Effect of icephobic coating on ice protection of ultrasonic anemometer with stack-type transducers

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***Abstract*: In cold climates, ultrasonic anemometers with stack-type heated transducers sometimes record extraordinarily higher instantaneous wind speeds than average wind speed during short periods in long series of measurements. A successive record of wind speed measured at a high sampling frequency indicates that those high-speed winds are not gusts because they suddenly jump from the speeds fluctuating around a certain value to a far higher speed and immediately return to almost the same value before the events of sharp increase. We have identified the cause of such abnormal measurement by repeatedly performing snowing wind tunnel tests; it is because of the formation of ice-bridge on transducers. The surface of a transducer is heated by an electric heating element in the longitudinal center. However, very narrow upper and lower parts of the transducer remain unheated because of inner structural constraints. Therefore, ice or snow accretion may occur on the upper part when the anemometer operates under icing or snowing conditions. When the condition is prolonged, the accretion grows downward and covers the transducer like a canopy. In the central part of the transducer, the temperature is kept constant at a certain positive value even in subzero environments such that snowflakes colliding with the surface melt upon impact. The meltwater runs down along the surface to the unheated lower end and then to the upper arm. Because the upper arm of the anemometer is unheated, water begins to freeze on the surface immediately below the transducer. As water continuously flows down and freezes, the ice grows upward. As a result, the accretions of ice growing downward from the upper end and upward from the lower end meet each other at the center of the transducer. However, because the middle region of the transducer is heated and maintained at a prescribed temperature regardless of ambient conditions, the ice melts and forms a gap at the interface between the ice and the transducer surface. Consequently, an ice bridge is formed, and it disturbs the normal transmission of ultrasonic waves between the transducers. Based on this finding, we applied a superhydrophobic coating to the unheated upper arm in order to accelerate the removal of molten water by wind force. The results from a snowing wind tunnel test showed that the coating imparted a low-wettability characteristic to the upper arm for preventing ice growth, and measurements could be taken without any missing or unusual data. In the present research, to further verify the effectiveness of coating on icing prevention, another snowing wind tunnel test was conducted using the same anemometer with extended superhydrophobically coated areas including the transducer, lower arm, and top cover of the body. Prior to the test, an acoustic impedance analysis was performed using a covering of silicon rubber to examine the transmissivity of the ultrasonic waves through the coating film and the ice deposit on the transducer. Moreover, an immersion test of the covering that was inherently attached to the transducer was carried out in accordance with the guidance of the Japanese Industrial Standard (in a short duration only for the wind tunnel test) in order to evaluate the influence of paint thinner on the covering.**

Keywords: snowing, ultrasonic anemometer, snowing wind tunnel test, ice/snow protection

INTRODUCTION

Wind measurements under cold climate conditions have become increasingly important for wind energy applications. Severe weather events can impose measurement challenges even for heated wind sensors. Therefore, there is a strong need to improve data availability, which requires improvements to the sensor's de-icing design. Regarding ultrasonic anemometers that have cylindrical transducer stacks, we have identified the ice-bridge forming process even on the heated transducer stack in wind tunnel tests during snowing. The surface of the transducer stack is heated by an internal electric heating element. However, the very narrow upper and lower parts of the transducer remain less heated because of inner structural constraints. Thus, the temperature profile is not uniform. Therefore, ice or snow accretion may occur on the upper part under harsh icing or snowing conditions. When the condition is prolonged, the accretion grows downwards and covers the transducer like a canopy. If this ice-bridge forms, it might disturb the normal transmission of ultrasonic waves between the transducers[1,2]. Based on this finding, we applied a superhydrophobic coating to the unheated upper arm in order to accelerate the removal of molten water by wind force. The results from a snowing wind tunnel test showed that the coating imparted a low-wettability characteristic to the upper arm in preventing ice growth, and measurements could be taken without any missing or unusual data[3]. In the present research, in order to further verify the effectiveness of coating on icing prevention, another wind tunnel test was conducted in the presence of snow using the same anemometer with extended, superhydrophobically coated areas, including the transducer, lower arm, and top cover of the body. Prior to the test, an acoustic impedance analysis was performed using a covering made of silicon rubber in order to examine the transmission of the ultrasonic waves through the coating film and the ice deposit on the transducer. Moreover, an immersion test of the covering that was inherently attached to the transducer was carried out in accordance to the guidance of the Japanese Industrial Standard (only for a brief time interval during the wind tunnel test) in order to evaluate the influence of the paint thinner on the covering.

I. TRANSMISSIVITY

A. Acoustic impedance and transmissivity

As known, the mechanism of wind measurement of an ultrasonic anemometer is based on the difference of the arrival time of the ultrasonic waves propagating between two transducers in the airflow. When the acoustic waves travel through the boundary between the different media some may be reflected, and the rest pass through, similar to light propagation under the same conditions. The tranmissivity is the ratio of the transmitted to the incident sound pressure at the interface of the media. It can be determined using the acoustic impedance of the respective media in accordance to the following equation[4].

$$t = \frac{2Z_2}{Z_1 + Z_2} \qquad (1)$$

where t denotes the transmissivity, and Z_1 and Z_2 the acoustic impedances of an incident and transmitted materials, respectively. It is clear from the equation that the transmissivity tends to become less if Z_1 of the transmitted side is greater than Z_2 in the incident side. The media through which the ultrasonic wave propagates between the two transducers are the surface coverings made of silicon rubber and with air in between. When ice accretes on the transducer surface, it has to be taken into account in regard to the existing media under normal conditions. If the air gap forms at the interface of the surfaces of the transducer stack and the ice, the total number of the media becomes equal to seven. The transmissivity can also constitute a measure to evaluate the applicability of the icephobic coating to the transducer stacks for ice protection. The acoustic impedance is a function of the density and acoustic speed of a material, and is defined as the product of these two parameters. The acoustic impedances used for the present calculation are shown in Table.1. The icephobic paint used for the present research was HIREC100, the product of Japanese Manufacturer NTT Advanced Technology.

Table 1 Acoustic impedance

Material	Acoustic impedance [Ns/m^3]
Air	4.13e+2
Ice	3.53e+6
Silicon	1.50e+6
PTFE	4.00e+4

B. Analyses results

Fig.1 shows a schematic of a situation for the VAISALA WMT 703 transducers where ice adheres to the coated transducer surfaces that face each other. In this case, the ultrasonic waves transmitted from one side travel to the receiver of the other successively through the silicon covering, ice accretion, air, ice accretion, and silicon covering.

The transmissivities calculated for all conceivable cases that may be considered in iced conditions are summarised in Table 2. In the table, the symbols S, A, I, and C, respectively denote the silicon covering, air, ice, and the coated film. For instance, Eq. 1 calculates the transmissivity to be approximately 3.5e-4 for the case shown in the figure. The surface which is clean, as expressed by the code S-A-S in an abbreviated form, is approximately 1e-3.

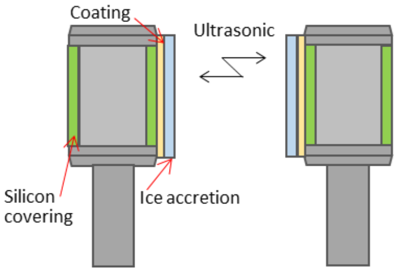


Fig.1 Schematic of ultrasonic transmission/reception between iced coated transducers

Table 2. Transmissivity

Conditions of transducer	Media	Transmission coefficient
Ice free	S-A-S	1.10e-03
Iced/ Iced + gap	S-I-A-S	1.96e-04
	S-I-A-I-S	3.92e-04
	S-A-I-A-I-S	5.16e-07
	S-A-I-A-I-A-S	2.41e-10
Coated	S-C-A-C-S	1.54e-03
	S-C-I-A-I-C-S	3.50e-04

For the cases of the ice-free state and the tight adhesion of ice to the surface, it can be found that the values of the transmissivity are of the order of magnitude of -3 or -4. From the results of the previously conducted tests with an imitated ice accretion, it can be deduced that wind speed can be normally measured, as long as ice attaches tightly to the transducer surface and there is no gap, even if ice accretion occurs on the transducer. This finding validates the deduction drawn from the analysis that the tight ice accretion may influence the wind measurement in a minor way. When the irregular wind speeds are measured, namely in the cases where an ice bridge forms on the transducer, the order of magnitude of the transmissivity tends to become considerably less, as indicated in the table. In regard to the two types of coating, the transmissivities between the two coated transducers have values that can be in the same order of magnitude as those at the ice-free state, regardless of the presence of the ice accretion. Accordingly, this suggests the applicability of the icephobic coating to the transducer in terms of the proper functionality of the ultrasonic anemometer and its protection from ice.

II. PRELIMINARY TESTS

A. Covering test

A wind tunnel test was conducted on the ultrasonic anemometer at room temperature using a substitute of the coating in order to ensure that the coating film on the transducers exerts no negative influences on the evoked measurement. The thin membrane of the polyvinyl chloride resin, the impedance of which was close to that of the icephobic paint, was used as the substitute as shown in Fig.2. Wearing the membrane covering on the transducer was conducted very carefully in order to remove any air present inside the covering. The test was first started with the membrane-covered ultrasonic anemometer, and was then carried out with the uncovered anemometer successively, so that the environmental conditions were kept constant.

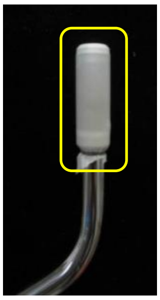


Fig.2 Transducer stack covered with a thin membrane made of vinyl chloride

The comparison of the measured wind speeds developed by the ultrasonic anemometer under the two different transducer surface conditions can be seen in Fig.3. The red curve shows the wind speed of the covered anemometer, while the blue curve shows the uncovered anemometer. The normalised absolute difference of the averaged wind speeds measured by these two ultrasonic anemometers in the range of the constantly regulated wind is 0.85%. This suggests that correct wind measurements using the ultrasonic anemometer with icephobically-coated transducers are feasible.

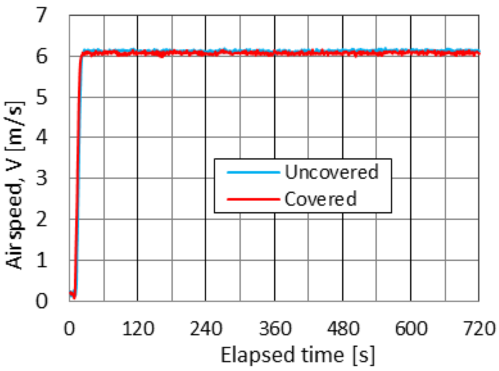


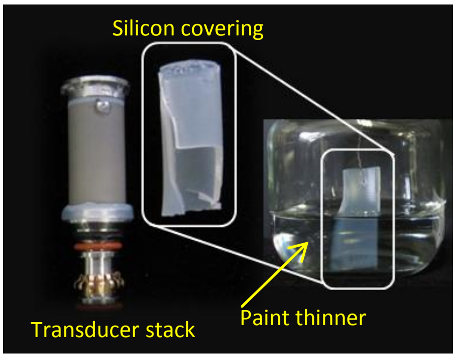
Fig. 3 Wind speeds measured by covered and original anemometers

B. Immersion test

The icephobic paint used for the present research was HIREC100. The paint thinner of butyl acetate was used to make a coated film on the surface of the body. Therefore, for the application of this paint to the ultrasonic anemometer, the chemical influences of the thinner on the properties of the silicon covering of the transducer were examined using the immersion test since the materials used for the coating of other surfaces were metallic, and are thus not subjected to a chemical change by the thinner. The immersion test was carried out in accordance with the guidance of the Japanese Industrial Standard k 5600-1 (ISO 2812-1) as shown in Fig.4[5]. The duration of the process was shortened to 21 d for the snowing wind tunnel test. The test results showed that no damage of the silicon-made covering was observed in terms of the thickness and surface conditions. We then applied the paint to the transducers, upper and lower arms, and to the top cover of the ultrasonic anemometer.

C. Wind tunnel test at room temperature

At the next stage, another wind tunnel test was conducted at room temperature in order to confirm the function of the anemometer equipped with the transducers that had a thin coated-film on their surfaces. The test was carried out by changing the airspeed in the test section of the wind tunnel. During the test, the flow started from a rest (calm) state and was then increased in speed. It was successively maintained at four different wind speeds equal to 3, 6, 12, and 19 m/s. Based on this procedure, the ability of the anemometer to follow the changing wind speed could be examined at the same time. For comparison, the wind tunnel airspeed was measured by the pitot-tube and digital-manometer (P-M) system during each test run. The variations of the wind tunnel airspeed measured by the anemometer and the P-M system are shown in Fig.5. The chart indicates that negligible discrepancies exist between the two wind speeds not only at steady state but also in the ascending and descending modes. This outcome can be interpreted as a capability of the coated anemometer to conduct highly reliable wind speed measurements.



Silicon covering peeled off from the transducer surface

Silicon covering immersed in the paint thinner for 21 days

Fig.4 Immersion test (shortened duration)

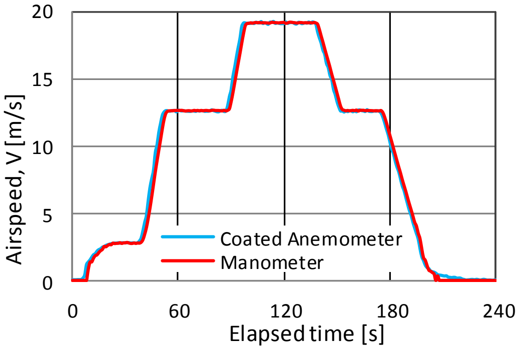


Fig.5 Wind speeds measured by coated anemometer and Pitot-tube manometer system

III. SNOWING WIND TUNNEL TEST

A. Facility, devices, and test conditions

The snowing wind tunnel test was conducted at the wind tunnel placed inside the Cryospheric Environment Simulator (Fig.6) of the Shinjo Cryospheric Environment Laboratory of the National Research Institute for Earth Science and Disaster Prevention. The aim of the test was to evaluate the effectiveness of the icephobic coating for snow/ice prevention in the case of the heated ultrasonic anemometer equipped with stack-type transducers, which are the original versions of the VAISALA WMT-703. The heating elements were embedded in the middle part of the transducers and the lower arms. As mentioned earlier, the paint was applied to the transducers, to the upper and lower arms, and to the top cover of the anemometer (Fig.7). Fig.8 depicts the schematic of the snowing wind tunnel test. The snowfall device was placed on the ceiling of the test section from which snowflakes were supplied into the test section. The ultrasonic anemometer was placed in the leeward side of the snowfall device at a distance that was determined in accordance to the airflow speed in the test section in order to optimally create the snowing environment around the anemometer.

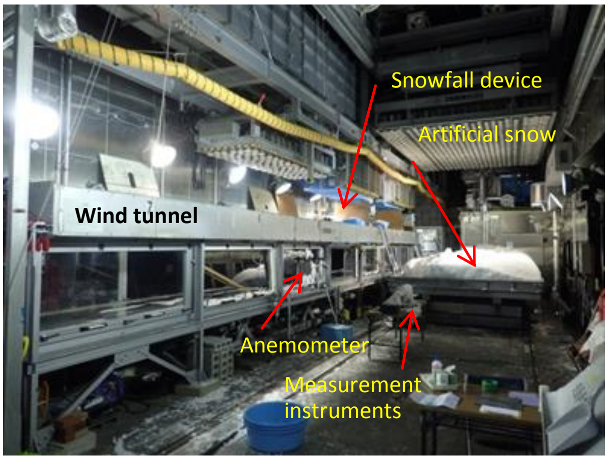
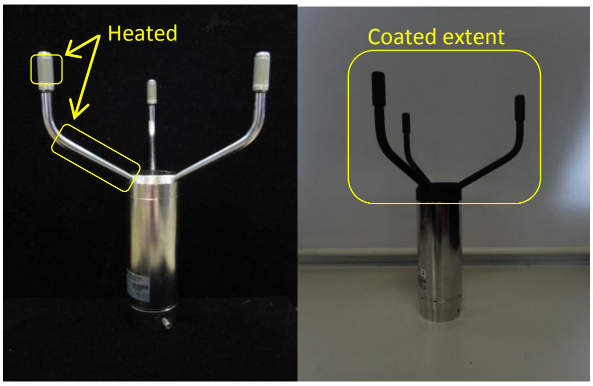


Fig.6 Snowing wind tunnel facility
at Shinjo Cryospheric Environment Laboratory



(a) Uncoated ultrasonic anemometer (b) Coated ultrasonic anemometer

Fig.7 Heating parts and coated extent of the ultrasonic anemometer VAISALA WMT 703

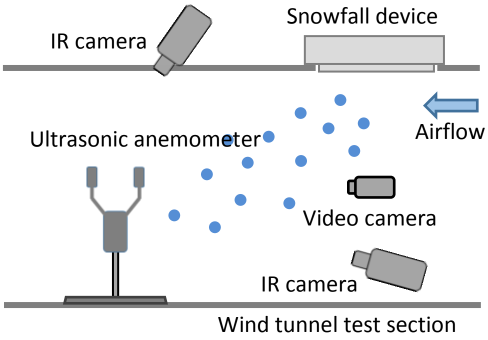


Fig.8 Schematic of snowing wind tunnel test

All tests were carried out at -12°C. The airflow speed was set at values between 1 and 6 m/s. In each test, the surface conditions were monitored using two video cameras set up in the windward location and outside of the wind tunnel test section. With the use of the video cameras, the frontal and side views of the anemometer were recorded throughout the test. For reference, two infrared(IR) cameras were used to measure the surface temperature. One IR camera was placed on the ceiling of the test section and the other besides the video camera in the windward. The measured wind data were transferred to the personal computer and stored in the hard disc. However, the wind data were not used for the evaluation of the effectiveness of the coating for ice/snow protection for two reasons: one was the inherent shortcoming of the characteristics of the snowing wind tunnel test for the wind sensors because ice and/or snow accretion occurs in the limited area of the transducer stack due to the stable, one-directional airflow. The other reason was in reference to the particular conditions of the present test where the video and IR cameras were placed in the windward section of the anemometer, disturbed the airflow inside the test section, and produced strong turbulence behind them.

B. Results and discussion

B-1. Weak wind condition

The duration of the snowfall test under the weak wind condition of 1 m/s was 30 min for the uncoated ultrasonic anemometer and 20 min for the coated one. In this wind condition, snowflakes fell from the ceiling at an angle that was approximately 45°. Figs.9 and 10 show the change of the surface condition along with the elapsed time of the test for the uncoated and coated transducers, respectively. It is clearly understood from Fig.9 that secondary icing occurred within a 10 min interval after the onset of the snowfall even if the transducer was heated. Ice grew to the windward side, spreading the covering area on the transducer frontal surface. At 30 min, snow largely accumulated on the ice deposit and covered the entire frontal area of the transducer. It has to be noted that even in a snowfall environment, ice accreted on the heated surface of the transducer through the secondary icing process, in the early stage of the icing event.

The middle part of the transducer was heated and regulated for temperature maintenance at 30°C regardless of the ambient temperature, so that a contact surface of an ice deposit totally covered the windward side of the transducer surface. This was shaped like an arch, maintaining a gap at the interface. As explained earlier, the presence of an air gap decreased the transmisivity of ultrasonic waves. Hence, the ice formation, as seen in Fig.9, led to incorrect wind measurements.

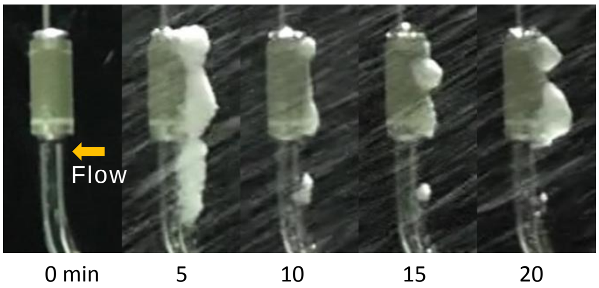


Fig.9 Original transducer stack at 1 m/s

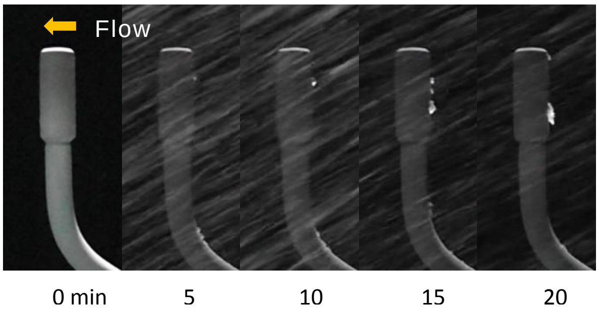


Fig.10 Superhydrophobically coated transducer stack at 1 m/s

In contrast, the surface of the transducer had been kept clean during the 20 min test run even though a minute quantity of ice deposit was found on it. In Fig.10, which was obtained at 10 min, although one small ice deposit was found on the heated middle part, it disappeared in 10 min. However, interestingly, another thin layer of an ice deposit that was larger than the ice that was previously accreted was observed at a location different than the location of the transducer in the picture at 20 min. Nonetheless, in all cases, no obvious ice accretion was formed on the coated surface, which resulted in the deduction that the superhydrophobic coating was dramatically effective in preventing the transducer from accumulating ice/snow accretion. Moreover, absence of ice accretion ensured the correct and stable wind measurement of the ultrasonic anemometer.

B-2. Higher wind condition

Ice accretion on the coated and the uncoated transducers at the wind speed of 6 m/s are shown in Figs.11 and 12. In this wind condition, the snowflakes travel and collide with the transducer surface almost horizontally.

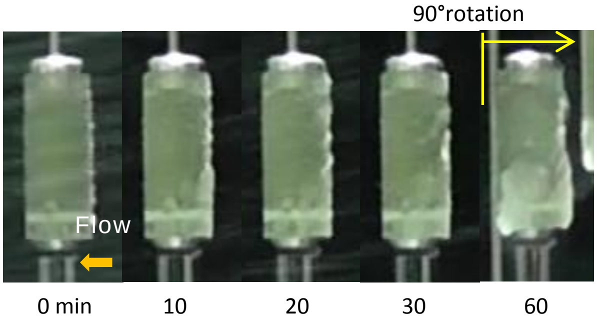


Fig.11 Uncoated transducer stack at 6 m/s

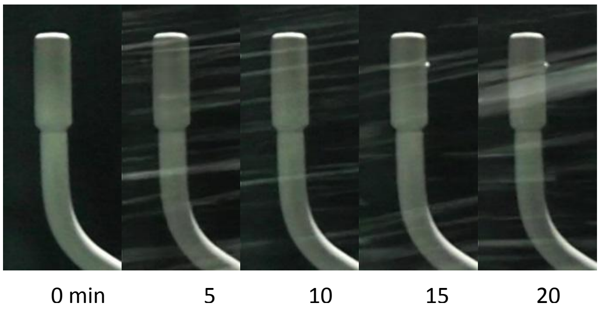


Fig.12 Superhydrophobically coated transducer stack at 6 m/s

For the uncoated anemometer, the total test duration was 60 min. After the first half of this time interval, the ultrasonic anemometer was rotated by 90° for widening the icing area on the transducer surface. Since the values of the snow flux and the speed in the weak and higher wind conditions were different from each other, the growth and range of ice accretion may undergo a different process. Therefore, the comparison between the higher and weak wind conditions in terms of the shape of the ice accretion cannot be simply conducted. Even so, as shown in Fig.11, ice grows on the surface as time elapses.

For the coated transducer, Fig.12 indicates that nothing happens on the transducer surface even though, as in the weak wind condition, a very small ice deposit like a frozen droplet is found at 20 min. From the video analysis, it is observed that the ice was blown off shortly after its formation. In addition, the small ice deposit formed on the transducer surface at almost the same area as in the weak wind condition. This implies that the surface roughness in the area was a bit different from the other area. Hence it would be required that painters have to carefully make a coating film on the surface since it should be as uniform as possible.

In regard to snow accumulation on the top cover of the anemometer, under the higher wind conditions, no snow was left on it after the 20 min test. This led to the suggestion that no heating would be needed for the superhydrophobically coated top cover as long as the wind speed was higher than some threshold, and that a better heating scheme has to be considered for energy saving.

IV. CONCLUDING REMARKS

As indicated by this research study, the secondary icing is the primary cause of incorrect measurements in a heated ultrasonic anemometer with stack-type transducers (VAISALA WMT-703) in areas subject to snowing and/or icing. The secondary icing under the snowy condition is a physical phenomenon where icing occurs through the process of refreezing of the meltwater from accumulated ice or from ice accreted on a surface, produced by artificial heating or by a localised temperature increase due to solar radiation. Therefore, enhancing the removal of meltwater from the surface would be considered the most effective way to prevent the secondary icing. The most promising measure to shape this concept is an icephobic coating applied to a surface of interest, and in particular, to superhydrophobic paint.

Prior to the actual application of such paint to the existing ultrasonic anemometer, and in order to ensure the capabilities of wind measurements after coating, several tests and analyses were implemented. The transmissivities of the ultrasonic waves is the most definitive measure for evaluation of the influence of ice accretion on the transducer in regard to wind measurements for the conceivable cases at which incorrect wind measurements were elicited by the ultrasonic anemometer due to snow and/or ice accretion. These were obtained by the acoustic impedance analysis. Moreover, the transmissivity was calculated when the superhydrophobic film was formed on the transducer surface. It was indicated from the analysis that the ice-bridge formation that had an air-gap at the interface between the ice and the transducer surface reduced dramatically the values of the transmissivity compared to the values when no icing occurred. More importantly, the coating film exerted no negative influence on the measurement.

At the next stage, the chemical damage to the transducer's silicon covering due to the thinner of the superhydrophobic paint NIREC-100 was evaluated using the immersion test, in accordance to the Japanese Industrial Standard and within a shorter testing period just for the snowing wind tunnel test. The result was favorable since no damage was found. Additional wind tunnel tests were carried out at room temperature using the same anemometer, with the transducers covered by a thin membrane of vinyl chloride that had an acoustic impedance value at the same impedance level as that of the superhdrophobic paint and the coated transducers, in order to examine the influences of a film on wind measurement. Consequently, it was suggested that the coated anemometer would work properly, regardless of the presence of the thin coating film.

The effectiveness of the coating of the superhydrophobic paint on the wind measurement of the heated ultrasonic anemometer equipped with the stack-type transducers was examined by carrying out the snowing wind tunnel test under weak and higher wind conditions, and at the temperature at -12ºC. The coating was applied to the upper half of the anemometer, and included the transducers, with an embedded electric heater in the middle part. It can be mentioned that the coated surfaces of the anemometer were kept clean throughout each test run in the higher wind condition. In contrast, in the weak wind condition, while the transducers and the arms were free from snowing or icing, snow accumulated on the superhydrophobically coated top cover of the body because snowflakes fell almost vertically and were not blown away by the weak airflow. As a result, it could be concluded that the superhydrophobic coating application to the ultrasonic anemometer equipped with the stack-type transducers would be effective for stable and accurate wind measurements in snowing and dangerous areas.

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