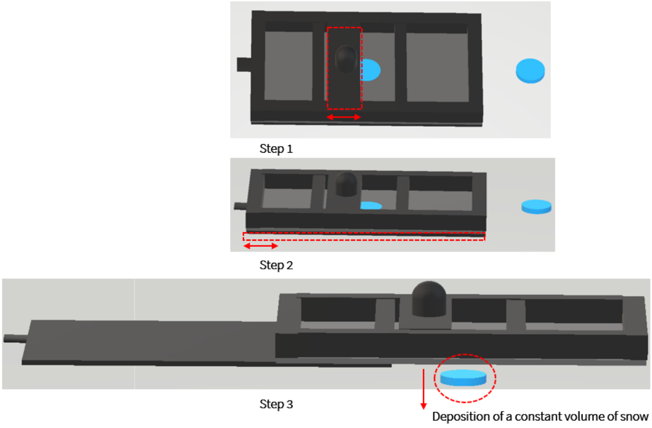

Fig. 2. The snow deposition system.

The deposition process of this system is based on three main steps (Fig. 2):

- Snow filling (Step 1): The first step involves sifting snow, filling it in the deposition volume, and ensuring it is correctly filled. The volume is equal to 13.17mm³.
- Levelling the snow volume (Step 2): The snow volume is levelled by moving the upper bar to remove any excess snow.
- Snow deposition (Step 3): The third step involves depositing the snow by removing the lower plate to allow the snow volume to fall.

These three steps ensure a precise and controlled snow deposition process for subsequent tests and measurements. The deposition area depends on the funnel height relative to the fluid level. Several trials were conducted to determine the optimal height, which was 2.3cm, resulting in an area of around 8-9mm. Artificial snow tends to densify over time, so density is measured on each testing day with the SLF snow sensor from FPGA Company GmBH. The mass of deposited snow is evaluated every test day by conducting multiple depositions and then calculating the average of each deposition. The snow morphology was investigated by taking pictures of natural and artificial snow using a Canon EOS70D camera with the EFS 18-135 mm macro 0.39/1.3ft lens.

An infrared camera (Optris Pi450i) and its corresponding software (Optris PIX Connect) are used to visualize the fluid-snow interaction thermally. The goal is to quantify the temperature drop when snow comes into contact with the anti-icing fluid, the snow melting, and the thermal re-equilibration of the environment. A visual camera, Canon EOS70D with EF-S lens, is also set up to capture video of visually observable phenomena and compare it with the data from the infrared camera.

The studied fluids are based on ethylene glycol, a green commercial anti-icing fluid Type IV and a clear reference fluid manufactured in AMIL laboratory which is a simple dilution of a pure ethylene glycol. Both fluids are studies are specific concentrations: 50%, 37.5% and 25% in volumetric concentration relative to the active component, ethylene glycol. The most concentrated solution is 50% because the commercial anti-icing fluid used in winter operations is at this concentration. This range of concentrations allows us to observe the effects of different fluid concentrations on the temperature drop.

The first type of test in our controlled environment is the single snow deposition test. In this test, a single snow deposition is performed on a 2.6mm thick layer of the studied fluid on a horizontal test plate. Three repetitions are conducted for each sample, ensuring the reliability of our measurements and aiming to measure the minimum temperature drop. The second type of test is intensity-based, where the snow is deposited in successive snow drops with time intervals between each snow drop. The time interval is defined based on the deposition area and the mass of deposited snow to achieve a targeted intensity. This test procedure aims to simulate different snowfall intensities on a small surface to thermally evaluate the failure of the anti-icing fluid. These tests were conducted in the cold chamber at an ambient temperature of -5°C in the anti-icing materials international laboratory (AMIL).

2) The study of morphology of natural snow and artificial snow

This research also delved into the morphology of natural and artificial snow. Photographs were captured of natural snowflakes collected during snowfall and artificial snowflakes produced in the AMIL laboratory.

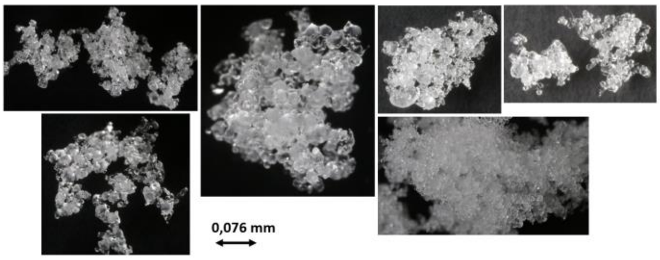

Fig. 3. Artificial snow crystals.

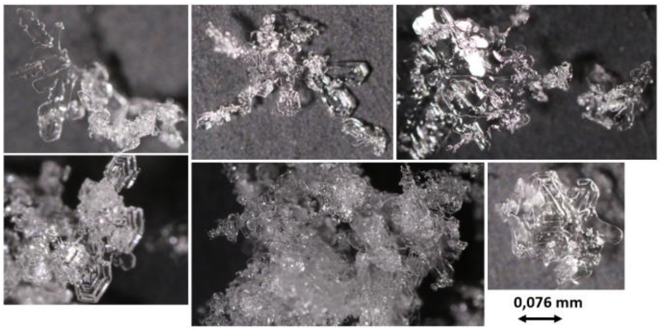

Fig. 4. Natural snow crystals.

Fig. 3 displays the artificial snow crystals we produced in AMIL, characterized by tiny frozen droplets and a 141.64 kg/m^3 density. In contrast, Fig. 4 showcases natural snow with a 53.55 kg/m^3 density collected during snowfalls with an air temperature of 0°C. This snow exhibits a crystalline structure with symmetrical and patterned shapes such as dendrites, hexagonal plates, and stellar forms [10, 11]. These distinct morphological differences highlight the unique characteristics of natural and artificial snow depending on the formation process. These pictures show the remarkable differences between them. Since the snow crystal formation mechanisms depend on environmental and meteorological conditions, they influence growth rates and generate various snowflake characteristics and morphologies [12].

The natural snow formation starts when the ice nucleation of water droplets begins in the clouds at higher altitudes when the temperatures decrease. The freezing of supercooled water droplets (liquid water at sub-zero temperatures) occurs due to the presence of ice nucleators. Ice nucleation is an exothermic process that releases energy to the surroundings. Ice nucleator defines a nucleus with an ice-like structure called a nascent snow crystal. The ice nucleators help water molecules to get into an ice crystal lattice. They also control the nucleation temperature, even though the nucleation mechanisms of ice nucleators are still unknown. They can be inorganic or organic materials. Many organic ice nucleators exist, commonly proteinaceous, including many microorganisms such as bacteria, birch pollen, and fungi. They provide higher ice-nucleating activity compared to inorganic particles. The ice-nucleating activity demonstrates the capacity to induce the crystallization of supercooled water [13], [14], [15]. The nascent snow crystal grows into more giant snowflakes by accumulating water vapour from supersaturated air [13]. The released energy allows the evaporation of encircling water droplets to get enough water molecules for snow crystal growth, in other words, to get the necessary supersaturated water vapour phase.

AMIL laboratory produces artificial snow in a cold chamber between -20°C and -25°C using fine spray hydraulic nozzles that spray supercooled water droplets which have mean volumetric diameter of approximately 25 µm. The sprayed water transforms into snow when it contacts a with a solid surface (the ground).

III. THE IR THERMOGRAPHY RESULTS OF ANTI-ICING FLUIDS BASED ON ETHYLENE GLYCOL WITH DIFFERENT TYPES OF SNOW

This section presents the study of the IR thermography results of anti-icing fluids conducted in this paper. Thermography methodology is used to investigate anti-icing fluids' effectiveness when subjected to various snow types. It allows one to examine the temperature changes within the fluid-snow system to understand the fluid's ability to facilitate snow melting.

A. The single snow deposition tests results

This test was conducted for two different productions of artificial snow. The temperature gradient after snow deposition was measured for each studied fluid and each test was repeated three times for each snow production. Both reference and industrial fluids were used with 50%, 37.5%, and 25% dilutions. Fig. 5 shows an example of the IR images of snow deposition on anti-icing fluid type IV, ethylene glycol-based (concentration of 50%). Upon contact with the fluid, a noticeable a temperature decline occurs with temperature gradient of -10.26°C due to an ensuing endothermic reaction and subsequent equilibration and melting processes until a new equilibrium state is achieved.

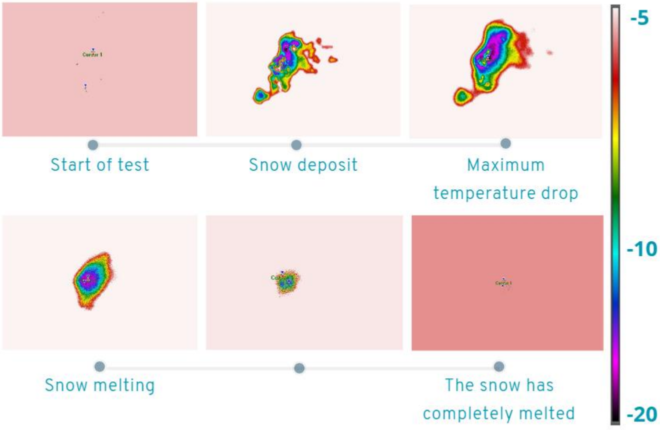

Fig. 5. IR images of the fluid Type IV based on ethylene glycol.

The temperature drop is the decrease of the minimal measured temperature in the measuring area. The gradient temperature represents the temperature change rate over a given space and time interval. The temperature gradient is calculated by dividing the temperature difference between the initial temperature before the snow deposition and the minimal temperature reached during the temperature drop. The obtained results in this section are presented in Fig. 6 and Fig. 7.

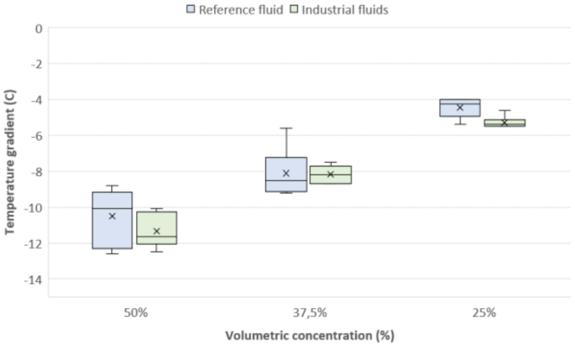

Fig. 6. Boxplot of temperature gradient for different concentrations depending on the type of fluid.

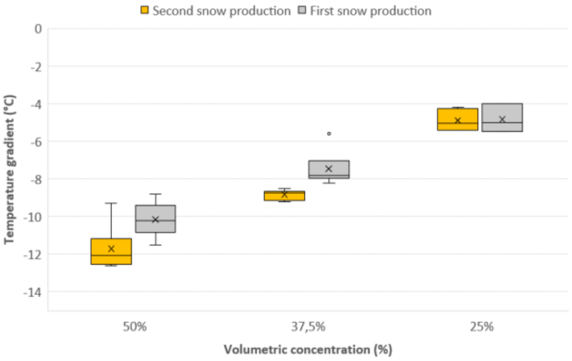

Fig. 7. Boxplot of temperature gradient for different concentrations depending on the snow type.

Fig. 6 and Fig. 7 show that the lower the concentration of ethylene glycol in the solution, the smaller the temperature gradient observed, which is expected because fewer active elements are responsible for the decrease in temperature. In other words, the effectiveness of the anti-icing fluid in reducing temperature is directly related to the concentration of ethylene glycol present in the solution.

The average mass of snow deposited per deposition from the first snow production is 8.56mg, and that of the second production is 9.67mg. The second production has a higher average mass of snow deposited per deposition, which explains why the temperature gradient obtained for the second snow production was slightly different than that of the first, as presented in Fig. 7. In addition, the temperature gradient difference for the 25% concentration is nearly similar regardless of the snow production. Indeed, at this lower concentration, both deposit masses appear to result in approaching the fluid to its saturation locally, where only a portion of the deposited snow is transformed into water. Conversely, the 50% and 37.5% concentrations are not saturated (100% snow mass is converted to water), and the temperature gradient varies accordingly. The difference in the deposited mass is due to the snow used since the mass depends on the density of the studied snow. The new snow deposition system is based on constant volume, which presents a technical limitation. The obtained results show how the ethylene glycol concentration in each tested sample affects the thermal behaviour and effectiveness of the sample by measuring the temperature drop and the temperature gradient upon snow deposition to quantify the temperature changes and asses the sample performance at different concentrations.

TABLE I. A COMPARATIVE ANALYSIS OF SINGLE DEPOSITION TESTS WITH NATURAL AND ARTIFICIAL SNOW

Volumetric Concentration	**Temperature gradient (°C)**	**Average snow mass per deposition (mg)**	**Type of snow**
50 %	-12	*4*	*Artificial snow*
50 %	-12.7	*4.09*	*Natural snow*
37.5 %	-9.2	*4*	*Artificial snow*
37.5 %	-9.3	*5.52*	*Natural snow*

Single deposition tests were conducted using both natural and artificial snow, where only the reference fluid was used for two concentrations, 50% and 37.5%. Table I shows that the temperature gradient obtained for identical concentrations remains consistent due to the proximity of the average snow mass per deposition. These preliminary results reaffirm a recurring trend observed in the previous experiments, indicating a significant correlation between the temperature gradient and the quantity of deposited snow, irrespective of its type (morphology).

B. *Snow intensity tests*

The snow precipitation rate (snow intensity) used for these tests was 30 g/dm^2/h. The tests lasted one hour and fifty minutes, with snow being deposited every two minutes. The fluids used were the reference and industrial, with a 50% volume concentration of ethylene glycol.

Figures Fig. **8** and Fig. **9** present the minimum temperature recorded of two zones: a reference zone defined away from the deposition zone and a specific measurement zone where the snow was deposed.

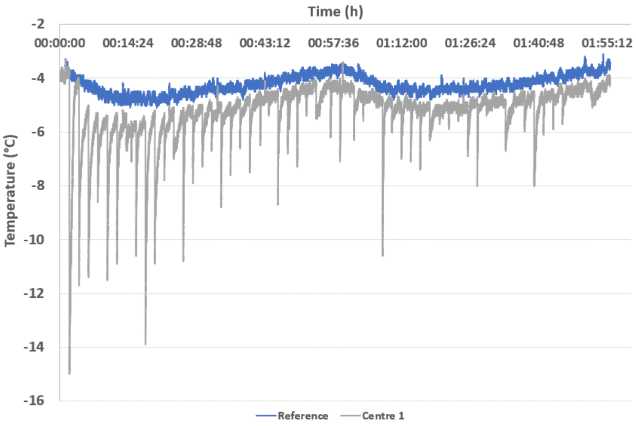

Fig. 8. The temperature over time for the intensity rate test at 30 g/dm^2/h for the industrial fluid at 50%.

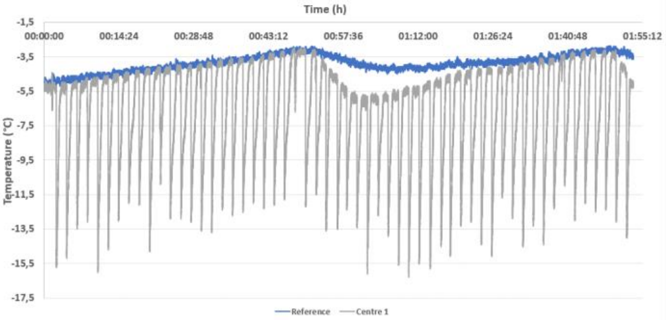

Fig. 9. The temperature over time for the intensity rate test at 30 g/dm^2/h for the reference fluid at 50%.

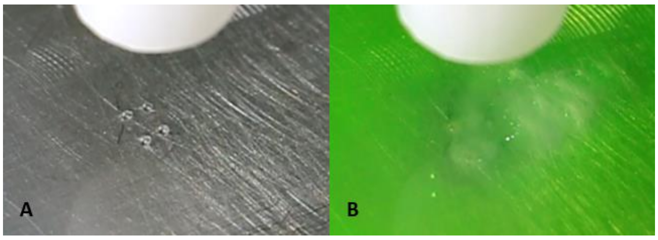

Fig. 10. Visual images at the end of the intensity test (A) for the reference fluid - (B) for the industrial fluid.

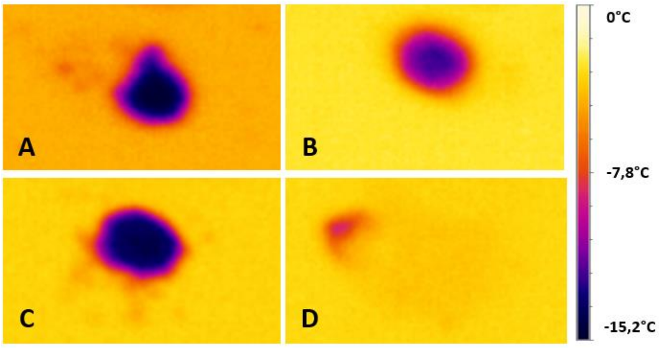

Fig. 11. Infrared images (A) First snowdrop in the reference fluid 50%- (B) Last snowdrop in the reference fluid 50%- (C) First snowdrop in the industrial fluid 50%- (D) Last snowdrop in the industrial fluid 50%.

Fig. 8 and Fig. 9 show notably that the temperature drop of industrial fluids decreases after several depositions, while the reference fluid's temperature drop varies more or less around the same values. Indeed, this is due to each fluid's viscosity. The industrial fluid is viscous (measured viscosity equal to 39.300cP), while the reference fluid has a viscosity similar to water since it contains no additives. The visual images in Fig. 10 confirm this: snow is observed on the industrial fluid, while no accumulation occurs in the reference fluid. The infrared pictures in Fig. 11 for each fluid's last snowdrop clearly show the industrial fluid's thermal failure being saturated. In contrast, the reference fluid is still able to perform thermally. The industrial fluid, which is thicker and where diffusion mechanisms take longer than in the reference fluid, decreases its ability to provide energy to the snow after successive depositions since it approaches saturation, where it can no longer perform (decline in local concentration of ethylene glycol).

When snow interacts with a solution that reduces the freezing point of water, the temperature of the solution decreases in proportion to the quantity of snow introduced. This phase change from solid to liquid, composed of a solid fraction and a liquid fraction of melted snow, necessitates energy, decreasing the solution's temperature. As the snow melts, the solution becomes more diluted locally, and diffusion equalizes the concentration to match the surrounding solution. Eventually, the temperature reduction stabilizes once a specific amount of snow is deposited, dictated by the concentration of the solution and its viscosity, impacting the diffusion mechanisms and leaving solid snow behind. This indicates saturation, suggesting that the solution has reached its melting point based on its local concentration, and snow accumulation begins, ultimately leading to the solution's inefficacy.

IV. CONCLUSIONS

This paper investigates the relationship between the concentration of ethylene glycol in a solution, the observed temperature gradient, and the effectiveness of anti-icing fluid. It also analyses the impact of the average mass of snow deposited per deposition on the temperature gradient obtained. The following points conclude the funding in this work:

- The study of natural and artificial snow morphology shows significant differences in morphology and density. Artificial snow crystals appear composed of frozen droplets, resulting in a higher density than natural snow, which exhibits a more intricate and symmetrical crystalline structure.
- For a given snow production, a consistent temperature drop is observed for both fluids at identical concentrations when a specific volume of snow is deposed. However, variations in snow density measurements between snow productions reveal that denser snow leads to a greater mass from the constant volume deposition approach which increases the temperature drop. This is true as long as the fluid is not saturated; at saturation the temperature drop becomes constant and the fraction of snow remaining solid increases leading to accumulation. However, fluid saturation occurs at lower concentrations, even in small deposit masses, which keeps the gradient unchanged.
- Consequently, if two snow productions exhibit different densities, the experiment would showcase varying gradients, as the snow deposition system controls volume deposition rather than mass.
- The viscosity of anti-icing fluids plays a significant role in determining the failure mechanism, as it affects diffusion rates, which are slower in thicker industrial fluids than the reference fluid. Consequently, the industrial fluid's capacity to supply energy to the snow diminishes with successive depositions, reducing its temperature drop. This decline occurs as the fluid nears saturation, where it becomes unable to function effectively due to a decrease in the local concentration of ethylene glycol. Higher viscosity correlates with lower diffusion rates due to reduced molecular mobility. As the snow melts, localized dilution of the fluid occurs, accelerating saturation and snow accumulation since diffusion from higher concentration regions is too slow.

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REFERENCES

[1] W. T. Yihua Cao, Zhenlong Wu, "Aircraft icing: An ongoing threat to aviation safety," *Aerospace Science and Technology,* p. 28, 2018.

[2] Y. Cao, Z. Wu, Y. Su, and Z. Xu, "Aircraft flight characteristics in icing conditions," *Progress in Aerospace Sciences,* vol. 74, pp. 62-80, 2015.

[3] J. MCLEAN, J, "Determining the effects of weather in aircraft accident investigations," in *24th aerospace sciences meeting,* 1986, p. 323.

[4] M. Elshamy, "Effect of atmospheric processes on launch decisions," *Journal of Spacecraft and Rockets,* vol. 32, no. 5, pp. 801-805, 1995.

[5] L. Chang, "Aircraft icing and aviation safety. Aeronaut," *Sci. Technol,* vol. 5, pp. 12-14, 2010.

[6] E. Villeneuve, C. Charpentier, J.-D. Brassard, G. Momen, and A. Lacroix, "Aircraft Anti-Icing Fluids Endurance Under Natural and Artificial Snow: a Comparative Study," *International Review of Aerospace Engineering (IREASE),* vol. 15, no. 1, pp. 1-11, 2022.

[7] *AS6285, Aircraft Ground Deicing/Anti-Icing Processes,* Aerospace Standard AS6285, revision A, SAE International, 2018.

[8] S. o. A. E. G12. *Guide to Aircraft Ground Deicing*, 2022, p. 400.

[9] M. S. Switzenbaum and et al., "Best management practices for airport deicing stormwater," (in eng), *Chemosphere,* vol. 43, no. 8, p. 1051, 2001.

[10] W. Shimada and K. Ohtake, "Three-Dimensional Morphology of Natural Snow Crystals," *Crystal Growth & Design,* vol. 16, no. 10, pp. 5603-5605, 2016, doi: 10.1021/acs.cgd.6b01263.

[11] W. A. Bentley and W. J. Humphreys, "Snow Crystals," *Nature,* vol. 129, no. 3265, pp. 778-779, 1932/05/01 1932, doi: 10.1038/129778a0.

[12] Libbrecht and K. G, "The physics of snow crystals," *Reports on Progress in Physics,* vol. 68, pp. 855-895, 2005-04-01 2005, doi: 10.1088/0034-4885/68/4/R03.

[13] B. Mohammadian, N. Namdari, A. H. Abou Yassine, J. Heil, R. Rizvi, and H. Sojoudi, "Interfacial phenomena in snow from its formation to accumulation and shedding," *Advances in Colloid and Interface Science,* vol. 294, p. 102480, 2021, doi: 10.1016/j.cis.2021.102480.

[14] K. E. Zachariassen and E. Kristiansen, "Ice Nucleation and Antinucleation in Nature," (in eng), *Cryobiology,* vol. 41, no. 4, p. 257, 2000.

[15] M. Joly and et al., "Ice nucleation activity of bacteria isolated from cloud water," (in eng), *Atmospheric Environment,* vol. 70, p. 392, 2013.