Helicopter icing

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ABSTRACT

Due to constraints of natural condition, cost and of available time associated with model fabrication and for extensive wind-tunnel tests or flight tests, Computational Fluid Dynamics (CFD) simulation was considered an alternative means of providing air vehicle icing simulation and aeromechanic performance analysis. Full-scale icing experiments and, therefore, certification and cost can be significantly reduced by developing full-numerical simulation methods to evaluate the air vehicle performance for a wide range of icing conditions. This paper summarises helicopter icing simulation methods that include the development of helicopter aerodynamics, calculation methods of helicopter icing, icing protection system performance, icing effects on the helicopter performance, and some challenges in helicopter icing simulation.

1.0 INTRODUCTION

The increased utility of general aviation aircraft and helicopters has resulted in an increased potential for unfavourable encounters with ice. Recent accidents and incidents have shown that undetected ice accretion or ineffective ice removal methods can lead to performance degradation and sudden loss of stability and control, with the potential for the most severe consequences. David Owen (1998)[(1)] summarised the accidents where icing was a contributing factor. Regarding the serious hazards of flight into icing conditions, the Federal Aviation Administration (FAA) requires any aircraft manufacturer to obey the strict requirements presented in Federal Airworthiness Regulations (FAR) Part 25, Appendix C (1914)[(2)]. For helicopter applications, it refers to FAA-AC29-2.

Though icing is less dangerous to helicopter flight than snow, slush and visibility factors and so on, it is still a great hazard factor. Because rotor blades, at temperature below –10℃, will collect leading-edge ice along the entire blade span, causing a substantial reduction in performance, ice accretion degrades greatly the helicopter performance.

Historically, certification of a helicopter for flight in icing conditions has been a problem. It is because not only the test program is dangerous and expensive, but also the icing conditions that are sought after cannot be readily found in nature. Thus, the development of efficient analysis methods is necessary to lower the cost and time of flight test in icing conditions.

The relative problems on aircraft icing have been summarised by Cebeci and Kafyeke (2003)[(3)], and by Gent, Dart and Cansdale (2000)[(4)]. Similar to aircraft icing, the calculation methods for helicopter icing can also be divided into several key fields. These are (a) ice accretion prediction, (b) anti- and de-icing system performance, and (c) helicopter performance in icing conditions. In addition, the flow field characteristics of a helicopter are also very important to icing problems due to its effect on the collection efficiency (a ratio used to determine the amount of ice). The research required to develop some tools consists of the examination and characterisation of the underlying physics for each of these fields so as to serve the applications in engineering and science research. In

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Figure 1. Helicopter Icing Spray System(HISS)[18].

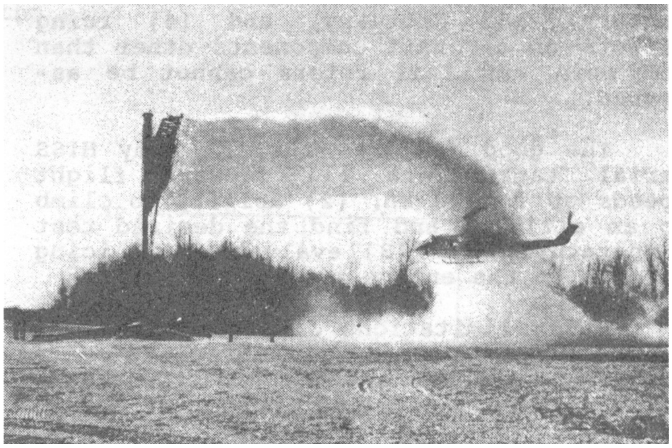

Figure 2. NRC icing tower at Ottawa. From Coffman (1983)[18].

addition to such basic studies, there are also important activities associated with code validation, maintenance, and support that must be factored into the development plans, which was pointed out by Potapzuk (1999)[5].

Prediction of ice accretion on a full aircraft/helicopter configuration and the resulting performance degradation is a long-term objective of icing research. The applications of computational methods to icing problems can be broadly categorised as being in one of two groups:

(1) Ice accretion: Given the flight and meteorological conditions, what is the resulting ice shape?

(2) Icing effects: Given an ice shape, what are the flow field and the resulting performance degradation?

In effect, the mixed problem of (1) and (2) is frequently an unsteady process.

Up to now, for both economic and research reasons, there are several analysis and calculation software packages developed in the United States, Canada and Europe, such as: LEWICE of NASA John H. Glenn Research Center, CANICE of Canada, ONERA 2D/3D of French ONERA, and 3D icing simulation system FENSAP-ICE3D at Canada.

The research fields associated with helicopter icing will be described in the following sections. Section 2 reviews the development of helicopter aerodynamics. Section 3 introduces the analysis and calculation methods of helicopter icing, and section 4 reviews the icing protection system performance. The effects of icing on the helicopter performance are addressed in section 5. At the end of this paper, there is a brief discussion of challenges in helicopter icing.

2.0 DEVELOPMENT IN HELICOPTER AERODYNAMICS

The literature surveys of Gesson and Myers (1952)[6], McCormick (1967)[7], Bramwell (1976)[8], Johnson (1980)[9], Stepniewski and Keys (1984)[10], Seddon (1990)[11] are classical in this field. Johnson (1986)[12] reviews the development of helicopter dynamics, and McCroskey (1995)[13] summarises the calculation methods in the wake prediction of rotor.

Helicopter aerodynamics is absolute challenge. Firstly, the flow past a rotary wing is never what aerodynamicists consider to be 'linear'. Secondly, it is difficult to study fluid flow from both an experimental and modeling perspective. Finally, helicopter experiments are extremely expensive to conduct. Currently, the research focuses on single blade to lower the study difficulties. The researches involve wake calculation, blade-vortex interactions, and dynamic stall and so on.

In classical approaches, the blade element theory is a common method that is widely used in research. In this theory, the blade is regarded as aerodynamically independent, chordwise-oriented, narrow strips or elements. Thus, the characteristics of 2D aerofoil can be used in the separated elements and the characteristics of the blade can be gained through integral. It is a common method applied by industry to calculate the rotor performance.

Classical approaches are simple and efficient to gain the characteristics of the blade. But it cannot predict the detailed structure of the fluid field, as the flow structure is very important to icing simulation. This shortage limited the usage of classical approaches in ice simulation that is based on modern CFD methods.

Modern theoretical and computational approaches make it possible to detail the structure of flow field. In wake calculation, three approaches have generally been used: rigid wake models, prescribed wake models, and free wake models. The rigid model has been summarised by Landgrebe (1972)[14]. To remedy the weakness of rigid models, the prescribed wake model is developed by Landgrebe (1972)[14]. It is very efficient computationally. However, experimental data is required and so the calculation of wake is not really predictive. In free wake calculation, the vortex system motion is calculated directly from the effects of all the other wake components and influence of the blade. This method determines the wake's position at each time step with Lagrangian methods.

There are two ways to determine the structure of a given flow field. An Eulerian description involves a grid system, while a Lagrangian description does not require.

More developments of helicopter aerodynamics may refer to the review of Conlisk (1997)[15].

3.0 ICE ACCRETION PREDICTION

3.1 Design of Icing simulation codes

There are several purposes in ice accretion prediction:

(1) To obtain estimates of ice accretion (impingement limits, catch rates, local and global collection efficiencies). These estimates are used in the design and research of ice protection system.

(2) To predict ice shapes on the blade surface. These shapes can be used in wind-tunnel test and flight tests.

(3) To predict the effects of ice accretion on aerodynamic performance and flight dynamics of helicopters. These results can be used to evaluate the helicopter flying qualities.

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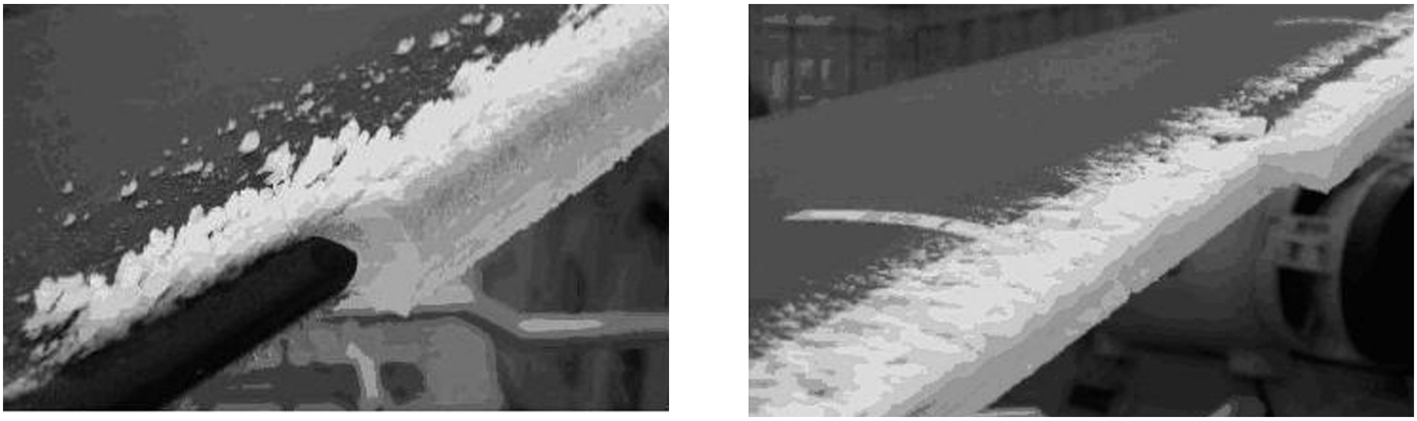

(a) Glaze ice and ice shedding without regrowth.

(b) Glaze ice and ice shedding with regrowth.

Figure 3. A part of the results of the S-92A man-made icing test. From Flemming (2004)[19].

Currently, ice accretion can be conducted through physics simulation and numerical simulation.

Physics simulation can obtain some experiment data through ice wind tunnel and other man-made icing conditions tests. The typical ice wind tunnels around the world include NASA IRT, Lockheed ice wind tunnel, Boeing ice wind tunnel, high speed ice wind tunnel at Canada, ONERA ice wind tunnel of France, CIRA ice wind tunnel of Italy. These facilities have been used to do many works in 2D aerofoil icing research. The early works focus on several typical aerofoils such as NACA0012, however, there is a lack of modern aerofoils used in today's aircraft design. Thus, NASA and FAA conducted a research on modern aerofoil icing in 1980s. This work was reported in the paper by Addy (1997)[16,17]. In addition, the Canada NRC icing tower, which is perhaps not used any more, and US Army Helicopter Icing Spray System (HISS) are special facilities for helicopter icing research (see Figs 1 and 2)[18]. They play an important role in the validation of icing protection system of helicopter and in the determination of helicopter performance in icing condition. However, these facilities fall short of simulating some icing conditions, such as those being affected by seasons.

Flemming (2004)[19] depicts in detail the man-made icing tests of S-92A in McKinley Climatic Laboratory. Currently, the certification of S-92A is conducted in nature icing conditions. Figure 3 presents a part of results of S-92A man-made icing test.

However, due to constraints of natural condition, cost and of available time associated with model fabrication and for extensive wind-tunnel tests or flight tests, Computational Fluid Dynamics (CFD) was considered an alternative means of providing icing simulation and aeromechanic performance analysis. Therefore, numerical simulation is a compensatory or substitution method for physics simulation. The typical numerical simulation tools include LEWICE developed by NASA Lewis Research Center, ONERA 2D/3D developed by ONERA in French, IMPIN3D developed by Italy, and the second-generation 3D icing simulation system FENSAP-ICE developed by Newmerical Technologies International and so on. These tools are efficient in predicting 2D aerofoil ice shapes. Wright *et al* compared the result of LEWICE with the experiment data in series papers. The latest version of this code is LEWICE2.2, of which Wright has summarised the validation in 2002[20]. Figure 4 shows the comparison between experiment data and LEWICE 2.0 calculation, which was conducted by Wright in 1999[21].

These tools are similar in configuration. A typical structure of an icing simulation code is shown in the following Fig. 5.

FENSAP-ICE is a new generation 3D icing simulation system. It contains several subroutines listed in the following:

FENSAP (Finite Element Navier-Stokes Analysis Package): a 3D compressible inviscid Euler or viscous turbulent Navier-Stokes equations solver;

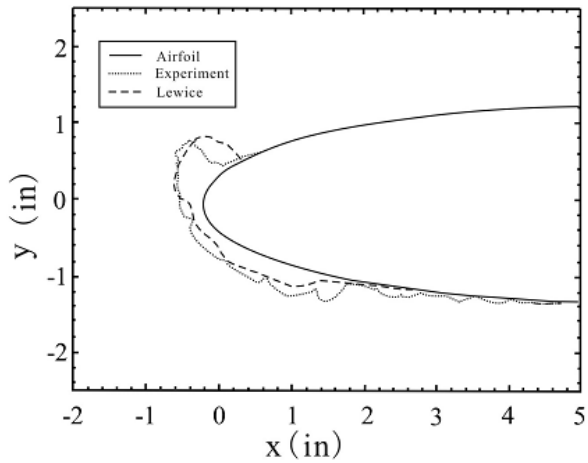

Figure 4. Comparison between calculation and experiment. From Wright (1999)[21].

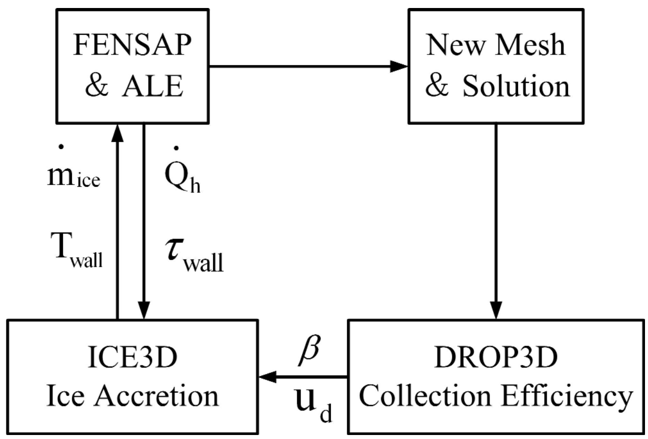

Figure 5. Module interaction within ICE3D. From Habashi (2003)[22].

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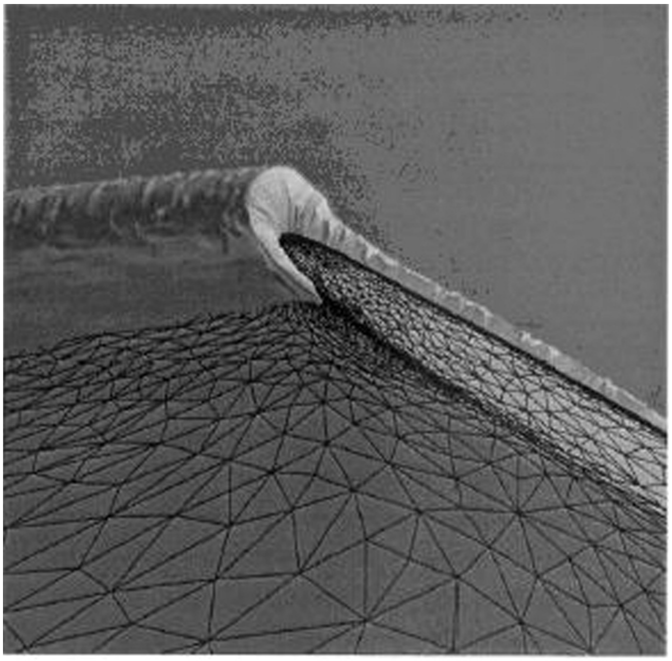

Figure 6. Application of FENSAP-ICE to blade tip ice accretion. From Habashi (2003)[22].

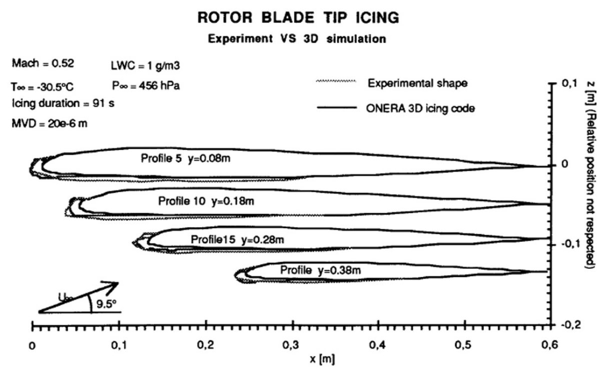

Figure 7. Comparison between calculation result of ONERA and experiment data. From Hedde and Guffond (1992)[29].

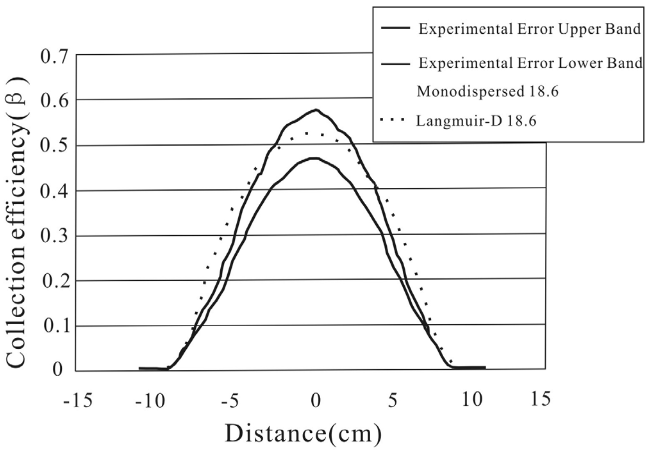

Figure 8. Comparison of DROP3D and experiment for collection efficiency on a sphere. From Narramore (2002)[24].

ALE: an automatic assistant grid tool (based on Arbitrary Lagrangian Eulerian scheme) used by FENASP;
DROP3D: a 3D collection efficiency solver with Eulerian method;
ICE3D: a 3D ice accretion shapes prediction program;
CHT3D: a 3D program conjugating heat transfer evaluation across the skin, which is used in the ice accretion process simulation of **FENSAP-ICE** but not shown in Fig. 5.

All these programs are based on PDE (Partial Differential Equations). FENSAP is an airflow solver based on FEM (Finite Element Method). It can solve flow field of complex geometry configurations, especially in engineering applications. DROP3D employs an Eulerian droplet impingement model that is essentially a two-phase flow (two-fluids) model consisting of Euler or Navier-Stokes equations for air. It overcomes the shortage of Lagrangian approach and reduces CPU times and RAM (random access memory). Crock (2002)[23], Habashi (2003)[22], Narramore (2002,2003) *et al* [24,25] detailed the structure and characteristics of FENSAP-ICE and its application in analysing the ice accretion of Bell-Augusta 609 tiltrotor vehicle (see Fig. 6).

In 3D ice accretion modeling, another attempt is ICECREMO developed in UK. This is a collaboration project between British Aerospace, Rolls-Royce, GKN-Westland Helicopters Limited, and DERA. This software package implement a modified theoretical model to deal with the problem of ice accretion when flowing water film occurs. A detail description of the model can refer to a paper by Myers *et al* (2002)[26] and the content of ICECREMO can be found in the paper of Bartlett (2000)[27] .

3.2 Validation of computer codes

In order to validate the analysis and calculation tools, icing tests must be conducted to document ice shapes formed on not only blades but also other components of helicopters/rotorcraft, which affect the operational performance of vehicles. In addition, comparing new tools with the validated ice accretion codes is also a common requirement for icing simulation analysis.

Flemming (2002)[28] overviewed the works in helicopter icing research at Sikorsky in the past several decades, especially in the past twenty years. The data obtained in the works are very useful to develop new analysis and calculation tools on helicopter icing.

Several studies have been conducted to validate ONERA 2D/3D. Hedde and Guffond (1992)[29,30] compared the predictions of these codes with the experimental data, including rotor blade tip icing. The comparison between calculation and experiment shows that the result of calculation has some shortage. To overcome the shortage, Hedde *et al* developed a ballistic model and defined the initial standard of ice accretion. It should be noted that ONERA 2D/3D solve an inviscid flow, which is governed by Eulerian equations, and the effect of this predigesting on ice shapes should be considered in the simulation. A typical result of comparison between experiment and 3D simulation is shown in Fig. 7.

A detailed comparison of the FENSAP-ICE computed ice accretion locations and shapes with the NASA Glenn Icing Research Tunnel (IRT) measurement by Narramore *et al* was conducted (see Figs 8 and 9). In this comparison, FENSAP-ICE was used to compute ice accretion for the following situations: an angle-of-attack of 3·1deg, an altitude of 821m, a static temperature of –20°C, a far field fluid speed of 359Km/h, a LWC of 0·3g/m^3, and monodisperse droplet diameter of 19·2 μm for 15 minutes of ice accretion. In this study, the generated ice would be a typical rime ice, which is the simplest ice for simulation. The computational result was compared to the NASA Glenn IRT experiment data and LEWICE computations. The result of this study indicates that FENSAP-ICE approach gives ice shapes that are consistent with experimental data and LEWICE computations.

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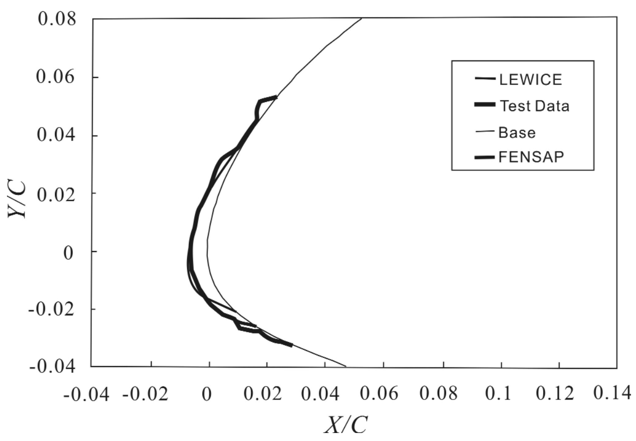

Figure 9. Comparison of 2D ice accretion from FENSAP-ICE, LEWICE and IRT test results. From Narramore (2002)[24].

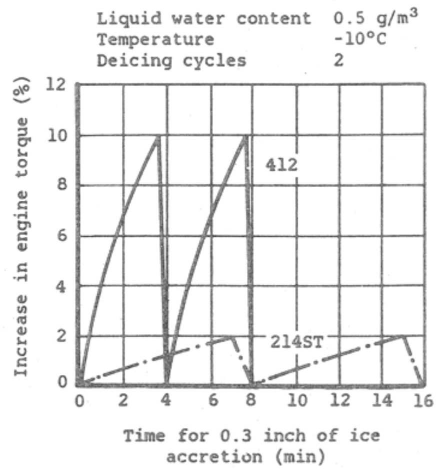

Figure 10. Torque increase *vs* time. From Coffman (1983)[18].

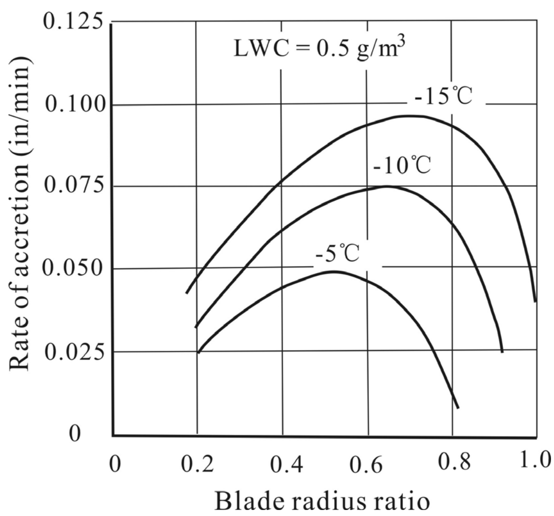

Figure 11. Typical rotor ice-accretion rates. From Coffman (1983)[18].

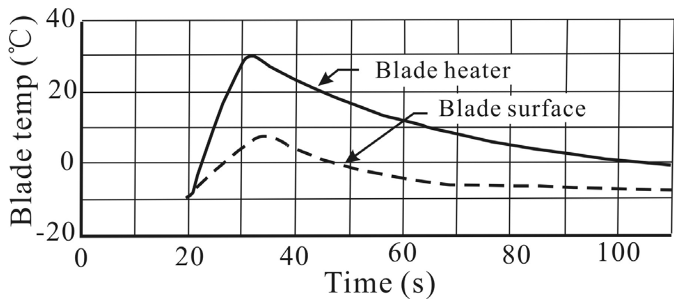

Figure 12. Time history of blade heater and surface temperature for 214ST: OAT, –15°C; LWC, 0·5g/m^3; airspeed, 120kt. From Coffman (1983)[18].

4.0 PERFORMANCE OF ICING PROTECTION SYSTEM

Icing protection system is required to prevent ice accretion on not only main rotor blade but also other helicopter components.

H.J. Coffman Jr (1983)[18] summarises the development and qualification tests for the main rotor deicing system on the Bell 214ST and 412 helicopters. The test conditions include man-made icing conditions of NRC Low-Temperature Laboratory icing tower at Ottawa and U.S. Army Helicopter Icing Spray System (HISS) and natural icing conditions. The results involved three points:

(1) The effects of blade chord: The curves presented in Fig. 10 show that the 33-inch-chord blade on the 214ST sustains about one-fifth of the percent torque rise between deicing cycles as the 17-inch-chord blade on the 412. Since the 214ST and 412 rotor tipspeeds are nearly the same and the aerofoils are very similar in shape and thickness, it is concluded that the difference in icing effects is due to overall blade size (i.e., chord).

(2) Aerodynamic heating effects on ice accretion: a typical rate of accretion *vs* blade radius ratio at various temperatures is showed in the Fig. 11. It shows that aerodynamic heating provides a significant reduction in blade ice accretion at ambient temperatures down to about –10℃.

(3) Heating temperature effects on ice accretion: The result of experiment on a 214ST aerofoil shows that heating of the leading-edge blade surface to about +7℃ appears to remove ice adequately without causing any significant runback water (see Fig. 12).

In addition, author also discussed the blade deicing sequence. Icing tests showed that ice was often not removed at the junction of two zones using the deicing sequence presented in the left of Fig. 13. The blade de-icing sequence was changed to what shown in the right of Fig. 13, and the problem was completely solved.

Flemming (2002)[27] reviewed the development of icing protection systems of the BlackHawk helicopter. He analysed the data gained in the scale and full size aerofoil and rotor icing test, discussed the methods of developing icing protection systems.

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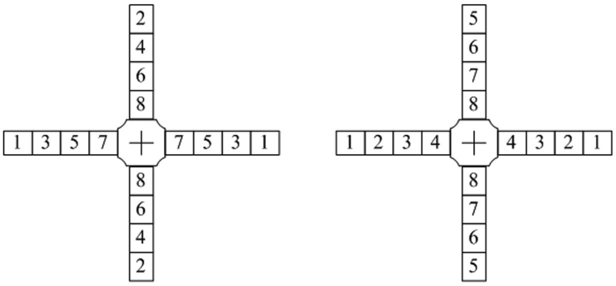
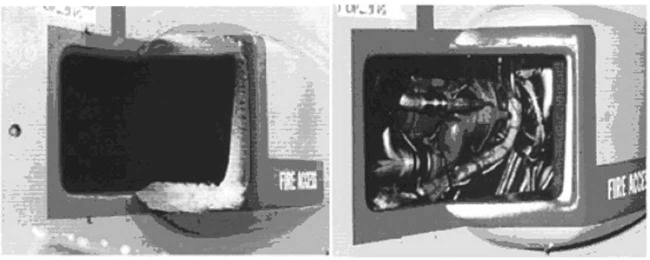
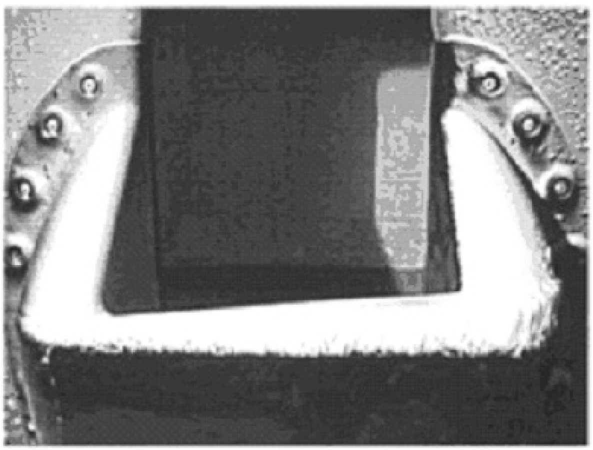


Figure 13. Deicing sequence of Model 412. Described by Coffman (1983)[18].



(a) Rime ice during flight on scoop 2 (b) Glase ice during flight on scoop 2



(c) Rime ice on scoop 2 with full size fairing

Figure14. Results of EH101 icing program.
From Al-Khai, Irani and Rowley (2002)[31].

Al-Khai, Irani and Rowley (2001)[31] conducted an icing program of engine cooling bay inlets of EH101 (see Fig. 14). They analysed the result of icing and de-icing system.

At present, several useful analysis and calculation tools have been established, such as LEWICE/Thermal and ANTICE. Both of them are developed at NASA GRC (Glenn Research Center). The former calculates the two-dimensional transient heat transfer in a composite body. It can handle multiple layer bodies, composite materials with anisotropic material properties, individually controlled heaters with separate on/off times and power densities, as well as ice growth with or without heater, ice shedding and water runback. The ANTICE is also a two-dimensional code of a composite structure with embedded heater. The code has a rivulet model, which is used to model the individual narrow streams of water on the surface, to simulate the flow of runback water on the surface. Miller *et al* (1997)[32] described the experimental setup to validate both codes for a NACA0012 aerofoil.

5.0 EFFECTS OF ICE ACCRETION ON HELICOPTER PERFORMENCE

It is well known that ice accretion caused the largest lift decrease and drag increase among all the ice shapes investigated in the earlier study. J. Shim (2001)[33] presented a computational investigation of ice geometry effects on aerofoil performance, i.e. a sharp drag rise and reduction of maximum lift for ice-contaminated aerofoils.

Ice accretion on main rotor has very bad effects on helicopter performance. It affects the total lift, power etc. In addition, the effects of ice accretions on the inlets, cooling bay inlets, tail rotor etc are also disadvantageous.

H.J. Coffman Jr (1983)[18] conducted a test about the effects of icing conditions on helicopter performance. The result of this test showed the beneficial effects of aerodynamic heating of the rotor blade that is shown in Fig. 15. These data showed that at –10℃ the performance loss for the 214ST is an 11% torque increase. In light icing conditions the helicopter would fly one hour before this maximum performance degradation would occur.

Flemming, Mutry, Papadakis and Wong (2004)[19] analysed the icing test of S-92A in 2004.

Britton, Bond and Flemming (1994)[34] discussed the icing test on model rotor. In Flemming's and his partner's research, the LEWICE code is used to obtain ice shape, and B-65 (from Boeing) and GRP (Sikorsky Generalised Rotor Performance) code are used to model the iced rotor performance. And the iced rotor performance in different icing time is calculated, which is conducted in a constant collective condition, also the performance at different ambient temperature from –25℃ to 0℃ is completed. The comparison between experiment data and the calculation results of GRP shows that they match each other very well (see Figs 16 and 17).

Nowadays, numerical simulation can become a useful tool alongside experiments. Flemming (1985)[35] developed an empirical method based on the experimental data. However, since it is a correlation derived from an empirical set of experimental data, it may have some limitations in terms of general application to full-scale rotors.

Kwon and Sankar (1992)[36] analysed the hover performance of helicopter with ice accretion through solving three-dimensional compressible Navier-Stokes equations (Fig. 18).

Britton (1992)[37] developed an analytical method to predict helicopter main rotor performance in icing conditions. This method uses IBL (Interactive Boundary-layer) analysis to gain the characteristics of each blade element, and then use these characteristics in lifting line theory to predict performance (see Figs 19 to 22).

According to the result, it is found that the jobstream is not so satisfied in torque rise prediction, though this method has advantage over the empirical method. The author also notes this point and hopes this method can improve the predictions of full-scale data.

Nowadays, many manufacturers predict helicopter performance using analytical packages based on lifting line theory. These codes include the Sikorsky Aircraft Generalised Rotor Performance (GRP) method, the Boeing Helicopter B-65 tool, the Sikorsky General Helicopter (GenHel) Code etc. Flemming *et al* compared the prediction performance in icing conditions with the model experiment data gained in 1994[38] and 1995[39].

6.0 CHALLENGES IN HELICOPTER ICING SIMULATION

As compared with aircraft, icing simulation for helicopters faces many greater challenges. These challenges are not only on physical simulation but also on numerical simulation.

As for physical simulation, the helicopter's short range essentially forces researchers to sit and wait for the correct weather conditions rather than seeking them out. Currently, flight test of helicopters in nature icing conditions is affected by weather and geography, and

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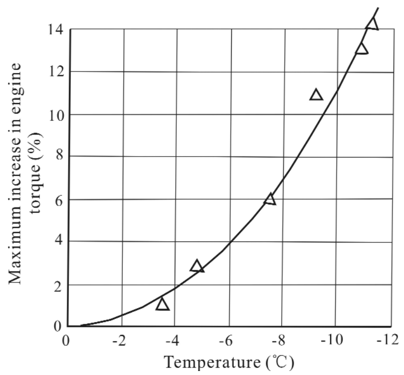
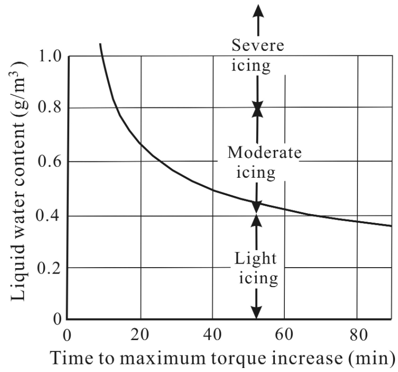


(a) Maximum torque increase vs temperature



(b) Effect of icing conditions on time to maximum torque increase

Figure 15. Icing conditions effects on helicopter performance. From Coffman (1983)[18].

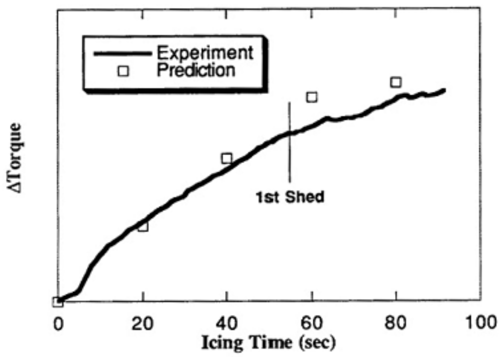


Figure 16. Comparison between experiment and theory for torque rise. From Britton, Bond and Flemming (1994)[34].

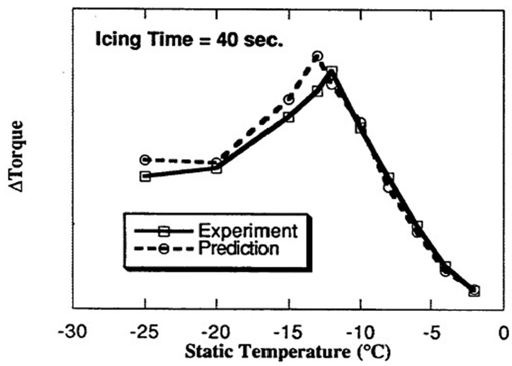


Figure 17. Comparison between experiment and theory for torque rise as a function of temperature for an icing time of 40sec. From Britton, Bond and Flemming (1994)[34].

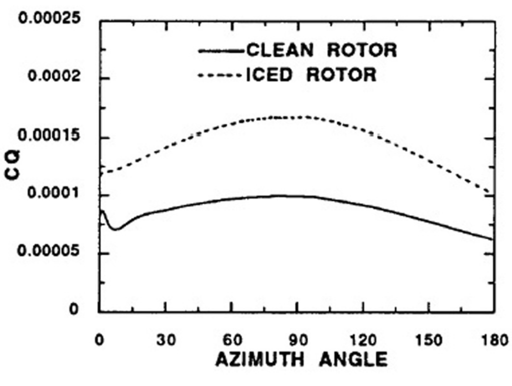


Figure 18. Required torque vs. azimuth angle for the non-lifting rotor in forward flight in CFD analysis. From Kwon and Sankar (1992)[36].

man-made icing conditions could not simulate nature-icing conditions in some required icing conditions.

There are also some difficulties in numerical simulation for helicopter icing:

(1) the unpredictable behavior of water on the blade surface: The flapping and lagging of rotor blades make this problem more serious than fixed-wing aircraft.

(2) the non-uniform flow around the blade: The velocity of flow varies from root to tip of the blade. It even can achieve local transonic zone at the tip of blade. The complex of rotor flow makes it difficult to simulate the flow field and its effects on the ice shape.

(3) ice-contaminated surface roughness: When ice starts accumulating, the resulting surface roughness varies significantly from one case to another and from one location on the blade surface to another. Roughness plays a key role on the heat transfer between the water and the airflow. The final ice shape is very sensitive to the evolution of local surface roughness.

In addition, ice density may experience an important contribution to ice shape formation and shedding. Because of centrifugal effect, the icing shedding near the blade tip is also difficult to simulate.

All these problems make it more difficult to simulate helicopter icing as compared with aircraft icing. Assumptions and simplified models have to be made in order to solve this complex problem numerically. Current models and empirical methods work reasonably well in some cases, but in some other cases they are inadequate.

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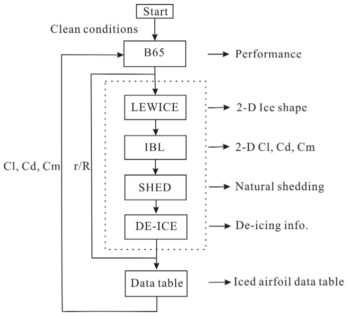

Figure 19. Helicopter performance in icing prediction jobstream. From Britton (1992)[37].

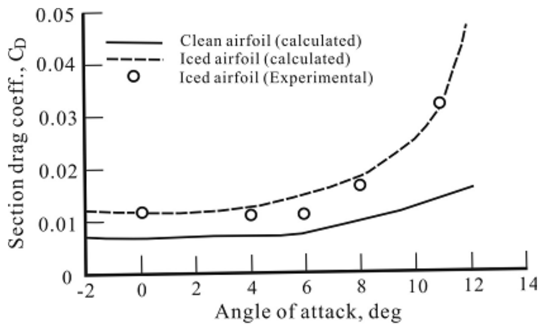

Figure 20. Comparison between experiment and theoretical prediction of IBL procedure (Φ = 4°, V = 58ms^{-1}, T_s = –27·8, LWC = 1·0g/m^3, MVD = 12μm, τ = 5min). From Britton (1992)[37].

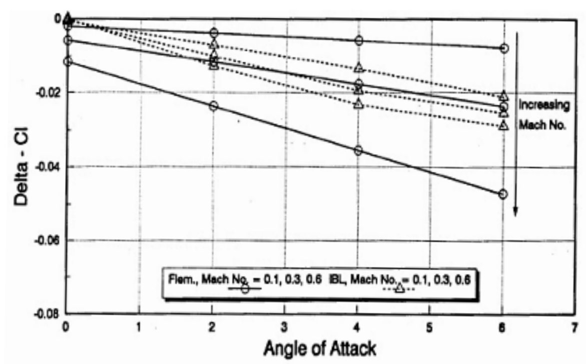

Figure 21. Comparison of IBL procedure and empirical method on (LWC = 0·5g/m^3, MVD = 15μm, μ = 0·197, ΩR = 205·7ms^{-1}, CL/σ = 0·064, T_s = –15). From Britton (1992)[37].

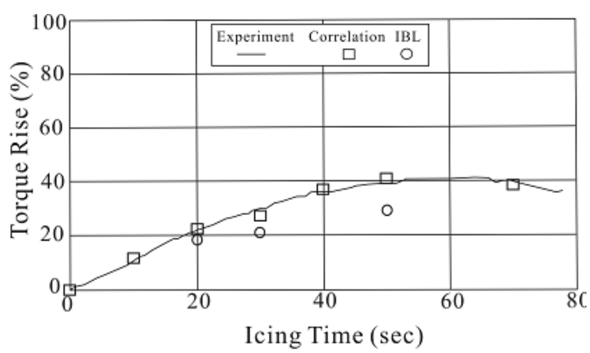

Figure 22. Comparison of rotor torque prediction (LWC = 0·5g/m^3, MVD = 15μm, μ = 0·197, ΩR = 205·7ms^{-1}, CL/σ = 0·064, T_s = –15). From Britton (1992)[37].

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