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Evaluation on Rain-Defense Performance of Temperature Sensors

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Abstract Rain-defense performance of temperature sensors is of concern in many important fields, while there has been no suitable method to evaluate their performance before. To solve this problem, an experiment is described in this paper. The experimental device used is a conventional temperature calibration wind tunnel. To simulate the practical environment as rainfall of 8 mm per hour, a water tank is set above the open experimental section of the wind tunnel, at the bottom of which many small holes are drilled so that rain can run down. Three new-type temperature sensors and an old-type temperature sensor are calibrated in the wind tunnel. The calibration method is similar to the recovery characteristic and dynamic characteristic calibration except that the environment here is a mixture of spray and air. As the authentic total temperature is unable to be obtained, an equivalent recovery factor is defined, which uses the total temperature outside the calibrated sensor to participate in the calculation instead of the authentic local total temperature. And through dynamic characteristic calibration, the time constant of the sensor is also obtained. During the calibration experiment, the gas Mach number, water temperature, and attack angle of the temperature sensors are varied. The result shows that the equivalent recovery factor of the new sensor design is lower than that of the old sensor design, which proved that the rain-defense performance of the new sensor design is better than the old sensor design, and some other comparisons can also demonstrate this point. Associating the design structure of the temperature sensor with the experimental result, the evaluation method is shown to be reasonable and feasible.

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1 Introduction

When air flows, a part of thermal energy carried by it changes into kinetic energy, while the total energy remains invariant. The total air temperature usually reflects the amount of total energy, and the static temperature usually reflects the thermal energy. Obviously, the former is always larger than the latter.

The total air temperature is an important parameter for aviators, which is usually measured by temperature sensors. In some cases, flyers will pass through clouds or fly in rain. As the medium varies, the total temperature measured will differ from that of dry air. To diminish the difference, a special structure of total air temperature sensors has been designed to ensure fine rain-defense performance of temperature sensors. The old sensor design and the new one are shown in Fig. 1. Compared with the old sensor design, the new sensor design adds a bar near the entrance of the shield and a throat at the exit.

For total air temperature sensors, the main performance indicators are a recovery characteristic and a dynamic characteristic, which are usually described by a recovery factor and a time constant, respectively. In order to evaluate the rain-defense performance of temperature sensors, an experiment is designed similar to that of recovery characteristic and dynamic characteristic experiments. Additionally, the effects of Mach number, attack angle, and water temperature are evaluated.

The equivalent recovery factor is used to evaluate the recovery performance and rain-defense performance of temperature sensors. Through comparing the new-type temperature sensor with the old-type temperature sensor and analyzing the experimental results, the rain-defense performance of temperature sensors is obtained. The main goal of this work is to provide a method to evaluate the rain-defense performance of

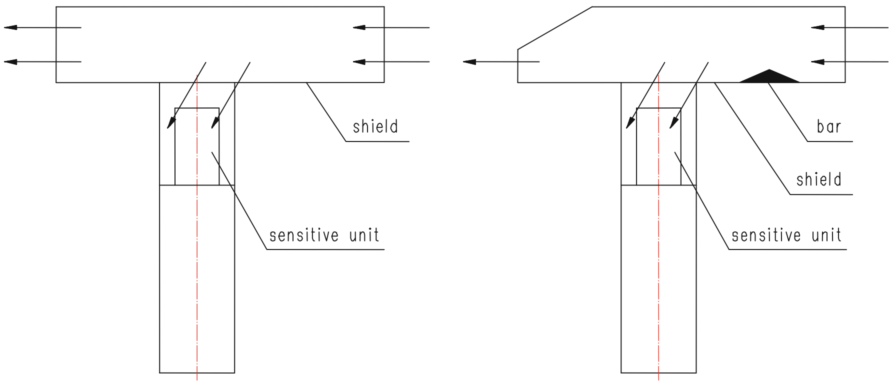

Fig. 1 (a) Old and (b) new sensor designs

total air temperature sensors, so that some guidelines can be given for designers of temperature sensors.

2 Principle

The structure of the temperature sensor is a single-shielded, platinum wire hidden in the shield, while maintaining a low inner velocity that can improve the recovery performance of the temperature sensor.

The recovery factor (r) reflects the recovery degree of the thermal energy of temperature sensors, and is calculated according to [1]

$$r = 1 - \frac{T_0 - T_g}{T_0}\left[1 + \frac{2}{(\kappa - 1)Ma^2}\right] \tag{1}$$

where T_0 is the total temperature of flow, T_g is the effective temperature or recovery temperature of the flow, κ is the ratio of specific heats of air, and Ma is the Mach number of flow. Another parameter r' can be a reflection of both the recovery performance and rain-defense performance, which is defined by

$$r' = 1 - \frac{T_0' - T_g}{T_0'}\left[1 + \frac{2}{(\kappa - 1)Ma^2}\right] \tag{2}$$

where r' and T_0' are named the equivalent recovery factor and equivalent total temperature, respectively. T_0' is calculated by

$$T_0' = \frac{c_{pw}m_w}{c_{pw}m_w + c_{pg}m_g}T_W + \frac{c_{pg}m_g}{c_{pw}m_w + c_{pg}m_g}T_0'' \tag{3}$$

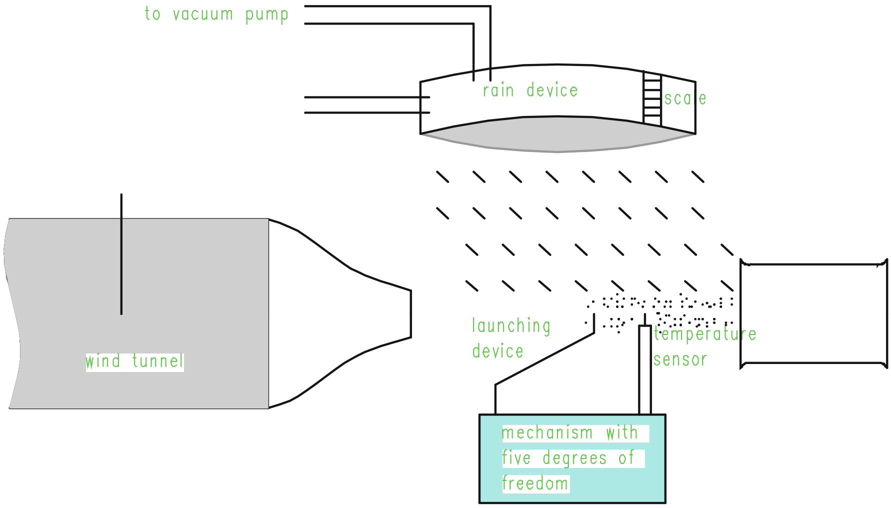

Fig. 2 Diagram of the experimental system

where $c_{p\mathrm{w}}$ and $c_{p\mathrm{g}}$ are the specific heats of water and air, respectively, m_w and m_g are the mass flows of water and air, respectively, T_0'' is the total temperature in the stable section of the wind tunnel (total temperature of dry air), and T_w is the water temperature. During the calculation, m_w and m_g depend upon a rainfall of 8 mm per hour and the Mach number of flow [2].

Heat is exchanged between water and air as they mix together, and the result of mixing will cause the temperature of wet air to tend towards the temperature of the composition whose product of specific heats and mass flow is larger [3]. In fact, T_0' is the total temperature of wet air outside the temperature sensor. As the amount of water entering the temperature sensor is no more than 8 mm per hour, T_0 (total temperature) will never be lower than T_0' if T_w is lower than T_0''. Obviously, we can find $T_0' < T_0 < T_0''$.

Table 1 Results of recovery characteristic experiment with normal water temperature

No. of sensor	Mach number	Attack angle (°)	Equivalent total temperature (°C)	Total temperature of dry air (°C)	Water temperature (°C)	r'
11	0.398	0	28.4	28.8	22.0	1.01
	0.502	0	30.5	30.8	22.1	0.98
	0.601	0	31.8	32.2	22.1	0.95
	0.701	0	32.7	33.1	22.1	0.94
	0.705	+10	32.9	33.2	22.1	0.94
	0.705	−10	32.9	33.3	22.1	0.94
13	0.400	0	35.9	36.4	22.7	1.03
	0.501	0	36.6	37.1	22.7	0.98
	0.600	0	37.8	38.3	22.7	0.95
	0.705	0	38.5	38.9	22.7	0.94
	0.705	+10	38.7	39.1	22.7	0.94
	0.705	−10	38.6	39.0	22.7	0.94
14	0.399	0	30.6	31.1	22.3	0.99
	0.505	0	31.9	32.3	22.3	0.96
	0.600	0	33.4	33.8	22.3	0.93
	0.701	0	34.8	35.2	22.3	0.93
	0.705	+10	35.2	35.6	22.3	0.93
	0.705	−10	35.5	35.9	22.3	0.93
57	0.401	0	35.6	36.3	22.5	1.05
	0.500	0	37.0	37.7	22.5	1.01
	0.597	0	37.8	38.4	22.5	1.00
	0.700	0	39.0	39.5	22.6	0.97
	0.700	+10	39.5	40.1	22.6	0.96
	0.700	−10	39.6	40.1	22.6	0.96

3 Experimental Method

The experiment is carried out in a conventional temperature wind tunnel. The temperature sensor to be calibrated is installed on a mechanism with five degrees of freedom (Fig. 2). A water tank made of glass is set above the open section of the wind tunnel, at the bottom of which many small holes are drilled so that rain can run down. The pressure above the water in the tank is controlled by a vacuum pump in order to keep the rainfall constant. A scale is installed on the side of the tank to measure the rainfall. The water temperature is measured with a platinum resistance thermometer. To keep a constant water temperature, the tank is thermally insulated. The temperature sensor to be calibrated is about 500 mm distance from the exit of the narrow section of the wind tunnel. The long distance ensures that the water has enough time and space to mix with air and atomize.

Table 2 Results of recovery characteristic experiment with water temperature of 15 °C

No. of sensor	Mach number	Attack angle (°)	Equivalent total temperature (°C)	Total temperature of dry air (°C)	Water temperature (°C)	r'
11	0.401	0	31.1	32.0	15.1	1.17
	0.498	0	31.4	32.2	15.1	1.10
	0.600	0	31.9	32.6	15.2	1.06
	0.700	0	32.5	33.1	15.2	1.03
	0.700	+10	33.1	33.7	15.2	1.01
	0.700	−10	32.3	32.9	15.2	1.05
13	0.400	0	30.7	31.6	14.5	1.28
	0.505	0	31.0	31.8	14.5	1.18
	0.603	0	31.5	32.2	14.6	1.12
	0.700	0	32.2	32.8	15.0	1.08
	0.700	+10	32.8	33.4	15.0	1.06
	0.700	−10	32.1	32.7	15.0	1.08
14	0.405	0	34.1	35.4	13.7	1.05
	0.500	0	35.4	36.4	13.8	1.01
	0.598	0	36.8	37.7	13.9	0.96
	0.700	0	38.2	39.0	13.9	0.94
	0.700	+10	37.7	38.3	13.9	0.93
	0.700	−10	37.9	38.4	13.9	0.93
57	0.397	0	33.4	34.3	14.1	1.38
	0.499	0	34.3	35.0	14.4	1.25
	0.598	0	35.1	35.7	14.9	1.17
	0.701	0	35.3	36.2	15.1	1.11
	0.701	+10	35.4	36.4	15.2	1.10
	0.701	−10	35.2	36.1	15.2	1.10

Table 3 Results of recovery characteristic experiment with water temperature of 4 °C

No. of sensor	Mach number	Attack angle (°)	Equivalent total temperature (°C)	Total temperature of dry air (°C)	Water temperature (°C)	r'
11	0.401	0	23.9	25.0	5.3	1.56
	0.500	0	25.5	26.4	5.4	1.33
	0.603	0	26.8	27.6	5.4	1.22
	0.700	0	27.7	28.4	5.4	1.17
	0.700	+10	28.2	28.9	5.4	1.17
	0.700	−10	28.3	28.8	5.4	1.17
13	0.401	0	26.6	27.8	6.1	1.44
	0.500	0	27.3	28.3	6.0	1.24
	0.601	0	28.0	28.8	6.2	1.13
	0.700	0	27.5	28.2	6.2	1.11
	0.700	+10	28.2	28.9	6.2	1.08
	0.700	−10	27.7	28.4	6.2	1.09
14	0.401	0	25.7	26.8	6.9	1.33
	0.500	0	26.4	27.3	7.1	1.16
	0.601	0	26.5	27.3	7.3	1.09
	0.700	0	27.0	27.7	6.2	1.05
	0.700	+10	27.5	28.2	6.2	1.03
	0.700	−10	26.8	27.5	6.2	1.05
57	0.398	0	25.5	26.5	7.6	1.67
	0.502	0	26.6	27.5	7.7	1.42
	0.600	0	27.0	28.1	7.8	1.33
	0.700	0	27.9	28.8	7.9	1.21
	0.700	+10	28.1	29.0	7.9	1.22
	0.700	−10	27.8	28.8	7.9	1.21

For recovery characteristic calibration, the reference temperature sensor is installed in the stable section of the wind tunnel, where the flow velocity is low and the velocity error is small because of its large diameter. Thermal insulation materials are used to wrap the part after the stable section, so heat loss is sufficiently small and can be neglected. Therefore, the temperature measured by the reference temperature sensor can be considered the total temperature of the dry air in the experimental section. The temperature measured by the temperature sensor being calibrated can be considered the effective temperature because radiation error and conduction error are negligible at low temperature. The data of the reference temperature sensor and temperature sensor being calibrated are both collected by a high-performance multimeter. In the experimental procedure, we adjust the flow Mach number to a certain value, make the water in the tank drop down and keep the rainfall constant at 8 mm per hour by adjusting the opening of the vacuum pump. After the state is

Table 4 Results of recovery characteristic experiment without water

No. of sensor	Mach number	Attack angle (°)	Total temperature (°C)	r
11	0.400	0	23.4	0.94
	0.496	0	23.2	0.94
	0.597	0	23.1	0.95
	0.697	0	22.8	0.96
	0.795	0	22.7	0.96
	0.898	0	22.6	0.97
13	0.404	0	23.7	0.96
	0.500	0	23.7	0.95
	0.600	0	23.6	0.96
	0.701	0	23.6	0.96
	0.705	−10	23.6	0.96
	0.705	+10	23.6	0.96
14	0.398	0	16.5	0.94
	0.499	0	16.3	0.95
	0.603	0	16.3	0.96
	0.703	0	16.5	0.96
	0.797	0	16.8	0.97
	0.899	0	17.3	0.97
57	0.403	0	22.5	0.94
	0.502	0	22.4	0.96
	0.601	0	21.9	0.96
	0.704	0	22.3	0.96
	0.801	0	22.3	0.97
	0.902	0	21.8	0.97

sufficiently stable, we record all the data including the Mach number, total temperature of the dry air, water temperature, effective temperature, attack angle, etc. We then adjust the Mach number, attack angle, water temperature, etc. Adjustment of the water temperature is carried out by adding appropriate amounts of ice into the water. Specific heats of water and air are obtained from the literature according to their temperature. Finally r' and T_0' are calculated according to Eqs. 2 and 3, respectively.

For dynamic characteristic calibration, we first adjust the flow Mach number and rainfall to the given value. Then we press the launching device down to make the temperature sensor being calibrated feel a moderate flow temperature, and after the state is stable enough, eject the launching device suddenly and the temperature sensor being calibrated feels a low flow temperature suddenly. In other words, the calibrated sensor feels a negative step of temperature. During the whole process, we record the signal of the calibrated sensor with a high-speed data collector. The time constant can be obtained from the response curve of the calibrated sensor.

4 Experimental Results

The calibrated sensors include both the new design (sensors No. 11, 13, and 14) and the old design (sensor No. 57). The results of the recovery characteristic experiment are shown in Tables 1, 2, 3, and 4; Fig. 3. The results of the dynamic characteristic experiment are shown in Tables 5 and 6. From the results of the recovery characteristic and dynamic characteristic experiments, we can draw some conclusions as follows:

1. For the old sensor design, the equivalent recovery factor with a water temperature T_w is higher than the recovery factor without water. For the new sensor design, compared with the recovery factor without water, the equivalent recovery factor with a normal water temperature is higher when *Ma* is 0.4 and 0.5 while lower when *Ma* is 0.6 and 0.7. When T_w is 15 °C and 4 °C, the equivalent recovery factor of all sensors with water is higher than the recovery factor without water.
2. When T_w is 15 °C and 4 °C, the equivalent recovery factor is generally higher than one. There are two reasons, one is that T_0' is used instead of T_0, and another is that the Prandtl number (*Pr*) of water at 15 °C and 4 °C is much larger than one [4].
3. The equivalent recovery factor of the new sensor design is lower than that of the old design, which proves that less water enters the new sensor. In other words, the rain-defense performance of the new design is better than that of the old design.

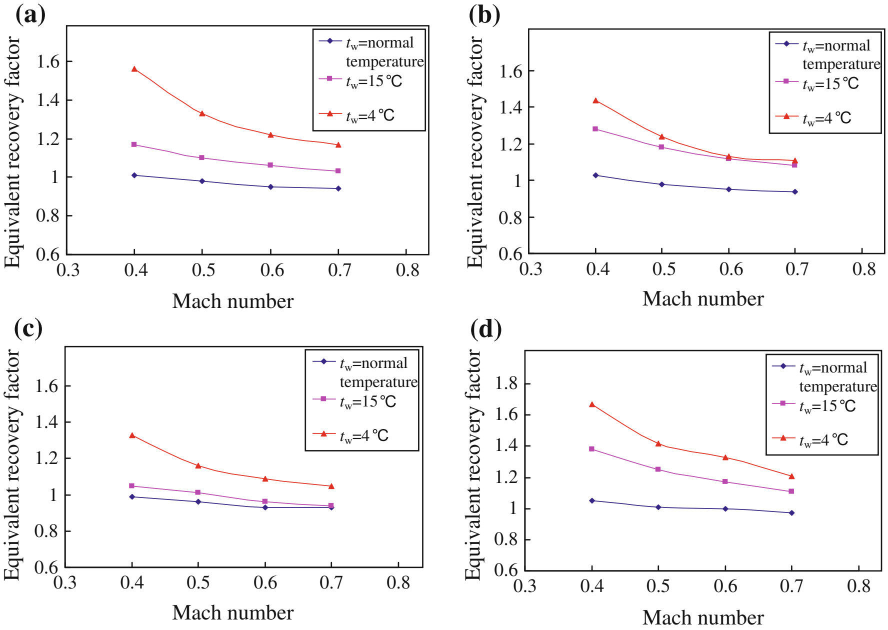

Fig. 3 Results of recovery characteristic experiment. (a) No. of sensor: 11, (b) No. of sensor: 13, (c) No. of sensor: 14, (d) No. of sensor: 57

Table 5 Results of dynamic characteristic experiment with normal water temperature

No. of sensor	Mach number	Attack angle (°)	Time constant (s)
11	0.402	0	1.31
	0.501	0	1.10
	0.605	0	1.08
	0.705	0	0.95
	0.705	+10	0.95
	0.705	−10	0.93
13	0.401	0	1.30
	0.496	0	1.17
	0.600	0	1.04
	0.705	0	0.92
	0.705	+10	0.92
	0.705	−10	0.92
14	0.401	0	1.35
	0.499	0	1.23
	0.604	0	1.05
	0.705	0	0.94
	0.705	+10	0.95
	0.705	−10	0.95
57	0.401	0	1.87
	0.503	0	1.57
	0.604	0	1.38
	0.702	0	1.20
	0.702	−10	1.13
	0.702	+10	1.12

Table 6 Results of dynamic characteristic experiment without water

No. of sensor	Mach number	Attack angle (°)	Time constant (s)
11	0.402	0	1.41
	0.702	0	0.81
13	0.397	0	1.35
	0.699	0	0.95
	0.699	−10	0.95
	0.699	+10	0.95
14	0.400	0	1.35
	0.702	0	0.82
57	0.401	0	0.93
	0.698	0	0.64

4. The equivalent recovery factor of the sensors follows the same laws, that is, the lower the water temperature is, the higher is the equivalent recovery factor. This is because when the water temperature is low, *Pr* is large, and

so the effect of viscous dissipation is strong, and causes the temperature to rise.

5. For the new sensor design, the time constant with water is close to that without water, demonstrating that little water enters the sensor, otherwise, the time constant would become small due to enhancement of the heat exchange. For the old sensor design, the time constant with water is smaller than that without water [5]. So we can draw a further conclusion that the rain-defense performance of the new-type sensor is better than that of the old-type sensor.
6. Under the condition of rain, there is no clear indication that the equivalent recovery factor and time constant are influenced by an attack angle ranging from $-10°$ to $+10°$.

5 Conclusions

From the results of recovery characteristic and dynamic characteristic experiments, we can draw the following conclusions:

1. The method to evaluate the rain-defense performance of temperature sensors introduced in this paper is effective and feasible.
2. The degree of coincidence of the equivalent recovery factor with the recovery factor can be taken for the measurement of the rain-defense performance of temperature sensors.
3. The new-type sensor mentioned in the paper is better than the old-type sensor for rain-defense performance.

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