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Experimental evaluation of the impact behavior of partially melted ice particles

Miguel Alvarez*[a,b], Richard E. Kreeger[c], Jose Palacios[a,b]

[a] 229 Hammond Bldg, University Park, PA 16802, United States
[b] The Pennsylvania State University, United States
[c] NASA Glenn Research Center, United States

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ABSTRACT

Operations in ice crystals conditions are a threat to commercial aviation. The ingestion of ice crystals can affect different aircraft probes but can also affect jet engines. As fully frozen ice crystals enter an engine, partial melting occurs on the low-pressure compressor region of the engine, and ice accretion could occur on warm surfaces due to the presence of water coupled with the cooling capacity of the unfrozen portion found on the particles. Understanding the fundamental fracture dynamics that occur when partially melted ice crystals impact a surface is needed for model development and verification. To experimentally measure such fracture/splashing dynamics, a test rig was designed and fabricated to observe the impacts of partially melted ice particles. Ice particles ranging from 403 μm to 1028 μm were suspended on an ultrasonic levitator and were allowed to melt under natural convection. A fluorescence-based technique was used to quantify the water content of the melting ice particle in real time. A pneumatic launcher was automatically triggered at a requested water content to ice ratio, and a stainless steel impactor was launched at speeds ranging from 2.8 ms^{-1} to 65.5 ms^{-1}. The impacts were recorded with a high-speed camera at 75,000 frames per second. The qualitative behavior of these impacts was observed, and an empirical model to determine the threshold velocity for an ice particle to fracture for varying water contents to ice ratios was proposed. From this empirical model, when the water content ratio was 79%, the impact velocity required to fracture a particle increased by 81% from the value obtained for fully frozen cases. Moreover, a new technique to measure the water content of a melting ice particle based on the diameter of the ice core observed post impact was conducted. The post-impact direct measurement technique was compared to the real-time fluorescence-based water content quantification technique to asses its accuracy and to understand partial melting quantification uncertainties.

1. Introduction

In 1998, Lawson et al. identified ice crystals as a threat to aircraft turbofan engines [1]. Ice particles, as opposed to supercooled droplets, are expected to bounce off cold surfaces. In 2006, Mason et al. [2] hypothesized that ice crystals were partially melting and accretting in the first compression stages of the engine. They created a database with 46 turbofan engine power loss events attributed to icing in glaciated conditions which was later expanded to include over 150 events [3].

In an effort to characterize the environment where this type of icing can occur, the engine harmonization working group (EHWG) launched the high ice water content (HIWC) flight test campaign in Darwin, Australia [4]. In this campaign the median mass diameter (MMD) of the crystals was determined to be between 250 μm to 500 μm in environments with an ice water content (IWC) higher than 1.5 gm^{-3} and between 400 μm to 800 μm in proximity of long standing thunderstorms [5,6].

As of the time of this writing, only NASA Glenn propulsion systems laboratory (PSL) is capable of testing turbofan engines in glaciated conditions [7]. While a full scale engine can be tested at PSL, the water content of melting ice particles cannot be measured to date. It is not possible then to obtain complete fundamental understanding of the ice accretion process in these conditions.

Laboratory tests of single ice particles can contribute to shed light in the fundamental physics of ice accretion needed to develop the tools required for simulation and engine design.

The early studies of impacts of ice projectiles were in the context of hail impacts, where the ice projectiles ranged from 6.2 mm to 50.8 mm [8–11]. More recently, the impact behavior of smaller particles, in the context of engine icing were studied [12–15]. In these studies particles

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* Corresponding author at: The Pennsylvania State University, 336A Reber Bldg., University Park, PA 16802, United States.
E-mail address: mqa5359@psu.edu (M. Alvarez).

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with a size ranging from 30 µm to 3500 µm were tested.

In all these studies, it was not possible to replicate the partially melted status of the ice particles before impact. This study is the first successful attempt to replicate the impact of a particle undergoing the melting process. This paper aims to analyze the impact behavior of partially melted ice particles by characterizing the threshold for particle fragmentation at different water content ratios.

2. Methods

2.1. Droplet levitation

To reproduce the impact of an engine surface with a partially melted ice particle, an ultrasonic levitator was used to suspend a single droplet of water. Cold nitrogen gas was then directed at the levitating droplet to freeze it. The cold flow was then stopped and, as the droplet melted, a stainless steel impactor was launched. The impact was recorded with a high-speed camera through high magnification lenses.

The levitator, from Tec5USA Inc, is composed of a 58 kHz transducer that measures 12 mm in diameter and has a 18 mm diameter concave reflector. The multiple reflections between the transducer and reflector result in an acoustic pressure field shown in Fig. 1 and hold the particle in one of its nodes. The model shown in Fig. 1 was obtained using a multi-physics commercial package, and the results were instrumental in the design of an impactor launcher (see Section 2.2), since knowledge of the position of suitable nodes to levitate the partially melted crystals was required.

Once a droplet is levitating in the selected nodes of the pressure field, cold gas was directed to the droplet to freeze it. The gas was injected at very low velocities to minimize drag forces over the droplet that could push it off the pressure node created by the levitator. The gas was also injected at extremely low temperatures so it could maintain a low enough temperature to freeze the droplet as it mixes with the warm air of the room. To achieve such low temperatures, the gas was sent through a copper helical heat exchanger immersed in a liquid nitrogen bath. Pure nitrogen gas was used to avoid the deposition of carbon dioxide found in air which could clog the pressure line.

2.2. Particle impact

A pneumatic launcher was fabricated to replicate the impact of an engine low-pressure chamber component surface with a partially melted ice particle. The launcher consists of three main parts: An impactor, a barrel, and a stopper. In a test, the impactor was accelerated through the barrel by pressurized air from a tank. The front end of the impactor would then impact the suspended particle before being stopped by the stopper. The impactor and the stopper were machined from a high-strength stainless steel alloy and were heat treated to minimize the wear of every impact. The impactor before and after an impact is shown in Fig. 2.

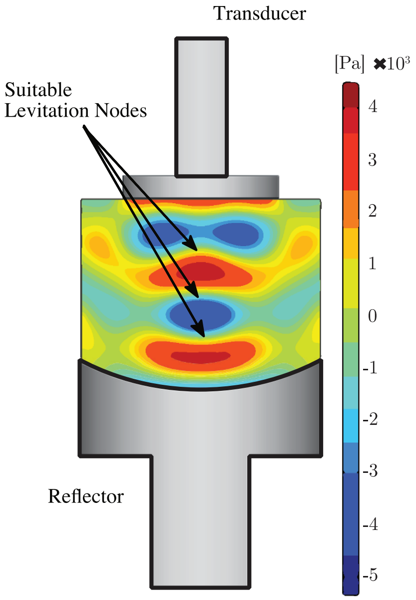

Fig. 1. Acoustic pressure field generated by levitator.

The highest pressure available for the test was 8bar, which was enough to accelerate the impactor to 100 ms^{-1}.

A Photron FASTCAM SA-Z with a Navitar Zoom 6000 lens system were used to capture the high-speed impacts. The Navitar Zoom 6000 lens system consist on a 2 × F-mount adapter (1-62922), a 12 mm F.F. zoom lens (1-60135), and a 1.5 × lens attachment (1-60112).

The SA-Z is capable of recording at 75,000 frames per second at a resolution of 560 × 384 and an exposure time of 248ns. With this configuration it is possible to record impacts of up to 60 m/s with a pixel deformation smaller than 1 pixel.

2.3. Water content of a melting particle

To investigate the effect of the melting ratio on the impact characteristics of partially melted ice particles it is necessary to quantify and control the melt ratio of such particles. Yan and Palacios [16] excited a solution of rhodamine-B with a laser and found a relationship between the intensity of the fluorescent emission of the rhodamine-B and the water content ratio of partially melted ice particles. To obtain this information, Yan recorded videos of frozen water/rhodamine-B melting while being excited with a laser. The rhodamine-B is fluorescent when excited at a wavelength close to 544 nm and when it is diluted in liquid. Knowing the amount of liquid in the particle by measuring its fluorescent emission intensity allows for the measurement of the liquid water content ratio. Based on this fluorescence technique, a real-time water content quantification routine was developed.

The working principle of liquid water content quantification is based on the fluorescence of rhodamine-b in water. As observed by Tanaka et al. [17], when water freezes, the emission of the rhodamine-B cannot be observed. At a given temperature, the intensity of the rhodamine-B emission is then proportional to the number of molecules in the liquid water. If the concentration of rhodamine-B is assumed to be invariant during the freezing process, the liquid water content can be estimated to be proportional to the intensity of the rhodamine-B fluorescent emission.

A 10W 532 nm laser with a beam expander was used to excite the rhodamine-B solution droplet. An STC-MC33USB camera with a charged coupled device (CCD) detector, with a band pass filter of the same wavelength of the laser, was used to capture the emission from the droplet and block laser reflections. A diagram of the complete experimental setup is shown in Fig. 3.

A routine written in National Instruments' LabVIEW was used to process the incoming Red, Green, Blue (RGB) images from the CCD camera. An RGB image consists of three arrays of the pixel values representing the intensity value of the red, green and blue pixels. The three arrays of pixel values are added together to calculate the total intensity of the fluorescent emission of the droplet. The sum of the elements of the resulting array is then the total intensity used to calculate the amount of liquid water in the droplet.

The intensity of the droplet was recorded before the cooling started and after it was frozen. The melt ratio η is then given by Eq. (1).

$$\eta = \frac{I - I_{frozen}}{I_{liquid} - I_{frozen}} \tag{1}$$

Where I is the total intensity of the image, I_{frozen} is the total intensity of the image when the particle is frozen and I_{liquid} is total intensity of