48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition
4 - 7 January 2010, Orlando, Florida

AIAA 2010-1237

Ice Accretion Effect on the Aerodynamic Characteristics of KC-100 Aircraft

S. K. Jung[1], S. M. Shin[1], R. S. Myong[2] and T. H. Cho[3]
Department of Mechanical and Aerospace Engineering and Research Center for Aircraft Parts Technology, Gyeongsang National University, Jinju, Gyeongnam, 660-701, South Korea

H. H. Jeong[4] and J. H. Jung[4]
Research and Development Division, Korea Aerospace Industries Inc., Sacheon, Gyeongnam, 664-710, South Korea

In-flight icing is a serious hazard for flight safety. Ice accretion due to in-flight icing can affect the air flow of an aircraft; for example, it can increase drag, decrease lift, and degrade control authority. Thus, its effects must be checked during design and development by various methods such as theoretical analysis, icing wind tunnel experiments, and flight testing. Traditionally, icing simulation techniques based on the Lagrangian approach for droplet impingement and the potential flow code for aerodynamic simulation have been applied. However, such methods have difficulty in analyzing the icing effect on a full three-dimensional configuration of an aircraft. In this work, in order to realistically compute three-dimensional droplet impingement and ice accretion on an aircraft, an Eulerian model for biphasic airflows containing water droplets was employed. Using numerical simulation, the effect of ice accretion on the aerodynamic characteristics of KC-100 aircraft, particularly, the maximum lift coefficient and the stall, were investigated. Finally, the collection efficiency and the shape of ice accretion on the full-scale KC-100 aircraft were predicted.

I. Introduction

IN-FLIGHT aircraft icing remains an important operation and certification issue far from resolved. In particular, general aviation, commuter aircraft and small transport aircraft are more sensitive to the adverse effects of icing than large commercial transport aircraft because of their absolute size. For example, the large C-5A cargo transport aircraft does not have airframe ice protection because the water collection and resulting ice accretion on such large aircraft is so low. Ice contamination on wings and tail surfaces reduces maximum lift and stall angle of attack, while increasing profile drag. Ice on wings and tail surfaces can be particularly hazardous incidents and have led to the loss of aircraft. Recent trends in the aviation industry, such as the increasingly widespread usage of lower altitude regional aircraft, have also increased the potential for icing incidents and accidents. In addition, concern about the dramatic effects of super-cooled large droplets has forced the icing community to reconsider certification minimum requirements and to re-evaluate the icing environment and the simulation tools used to comply with those requirements. Such concerns have reanimated the research, as well as the review of engineering and certification efforts to tackle the in-flight icing problem.[1-4]

Efforts to understand the effects of ice on performance and flight mechanics started in the 1940s. These were mainly based on experiments and in-flight testing. Among the pioneering works in the field, the published work of Messinger[5] represents an important foundation and a milestone in numerical ice accretion simulation. Mingione and Brandi[6] presented results on ice shape simulation over multi-element airfoils. They described and compared different ways to solve the transient ice accretion problem, i.e., the single-step, multi-step and predictor-corrector methods. In a review paper, Gent et al.[2] presented the background and the status of analyses addressing the aircraft icing problem. Methods for water droplet trajectory calculation, ice accretion prediction and aerodynamic performance degradation were discussed and recommendations for further research made. Myers[7] presented a one-

[1] Graduate Student, Department of Mechanical and Aerospace Engineering.
[2] Professor, Department of Mechanical and Aerospace Engineering, myong@gnu.ac.kr, and AIAA Member.
[3] Professor, Department of Mechanical and Aerospace Engineering.
[4] Research Engineer, Research and Development Division.

dimensional mathematical model, extending the original Messinger model describing ice growth. It was demonstrated that the model can also be extended to two and three-dimensions. Myers et al. [8] also discussed a mathematical model for water flow under glaze ice conditions. Fortin et al. [9] proposed an improved roughness model, in which the water state on the surface is represented in the form of beads, film or rivulets. This model was tested for severe icing conditions at six different temperatures corresponding to dry, mixed and wet ice accretion.

The numerical simulation of ice accretion and aerodynamic performance penalties has been traditionally based on the Lagrangian particle tracking techniques for droplets impingement, such as the NASA LEWICE[10] and ONERA codes[11] using the inviscid panel or Euler plus boundary layer correction computations for air flow. However, if solving the compressible Navier-Stokes equations, one can fully and more directly account for the influence of the viscous effects on the degradation of performance. Such a method is more natural to compute ice accretion on airfoils by an Eulerian model rather than the traditional Lagrangian particle tracking approach. Droplet velocity and the volume fraction of water would have to be computed only at the nodes, where the air flow variables are determined, and no particles would have to be tracked as they go through the mesh as in a Lagrangian approach.

In this study, the effects of ice accretion on the aerodynamic characteristics of KC-100 (KAI Civil) aircraft were investigated using the Eulerian approach instead of the traditional Lagrangian particle tracking approach, since such a method has difficulty in analyzing the icing effect on a full three-dimensional configuration of an aircraft. In the first step, an airfoil at mid-section of the main wing is considered in order to analyze the ice accretion effect on aerodynamic characteristics (lift and drag coefficients and stall). The computational model derived from the compressible Navier-Stokes equations, droplet impingement method based on an Eulerian approach, and ice accretion module utilizing the shear stress and heat flux on the solid wall were applied in the icing simulation. The finite element method and finite volume method were applied to the droplet impingement module and ice accretion solvers, respectively.

II. Numerical Simulation

To simulate the flow fields around a clean KC-100 aircraft, the compressible Navier-Stokes equation based on the finite volume method was used. The Spalart-Allmaras model was employed as the turbulence model for the Reynolds Average Navier-Stokes equations. To simulate the aerodynamic effects due to ice accretion, the commercial program, FENSAP-ICE[12-15], was used. This is an aid-to-certification tool to achieve in-flight icing protection and a virtual tunnel that simulates aerodynamics and icing: flow, impingement limits, ice shapes, aerodynamic performance and anti- and de-icing heat loads. The droplet impingement (DROP3D) is based on an Eulerian approach augmented by droplet-related continuity and momentum equations. It solves the fine-grain partial differential equations for droplet velocity and concentration everywhere in the field. It yields collection efficiency (β) distributions, impingement patterns and shadowing limits for droplets over arbitrarily complex bodies or in internal passages. Ice accretion (ICE3D) solves fine-grain partial differential equations for thermodynamics and yields the three-dimensional shape of ice and the water film thickness on complex three-dimensional surfaces. Fig. 1 shows a process for simulating the aerodynamic effects of ice accretion. First of all, aerodynamic grids are required to simulate the flow-field around the clean shape without ice contamination, and then water droplet impingement is calculated by droplet continuity and momentum equations based on the air solutions. From the droplet impingement solver, collection efficiency is obtained. It is applied to an ice accretion solver based on the continuity and energy equations. Finally, a change in shape due to ice accretion is needed to move the original mesh toward the changed shape. While the mesh is moved, an Arbitrary Lagrangian Eulerian (ALE) which accounted for the relative motion of the grid with respect to the fluid was applied. Those procedures were repeated during user-defined simulation time.

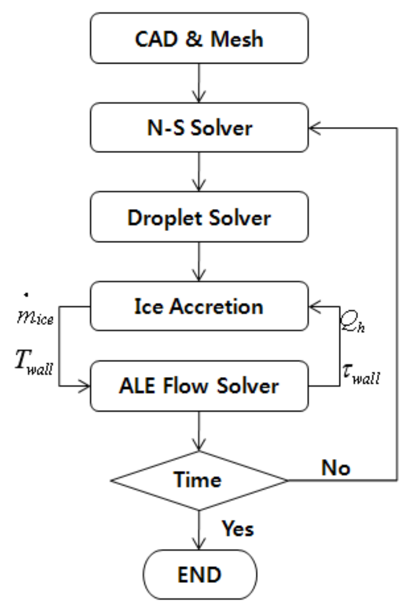

Figure 1. Flowchart

A. Droplet Impingement

The droplet impingement was based on an Eulerian approach proposed by Bourgault et al.[12-13] It was essentially a two-fluid model, which was an air and water, consisting of the set of Navier-Stokes or Euler equations, augmented by droplet-related continuity and momentum equations. Droplets clouds, however, usually present themselves with a distribution of droplet diameters instead of droplets of the same size. One common distribution definition is called the Langmuir D distribution. The resulting collection efficiency and impingement limits can differ slightly for these two approaches to modeling cloud contents. [12]

B. Ice Accretion

Ice accretion is mainly divided in two due to icing conditions, such as rime and glaze icing. In the case of the rime the shear stress and heat flux are not considered since the droplet is simultaneously iced as soon as droplet impingement occurs on the solid surface. However, droplets in glaze condition are moved in streamlined direction. Therefore, the shear stress and heat flux should be considered. This means that the Navier-Stokes equation should be calculated to employ the shear stress and heat flux in the ice accretion solver. In this study, the FENSAP commercial code[14-15] was used to simulate droplet impingement and ice accretion on the surface of a KC-100 aircraft.

III. Results

A. Wing Section of the KC-100 Aircraft

A wing with an airfoil cross-section shape is used to generate aerodynamic lifting force to support the aircraft in flight. But when the wing is exposed to ice conditions, it has penalties for aircraft performances. Changes in the wing section due to ice accretion induce a decrease in the lift and an increase in the drag. This is directly related to aircraft performance. In this study, aerodynamic characteristics on the iced wing section of KC-100 aircraft were investigated and then droplet impingement of a whole KC-100 aircraft was calculated as preliminary research for the anti-icing equipment. Also, a simulation was performed on the cases of ice conditions under FAR 25 Appendix C.

Table 1 Various conditions under FAR 25 Appendix C.

Cases	T($°C$)	LWC(g/m^3)	MVD(μm)
1	-0.6	0.788	15
2	-10	0.6	15
3	-15	0.3	15
4	-30	0.2	15
5	-0.6	0.448	25
6	-10	0.305	25
7	-15	0.229	25
8	-30	0.099	25
9	-0.6	0.255	35
10	-10	0.154	35
11	-15	0.117	35
12	-30	0.049	35

The effects of ice accretion on the aerodynamic effects of the airfoil were analyzed using the glaze ice accretion module for the cases selected from the ice condition specified in Table 1, since the icing type is not well classified on the boundary between rime and glaze conditions. Moreover, the effects of glaze icing were expected to be quite limited at very low temperatures. Therefore, the glaze ice module was applied to all cases. Langmuir D distribution was also employed to represent the physical cloud droplets. The flight time exposed to the ice condition was assumed to be 15 minutes, the Mach number was 0.24 and the air temperature is -0.6 Celsius. The angle of attack of a section of the main wing is two degree. In the FAR 25 flight endurance time was fixed at 45 minutes under an icing condition. However, deicing equipment on the KC-100 aircraft is supposed to go into operation within 15 minute of detecting the ice accretion. Figs. 1 and 2 show the collection efficiency and the change of lift and drag coefficients by ice accretion. Fig. 2 shows that the mean volume diameter (MVD) has a dominant effect on the collection efficiency more than other parameters. Fig. 3 indicates that the aerodynamic coefficients depended not only on MVD but also on LWC. In the same MVD the aerodynamic effectiveness of lift and drag are accounted for in the LWC. This makes sense since ice accretion increased where LWC was high. Fig. 4 shows the aerodynamic effects due to the angle of attack under special ice conditions, such as when the LWC, MVD, Mach number, air temperature and exposure time were 0.12 g/m^3, 35 ㎛, 0.24, -0.6 °C, and 15 min., respectively. This indicates that the maximum lift coefficient and the stall angle of the iced airfoil were reduced about 38.3% and 25%, respectively. Furthermore, the drag coefficient was increased about a maximum of 250%.

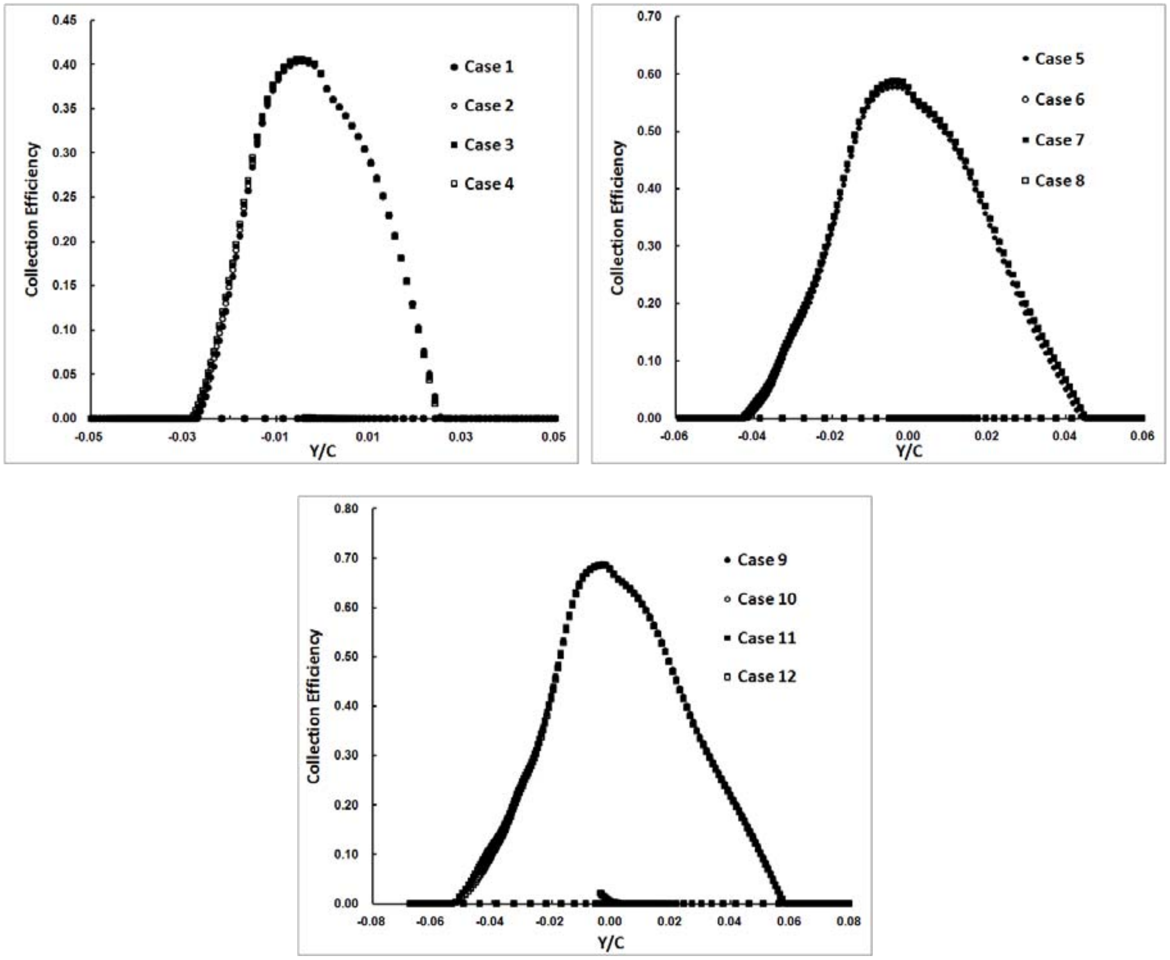

Figure 2. Collection efficiency on the airfoil of KC-100 aircraft w.r.t. MVD, LWC. Temperature variations are represented with the same indices.

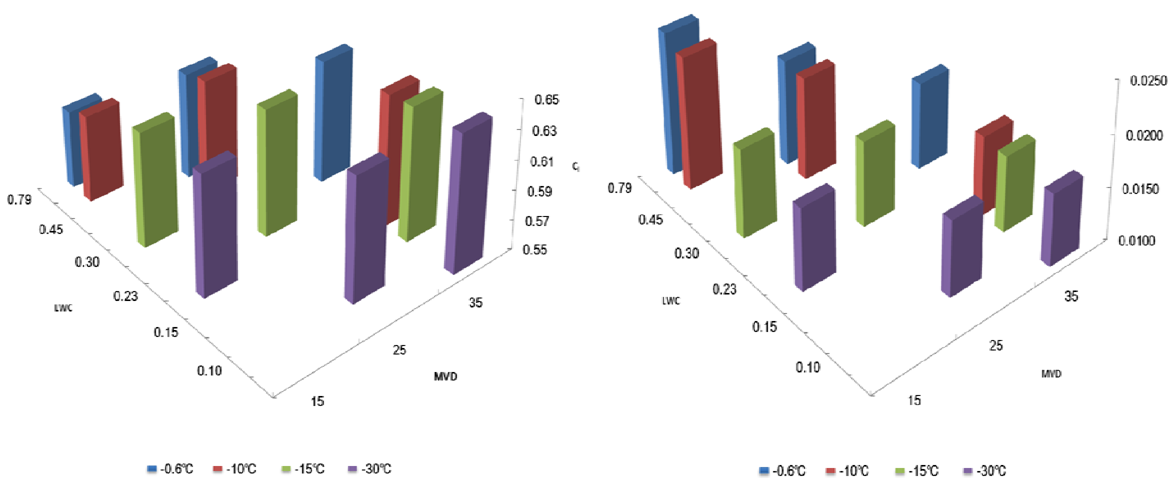

Figure 3. Lift (left) and drag (right) coefficients w. r. t. MVD, LWC. Temperature variations are represented with the same color.

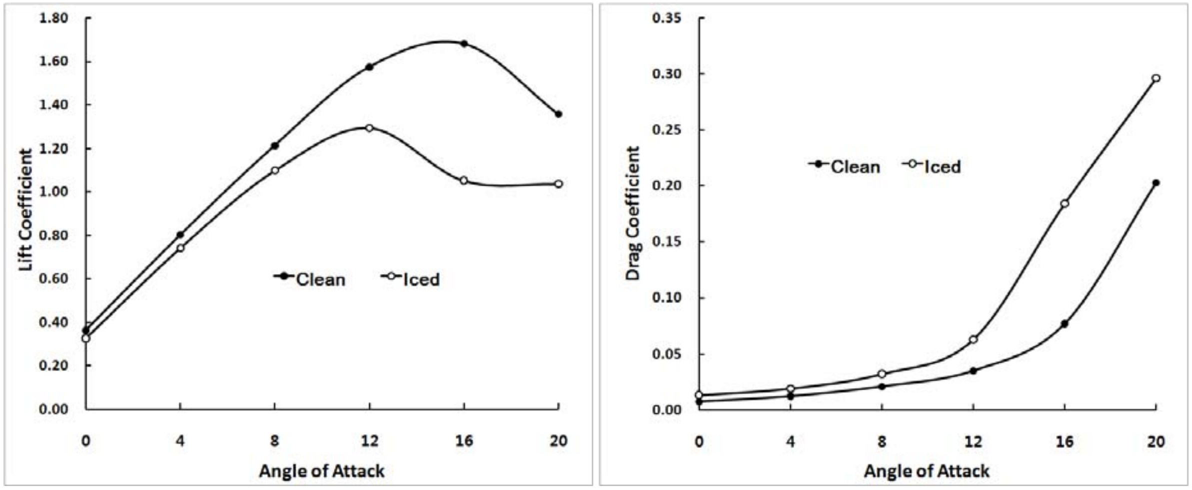

Figure 4. Lift (left) and drag (right) coefficients of a wing section at various angles of attack (LWC: 0.12 g/m^3, MVD: 35 ㎛, temperature: -0.6°C, Mach: 0.24, time: 15min.)

B. Full Configuration of KC-100 Aircraft

The proper assessment of ice accretion effects on three-dimensional wings, tails, winglets, etc. becomes somewhat more complex because, in addition to all of the factors critical in assessing two-dimensional airfoil effects, it becomes necessary with three-dimensional configurations to determine and account for the spanwise variation in stall initiation on the clean configuration, because it can be a critical factor in establishing subsequent lift and pitching moment changes caused by ice accretions.

In this study, ice accretion on three-dimensional full-scale KC-100 aircraft model was investigated as preliminary research for anti-/de-icing equipment. The propeller of the KC-100 aircraft was not considered in this simulation of ice accretion while the Mach number and air temperature were the same as in previous section. LWC, MVD and exposure time were 0.7 g/m^3, 15 ㎛, 22.5 and 45 minutes, respectively. As an icing type, rime ice was employed. Fig. 5 shows the collection efficiency and the shape of ice accretion of the KC-100 aircraft found at the leading edge of the main wing, the horizontal and vertical tails, the wind shield, and the nose. Since the propeller effect was not included, collection efficiency and ice accretion on the nose and wind shield were found more pronounced.

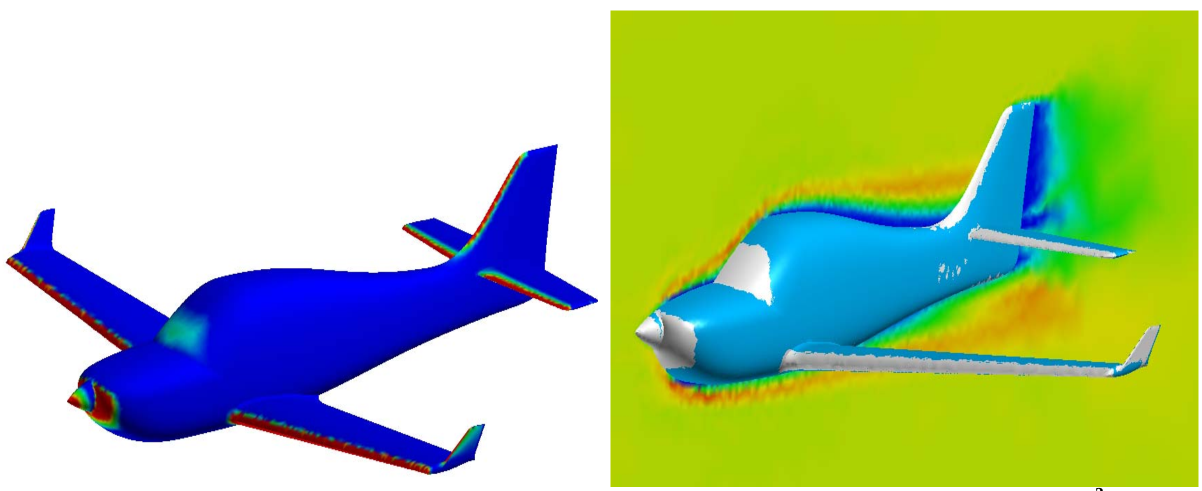

Figure 5. Collection efficiency (left) and ice accretion and LWC contours (right) (LWC: 0.7g/m^3, MVD: 15 ㎛, temperature: -0.6°C, Mach: 0.24, time: 22.5min.)

Fig. 6 shows the comparisons of the iced and clean main wing for the exposure times of 22.5 and 45 minutes, respectively. In a sense the more exposure time increases, the greater the ice accretion on the wing and wing tip.

Because LWC, MVD, air temperature and Mach number were fixed, captured areas due to droplet impingement showed almost no difference between 22.5 and 45 minutes. Three-dimensional ice effects were observed at a part connecting wing tip with the winglet; for example, reduction of ice accretion. Those ice accretions may influence the local angle of attack at which the winglet and the wing flow separation, and stall, occur. The lift and drag coefficients of KC-100 aircraft due to ice accretion were compared to the clean shape in Table 2. The lift coefficients of the iced shape for exposure time were reduced about 64.28%. Furthermore, the drag coefficients increased about 6.89%, and 55.17% respectively.

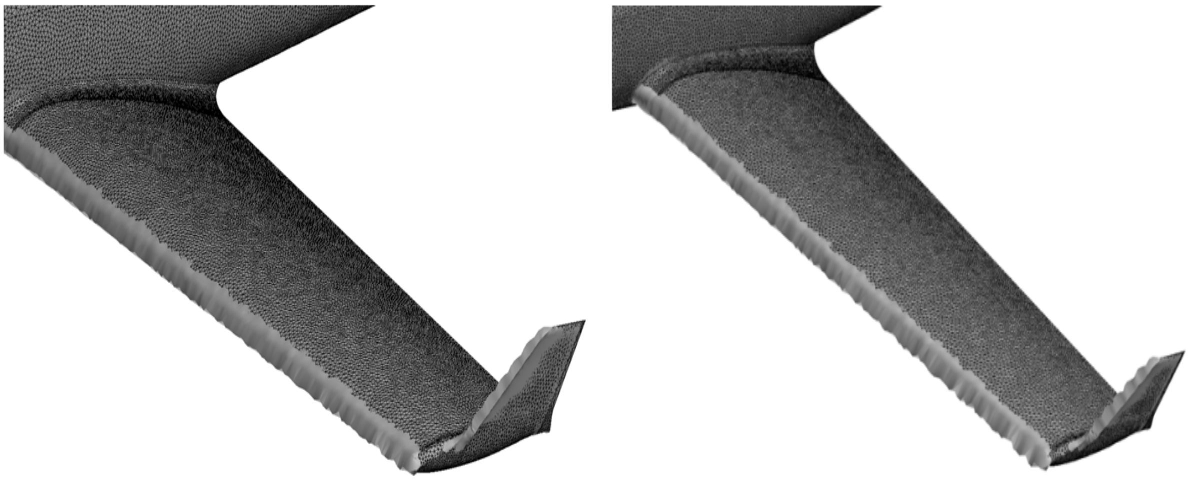

Figure 6. Ice accretion on the main wing (LWC: 0.7g/m^3, MVD: 15 μm, temperature: -0.6°C, Mach: 0.24, time: 22.5 (left) and 45 (right) min.).

Table 2 Comparisons of lift and drag coefficients between clean and iced shape

Cases	C_L	C_D	Cases	C_L	C_D
Clean	0.322	0.029	Clean	0.322	0.029
Iced (22.5 min.)	0.115	0.031	Iced (45 min.)	0.115	0.045
Loss (%)	64.28	6.89	Loss (%)	64.28	55.17

IV. Conclusion

In this study the effect of ice accretion on the aerodynamic characteristics of the KC-100 aircraft was investigated using a state-of-art icing simulation code FENSAP-ICE. In the first step, an airfoil at mid-section of the main wing was considered in order to analyze the ice accretion effect on aerodynamic characteristics (lift and drag coefficients and stall). Computational models derived from the compressible Navier-Stokes equations, the droplet impingement method based on the Eulerian approach, and the ice accretion module utilizing the shear stress and heat flux on the solid wall were applied in an icing simulation. The effects of ice accretion on the aerodynamic effects of the wing section were analyzed for the cases selected from the FAR part 25 Appendix C. The mean volume diameter (MVD) had a more dominant effect on the collection efficiency than the Liquid Water Contents (LWC). The maximum lift coefficient and the stall angle of the iced wing section in the case considered were reduced about 38.3% and 25%, respectively. Furthermore, the drag coefficient was increased about a maximum of 250%. Those results are similar with those of research by Lynch, F.T. et al.[4] on a single-element airfoil. The aerodynamic coefficients of KC-100 aircraft were compared to those of iced and clean shapes at special exposure times. The lift coefficients were reduced about 64.28%, and the drag coefficients were increased about 6.89% and 55.17%, respectively. Finally the collection efficiency and the shape of ice accretion of the full-scale KC-100 aircraft at the leading edge of the main wing, horizontal and vertical tails, wind-shield, and nose are predicted. In the future the aerodynamic effects caused by icing of the propeller will be investigated.

Acknowledgments

This work was supported by 2nd stage Brain Korea 21 project and the project 'Development of Small Scale Airplane for BASA Certification' of Korea Aerospace Industries and Ministry of Land, Transport and Maritime Aviation Safety R&D Center.

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