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IMPACT CHARACTERISTICS OF SIMULATED HAILSTONES DURING INGESTION BY TURBOFAN AERO ENGINES

By

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A Thesis Submitted in Partial Fulfilment of the Requirements for the Award of Doctor of Philosophy of Loughborough University of Technology

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Recent in-flight instances of aircraft engine power loss involving hail ingestion have forced the manufacturers to demonstrate successful engine operation whilst ingesting hail. The main objective of this research project has been to obtain an understanding of the basic characteristics of hailstone impacts. A hail gun was designed to fire simulated hailstones at speeds up to 175 m/s. Three measurement techniques were used to determine the impact characteristics of the hailstones, i.e., patternator, high speed cine photography, and still photography with short duration flashes. Using these techniques, the basic impact characteristics in terms of post-impact particle size, velocity and mass distribution were obtained for a variety of target configurations. The influence of seemingly important parameters on the impact characteristics were investigated, including approach angle and velocity, target curvature, and target rotation. Studies were further made into multiple impacts, and the effect of target curvature and rotation on the impact characteristics. Based on the experimental results, a set of empirical rules and a mathematical model describing hailstone break-up were defined.
NOMENCLATURE

a Rate of deceleration of ice ball while crushing (m/s^2)
aL Speed of sound in the laboratory (aL = 340 m/s)
B Width of patternator after being masked (mm)
D0 Initial ice ball size (mm)
d Post-impact particle size (mm)
d_max Maximum particle size after impacts (mm)
d_mean Mean Particle size after impacts (mm)
e Curvature ratio
h Height in an ice ball from bottom (m)
H Height of the curved plate (mm)
HG Gun position measured from the symmetrical axis of Williams fan (mm)
k_s Ratio δ/d
K_n Deduction factor for normal impact energy
K_t Deduction factor for tangential component of impact velocity V_t (m/s)
N_d Rosin-Rammler coefficient for size distribution
N_v Rosin-Rammler coefficient for velocity distribution
r Radial distance to the impact point (mm)
S Chord of the curved plate (mm)
t_cr Ice ball crashing time (s)
Δt Time interval between two flashes (μs)
V_0 Impact velocity (m/s)
V_n Normal component of impact speed (m/s)
V_t Tangential component of impact speed (m/s)
v Post-impact particle velocity (m/s)
v_max Maximum particle velocity after impacts (m/s)
v_mean Mean particle velocity after impacts (m/s)
β Direction of ice particle travel (°)
δ Particle depth (mm)
θ Incident angle - between the ice ball path and the plate face, (°)
$\phi$ Spread Angle (°)

$\varphi$ Angular position in spinner base (°)

$\mu_d$ Mass fraction for particle size distribution

$\mu_v$ Mass distribution for particle velocity distribution

$\omega$ Rotation speed of spinner or fan (rpm)
CHAPTER 1. INTRODUCTION

1.1 Background

A relatively small but significant number of power loss events involving inclement weather had been noted in the past twenty five years of high bypass ratio engine service. In June 1988, the Aerospace Industries Association (AIA) formed a technical sub-committee named “PC 338-1” whose primary task was to produce a report on the effects of extreme rain and hail. This report (Reference [1] ) was presented to the airworthiness authorities in June 1990.

The PC 338-1 investigated engine power loss events in inclement weathers since 1970. Two examples of the incidents investigated are given below so that the kind of danger involved can be appreciated.

Example 1. A Boeing 737-300 aeroplane, equipped with CFM56-3 turbofan engines, experienced flame-outs on both engines during descent in rain, heavy hail, and moderate turbulence.

The flame-outs occurred when the aeroplane was descending through 8,900 feet, airspeed 289 knots, TAT +15 degrees C, left ignition on “continuous,” engine anti-ice off, thrust levers idle, left engine N1=33 percent and right engine N1=35 percent. Both engine generators were lost at flame-outs, and the crew reverted to standby instrumentation.

Number 2 engine was quickly re-lit, using a rapid relight procedure, bringing the generator on line and restoring normal instrumentation. The Number 1 engine was restarted using the normal in-flight start procedure and its generator brought on line.
An uneventful landing followed a visual approach. No visible damage to either engine was detected during a post-flight inspection, which included a borescope inspection, nor was there any damage to the inlets or nacelles. There was hail damage to the stabilizer leading edge. Subsequent testing of the number 1 engine, by CFMI, did not reveal any abnormalities which could have caused a flameout. It is suspected that the ingestion of intense rain and hail was the cause of the flameouts.

Example 2. A Douglas DC-9-31 aircraft was on a scheduled domestic passenger flight from Huntsville to Atlanta. During descent for Atlanta, the aircraft entered a small but intense precipitation area at about 15,000 feet. This small area was part of a much larger area of lesser intensity. In the area of intense rain and hail, both engines flamed out and the windshield glass was crazed or shattered. The pilot radioed ground control requesting vector to the nearest airport. During the glide the aircraft lost electrical power for about 25 minutes. Unable to reach an airport, the pilot elected to land on a narrow road.

Initial ground contact came with the wings clipping trees and poles on both sides of the road. The fuselage contacted the road, impacting cars and a country store before breaking up and burning. Some survivors were thrown clear during fuselage break-up.

During the glide, the flight crew had tried to restart engines without success.

In the study carried out by PC 338-1, data for the following aeroplanes and engines were examined.

Aeroplanes: Airbus: A300, A310
Douglas: DC8-70, DC10
Lockheed: L1011, B737-300
During the period from January 1, 1980, through June 30, 1988, there were 45.0 million engine departures accumulating 134 million engine hours. During this same period, 84 in-flight power loss events occurred with 70 of the events resulting in engine shutdown (rundown, flameout). The majority of in-flight shutdowns in cruise occurred with turbulence as the only weather factor involved. However during descent, approach, and hold, most of the in-flight shutdowns involved more than one weather factor (including rain, hail, snow, icing, etc.). It was felt by the aviation community that some measures had to be taken to safeguard future operational safety, and that possibly airworthiness regulations were not covering all extreme weather situation. Hence the AIA PC338-1 committee was formed and research work started by major engine manufacturers and research institutions.

1.2 The Consequences of Rain/Hail Ingestion into a Turbofan Engine

1.2.1 Factors affecting the amount of hail entering an engine

When an engine is operated in hail conditions, the engine inevitably ingests some hailstones, the amount of which depends on the following factors.

(i) The hail concentration in air

The AIA group studied the available world-wide data base on rainstorms and unique ground radar-based investigations of hailstorms in the continental USA and the southern European alpine region. The hailstorm studies deduced that in the particular regions noted for the severity of summer storms, very high concentrations of rain and hail could occur. The AIA group plotted the overall probability of occurrence of such events vs. concentration of
rain/hail in the atmosphere. The group identified a 1 in $10^8$ chance of hail at 10 g/m$^3$ (grams of hail per cubic metre air) at 12,000 to 15,000 ft altitude.

(ii) The aircraft speed and scooping effect of the engine inlet

The column of air in front of the engine is captured by the inlet for use by the engine (Fig. 1.1). When flying in rain or hail, this column is actually two columns; one of air and the other of water droplets or hailstones. The amount of air ingested by the engine depends on the aircraft speed and the engine RPM. At high aircraft speed and low engine RPM, more air is intercepted by the inlet than the engine requires. Thus air is spilled around the inlet, effectively reducing the cross section of the column of air being ingested. The water droplets and ice particles, having greater momentum, are not spilled around the inlet and the column of liquid or solid particles thus remains essentially the same size as the inlet's projected frontal area (Fig. 1.1). This "scoop factor" can increase the water/air ratio by as much as 200 percent. Increasing engine RPM increases the air flow requirement, thus reduces the spillage, while maintaining the same capture area for water ingestion. Reducing aircraft speed will also reduce air spillage around the inlet. The combined action of increasing thrust while decreasing aircraft speed (by increasing the drag, e.g. lowering the landing gear) can significantly reduce the ingested particle/air ratio.

1.2.2 Engine power loss caused by ingested water/ice

The mechanism by which ingested rain/hail deteriorates engine performance is analysed below. Water and ice are discussed together because hail is normally accompanied by rain, and in addition ice may melt in the engine forming water.

After passing the fan, the ice may go to the bypass duct or the core engine. Ice that goes to the bypass duct does little harm, but ice into the core engine can cause serious engine power loss in the following forms.
(a) Inlet Air Spillage at Low Engine RPM/High Aircraft Speed
Increases Engine Face Water/Air Ratio

(b) High Engine RPM/Low Aircraft Speed
Decreases Engine Face Water/Air Ratio

Fig. 1.1 The scoop effect at engine inlet
(1) Loss of surge margin due to compressor re-matching

Ingestion of water in liquid or solid form will affect engine operation because of the higher specific heat and latent heat of evaporation for water, and the result could be the ruining of the compressor matching which is specified for each engine design. A high bypass turbofan engine consists of a number of independent rotors. The speeds at which each rotor operates are intended to provide an uninterrupted flow of air through the engine and an appropriate pressure rise across each compressor. The parameters having a primary influence on the operation of each compressor include airflow, rotor speed, air pressure and air temperature. The thermodynamic relationship between the compressor and its respective turbine is referred to as matching.

The ingestion of water (in liquid or solid form) in the air imposes new operating conditions on the compressor and causes the compressor re-matching. The reason for this re-matching is that when the water is vaporised within the engine, it reduces the air temperature in the downstream stages of the compressor and in the combustion chamber. The ingestion of ice further increases the cooling in the compressor as it absorbs heat while melting into water and then more heat as it evaporates. Quantitatively the degree of re-matching is a function of the water/air and ice/air ratio, and the compressor design. The compressor re-matching moves the high pressure compressor operating line toward the surge line, as illustrated in Fig. 1.2, thus causing the compressor to be more susceptible to surge.

(2) Influence of water content on fuel/air ratio

Fig. 1.3 illustrates the effect of water ingestion on engines fuel/air ratio. The dashed lines represent fuel required (operating) lines for various rates of water ingestion. As the water/air ratio is increased, the operating line moves towards the acceleration schedule. The higher the operating line, the more fuel is required to maintain steady-state. The slope of the lines of constant throttle position on the diagram describes the basic characteristic of droop governing control. From this, it is apparent that a rise in the operating line results in a loss in
Fig. 1.2 Change of surge margin due to water content in airflow

Fig. 1.3 Typical engine control characteristics
(Diagram from PC338-1 report)

$N_2$ decay due to water ingestion at constant throttle position
higher pressure compressor speed ($\Delta N2$ for two-spool and $\Delta N3$ for three-spool engines) when throttle position remains fixed. The acceleration schedule represents the maximum fuel/air ratio available to the engine. As the operating line rises, it can, under the most severe condition, reach the acceleration schedule, at which point the fuel control would be unable to deliver additional fuel to accommodate the increasing water ingestion. Under this condition, the engine will run down to the point where the maximum fuel flow available is insufficient to operate the engine at steady-state. This could, depending on the water being ingested, result in rundown to below idle, loss of throttle response and loss of electric power if the generator drops off line. As the aircraft leaves the area of heavy precipitation, the water/air ratio will decrease and fuel required line may return to its normal operating line, and thus allow the engine to re-accelerate to the original set speed.

The engine is most susceptible to flameout or compressor surge when it has been put in a sub-idle operating condition. The above mentioned self-recovery, when exiting the rain encounter, is, of course, dependant on the engine not having experienced flameout or another non-recoverable operating condition during rundown. Experience has also shown that an engine may hang in a sub-idle operating condition and not recover as mentioned above. In this case, the engine must be shut down and restarted by the flight crew in order to return to normal operation.

1.2.3 Engine physical damage resulting from water/hail ingestion

Engines may experience erosion during ingestion of liquid or solid water, but this is beyond the scope of this thesis. Some literature on this topic will be given in the literature review. In case of hail ingestion, engine ground tests in industry (to be described in section 1.5) have not revealed serious physical damage so far. This has been attributed to the small sizes of ice particles required by the regulatory organisations for such tests, and the very short time (in the order of 10 to 20 seconds) required to operate under such a condition.
It needs to be pointed out that engines may suffer serious mechanical damage during flameout or surge caused by rain/hail due to continuing operation under an adverse condition. In a case investigated by the PC 338-1, multiple engines were severely damaged while operating in an unusually heavy rain storm. The accident investigation found that the engines probably surged as a result of throttle movement during the period of reduced surge margin. The surge, coupled with the massive amount of water and hail, caused severe compressor damage. Continued operation of the engines with damaged compressors caused severe over temperature in the turbines resulting in complete loss of engine thrust.

1.3 Critical Engine Operating Condition for Hail Ingestion

The critical condition should reflect the highest hail concentration in atmosphere that an aircraft may encounter when its engines are at the most vulnerable state. As has been shown, an engine’s tolerance decreases as the engine’s power setting is reduced. The lowest engine power setting occurs at decent idle state, which is the typical setting when an aircraft is at altitudes of possible high concentration of hail. Hence this state is considered as the critical condition. The incidents studied by PC338-1 have shown that most of the engine power loss occurred at this state.

1.4 Current Engine Certification Requirements for Hail Ingestion

Whilst international regulations embodying the rules of hail ingestion tests have not yet been published because of the many formal processes and procedures to be complied with, new engines are having to conform to a set of interim rules on hail ingestion.

Because the relative newness of the power loss problem and the lack of detailed understanding which can be embodied in engine design rules, engine manufacturers have to use whatever methods are available to them to satisfy the airworthiness authorities on the rain and hail tolerance of their powerplants.

An engine test at altitude with hail ingestion is apparently not practical due to the high expense, potential danger, and difficulties of arranging hail encounter. It has been found that
the engine power loss can be reproduced on ground by ingesting simulated hail into an engine that has been run to a required state. Rolls-Royce and General Electric have manufactured (different) hail guns so that a full-size engine can be tested on a ground level test bed. Pratt & Whitney has relied on sophisticated analytical techniques backed up by extensive component rig testing and full size engine tests with water. Other manufacturers are using whatever combination of techniques which are deemed appropriate to their particular need.

1.5 Introduction to Full Size Engine Ground Tests with Hail Ingestion

A full size engine hail ingestion test can be briefly described as firing ice into an engine that has been run to a required state on a test bed, and observing the performance of the engine. In carrying out these tests, the first two tasks are to make simulated hailstones and to build a hail “gun”.

1.5.1 Simulated hailstones and hail guns for engine ground testing

Various techniques have been used to manufacture simulated hailstones, resulting in a variety of sizes and shapes of ice particles. Some testers make their simulated hailstones by pouring water into specially made moulds and then freezing the water into ice. Rolls-Royce make hemispherical ice particles of 3/4 inch diameter with this method (Fig. 1.4). The ice particles have controlled shapes and sizes. According to the information obtained, the shapes of simulated hailstones used by engine manufacturers included spheres, hemispheres, and cubes. Some testers simply used crushed ice, in which case it is more difficult to control the particle size and shape, hence the only parameter is the mass of ice fired.

The hail “gun” designs of different manufacturers are diverse, but they all employ compressed air to accelerate the ice particles to required speeds. The differences are in size, number of barrels, and feeding mechanism. Fig. 1.5 is a sketch of one barrel of the Rolls-Royce hail gun (the author’s publication 5). The hail gun used at Rolls-Royce consists of seven of these barrels, as shown in the centre of Fig. 1.6. Each barrel is connected to a breech
(the pipe at the top in Fig. 1.5) and a compressed air supply. Before firing, the breeches are filled with ice particles manufactured with the technique shown in Fig. 1.4. On top of the ice particles was a piston pulled by a wire connected to a motor. When firing the gun, the piston causes the ice particles to pass through the breeches into the barrels. The mass rate of ice fired is controlled by the speed of the pistons. The relation between the ice particle speed and
the pressure of the air supply was found out with high speed cine photography. The typical speed used in the tests were 350 - 400 ft/sec. The Rolls-Royce hail ingestion tests investigated the effect of various gun barrel arrangements which affects the mass distribution of ice at engine inlet. Other parameters includes the engine power setting and the different possible pilot actions when the engine ingests hail. The engine performance is closely observed during the test and the engine is thoroughly checked for physical damage after each test.

1.5.2 Advantage and disadvantage of full size engine test

A full size engine test is the most direct method of demonstrating an engine’s tolerance to hail. It is required by the airworthiness authorities as part of an engine’s certification procedure. However, these tests have the disadvantages of high cost and being time consuming in terms of preparation. Also these tests can only be run after an engine is manufactured, and hence have limited value at the design stage of a new engine.
1.6 Numerical Modelling

Numerical models have been developed to study the mechanism and consequences of hail ingestion. Since the hazard is from the ice entering the core engine, the main task of
numerical modelling is to trace the ice particles and determine the amount of ice that can enters the core engine. The models can be used as design tools for new engine, to provide a picture of the performance of the new design under hail condition. They can also be used to do parametric studies and show the effects of various factors on ingested hail, and hence guide the engine designers.

Below is a brief description of the numerical model being developed by Rolls-Royce for which the experimental work of this project has provided data.

This model is based on a CFD (Computational Fluid Dynamic) solution of the flow field at the inlet and fan stage. The particles are then seeded into the flow, and their trajectories calculated allowing for the influence of air drag. Fig. 1.7 is a preliminary result from this model. The picture shows the geometry of the spinner and fan blades, and the coloured lines are the trajectory of the ice particles. After being ingested into an engine, most of the particles hit the solid surfaces of the engine, hence the impact characteristics of the particles are definitely needed for the numerical model. The impact rules used in Fig. 1.7 are some simple assumptions combined with limited experimental results. Previous research into the impact characteristics based on sand, coal ash, etc., can not be applied to ice because ice is brittle. The impact characteristics of hailstones can only be obtained through experiments.
Particle Velocity = 184 m/s
Rotational Speed = 0 rad/s

Fig. 1.7 Preliminary results from the numerical model.

Photo Courtesy of Rolls-Royce plc.
1.7 Experimental Study of Impact Characteristics of Simulated Hailstones

This is the main task of this thesis. The impact characteristics that a numerical model needs are three-fold, and are defined as the *basic impact characteristics*.

1. Post-impact particle size
   The size of the post-impact particles determine the aerodynamic drag which is required to compute the trajectories.

2. Post-impact particle velocity
   The velocities of post-impact particles decide the initial momentum for the particle tracking following the impact.

3. Post-impact Mass distribution
   Mass distribution means the mass of ice particles against their directions of travel. It illustrates the orientation of the particles after an impact.

1.8 Program Objectives

1. To devise techniques for studying the hail ingestion characteristics of aero engines, and to determine the significance of all seemingly important parameters.

2. To determine the basic impact characteristics of simulated hailstones as defined above.

3. To investigate the influence of target shape and rotation on the impact characteristics.

4. To investigate the characteristics of secondary impacts.

5. To develop models of ice particle disintegration for use in numerical modelling of hail ingestion.
CHAPTER 2. LITERATURE REVIEW

2.1 A Family Tree of Particulate Laden Flow

Hail ingestion is a relatively new subject. However, the concept of ingestion of foreign objects into engines is not new. It is said that a turbofan aero engine is, in a sense, a giant Hoover-cleaner. A simple list of these foreign objects includes sand, water, birds, insects, and ice. Coal ash impacts on turbine blades are exactly the same problem in industrial engines using coal as fuel. Bolts and nuts that come off accidentally are relatives of this family, but since there are usually only one or two objects hence cannot be termed particulate laden flow. The following family tree can be drawn.

Ice is solid but may easily melt itself into liquid. Even in solid state, its physical nature is completely different from that of sand or coal ash. No reference could be found on hail ingestion when this work started, and even now there are only a very limited number of references (Helbling [3] 1994, and Gapalaswamy & Murthy [4] 1994). Helbling's publication ([3] 1994) was on the design of the gun facility which had been used in Allison Gas-turbine to fire birds, hail, etc. Gapalaswamy & Murthy ([4] 1994) published a numerical model for hail ingestion, but the impact characteristics used were lacking in experimental support. A fair amount of research work has been done on the other two members of the family, and the
knowledge obtained has been useful input for the hail ingestion research. Therefore the literature review is first made on sand ingestion and coal ash impacts, and then on water droplets ingestion.

The interest of this thesis is hail ingestion, and it is commonly known that hail is a rather special kind of ice due to its special process of formation. Simulated hailstones have been used in the research. To what degree do the simulated hailstones represent real hailstones? This has been a query throughout the whole research project. Meteorological scientists have done enormous amount of research work into the nature of hail, and the literature that they produced is abundant but not all entirely relevant to hail ingestion research. Hence the third part of the literature review is on the characteristics of natural hail.

2.2 Literature Review of Sand Impacts and Flow Involving Sand or Fly Ash

Solid particles in air have long been known to be a great hazard to aircraft engines. Frequently working under such conditions may considerably shorten the life of an engine, and may also cause sudden accidents. Below is a brief discussion of the hazard, and a review of the research work that has been carried out. To make things simple, the term 'sand' is sometimes used in place of 'solid particles' which may include sand and coal ash.

2.2.1. Sources of solid particles

(1) The ingestion of solid particles into air breathing engines occurs when an engine is being operated in areas where the atmosphere is polluted by solid particles which are made airborne either by the aircraft itself or other disturbances. Sometimes the concentration of solid particles in air is high, for example, in case of a helicopter engine operating in sandy areas or aircraft flying through clouds of volcanic ash.

(2) The development of industrial gas turbine engines burning coal as fuel inevitably encounters the problem of working under particulate laden flow conditions. By using
cyclones - which separate sand from air by making a circulating flow, about 85% of the ash from combustion can be removed, but particles sizing between 1 and 15 microns cannot be removed and will pass with the hot air through the turbine.

2.2.2. Hazards from particles in the airflow through an engine

The hazards of particles in the air flow is two fold.

(1) Erosion of engine components.

The erosion caused by solid particle impacts is manifested by pitting and cutting of engine components, mainly the blades. The result is the removal of material and obvious ruin of surface finish. The pitting and cutting of the components can cause serious structural damage; and the change of surface finish can cause deterioration of the aerodynamic condition, mainly in the form of increase of the total pressure loss across the blade row.

(2) Alteration of aerodynamic conditions

The existence of solid particles can considerably alter the characteristics of air, and hence affect the flow between the blade channels. Considering the mixture of air and particles as two phase flow, the density of particle laden air is significantly higher than that of "pure" air at the same pressure and temperature, and the particles have different inertia from that of air, so the pressure acting on the blade departs from the design working point. The engine can tolerate the shift of working point to a certain extent, beyond which engine failure will occur.

2.2.3. Experimental studies

Experimental work has included the study of basic sand impact characteristics and the characteristics of particulate laden flow through a compressor or turbine.
The study of basic sand impact characteristics can generally be described as firing solid particles at chosen targets with various impact speeds and angles. These experiments provided data on the erosion characteristics of various materials. The impact characteristics of the particles were also obtained, and they are of fundamental importance for the numerically modelling of multi-phase flow, or particle tracking.

The study of the characteristics of particulate laden flow in turbomachinery enabled the understanding of the effect of particles on the pressure distribution on compressor or turbine blades. Also the experiments provided the comparison of various designs of filters and determined the associated pressure loss.

The experimental work of different researchers was devoted to the tackling of the following problems

(1) The acceleration of sand particles

In order to study the impacts of solid particles on a target, the first task is to accelerate the solid particles to the required speed before they reach the target. The acceleration of particles is normally achieved by introducing the particles into an airflow which brings the particles to the required speed. Various designs of mechanism have been reported by Tabakoff et al. [5] (1971), [6] (1974), and [7] (1987); Armstrong et al. [8] (1984); and Tan et al. [9] (1994). The speed of the particles can be controlled by varying the strength of the airflow. Various sand feeders have been used and the density of the solid particles can be adjusted by controlling the feed rate of the particles. A collector is required to collect the sand after impacts, if for no other reason, to keep a clean laboratory. The post-impact sand can be separated from the airflow with a cyclone (Tabakoff et al [7] (1987)).

An important consideration is that the air-stream used to accelerate the sand may also affect the post-impact movements of the particles, which may cast some doubts on the measured coefficients of restitution. To solve this problem, Tan et al [9] (1994) used a ‘Coanda’ particle injector and a target chamber. The injector used the ‘Coanda effect’ to
deviate the main air-stream before it reached the target. The target was placed in a chamber with a pin hole to let the sand in. The target chamber also performed as a collector which retained the particles from the impacts for any further investigations.

(2) Particle speed measurement

It is essential to monitor sand velocities in experiments so that they can be controlled and hence parametric studies regarding impact velocity can be carried out. Also a fundamental aim of the work is to obtain the coefficient of restitution of the sand particles. Tabakoff et al [7] (1987) used a technique employing two-element laser Doppler anemometer to measure two simultaneous velocity components of a single particle using a two-counter processor. Tan et al [9] (1994) described a system using a 35 mw He-Ne laser transit anemometer.

(3) Outcome of experimental work


The techniques used and the researchers’ discussions in the above publications are of fundamental importance in the study of hail ingestion. The results are also of reference value because the behaviour of ice particles in air is similar to that of sand. The major difference
between sand and ice lies with the impact characteristics which depend on the material forming the particles.

2.2.4. Theoretical and numerical work


The equations governing sand particle motion in air published in the above references can also be used for ice particles when they are moving in air. Different impact rules should be used for ice particles due to the radical differences in the physical properties of ice and sand, which affect the impact characteristics. Obtaining these impact rules for ice particles is the main objective of this thesis.

2.2 Literature Review of Liquid Droplet Impacts and Flow Involving Liquid Droplets

The study into water droplet impacts has been going on for many years. The thrust of this research was the erosion from water drops occurring when an aircraft is flying at high speed.
through rain. The erosion can happen to aircraft body, windscreen, or fan blades. Apart from erosion there is another serious hazard when an aircraft is flying in rain - the engine power loss caused by ingested water. Water ingestion tests have been, and continue to be practised in the aero-engine industry as part of engine certification procedure. The characteristics of liquid droplet impacts is also required in understanding these process. Also in the study of aircraft icing, data on water droplet impingement on aircraft surfaces is needed for modelling ice accretion. Researchers studied water droplet impact with different experimental techniques, but they all needed to solve some similar problems.

2.2.1 The Acceleration of Water Droplets

The first task in the study of water droplet impacts is to create a relative velocity between the target and the droplet. Lane and Green [23] (1956) concluded that it was not possible to accelerate a sizeable liquid drop to a high velocity without the drop disrupting into a mist of fine droplets. The critical velocity for the break-up of the drop depended upon the drop size. This is one of the main differences between hail and water since hail does not break up while flying in air.

Bowden and Brunt ([24] 1958, [25] 1961a, & [26] 1961b) overcame this obstacle by making a jet of a small mass of liquid which may consist of many fine drops, instead of one drop, to a high speed. Field et al [27] (1985) used the same technique to produce impacts of a two-dimensional liquid wedge. They filled the liquid into a small steel chamber and then sealed the chamber with a Neoprene disk. Then a steel slug was fired at the Neoprene disk with a gun. The liquid was extruded through an orifice at the other end of the chamber. With this technique, they achieved jet velocities up to 1,200 m/s as determined by high speed photography. The limit to this technique is actually the bursting strength of the chamber. After leaving the orifice, the jet hits the target 4 to 12 mm away from the orifice.

Another way of getting round the problem is to move the target rather than accelerate the droplet. This technique was used by Povarove et al [28] (1986). The relative velocity
achieved between the target and the droplet was (0-200)m/s, and the droplet sizes varied from $5 \times 10^{-6}$ to $10^{-3}$ m.

### 2.2.2 Data Recording Techniques and Results

For recording the behaviour of a water droplet during the whole process of an impact, high speed photography is the apparent technique to use. Bowden and Brunton ([24]1958, [26]1961a, & [26]1961b), and Povarov et al. [28] (1986) all used high speed photography with frame rates up to the order of $10^6$ frames per second.

The impact speeds that the two groups of researchers used were significantly different (1200 m/s and 200 m/s), but the pictures of the impact process showed similarities. Bowden and Brunton's description was, “The nose of the jet has spread out radially in such a way that a fine mist of droplets hangs back to form an envelope around the uniform cylindrical core. The core diameter in this case is 1.3 mm. The envelope normally curls up on itself to form a thickened collar. As the jet moves through the air it is continuously turned back on itself to form the envelope. In this way the jet is atomised.” Fig. 2.1(a) is an illustration of the above description. The picture that Povarov et al obtained is illustrated in Fig. 2.1(b). After the drop touches the surface, a thin film of liquid spread out sideways, and curls up forming a hollow cone. The cone extents as the liquid drop presses itself down. The major differences between the two descriptions are that in the experiment of Povarov et al, there was a film of water that curled back in an angle to the target surface, rather than an envelope of fine mist of particles that normally curled back. Intuitively, it can be said that the differences are showing the two different orders of impact velocities.
With a piezo-electric pressure transducer, Bowden and Brunton ([25] 1961a, [26] 1961b) measured the time-dependant impact load and found that the load rose to a peak value within 1 µs and then fell rapidly within 2 or 3 µs to a much lower value. The transient compressible behaviour of the liquid drop was suggested to give rise to this phenomenon.

Von Glahn et al [29] (1955) used a dye tracer technique to study water drop impingement on an arbitrary body and techniques based on this principle were developed and applied in water impingement studies (Gelder et al [30], Lewis & Rugeri [31] 1957, Gelder [32] 1958, and Papadakis et al [33] 1991). With this technique, the target was covered with some blotter strips and then the liquid which was a dye/water solution of a known concentration was sprayed on to the target. Local impingement rate on the blotter strips was related to the variation in colour density. The areas of higher impingement rate were darker and those with lower impingement rate were lighter in colour. The blotter strips were then cut into pieces to analyse the colour content, using chemical methods in early days, and more recently laser reflectometer.

Fig. 2.1 Water jet and water drop impacts
2.2.3 Analytical work on water droplet impacts

Not as many references on analytical work were found as on experimental work into liquid impact problems. Rosenblatt and Eggum [34] (1979) reported a numerical treatment. Lesser [35] (1981) published an analytical solution of liquid-drop impact. Field [27] (1985) studied the liquid impact problem analytically.

2.2.4 Numerical Modelling of Flow Involving Liquid Droplets

Numerical modelling of liquid particle trajectories has been reported in [36] to [40]. These models were generally based on some CFD (Computational Fluid Dynamics) solutions. Haykin and Murthy [40] (1988) reported study of engine performance under a water ingestion condition.

2.3 A Literature Review of Natural Hailstones and the Laboratory Simulation

It was inappropriate to carry out the present research without having knowledge of the features of natural hailstones. The natural hailstone features considered to be relevant are extracted from the large amount of literature, and expressed as follows.

Hailstones are formed in the atmosphere from embryos of ice granules, dropping due to gravity, and then being brought up by strong up-draughts, during which time the granules pick up more water droplets or ice crystals and grow in size. The up and down movements go on till the ice stones become too heavy for the up-draught to bring them back up, and they fall to the ground. Due to the process of formation, hailstones have distinctive features.

Huge amounts of research work have been carried out into the characteristics of natural hailstones. The thrust of the research was the belief that the structure of hailstones must
reflect the conditions under which they are formed in the parent cloud. It was hoped that the understanding obtained could be of great assistance in the suppression of hail. The researchers did not have in mind the problem of the hail ingestion of turbofan engines, for which they should not be blamed. The research results were mainly published in journals of atmospheric and meteorological science (Reference [41] to [58]), and the detailed review of these references will be given below.

This literature review is aimed at obtaining the following information.

(1) The techniques of collecting, and storing natural hailstones;

(2) The techniques of studying natural hailstones in laboratories and the outcomes;

(3) The techniques of making simulated hailstones in laboratories.

2.3.1. The Techniques of Collecting And Storing Natural Hailstones

The techniques of collecting hailstones fall into two categories.

(1) Hailstones are picked up by the observers when they fall onto lawns or grassy surfaces where the impact is deadened and the insulation is adequate. This method is only suitable for larger hailstones, and smaller hailstones have to be collected by the second method.

(2) Hailstones are collected with hail collectors. There were two kinds of hail collectors. One is a container cooled by dry ice and has a funnel on the opening (Douglas & Hitchfeld [41] 1958). The other one is also a container but contains low temperature fluid (below 0°C) and the hailstones fall directly into the fluid. The disadvantage of this method is that the collectors have to be checked every two days and refilled with dry ice in the case of the dry ice collector. The collector using cooled fluid is only suitable when the water content is not to be measured.
After collection, hailstones can be shipped in plastic bags surrounded by dry ice at temperature -24°C, (List, et al [42] 1970). In laboratories, hailstones can be kept in dry ice for a considerably long time. According to Macklin et al, [43] (1976), the hailstones were stored in a laboratory in dry ice for 2 to 3 years before the analyses were made.

2.3.2. Techniques and Results of the Laboratory Studies on Natural Hailstones

(1) Hailstone Sizes and Weights

Hailstones range in size from a few millimetres to some 150 mm in maximum dimension (Macklin [44] 1977). Knight & Knight [45] (1971) reported a very large hailstone which fell at Coffeyville, Kansas. It weighed 0.77 kg. Prohoska [46] (1905) has reported hailstones 150 mm in diameter and weighing between 0.8 and 1.1 kg.

(2) Hailstone Shapes

Weickmann [47] (1953) classified hailstone shapes into three main shapes (in the order of probability), spheroidal (spherical and ellipsoidal), conical, and irregular.

(3) Hailstone Densities

Density measurement is based on an assessment of weight and volume, which in both cases must be undertaken in temperature below 0°C. It rarely occurs that the volume can be measured geometrically. The hailstone volume is normally measured indirectly by measuring the buoyancy of the hailstone using a wire device immersed to a fixed point which presses the hailstone into a liquid. The extra weight created on the liquid and its container can be weighed and corrected for the buoyancy of the wire device, which enables the desired buoyancy of the hailstone to be calculated. Then the volume of the hailstone can be
calculated. It is important that the liquid does not attack ice and it is fully saturated with water so that it does not absorb H₂O. The most advantageous choice is tetralin (List [48] 1961).

The above method is not suitable for measuring the volume of porous particles because the liquid will be sucked into the air capillaries having open ends on the surface of the particles. This obstacle can be overcome by using phthalic acid, diethylester (de Quervain [49] 1954). This is a liquid that freezes at approximately -7°C and can thus be easily injected by means of a hypodermic syringe at a higher temperature into the open capillaries of the porous particle under investigation. If accurate doses are given, the surface tension of this liquid brings about a evenly curved surface. If the temperature is brought down below -7°C, the liquid freezes and a compact particle is formed. The particle’s volume can be measured using the method described in the last paragraph.

An extremely simple method to measure density was suggested by Macklin. He used a number of glass cylinders each of which was filled with a fluid of different density. By establishing the liquid in which the hailstone under observation just began to sink, a first rough indication is given. Further measurement of free fall acceleration rate in the cylinder gave the difference between the hailstone weight and the buoyancy which can be used to determine the hailstone density more accurately.

Macklin [44] (1977) summarised the results of some researchers about density of hailstones, and he recommended that for most computational purposes the hailstone density may be taken to be approximately constant with a value of 0.9 gm cm⁻³.

(4) The Interior Structure: Layer and Lobe Structure

The break through in the study of the interior structure of a hailstone was marked by the success of obtaining thin slices of hailstones, normally down to 0.3 mm or less. The detailed technique of the thin-section saw is described by List [48] (1961). The thin sections can be investigated with normal or polarised light.
The interior structure of a hailstone can be described in the two directions of a polar coordinate located at the centre of the embryo. In radial direction the hailstone shows layered structure, and in angular direction a lobe structure, as illustrated in Fig. 2.2.

![Fig. 2.2. Lobe and layer structure of a hailstone](image)

(a) Layer Structure

One of the most obvious features of large hailstones is that they are frequently composed of alternate layers of clear and opaque ice. The changes in opacity are the result of changes of either the crystal sizes, or content of air bubbles, or both. The changes in opacity sometimes are gradual; some layers are very thin; some layers are incomplete. The number of layers ranges from 2 to 9, relating to the hailstone size, with 4 being the most common number (Mossop & Kidder [50] 1961, Browning et al [51] 1966).

Some layers still contain water which forms the so-called spongy ice. This can be detected from freshly fallen hailstones using a calorimetric technique (Gitlin et al [52] 1966).
(b) Lobe Structure

Sarrica [53] (1965) and Browning [51] (1963) both emphasised the existence of lobe structure within large hailstones. The growth variations, in spherical polar co-ordinates, have an angular dependence (Fig. 2.2). Sections of large hailstones exhibit approximately regularly spaced radial channels of transparent ice containing large air bubbles frequently elongated in the radial directions. The layers between the channels are not spherical, but strongly convex outward.

(5) Aerodynamic Characteristics

It is exciting to know that the meteorological scientists have studied the aerodynamic features of hailstones, e.g. drag coefficients. List (1959 [54] & [48] 1961) described the wind-tunnel tests with hailstones to assess the drag coefficients. Macklin [44] (1977) summarised the results of previous researchers and recommended the reasonable value for the drag coefficient of roughly spherical hailstones was 0.55. His interest was in the free fall behaviour of hailstones, so the wind speed is in a different order from that which may occur with hail ingestion in turbofan engines, hence this value cannot be simply adopted for the study of this thesis.

2.3.3. Technique for Making Artificial Hailstones

The techniques used for making artificial hailstones can be classified into two categories. One makes the hailstone on the tip of a thin stick; the other by suspending the particle in free air stream.

The use of the first technique to make artificial hailstones was reported by List [55] (1960), Mossop and Kidder [50] (1962), Kidder and Cart [56] (1964), Aufdermaur and Mayes [57] (1965), and Macklin [44] (1977). These experiments were carried out in icing tunnels. The starting embryo, which is a tiny ice particle is either stationary or fixed onto the
end of an arm. Air containing moisture is then blown across the embryo, and the embryo grows to the required size. The advantage of fixing the embryo on the end of an arm is that the arm can be made to rotate in an arbitrary way about three axes hence all sides of the embryo can be exposed to the air stream homogeneously.

The second technique was reported by Baily and Macklin [58] (1968). They used an icing tunnel that produced a vertical air stream and the embryo was suspended freely by the air stream. This technique was closer to the formation of natural hailstones.
CHAPTER 3 SIMULATED HAILSTONES AND HAIL GUN

The research was on a completely new subject and was mainly experimental, so designing and building the experimental facility became the first job. As natural hailstones were not readily available, equipment was required to make simulated hailstones. To study the impact characteristics, a gun was needed to accelerate the simulated hailstones to required speeds. Also facilities were required to measure the speed of each simulated hailstone fired, so that each shot could be monitored. This chapter will describe these facilities which were essential for the research. Among these facilities, the hail gun, and equipment for making simulated hailstones, and the laser-diodes for speed measurement already existed when the author joined the project. The author's main contribution was on interfacing the facility with a computer.

3.1 Manufacturing Simulated Hailstones

The characteristics of natural hailstone were discussed in the literature review. However, natural hailstones are not readily available, hence engine manufacturers are required by the airworthiness authorities to use simulated hailstones (section 1.5). In this thesis, the term ice ball will be used for simulated hailstones, while hail will only be used for naturally formed hail. An A.I.A. weather survey (Reference [1]) provided data on the distribution of hail size in atmosphere as shown Fig. 3.1. The vertical axis is Hail Water Content per Size Interval. This value was obtained by cutting the hail sizes into intervals, and then dividing the hail content included in each interval with the width of the interval. Hence to obtain the hail water content (expressed as grams of hail per cubic metre of air) between two sizes, one needs to integrate the curve between these two sizes. From this spectrum, the median volume diameter is 16 mm. Based on this figure, the ice particle sizes proposed by the regulatory bodies for engine ground testing are 12 - 19 mm. Accordingly, the study in this project used spherical ice particles of two sizes 12.7 mm and 19 mm. The average weight of a single ice ball is 0.91 gram for 12.7 mm, and 3.05 gram for 19 mm. The spherical shape gave good fit between the ice balls and the gun barrel (Section 3.2), hence produced relatively consistent ice ball speed.
Median Volume Diameter: 1.6 cm

Fig. 3.1 Hail size distribution in atmosphere
The ice balls used were made by moulding flaked ice from a commercial ice machine into a spherical shape. Three moulds were made for this purpose. The first mould was a pair of pliers with two hemispherical brass moulds welded on the top ends, as shown in Fig. 3.2. This mould can make one ice ball of 12.7 mm diameter at a time, which is a slow process when a large number ice balls are needed. A multiple ice ball mould was designed and manufactured, as shown in Fig. 3.3. After the lower part of the mould was filled with ice, the upper part was placed on the top, and then the two parts were put under a fly-press to be pressed together. The lower part of the mould was made of Tufnel instead of metal because metal melted the ice quickly. This technique had the capability of making 34 ice balls of 12.7 mm diameter in one go. The advantage of using a fly press was that constant pressure could be achieved, and the ice balls had a more consistent density. Similarly, a 19 mm ice ball mould was made that also used a fly press. As only a small number of 19 mm ice balls were required, the mould was designed to make one ice ball each time.

The ambient temperature when an aircraft encounters hail is normally around freezing. However, the temperature of hailstones could be anywhere between freezing and -40 °C. The hail temperatures used in this project were -14 °C and -40 °C which were chosen to cover the possible range. After being made with the moulds, the ice balls were then stored in a freezer for 24 hours before they were used. Two freezers were used to provide the two storage temperatures.

![Fig. 3.2 Pliers with hemi-spherical mould welded on the tops](image-url)
3.2 The Hail Guns

Two hail guns were built, one to fire 12.7 mm ice balls, and the other to fire 19 mm ice balls. The hail guns employed the compressed air line within the department via an air reservoir which worked as a buffer to maintain a constant air pressure for the gun. The air pressure ranged from 20 to 100 psi. Fig. 3.4 shows the layout of the hail gun. The gun was fitted on a frame so that the gun could be moved vertically and horizontally to give the shot position required. The gun could also be rotated to give a range of approach angles relative to the target.
Fig. 3.4 Layout of the hail gun

The firing mechanism was required to release pulses of air to accelerate the ice ball when the gun was ready for firing. A combination of pilot valve and solenoid valve was selected, as shown in Fig. 3.5. The pilot valve had a large port area, and hence could supply a large quantity of air when opened. The pilot valve was air-operated by the solenoid valve positioned on top of it. When activated the solenoid valve allowed the air pulse to power the pilot valve open, and hence produce a blast of air. The blast was then fed into the breech to accelerate the ice ball.

Fig. 3.6(a) shows a section of the breech and the barrel of the 12.7 mm hail gun, with the breech at loading position. The breech was made from Tufnel so that it did not cause the ice ball to melt quickly as would be the case if metal were used. The ice ball was loaded from the top and then the breech was turned through 90 degrees. A packing piece was place behind the ice ball to seal the barrel so that the air blast could accelerate the ice ball effectively; and also to protect the ice ball from being broken by the blast. The packing
piece was made of etherfoam, and had a wedge shape so it was deflected from its original path after leaving the barrel. When the pilot valve released a blast of air, the ice ball was blown out and accelerated in the barrel.

![Diagram of the arrangement of the valves]

Fig. 3.5 The arrangement of the valves

Fig. 3.6(b) shows the breech of the 19 mm hail gun. It was simply a hole on the barrel. After the ice ball was loaded, a sleeve was pulled back to seal the hole, and then a blast of air blew the ice ball away. Compared to the 12.7 mm hail gun, the second design was simple, but the disadvantage was that the ice ball was in contact with metal before being fired and could melt quickly. This required quick action from the operator so that the ice ball was fired before it melted. This did not cause too much of a problem since only a small number of tests were required with 19 mm ice balls.
In front of the gun barrel was a blast deflector - a round metal plate with a 20 mm diameter hole at the center to allow ice balls to pass through. The purpose of putting on this plate was to prevent the air blast following an ice ball from reaching the target and affecting ice distribution after the impact. The effectiveness of the blast deflector was shown with high speed cine photography. A piece of tracing paper was placed besides the target. Without the deflector, the paper moved as the ice ball hit the target; while with the
deflector, the paper moved well after the impact, which meant that air blast was not affecting the impact. Three laser-diodes were placed after the barrel to measure the speeds of the ice balls. Details about the laser speed measurement will be given in sections 3.3.

A turntable was built in front of the gun so that any target could be placed on it. The turntable could be rotated to provide an alternative means of varying the approach angle of the ice balls.

Due to the slight differences between each individual ice ball, the shot position showed a scatter. By firing 30 shots at a piece of cardboard placed at the normal target position, the penetration marks left on the cardboard scattered in an area of about 30 mm in diameter. This was taken as the normal accuracy of the gun.

3.3 Ice Ball Speed Measurement and Shot Quality Detection

The speed at which an ice ball traveled after being fired from the gun was an important parameter and needed to be monitored during tests. Also as an ice ball was blown out of the breech by a high pressure air blast, the ball may have broken before it reached the target. Therefore, a technique was needed to detect whether an ice ball broke. High-speed cine photography was obviously one possible technique. The movement of an ice ball could be filmed, and the ice ball speed could be calculated. The ice ball break-up could also be found on the film. However, two problems made this method impractical:
1) The high-speed cine films are rather expensive.
2) Processing the film takes a long time which means that results are only available some significant length of time after the test.

A cheap and accurate method was required. The adopted method was the laser-diodes system.

3.3.1 Basic Principle of the laser-diode speed measurement system

As shown in Fig. 3.4, three laser-diodes were placed in front of the gun barrel and the distances between them were fixed. Each laser-diode was focused on a photo-electric cell.
After an ice ball came out of the gun barrel it cut the three laser beams successively and each gave a pulse generated in the associated electronic circuit. If the time intervals between the pulses were measured, the velocity of the ice ball could be determined. With three laser beams, two-speed values were obtained which confirmed that the ice ball had reached a constant speed.

The laser system was also used to detect the breaking up of ice balls fired. The basic principle was based on the phenomenon that a perfect whole ice ball gave one pulse after cutting a laser beam, as shown in Fig. 3.7, while a broken ice ball gave multiple pulses, as shown in Fig. 3.8.

Fig. 3.7 Pulse of a perfect ice ball cutting a laser beam
(Oscilloscope trace, horizontal axis = time)

Fig. 3.8 Pulse of a broken ice ball cutting a laser beam
(Oscilloscope trace, horizontal axis = time)
3.3.2 The automatic data logging system for the speed measurement and shot quality detection

Originally, the laser signals were put into two electronic digital timers. When an ice ball cut the first laser, the first timer was started. When the ice ball cut the second laser, the first timer was stopped and the second laser was started. When the ice ball cut the third laser, the second timer was stopped. The disadvantage with the digital timers was that they could only show the time on the screen of the timers and the test operator had to record the time manually after each shot. It should also be noted that the test was dealing with ice and the ice balls kept melting in their container, so once a test had been started it needed to be finished as quickly as possible. Also frequent stopping during tests to record timing was a factor that could cause errors in operation, or even accidents. It would be ideal if the ice ball speed could be recorded automatically after each shot. This called for an interface between the laser system and a computer.

A computer interfacing card CTM05 (made by Metrabyte) was used. It had 5 counter-timers, 8 digital input lines, 8 digital output lines, and a 1 MHz on-board oscillator. As shown in Fig. 3.7 and Fig. 3.8, the direct output from a laser-diode has a spike and some high frequency oscillation. This signal has to be converted into a square shape - the form that a computer interfacing card can accept. An electronic circuit was required to do the conversion. Fig. 3.9 is the block diagram of the circuit, and the main working principle is explained as follows.

1) The photo-electric cell outputs were put through operational amplifiers which simply amplified the signals.

2) The signals were then fed into three comparators which converted the signals into square shapes with the widths unchanged.

3a) The comparator outputs were then fed into an OR gate, followed by a counter, which counted the total number of pulses obtained from the laser-diodes. If the number was three, it meant an unbroken ice ball. If the number was greater than three, it meant a
broken ice ball. If the number was smaller than three, it meant that the ice ball had not cut all the laser beams.

3b) The comparator outputs were also fed into three monostables in parallel which made the signals into definite widths of 400 μs with the rising edges unchanged.

4) The monostable outputs were put into two latches. When the first laser gave a ‘1’ (or ‘high’), the first latch rose to ‘1’ (or ‘high’); when the second laser gave a ‘1’, the first latch dropped to ‘0’ (or ‘low’) and the second latch rose to ‘1’. When the third laser gave a ‘1’, the second latch dropped to ‘0’. The length of the time that the first latch stayed on high can be measured with CTM05, and it is the time interval between the hailstone cutting the first and second lasers. Then similarly the time interval between the second and third lasers is recorded in the second latch.

The time relation between the different stages of output is shown in Fig. 3.10.

Programs were written in Quick Basic for two operational modes, single shot mode and multi-shot mode. In single shot mode, the system performs speed measurements and ice ball breaking detection, while in multi-shot mode it performs gun firing, speed measurements and ice ball breaking detection. The detailed instructions for using the two programs are given in Appendix II.
Fig. 3.9 Block diagram of the laser circuit
Fig. 3.10 Timing relation of the stages of output in the laser circuit (Horizontal axis = time)
CHAPTER 4 ICE BALL IMPACTS ON A STATIONARY FLAT PLATE

In order to obtain the basic ice ball impact characteristics defined in section 1.7, experiments were carried out by firing ice balls at a stationary flat steel plate. These experiments eliminated influences of target shape and motion, so that only effects of approach angle, impact velocity, and ice ball size were investigated. The size of the plate was 200 mm wide, 350 mm high, and 6 mm thick. It was fixed vertically on the turntable with a metal bracket.

As a completely new subject, no experimental technique was readily available for the work when the project started. Various techniques were tried and eventually three techniques were employed for the study of basic ice ball impact characteristics. They were photography with high speed cine camera or programmable image converter camera, patternator, and still photography. Each of the techniques had its advantages and disadvantages, but they complemented each other and provided clear views of different aspects of ice ball impact characteristics. These techniques are described in this chapter with the flat plate study, although they were also used with other targets which will be described in later chapters.

4.1 Flat Plate Study With High Speed Photography Using Cine Camera or Electronic Image Converter Camera

A 16 mm high speed cine camera was employed to film the ice ball impacts. The camera speed was 5,800 frames per second. Also a NAC programmable image converter camera was later used. The image converter was a high speed electronic imaging system which could reach a frame rate up to $4 \times 10^4$ frames per second. One of the main features of this image converter was that its speed could be controlled at each frame, or in other words, the timing of each frame was adjustable.
Fig. 4.1.1 illustrates the high speed camera arrangement for the flat plate tests. The camera was placed square to the plate. A mirror was placed on the top of the plate inclined at 45° angle. This mirror provided a view from the top of the plate, therefore each frame had two parts: one part was the picture viewing from above the plate; and the other part was from the front of the plate.

Fig. 4.1.1 High speed cine camera or NAC image converter set-up for flat plate tests

Fig. 4.1.2 is the film of an ice ball impact obtained with the high speed cine camera running at 5,800 frame per second. The impact angle was 45° and the impact velocity was 175 m/s. The “L” shaped mark in the photograph was a length reference showing 10 mm horizontally and 10 mm vertically. Films were also taken for other impact angles and velocities, and many common features were found in all these films.

It is hard to recognise the individual ice particle after the impact. What can be seen is a cloud of ice debris flying away from the impact point with some larger particles trailing behind. For the case of Fig. 4.1.2, the larger particles became visible about 0.7 ms after the impact. The
Fig. 4.1.2 High speed cine photograph of an ice ball impact
\(D_0=12.7 \text{ mm}, \ V_0=175 \text{ m/s}, \ \theta=45^\circ\)
reason that ice particles appeared to be a cloud was that the speed of the cine camera was not high enough and the particles smeared. This explanation was established by studying frame 1 to 4 in Fig. 4.1.2 in which the ice ball smeared. The post-impact ice particles also smeared if they travelled at speeds similar to or higher than that of the ice ball. Some large particles trailing behind were visible because their velocities were low.

Although most of the particles are not visible, two distinct characteristics were found from the films:

1. Ice debris did not bounce from the plate, or in other words, the debris lost its normal velocity and flew in a narrow band along the surface of the plate. This is shown in the profile view (mirror view) in which ice debris remains close to the plate.

2. On the surface of the plate, the debris left the impact point in a ‘fan’ shaped envelope. This ‘fan’ shape can be seen in the plan view of the picture.

Summing up these two features, the picture illustrated in Fig. 4.1.3 is established as the first impression of an ice ball impact, that is, ice debris comes off impact point in a ‘fan’ shaped envelope with low bounce angle.

![Diagram of ice ball impact](image)

Fig. 4.1.3 An illustration of ice debris leaving impact point in a ‘fan’ shaped envelope with low bounce angle

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Fig. 4.1.4 is the photograph obtained with the NAC high speed electronic image converter camera. The frame order and the time intervals between the frames are listed in the caption. It is still not possible to recognise ice particles after the impact. This is due to the low resolution of electronic image conversion. However, the feature of ‘low bounce’ can still be found in the mirror view (top part of each frame). The feature of ‘fan distribution’ is not clear because these pictures were earlier stages after the impact (within 0.575 ms) compared to the cine film in Fig. 4.1.2 (within 2.07 ms), and the ice debris has not spread far enough to show the ‘fan’ shape. The main advantage of this technique was its very high speed. Nine frames were obtained before the ice ball was fully disintegrated. The ice ball touches the plate in frame number 3 and ceases to be recognisable in frame 11. If ice ball crushing time is defined as the time required for an ice ball to fully disintegrate, then for this particular case, it was 200 µs. Ice ball crushing time is of special importance when setting up a mathematical model of ice ball disintegration because it provides information about how the ice ball loses normal velocity during the crushing. This crushing will be discussed in more detail in chapter 5.
Fig. 4.1.4 NAC photograph of an ice ball impact
(D=12.7 mm, V=175 m/s, 0.15s)

1-12, 25 μs BETWEEN FRAMES
13-15, 100 μs BETWEEN FRAMES
4.2 Flat Plate Study With Patternator

4.2.1 The Patternator Technique

A patternator was designed to determine the distribution of ice fragments and water following an impact. A number of different techniques for catching the ice and water were considered before the design of the patternator were finalised. The requirements for a successful patternator design include:

a) All of the ice and water entering a patternator element must be caught.

b) Any ice fragment entering a patternator element must not displace ice and water already caught by the patternator.

The patternator consisted of a back plate on to which elements were placed in any desired arrangements, as shown in Fig. 4.2.1(a). The elements and spacers were then clamped into position by top and side clamps. Each element was made from 25.5 mm square steel tube with a wall thickness of 0.8 mm. A paper insert was used to prevent ice rebounding out of the element, and also to prevent ice and water already caught being displaced by subsequent ice fragments. The paper insert was a coarse woven paper towel which absorbed ten times its own weight of water. After carrying out the desired experiment, each element plus insert was weighed. The difference between initial and final weights was the weight of the ice and water caught.

Prior to a test with the patternator, a preliminary test was normally carried out which involved placing a piece of cardboard across the expected path of the ice debris. The debris left marks of penetration and wetness which were used to find the extent of ice. This helped with making an effective arrangement of the patternator elements, so that they covered the area the ice debris flew to, without too many of them being redundant.

A Sartorious electronic balance PT210 was obtained for weighing the patternator elements. The PT210 gave a weighing capacity of 0 - 210 gm and readability of 0.01 gm. As a large amount of weighing work was required and the results were to be loaded into spreadsheets for
(a) Front view of the patternator

Fig. 2.6 Patternator Element Design

(b) A Patternator element

Fig. 4.2.1 The patternator design
analysis, the balance was interfaced with a computer. For such purposes, the balance was installed with a RS-232 kit and the interface was achieved with a Microsoft software package Labtech Notebook through a serial port on the computer. The detailed instructions for using the data logging system and loading the data into a spreadsheet are given in Appendix III.

4.2.2. Typical Result for Flat Plate Tests

The Pattermator arrangement for flat plate tests is illustrated in Fig. 4.2.2. As a standard reference test case, ice balls were fired at an incidence angle (θ) of 45 degrees relative to the plate, and an impact velocity of 175 m/s. Each run consisted of 30 shots. The pattermator was placed 175 mm away from the impact point. The distance between the pattermator and the impact point had an effect on the result and will be discussed in next section. Tests with this arrangement was repeated on a number of occasions to ensure that no unexplained or unexpected influences, which varied with time, were affecting the outputs of the experiments.

After some tests, it was found that the pattermator was collecting, on average, 85% of the ice fired. The rest could possibly be lost in the gun breech and barrel, or evaporated while weighing the elements. Some water was found on the turntable and back plate of the pattermator, but by soaking up the water with a paper towel and obtaining the weight, it was found that the weight of the water was only a small fraction among the total ice/water caught.

Although initially one and half rows of elements were arranged to collect ice, only the half row which was exposing a width of 12.5 mm collected ice. This meant that ice particles came off the impact point in a very low bounce, which confirmed the observation obtained with high speed cine photography and the NAC camera. In this particular case, the bounce angle was lower than 4.2 degrees.
Fig. 4.2.2 The patternator arrangement for flat plate test
Fig. 4.2.3 Mass distribution after an ice ball impacts on a flat plate

The patternator provided a quantitative description of the post-impact mass distribution, and the result for this specific case is shown in Fig. 4.2.3. The test was repeated twice to show repeatability. The vertical axis is the normalised ice caught, i.e., the ice and water caught by an individual element, divided by the total ice and water caught by the patternator. The horizontal axis represents the height of the centre of the patternator element above, or below, the impact point on the plate. For the purpose of plotting the results, all of the ice and water caught by an element has been plotted at the height, corresponding to the centre of the element.

One important feature of ice ball disintegration is that no two ice balls break up in exactly the same way. The disintegration of an ice ball may result in some large particles, and the directions these large particles travel in are random. Therefore the results of different runs always contain scatter although they are under normally identical test conditions. Experience from the experiments showed that the spread in the data for the central element could reach 9%. The data in the two elements adjacent to the central element often showed large scatter.
This was because the distribution curves sometimes did not show perfect symmetry. Normally, when the element on one side of the central element caught more ice, the corresponding element on the other side caught less. One possible explanation is the bias of the impact point. Among the thirty shots of a test run, if more impacts biased to one side, then the element on this side would catch more ice. Since the bias of the impact points is not controllable, the high value on the distribution curve could occur to either side about the central element, hence caused scatter.

A significant feature of the distribution in Fig. 4.2.3 is the ‘bell’ shape, which means that the highest concentration of ice was at the height of the impact, and the amount of ice decreased for positions further away from the impact height.

4.2.3 The Influence of Patternator Position on Results

An important factor that affected patternator results was its position relative to the plate.

![Fig. 4.2.4 The Influence Of Patternator Position on Results](image)

Fig. 4.2.4 The Influence Of Patternator Position on Results

\(D_0=12.7 \text{ mm, } V_0=175 \text{ m/s, } \theta=45^\circ\)

\(Z\): Distance between the patternator and the impact point
Fig. 4.2.4 shows the mass distribution when the patternator was put at different distances (i.e. different values of Z) from the impact point. A flatter curve means a more spread distribution. It is shown that the ice was more spread when the patternator was moved further away. This confirms the description of ice coming off the impact point in a ‘fan’ which has been illustrated in Fig. 4.1.3.

4.2.4 A Parametric Study

1. The Effect of Impact Angle

Fig. 4.2.5 compares the mass distribution of four impact angles 20°, 30°, 45°, and 60° relative to the plate. The ice ball size was 12.7 mm, and the ice ball velocity was $V_0 = 175$ m/s. It is shown that the impact angle had a significant effect on mass distribution. As the impact angle became shallower, the mass became more concentrated to the centre line, while a larger impact angle results in a wider spread. Intuitively, from considering the extreme approach angles of 90° and 0°, this trend appears to be correct. At 90°, the ice ball is

![Graph showing percentage of ice caught vs height from impact point for different impact angles](image-url)
approaching normal to the plate. Debris from the impact point would be expected to be evenly distributed in a circle about the impact point, and the distribution curve would become a horizontal line. At the other extreme of 0°, the ice ball would pass tangentially along the surface of the plate and straight into one patternator element, without breaking up, and the distribution curve would reduce to a vertical line.

2. The Effect of Impact Velocity

The impact velocity effect is shown in Fig. 4.2.6. Three impact velocities were tested, i.e. 175 m/s, 136 m/s, and 102 m/s, with 12.7 mm ice balls at 45° impact angle. With the central element, the data shows a scatter, but it is within the normal scatter. The patternator did not detect a significant effect of impact velocity.

Fig. 4.2.6 Effect of Impact Velocity (D₀=12.7 mm, θ=45°)
3. The Effect of Ice Ball Size

Fig. 4.2.7 compares the mass distribution of impacts of 19 mm ice balls and 12.7 mm ice balls. The impact angle was $45^\circ$ for both cases, and the impact velocity was 136 m/s. It can be seen that the ice ball size has little effect on post-impact mass distribution.

4. Effect of Ice Ball Temperature

Ice balls of different temperatures were obtained by using two freezers which provided two storage temperatures of -14°C and -40°C. Fig. 4.2.8 compares the mass distribution (12.7 mm ice balls, impact velocity = 175 m/s, impact angle = 45°). No apparent ice ball temperature effect was shown.
5. The Effect of Target Temperature

Tests were normally conducted with the target at room temperature (18°C to 20°C). As stated in Chapter 2, the ambient temperature when an engine encounters hail is normally around freezing. To study the effect of target temperature, a group of tests was carried out with cooled plate. The plate was left in a freezer until it was cooled down to -14°C. The plate was then installed on the turntable. During the installation, the plate was warmed up by the surrounding ambient conditions. To reduce the rate of increase in temperature, a pack of ice was attached to the non-impact surface of the plate, and the temperature of the plate was monitored with a thermocouple throughout the tests. Other test parameters were: ice ball size = 12.7 mm; impact angle = 45°; impact velocity = 175 m/s. As shown in Fig. 4.2.9, the result did not reveal a significant effect of the target temperature. It is admitted that the lowest temperature achieved was -2.3°C due to the difficulty of keeping the plate cold in open air. The conclusion drawn above is on basis of temperature above -2.3°C, which is the normal ambient temperature when an engine encounters hail.
Fig. 4.2.9 Effect of Target Temperature ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=45^\circ$)
4.3 Flat Plate Studies with Still Photography

4.3.1 Basic principles

The still photography technique employed a conventional Single Lens Reflex (SLR) camera and one or two high speed (short duration) flash guns. The arrangement is sketched in Fig. 4.3.1. The flash guns could generate 1 μs duration flashes. These very short flashes froze the movement of the particles being illuminated. The test was conducted in darkness with the camera shutter left open initially, and shut after the flash gun(s) were triggered. If one flash gun was used, each ice particle left one image on the photograph, hence particle sizes were measured and mass distribution obtained. If two flash units were used with a known time interval between them, each particle left two images on the photograph, hence the velocity of the particles was measured.

![Diagram of SLR camera and flash units](image)

Fig. 4.3.1 Arrangement of SLR camera and flash units
The triggering of the flash guns were achieved using one of the laser beams in front of the gun barrel. After the hail gun was fired, the ice ball cut the laser beam and the corresponding photo-electric cell sent a triggering pulse to the flash gun(s). The flash guns had their built-in timing circuits which allowed a time delay to be set to each flash gun from the triggering pulse. In case of using one flash, the flash gun was set to fire shortly after the ice ball hit the target. The criteria for setting this delay was that the particles should be well spread, but still within the view of the camera. In case of using two flash guns, the first flash was set as in single flash tests, but the second flash was set a short time interval later. The criteria for setting this time interval is that the two images of each particle are at a recognisable distance.

4.3.2. Typical Result from Still Photography Technique

Fig. 4.3.2 is the photograph obtained using a single flash, and Fig. 4.3.3 is the photograph using double flashes ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=45^\circ$). In these two photographs, the ‘L’ shaped marks on the plate are length references showing 10 mm vertically and 10 mm horizontally. The photographs were taken approximately 1.8 milli-sec after the impact. In Fig. 4.3.3, the time delay between the two flashes were 39.7 $\mu$s. Analysis of the two photographs gave post-impact particle size, post-impact particle velocity, and post-impact mass distribution.

(1) Post-impact Particle Size

Effort was made towards setting up an automatic system to measure the particle sizes from Fig. 4.3.2, but this failed because the picture contained a wide variation of grey level, and also some particles overlapped on each other. When image processing systems were used to analyse the photographs, some particles were wiped out or reduced in size because their images contained grey level which fell below the cut-off threshold of the image processor. Where the particles overlapped, they were joined together by the image processor to form one particle. No automatic image processing facility was found to give acceptable interpretation of the photographs. Therefore the analysis of the photographs was done by manual measurement. The image was first projected onto a screen with a grid. Fig. 4.3.4 is a sketch of the grid. The
Fig. 4.3.2 Photograph using one flash - (D₀=12.7 mm, V₀=175 m/s, θ=45°)
Ice particle travelling from left to right

Fig. 4.3.3 Photograph using two flashes - (D₀=12.7 mm, V₀=175 m/s, θ=45°)
Ice particle travelling from left to right
Fig. 4.3.4 The grid for analysing the photographs

size measurement was done using a template with various sizes of holes ranging from 1 mm to 14 mm, in steps of 0.5 mm. For each particle, one needed to find a hole on the template that gave the best ‘fit’. The purpose of the grid was to cut the interrogation area into small segments so that the measurement could be carried out systematically. As the projected image
was at least twice the full size, particles were sized to a resolution higher than 0.25 mm. It can be easily seen that this work was highly labour intensive.

Particle sizes were analysed against mass fraction, as shown in Fig. 4.3.5(a). To ensure repeatability, three runs were carried out under identical conditions and the results were plotted together for comparison. Mass Fraction for a certain size was defined as the ratio of the mass of the particles whose sizes were equal to or less than this certain size divided by the total mass seen in the photograph. The commonly used Rosin-Rammler [59](1933) distribution was found to give a good fit to the experimental data, and is shown as a line in Fig. 4.3.5(a). The expression of the Rosin-Rammler distribution is

\[ \mu_d = 1 - \exp \left( - \left( \frac{d}{d_{\text{mean}}} \right)^{N_d} \right) \]  (4.3.1)

in which, \( d \) is the particle size; \( d_{\text{mean}} \) is the mean particle size which is defined as the size covering 63% of the ice particles; \( N_d \) is Rosin-Rammler coefficient which can be varied to produce a suitable curve through the experimental data; and \( \mu_d \) is the mass fraction. A disadvantage of Rosin-Rammler distribution is that there is no upper limit on the horizontal axis. In other words, by solely looking at Rosin-Rammler distribution, the particle size could be infinite, which does not make physical sense. For this reason, the maximum value of the horizontal axis always need to be stated alongside the other two parameters when using Rosin-Rammler distributions. The Rosin-Rammler parameters for the three cases in Fig. 4.3.5(a) are listed in table 4.3.1, and the Rosin-Rammler curve in the same figure uses the average value of the three cases. The results show good repeatability.
(a) Post-impact particle size distribution

(b) Post-impact mass distribution

(c) Post-impact particle velocity distribution

Fig. 4.3.5 Ice ball impact characteristics - \((D_0=12.7 \text{ mm}, V_0=175 \text{ m/s}, \theta=45^\circ)\)
Table 4.3.1 Rosin-Rammler parameters for size distribution ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=45^\circ$)

<table>
<thead>
<tr>
<th></th>
<th>$d_{\text{max}}$</th>
<th>$d_{\text{mean}}$</th>
<th>$N_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st Run</td>
<td>3.46</td>
<td>2.25</td>
<td>2.3</td>
</tr>
<tr>
<td>2nd Run</td>
<td>4.23</td>
<td>2.35</td>
<td>2.2</td>
</tr>
<tr>
<td>3rd Run</td>
<td>3.85</td>
<td>2.55</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Some assumptions used during the measurements and data reduction need to be discussed.

(i) Ice balls were weighed before firing. There were losses of mass in the gun barrel and whilst the ice ball was moving through the air towards the target. From the patternator results, 85% of the ice was caught on average in the patternator after ice ball impacts. Therefore, it was assumed that the ice seen in the photograph shown in Fig. 4.3.2 was 85% of the mass of ice fired.

(ii) In Fig. 4.3.2, only the two-dimensional view can be seen. No measurement could be made for the third dimension which was the depth of the particles, so the mass calculation had to be done on the basis of some assumptions about the third dimension. It was reasonable to assume that after the impact, the ice particles were flakes rather than spheres, and that most of the flakes were flying in a flat manner along the surface of the plate. Furthermore, it was assumed that for every particle, there was a constant ratio between its depth ($\delta$), i.e. the third dimension, and its diameter ($d$). This assumption can be expressed as

$$k_\delta = \frac{\delta}{d} = \text{Constant} \quad (4.3.2)$$

$k_\delta$ could be obtained from mass conservation: As stated above, the ice seen on the photograph was 85% of the ice fired, hence
\[
\frac{1}{6} \pi d^3 \cdot 0.85 = \sum_{i=4}^{1} \pi d^2 k_i \cdot d \quad (4.3.3)
\]

From this equation, the average value of \( k_i \) obtained was 0.65.

(2) Post-impact Mass Distribution

Experiments with the patternator showed that after an impact, ice particles flew off the impact point with a very low bounce angle. In other words, ice particles lost their normal velocities and travelled in a narrow band along the surface of the plate. This reduced the mass distribution problem to a two dimensional problem in the plane of the plate's surface. A radial co-ordinate system \((r, \phi)\) was set up which is illustrated in Fig. 4.3.4. Referring to the grid in Fig. 4.3.4, the mass of particles in each segment could be readily obtained, since the sizes of all the particles had been previously determined. The mass of the ice particles in each segment could then be calculated. If the mass in each of the segments along the same angular position is added up, then the result is the total amount of ice travelling in that direction, and the mass distribution against spread angle can be obtained. The result is presented in normalised form in Fig. 4.3.5(b). The horizontal axis is the spread angle \( \phi \), and the vertical axis is the amount of ice per degree, expressed as a percentage of the total ice in the photograph. Therefore, the amount of ice between any two angles is the area under the curve between the two angles. The three lines on Fig. 4.3.5(b) are results from three different shots of identical conditions. There are similarities between the three lines, and also considerable differences. All the curves show a 'bell' shape, which means that more ice went to the middle than to the sides. However, none of the curves are smooth, as they all have dips and spike on them. From the process of data reduction, it was found that the spikes occurred where there was one or more big chunks of ice in that direction and they tend to dominate the mass distribution. The positions of these large chunks of ice were random. It may be recalled that the mass distribution obtained with the patternator did not show these spikes(Fig. 4.2.3). This was because the patternator result was an average of 30 shots. The spikes occurred at various position randomly, and were smoothed out. If 30 shots were done with still photography, and the individual mass distribution obtained and then averaged, one would expect to get a smooth curve.
Unfortunately this was not a practical option, because the measurement of the photographs is highly labour intensive. Nevertheless, an average can be made out of the three curves in Fig. 4.3.5(b) and then compared to the patternator result of Fig. 4.2.3. This comparison is illustrated in Fig. 4.3.6. The patternator result was converted to the format of Fig. 4.3.5(b) for this comparison. It can be seen that results from the two techniques show reasonable agreements, and the differences were attributed to the small number of photographs used.

![Graph showing comparison of mass distribution from patternator and from still photography](image)

Fig. 4.3.6 Comparison of mass distribution from patternator and from still photography - \((D_0=12.7 \text{ mm}, V_0=175 \text{ m/s}, \theta=45^\circ)\)

(3) Post-impact Particle Velocity

The post-impact velocity was obtained from the double image photograph shown in Fig. 4.3.3. It was easy to identify the two images of a particle by eye. Again no automatic system was found to measure the distance between the pairs of particles. This time the problem was not only with interpreting the images on the photograph accurately, but also with asking the
automatic system to pair the particles. The analysis of the photograph was done by manual measurement with a pair of callipers. Again the image was projected onto the grid shown in Fig. 4.3.4, and the callipers were used to measure the distances between the pairs of images in each segment. The accuracy of this measurement, on average, was estimated at 5%. A typical result is plotted in Fig. 4.3.5(c). As with the size distribution, the mass fraction with respect to a certain velocity is the mass of ice that is travelling at or below the velocity divided by mass of the ice seen on the photograph. Again the commonly used Rosin-Rammler [59](1933) expression is used here.

\[ \mu_v = 1 - EXP \left[ -\left( \frac{v}{v_{mean}} \right)^N_v \right] \]  

(4.3.4)

In equation 4.3.4, \( \mu_v \) is the mass fraction; \( v \) denotes particle velocity; \( v_{mean} \) is the mean particle velocity which is defined as the velocity that is corresponding to 63% of mass fraction; \( N_v \) is Rosin-Rammler coefficient which can be adjusted to produce a curve that fits the data. Table 4.3.2 is the summary of the Rosin-Rammler parameters. As with size distribution, the maximum velocity is also listed. The line representing Rosin-Rammler distribution in Fig. 4.3.5(c) uses the average value of the three Rosin-Rammler parameters listed in table 4.3.2.

Table 4.3.2 Rosin-Rammler parameters for velocity distribution (D0=12.7 mm, V0=175 m/s, \( \theta=45^\circ \))

<table>
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<th>Run</th>
<th>( v_{max} )</th>
<th>( v_{mean} )</th>
<th>( N_v )</th>
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</thead>
<tbody>
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<tr>
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</tr>
<tr>
<td>3rd Run</td>
<td>158.5</td>
<td>108</td>
<td>3</td>
</tr>
</tbody>
</table>

4.3.3 A Parametric study

The parameters studied included impact angle, impact speed, and ice ball size. A matrix of tests listed in table 4.3.3 were carried out and the results are shown in Fig. 4.3.5 and Fig. 4.3.7.
to 4.3.12. For the post-impact particle size and velocity, the Rosin-Rammler coefficients are listed in table 4.3.4 to 4.3.6. The Rosin-Rammler distribution curves in Fig. 4.3.7 to 4.3.12 use the mean value of the Rosin-Rammler parameters of the three runs in each figure.

Table 4.3.3 Test cases and run numbers for the parametric study

<table>
<thead>
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<th>D0=12.7mm</th>
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<td>/</td>
<td>/</td>
<td>3 runs</td>
<td>/</td>
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<td>/</td>
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<tr>
<td>$V_0=175$ (m/s)</td>
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</table>
Fig. 4.3.7 Ice ball impact characteristics - (D₀=12.7 mm, V₀=175 m/s, θ=20°)
Fig. 4.3.8 Ice ball impact characteristics - (D₀=12.7 mm, V₀=175 m/s, θ=30°)
Fig. 4.3.9 Ice ball impact characteristics - \((D_0=12.7 \text{ mm}, \ V_0=175 \text{ m/s}, \ \theta=60^\circ)\)
Fig. 4.3.10 Ice ball impact characteristics - (D₀=12.7 mm, V₀=102 m/s, θ=45°)
Fig. 4.3.11 Ice ball impact characteristics - \((D_0=12.7 \text{ mm}, V_0=136 \text{ m/s}, \theta=45^\circ)\)
Fig. 4.3.12 Ice ball impact characteristics - (D₀=19 mm, V₀=136 m/s, θ=45°)
Table 4.3.4 Effect of impact angle on Rosin-Rammler Coefficients

\((D_0=12.7 \text{ mm}, V_0=175 \text{ m/s})\)

<table>
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</tr>
<tr>
<td>Run 2</td>
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<td>187.8</td>
<td>111.4</td>
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<td>162.67</td>
<td>111.5</td>
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<td>6</td>
<td>3</td>
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80
Table 4.3.5 Effect of impact velocity on Rosin-Rammler Coefficients
(D₀=12.7 mm, θ=45°)

<table>
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<tbody>
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<td>$N_v$</td>
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<td>2.7</td>
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Table 4.3.6 Effect of ice ball size on Rosin-Rammler Coefficients
($\theta=45^\circ$, $V_0=175$ m/s)

<table>
<thead>
<tr>
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<th>$D_0=12.7$ mm</th>
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<td>2.2</td>
</tr>
<tr>
<td>Run 2</td>
<td>2.3</td>
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<td>2</td>
<td>2.2</td>
</tr>
<tr>
<td>$V_{max}$ (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>93.14</td>
<td>108</td>
</tr>
<tr>
<td>Run 2</td>
<td>91.66</td>
<td>113.7</td>
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<td>97.89</td>
<td>96.46</td>
</tr>
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<td>$V_{mean}$ (m/s)</td>
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</tr>
<tr>
<td>Run 1</td>
<td>59</td>
<td>71</td>
</tr>
<tr>
<td>Run 2</td>
<td>61</td>
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<td>62.5</td>
<td>66</td>
</tr>
<tr>
<td>$N_v$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Run 1</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Run 2</td>
<td>2.8</td>
<td>2.8</td>
</tr>
<tr>
<td>Run 3</td>
<td>2.6</td>
<td>2.7</td>
</tr>
</tbody>
</table>
Fig. 4.3.13 Effect of impact angle, impact velocity, and ice ball size on mass distribution
Effect of Impact Angle

Ice ball impact angle has a significant effect on the impact characteristics of an ice ball. This has been illustrated by the patternator tests (Fig. 4.2.5). The still photography revealed more effects that the impact angle had on the impact characteristics. The results of 45° was plotted in Fig. 4.3.5; and the results of 20°, 30°, and 60° are plotted in Fig. 4.3.7, 4.3.8, 4.3.9, with the Rosin-Rammler parameters listed in the captions. For the ease of comparison, these coefficients are listed in Table 4.3.4 to show the effect of impact angle. This effect can be summarised in the following aspects.

(i) The effect of impact angle on particle sizes

A higher impact angle results in smaller mean particle size, and smaller maximum particle size, although the maximum particle size shows larger scatter. The qualitative explanation is that the ice ball is crushed by the kinetic energy associated with the normal component of the impact speed, so the post-impact particles size is expected to be a function of the normal component. Higher impact angle causes higher normal impact velocity, and hence produces finer particles.

(ii) The effect of impact angle on mass distribution

The mass distributions for different impact angles are shown in Fig. 4.3.5(b), 4.3.7(b), 4.3.8(b), 4.3.9(b). For ease of comparison, the results from the three runs of each case were averaged and plotted in one co-ordinate, as shown Fig. 4.3.13 (a). A higher impact angle causes a wider spread, This agree with the conclusions drawn from the patternator results, and the same explanation stated in section 4.2.4 can still be applied.

(iii) The effect of impact angle on post-impact velocity

A higher impact angle results in a smaller $v_{\text{mean}}$ and $v_{\text{max}}$ (Table 4.3.4). If the ice ball impact speed is split into a tangential and a normal components, It can be reasoned that they both
affect the velocities of the resulting particles. It is reasonable to accept that part of the
tangential momentum of the ice ball will be passed to the particles. It also appears to be
reasonable that the normal component has an effect if one considers that after a normal impact,
the resulting particles also gain speeds. Intuitively the normal and tangential components
contribute to the particle speeds by two different mechanisms, i.e., the tangential component is
more or less inherited; and the normal component needs to transfer its energy through the
crushing process. The fact that particle velocity decreased as impact angle increased meant
that the tangential component of the impact speed had the major effect.

2 Effect of Impact Velocity

The effect of impact velocity is shown in Fig. 4.3.10, 4.3.11, and 4.3.5. For the ease of
comparison, the corresponding Rosin-Rammler coefficients are listed in Table 4.3.5.

(i) Impact velocity effect on post-impact particle sizes

A greater impact velocity results in smaller \( d_{\text{mean}} \), and \( d_{\text{max}} \). This is easily understandable
because the particle sizes depend on the kinetic energy at impact which is in square relation to
the normal component of the impact velocity. Higher impact velocity means higher impact
energy, hence certainly results in finer particles.

(ii) Impact velocity effect on post-impact mass distribution

Fig. 4.3.13(b) compares the mean mass distribution for three impact velocities. As explained
previously in section 4.3.2, the mass distribution shows high degree of randomness. By
comparing the three curves, it can be said that they basically conform each other. The impact
velocity has little effect on post-impact mass distribution. This agrees the conclusion drawn
from patternator results.

(iii) Impact velocity effect on post-impact particle velocity
As expected, higher impact velocity caused greater particle velocity. There was more energy with the ice ball initially, which resulted in a increased level of kinetic energy being transferred the particles.

3 Ice Ball Size Effect

Two ice ball sizes were studied 12.7 mm and 19 mm, at impact velocity of 136 m/s and impact angle of 45°. The impact velocity was restricted by the available pressure of compressed air. The 19 mm ice balls had a larger mass, hence the available air pressure can only accelerate them to 136 m/s. The results are plotted in Fig. 4.3.11 and Fig. 4.3.12, and the Rosin-Rammler coefficients are compared in Table 4.3.6.

(i) Ice ball size effect on post-impact particle size

A larger ice ball results in larger particle size. In comparing the particle sizes from different initial ice balls, the relative size $d/D_0$ should be used. It will be seen in section 4.4 that the relative particle size $d/D_0$ do not show apparent dependence on $D_0$.

(ii) Ice ball size effect on post-impact mass distribution

The Ice size effect on mass distribution is shown in Fig. 4.3.13(c), which compares the mean mass distribution of three test runs for each ice ball size. Ice ball size is shown to have little effect on mass distribution. This agrees the conclusion from patternator (Section 4.2.4).

(iii) Ice ball size effect on post-impact particle velocity

In table 4.3.6, the $V_{max}$ and $V_{mean}$ for 19 mm ice ball are generally higher than those for 12.7 mm ice ball. The explanation is not yet known.
4.4 A Set of Empirical Rules for Ice Ball Disintegration following Impact

The values of $d_{\text{max}}$, $d_{\text{mean}}$ and $N_d$ have been shown to depend upon the impact velocity and angle. Therefore when defining any impact rules, the squared normal velocity $(V_0 \sin \theta)^2$ was assumed to be a primary variable. As a first approximation, this seems reasonable, since particle size would be expected to be a function of normal impact energy. $N_d$ did not appear to be related to $(V_0 \sin \theta)^2$, and was therefore assumed to be simply a function of $(V_0 \sin \theta)$. A set of empirical rules were obtained by curve-fitting the experimental data using the rule of least squares, and the resulting curves are shown in Fig. 4.4.1, Fig. 4.4.2, and Fig. 4.4.3. The corresponding expressions for these curves are

\[
\frac{d_{\text{max}}}{D_0} = 0.437 - 0.922 \left( \frac{V_0 \sin \theta}{a_L} \right)^2 \]  
\tag{4.4.1}

\[
\frac{d_{\text{mean}}}{D_0} = 0.3 \left( \frac{V_0 \sin \theta}{a_L} \right)^2 \]  
\tag{4.4.2}

\[
N_d = 3512 - 4 \left( \frac{V_0 \sin \theta}{a_L} \right) \]  
\tag{4.4.3}

The above equations are simple regression from experimental results, and should only be applied to the range of $\frac{V_0 \sin \theta}{a_L}$ covered by the experimental data. The quantity $a_L$ is the speed of sound in the laboratory. It was used simply for the purpose of non-dimensionalisation and curve fitting. It should be treated as a constant given by $a_L=340\text{m/s}$.
Fig. 4.4.1 Curve Fit for $d_{\text{max}}$

Fig. 4.4.2 Curve Fit for $d_{\text{mean}}$
As with particle size, $v_{\text{max}}$, $v_{\text{mean}}$ and $N_v$ were shown to vary with approach velocity and approach angle. In establishing the expression of the empirical rules, the post-impact particle velocities and $N_v$ were assumed to be related to both the tangential component of the impact velocity ($V_0 \cos \theta$) and the normal impact energy ($V_0 \sin \theta$)$^2$. As $\sin^2 \theta$ can be easily replaced by $1 - \cos^2 \theta$, the expression contains only ($V_0 \cos \theta$) and ($V_0 \cos \theta$)$^2$. This idea worked well with $v_{\text{max}}$ and $N_v$, but a linear expression containing only ($V_0 \cos \theta$) gave a better interpretation for the experimental data of $v_{\text{mean}}$, and the explanation has yet to be found. For the matrix of test cases carried out (Table 4.3.3), curve-fits using least square rules were obtained (Fig. 4.4.4, 4.4.5, and 4.4.6). The expressions describing these curves are

$$\frac{v_{\text{max}}}{V_0} = -1 + 8.4 \left( \frac{V_0 \cos \theta}{a_L} \right) - 8.4 \left( \frac{V_0 \cos \theta}{a_L} \right)^2 \quad (4.4.4)$$
\[ \frac{V_{\text{mean}}}{V_0} = -0.17 + 2.2 \left( \frac{V_0 \cos \theta}{a_L} \right) \]  
(4.4.5)

\[ N_* = 8 - 5 \left( \frac{V_0 \cos \theta}{a_L} \right) + 105 \left( \frac{V_0 \cos \theta}{a_L} \right)^2 \]  
(4.4.6)

Like with particle size distribution, Eq. (4.4.4), (4.4.5), (4.4.6) are only valid for the range of experimental data, and \( a_L \) should be treated as a constant (\( a_L = 340 \) m/s).

In section 4.3, it was found that the ice ball size had an effect on post-impact particle velocity. However, fig. 4.4.4 to Fig. 4.4.6 shows that applying the same empirical rule for 12.7 and 19 mm ice ball gives reasonably good result.
Fig. 4.4.5 Curve Fit for $v_{mean}$

Fig. 4.4.6 Curve Fit for $N_v$
4.5 Comparison of the Three Experimental Techniques

Each of the three techniques described in the previous sections has its advantages and disadvantages, but they complement each other and give various views of the ice ball impact phenomenon.

1. High Speed Photography with Cine Camera or Electronic Image Converter

The two techniques give a whole series of images before and after an impact. The photograph from the image converter camera is the most suitable for the investigation of ice crushing time. The disadvantage of both techniques is that they do not give information about the details within the cloud of ice particles, and hence cannot give information about post-impact particle size or velocity. For high speed cine this is due to the restricted frame rate, and for programmable image converter camera, due to the low resolution of electronic image conversion.

2. Patternator

The patternator technique is a reliable way of obtaining mass distribution, and it is cheap and easy to run, so a large number of tests can be done to give high level of confidence. The disadvantage of the patternator is that it gives no information about post-impact particle sizes and velocities.

3. Still Photography

The still photography technique is an effective way of studying ice ball impact characteristics in terms of post-impact particle size, velocity, and mass distribution. The results showed good repeatability. The disadvantage of the still photography is that it can only give one photograph of a given impact. Therefore changes in mass distribution and particle velocity about time after an impact cannot be readily determined. Also it is not possible to obtain particle velocities when the particles are very fine, e.g. after secondary impacts.
CHAPTER 5. A MATHEMATICAL MODEL OF ICE BALL DISINTEGRATION FOLLOWING IMPACTS

5.1 Introduction

A mathematical model is required to model the process of ice ball disintegration. It is expected that by inputting the initial conditions such as ice ball size, impact velocity, and impact angle, the model will output the characteristics of each fragment, i.e. the size, velocity, and direction of travel. This model can then be implanted into a CFD model of engine ice ingestion as a subroutine to deal with the impacts of ice balls. Every time an ice ball hits a solid surface, this subroutine will be called and then each fragment yielded will re-enter the CFD flow field with its initial size, velocity, and orientation provided by this mathematical model.

It ought to be borne in mind that this model will only be a small part of the whole CFD model. The CFD model needs to deal with thousands of ice balls, and each ice ball, upon impact, will break into a considerable number of fragments. Tracking each particle is time consuming. This raises the requirement that this model should not take too much computing time. A disintegration model that introduces large increases in requirement for computing power will not be practical. In other words, this disintegration model needs to be straightforward.

The attempt at making the ice ball disintegration model was only made after a fair amount of experimental data had been obtained against which the model could be validated.

The process of an ice ball disintegration is very complicated and contains a pretty high degree of randomness. The model to be described below is, to a large extent, based on a number of assumptions, some of which are intuitive. The author will try to give as much supporting material as possible for these assumptions.
shows good agreement with experimental results, while others only show good agreement when assigned with some coefficients, and these coefficients will be discussed.

Fig. 5.1 Definition Sketch

5.2 Analysis of the Physical Process of An Ice Ball Disintegration and the Assumptions Made In the Model

Referring to Fig. 5.1, consider an ice ball impacting on a solid surface with a velocity $V_0$ at an angle $\theta$. The velocity $V_0$ can be replaced with a normal component $V_n$ and a tangential component $V_t$. The normal component $V_n$ is assumed to be the main contribution towards breaking the ice ball. This idea has been applied in setting up the empirical rules (section 4.4). Hence the following assumption is made:

Assumption 1: Only the normal component of the approaching velocity $V_n$ forms the energy that breaks the ice ball, while the tangential velocity $V_t$ will be inherited by the fragments with a certain deduction factor $K$, which accounts for the energy loss due to the interaction between the ice particles.
Based on this assumption, the disintegration will only be analysed with $V_n$, and the factored tangential velocity $K_\text{*}V_t$ will be superimposed onto each particle formed from the disintegration. The value of $K_\text{*}$ will be discussed in assumption 5.

After the ice ball touches the solid surface, the resulting fragments will be extruded sideways. When the ice ball first touches the surface, the impact energy is high and the fragments yielded are small. As the ice ball presses itself down, it decelerates and the crushing energy becomes lower, so the fragment size becomes larger. This idea forms the second assumption.

**Assumption 2:** The size of a fragment is proportional to its vertical position in the original ice ball.

In other words, the finest particles will be released first from the bottom of the ice ball, and the largest particles will be released last from the top of the ice ball. Based on this assumption, the ice ball can be sliced horizontally into layers of various thickness and the thickness are equal to the particle size which are proportional to the vertical position in the ball. The input for the smallest particle size can be any small number, e.g. 0.001 mm. Hence once the maximum particle size is given, the sizes of all the particles can be determined. Instead of making a mathematical assumption about the maximum particle size, which would essentially be a guess, the maximum particle sizes from experiments are used. This makes the model a semi-empirical and semi-mathematical one.

**Assumption 3:** The maximum post-impact particle size is input on basis of the experimental results or empirical rules described in section 4.3.

Referring to Fig. 5.2, the expression for calculating the particle size at a given height $h$ is obtained as follows.

$$d(h) = D_{\min} + \frac{h}{D_0 - D_{\max}}(D_{\max} - D_{\min})$$ (5.1)
As stated above, the ice ball decelerates during the process of crushing. The crushing process is a very complicated energy transfer process. Part of the kinetic energy is consumed in breaking up the forces between the ice molecules and generating heat energy; part is kept in the un-crushed ice ball in form of kinetic energy; and the rest transferred into kinetic energy of particles. The way in which the ice ball decelerates during the crushing apparently depends on the distribution of these various parts of energy. Unfortunately no previous knowledge is available to quantify these different parts of energy. Given no information about the distribution of the various parts of energy, it may be better off to assume a simple relationship about the deceleration of the ice ball while crushing, and check the result with the experimental data that has already been obtained. The model has been made so that option is kept open for an alternative relationship to be used. At the present, the following assumption is made.

Assumption 4: During the crushing, the ice ball experiences a linear deceleration, and the normal impact speed drops from the initial value to zero.

This assumption can be mathematically expressed as
\[ V_n(t) = V_{n0} - at \quad (5.2) \]

\[ h = V_{n0} \cdot t - \frac{1}{2} at^2 \quad (5.3) \]

in which \( a \) is the rate of the deceleration; \( t \) is the time starting from the ice ball touching the plate; and \( V_{n0} \) is the initial normal impact velocity; and \( h \) is the crushed height in the ice ball at time \( t \). Now if \( t_{cr} \) is defined as crushing time, i.e., the time required for the full disintegration, then the following relations can be obtained

\[ 0 = V_{n0} - at_{cr} \quad (5.4) \]

\[ D_0 = V_{n0} \cdot t_{cr} - \frac{1}{2} at_{cr}^2 \quad (5.5) \]

in which \( D_0 \) is the ice ball diameter. Then \( t_{cr} \) and \( a \) can be derived

\[ t_{cr} = \frac{2D_0}{V_{n0}} \quad (5.6) \]

\[ a = \frac{V_{n0}}{t_{cr}} = \frac{V_{n0}^2}{2D_0} \quad (5.7) \]

If the expression for \( t_{cr} \) is applied to the case of \( D_0=12.7 \text{ mm}, V_0=175 \text{ m/s}, \text{ and } \theta=45^\circ \), the crushing time obtained is 205.3 \( \mu \text{s} \). The NAC photograph(Fig. 4.1.4) is the only result that can be used to show the crushing time. By counting the frames, it can be found that a crushing time was 200 \( \mu \text{s} \). The model is providing a close prediction. This provides some confidence in assumption 3.

During the process of disintegration, only part of the impact energy is converted into the kinetic energy of resulting particles. The following assumption gives a coefficient \( K_a^2 \) for the kinetic energy of the particle.
Assumption 5: For each particle resulting from a normal impact, if its kinetic energy before impact is \((M \cdot V^2/2)\), then the kinetic energy of this particle after impact is assumed to be \(K_n \cdot (M \cdot V^2/2)\).

\[ K_n \cdot (M \cdot V_n^2/2) = (M \cdot V_f^2/2) \]  \hspace{1cm} (5.8)

hence

\[ V_f = K_n \cdot V_n \]  \hspace{1cm} (5.9)

The value of \(K_n\) can be obtained with normal impact tests, in which ice balls are fired normal to a flat plate, hence \(K_n\) can be measured. By investigating the final particle velocities of other impact angles, and applying \(K_n\) to work out the contribution from \(V_n\), then the contribution of \(V_f\) can be found, and hence \(K_f\) can be derived. These tests have not been finished yet. At the current stage, this has been dealt with by choosing the values of \(K_n\) and \(K_f\) so that the results fit the experimental data, and then studying the relation between the impact condition and the two coefficients, \(K_n\) and \(K_f\).

Next, an assumption has to be made about the orientation of each particle after being extruded. If only the normal component of the impact velocity is considered, a particle has equal chance to fly towards any direction between \(-\pi\) to \(+\pi\). This forms the following assumption.

Assumption 6: With normal impact, the orientation of a single particle is random between \(-\pi\) and \(+\pi\).
This is treated in the model by generating a random number between \(-\pi\) and \(+\pi\).

### 5.3 The Results of the Mathematical Model

The programming of the mathematical model was done with FORTRAN language. An annotated listing of the program is given in Appendix IV. The mathematical model was run for the following cases in conjunction with the experiment cases that have been carried out. The coefficients \(K_a\) and \(K_t\) used for each case are also listed.

#### Table 5.1. Cases For Running the Mathematical Model and values of \(K_a\) and \(K_t\)

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<th>Ice Ball Size (D0: mm)</th>
<th>Impact velocity (V0: m/s)</th>
<th>Impact Angle ((\theta): (^\circ))</th>
<th>(K_t)</th>
<th>(K_a)</th>
</tr>
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<tr>
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<td>12.7</td>
<td>102</td>
<td>45</td>
<td>0.25</td>
</tr>
<tr>
<td>Case 2</td>
<td>12.7</td>
<td>136</td>
<td>45</td>
<td>0.5</td>
</tr>
<tr>
<td>Case 3</td>
<td>12.7</td>
<td>175</td>
<td>20</td>
<td>0.875</td>
</tr>
<tr>
<td>Case 4</td>
<td>12.7</td>
<td>175</td>
<td>30</td>
<td>0.775</td>
</tr>
<tr>
<td>Case 5</td>
<td>12.7</td>
<td>175</td>
<td>45</td>
<td>0.75</td>
</tr>
<tr>
<td>Case 6</td>
<td>12.7</td>
<td>175</td>
<td>60</td>
<td>0.6</td>
</tr>
<tr>
<td>Case 7</td>
<td>19.0</td>
<td>136</td>
<td>45</td>
<td>0.55</td>
</tr>
</tbody>
</table>

For each case, the result consists of three graphs, i.e. particle size distribution, mass distribution, and velocity distribution. The results are plotted in Fig. 5.3 to Fig. 5.9, with the corresponding experimental results overlapped for comparison.

The results of particle size constantly show good agreement with the experimental data. Only with one case illustrated in Fig. 5.8 (\(D_0=12.7\) mm, \(V_0=175\) m/s, \(\theta=60^\circ\)), there is an apparent discrepancy between the model and the experiment. It is also noticed that the...
experimental result of this case shows a different curve shape from other cases between particle sizes of 0.5 and 2 mm, and the explanation is not readily known.

Concerning mass and velocity distributions, it is found that by choosing an appropriate combination of values for $K_t$ and $K_n$, the model can provide results reasonably close to the test data. As stated previously, the rules according to which $K_t$ and $K_n$ should be calculated are not readily known yet. The values of $K_t$ and $K_n$ used for calculation of different cases are listed in table 1, and will be discussed in next section.
Fig. 5.3 Comparison Between Model and Experiment ($D_0=12.7\, \text{mm}, V_0=102\, \text{m/s}, \theta=45^\circ$)
Fig. 5.4 Comparison Between Model and Experiment (D₀=12.7 mm, V₀=136 m/s, θ=45°)

(a) Post-impact Particle Size Distribution

(b) Post-impact mass distribution

(c) Post-impact Particle Velocity Distribution
Fig. 5.5 Comparison Between Model and Experiment ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=20^\circ$)
Fig. 5.6 Comparison Between Model and Experiment ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=30^\circ$)
Fig. 5.7 Comparison Between Model and Experiment (\(D_0=12.7\) mm, \(V_0=175\) m/s, \(\theta=45^\circ\))
Fig. 5.8 Comparison Between Model and Experiment ($D_0=12.7$ mm, $V_0=175$ m/s, $\theta=60^\circ$)
Fig. 5.9 Comparison Between Model and Experiment ($D_0=19$ mm, $V_0=136$ m/s, $\theta=45^\circ$)
5.4 The Relation Between the Impact Conditions and $K_n$, $K_t$

By comparing the results of case 2 and case 7, it can be found that $K_t$ and $K_n$ for two ice ball sizes are very close. From the data with only two ice ball sizes, it is not possible to draw a firm conclusion that $D_0$ does not affect $K_t$ and $K_n$, but this possibility does exist.

Fig. 5.10 is a plot of $K_n$ against $\sin^2(\theta)$. $K_n$ is plotted against $\sin^2(\theta)$ because it is intended to be a coefficient associated with energy of the normal impact velocity. As $\theta$ changes from 60° to 20°, $K_n$ rises. The explanation is as follows. The normal component of the impact speed forms the energy for crushing the ice ball, hence when $\theta$ becomes lower, less energy is available for the crushing. A consequence is that particles become larger and their number becomes fewer, which has been proved by the experiments (Fig. 4.4.1, and 4.4.2). The fact that larger but fewer particles are generated means that less energy is consumed in generating new surfaces, and hence more energy remains as the kinetic energy of the ice particles, so $K_n$ becomes higher.

Fig. 5.11 is a plot of $K_t$ against $\cos(\theta)$. $K_t$ is plotted against $\cos(\theta)$ because it is intended to be a coefficient associated with the reduction of the tangential component of the impact velocity, which accounts for the tangential interactions between the particles. As $\theta$ changes from 60° to 20°, $K_t$ increases constantly. The explanation is as follows. As stated in assumption 5, the normal component of the impact velocity makes the particles fly in a random direction between -180° to +180° in the plane of the plate. It is the particles that fly against the tangential component of the initial impact speed that causes the interaction between the particles. As the impact angle becomes lower, the normal component becomes smaller, and hence the particle velocities induced by the normal component are also smaller. This includes the particles which travel against the initial tangential speed. The interaction between the particles are thus reduced, therefore $K_t$ becomes higher.
Fig. 5.12 and 5.13 plot $K_n$ and $K_t$ against the initial impact velocity $V_0$. As $V_0$ changes from 102 to 175 m/s, both $K_t$ and $K_n$ increase. According to Eq. 5.5, high impact velocity results in short crushing time, hence the energy consumed for crushing is also expected to be less. Thus more energy remains as kinetic energy of the particles.

It is admitted that the above analysis is intuitive, and may not be strictly correct. This is expected considering the complexity of the impact process of an ice ball, and the randomness involved. The model is providing satisfactory results for particle size and mass distribution. For the calculation of particle velocities, some further work is required in determining $K_n$ and $K_t$.

![Graph showing the relation between $K_n$ and $\sin^2(\theta)$](image)

Fig. 5.10 The relation between $K_n$ and $\theta$
Fig. 5.11 The relation between $K_1$ and $\theta$

Fig. 5.12 The relation between $K_0$ and $V_0$

Fig. 5.13 The relation between $K_t$ and $V_0$
5.5 The Randomness Of The Disintegration Process

In practice, no two ice balls break up exactly the same way. In this model, random numbers are used, and hence the result shows a certain degree of randomness. In other words, if the model is run a number of times with identical input conditions, the result would be different each time. It is interesting to investigate the range of this scatter.

Case 5 was run three times with identical input conditions. The particle size distribution was obtained before any random number was introduced, hence there is no variation for the particle size distribution. Fig. 5.14 illustrate the three mass distributions and Fig. 5.15 velocity distributions. The variation due to the randomness can be seen, but the results of different runs are reasonably close because the disintegration is controlled by the same underlying principle.

Fig. 5.14 The Effect of randomness in mass distribution
(D₀=12.7 mm, V₀=175 m/s, θ=45°)
Fig. 5.15 The Effect of randomness in velocity distribution
\((D_0=12.7 \, \text{mm}, V_0=175 \, \text{m/s}, \theta=45^\circ)\)
CHAPTER 6 SECONDARY IMPACTS

In a turbofan engine, ice debris resulting from an impact of a hailstone may impact on another solid surface and further disintegrate. These impacts are defined as secondary impacts. In the following discussion, the first impact of an ice ball is named a primary impact. Secondary impacts may occur frequently during a hail ingestion process, e.g. ice debris resulting from impacts on spinner hit fan blades; and debris resulting from impacts on fan blades hit the shroud. The nature of secondary impacts may have significant effect on the trajectories of ice particles, in particular, on the amount of ice entering the core engine.

![Diagram of the Arrangement of the Two Plates for Secondary Impact Test](image)

Fig. 6.1 The Arrangement of the Two Plates for Secondary Impact Test

The ways in which secondary impacts occur are diverse. There are a large number of combinations of the two impact angles, and the distances between the two surfaces. If different initial impact velocities and ice ball sizes are considered, the number of cases are again multiplied. As a first attempt, this thesis only studied a few of those cases. As illustrated in Fig. 6.1, the two plates were arranged adjacent to each other. The first impact angle $\theta_1$ was
fixed at 30 degs, while the second was varied between 15 to 45 degs. The initial ice ball velocity was 175 m/s, and the ice ball size was 12.7 mm.

Still photography was initially used to film the ice particles from secondary impacts, but was found to be unsuitable because the particles were very fine. Most of them were beyond the measurability with still photography (about 0.5 mm). When double flash technique was used, it was also difficult to recognise the pairs of particles. Therefore the secondary impacts were studied with the patternator and high speed cine photography.

6.1 Study into Secondary Impacts Using a Patternator

The patternator arrangement is shown in Fig. 6.2. Three rows of elements were arranged to collect the ice from the secondary impact. A matrix of tests as listed in Table 6.1 were carried out.

Fig. 6.2 Patternator Element Arrangement for Secondary Impact Tests
Table 6.1 Test Cases of Secondary Impacts

<table>
<thead>
<tr>
<th>Case</th>
<th>$\theta_1$ (°)</th>
<th>$\theta_2$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>30</td>
<td>15</td>
</tr>
<tr>
<td>Case 2</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Case 3</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>

Ice mass distribution was studied in two directions, i.e. spread distribution and bounce distribution. Spread distribution describes the distribution of ice along the surface of the second plate; and the bounce distribution describes the lifting off of ice from the second plate, i.e. the distribution normal to the second plate.

The results of spread distribution are shown in Fig. 6.3, 6.4, and 6.5, each figure containing part (a) and part (b) representing two runs under identical test conditions to ensure repeatability. Each run contained 30 shots. As for the primary impact, the mass distributions still showed a 'bell' shape. However, unlike with the primary impact, the second and third row of the patternator elements were collecting ice. This meant that ice particles were travelling with a higher bounce angle. As the second impact angle increased, the second and third row of elements collected more ice, meaning the bounce angle became higher. Table 6.2 illustrates how the amount of ice caught in each row varied with the second impact angle.
Fig. 6.3  Mass distribution after secondary impact - $\theta_1=30^\circ$, $\theta_2=15^\circ$
Fig. 6.4 Mass distribution after secondary impact - $\theta_1=30^\circ$, $\theta_2=30^\circ$
Fig. 6.5 Mass distribution after secondary impact - $\theta_1=30^\circ$, $\theta_2=45^\circ$
Table 6.2 The percentage of ice caught in each row

<table>
<thead>
<tr>
<th></th>
<th>1st Row</th>
<th>2nd Row</th>
<th>3rd Row</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_2=15^\circ$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Run</td>
<td>96%</td>
<td>3.9%</td>
<td>0.1%</td>
</tr>
<tr>
<td>2nd Run</td>
<td>95.5%</td>
<td>3%</td>
<td>1.5%</td>
</tr>
<tr>
<td>$\theta_2=30^\circ$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Run</td>
<td>83%</td>
<td>16.6%</td>
<td>0.4%</td>
</tr>
<tr>
<td>2nd Run</td>
<td>83%</td>
<td>17%</td>
<td>0</td>
</tr>
<tr>
<td>$\theta_2=45^\circ$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st Run</td>
<td>66.8%</td>
<td>27.7%</td>
<td>5.5%</td>
</tr>
<tr>
<td>2nd Run</td>
<td>71.7%</td>
<td>25.2%</td>
<td>3.1%</td>
</tr>
</tbody>
</table>

Knowing that the ice has a higher bounce angle, it is necessary to study the mass bounce distribution. From Fig. 6.2, it can be seen that each row of elements covered a certain bounce angle. Some simple geometrical calculation revealed that the first row covered 3.35°; the first and second row together covered 9.96°; and the three rows covered 16.31° altogether. If the percentage of ice caught in each row of elements was plotted against the bounce angle, then the mass bounce distribution could be shown. The problem was that with the three rows of elements, the data points of mass bounce distribution obtained was sparse. To obtain a finer mass bounce distribution, a mask technique was used. The mask technique simply applied a metal shield to cover up part of the patternator elements, and only the elements left uncovered collected ice (Fig. 6.6). The width $B$ was adjusted so that ice was only collected within the specified bounce angle. In practice, tests were carried out with the mask placed at two positions $B_1=22.8$ mm, $B_2=46.1$ mm; and the bounce angles were $6^\circ$ and $12^\circ$ respectively. The result is plotted in Fig. 6.7 which compares the amount of ice caught in various bounce angles. The vertical axis is the ice caught expressed as a percentage of the ice fired. For the $\theta_2=15$ deg curve, the percentages of ice caught were nearly constant for all angle values, i.e. a 16 deg angle was collecting no more ice than a 3.35 deg angle; while with
the $\theta_2=45$ deg line, there was an apparent increase in the amount of ice caught when the angle changed from 3.35 degs to 16.31 degs. As expected, $\theta_2=30$ deg curve lay between 15 and 45 deg curves. This shows that as $\theta_2$ increased, the ice became more spread normal to the plate. The explanation will be given in next section.

Fig. 6.6 Conceptual Sketch of The Mask (Viewed looking from second plate into patternator)
Fig. 6.7 Percentage of ice caught in different bounce angles
6.2 Studies into Secondary Impacts Using High Speed Cine Photography

A Hycam cine camera was run at 5,800 frames to film the process of the primary and secondary impacts. Fig. 6.8 illustrates the arrangement of the camera and the plates. To obtain a profile view, a mirror was placed on the top of the second plate at a 45° angle to the plate, hence the pictures contained two parts: one part illustrating the front view of the event, and the other part the profile view of the event. Table 6.3 lists the test cases conducted with high speed cine photography.

![Cine Camera and Mirror Arrangement](image)

Fig. 6.8 Cine Camera and Mirror Arrangement
Table 6.3  Test Cases of Secondary Impacts with High Speed Cine Photography

<table>
<thead>
<tr>
<th>Case</th>
<th>$\theta_1$ (°)</th>
<th>$\theta_2$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>Case 2</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Case 3</td>
<td>30</td>
<td>45</td>
</tr>
</tbody>
</table>

Fig. 6.9 is an example of the high speed cine film of the secondary impacts. As explained in Chapter 4, the relatively slow frame rate meant that the ice appeared as a cloud moving away from the impact point. As the ice cloud crossed the junction of the two plates, the higher bounce angle can be seen in the mirror view.

The cine results showed that the bounce angle for a secondary impact became higher as the second impact angle increased, a phenomenon which was detected with the patternator technique. From the mirror view of the cine film, one can see a humped shape of ice cloud after it crosses the junction of the two plates. By studying the series of pictures of the impact, it can be seen that this was because the ice particles decelerated suddenly at the second impact position and the following ice particles hit them from behind. Then the ice particles piled up, and hence travelled in a wider range normal to the plate. By comparing the films of different second impact angles, it was found that the bounce angle became higher as the second impact angle increased. This was because a steeper second impact angle caused a greater deceleration of the ice particles, and hence caused a more severe piling up of ice particles.
Fig. 6.9 An example of cine films of secondary impacts
(θ = 30°, φ = 45°, V = 175 m/s)
CHAPTER 7 EFFECTS OF TARGET CURVATURE ON ICE BALL IMPACT CHARACTERISTICS

In chapter 4, 5, and 6, basic ice ball impact characteristics were studied experimentally and mathematically on the basis of impacts on flat plates. However, most of the surfaces that hailstones encounter within an engine are curved surfaces, e.g. the fan blades. It is unknown to what extent the target curvature affects the basic impact characteristics.

7.1 The Curved Plates

Curved surfaces in an engine are normally of complex three dimensional shapes, and there could be a infinite number of shapes of surfaces. As a start to the study into this area, only two-dimensionally curved surfaces were studied. Two plates were made from 4 mm thick steel and Fig. 7.1 shows their cross sections. The curvature of the plates were quantified by the ratio \( e = \frac{H}{S} \), where \( S \) is the chord and \( H \) is the camber height. The two plates were chosen to represent the typical curvature on engine fan blades, \( e_1 = \frac{H}{S} = 0.08 \) (curve 1), and \( e_2 = \frac{H}{S} = 0.18 \) (curve 2). From simple geometrical calculations, it can be seen that the radii of the two curves were \( R_1 = 320.5 \) mm and \( R_2 = 156.9 \) mm. The height of the plates were 350 mm.

Within an engine, hailstones may hit a concave or a convex surface. Through a qualitative analysis, the author felt that the convex curvature should not have a significant effect on the
impact characteristics. In chapter 4, it was concluded that after an ice ball impacts on a flat plate, the resulting ice particles fly along the surface of the plate in a narrow band. After an ice ball impact on a convex surface, the ice particles will fly in the tangential direction of the surface at the impact point. The plate bends away from the path of the resulting ice particles, hence cannot have any effect on the particles. Therefore it is reasonable to apply the disintegration rules obtained from ice ball impacts on a flat surface to a convex surface. However, in the case of ice ball impacts on concave surfaces, the situation becomes more complicated because the plate bends into the path of the resulting ice particles. Hence there is interaction between the plate and the particles after the initial impact. It needs to be determined what effect this interaction may have on the particles. This chapter will concentrate on the possible effects of a concave curve on the impact characteristics of ice balls.

7.2 Ice Ball Impacts on the Concave sides of the Curved Plates

Ice ball impacts on the concave side of the curved plates were first investigated with the patternator. Fig. 7.2 shows the arrangement of the patternator elements. The plates were placed so that the approach path of the ice ball was at 45° to the impact point which was mid-way along the chord of the plate. The ice ball size was 12.7 mm and the approaching speed was 175 m/s. Although three rows of elements were arranged to collect ice, only the first row, which had exposed a width of 12.5 mm, collected ice. This meant that the ice moved along the surface of the plate in a very narrow band. In other words, the ice debris left the impact point with a very low normal velocity component. Similar conclusions were drawn for ice impacts on a flat plate (chapter 4). Fig. 7.3 (a) and (b) show the ice mass distributions from curve 1 and curve 2 respectively, compared to the flat plate. To ensure repeatability, each test consisted of three runs, each run with thirty shots. The axes in Fig. 7.3 are explained in section 4.2. The total amount of ice caught was, on average, 85% of the ice fired, and the rest was lost in the gun or the gaps between the patternator elements. The distribution show a 'bell' shape. This implies that the ice particles left the impact point in a fan along the surface of the plate with most of the ice debris concentrated at the impact.
height. The result from curved plates show good agreement with flat plate which means that target curvature has little effect on post-impact mass distribution, i.e., the direction of travel of the ice particles from the impact point is not affected by the curvature.

Fig. 7.2 Patternator arrangement for concave side of the curved plates
Fig. 7.3  Pattern results of Mass distribution after ice balls impact on concave side (D₀=12.7 mm, V₀=175 m/s)
Ice impacts were also studied with still photography described in section 4.3, to show the effect of target curvature on post-impact particle size and velocity. Fig. 7.4 is an example of a photograph taken with a single flash after an ice ball impact. This is a image approximately 2 ms after the impact. Fig. 7.5 is an example of a photograph used to determine particle velocity. Two flashes which were 130 µs apart produced double images of each particle, and the first image was approximately 2 ms after the impact. The ‘L’ shaped marks in both photographs are length reference showing 10 mm horizontally and 10 mm vertically.

Fig. 7.6 shows the typical form of post-impact particle size distribution and Fig. 7.7 the post-impact velocity distribution. The axes are explained in section 4.3, and the Rosin-Rammler expression for particle size and velocity distribution are Eq. 4.3.1 and 4.3.4 respectively. To ensure repeatability, three runs were done for each curved plate.

Table 7.1 summarises the Rosin-Rammler parameters with the two curved plates, and compares them to the flat plate result (D₀=12.7 mm, V₀=175 m/s, θ=45°). Fig. 7.8 does the same comparison for particle size in form of curves. The results for the two curved plates are close, which meant that the change in curvature did not significantly affect the particle size.

<table>
<thead>
<tr>
<th>Table 7.1. Comparison of the Rosin-Rammler Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Run No</td>
</tr>
<tr>
<td>Flat Plate(45°)</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>Curve1</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>Curve2</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
</tbody>
</table>
However the particle sizes from curved plates are slightly larger than those from the flat plate. One possible explanation for this difference between the curved and flat plates is as follows. When an ice ball impacts upon a flat plate the contact area between the ball and the surface is very small (i.e. tending towards zero) and the kinetic energy per unit contact area is high. Therefore the ice ball breaks into many small particles. For impacts on a concave surface, the contact area is increased, although it is still small. This increase reduces the kinetic energy per unit contact area, and effectively dissipates the energy available to break the ball. As a result, the size of the particles is increased.

Fig. 7.9 compares the post-impact particle velocity distributions and shows that the ice particle velocities after impacting on the concave side of a curved plate were significantly lower than after impacting on a flat plate. This phenomenon is explained as follows. After an ice ball impacts on a flat surface, the ice particles fly along the surface in a narrow band. In case of a concave surface, the ice particles fly in direction tangential to the surface, and experience a series of successive impacts on the concave surface. Compared with the initial impact, these subsequent impacts have lower impact velocities and very shallow impact angles. These impacts have insufficient energy to cause further break-ups, but significantly decelerate the ice particles. The experimental results showed that tighter radius (curve 2) produced greater deceleration. This is expected because a tighter curve produces higher impact angles for the subsequent impacts. As discussed in section 4.3, a higher impact angle induces more energy loss in crushing, hence the particle velocities are low.

The following comments need to be made about the particle velocity measurements. When taking the photographs, the camera was placed square to the tangential plane of the right hand edge of the plate where the particles left the plate. The measurement of the distance between any pair of images may contain an error if they did not lie in this plane. This actually happened for the particles which were still on the surface of the plate when the photograph was taken. The mass fraction of these ice particles was small and their velocities were low, hence any errors had only a small influence on the overall results.
Fig. 7.4  Single image photograph, Curve 2, $D_0=12.7$ mm, $V_0=175$ m/s

Fig. 7.5  Double image photograph, Curve 2, $D_0=12.7$ mm, $V_0=175$ m/s
Fig. 7.6  Post-impact particle size distribution - Curve 1
\(d_{\text{mean}}=2.73\) mm; \(N_d=2.97\)

Fig. 7.7  Post-impact particle velocity distribution - Curve 1
\(v_{\text{mean}}=89\) m/s; \(N_v=2.8\)
Fig. 7.8  Comparison of post-impact particle size distribution

Fig. 7.9  Comparison of post-impact particle velocity distribution
CHAPTER 8 EFFECTS OF TARGET ROTATION ON ICE BALL IMPACT CHARACTERISTICS

It has been suggested that rotation of engine components can exert a centrifuging effect on ice particles after impacts, and throw more ice into the bypass duct. Part of the A.I.A.'s report suggests that higher fan speed increases the centrifugal effect. However, it is not known to what extent the target rotation affects impact characteristics, nor how any such effects should be considered quantitatively in numerical modelling. This chapter discusses the effect of target rotation on ice ball impact characteristics. This effect was first studied with two rotating flat plates. Then ice ball impacts on rotating conical spinner were studied, followed by experiments on an assembly of a spinner and fan blades.

8.1 Ice Ball Impacts on Rotating Flat Plates

8.1.1 The Rotating Flat Plate Rig

Flat plates were chosen for the study to eliminate any target curvature effects. Only two, instead of a cascade plates were used in order to avoid secondary impacts, and also for ease of photography. Each plate was 250 mm long and 200 mm wide. They were mounted onto a hub by means of a cylindrical root which allowed the plates to be set to any pitch angle. Fig. 8.1.1 shows the design of the plates and the hub. The hub was driven by a 10 horse-power electric motor via a pulley and belt.

The rotational speed of the blades was decided by the available motor power and the strength of the roots holding the blades to the hub. The maximum speed achieved was 2,000 rpm beyond which problem arose with the motor power. It should be noted that this speed is lower than the normal fan speed at descent. (The typical fan speed at descent varies for different engines, e.g. for Tay this speed is 2,000 to 3,000 RPM; while for Williams fan it may reach 30,000 RPM). It is unfortunate that these speeds could not be achieved in the laboratory,
but the following results can give some understanding about the rotational effects. The fact that
these results are obtained with low rotational speeds should always be borne in mind.

The pitch angle of the plates was limited by the power of the motor and the strength of the
plate root. The angle was set at 60° relative to the ice ball path (i.e. 30° to the direction of
rotation).

8.1.2 The Electronic Circuit for Firing Ice Balls at a Rotating Plate

The first problem to overcome with the rotating flat plate tests was to hit the plate. This
was the reverse of the problem facing fighter aircraft designers during the First World War, i.e.
how to fire machine-guns pass the propeller blades. In both cases, the solution was to tie up
the rotation of the blades with the gun firing. For the present study, an electronic gun firing
circuit which interfaced with a computer was built. Fig. 8.1.2 is the sketch of the firing system.
The whole system consisted of a shaft-encoder, a personal computer (PC) with an interface
card installed, and the gun control unit. The shaft-encoder was connected to the shaft of the
rotating flat plate rig with a flexible coupling. When the shaft rotated, the encoder yielded two
sets of pulses: Top Dead Centre (TDC) pulses and one-degree pulses. The PC worked as the
central controller. The two sets of pulses were fed into the interface card. At the TDC pulse,
the computer started counting the one-degree pulses. When the computer counted to a certain
number (named pre-delay angle), it sent a firing signal to the gun control unit and the gun was
fired. When the firing signal was sent out, a period of time was required for the gun
mechanism to act and for the ice ball to reach the target. The pre-delay angle needed to be set
so that the ice ball hit one of the plates. Fig. 8.1.3 illustrates the timing relation in the firing
system. In theory, if the pre-delay angle was well chosen, the ice ball would hit the target every
time, but this relied on accurate and constant motor and ice ball speeds. Unfortunately both of
these requirements were not always satisfied. Firstly, the ice ball speed could vary by 4 m/s
about a nominal speed of 175 m/s due to slight differences between each ice ball, and secondly
the motor speed also drifted slightly. However, enough data could be obtained by firing a large
number of shots.

Fig. 8.1.2  Schematic diagram of the firing mechanism
Hit ing a rotating blade was possible using the above system, but the impact position on a blade could not be controlled. By firing a large number of shots, enough photographs of the required impact position on the plate could be obtained. The impact position that is of interest is the central area of the plate.

8.1.3 Results and Analysis

The still photography technique described in section 4.3 was used and Fig. 8.1.4 illustrates the layout of the camera and the flash units. The camera was aligned normal to the plate when it was at up-right position.

By considering a cascade of fan blades it can be seen that in the majority of cases, hailstones hit the suction sides of the blades. However, there exists the possibility that hailstones, or ice debris resulting from impacts can hit the pressure side. This is especially true in the case of ice debris resulting from impacts on a spinner. Therefore the study of impacts on a rotating flat plate consisted of two parts: suction side and pressure side.
Fig. 8.1.4 Camera and flash set-up of the rotating flat plate test

(1) Suction side

Fig. 8.1.5 is a photograph taken with two flashes shortly after an ice ball impact on the suction side of the plate. The plate was rotating anti-clockwise (i.e. right to left in Fig. 8.1.5) at 1,200 rpm. Though it was possible to rotate the plate at higher speed, the resulting ice debris was scattered over a large area which caused difficulties for the photography. The radius at the impact point was 250 mm, forming a relative impact velocity of 177.8 m/s and impact angle of 49.8° (Fig. 8.1.6). The first flash was approximately 2.6 ms after the impact, and the time
Fig. 8.1.5  Ice ball impact on suction side of a rotating plate

Rotation Speed=27.8m/s  

Blade Movement  

Ice Ball Speed=175m/s  

49.8°  

10.2°  

Relative Speed=177.2m/s

Fig. 8.1.6  Relative velocity for impacts on suction side of a rotating plate
interval between the two flashes was 112 ms. The ‘L’ shaped mark on the plate was a length reference showing 10 mm vertically and 10 mm horizontally. The two images of the ‘L’ mark show the movement of the plate between the two flashes. The elliptical mark in the photograph was a hole in the background to let through the ice balls that missed the plate and should be ignored in the analysis. Each ice particle has two images and the direction of travel can be determined by joining the images with a straight line. By extending the lines joining each pair of images backwards, it can be shown that all of the lines converge to an area corresponding to the impact point. As the impact was on the suction side, there was only a short contact between the ice ball and the plate. The plate was effectively moving away from the impact and there was no interaction between it and the ice particles, hence there were no rotational effects. Because some of the particles are out of focus due to the rotation of the plate, it is not possible to obtain a quantitative particle size distribution. However, the above analysis shows that it is reasonable to calculate the post-impact particle size, velocity and mass distribution using the relative velocity and angle between the plate and the ice ball.

(2) Pressure side

In studying ice ball impacts on the pressure side, the following two terms are defined: *ice crushing time* is defined as the time from the ice ball touching the plate to full disintegration; and *on-plate-residence time* for a given particle is defined as the time from the end of the ice crushing time to when the ice particle leaves the plate.

It is reasonable to assume that the results of chapter 4 are valid in terms of post-impact particle size, velocity, and mass distribution at the end of the *ice crushing time*, if the relative impact angle and velocity between the ice ball and plate are applied. The difference between an ice ball impact on a stationary plate and a rotating plate is likely to occur during the *on-plate-residence time*. There is no interaction between a stationary plate and the ice particles; but there may be interaction between the pressure side of a rotating plate and the ice particles.
Fig. 8.1.7 Ice ball impact on the pressure side of a rotating flat plate - double flash photograph

Fig. 8.1.8 Relative velocity for impacts on pressure side of a rotating plate
As the pressure side of the plate is advancing towards the impact, one possible interaction is that the ice particles resulting from the initial impact are subjected to secondary impacts resulting in further break-ups. Fig. 8.1.7 is a photograph of an ice ball impact on the pressure side of a rotating plate using two flashes. Rotation is from left to right in the photograph.

Fig. 8.1.8 shows the relative velocity of the impact. The first flash was approximately 2.6 ms after the impact and the time interval between the two flashes was 112 μs. From the stationary flat plate studies, a characteristic of ice particle break-up is that the debris comes from the impact point in a ‘fan’ (Chapter 4). As with Fig. 8.1.5, the impact point can be determined by extending the straight lines joining each pair of particles. In Fig. 8.1.7, the lines joining the pairs of images converge to an area of the size of the ice ball (i.e. the impact point), with no evidence of any further (or secondary) break-ups. This is strong evidence to conclude that the ice particles from the first impact do not break up further during the on-plate-residence time. This is explained as follows. During impact on a rotating plate, the ice particles gain the speed of the plate in the direction of rotation. Since there is no relative normal velocity between the ice particles and the plate, there can be no secondary impacts, and therefore no further ice break-up.

During the on-plate-residence time, particles are subject to centrifuging effect. To help detect any deviations of particle paths, a third flash gun was added to the set-up shown in Fig. 8.1.4. Fig. 8.1.9 is a typical of the photographs obtained. In this photograph, the first flash was arranged to fire when half the ice ball had disintegrated on the plate. This image shows the position of the impact point and the position of the plate when the impact occurred. The second and third flashes were the same time interval after impact as the two flashes in Fig. 8.1.7. For most of the particles, the on-plate-residence time was short. This is illustrated in Fig. 8.1.7 and Fig. 8.1.9, where the majority of particles have clearly left the plate in approximately 2.6 ms after the impact. Slow moving particles have much longer on-plate-residence times, hence are expected to be deviated from their original path, but this is not apparent in Fig. 8.1.9, in which it is found that all the directions of the paired particles converged back to the half ice ball. Fig. 8.1.10 is a drawing illustrating this feature. This means the centrifuging effect
on even the slow moving particles was minimal. This may be due to the relatively low rotational speed of the plate (1,200 rpm) resulting in small centrifuging effect which cannot be easily detected. However, as the on-plate-residence time was very short for most of the particles, the centrifuging effect can only affect the slowest moving particles.

Fig. 8.1.9  Ice ball impact on the pressure side of a rotating flat plate - Triple flash photograph
Fig. 8.1.10 The interpretation of the triple-flash photograph
8.2 Ice Ball Impacts on a Spinner

8.2.1 Introduction

A spinner is located at the centre of an engine intake, and can take up a considerable area. A significant proportion of the ice that enters an engine results from impacts on the spinner. When making a numerical model of hail ingestion, one inevitably needs to deal with hail impacts on the spinner. Although some understandings about ice ball impacts have been obtained for stationary flat and curved plates, ice ball impacts on a spinner show special complexity due to the following reasons:

(1) The complex three dimensional shape
Spinners fall into two shapes, i.e. conical and elliptical, both being three dimensional and axi-symmetric. The results from the study of two-dimensional curves in Chapter 7 could not be applied to a spinner directly because of a spinner's three dimensional shape, hence further experiments were required.

(2) The Rotation
A major concern with ice ball impacts on a spinner is whether the ice particles resulting from impacts are thrown out when the spinner is rotating. If so they will approach the fan at a larger radius; and if not they will reach the fan at the root of the fan blades.

A Rolls-Royce Tay spinner was borrowed from the manufacturer to conduct the experiments. The Tay spinner had a conical shape with a cone angle of 65.5°. Fig. 8.2.1 illustrates the three parts and the size of the spinner. The typical rotational speed of a Tay spinner at descent is 2,000 to 3,000 rpm, therefore the spinner was motorised with an electric motor which drove the spinner at speeds up to 2,300 rpm.
8.2.2 Study of Ice Ball Impacts on Spinner Using a Patternator

The hail gun was placed parallel to the spinner axis at four shot positions as shown in Fig. 8.2.1. The gun was set at the same height as the spinner axis, and moved horizontally. As the spinner had a conical shape, this horizontal movement resulted in impact positions which were at different distances to the spinner base.

After some preliminary tests with cardboard, it was found that following impact, ice debris distributed itself in an arc-shaped strip along the edge of the spinner base. This meant that the
ice debris came off the impact point in a curved 'fan' wrapped around the surface of the spinner (Fig. 8.2.2). Correspondingly, the patternator elements were arranged behind the spinner and a polar co-ordinate \((r, \phi)\) was set up in the that plane as shown in Fig. 8.2.2. The co-ordinate, \(r\) is the distance to the spinner centre and \(\phi\) is the angular position. Therefore the mass distribution were investigated and described in two directions, i.e. angular and radial.

Fig. 8.2.2  Ice comes off the impact point in a curved ‘fan’

As the patternator elements were square, the data reduction in co-ordinate \((r, \phi)\) would be difficult. Therefore a set of masks were designed and one was placed in front of the patternator when testing. Fig. 8.2.3 is the arrangement of the patternator elements and mask looking from the tip of the spinner. Each mask left a gap of a certain width between the edge of the spinner base and the mask. The mask only allowed ice debris to go through the gap and enter the patternator elements. By varying the width of the gap (5 mm, 10 mm, and 15 mm), the radial mass distribution was obtained. As the width of the gap went wider, the amount of ice caught by the patternator increased. At a certain width, the amount of ice caught did not increase any further, then this width was taken as the extent the ice went to.

(1) Impacts on stationary spinner

Fig. 8.2.4 plots the amount of ice caught expressed as percentage of ice fired. The three
curves are for three gap widths. The relative shot position is defined in Fig. 8.2.1. By looking at the result 5 mm gap, it is found that the amount of ice caught declines when the impact
point moves further from the patternator. This is understandable since the ice debris travels in a wedge shaped envelope (Fig. 8.2.2). As the impact point moves further from the spinner base, the envelope becomes thicker radially when it reaches the patternator, hence the 5 mm width gap collects less ice. When the gap width increases to 10 mm, there is a significant rise in the amount of ice caught, especially for the last three shot points. It is noted that the 10 mm gap data line is nearly horizontal, which means that the position of the impact point has no significant effect on the amount of ice caught in the 10 mm gap. When the gap width increases to 15 mm, there is no significant increase in the amount of ice caught, meaning that a 15 mm gap is enough to take all the ice, or in other words, the envelope of ice debris is thinner than 15 mm at the patternator position. This confirmed the image obtained from the cardboard test which showed after impacts, ice particles travel in a narrow band along the surface of the spinner.

As a 15 mm gap was enough to take all the ice, the angular distribution was only studied with this gap width, and the result is plotted in Fig. 8.2.5. The horizontal axis represents angular position (ϕ), as defined in Fig. 8.2.2, and the vertical axis represents the percentage of ice caught in per degree angle (ϕ), which is obtained with the following calculation:

![Percentage of Ice Caught Per Deg vs Angular Position (Deg)](Fig. 8.2.5 Angular distribution in 15 mm slot - stationary spinner (D₀=12.7 mm, V₀=175 m/s))
The distribution curves show a bell shape, and as the shot position moves towards the tip of the spinner (away from the patternator), the curves tend to be flat, meaning a more spread distribution. This further confirms the image of Fig. 8.2.2.

(2) Impacts on rotating spinner

To study the rotational effects, ice balls were fired at position 2 with spinner rotation speeds of 1900 rpm and 2300 rpm. The patternator was arranged with a mask that provided a 15 mm gap and the results are shown in Fig. 8.2.6. Although the three data lines do not overlap each other exactly, the differences are within the range of normal scatter. It is reasonable to say that no rotational effect was detected. This was attributed to the smoothness of the spinner surface which did not have any friction on the ice travelling along its surface.

![Diagram showing angular distribution](image)

Fig. 8.2.6 Angular distribution in 15 mm slot - rotating spinner (D₀=12.7 mm, V₀=175 m/s)
It is necessary to know whether the above conclusions can be applied to low ice ball speed, since in this case the ice ball and ice particles stay longer on the surface of the spinner. Similar tests were carried out with an impact velocity of 102 m/s, and the results are shown in Fig. 9.2.7. Again no rotational effects were detected.

![Graph showing percentage of ice caught per degree vs. angular position. The graph has three lines for 0 RPM, 1900 RPM, and 2300 RPM.]

Fig. 9.2.7 Spinner rotation effect at low impact velocity (D₀=12.7 mm, V₀=102 m/s)

8.2.3 Studies Into Ice Ball Impacts On Spinner Using High Speed Cine Photography

As an alternative technique to verify some of the conclusions obtained from the patternator technique, high speed cine photography was used to film the process of ice ball impacts on a spinner. As described in section 4.2, a Hycam camera was used at a frame rate of 5,800 frames/sec.

(1) Camera Set Up

To get a plan view and profile view of ice impact on a spinner, ice balls were fired on the side and top of the spinner. The camera was placed to the side of the spinner at two different
heights to take the two views. The relative position of the camera, spinner and shot position is shown in Fig. 8.2.8.

```
IMPACT POSITION FOR PROFILE VIEW

IMPACT POSITION FOR PLAN VIEW

CINE CAMERA
```

Fig. 8.2.8 Plan View of Impact Point and High Speed Cine Camera Arrangement For Top View and Side View of Ice Ball Impact

(2) Test Cases and Typical Results

Efforts were made to cover as many spinner states and ambient conditions as possible, but the high expense of cine film and processing limited the number of shots. The filming was only made on three typical cases. The three test cases are listed below and each case was repeated once to ensure repeatability.

<table>
<thead>
<tr>
<th>Run Number</th>
<th>Spinner Speed (rpm)</th>
<th>Ice ball Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0</td>
<td>175</td>
</tr>
<tr>
<td>1.2</td>
<td>0</td>
<td>175</td>
</tr>
<tr>
<td>2.1</td>
<td>2300</td>
<td>175</td>
</tr>
<tr>
<td>2.2</td>
<td>2300</td>
<td>175</td>
</tr>
<tr>
<td>3.1</td>
<td>2300</td>
<td>102</td>
</tr>
<tr>
<td>3.2</td>
<td>2300</td>
<td>102</td>
</tr>
</tbody>
</table>
Fig. 8.2.9 is the top view of Run 2.2, and Fig. 8.2.10 is the side view of the same test case. The frame sequence is marked in the photograph. It should be noted that the two figures are for the same test conditions but are two different shots, so they may not completely agree with each other in timing. Obtaining two views for one shot would require two synchronised cameras which were not available. The two white lines on the middle of the spinner were length references which were 10 mm apart. The white line on the right hand side of the spinner was the bottom of the spinner.

Restricted by the camera speed, the post-impact particles appears to be a cloud of ice proceeding away from the impact point. The images obtained from rotating and stationary spinner are similar. From the top view, it is shown the ice was not thrown away from the spinner, but slid along the surface towards the base in a low bounce angle. The side view reveals that the ice was distributed in a 'fan', and the 'fan' was not tilted by the rotation. There the results from cine photography support the conclusions obtained with the patternator technique.
Fig. 8.2.9 High speed cine film of ice ball impact on spinner - top view
(Ice ball speed 175 m/s)
Fig. 8.2.10 High speed cine film of ice ball impact on spinner - side view
(Ice ball speed 175 m/s)
8.3 Preliminary Results for a Full Assembly of Spinner and Fan

Ice ball impacts on a spinner and fan assembly were studied using an unshrouded Williams FJ-44 fan. The experimental arrangement of the fan is shown in Fig. 8.3.1 and Fig. 8.3.2. The Williams fan was chosen because its size was suitable for handling in the laboratory. The spinner was basically a conical spinner in shape, but with a slightly concave profile. The fan had 20 fan blades, each with a tip chord of 95 mm. A pulley was fitted on to the fan shaft which allowed an electric motor to drive the assembly up to a speed of 2,000 rpm. The Williams fan runs at much higher speed in operation, but in the experiments, the fan speed was limited by the motor power. The results of the study cannot produce data for Williams fan specifically, but will produce some general understanding.

The hail gun was placed parallel to the axis of the fan shaft. Fifteen ice balls were fired from the hail gun at each of the positions shown in Fig. 8.3.2. The nominal velocity of each ice ball was 175 m/s. As shown in the following table, the four gun positions were selected to give impacts on different parts of the fan assembly.

![Fig. 8.3.1 Photograph of Williams Fan on Test Rig](image-url)
Fig. 8.3.2 The Williams FJ-44 Engine Fan Test Rig

<table>
<thead>
<tr>
<th>Gun Position</th>
<th>Radius (mm)</th>
<th>Part Hit</th>
</tr>
</thead>
<tbody>
<tr>
<td>HG1</td>
<td>40</td>
<td>Middle of spinner</td>
</tr>
<tr>
<td>HG2</td>
<td>90</td>
<td>Root of fan blades</td>
</tr>
<tr>
<td>HG3</td>
<td>150</td>
<td>Middle of fan blades</td>
</tr>
<tr>
<td>HG4</td>
<td>210</td>
<td>Tip of fan blades</td>
</tr>
</tbody>
</table>
The mass distribution was qualitatively investigated using a cardboard technique. A piece of cardboard was placed behind the fan. Ice that passed through the fan hit the cardboard and left marks of penetration and wetness which revealed the spread and extent of the ice debris. Sketches of these marks are shown in Fig. 8.3.3, and are viewed from the spinner, looking into the fan. The direction of the rotation was anti-clockwise.

(1) Shot position 1 - on spinner

From Fig. 8.3.3(a), it can be seen that the bulk of the ice was shifted towards the direction of fan rotation. The path of the ice debris after the impact on the spinner can be divided into two parts, i.e. the path on the spinner and the path in the blade channels. As stated above, after an ice ball strikes a spinner, the ice debris comes off the impact point in a curved 'fan' wrapped around the surface of the spinner, and there is no rotational effect. Hence the ice debris travelled straight towards the root of the fan blades and arrived as a well dispersed cloud of particles. By the time the particles reached the blade root, most of them were travelling at speeds significantly less than the original impact velocity. During the time when the ice debris was in the blade channel, it gained the rotational velocity of the blades and got carried away down the direction of rotation. When passing through the blade channel, the ice debris was moved radially outwards. A possible explanation is that this movement was due to three effects, i.e. spinner geometry, radial air flow, and centrifuging of ice particles. As the ice debris entered the blade channels, it followed the spinner profile. Without any additional influences, the ice debris would have continued along this path. However the debris was centrifuged in the blade channels, with the slowest moving particles most affected. Also as the fan was unshrouded, there was a significant radial flow which would tend to throw the ice particles radially outwards.

(2) Shot position 2 - blade root

The results are shown in Fig. 8.3.3(b). Compared to shot position 1, this shot did not hit the spinner so the ice particles were more concentrated when they entered the blade channel. They were carried away in the blade channel, and the bulk of ice was found at further down the direction of the rotation, but more concentrated than shot position 1. The shift of the debris towards the direction of rotation was less marked than for shot position 1. This was probably
due to the fact that compared to impacts on the spinner, the particles were travelling faster and hence had a shorter residence time in the blade channel. Compared to Fig. 8.3.3(a), the radial shift of the ice debris was less marked. This was probably due to changes in the three effects described previously: geometry, radial air flow, and centrifuging. At the blade root, the ice debris followed the profile of the fan hub. However, on the Williams fan, there is a change of surface slope in the hub compared to the spinner, and as a result, the debris experienced less of a radial shift. In addition, the centrifuging and air flow effects were reduced compared to the spinner impacts, because of the shorter residence times in the blade channel.

(3) Shot position 3 - middle of blade
The results for this position are shown in Fig. 8.3.3(c). With impacts on fan blades, there are two major effects, i.e. blade geometry, and fan rotation. The twisted shape of fan blades tended to force the ice debris in the opposite direction of the rotation, but the blade movement carried it in the direction of the rotation (Fig. 8.3.4). For this shot position, the effects of geometry and blade movement nearly cancelled each other, so the contour was found at approximately the same circumferential position as that of the shot point. Following an impact, the debris was distributed radially. This distribution hid any centrifuging or air flow effects, which were small due to the short residence time of the particles in the blade channels.

(4) Shot position 4 - tip of blade
The results are shown in Fig. 8.3.3(d). At this point, The impact angle was high (approximately 70 degs, as illustrated in Fig. 8.3.5) and the geometry effect dominated, so the ice contour was found in the opposite direction of the rotation. It should be noted that this result is not representative of a shrouded fan because the nacelle will modify the air flow around the tip and provide a surface for secondary impacts.

The above results are only qualitative, hence are not sensitive enough to illustrate the process to further details. Also some errors exist due to the lack of shroud. However, the results appeared to be explainable with the understanding obtained from previous studies, and more importantly, provides a guidance for an effective arrangement of the patternator elements in any further work.
Fig. 8.3.3 Extent of Ice Behind the Fan as Recorded by Cardboard (Not To Scale)
Fig. 8.3.4 Blade geometry at half-span

Fig. 8.3.5 Blade geometry at tip
Chapter 9. Conclusions

(1) Basic ice ball impact characteristics were first studied using a flat plate. A parametric study was carried out and the parameters studied included impact angle, impact velocity, ice ball size, ice ball temperature, and target temperature. The following conclusions were drawn:

- After an ice ball impacts on a flat surface, the particles lose their normal velocity and fly with a low bounce angle along the surface of the plate. The debris spreads in a ‘fan’ shaped envelope on the surface plane, and the ‘fan’ angle increases as the impact angle (relative to the plate) becomes higher.

- Good agreement was found with mass distributions from the patternator and still photography. The still photography technique also revealed the post-impact particle size and velocity distributions, and it was found that these distributions could be expressed in terms of the Rosin-Rammler relationship.

- The impact angle was found to have a significant effect on all aspects of the impact characteristics. A greater impact angle resulted in finer particles and lower particle velocities, and a more evenly spread mass distribution.

- The impact velocity had no effect on particle mass distribution, but had effects on post-impact size and velocity distribution. A higher impact velocity resulted in finer particles, and greater particle velocities.

- The experimental results lead to the assumption that the particle size only depends on the normal impact energy, but the particle velocity depends on both normal impact energy and the initial tangential velocity.

- Ice ball size has an effect on post-impact particle size, but the normalised size distribution does not show dependence on ice ball size. Other factors, i.e. ice ball temperature, target temperature were shown to have little effect.
(2) The test results showed apparent trends and led to the establishment of a set of empirical rules. These rules were derived by assuming that particle size was a function of normal impact energy; and the particle velocity was a function of both normal impact energy and tangential component of impact energy.

(3) A mathematical model was set up about ice ball disintegration. The model was based on some intuitive assumptions, but the results showed reasonable agreement with the experimental data, which illustrated the validity of these assumptions.

(4) Tests with curved plates revealed that with concave surfaces, the curvature had a small effect on post-impact particle size, but significantly decelerated the particles. The effect on particle size was attributed to the slightly larger contact area between the ice ball and the concave surface compared to flat plate; and the deceleration was caused by the successive impacts at low impact angles as the particles moved along the surface.

(5) Tests with two rotating flat plates revealed that there were no rotational effects if the impacts were on the suction side. This was because the plate moved away from the particles after the impact, and there was no further contact between the plate and the particles. Impacts on the pressure side also showed little centrifuging effect, but this may be due to the relatively low blade rotation speed and short residence time of the particles on the plate, and a firm conclusion could not be drawn.

(6) Experiments of ice ball impacts on a conical spinner showed that ice particles came off the impact point in a curved ‘fan’ wrapped on the surface of the spinner, and the rotation of the spinner had no effect on the movements of the ice particle. This was attributed to the smoothness of the spinner surface and lack of friction.

(7) Secondary impact tests revealed that the resulting particles were very fine. During the secondary impacts, the particles experienced sudden deceleration, and the piling-up of the
particles caused higher bounce angles. The bounce angle became higher as the second impact angle increases.

(8) Some preliminary tests were carried out with a whole assembly of spinner and fan. Ice debris showed a large spread after impacting on the spinner. With impacts on fan blades, there were two major effects, i.e. blade geometry, and blade movement. The twisted shape of fan blades tended to force ice debris in the opposite direction of the rotation, but the blade movement carried it in the direction of rotation. As the impact point moved from blade root to tip, the blade geometry caused higher impact angles which forced the ice to fly towards the opposite direction of the rotation.
Chapter 10. Recommendation For Further Work

Further work is recommended in the following areas

(1) The impact characteristics of natural hailstones.

It needs to be borne in mind that the structure of natural hailstones is so diverse, and there is not a standard hailstone. It is not practical to repeat all the tests described in this thesis with real natural hailstones. Throughout the research, one case of flat plate tests ($\theta=45^\circ$, and $V_0=175$ m/s, $D_0=12.7$ mm) has been used as datum. For any change of experimental condition, this test was run to show whether the change affects the result. If possible this case should be run with natural hailstones to show the effect. If significant effects are found, then more work should be done.

(2) More study into the target curvature effects

Target curvature has been shown to have effects on post-impact characteristics, as stated in previous section. More experiments are required to obtain a quantitative relationship between the curvature and these effects. On a concave surface, the curvature has been known to decelerate the particles, and the rate of deceleration was affected by the curvature and the length of the curve. It would be useful to obtain a quantitative relation between the deceleration and the curvature and the length of the curve.

(3) Ice ball impacts on an elliptical spinner have not been studied. Considering the complex three dimensional shape of an elliptical spinner, the mass distribution must have some special features that are worth finding out.
(4) The mass distribution after ice balls hitting various parts of a William's fan rotating at various speeds needs to be studied quantitatively with the patternator. Such a study will provide the valuable data to calibrate the CFD model of particle tracking being developed in Rolls-Royce.

(5) The mathematical model of an ice ball disintegration needs experimental data to determine $K_n$ and $K_t$, which are coefficients associated the reduction of normal impact energy, and reduction of tangential component of impact velocity. $K_n$ can be found out by firing ice balls normally at a flat plate. After getting $K_n$, $K_t$ can be obtained by studying impacts at other angles.
References
(In the order of citation)

1. Aerospace Industries Association, PC338-1 Project report, "Investigation of Engine Power Loss and Instability in Inclement Weather"


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53. Sarrica, O., "Observational Results on Hail Formation and Structure", Ric. Sci., 35, 345-359


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Appendix I. Publications From This Project

(1) Pan, H., and Render, H., “Impact Characteristics of Simulated Hailstones Simulating Ingestion by Turbofan Aero Engines”, Accepted (26th September, 1995) and being scheduled for publication on Journal of Propulsion and Power


(4) Pan, H., and Render, P. M., “Experimental Studies into the Hail Ingestion of Turbofan Engines”, 30th Joint Propulsion Conference & Exhibit, Indianapolis, IN, USA. AIAA Paper No. 94-2956, June, 1994

Appendix II

Instructions For Using the Laser-Diode Speed Measurement System

The purpose of interfacing the PC and the laser system is expressed in 2.5.2. Separate programs were set up for two operating modes: single shot mode and multi-shot mode. The instruction for using the two programs are given below.

1. Single Shot Mode

In this mode, gun firing is still manual. The system performs speed measurement and detection of ice ball breaking after each shot.

The program can be run in any directory. Enter:

```
sg  filename
```

in which `filename` is the result file into which the result will be written after being displayed on the screen. It could be with a path name. If no path name is given, the file will be created in the current directory.

After this, the user can simply follow the instructions given on the screen.

Example:

a) Enter

```
sg  run3_1
```

Screen response:

```
Enter File Header information
```

b) Enter (for example)
Date: 16, Nov. 1992
Run No. 3_1

Strike F6 and then Enter

Screen response:

Ready for shot. Press S to stop

Now fire the gun

c) Strike S when the run is finished

Screen response:

Enter Notes About The Run

Enter (for example)

Run is OK

Strike F6 and Enter

d) The run finished. The result file can be viewed.

Take A1 as the example

Table A1: Result of Single Shot Mode

Date: 16, Nov. 1992
Run No. 3_1

<table>
<thead>
<tr>
<th>SHOT</th>
<th>T1</th>
<th>T2</th>
<th>VEL1(m/s)</th>
<th>VEL2(m/s)</th>
<th>NBR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>568</td>
<td>565</td>
<td>176.0563</td>
<td>176.9911</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>584</td>
<td>582</td>
<td>171.2329</td>
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</tr>
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<td>621</td>
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</tr>
<tr>
<td>4</td>
<td>589</td>
<td>587</td>
<td>169.7793</td>
<td>170.3577</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>617</td>
<td>621</td>
<td>162.0746</td>
<td>161.0306</td>
<td>4</td>
</tr>
</tbody>
</table>

Run is OK
The meaning of the terms are given below:

<table>
<thead>
<tr>
<th>No.</th>
<th>T1</th>
<th>T2</th>
<th>Vel1</th>
<th>Vel2</th>
<th>NBR</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>shot number</td>
<td>Time interval between laser 1 and laser 2 (s)</td>
<td>Time interval between laser 2 and laser 3 (s)</td>
<td>Velocity obtained from T1</td>
<td>Velocity obtained from T2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>= 3, complete ice ball, good shot</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&gt; 3, ice ball broke</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt; 3, ice ball missed one or two lasers</td>
</tr>
</tbody>
</table>

2. **Multi-shot Program**

Before running the multi-shot program, make sure the mode switch at the back of the solenoid is on computer mode and the key-switch on the front panel of the solenoid box is at the ON position.

In any directory, enter

`mt filename`

in which `filename` has the same meaning as in single shot mode.

After this, the user can simply follow the instructions given on the screen.

*Example*

a) Enter

`mt run2`
Screen response

Enter File Header Information

b) Enter Information (as example)
   Date: 16, Nov. 1992
   Run No.2

Strike F6 and then enter, screen response

Input Number of shots

c) Make sure your ears are protected and then press the ENABLE button. Input number of shots and enter. The gun fires now.

d) After the shots, screen response
   Enter Notes About the Run

Enter
   Run is OK

Strike F6 and Enter.

e) A multi-shot run is finished and the result file is the in the same form as Table A1.
APPENDIX III

Instructions for Using the Balance Interface Program

1. **Weighing Procedure**

   The interface between the PC and the balance is achieved by using a software package Labtech Notebook. Before starting the program, check that the balance is powered and connected to the PC. The following steps can be followed.

   a) Go to the sub-directory C:\NB by entering
      
      \texttt{cd C:\nb}

   b) Enter
      
      \texttt{run br filename}
      
      in which filename has the same meaning as with laser interface. (Appendix I)

      Screen response
      
      *Enter File Header Information*

      Press F6 to End

   c) After pressing F6 and then return, the PC will take the reading on the balance and be ready to take the next one.

   d) Put a weight on the balance, and press\(\bigcirc\) on the balance. The reading will be taken when the balance reading is stable (The \(g\) appears on the balance readout panel).

   e) Repeat (d) to finish all the weights.

   f) Press Esc when weighing finished.
Enter Notes, Press F6 and then Enter to End.

The result can be found in the filename specified in the first command line.

It should be noted that the result file is a text file. In other words, the result file contains characters rather than numbers. Conversion is needed if they are going to be used for calculations.

2. Loading the result file into a spreadsheet program

The results file can be loaded into a spreadsheet for analysis. As the result file is a text file, the facility of converting a text file to a data file in Microsoft Excel should be used when loading the file. The procedure is as follows:

a) Start Excel

b) From main manual, select file/open

c) Select text

d) Select Custom for delimiter and enter g.

e) In file\open manual, select the directory in which the file is stored.

f) Select the file, and click OK.
Appendix IV: Listing of the Program of Ice Ball Disintegration Model

```
$DEBUG
DIMENSION HTTOP(30),HTBTM(30)
DIMENSION XD(30),VOLP(30),NPART(30),VOLRES(30)
DIMENSION DVOL(30),VOL(30)
DIMENSION VN(30),VR(30)
DIMENSION VMASS(40),VSEC(40)
COMMON/A/D0,VNO,N
COMMON/A1/DANGLE,ANGLE(36),AMASS(36)
C
C---- INPUT: D0 - ice ball size; V0 - impact velocity;
C THETA - impact angle; DMAX - maximum particle size;
C DMIN - minimum particle size; VTK - Kt; VNK - Kn
C
READ(*,*) D0
READ(*,*) V0
READ(*,*) THETA
READ(*,*) DMAX
READ(*,*) DMIN
READ(*,*) VTK
READ(*,*) VNK
C
C CALCULATE TANGENTIAL AND NORMAL COMPONENTS OF V0
C
VNO=V0*SIN(THETA*3.14159/180)
VTAN=VTK*V0*COS(THETA*3.14159/180)
C
C POSSIBLE MAXIMUM PARICLE VELOCITY
C
VPMAX=(VNO*VNK+VTAN)*1.05
DVPMAX=VPMAX/40
C
DO 70 I=1,40
70 VSEC(I)=I*DVPMAX
VOL0=3.1415926*D0*D0*D0/6
C
C---- CALCULATE CRASHING TIME TCR
C
TCR=2*D0/VNO
C
C CALCULATE THE NUMBER OF LAYERS - N, AND
C PARTICLE SIZES FOR EACH LAYER XD(I)
C
XXD=DMIN
N=1
HH=0
490 XD(N)=XXD
```
C
N=N+1
HH=HH+XXD
IF(HH.GT.DO) GOTO 495
XXD=DMIN+(DMAX-DMIN)*HH/(DO-DMAX)
GOTO 490
C
FOR THE LAYER AT THE TOP, maximum particle size
is assigned
495 N=N-1
XD(N)=DMAX
C
START CALCULATION FROM BOTTOM OF THE ICE BALL
C
DVOL0=0
DO 10 I=1,N
C
CALCULATE SINGLE PARTICLE VOLUME
C
VOLP(I)=3.14159*0.65*XD(I)*XD(I)*XD(I)/4
C
POSITION OF TOP AND BOTTOM OF THIS LAYER IN THE BALL
C
IF(I.EQ.1) THEN
HTTOP(I)=XD(I)
HTBTM(I)=0
GOTO 270
ENDIF
HTTOP(I)=HTTOP(I-1)+XD(I)
HTBTM(I)=HTTOP(I-1)
IF(I.EQ.N) THEN
HTTOP(I)=DO
HTBTM(I)=HTTOP(I-1)
ENDIF
C
NORMAL VELOCITY OF THE BOTTOM OF EACH LAYER AT
THIS TIME
C
270 VN(I)=VN0-VN0*HTBTM(I)/(DO-DMAX)
C
VOLUME of ice CRASHED TO TOP OF THIS LAYER
C
VOL(I)=3.14159*HTTOP(I)*HTTOP(I)*(DO/2-
HTTOP(I)/3) DVOL(I)=VOL(I)-DVOL0
DVOL0=VOL(I)
10 CONTINUE
C
OUTPUT PARTICLE SIZE DISTRIBUTION
C
DO 90 I=1,N
FSIZE=VOL(I)/VOL0
90
90 WRITE(*,260)XD(I)*1000,FSIZE
260 FORMAT(1X,F13.3,',',F13.3)
C---------------------------------------------
C NUMBER OF PARTICLES IN EACH LAYER
C
DO 20 I=1,N
PARTN=DVOL(I)/VOLP(I)
N PART(I)=INT(PARTN)
C
C --- RESIDUE PARTICLE VOLUME
C
DDD=PARTN-NPART(I)
VOLRES(I)=DDD*VOLP(I)
C---------------------------------------------
C VELOCITY OF PARTICLE FROM THIS LAYER DUE
C TO NORMAL IMPACT
C
VR(I)=VNK*VN(I)
20 CONTINUE
C---------------------------------------------
C PREDICT MASS AND VEL DISTRIBUTION
C
DO 25 I=1,36
25 AMASS(I)=0.0
DO 75 I=1,40
75 VMASS(I)=0.
CALL DIRECT
C
Generate a random number for direction of each particle
C
CALL GETTIM(IHR,IMIN,ISEC,I100TH)
CALL SEED(I100TH)
DO 30 I=1,N
DO 35 J=1,NPART(I)
CALL RANDOM(RAN)
RAN=(RAN-0.5)*2*3.14159
VY=VR(I)*SIN(RAN)
C
C superimpose the tangential velocity c
VX=VTAN+VR(I)*COS(RAN)
VP=SQRT(VY*VY+VX*VX)
C
direction of travel
C
DIR=TTAN(VY,VX)
CALL LOCATE(DIR,IDIR)
AMASS(IDIR)=AMASS(IDIR)+VOLP(I)
C
C CALCULATE VELOCITY DISTRIBUTION
C
DO 250 K=1,40 IF(VP.LT.VSEC(K)) THEN
  VMASS(K)=VMASS(K)+VOLP(I) ENDIF
250 CONTINUE
35 CONTINUE
C -----------------------------------------------
C DEAL WITH THE RESIDUE PARTICLE
C
CALL RANDOM(RAN) RAN=(RAN-0.5)*2*3.14159
  VY=VR(I)*SIN(RAN) VX=VTAN+VR(I)*COS(RAN)
  VP=SQRT(VY*VY+VX*VX) DIR=TTAN(VY, VX)
CALL LOCATE(DIR, IDIR)
AMASS(IDIR)=AMASS(IDIR)+VOLRES(I)
C-----------------------------------------------
C CALCULATE VELOCITY DISTRIBUTION
C
DO 255 K=1,40 IF(VP.LT.VSEC(K)) THEN
  VMASS(K)=VMASS(K)+VOLRES(I) ENDIF
255 CONTINUE
30 CONTINUE
C-----------------------------------------------
C OUTPUT VEL DISTRIBUTION
C
DO 265 K=1,40 VMASS1=VMASS(K)/VOLO
265 WRITE(*,400)VSEC(K), VMASS1
  FORMAT(1X,F12.4,',',F12.4)
C
C OUTPUT MASS DISTRIBUTION
C
DO 40 I=1,36 AMASS1=AMASS(I)/VOLO/10*100
40 WRITE(*, 520)ANGLE(I)*180/3.14, AMASS1
520 FORMAT(1X,F13.4,',',F11.4)
END
C-----------------------------------------------
FUNCTION TTAN(VY, VX)
c knowing VY, VX, decide the direction
C -- TTAN IS FROM -3.14159 TO +3.14159 PI=3.14159
IF(VX.EQ.0.AND.VY.GT.0) THEN
  TTAN=PI/2
GOTO 100
ENDIF
IF(VX.EQ.0.AND.VY.LT.0) THEN
  TTAN=-PI/2
GOTO 100
ENDIF
IF(VX.EQ.0.AND.VY.EQ.0) STOP 4444
T=VY/VX
IF(VY.GE.0.AND.VX.GT.0) THEN
  TTAN=ATAN(T)
GOTO 100
ENDIF
ENDIF
IF(VY.GE.0.AND.VX.LT.0) THEN
TTAN=PI-ATAN(-T)
GOTO 100
ENDIF
IF(VY.LT.0.AND.VX.GT.0) THEN
TTAN=ATAN(T)
GOTO 100
ENDIF
IF(VY.LT.0.AND.VX.LT.0) THEN
TTAN=-PI+ATAN(T)
GOTO 100
ENDIF
100 RETURN
END

SUBROUTINE DIRECT

c divide -3.14 to +3.14 into 36 sections

COMMON/A1/DANGLE,ANGLE(36),AMASS(36) PI=3.14159
DANGLE=PI/18
DO 10 I=1,36
10 ANGLE(I)=(I-18)*DANGLE-DANGLE/2
END

SUBROUTINE LOCATE(THETA,IDIR)

c Knowing THETA, decide which section it is in

COMMON/A1/DX,X(36),AMASS(36)
DO 10 I=1,36
T1=X(I)-3.14159/18/2 T2=X(I)+3.14159/18/2
IF(THETA.GE.T1.AND.THETA.LE.T2) THEN IDIR=I
GOTO 100
ENDIF
10 CONTINUE
100 RETURN
END