T-50 고등훈련기 빙결시험을 위한 과냉각구름 생성시스템 개발

Super-cooled State Cloud Generation System Development for T-50 Supersonic Jet Trainer Icing Test

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Abstract : Icing cloud generation system was developed to perform the in-flight icing simulation test for T-50 Supersonic Jet Trainer on the ground. The developed system successfully generated the almost natural icing cloud in the super-cooled state (liquid state) below freezing point and with the required LWC (Liquid Water Content). For full-scale aircraft icing test, an icing scaling method was adopted due to the limitation of wind generation speed with open-circuit type blower and its applicability was experimentally verified. Under the required in-flight icing condition based on the icing scaling method, T-50 aircraft subsystems were successfully operated and functionally checked.

Keywords : icing cloud, icing test, icing scaling, LWC(Liquid Water Content), super-cooled water droplet

I. Introduction

The in-flight ice accretion on the aircraft has been a safety-critical problem since World-War II [1,2]. For the ice accretion on the aircraft to occur during the flight, the "super-cooled" water droplets suspended in the air are to be collided and frozen on the aircraft surfaces of which temperature is below the freezing point of water. However, the actual ice accretion phenomenon is more complex. There have been many studies to analyze and simulate the in-flight aircraft-icing phenomenon under the icing cloud exposure [3]. Significant progresses in computational analysis and subscale model test in icing wind tunnel have been accomplished, but lack of confidence in the methods requires verification of the icing simulation and analysis by flight tests [4].

For the icing simulation on the ground with full-scale aircraft, it is very difficult to generate the flight-speed wind with open-circuit type wind blower. But Garry Ruff had analyzed and verified Icing Scaling Methods [5,6], which can be applied with the low wind speed. Based on this method, Icing Cloud Generation System was developed, as shown in Fig. 1. The generated icing cloud limitedly covers approximately the lower half of FAR (Federal Aviation Regulation) Part 25 Appendix C Icing Cloud Envelop conditions, which has the low LWC and small MVD (Median Volumetric Diameter). Icing cloud condition of super-cooled liquid state and suspended cloud droplet size almost as natural was successfully made and blown toward the T-50 Supersonic Jet Trainer with engine-run. This paper presents an implementation approach to generate the tiny cloud size droplets in super-cooled state, and an icing scaling application for in-flight simulation for a full-scale aircraft.

II. Icing Simulation and Icing Scaling

An important issue in simulating the natural icing cloud is whether the generated water droplets are super-cooled. The natural icing cloud has the suspended water droplets in the air, which remain in the liquid state in spite of their low temperature below freezing point of water. The size of water droplet is several tens of micrometers, as FAR Part 25 describes. To make this tiny size of water droplet, the air-atomizing nozzles are utilized. However, the rapid expansion of compressed water and air from the air-atomizing nozzle involves crystallization of projected droplets in ambient low temperature. Hence, the air and water in the nozzle are to be heated to prevent freeze-out of the droplets. The second concern is that the heated water droplets have to be cooled down to reach the ambient cold air temperature by the time they enter the test section. During the travel to the test section the droplets become super-cooled by convection during their entrainment in the low temperature airflow.

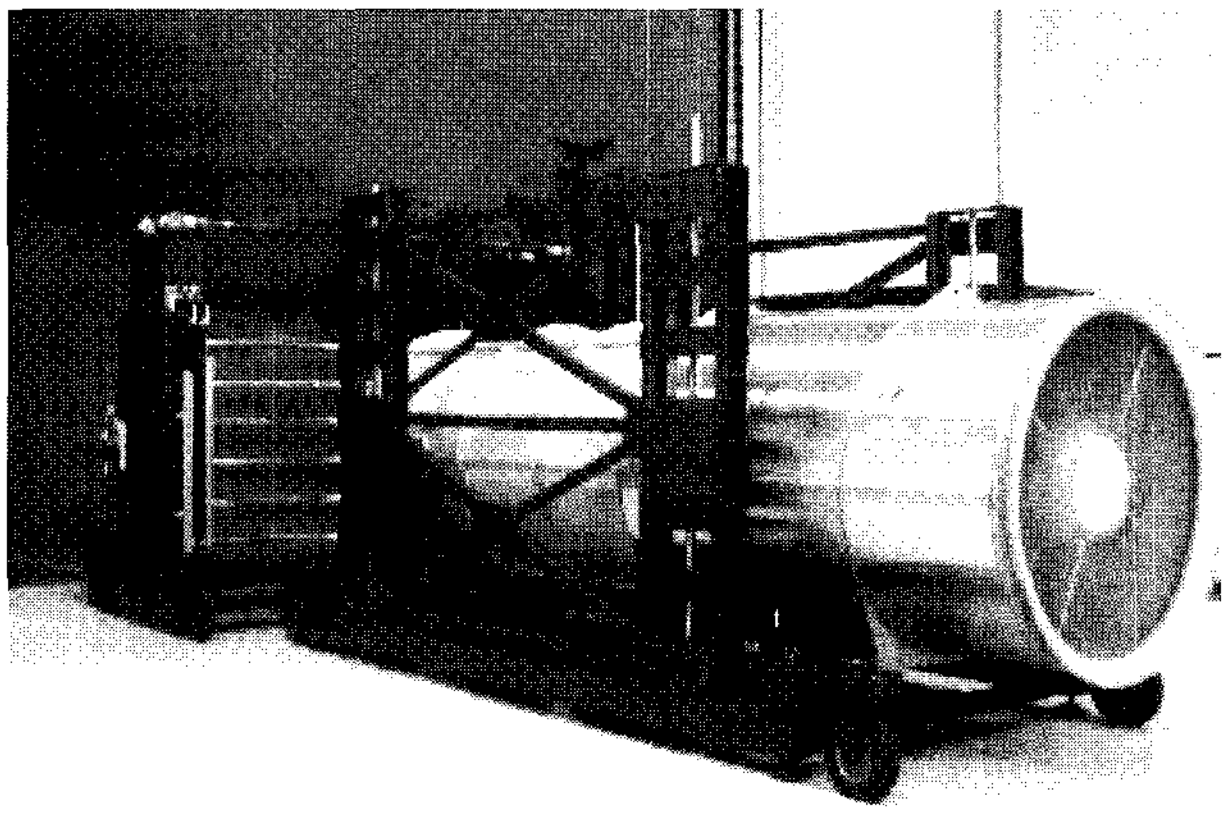

그림 1. 과냉각 구름 생성장비.

Fig. 1. Super-cooled cloud generation system.

$$Ac = LWC \times Wind\ Velocity \times Icing\ Cloud\ Exposure\ Time \quad (1)$$

For full-scale aircraft test on the ground, the icing scaling method was adopted, which is described in equation (1). If the ice accumulation parameter Ac is held constant, the total mass of water impinging on the aircraft surface remains same. From Equation (1) the flight in the icing cloud condition was ground-simulated with the limited wind speed by increasing the icing cloud exposure time and LWC to make the same icing effects.

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III. System Design

1. Droplet size and nozzle selection

The tiny size water droplets as the same as those in natural light icing cloud were generated in the test setup in Fig. 2. To produce tiny size droplets, the atomizing nozzle passes the water through a central channel and injects compressed air into a common cavity before expelling the mist. The nozzle of SSC SU26B 1/4J of Spray System Co. was chosen from trade-off studies and tests. The selected nozzle can cover approximately the lower half of FAR Part 25 Appendix C Icing Cloud Envelop conditions, which means the low LWC and small MVD. To make the wide spraying area with the limited numbers of nozzles, the wide-round type was selected. The droplet size depends on the both water and air supply pressure. The droplet size measurement test was performed at a test lab in Spray System Co. and *Malvern Mastersizer S* was utilized. The droplet size was measured as about 30㎛ MVD and was distributed in the range of about 15 ~ 50㎛. in Fig. 3.

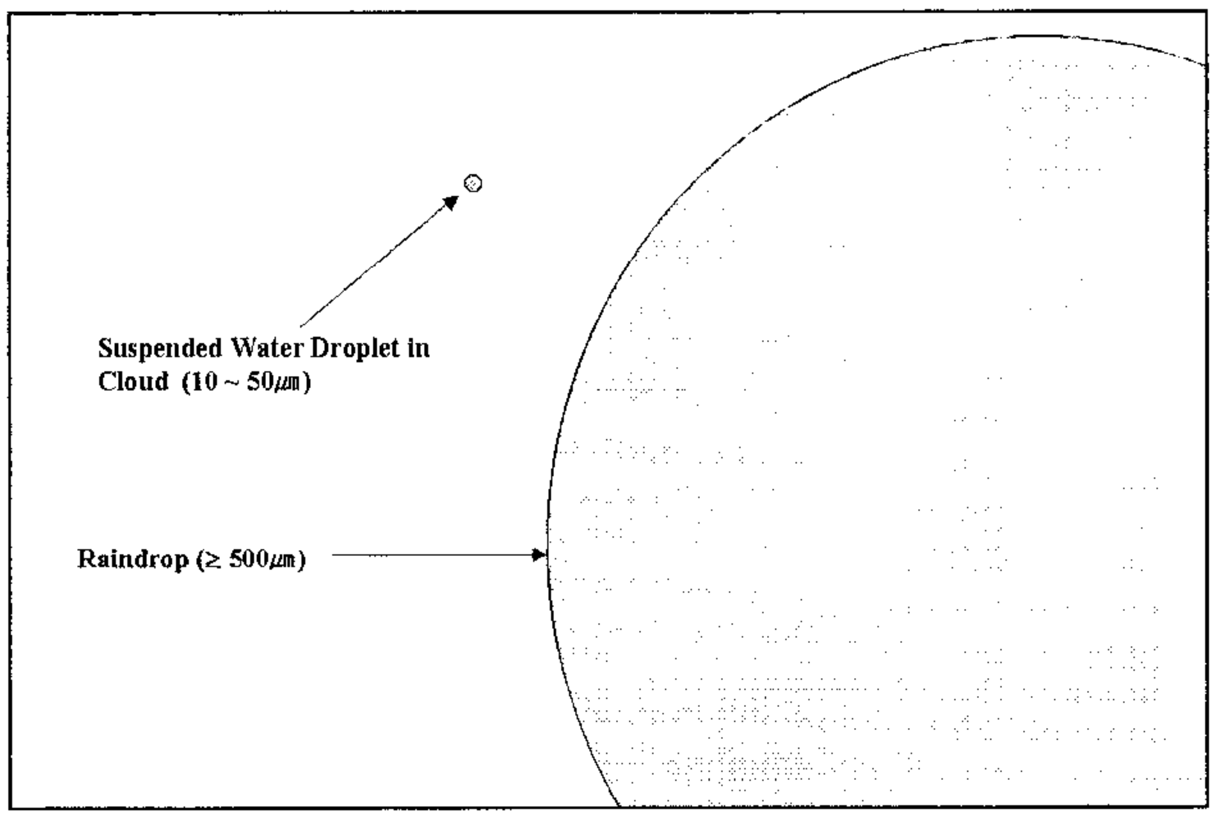


그림 2. 구름 중 물방울 입자.

Fig. 2. Water droplet sizes in cloud.

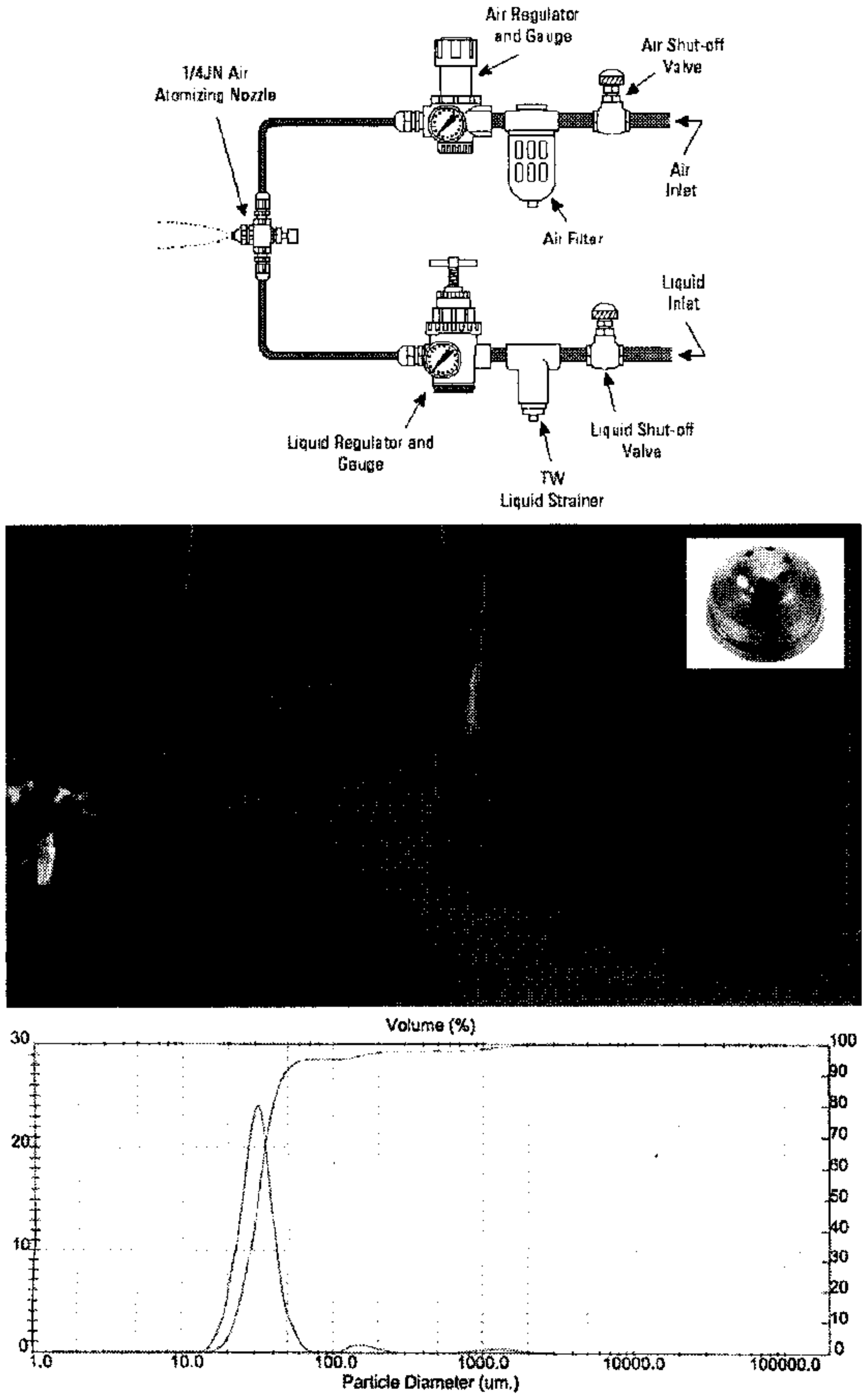


그림 3. 물방울 입자 측정 및 결과.

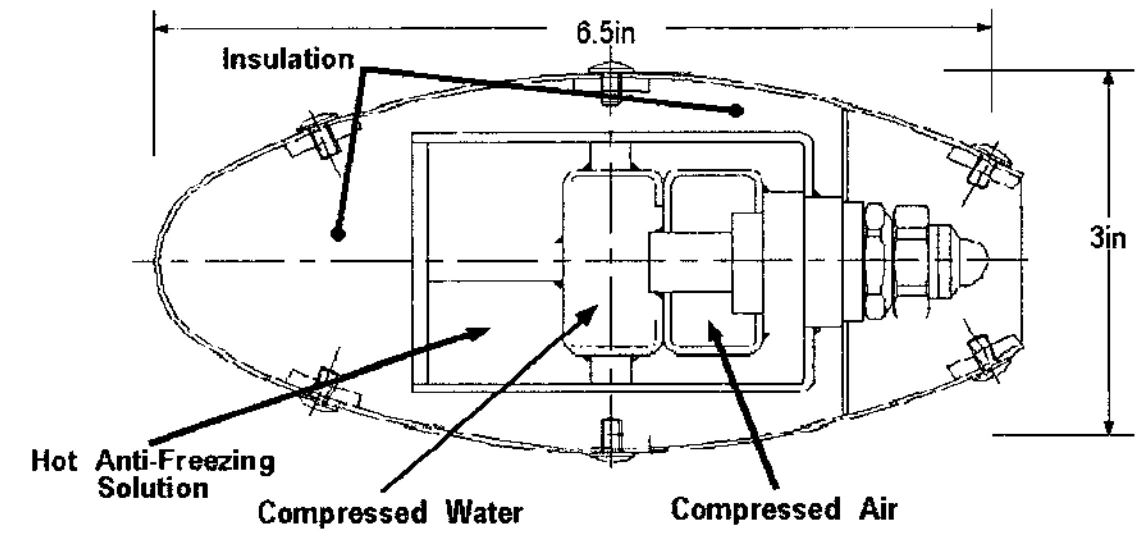
Fig. 3. Droplet size measurement setup and result.

2. Spray-bar design and super-cooling

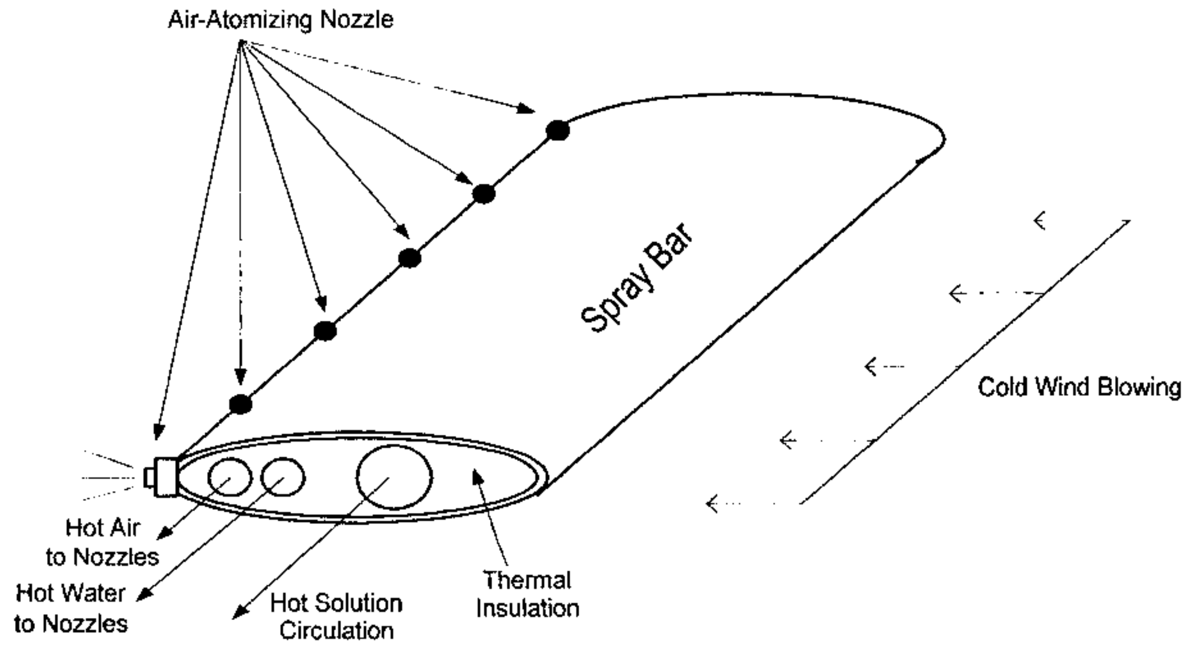
As shown in Fig. 4, spay bar was designed in the form of serialized airfoil. Its aerodynamic contour minimizes the drag and downstream turbulence. Downstream turbulence may cause the supercooled water droplets to be frozen out (crystallized). Theoretically the water droplet can exist in liquid state between 0 ~ - 40 degree C, but its state is unstable and some nucleus or disturbance may induce to solid state. Therefore, to make this icing cloud not disturbed, the spray-bar distance and nozzle space were designed based on the nozzle's spraying angle and coverage data, for each spray not to be interfered with each other.

Rapid expansion from the air-atomizing nozzle in the low ambient air temperature results in the fast temperature drop through the energy conversion (work to heat) by expansion. And finally it brings crystallization of water droplets.

Once the water droplets are crystallized, the crystals could collide on aircraft surface but not accreted on it, which means that it does not affect aircraft icing. And more also it brings incorrect LWC, which is related with liquid. The water and air supplied to nozzles are designed to heat up to prevent the crystallization. The droplet temperature after passing through this rapid expansion should be slightly above the freezing point. Then, the water droplets are slowly cool-down for super-cooled state, by traveling through the enough distance toward the aircraft in the cold ambient temperature.



(a) Cross-sectional view of spray-bar



(b) Nozzle arrangement on spray-bar

그림 4. 스프레이 바 설계.

Fig. 4. Spray-bar design.

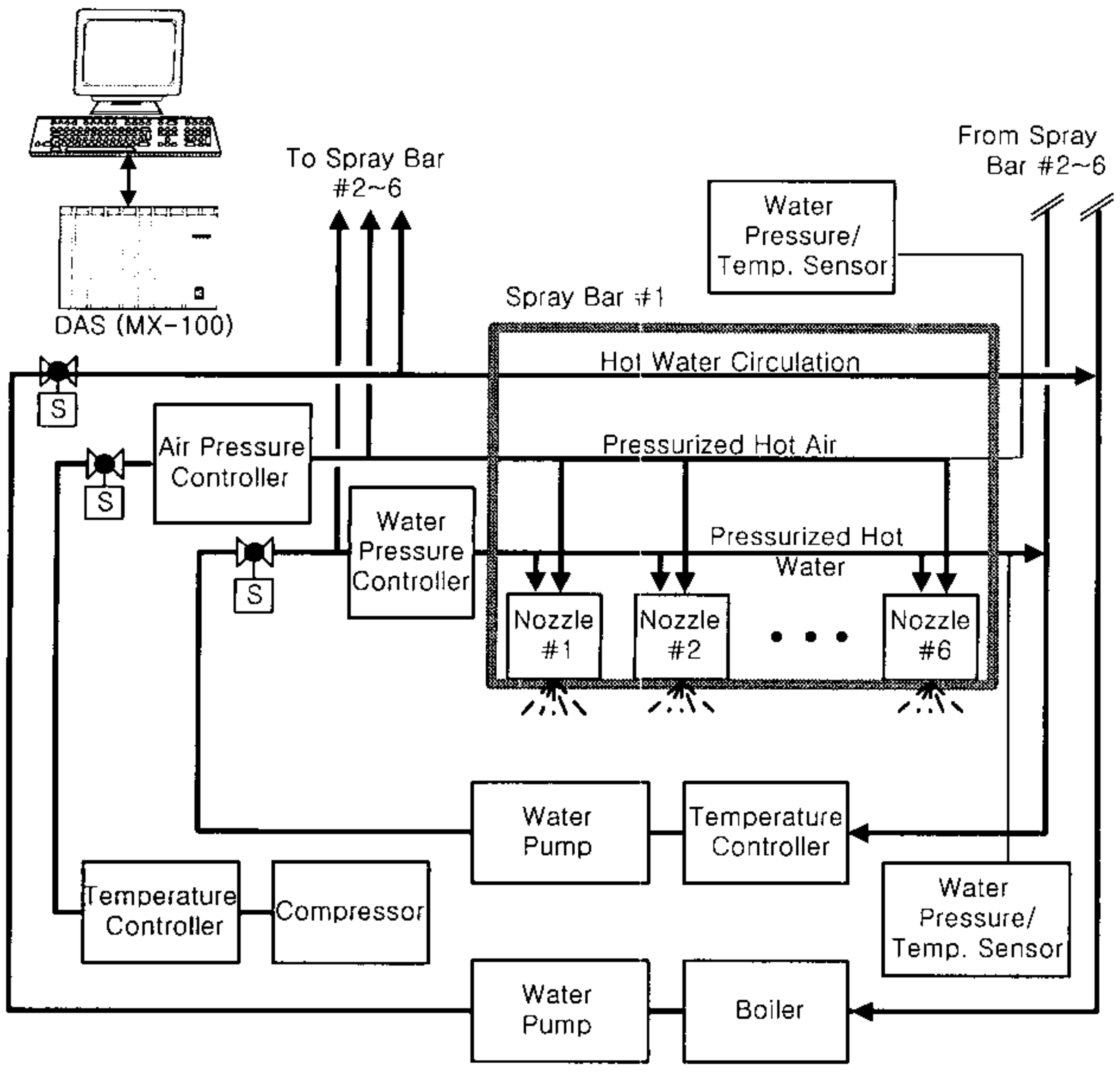


그림 5. 시스템 구성 개략도.

Fig. 5. System schematic.

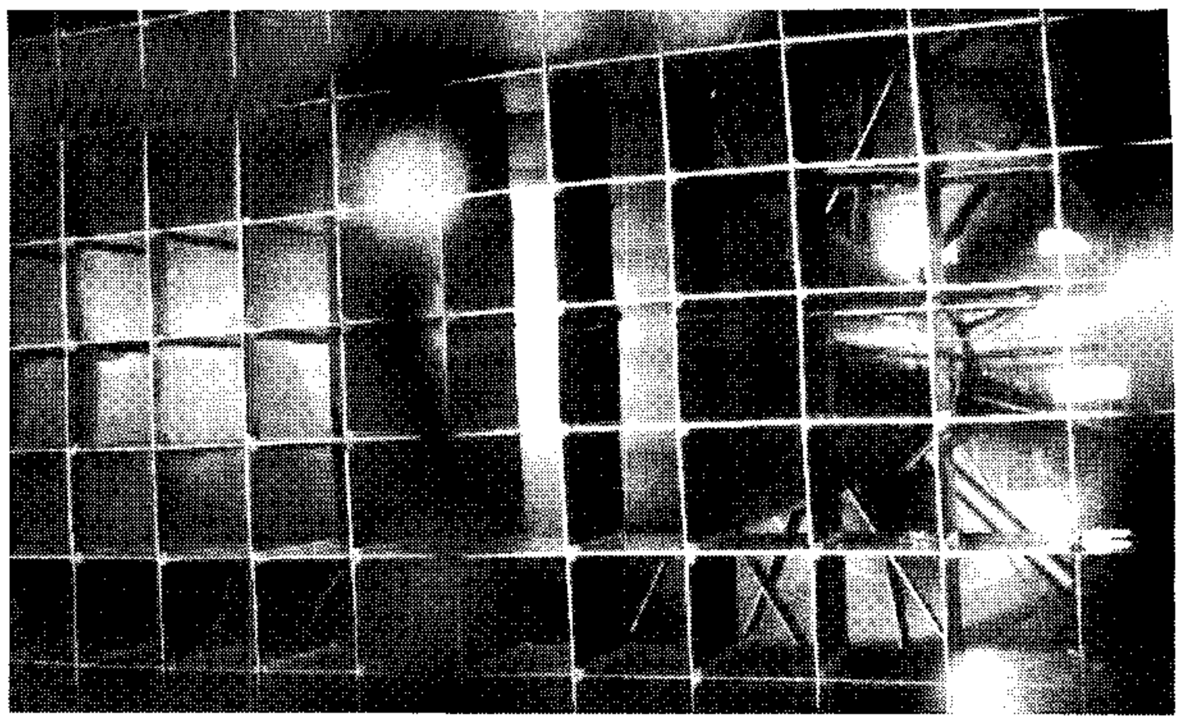
Hot air and water are circulated through spray bars under the pressure/temperature control as shown in Figs. 4 and 5.

For icing test conduction in the cold weather, there could be many stopping periods for aircraft operation, inspection, test preparation, or series of icing cloud blowing. Frozen nozzle during these stopping periods was big-concern during equipment design phase. With circulations of anti-freezing solution, nozzles on the spray bar were able to be safe from freeze-out. Another reason of this anti-freezing solution's circulation is that in the case of very slow icing cloud generation like ground fog, atomizing nozzle consumes very low quantity of water. The hot water and air to nozzles have not enough heat capacity to prevent nozzles from freezing. Therefore, this additional circulation line of hot anti-freezing solution could be effective.

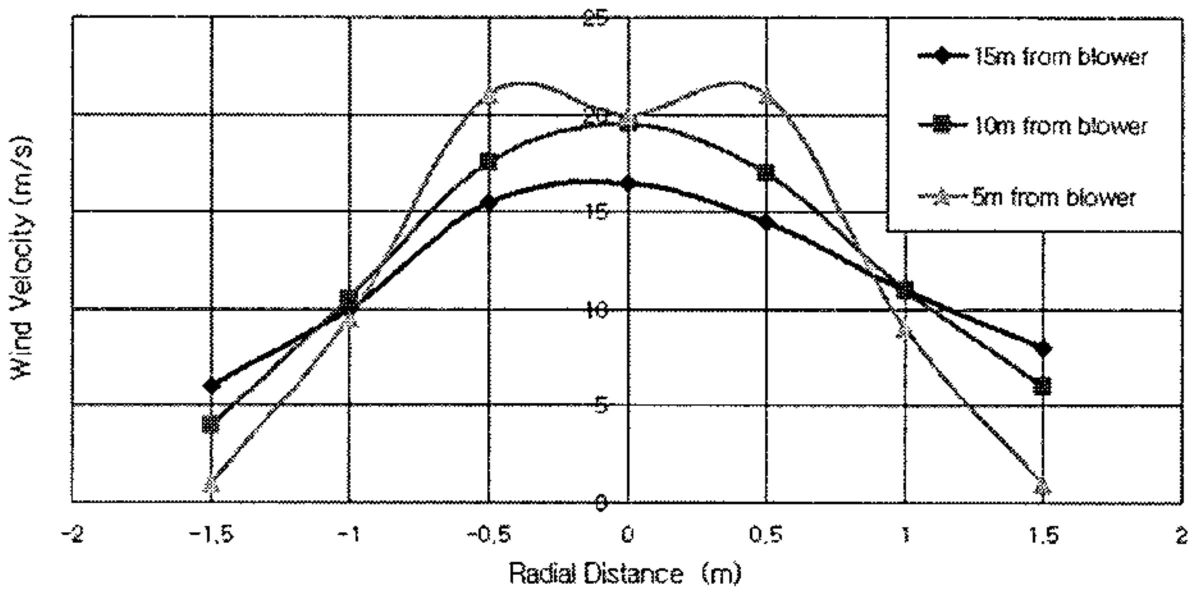
3. Water/Air pressure control design

Tradeoff studies between nozzle selection, nozzle spacing, and the required total water flow rate were performed. The icing cloud generation system was designed to deliver 3.6 liter/min of water at 20psig and air at 35psig in order to achieve the 0.8 g/m3 LWC at about 30㎛ MVD. For water pressure control in the spray-bar, there were two options. One is to control water flow rate (which will result in a specific pressure) while the other is to control water pressure (which will result in a given flow rate). The major advantage to controlling flow rate is that it provides a more direct determination of cloud liquid water content.

The major disadvantage of controlling flow rate rather than pressure is that if one or more nozzles within a spray bar, which has a common manifold to many nozzles, are clogged or frozen, all remaining entire nozzles in the spray bar must flow a proportionately higher flow rate to make up the difference. This means that the entire row of nozzles would operate at increased flow rate and therefore increased pressure too, thus creating the wrong size MVD and LWC for the entire portion of the cloud. On the other hand, a spray bar, which is controlled by pressure, is unaffected by a clogged or frozen nozzle and only the local MVD and LWC associated with the part of the cloud covered by that single nozzle is affected. Because there could be many stopping periods for test condition, there is lot of possibility of frozen nozzle during stopping-time. Therefore, water pressure control approach was chosen.



(a) Wind blower and wind straighter



(b) Wind velocity profile measurement result

그림 6. 송풍장치 및 풍속 프로파일.

Fig. 6. Wind blower and its velocity profile.

Since the nozzles are of the internal mix type, changes in water pressure affect the air pressure and vice versa. Therefore, water pressure and air pressure had to be independently PID-controlled. Six spray-bars are vertically equal-spaced with 30cm and the total height is 150cm. Water-head (static pressure term) difference between spray-bars was not a negligible value for water pressure control of spray-bars. So, water pressure of each spray-bar was PID-controlled independently. Water and air pressure stabilization was achieved within the first 10 seconds. Water pressure control accuracy was +/- 0.5psig to desired pressure value for all spray-bars, and air pressure control was slightly fluctuated within +/- 1.5psig to desired pressure level.

For aircraft test, the de-ionized and filtered water was sprayed (a) to prevent the aircraft chlorine corrosion, (b) to prevent clogging of the small water passages inside the nozzles and ingestion of impurities into operation jet engines, and (c) to reduce an electronic conductivity. Prior to the test conduction, the nozzles, hoses, water headers, and spray bars were cleaned and flushed.

4. Wind generation

The designed wind blower consists of a vane-axial motor fan and its duct. To reduce down-stream turbulence, the axial fan is attached with extruded cone. The duct configuration was designed to allow the uniform downstream velocity as possible. The consumption power is 55kW, maximum flow rate is $55m^3$, and duct diameter is 1530mm. As shown in Fig. 6, rectangular wind-straighter was installed in the size of 100mm by 100mm and depth of 200mm. Duct inlet and outlet were installed with wiremeshed screen in the size of 10mm by 10mm, to prevent FOD (Foreign Object Damage) from ingesting into aircraft engine. Wind velocity profile was measured by portable anemometer to obtain volumetric velocity for LWC calculation.

From the required flight profile analysis in the icing condition, the average airspeed and exposure duration were calculated as about 430knot and about 2.5 minutes, respectively. For conservative test condition, these speed and exposure time are more severe than natural light icing condition, because icing cloud exits only under about 20,000ft per FAR Part 25.

5. LWC measurements and icing scaling verification

5.1 LWC measurements

LWC is the density of liquid water in a volume of icing cloud, and is expressed as grams of water per cubic meter. It was measured by the water mass flow rate divided by volumetric wind velocity. Airborne icing tankers use Calculated Average LWC method, which is the supplied total water flow rate divided by flow volume velocity [7]. This method is calculated from bulk measurement as described in Equation (2). For the icing scaling verification purpose, SAE ARP "Icing Blade Technique" was introduced.

In Calculated Average LWC method, LWC was measured using the consumed water mass flow rate, airspeed, and icing cloud cross-sectional area as shown in equation (2). The water mass flow rate was 0.055 liters/s (55grams/s), measured by flow meter. The volumetric wind velocity was 68 cubic meters per second.

$$LWC = \frac{Total\ Water\ Mass\ Flow\ Rate\ at\ nozzles}{Volumetric\ Airspeed} = \frac{55grams/\sec}{68m^3/\sec} = 0.81grams/m^3 \qquad (2)$$

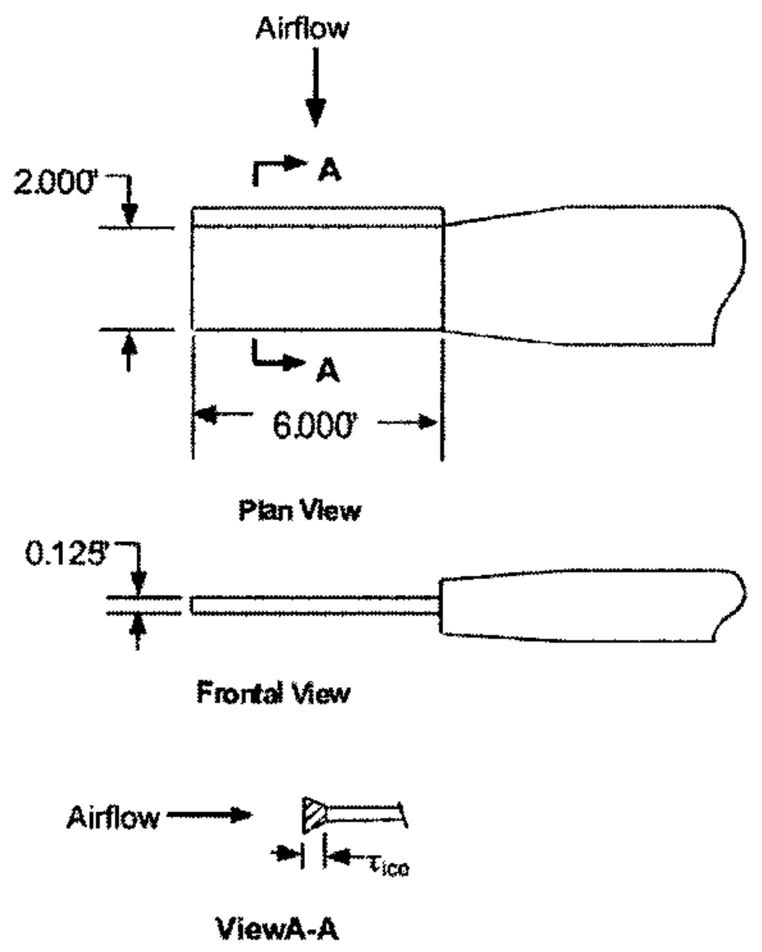
For a fixed airspeed and cloud size, LWC is a linear function of flow rate. In LWC calculation, no loss of liquid water through evaporation was assumed, which means the need of high humidity in test site. More also, high humidity prevents the supercooled water-droplet from freezing-out (crystallizing). In winter season, dawn period is most humid in a day. T-50 aircraft icing test was conducted of dawn with the record of high humidity.

$$LWC = \frac{IceDensity \times IceAccretionDepth}{CollectionCoeff \times WindVelocity \times ExposureTime} = \frac{917000g/m^3 \times 0.00223m}{0.94 \times 15.5m/s \times 180\sec} = 0.78g/m^3 \qquad (3)$$

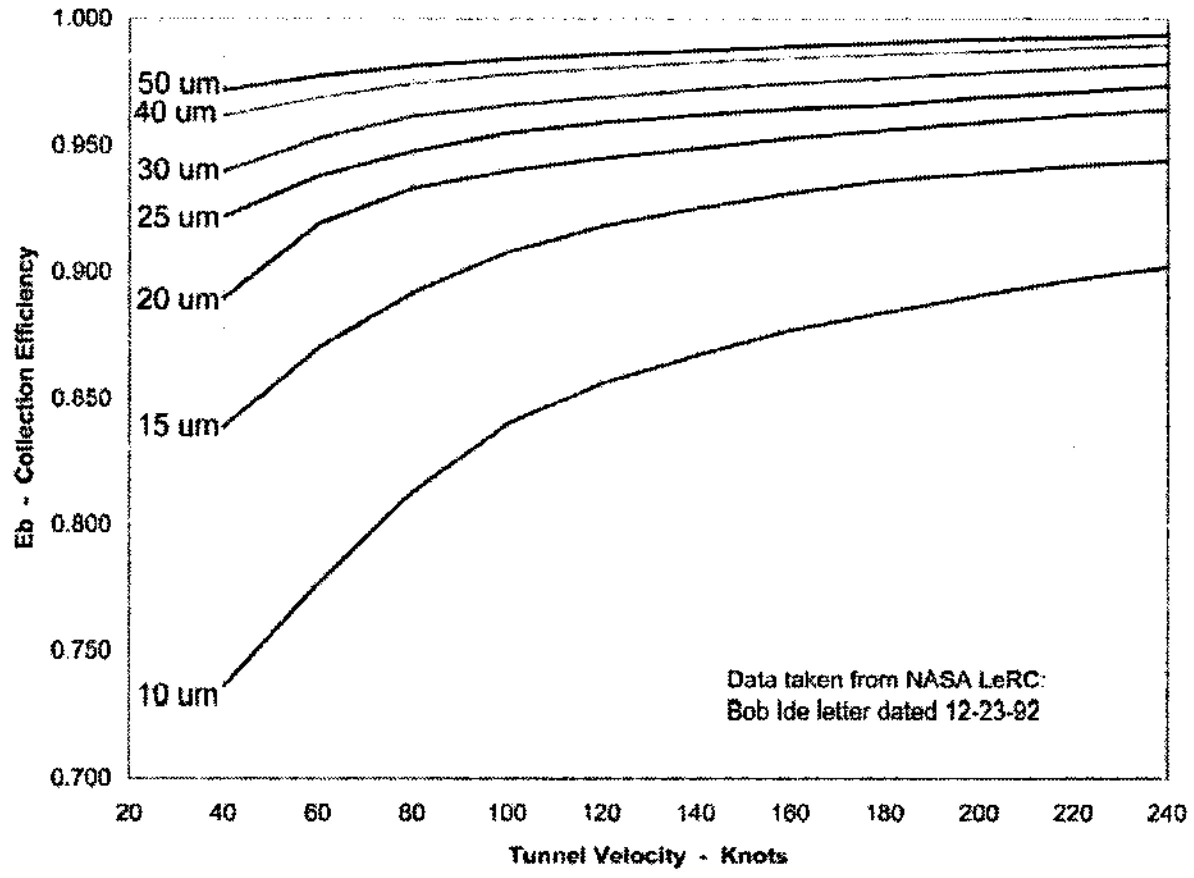
Equation (3) describes another LWC measurement equation, which is from Icing Blade Technique [8]. Fig. 7 shows icing blade dimension and collection coefficient, based on NASA icing wind tunnel data. The collection coefficient of this equation was 0.94. Ice Accretion Depth was measured as 2.23mm in Fig. 8. The measurement result was 0.78g/m^3.

5.2 Verification of icing scaling equation

The icing blade technique and the icing scaling equation have the same basis condition, which is low LWC, small size droplet, low-temperature [9]. The prove of the icing blade technique's applicability in an icing cloud condition means that icing scaling equation could be applicable in that icing condition too. From the results of the previous chapter, LWC value from the Calculated



(a) Icing blade dimension



(b) Icing blade collection efficiency curve

그림 7. Icing blade 치수 및 collection coefficient.

Fig. 7. Icing blade dimension and its collection coefficient.

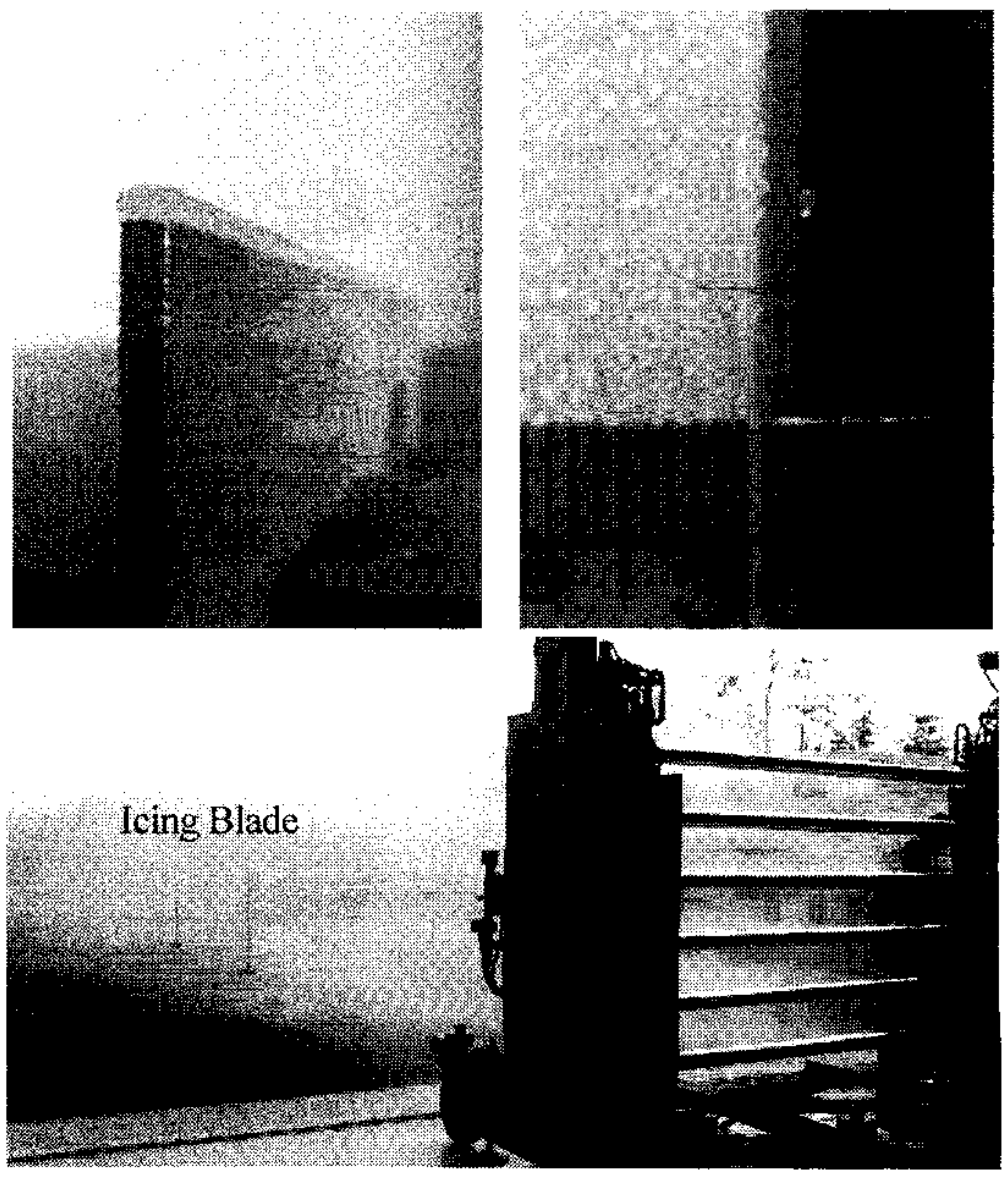


그림 8. Icing blade technique를 이용한 LWC 측정.

Fig. 8. LWC measurement test using icing blade technique.

Average LWC method was 0.81g/m^3 and LWC value from blade technique was 0.78g/m^3.

This close difference explains that the generated icing cloud can be applicable for in-flight icing simulation test through the icing scaling equation, and its cloud is successfully in the super-cooled state. The reason of the slight difference is from the freeze-out of some tiny droplets due to the temperature decrease of the compressed air as it undergoes a rapid expansion from the nozzle [10]. Another reason could be boundary flow dispersion of free-jet flow, which will be described later.

IV. Test Conduction on T-50 Aircraft

1. Test conduction

T-50 icing test was performed of dawn for the ambient high humidity and the recorded relative humidity was over 80%. High humidity prevents super-cooled droplet from crystallizing, and brings the accurate LWC. Based on the equation (1), 221m/s and 2.5minutes was scaled to 15m/s and 7.5minutes as shown in Table 1. As discussed earlier, preventing crystallization, the heated droplet temperature after passing through this rapid expansion needs to be slowly cooled down, by traveling in the ambient cold air stream. Therefore droplets need some traveling distance for super-cooling between test section and spraying nozzles. From wind profile data in Fig. 6 and pre-tests as in Fig. 8, the aircraft distance was set to 15m (blower to aircraft engine inlet) and the scaled wind speed was set to 15m/s in Table 1. CFD analysis was performed for this open-field wind generation (free-jet flow). Different from duct flow or in-flight flow (behind the spray of airborne icing tanker), the free-jet flow has the shear effect on boundary static air and therefore it is dispersed and enlarged from its original cross-sectional area, and its power is decreased. However, the distance of 15~20m from the wind blower was empirically appropriate from pre-test result. Wind blowing cross-sectional area at test section was set to 3m diameters from Fig. 6. This value was also used for LWC calculation.

Before icing cloud spray, the aircraft surface temperature was required below the freezing temperature of water. T-50 aircraft was cold-soaked at a run-station with front and rear doors opened. To accentuate the aircraft surface cooling, the high-speed cold wind was blown toward the aircraft before test start. Due to the limited cross-sectional area of icing cloud, it was sprayed to center area and wing area in Test-I (With engine-run) and Test-II (Without Engine-run) as described in Fig. 9. Test-II had two different area exposures of icing cloud at wing and center areas.

Test-II (Without Engine-run) was performed with 7.5min of icing cloud exposure period. During or after icing cloud exposure, subsystems were operated and checked with ground maintenance carts of electric, hydraulic and ECS air supplies. Test-I (With Engine-run) was performed with engine run, and subsystems were checked concurrently. For the safety measure, Test-II (Without Engine-run) was performed at first. Including the aircraft moving for different test condition, the caution for ground crews had to be made for iced test-site. For the aircraft safety concern, icing cloud was sprayed during engine-run for 3 minutes, not 7.5 minutes. Originally it was planned that engine was to be shutdown immediately if INLET ICING caution lamp in the aircraft cockpit illuminated. But the confidence based on the accurate icing cloud generation and lots of pre-tests was developed. Therefore, aircraft engine-run time was increased to 3 minutes. INLET ICING caution lamp illuminated at about 30 seconds after icing cloud exposure.

표 1. 지상모사 스케일링.

Table 1. Ground simulation scaling.

Icing Parameter	In-flight		Ground Simulation	Remarks
LWC	0.1g/m^3	⇨	0.7g/m^3	115%(0.8g/m^3)
Airspeed	221m/s		15m/s	
Exposure	2.5min		5min	150%(7.5min)

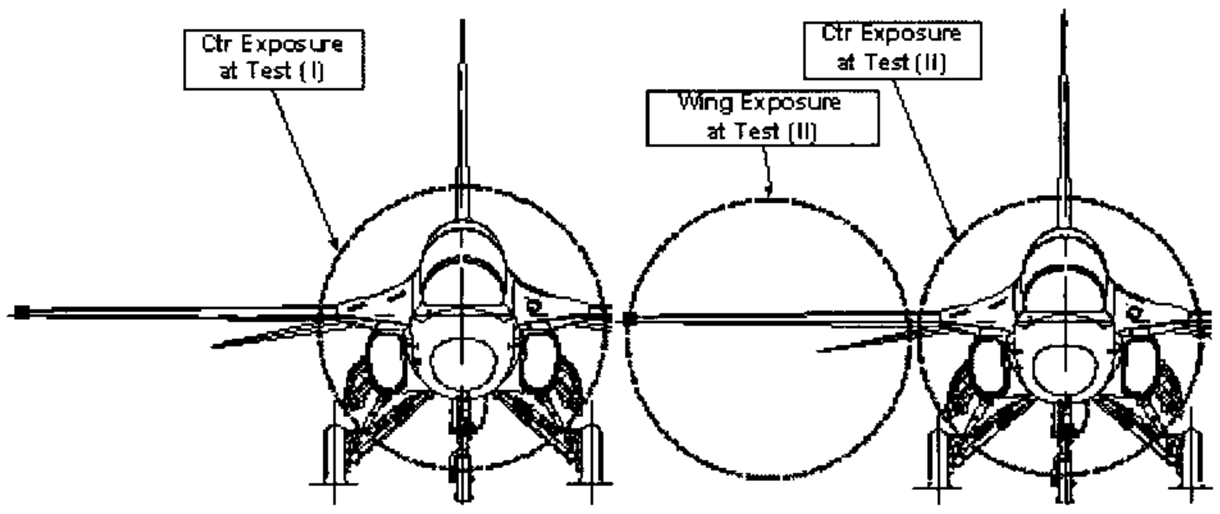


그림 9. T-50 과냉각 구름 시험 영역.

Fig. 9. T-50 icing cloud exposure areas.

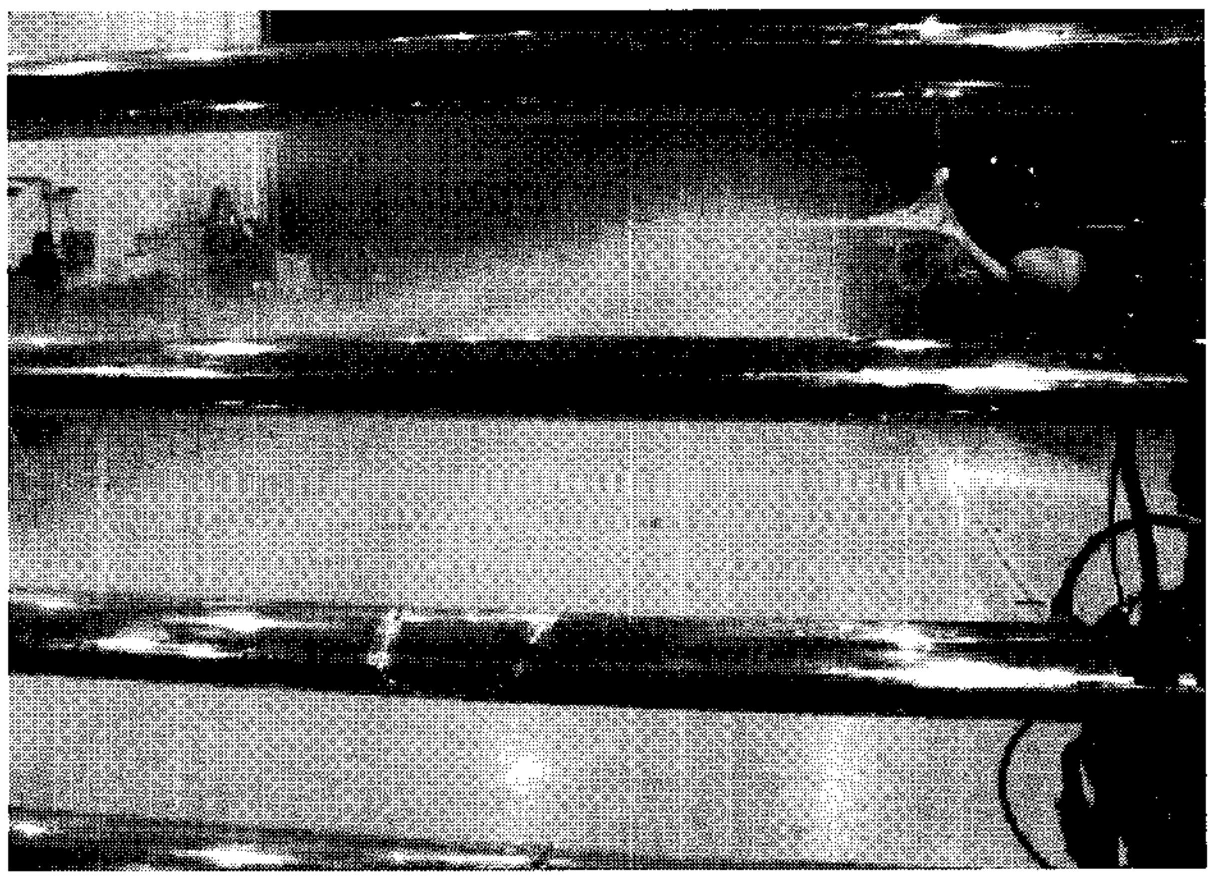


그림 10. T-50 빙결구름 노출 (날개).

Fig. 10. Icing cloud exposure (wing).

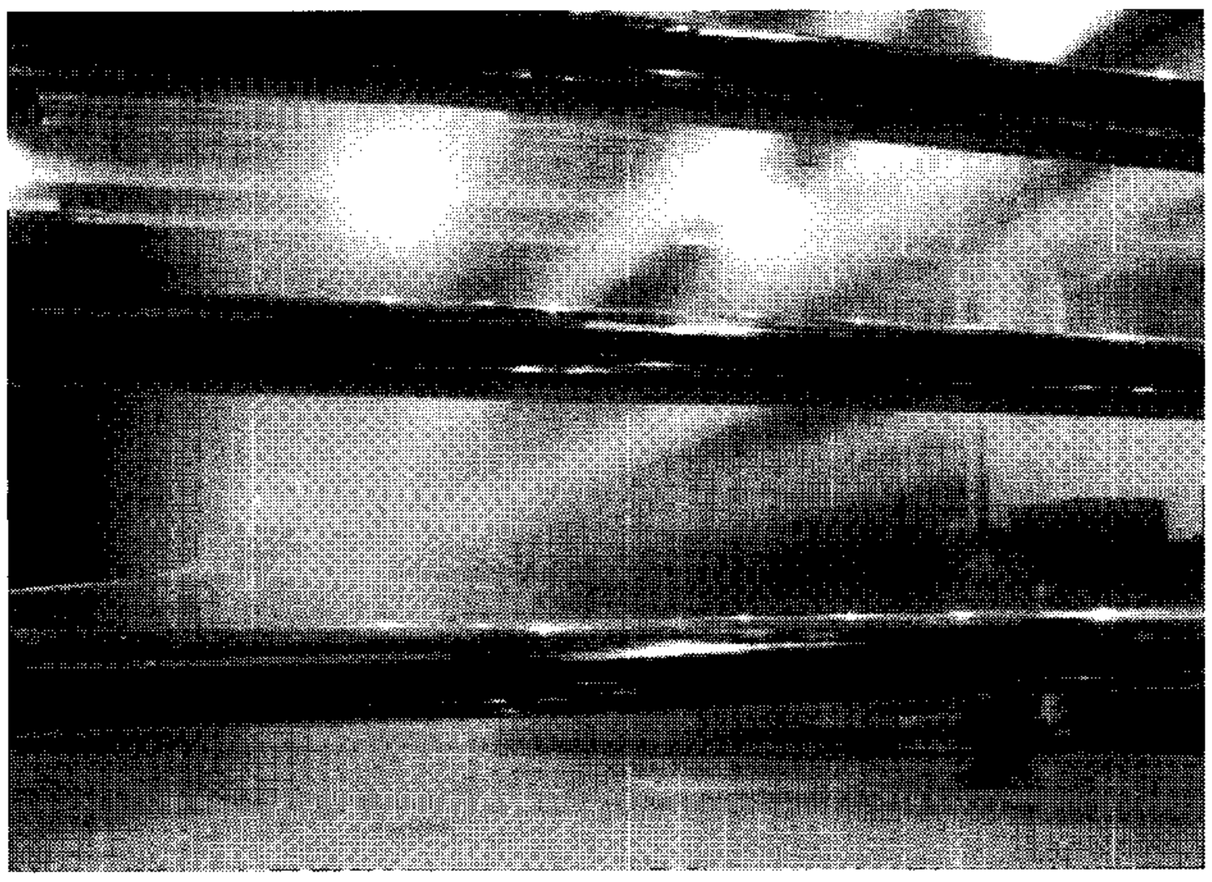
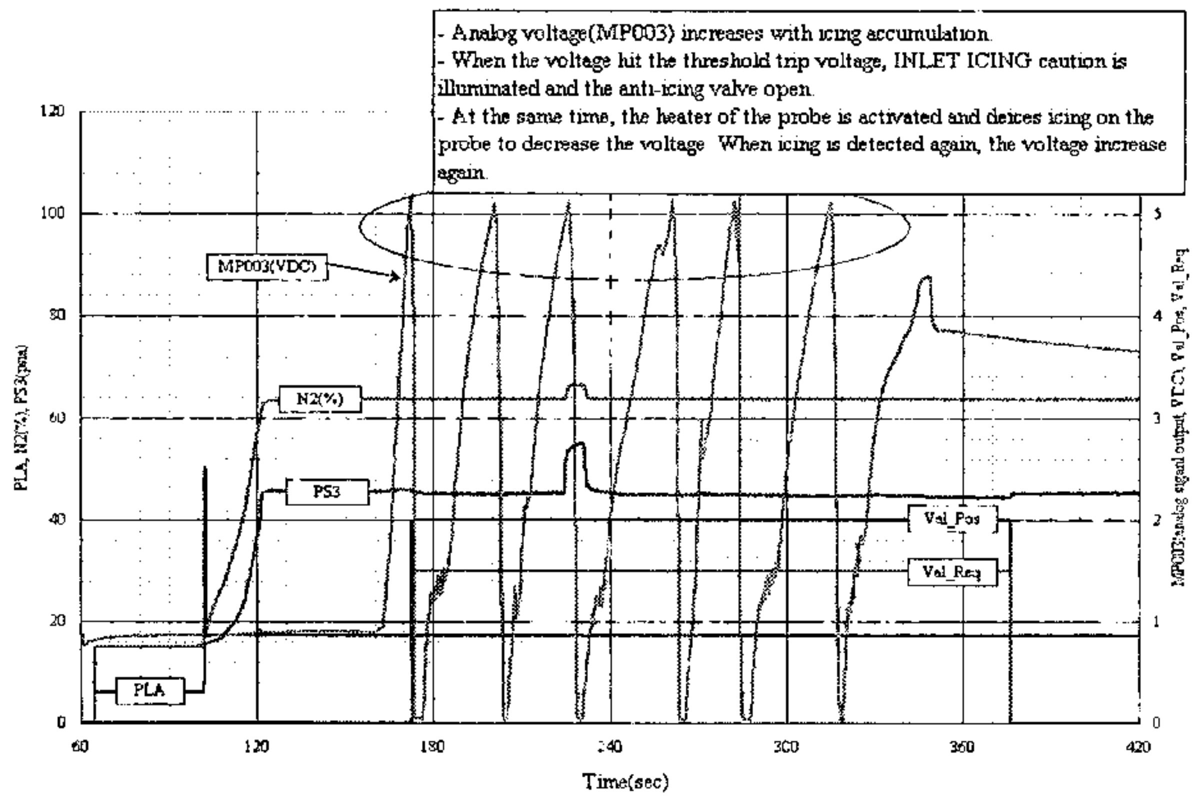


그림 11. T-50 엔진 구동 중 빙결구름 노출 (중앙).

Fig. 11. Icing cloud exposure (center) with engine-run.



- Analog voltage(MP003) increases with icing accumulation.
- When the voltage hit the threshold trip voltage, INLET ICING caution is illuminated and the anti-icing valve open.
- At the same time, the heater of the probe is activated and deices icing on the probe to decrease the voltage. When icing is detected again, the voltage increase again.

그림 12. 항공기 엔진 및 anti-icing 시스템 신호.

Fig. 12. Signals of aircraft engine and anti-icing system.

For the engine safety, the voltage signal of engine anti-icing sensor in the engine inlet duct was remotely monitored during engine running. During and after test conduction, the aircraft subsystem was checked for normal operation in the icing cloud exposure. Finally, T-50 aircraft subsystems were successfully operation-checked under the required test condition. It includes anti-icing/de-icing functional check, moving part operational check, avionic system telemetry check, and other subsystem operational checks.

2. Icing cloud verification with engine icing sensor

After the normal engine start, the icing cloud started to blow toward aircraft. As soon as the icing cloud was sucked into engine, the analog voltage (MP003) of anti-icing sensor in Fig. 12, which is considered to be in the linear relation with the amount of the accreted on the sensor probe, began to increase. The threshold trip point of this anti-icing sensor is 0.5mm of ice accretion. When the analog output signal during the test reached to around 5Vdc, which is considered as ice is accumulated to 0.5mm threshold trip point of the sensor probe, a timed 28Vdc was provided to activate the ANTI-ICING VALVE REQUEST ON and ANTI-ICING VALVE POSITION ON, which means engine bleed air valve was open.

While icing cloud spraying, the analog signal output (MP003) was increased and decreased as shown in Fig. 12. This explains that the sensor deicing-heater was activated to deice the sensor probe at the time that the ice on the sensor probe was detected with the preset threshold trip point. The sensor was then ready to sense a subsequent icing encounter. When the ice was again detected, the analog signal output (MP003) increased again. In this Fig., 6 times of analog signal peaks to around 5Vdc was shown per this logic. Based on this signal output and the function of valve open ON/OFF, the function of the anti-icing sensor was checked as normal. Fig. 13 shows the ice accreted around the engine inlet duct lip for about 3 minute-icing cloud spraying. This ice thickness was measured as approximately 3~4 mm. This explains that the total accreted thickness is closely equal to the 6 times of the threshold trip point (0.5mm) value. Therefore, anti-icing sensor was checked for being successfully operational in aircraft integration test. The almost same consecutive six activation shows that the generated icing cloud condition was steady state. About 3~4mm ice thickness measurement shows that the required icing cloud condition was successfully generated.

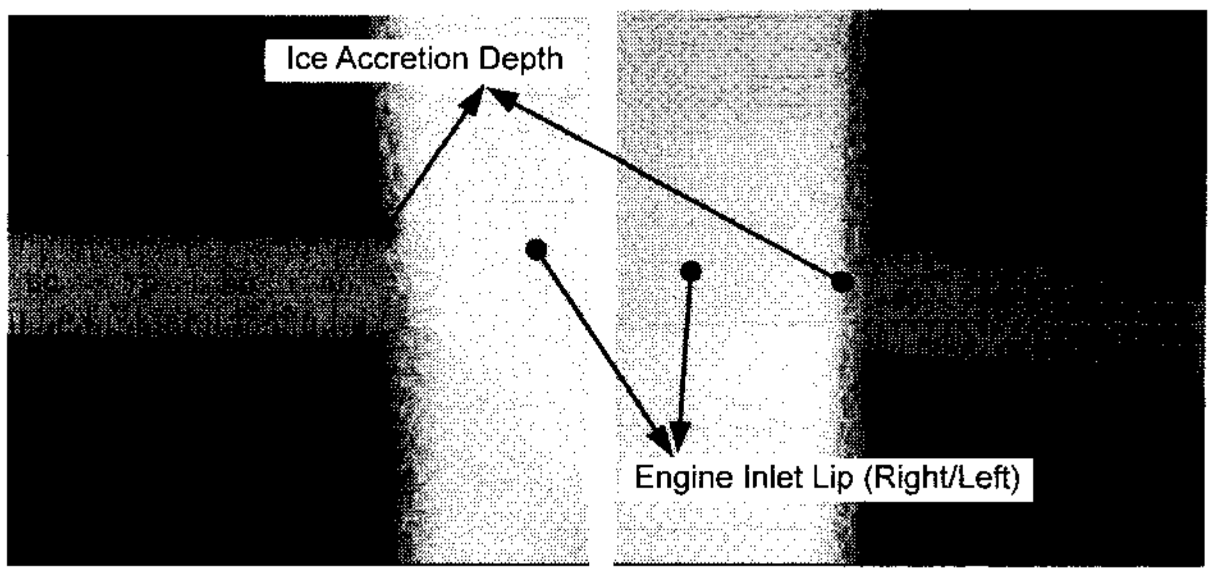


그림 13. 엔진덕트 입구 착빙.

Fig. 13. Ice accretion on engine inlet lip.

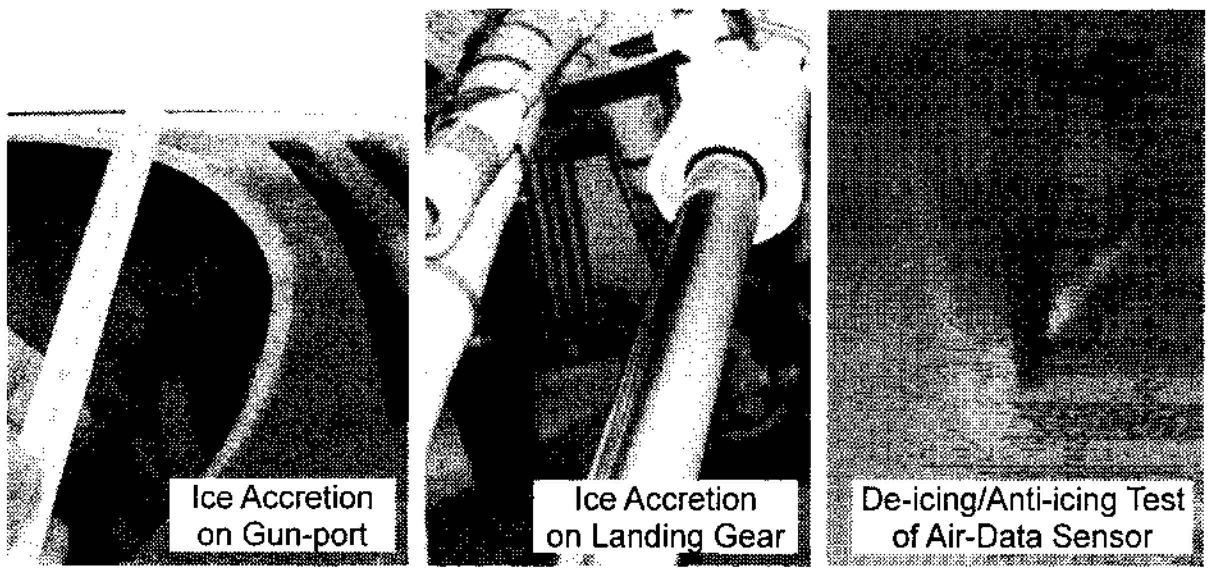


그림 14. 항공기 표면 착빙.

Fig. 14. Icing on the aircraft surface.

3. Discussion on in-flight icing simulation on ground

Even thought the icing test was conducted on the open-site, not in an environmental chamber, the good test result was acquired. The test was performed in the coldest winder season for low-temperature and at dawn for high ambient humidity. The recorded relative humidity of ambient test site was over 80% and this high humidity prevents super-cooled water droplets from crystallizing, and brings the more accurate LWC.

Another disadvantage on ground simulation test is that the engine suction volumetric flow in front and side of engine inlet cannot be fully simulated, because the flight-speed wind generation is very difficult for the full-scale aircraft exposure with open-circuit type wind blower. Of the icing scaling approaches, only the total water-catch scaling is adopted and the other thermodynamic scaling is not considered, which is more complex phenomenon. However, in the case of the light-icing requirement and supersonic jet aircraft, the exact scaling up to thermodynamic scaling approach is meaningless.

Some military standard describes icing effect to supersonic jet trainer as following "Aeroplanes with ability to pass quickly through icing conditions and with the aerodynamic (kinetic) heating resulting from high speeds will be less susceptible"[11]. Having supersonic capability and high handling quality by digital fly-by-wire flight control, T-50 aircraft is considered to have enough margins for in-flight icing condition. Excluding aerodynamic heating effect on ground test, T-50 aircraft was exposed with more severe icing condition.

V. Conclusion

An implementation approach to generate the super-cooled, liquid state, and suspended droplet size icing cloud was developed. The developed system successfully generated the almost natural icing cloud in the super-cooled state below freezing point and with the required LWC. For the in-flight simulation test of full-scale aircraft icing, an icing scaling method was adopted under the limitation of wind speed generation with open-circuit type blower. The applicability of icing scaling method to T-50 was experimentally verified.

The icing cloud generation system was designed, fabricated, and applied to the full-scaling aircraft-icing test. Under the required icing condition, T-50 aircraft subsystems were successfully operated and functionally checked.

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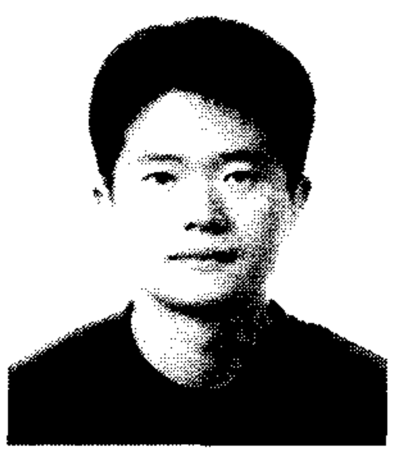

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