Experimental Investigations of Physical Factors Which Influence Runoff and Failure Behavior of Aircraft De-icing Fluids

by

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Non-Newtonian (Type II) de-icing fluids are currently used to prevent aircraft ground icing. Lack of a clear understanding of the mechanisms that determine the fluid behavior under different icing conditions has resulted in operational problems. Field and laboratory observations were conducted at a microscale level, in order to gain a better understanding of the microphysical phenomena that influence the performance and degradation of de-icing fluids.

In the field tests, two flat plates and a cylindrical surface were treated with Type II fluid and were exposed to natural precipitation. High magnification cameras were used to observe the performance of the fluids, under snow, ice pellets and freezing drizzle conditions. Depending on the precipitation type, different modes of fluid failure were identified. For snow and ice pellet precipitation, failure appeared as inability of the fluid to melt the incoming precipitation elements. In snow cases, the melting time of individual snow flakes, was identified as a potential metric to characterize fluid failure. In most cases, precipitation water did not mix homogeneously into the fluid film. Bonding between snow or ice accumulations and the test surface was not observed in any of the cases analyzed.

In the laboratory tests, close-up video analysis was conducted on the impact of individual precipitation elements on a Type II fluid film. The mixing and runoff behavior observations from these experiments, were consistent with the data from the field exposures.

Thesis supervisor : Dr. R. John Hansman, Jr.
Associate Professor of Aeronautics and Astronautics
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Chapter 1

Introduction

It has been recognized within the commercial aviation community, that it is necessary to provide airlines and airport authorities with safer, more reliable and cost effective ground de-icing and anti-icing regulations and procedures. Recent accidents involving large transport as well as small general aviation aircraft, document the seriousness of the problem. There have been 11 major accidents related to ground de-icing in the past 15 years [Haase D.J., 1991].

Currently, most transport aircraft used in commercial aviation are certified for flight in icing conditions. This capability is typically based on the use of ice protection devices installed on the leading edge of critical surfaces. However, the most severe problems for transport aircraft are encountered during takeoff. Ice accumulation on unprotected aircraft surfaces introduce slight roughness which may result in considerable deviations from the desired takeoff aerodynamic performance and significantly affect aircraft stability and control.
Freezing Point Depressant (FPD) fluids were introduced in the aviation industry as a solution to icing problems. Their use prior to takeoff in hazardous freezing or frozen precipitation is currently the primary method for removing and preventing the freezing of contaminants on the aircraft. Two types of FPD fluids are currently used by airport ground de-icing authorities. Type I fluids have Newtonian viscosity characteristics. A Newtonian fluid displays a linear relationship between shear stress and shear strain rate for any non-zero stress and therefore their viscosity is independent of shear force or flow rate. Type II fluids are non-Newtonian, their viscosity depends both on the shear stress and shear rate [Ross F., 1991]. Type II fluids are typically more effective than Type I. At low shear stress prior to takeoff, they are generally more viscous than Type I fluids, which allows them to remain on the treated surface for a longer period of time. Recently, several experimental investigations of ground de-icing fluid performance has been conducted [Bilanin et al., 1993, Kuperman et al., 1993, Louchez et al., 1994, Polomski et al. 1993]. However, in order to develop improved ground de-icing procedures, detailed observations of the mechanisms that determine degradation of fluid performance under icing conditions are needed.

This report documents microscale experimental investigations of various types of freezing precipitation falling on Type II fluids in realistic environmental conditions. Several factors that contribute to de-icing fluid performance degradation and influence their Hold Over Time (HOT) are identified. Analysis at an individual droplet and snowflake level is made in order to suggest new methods to characterize fluid failure. Several different characteristics of de-icing fluid failure are observed.

The results are presented in the following format. Chapter 2 gives the background information on de-icing fluid technology and de-icing procedures and also describes a few of the issues that motivated the microscale study. Chapters 3 and 4 discuss laboratory and field tests conducted during the winter of 1993-94 in Cambridge, Massachusetts. Chapter 5 gives a summary of the effort and the conclusions extracted from the observations.
Chapter 2

Background and Motivation

It is a requirement in the United States, to de-ice and anti-ice aircraft before takeoff under severe weather conditions. Freezing and frozen precipitation is a significant winter hazard for flights originating from many airports in the North American region. In the past few years, there have been efforts in this country to enhance aviation safety pertinent to ground de-icing and anti-icing procedures. The need for improved de-icing practices has been highlighted by several recent aviation accidents.

2.1. Ground de-icing related accidents

Ice contamination has been documented as the cause of at least 15 aircraft accidents in the past 23 years. Some of these, as reported by the National Transportation Safety Board, are shown in Table 2.1. Two of the most significant were the loss of an Air Ontario Fokker F28 in Dryden, Canada in 1989 and the crash of
<table>
<thead>
<tr>
<th>Accident ID</th>
<th>Ambient precipitation conditions</th>
<th>Ground de-icing</th>
</tr>
</thead>
<tbody>
<tr>
<td>December 27, 1968</td>
<td>Fog, light freezing drizzle, Temp 22 °F</td>
<td>Not de-iced</td>
</tr>
<tr>
<td>Ozark DC9-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sioux City, Iowa</td>
<td></td>
<td></td>
</tr>
<tr>
<td>November 27, 1978</td>
<td>Snow and fog, Temp 27 °F</td>
<td>Not de-iced</td>
</tr>
<tr>
<td>TWA DC9-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Newark, New Jersey</td>
<td></td>
<td></td>
</tr>
<tr>
<td>February 16, 1980</td>
<td>Light wet snow, fog, Temp 30 °F</td>
<td>De-iced at 13:25, Take-off at 14:08, Impact at 14:16</td>
</tr>
<tr>
<td>Redcoat Air Cargo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bristol Britannia</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boston, MA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air Florida B737</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Washington DC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>February 5, 1985</td>
<td>Light Freezing drizzle, ice pellets, snow, Temp 25 °F</td>
<td>Not de-iced</td>
</tr>
<tr>
<td>Airborne Express DC9-15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Philadelphia, Penn.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>December 12, 1985</td>
<td>Light freezing drizzle, snow grains, Temp 25 °F</td>
<td>Not de-iced</td>
</tr>
<tr>
<td>Arrow Air DC8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gander, Newfoundland</td>
<td></td>
<td></td>
</tr>
<tr>
<td>November 15, 1987</td>
<td>Light to moderate snow, Temp 28 °F</td>
<td>De-iced at 13:52, Take-off at 14:14, Impact at 14:15</td>
</tr>
<tr>
<td>Continental Airlines</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC9-10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Denver, Colorado</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March 10, 1989</td>
<td>Moderate snow</td>
<td>Not de-iced</td>
</tr>
<tr>
<td>Air Ontario Fokker F28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dryden, Ontario, Canada</td>
<td></td>
<td></td>
</tr>
<tr>
<td>March 22, 1992</td>
<td>Snowfall conditions</td>
<td>De-iced (Type I) at 20:30, Take-off at 21:35, Impact at 21:36</td>
</tr>
<tr>
<td>USAir Fokker F28</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LaGuardia Airport, NY</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: Icing related aviation accidents [Haase D.J., 1991]
USAir flight 405 during takeoff at LaGuardia Airport in New York on March 22, 1992. The latter resulted in the death of 27 people and the injury of 24. This accident prompted the Federal Aviation Administration to revise de-icing procedures.

2.2 Current de-icing technology and practices

Currently the most common method of dealing with ground icing contamination is the use of de-/anti-icing fluids, which are applied on critical aircraft surfaces prior to takeoff. Two types of fluids are in common use: i) older Type I fluids, with Newtonian viscosity behavior and ii) non-Newtonian Type II fluids, which are more viscous than Type I fluids, protect the aircraft surfaces for a longer period of time and run off easily during takeoff rotation.

2.2.1 Freezing Point Depressant (FPD) fluids

De-/anti-icing fluids are glycol based mixtures which are fully miscible in water. They prevent ice adhesion by creating a protective film which melts the incoming freezing or frozen precipitation. At the same time they lower (depress) the freezing point of the resulting mixture to below the freezing point of pure water (0°C / 32°F). The dependence of the freezing point on the mixture concentration can be seen in Figure 2.1 which is a typical phase diagram of aqueous glycol solutions.

The basic difference between Type I and Type II Freezing Point Depressant fluids, is their viscous properties. Type I de-icing fluids have relatively low viscosity and display Newtonian characteristics. The "apparent viscosity" (η) is defined as the ratio of shear stress to strain rate at any given point:

\[
\eta = \frac{\tau}{\dot{\gamma}} \quad (2.1)
\]

1 In the International Standards Organization (ISO) guidelines, Type I fluids are mentioned as "Aircraft deicing / anti-icing Newtonian fluids ISO Type I" (ISO # 11075) and Type II as "Aircraft deicing / anti-icing non-Newtonian fluids ISO Type II" (ISO # 11078). SAE (Society of Automotive Engineers) Type I and Type II fluids are very similar to ISO fluids. The U.S. Department of Defense has also issued specifications for "Anti-icing and Deicing - Defrosting Fluids". A complete table of the general characteristics of all the commercially available fluids can be found in the FAA AC 120-58.
Newtonian fluids have a linear relationship between shear stress and shear strain rate for any non-zero shear stress value and therefore their apparent viscosity is constant under a changing shear rate. Type I fluids contain at least 80% ethylene or propylene glycol and no chemical thickeners.

Type II de-icing fluids demonstrate pseudoplastic flow behavior and have measurable yield values. They exhibit high viscosity at low shear rates and
temperatures and lower viscosity when they are sheared at higher rates. They contain at least 50% of glycol, as well as polymeric thickeners that increase their viscosity. The higher viscosity allows the fluids to maintain a thicker film on the aircraft surfaces after application, in order to achieve protection for a longer period of time. At takeoff, the shear forces created by the aerodynamic flow around the wings, decrease the fluid’s viscosity and slide off the aircraft surfaces together with any accumulated precipitation. Type II fluids are designed to be used on aircraft with rotation speeds greater than 85 knots.

The difference in flow between Newtonian and non-Newtonian (pseudoplastic) fluids is demonstrated in the following Figure 2.2.

![Comparison between Newtonian and non-Newtonian fluids](image)

Figure 2.2 - Comparison between Newtonian and non-Newtonian fluids [Bilanin et al., 1993]

The most complete model that represents the non-Newtonian behavior in Figure 2.2 is the "Herschel-Bulkley model" which is characterized by three parameters:

\[ \tau = \tau_0 + m\dot{\gamma}^n \]  \hspace{1cm} (2.2)

the yield stress \( \tau_0 \), the consistency \( m \) and the flow index \( n \).
2.2.2 FAA ground de-icing regulations - Advisory Circulars

In 1950, the Civil Aeronautics Board developed regulations which require that the aircraft is free of any kind of ice contamination on the wings, propellers, control surfaces and engine inlets. According to Federal Aviation Regulations 91.527(a)

"no pilot can take off an airplane that has: (1) frost, snow, or ice adhering to any propeller, windshield, or powerplant installation or to an airspeed, altimeter, rate of climb, or flight attitude system, (2) snow or ice adhering to the wings or stabilizing or control surfaces, or (3) any frost adhering to the wings or stabilizing or control surfaces, unless that frost has been polished to make it smooth"

Takeoff is prohibited unless the Pilot-In-Command has ascertained that there is no adherence of contaminants to any of the aircraft critical surfaces.

The Federal Aviation Administration has issued two separate Advisory Circulars to be distributed to the pilots as a means of basic understanding and quick reference guide on the existing de-icing procedures and the technology available. AC 20-117 was the first one to be issued on April 15, 1983 after the 1982 Air Florida accident in Washington DC and the AC 120-58 was issued on September 30, 1992, several months after the fatal USAir accident at LaGuardia Airport.

**FAA Advisory Circular 20-117**

AC 20-117 stresses that the essence of flight safety under weather conditions conducive to ice accretion is the "Clean Aircraft Concept". The only acceptable and reliable method of positively ascertaining that the aircraft body is clean of any ice contaminants prior to takeoff, is close inspection by the flight crew. The document also provides a basic description of the frozen contaminants that can possibly be encountered on an aircraft and a simplified model of the de-icing fluid behavior under constant rate precipitation addition is suggested.

**FAA Advisory Circular AC 120-58**

The de-icing process is analyzed, within this document, in several different stages, before and after the application of the FPD fluid on the aircraft. The one-step
process, which includes only de-icing, and the two-step process that consists of a de-icing and an anti-icing stage are described in the Circular. The issue of time effectiveness of Type I and Type II fluids is addressed by introducing Hold Over Time (HOT) tables as an aiding tool for the pilots. These tables include guidelines for HOT as a function of weather conditions and ambient temperature. Post de-icing/anti-icing checks are also required and a detailed pre-takeoff checklist is given. A final check is also required right before takeoff and it is described to be the most important step of a ground de-icing process. At this point, the Pilot In Command still has total responsibility for the decision to takeoff.

2.2.3 Hold Over Time (HOT) tables

*Hold Over Time* is a term initially adopted by the Association of European Airlines (AEA) and is defined as the time between the fluid application and the time that it is still safe for the aircraft to take off. Greater Hold Over Times require the use of more glycol in the initial dilution of the applied fluid. Pilots are expected to make their final (pre-takeoff) decisions based on the time that has elapsed between the start of the fluid application and the clearance for takeoff, after consulting the Hold Over Time tables. An example of these tables for Type I and Type II fluids modified by an SAE committee, can be seen in the next two figures, taken from the FAA Advisory Circular 120-58.

<table>
<thead>
<tr>
<th>OAT</th>
<th>Approximate Holdover Times Anticipated Under Various Weather Conditions (hours:minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FROST</td>
</tr>
<tr>
<td>( ^\circ C ) &amp; ( ^\circ F )</td>
<td>( 0:18-0:45 ) &amp; ( 0:12-0:30 ) &amp; ( 0:06-0:15 ) &amp; ( 0:02-0:05 ) &amp; ( 0:08-0:15 )</td>
</tr>
<tr>
<td>0 &amp; above &amp; 32 &amp; above</td>
<td>( 0:18-0:45 ) &amp; ( 0:06-0:15 ) &amp; ( 0:06-0:15 ) &amp; ( 0:01-0:03 ) &amp; ( \text{CAUTION! Clear ice may require touch for confirmation} )</td>
</tr>
<tr>
<td>below 0 to -7 &amp; below 32 to 19</td>
<td>( 0:12-0:30 ) &amp; ( 0:06-0:15 ) &amp; ( 0:06-0:15 )</td>
</tr>
<tr>
<td>below -7 &amp; below 19</td>
<td>( 0:12-0:30 ) &amp; ( 0:06-0:15 )</td>
</tr>
</tbody>
</table>

Figure 2.3 - Hold Over Time tables for SAE and ISO Type I fluids [FAA AC 120-58]
2.3 Hold Over Time and mixing issues

In the process of developing HOT tables, various parameters such as ambient temperature, type of fluid used and its initial concentration (% per volume), precipitation type and rate, were taken into account. However, the individual effect of each of these parameters on HOT have not been fully studied yet. Experimental HOT data from field tests that have been conducted throughout the world, contain significant scatter making it difficult to validate HOT tables from simple field tests. Figure 2.5 contains examples of failure time data that have been collected at various experimental sites, as a function of ambient temperature, showing the typically large scatter in HOT. Failure time is considered to be the time between the start of fluid application and the appearance of ice contamination on the test surface. [Polomski and Muller, AIAA 93-0749, 1993]. Similar scatter is observed, if the failure time data is plotted as a function of precipitation rate or initial fluid film thickness.

Part of the reason for the field data scatter is the ambiguity in the existing
definitions of de-icing fluid failure. Researchers, as well as pilots and ground de-icing crews, have difficulty in determining the precise time when the de-icing fluid has failed.

Because of the scatter in the field data, HOT tables are not definitive and may cause unnecessary operational delays and confusion. A range of anticipated HOT is therefore provided in the HOT tables, with the lower end of the range being at one to four minutes depending on the case. According to the FAA the responsibility for the application of the table data remains with the pilot and the tables are only to be used in departure planning and always in conjunction with pre-takeoff check procedures. However, since the table data is inherently uncertain, the pilots tend to use it in a conservative manner.

In addition, existing models for predicting HOT, are based on certain simplifications and assumptions, whose validity has not been thoroughly examined. In particular, incoming precipitation water is assumed to mix homogeneously in the fluid film. Some field studies have questioned this assumption, indicating that other mixing modes may be encountered, depending on the precipitation type that the de-icing fluid is exposed to. The experimental investigation of the influence of different parameters on the runoff and mixing properties of the fluids documented in this study, aims to contribute to the improvement of these models.
The FAA AC 20-117 simple model assumes that the incoming precipitation (of constant rate) mixes homogeneously with the glycol contained in the de-icing fluid film. Based on this assumption, the model is used to estimate the fluid Hold Over Time by calculating the dilution ratio of the glycol-water mixture as it changes with time and by consulting the appropriate mixture phase diagram in order to find the critical (phase transition) dilution ratio. This model also assumes that the fluid film thickness increases as the incoming precipitation water dilutes fully in the glycol mixture.

A second model that has been proposed [Bilanin et al., 1993] also assumes, that homogeneous mixing occurs between the glycol and the precipitation water. It also incorporates the runoff process in the calculations, under the assumption that the runoff rate is equal to the incoming precipitation water addition rate and therefore the film thickness remains constant with time. The mass balance law for incompressible flow is finally applied in order to find an expression for the HOT.

2.4 Ice detection and sensors

An alternative to HOT and visual inspection could be reliable ice detection [Polomski and Muller, AIAA 93-0748, 1993]. However, since fluid failure is not well defined, the validity of sensing is questionable. A microphysical understanding of fluid degradation and failure is a prerequisite for the development of reliable sensors to detect the failure of de-icing fluids. The design and operation of ice sensing devices, requires that the expected icing failure patterns are known and can be detected successfully.

2.5 Need for microphysical studies

The underlying microphysical mechanisms of de-icing fluid failure are not yet very well understood. There is a need for detailed microscale studies of the fluid behavior. Microscale investigations will provide a better understanding of the phenomena involved in the performance of de-icing fluids. A more accurate definition of fluid failure may be derived, which will help to eliminate some of the scatter in the failure time data and also develop more definitive HOT tables. In addition, microscale studies will aid in developing new effective methods of ice detection by identifying physical phenomena which indicate fluid failure and can be used as a basis for detection.
Chapter 3

Field Tests

Freezing rain, snow and ice pellets are difficult to simulate in the laboratory. Particularly for snow, long fall times are required in order to produce large snow flakes. Therefore, a simple experimental rig was prepared to be used to take advantage of natural snow and rain precipitation, during the winter of 1993-94.

High magnification video recordings were made of a cylinder and two flat plates with varying tilt angles protected with Type II fluid. The objective was to provide high magnification observational examples of Type II fluid failure modes. The dilution process of incoming precipitation elements, such as snow flakes, ice pellets and freezing drizzle droplets, was examined at a microscopic scale in order to understand how individual precipitation elements interact with the fluid film. The experimental recordings aimed to identify the different fluid failure mechanisms resulting from different type and rate of natural precipitation.

3.1 High magnification video setup

Figure 3.1 depicts the functional elements of the high magnification video setup. It consisted of two parts: i) the test objects were located outdoors in order to be exposed to natural precipitation and ii) the high magnification cameras were located indoors.
The set of test surfaces that were used, included a cylinder and a pair of flat aluminum plates that were directly adjacent to each other. The outer diameter of the aluminum cylinder was 4 inches and the inner diameter 3.8 inches. The cylinder was painted black in order to avoid undesirable reflections that distorted the quality of the recorded image during daytime recording sessions. The cylinder was in a horizontal position with its axis perpendicular to the window.

The two square aluminum flat plates each had a 1 sq. ft. polished surface area and a thickness of 0.125 inches. The plates were placed adjacent to each other and the support system was constructed in such a way that the plates' angle of inclination with respect to a horizontal plane could be controlled independently. The plates rotated around a common pivot point, close to the midpoint between the top and the bottom edge. The lower edge of each plate had been beveled to resemble the sloping edge of an aircraft wing as closely as possible and to avoid accumulation of fluid on the lower part of the plate due to surface tension.
The set of two high magnification cameras were located indoors and viewed the test articles through a window. One camera was focused on the cylinder and the other was focused on the plates. The approximate distance between the test surfaces and the camera lenses was 3 feet. Each camera was placed above and looking down at the test surface. Both cameras were zoomed in to the highest possible magnification and each was connected to a monitoring screen in order to aid in maintaining proper focus. A high intensity light source was used during night time in order to provide sufficient illumination to maintain depth of field in the close up recordings.

The cylinder camera was focused on the midpoint of the cylinder. The plate camera was focused on the midpoint between the top and bottom of the plates such that the central portion of each plate was in the image at all times. The nominal observation region is shown in Figure 3.2. It included a rectangular portion of the two plates, with dimensions of 2.9 inches width and approximately 2.2 inches height. The plates could be tilted at different angles but the midpoint on the rotation axis, was in focus at all times.

A side view of both setups (cylinder and plates) is depicted in Figure 3.3.
The procedure for each recording session included several steps. The aviation weather forecast was checked regularly and the experimental team was alerted for approaching snowstorms. When snow was expected, the experimental setup was assembled. The angle of inclination of the plates was adjusted with the help of a digital protractor prior to fluid application and the experimental recording session started.

When the icing event begun, the cameras were first used to record the precipitation impact on a dry unprotected surface to aid in characterizing the precipitation type. The next step was the application of the de-icing fluid on to the test surfaces. The fluid that was used in all the experimental cases, was “Octagon Forty Below” manufactured by Octagon Process Inc. [Octagon Process Inc. Product Documentation]. The application of the fluid was done manually. The fluid was poured on the test surface from a small beaker. Application always started from the top part of the plates or the cylinder. The application would typically last for approximately 3 or 4 seconds. Sufficient quantity was applied until all of the desired area was treated.
On the cylinder, the fluid was applied only on the half closest to the camera in order to make observations on both treated and untreated areas simultaneously. The same method was not applicable in the plate recordings, because the relative position of the plates and the camera did not allow the same image depth of field as in the cylinder recording frames.

Once the fluid application was completed, the plate angles of inclination were documented and an ambient temperature measurement was taken with a thermocouple sensor. A ruler was incorporated in the image during each recording session in order to provide a measuring scale that would allow size calibration in the images. The precipitation type and size was noted and the intensity was qualitatively characterized by observation as: light, moderate, or heavy.

Initially, tests were conducted only on the cylinder and a single plate. Cases with two plates were not examined until later in the winter. In these cases, a certain part of both plates was recorded in the same frame, each tilted at a different angle of inclination, in order to compare the fluid behavior on two different geometries under identical precipitation conditions.

3.2 Summary of natural icing events

Icing events during 14 different storms were recorded. There were days that two or more tests were conducted. However, a few of the cases were not of good recording quality due to focus problems or defective tapes. Therefore, 22 cylinder and 28 plate exposures (approximately 100 hours of events) were analyzed. A summary of all the recorded precipitation cases on the cylinder and the aluminum plates, are documented in Tables 3.1, 3.2 and 3.3. In the cases of snow precipitation, the flake size was characterized as: small if the average diameter of the flakes was estimated to be less or equal to 5 mm, medium if it was less or equal to 10 mm and greater than 5 mm and large if it was greater than 10 mm. It should also be noted that a range of angles of inclination was used throughout the plate cases.
### Cylinder cases

<table>
<thead>
<tr>
<th>Case #</th>
<th>Precipitation type (snowfall rate, flake size)</th>
<th>Ambient Temp. ('F)</th>
<th>Time of fluid application</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Light, mostly small size</td>
<td>29</td>
<td>12:26</td>
<td>1/7</td>
</tr>
<tr>
<td>2</td>
<td>Light, mostly small size</td>
<td>29</td>
<td>16:16</td>
<td>1/7</td>
</tr>
<tr>
<td>3</td>
<td>Freezing rain</td>
<td>30</td>
<td>7:02</td>
<td>1/28</td>
</tr>
<tr>
<td>4</td>
<td>Light, mostly large size</td>
<td>15</td>
<td>15:43</td>
<td>1/27</td>
</tr>
<tr>
<td>5</td>
<td>Ice pellets mixed with large flakes</td>
<td>11</td>
<td>11:50</td>
<td>2/8</td>
</tr>
<tr>
<td>6</td>
<td>Ice pellets</td>
<td>13</td>
<td>16:11</td>
<td>2/8</td>
</tr>
<tr>
<td>7</td>
<td>Light, mostly large size</td>
<td>11</td>
<td>9:13</td>
<td>2/9</td>
</tr>
<tr>
<td>8</td>
<td>Moderate, mostly large size</td>
<td>14</td>
<td>12:43</td>
<td>2/9</td>
</tr>
<tr>
<td>9</td>
<td>Moderate, medium size</td>
<td>14</td>
<td>15:59</td>
<td>2/9</td>
</tr>
<tr>
<td>10</td>
<td>Moderate, medium size flake</td>
<td>13</td>
<td>16:50</td>
<td>2/9</td>
</tr>
<tr>
<td>11</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>13:50</td>
<td>2/11</td>
</tr>
<tr>
<td>12</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>14:26</td>
<td>2/11</td>
</tr>
<tr>
<td>13</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>15:10</td>
<td>2/11</td>
</tr>
<tr>
<td>14</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>16:38</td>
<td>2/11</td>
</tr>
<tr>
<td>15</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>17:23</td>
<td>2/11</td>
</tr>
<tr>
<td>16</td>
<td>Heavy, medium size</td>
<td>29</td>
<td>12:24</td>
<td>2/23</td>
</tr>
<tr>
<td>17</td>
<td>Light, small size</td>
<td>29</td>
<td>15:13</td>
<td>2/23</td>
</tr>
<tr>
<td>18</td>
<td>Light, small size</td>
<td>30</td>
<td>16:34</td>
<td>2/23</td>
</tr>
<tr>
<td>19</td>
<td>Light, small size</td>
<td>30</td>
<td>17:20</td>
<td>2/23</td>
</tr>
<tr>
<td>20</td>
<td>Light, small size</td>
<td>30</td>
<td>18:03</td>
<td>2/23</td>
</tr>
<tr>
<td>21</td>
<td>Light, small size</td>
<td>31</td>
<td>19:22</td>
<td>2/23</td>
</tr>
<tr>
<td>22</td>
<td>Light, small size</td>
<td>21</td>
<td>9:32</td>
<td>2/26</td>
</tr>
<tr>
<td>23</td>
<td>Heavy, large size</td>
<td>35</td>
<td>8:13</td>
<td>3/3</td>
</tr>
</tbody>
</table>

Table 3.1 - Summary of natural precipitation events on the cylindrical test surface

### Single plate cases

<table>
<thead>
<tr>
<th>Case #</th>
<th>Precipitation type (snowfall rate, flake size)</th>
<th>Plate angle (deg.)</th>
<th>Ambient Temp. ('F)</th>
<th>Time of fluid application</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Moderate to heavy, mostly small size</td>
<td>21</td>
<td>11</td>
<td>12:51</td>
<td>2/8</td>
</tr>
<tr>
<td>2</td>
<td>Moderate, very fine size</td>
<td>21</td>
<td>13</td>
<td>16:11</td>
<td>2/8</td>
</tr>
<tr>
<td>3</td>
<td>Moderate, medium size</td>
<td>35</td>
<td>10 to 11</td>
<td>9:13</td>
<td>2/9</td>
</tr>
<tr>
<td>4</td>
<td>Moderate, medium size</td>
<td>35</td>
<td>14</td>
<td>12:39</td>
<td>2/9</td>
</tr>
<tr>
<td>5</td>
<td>Moderate to heavy, medium size</td>
<td>45</td>
<td>14</td>
<td>16:02</td>
<td>2/9</td>
</tr>
<tr>
<td>6</td>
<td>Moderate to heavy, varying sizes</td>
<td>45</td>
<td>13</td>
<td>16:47</td>
<td>2/9</td>
</tr>
</tbody>
</table>

Table 3.2 - Summary of natural precipitation events on a single aluminum plate
Table 3.3. - Summary of natural precipitation events on a pair of aluminum plates

Close up observations of the natural precipitation recordings, show that the degree and type of mixing between de-icing fluid and precipitation water is primarily driven by the type and rate of precipitation that the fluid is subjected to. Among the observed cases, three main types of precipitation were identified: i) snow, ii) ice pellets and iii) freezing rain/drizzle. The mixing modes and the type of fluid failure that was
observed for each of the three precipitation types is analyzed in the following paragraphs.

3.3 Snow observations - Cylinder cases

After the de-icing fluid application, a number of different stages of fluid behavior in snow were observed.

Initial stage

In the initial stage, the fluid was observed to perform as expected. The incoming snow flakes are melted completely. An example of a snow flake melting is presented in Figures 3.4 to 3.7. They were taken from cylinder case 23, in which the test surface was treated at 8:13:20 am and the ambient temperature was 35 °F. When the flake contacted the fluid in Figure 3.4, its dendritic ice structure was forced by the fluid to melt and the flake vanishes in the fluid film, as it is shown in Figure 3.5. The water that was generated in the fluid film by the melting precipitation elements was not observed to mix homogeneously with the fluid glycol, but instead to pool at the impact point or run off the surface, creating water streams within or on top of the film. Eleven minutes later, the fluid still melted the snow flakes. As the resulting water run off the cylinder surface it created visible ripples in the fluid film, which can be seen in Figures 3.6 and 3.7.

Additional examples of initial stage snowflake melting are shown in Figures 3.8 to 3.10, which were taken from cylinder case 10. The cylinder surface was treated with de-icing fluid at 4:50:15 pm and the ambient temperature was 13 °F. As is observed in Figure 3.8, four minutes later, the fluid film was still able to melt incoming snow flakes. The melting time for the flake seen at the right side of Figures 3.8a to 3.8e, is about 6 seconds. Two minutes later, a slightly larger snow flake that can be seen at the center of Figures 3.9a to 3.9f, impacts at almost the same point on the cylinder as in the previous case and melts within almost 10 sec. Figure 3.10 documents the melting process of another snow flake that impacts the fluid film at the top of the cylinder and can be seen at the upper right corner of the frame. The flake in Figure 3.10 is observed to melt more slowly than the flakes in Figures 3.8 and 3.9. The melting time measured was approximately 17 seconds.
Figures 3.4 and 3.5 - Water runoff resulting from snow flake melting
Cylinder case 23 - fluid application time: 8:13:20 am, temperature: 35 °F
Figures 3.6 and 3.7 - Water runoff resulting from snow flake melting
Cylinder case 23 - fluid application time: 8:13:20 am, temperature: 35 °F
Figures 3.8a-e: Snow flake melting - melting time is 6 sec
Cylinder case 10 - fluid application time: 4:50:15 pm, temperature: 13 °F
Figures 3.9a-f: Snowflake melting - melting time is 10 sec
Cylinder case 10 - fluid application time: 4:50:15 pm, temperature: 13 °F
Figures 3.10a-f: Snowflake melting - melting time is 17 sec
Cylinder case 10 - fluid application time: 4:50:15 pm, temperature: 13 °F
Intermediate stage

At this stage, the fluid started to display inability to completely melt the incoming precipitation elements. Even in the case of flakes that melted and disappeared in the fluid film, the time that it took for a particular flake to melt was observed to increase as the fluid became degraded. A fluid film that has entered the intermediate “slush” stage is shown in the set of Figures 3.11 to 3.13. All figures were taken from the same experimental cylinder case 10 that was used for the initial stage description and was presented in Figures 3.4 to 3.10. The surface was de-iced at 4:50:15 pm and the temperature was 13 °F. Several snow flakes that can be seen at the right side of the frame in Figure 3.11, impacted on the fluid film and are still not melted approximately three minutes later in Figure 3.13. The incomplete melting of flakes that occurred during this intermediate stage, introduced visible roughness on the test surface and resulted to accumulation of a snow flake layer on the treated surface at this stage.

Final stage

In the final stage, as it can be seen in Figures 3.14 and 3.15, several additional layers of snow (“snow bridges”) were observed to form on top of the initial layer. The
Figures 3.12 and 3.13 - Intermediate stage: Partial melting of snow flakes
Cylinder case 10 - fluid application time: 4:50:15 pm, temperature: 13 °F
Figures 3.14 and 3.15 - Final stage: Snow bridge formation
Cylinder case 10 - fluid application time: 4:50:15 pm, temperature: 13 °F
flakes in these layers did not melt at all and failed to disappear in the fluid film (Figure 3.16).

3.4 Snow observations - Flat plate cases

The initial, intermediate and final stages, were also observed on flat plates. Examples from four different plate tests are shown in Figures 3.17 to 3.24. The tests analyzed, are plate cases 17, 19, 22 and 29 which are summarized in Table 3.4.

Figures 3.17 to 3.20 were taken from plate case 17. The plates were treated with de-icing fluid at 3:14:05 pm and the temperature was 29 °F. Thirty three minutes later, the accumulation of an initial snow layer on the steeper plate (left side) is shown in Figure 3.17, indicating intermediate stage behavior. In Figure 3.18, forty five minutes after fluid application final "snow bridge" formation has started on the 40° plate, while the 10° plate is just entering the intermediate stage. In Figure 3.19, fifty minutes after...
<table>
<thead>
<tr>
<th>Case #</th>
<th>Precipitation type (snowfall rate, flake size)</th>
<th>Plate angles (deg.)</th>
<th>Ambient temp. (°F)</th>
<th>Time of fluid applic.</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>Light to moderate, mostly medium size</td>
<td>40 and 10</td>
<td>29</td>
<td>15:14</td>
</tr>
<tr>
<td>22</td>
<td>Moderate to heavy, mostly small</td>
<td>35 and 10</td>
<td>31 to 32</td>
<td>23:19</td>
</tr>
<tr>
<td>27</td>
<td>Heavy, mostly large size</td>
<td>25 and 10</td>
<td>32 to 33</td>
<td>0:47</td>
</tr>
<tr>
<td>19</td>
<td>Moderate to heavy, mostly small</td>
<td>20 and 10</td>
<td>31</td>
<td>17:28</td>
</tr>
</tbody>
</table>

Table 3.4 - Examples of flat plate tests analyzed

treating the surface with de-icing fluid, the first layer of snow flake accumulation is visible on the 10° plate. In some cases the accumulated flakes did not remain at the initial contact point but they were observed to slide downwards. Final “snow bridge” formation on top of the initial layer of flakes on the 10° plate, can be seen in the last Figure 3.20, fifty six minutes after the fluid application.

![Image](image_url)

Figure 3.17 - Intermediate and final stage
Plate case 17 - fluid application time: 3:14:05 pm, temperature: 29 °F
Figures 3.18 and 3.19 - Intermediate and final stage
Plate case 17 - fluid application time: 3:14:05 pm, temperature: 29 °F
Figure 3.20 - Intermediate and final stage
Plate case 17 - fluid application time: 3:14:05 pm, temperature: 29°F

Similar behavior can be identified in the other three events presented in Figures 3.22 to 3.24. In all four tests, snow flake accumulation is first observed to occur on the steeper plate. It should be noted that no adhesion of the final stage “snow bridges” on the treated surface was observed in any of these four cases and a layer of de-icing fluid was present between the snow accumulations and the test surface at the end of each exposure.

The plate observations motivated an attempt to quantitatively characterize the fluid failure, by using the time that it took for an individual precipitation elements to melt after contact with the fluid film as a measure of fluid performance. A similar trend of the "time to melt" was identified in all the cases.

In each of the four cases, a standard method was used to measure the snow flake melting time. The flakes were taken from the middle area of the recording frame and
flakes were examined randomly within this zone. A stop watch was used to estimate the melting time of each flake selected. The time measurement started at the moment of impact of the flake on the fluid film and ended when there was no trace of the flake (white color) visible on the fluid surface. The size of every flake was also measured with the help of a length scale that was attached to the recording frame.

The results are presented in Figures 3.21 to 3.24 together with a sequence of four recorded frames as a summary of the observed behavior in each test (parts (a) to (d)). Each of the graphs contains two sets of data. One corresponds to the flakes that impact on the steeper plate and the other represents the flakes that contacted the plate that was tilted at 10°. The abscissa is the time elapsed from the fluid application and the ordinate is the time that it takes for a particular flake to melt. For each of the four recorded frames that are presented together with these graph, the corresponding time elapsed from fluid application is indicated, so that each frame can be related to the melting time data curves.

A similar trend can be identified in all the cases. Initially, the melting time was kept to a level below 5 seconds. Later in the process, in all four cases, a sudden increase of the measured variable was recorded, which corresponded to the beginning of the intermediate stage. The separation observed between the data curves for the two plates is expected. The test surfaces were tilted at different angles and the fluid runoff from the steeper surface occurred at a faster rate, which caused the fluid on this surface to fail first.

One last observation shows that the measured data display significant scatter in some cases. For example, early in the process, there were a few cases of flakes that melted slowly and close to the end of the process, there were also flakes that did not follow the increasing melting time trend. The stochastic nature of individual flake melting time is additional evidence of the non-homogeneous mixing that occurs between the fluid and the flakes. If a flake lands on a highly diluted region of the test surface, it will melt slowly. If it lands on a high fluid concentration region, it will melt quickly. As the fluid becomes degraded, the high water dilution areas on the surface will increase.

The experimental observations indicate that the interaction between snow precipitation and the de-icing fluid film, is typically based on the melting of individual
Figure 3.21a

40° Time: 2006 sec 10°

Figure 3.21b

40° Time: 2714 sec 10°

Figure 3.21c

40° Time: 3034 sec 10°

Figure 3.21d

40° Time: 3360 sec 10°

Figure 3.21e - Melting time measurements

Plate case 17 - fluid application time: 3:14:05 pm, temperature: 29 °F
Figure 3.22a - Melting time measurements

Plate case 22 - fluid application time: 11:19:05 pm, temperature: 31 to 32 °F
Figure 3.23a - Melting time measurements
Plate case 27 - fluid application time: 0:47:48 am, temperature: 32 to 33 °F
Figure 3.24a - 20° Time: 1269 sec 10°

Figure 3.24b - 20° Time: 1380 sec 10°

Figure 3.24c - 20° Time: 1635 sec 10°

Figure 3.24d - 20° Time: 1836 sec 10°

Figure 3.24e - Melting time measurements

Plate case 19 - fluid application time: 5:28:10 pm, temperature: 31 °F
snow flakes. The water produced by this melting process, appears to mix in the de-icing fluid film in a non-homogeneous way. When a single flake contacts the surface of the fluid and melts in the glycol film, a water bead is created at the contact point. In some cases, this bead remains at the impact point where the local dilution is significantly increased. Often the water appears to be at a separate layer on the fluid film, and runs off the treated surface as it was observed in Figures 3.9 to 3.11. This water behavior is thought to be determined by the slope of the surface at the particular point. At steeper angles of inclination, it runs off and creates in the fluid the ripples that were seen in Figure 3.11.

The local water-glycol dilution ratio at the flake impact point or within the paths that the runoff water follows, is increased and the fluid’s performance as a freezing point depressant is degraded. With time, the fluid becomes diluted to the point that the ability of the fluid to melt incoming flakes is impeded. However, it should be noted that in all the snow events that were analyzed, no bonding between snow or ice contaminants and the substrate was observed. There was also no case in which the fluid was observed to freeze. After the end of each exposure, there was always a thin protective layer of de-icing fluid present between the “snow bridges” and the test surface.

An additional factor that influences the failure modes that may be encountered, is thought to be the characteristic structure of the snow flakes. A less densely crystallized flake, has a smaller amount of dendritic ice crystals in contact with the fluid surface (Figure 3.25a). These ice structures penetrate the film and begin to melt. Microscopic water pools most likely form at the penetration points increasing the local dilution. It is thought that the water dilutes the fluid and prevents the ice structure of the snow flake to penetrate further into the film. A typical example of this kind of behavior is the formation of the initial layer of snow flakes during the intermediate stage of a snow event (Figures 3.11 to 3.13). A snow flake with dense structure of small ice crystals has more surface contact with the fluid film (Figure 3.25b). Upon impact on the fluid film, it experiences partial melting of its crystallized structure. The water from this melting process, creates the "slush - like" contamination points that can be observed in Figures 3.26 and 3.27. The local dilution ratio is significantly increased and further melting is prevented.
Figure 3.25 - Two types of interaction of a snow flake with a film of de-icing fluid

Figure 3.26 - "Slush" intermediate stage
Plate case 11 - fluid application time: 3:09 pm, temperature: 29 °F
Figure 3.27 - "Slush" intermediate stage
Plate case 9 - fluid application time: 1:50 pm, temperature: 31 to 32 °F

3.5. Ice pellet observations

Ice pellets are usually round or irregularly shaped hard grains of ice which rebound after striking on hard untreated aircraft surfaces. However, upon impact on a de-iced surface, they were observed to penetrate through the film and remain captured in it. A typical ice pellet precipitation event is shown in Figures 3.28 to 3.31. The event is cylinder experimental case 6. The fluid was applied at 4:11:05 pm and the ambient temperature was 13 °F. Initially, the pellets were forced by the de-icing fluid to melt (Figure 3.28). Approximately eleven minutes after de-icing the surface, a roughness layer was introduced due to the ice pellets being encapsulated by fluid. The development of visible roughness is presented in Figures 3.29 and 3.30. With time, additional pellets were observed to accumulate above the initial layer (Figure 3.31), similar to the “snow bridges” seen in the snow cases.

In Figure 3.31, a comparison can be performed between the treated and untreated part of the cylinder. Ice pellets seem to concentrate only on the top part of the untreated
Figure 3.28 - Initial stage: ice pellets are still melting
Cylinder case 6 - fluid application time: 4:11:05 pm, temperature: 13 °F

Figure 3.29 - Surface roughness introduced by ice pellet precipitation
Cylinder case 6 - fluid application time: 4:11:05 pm, temperature: 13 °F
Figure 3.30 - Surface roughness introduced by ice pellet precipitation
Cylinder case 6 - fluid application time: 4:11:05 pm, temperature: 13 °F

Figure 3.31 - Accumulation of ice pellets
Cylinder case 6 - fluid application time: 4:11:05 pm, temperature: 13 °F
area. In the fluid treated region, they accumulate both on the top and at the sides. The presence of the de-icing fluid seems to keep the pellets attached on the surface, even though they would have rebounded off the sides, if the fluid had not been applied.

Depending on the size of the ice pellets relative to the fluid film thickness, the viscous glycol appears to surround the pellet grains. Figure 3.32, is a schematic representation of an ice pellet captured in the fluid film.

![Figure 3.32 - Schematic representation of ice pellet encapsulated in a de-icing fluid film](image)

Total or partial submersion of the pellets in the film and encapsulation by the fluid causes melting to occur at the interface between the ice structure and the de-icing fluid. A melted water buffer is thought to be generated due to this melting process and the local dilution ratio around each pellet is increased, similar to the snow precipitation cases. Further melting appears to stop since the fluid performance has been locally degraded at the ice pellet surface. This is thought to lead to the ice roughness formation that was observed in the ice pellets exposure cases. Bonding between the ice pellets and the de-iced surface was not observed in any of the ice pellet tests, similar to the snow exposures. The ice pellets always accumulated on top of a thin residual layer of fluid that prevented them from adhering to the test surface.

### 3.6 Freezing rain/drizzle precipitation

Freezing rain or drizzle consists of rain droplets that are cooled while falling through cold air, and freeze upon impact with the ground or with other objects near the
earth surface. Being a less frequent meteorological phenomenon, it was observed only once in the field tests, in the form of drizzle (droplet diameters ranging from 100 μm to 1 mm). In this case, the event ended before any fluid failure was observed on the de-iced surface.

Freezing drizzle was observed in cylinder case 3. The temperature in this test was 30 °F and the fluid was applied on the cylinder surface at 7:02:25 am. Figure 3.34 was recorded twenty six minutes after the fluid application. The film condition in this figure, can be compared to the recorded frame at the beginning of the process (Figure 3.33). The comparison indicates that rippling of the fluid film occurs, similar to the rippling that was observed in the snow precipitation cases. This phenomenon becomes more obvious in Figure (3.35), which was recorded forty six minutes after fluid application. Finally, Figure (3.36) shows how the condition of the treated surface developed with time. Fluid is still present on the cylinder, even though a significant amount of it seems to have been washed off by the drizzle droplets. It should be noted that the white marks that can be seen on all figures, were scratches on the black paint of the cylinder surface.

No roughness was observed to form on the de-iced surface throughout the freezing drizzle experiment, because the event ended prior to fluid failure. In Figures (3.32) to (3.35), the smooth treated surface can be compared to the untreated part of the test object where roughness appeared soon after the surface was exposed to the precipitation, due to the freezing of the drizzle droplets.

The freezing drizzle precipitation case appears to have similarities to the snow case, as far as the interaction between the fluid film and the precipitation is concerned. It seems that the freezing drizzle droplets, upon impact on the fluid film, concentrate in small water pools that do not mix homogeneously in the film (Figure 3.34), but instead remain at a separate stratum on top of it. Mixing at a low level may occur at the interface between the water and glycol strata due to molecular diffusion. With time, the water pools that form on the fluid run off, if there is sufficient slope to the surface.

The water runoff process was thought to be the cause of the fluid film rippling that was identified. A very simple laboratory test was conducted in room temperature,
Figures 3.33 and 3.34 - Freezing drizzle precipitation case
Cylinder case 3 - fluid application time: 7:02:25 am, temperature: 30 °F
Figures 3.35 and 3.36 - Freezing drizzle precipitation case
Cylinder case 3 - fluid application time: 7:02:25 am, temperature: 30 °F
which verified this last conclusion. De-icing fluid was applied on the same cylindrical object that was used in the field tests. The fluid was left to run off the surface with no incoming precipitation. It was observed periodically, but no rippling was identified. The fluid runoff process did not seem to affect at all the initial smooth texture of the fluid surface. After observing the fluid runoff for approximately thirty minutes, water droplets were sprayed on the treated surface with a regular spray nozzle. At this point, visible ripples were seen to form on the fluid surface.

Despite of the similarities between the interaction of freezing drizzle and snow with the de-icing fluid, the event ended before the intermediate and final stages occurred and therefore fluid failure was not observed.

3.7 Implications of field tests

In general, field tests indicated that snow and ice pellet failure is observed to be the inability of the fluid to melt the incoming snowflakes. The non-homogeneous mixing that was observed to occur between the precipitation water and the de-icing fluid glycol, is an important factor that influences the local dilution of the fluid and affects its performance. Due to the non-homogeneity in the fluid film, the snowflake melting process assumed a stochastic nature. However, a general increasing trend with time was identified in the time that it takes an individual snowflake to melt. Different types of precipitation resulted to different failure modes. However, in all the cases of failure encountered, bonding of the accumulated ice or snow to the treated surface was never observed. No definite conclusions could be made in the case of freezing rain precipitation. The event ended before the fluid even entered the intermediate stage of behavior. It is possible that in the case of freezing rain, homogeneous mixing may occur. The rain droplets may also penetrate through the fluid film and adhere to the treated surface upon impact on it.
Chapter 4

Laboratory Tests

The high magnification precipitation impact setup was used in the laboratory tests that were conducted at the MIT Aeronautical Systems Laboratory. It was designed to investigate the microscopic interaction of individual precipitation elements that were encountered in the field tests, such as snow flakes, ice pellets and rain droplets with the de-icing fluid film.

4.1 High magnification precipitation impact setup

The natural precipitation tests discussed in Chapter 3 indicated that the precipitation elements do not mix homogeneously with Type II de-icing fluid. These observations motivated the design of the high magnification precipitation impact facility. Experiments on snow and ice pellet impact were conducted at cold temperature in an environmental chamber, while rain droplet experiments were conducted at room temperature.

The high magnification precipitation impact setup (Figure 4.1) consisted of a small transparent Plexiglas view plate on which the precipitation elements impacted.
The plate rested on an 18" high support table with a 3" x 4" slot above which the plate was placed. The view plate had walls on the sides. Its outer dimensions were: 1.5" wide and 7" long and its inner dimensions: 1" wide and 6.5" long.

A high magnification camera was focused on the bottom of the plate in order to record a bottom view of the precipitation impact through the transparent Plexiglas. The camera was enclosed in a container of appropriate dimensions during all the tests and the container was supported on a crane-stand of adjustable height. One side of the container had a plastic transparent window through which all the recordings were made. A heating system was constructed in order to operate the camera in sub-freezing temperatures for a long period of time. The heating system consisted of water pipes that carried warm water through the camera container box and kept the camera at room temperature, even when the cold chamber was operating at the lowest possible temperature.
In order to produce a side view in the same view plane as the bottom view, a right triangular prism was mounted on one of the plate sides. In some of the rain droplet experiments, this feature was used to simultaneously record bottom and a side views of the impact in the same image frame. However, for very thin fluid films, the side view was not visible, because the impact was too far from the prism. In addition, in the cold chamber, there were often problems with fog formation at the bottom of the view plate, which degraded the image quality.

In the water droplet impact tests, simulated rain droplets were produced with a hypodermic needle that was attached above the view plate. The size of the droplets varied according to the size of the diameter of the needle that was used.

4.2 Environmental chamber tests

The laboratory experiments were designed to replicate the field tests. Therefore, the need to perform experiments under simulated freezing and frozen precipitation conditions, led to the decision to use a regular upright freezer as a cold temperature chamber, modified in order to meet the experimental requirements. The temperature range that could be achieved was from \(-8\) °F (\(-22\) °C) to \(32\) °F (0 °C). The freezer had a capacity of 29.2 cu. ft. and its interior dimensions were: 58 inches high, 30 inches wide and 29 inches deep.

Two kinds of experiments were performed in the cold chamber: snow and ice pellet impact tests and in both cases, the view plate could be tilted to a specific angle of inclination. A fluorescent dye technique was used for identification of melting and tracking of the behavior of the subsequent water. Under ultra-violet (UV) illumination, the fluorescent dye that was used, would glow if it was melted, but not if it was frozen [Hansman & Dershowitz, Optically Indicating Surface De-Icing Fluids, U.S. Patent # 5039439, issued August 13, 1991]. Ice pellets were produced by simply crashing ice cubes. The water that was used to produce the ice, was mixed with fluorescent dye. The snow was produced with the help of an ultrasonic humidifier with water that was also mixed with fluorescent dye. The humid air produced by the humidifier, was blown through a pipe, in a cold chamber at a temperature of \(-20\) °C. Due to the low temperature in the chamber, the air froze upon impact to any object and produced fluorescent snow-like ice crystals.
In each test, ice pellets and snow flakes were released from approximately 10 cm above the plate. The entire view plate could not be seen in the recording frame, because the camera was always zoomed to the highest possible magnification. Therefore, whenever the precipitation elements started sliding downwards after their impact on the plate, they were kept in the recording frame by moving the view plate appropriately. In both types of experiments, melting of the pellets was identified by the fluorescent color given by the water that was produced.

4.2.1 Ice pellet observations

The ice pellets that were produced in the laboratory, were in most cases heavier and had a larger size compared to the fluid film thickness, than the pellets encountered in the field exposures. In the two field events of ice pellet precipitation, the typical diameter of ice grains was estimated to be 1 to 2 mm. The nominal diameter of the simulated ice pellets was approximately 5 to 6 mm. As a result, the laboratory pellets were never observed to be completely submerged in the thin fluid film. Nevertheless, the behavior observed in the laboratory tests was consistent with several field observations.

Cases of total melting of the ice pellets was observed, similar to the initial stage behavior in the field tests. However, a water shield was observed to form around the ice pellets in some other cases and prevented the pellets from melting completely, as it was observed in the intermediate stage of the field ice pellet exposures.

Figures 4.2 to 4.4, describe a characteristic example of initial stage melting of a single ice pellet of a larger size. The view plate was inclined at an angle of 10°. Figure 4.2 was recorded immediately after the impact of the pellet on the treated surface. Only a few seconds later, in Figure 4.3, the pellet has started sliding because of the tilt of the plate and at the same time it is melting. Part of the water resulting from the melting process, separated from the pellet and ran off. The side view in Figure 4.2, demonstrates how the pellet structure is initially not submerged in the fluid film. As the pellet melts, it is observed to sink and disappear into the film. However, the fluorescence of the water in the side view of Figure 4.4, suggests that the remaining water possibly runs off as a distinct layer on top of the fluid film.
Figures 4.2 and 4.3 - Initial stage ice pellet melting
The set of Figures 4.5 to 4.8, were extracted from an experiment that involved impact of several ice pellets on the de-icing fluid film only one minute after fluid application. In Figure 4.5, the ice pellets have started to melt. The resulting water is visible in Figure 4.6. Each observed pellet, had an area in the center, which was still frozen and therefore did not produce fluorescence and a brighter area around it, which seemed to contain water that had just melted as indicated by fluorescence. In addition, in Figures 4.6 and 4.7, a less fluorescent region surrounded each pellet. It possibly contained water that slowly diffused away from the ice pellets. In Figure 4.8, the pellets were observed to melt completely, displaying similar behavior to that observed in the field ice pellet events during the initial stage.

After impact on the de-icing fluid film, ice pellets were observed to stick the treated surface, similar to the field ice pellet events. As the fluid run off and the film became thinner with time, the pellets were seen to penetrate in the film and adhere to the bottom of the view plate for some time. However, often the bond broke, possibly due to the presence of de-icing fluid under the pellet. An example of this behavior can
Figures 4.5 and 4.6 - Ice pellet encapsulation
Figures 4.7 and 4.8 - Ice pellet encapsulation
be seen in Figures 4.9 to 4.12. All four frames have been recorded without moving the test plate at all so that the position of the pellet in each figure can be related to its position in previous frames. The plate was inclined at 10°. The pellet impacted the fluid film at approximately 1:28 pm, twenty minutes after the fluid application. At the time of the recording, the temperature of the fluid was -9 °C and the temperature in the cold chamber was -5 °C. In Figure 4.9, the pellet seemed to have bonded with the bottom of the plate because it did not slide down at the rate the fluid was sliding. In Figure 4.10, the pellet was observed to be at the same point one minute and thirty-five seconds later. However, only a few seconds later the adhesion broke, (Figure 4.11) and the pellet was observed to move downwards (Figure 4.12). Occasionally, the motion of the pellet appeared to be obstructed, possibly because it ran into a small surface obstruction or re-adhered to the bottom until the bond was broken again.

4.2.2 Snow precipitation observations

The attempted laboratory simulation of snow flakes with the use of the ultrasonic humidifier that was mentioned formerly, produced "snow-like" structures that did not fully match the natural precipitation. The "snow-like" flakes that were generated,

Figure 4.9 - Ice pellet adhering to the test surface
Figures 4.10 and 4.11 - The bonding of the ice pellet with the substrate is broken
usually had a less dendritic structure than those observed in the field tests. A typical example of the snowflake melting that was observed in the initial stage of the fluid behavior during field snow exposures, can be seen in Figures 4.13 to 4.16, which were taken from one example laboratory snow test.

Both a bottom and a side view are included in each of these frames. The snowflake contacted the fluid film only two minutes after the fluid was applied on the plate and it was observed to start melting immediately (Figure 4.13). The melting process had similar patterns to those encountered in the field tests. As the flake structure melted, it was observed to sink in the fluid film, as the side views of Figures 4.13 to 4.15 demonstrate. The fluorescent trace of the resulting water indicates that it did not mix homogeneously in the fluid film, but appear to run down the plate on top of the de-icing fluid, as it can be seen in the side views in Figures 4.15 and 4.16.
Figures 4.13 and 4.14 - Laboratory snow flake melting
Figures 4.15 and 4.16 - Laboratory snowflake melting
4.3 Room temperature tests - Rain droplet observations

The droplet impact behavior was analyzed at room temperature. Some of the water runoff characteristics that were identified in the field exposures, were also observed in the laboratory tests. In the initial stage of the snow and freezing drizzle field events, the water resulting from the melting of snow flakes or from the drizzle droplets, appeared to concentrate in small pools on the fluid surface. At a steeper slope, they ran off in water streams, creating ripples on the fluid film. A similar behavior of initial stage water droplet runoff can be seen in Figures 4.17 to 4.20.

Figures 4.17 to 4.20 depict the impact of a single droplet on a de-icing fluid film that had run off the plate for almost twenty minutes. The plate angle of tilt was 10°. Figure 4.17 was recorded immediately after the impact. The water droplet impact point can be seen in the central part of this frame. The fluorescent glow that can be seen at the upper left corner of this frame, comes from the syringe that contains the fluorescent water used for the droplet generation. The syringe was located directly above the view plate, but it is out of the focal plane and should be ignored in this and the three subsequent figures. Initially, the water pool that was created in Figure 4.17, appeared to
Figures 4.18 and 4.19 - Individual water droplet impact and runoff
have contact with the bottom of the plate, as the strong fluorescent glow indicates. Only three seconds after the impact, in Figure 4.18, part of the water can be seen to have left the initial impact region and run off down the fluid surface, leaving a fluorescent trace behind it. In Figures 4.19 and 4.20, it can be seen that the runoff has continued. The fluorescent water front is now observed to move faster than the nominal runoff of the de-icing fluid, indicating that the low viscosity water runs off above the de-icing fluid, as was though to occur in the field tests.
Chapter 5

Summary and Conclusions

Field and laboratory tests were conducted in order to analyze the behavior of non-Newtonian Type II ground de-icing fluids at a microscopic level. The objective was to better understand the microphysical phenomena that determine de-icing fluid performance and cause the fluids to fail. In the field tests, two flat plates and one cylindrical test surface were treated with Type II fluid and were exposed to natural snow, ice pellet and freezing drizzle precipitation. High magnification cameras were used for close-up observations of the interaction between the fluid film and individual precipitation elements. Several factors that contribute to de-icing fluid degradation and influence their Hold Over Time (HOT) were identified. The laboratory experiments were designed to replicate the field tests, in order to further analyze the details of the impact and subsequent melting of single precipitation elements on a de-icing fluid film. Snow flake and ice pellet impact tests were conducted in a cold chamber, while droplet impacts were analyzed at room temperature. The following is a summary of the observations:
1. For snow and ice pellet precipitation, fluid failure appeared as *inability of the fluid to melt the incoming precipitation elements*. In the case of snow, the dendritic structure of the flakes penetrate in the fluid film and local freezing occurs which does not allow the flakes to melt completely. In the case of ice pellets, partial melting occurs at the intermediate stage and in the final stage the pellets become encapsulated by the resulting water and are prevented from melting completely.

2. Depending on the precipitation type, *different modes of fluid failure* were identified. In general, the fluid behavior was observed to have three distinct stages. The initial stage is characterized by complete melting of the incoming precipitation by the fluid film. At the intermediate "slush" phase, the fluid performance has been degraded by the precipitation water and only partial melting of the precipitation elements occurs. An initial layer of surface roughness is formed in this process. At the final stage, icing contamination builds up in "bridges" on top of the initial layer of partially melted precipitation.

3. De-icing fluid failure is typically determined by the mixing interaction of individual precipitation elements with the fluid film. In most cases, precipitation water *did not mix homogeneously* into the fluid film and resulted in variable melting time, in the case of snow precipitation.

4. In the only *freezing drizzle* event that was encountered during the field tests, the event ended before the process entered the intermediate stage, so no conclusion on fluid failure could be made.

5. In snow events, water is produced from the melting of snow flakes. The water was observed to form beads which, at a steeper slope, *run off* on top of the fluid film, causing ripples in the film.

6. The melting time of individual snow flakes, was identified as a potential metric to characterize fluid failure, only in the case of snow precipitation.
7. Adherence of ice contaminants on the treated surface was not observed in any of the cases analyzed.

8. The comparative analysis of the fluid behavior on flat plates tilted at different angles, proved that the surface geometry is a significant factor that influences fluid failure. De-icing fluid was always observed to fail first on the steeper plates.

9. Close-up video analysis in the laboratory tests confirmed most of the observations that were made in the field data.

The experimental results stress the importance of the microphysical phenomena that influence de-icing fluid performance. The microscale observations and the different types of interaction between the fluid and the precipitation water that were identified, can be used as a tool in accurately defining fluid failure. Surface roughness was observed to form on the treated surface in the intermediate stage of the fluid behavior under both snow or ice pellet precipitation conditions. This indicates that the design of reliable ice detectors that will be employed on de-iced aircraft surfaces during snow or ice pellet events, can possibly be based on roughness sensing techniques. In addition, the snow flake melting time measurements demonstrate that melting time may be used to sense and predict degradation in the fluid performance under snow precipitation. The non-homogeneity in the mixing of precipitation water in the fluid film is a critical issue that should be incorporated in future mixing and HOT models. In addition, the surface geometry is an equally important parameter as indicated by the effect of plate tilt on fluid failure, and should not be neglected in new models, as it was seen in the comparative analysis of fluid behavior on plates tilted at different angles. Identification of the intermediate and final stages in the fluid behavior, or melting time measurements, may also be used as a reliable criterion for characterizing fluid failure.

On a final note, no bonding between snow or ice and the substrate was observed in all the field events. This indicates that ice accumulation on a de-iced surface may not necessarily mean that it is unsafe to takeoff. Additional testing should be performed, in order to investigate the adherence of icing precipitation on de-iced surfaces, even after the fluid appears to have failed. Simulated takeoff experiments in a wind tunnel can possibly be valuable in this aspect.


Polomski Peter P. and Michael R. Muller (1993), Field studies of Hold Over Times for Type II Anti-icing Fluids: Results and Insights. 31st Aerospace Sciences Meeting and Exhibit (held in Reno, Nevada in January 1993), AIAA 93-0749.
