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THE EFFECT OF THE HUMIDITY ON THE CORRECTION COEFFICIENT OF THE SONIC THERMOCOUPLE USED IN AVIATION

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Abstract

Based on theoretical analysis, it is confirmed in this paper that the variation of the air humidity at normal temperature is the major cause of the instability in correction coefficient of the sonic thermocouple. Finally, the effects of air humidity on the correction coefficient are presented and the test results are explained.

1 Introduction

Having the advantages of the less radiation error and conduction error, the faster response, the higher accuracy and reliability, and measurability outside of the main air flow path of the aero engine, the sonic thermocouple is usually used to sense the variation of the temperature in the compressor inlet of the aero engine. Then, the former stages of guide vanes can be adjusted automatically to avoid the stall and surging of the compressor. The thermocouple can also be used to measure the total temperature of the atmosphere in the aircraft.

The thermocouple used to measure the inlet temperature of an aero engine is the axial wire-drawing sonic thermocouple, which consists of the three thermocouple wires connecting in parallel.

Although this kind of thermocouple has higher reliability, the sonic correction coefficient of the same thermocouple in the different atmosphere conditions is instable and out of the tolerance sometimes when calibrated and re-inspected.

In order to find the cause, the factors which affect the sonic correction coefficient have been analyzed in this paper. It is concluded that the variation of the air humidity is the main cause of the instability of the sonic correction coefficient for the sonic thermocouple. Based on the discussion of the mechanism and law of the effect of the air humidity on the sonic correction coefficient, the test data have been interpreted.

2 Theory analysis

2.1 The factors which affect the sonic correction coefficient

The measuring end(The join point of thermocouple) of the sonic thermocouple is installed in the throat of Venturi tube in order to make the air to flow through the measuring end in the sonic speed. Due to the high air speed and the shielding of the pipe and the outer shell, the radiation and conduction error of the sonic thermocouples are so small that it can be used as the relative standard to calibrate other thermocouples. In addition, the sonic thermocouple has the faster response for the high air speed in the nozzle [1].

When the air temperature is measured in the sonic speed, the conduction error is reduced and the response time decreases, but in the meantime the velocity error increases. However, according to the principles of the aerodynamics, as long as the total pressure of the inlet air is high enough to make the air to be in the critical condition in the throat of the nozzle, the air in the nozzle throat always keeps in the sonic speed no matter how the inlet air changes. So the temperature recovery coefficient (or coefficient of restitution) of the sonic thermocouple is constant in the rather wide range of the inlet air flow, and the velocity error is not related to the value of the inlet air flow speed (For instance, the temperature recovery coefficient '*r*' of the thermocouple in which the air flows parallel to the wires is 0.86±0.09). In consequence, the concrete value of the inlet velocity does not need to be known while estimating speed error, due to the high measuring accuracy, stability and reliability. The value of sonic correction coefficient can be corrected conveniently, and it is usually expressed by a constant coefficient (sonic correction coefficient) and shown in formula (1).

As discussed above, the sensing temperature Tj in the measuring end of the thermocouple can be considered the effective temperature Tg of the inlet air flow because the conduction error is small. Therefore, the total temperature T^* can be calculated according to the following formulas.

$$T^*=aTj \qquad (1)$$

$$a=(k+1)/(2+r(k-1)) \qquad (2)$$

k—adiabatic index
r—temperature recovery coefficient

Here, a is the sonic correction coefficient of the sonic thermocouple.

As it is shown in the formulas above, the sonic correction coefficient a is the function of the adiabatic index k and the temperature recovery coefficient r. The sonic correction coefficient a and the temperature recovery coefficient r tend towards 1 at the same time and a is not related to the adiabatic index k if the temperature recovery coefficient r tends to 1.

Generally, the sonic correction coefficient a keeps constant when the velocity of air in the throat of Venturi tube of the thermocouple arrives at sonic speed, for example, a sonic correction coefficient a is 1.028±0.004.

However, the sonic correction coefficient a is not completely irrelevant to the operating condition. In fact, the sonic correction coefficient a is affected by the variation of the adiabatic index k and the temperature recovery coefficient r since the temperature recovery coefficient r is less than 1.

2.2 The main factor affecting the temperature recovery coefficient

The temperature recovery coefficient expresses the extent of the kinetic energy recovering to the thermal energy in the adiabatic and stagnation air flow and it is defined in the formulas as follows:

$$r=(Tg-T)/(T^*-T)$$

T—static temperature of the air flow

The temperature recovery coefficient r has been expected to be close to 1 and constant for the measurement of the air flow temperature. However, the temperature recovery coefficient is very complicated, which is relevant to Mach number M (expressing the speed of air flow), Prandtl number Pr (expressing the characteristic of the measured medium), Reynolds number Re (expressing the flowing condition of the air flow), the dimension, structure, installed position, material and the temperature and pressure of the measured medium. In general, the function of the temperature recovery coefficient r is difficult to derivate, and it is confirmed by the test. The qualitative analysis is only shown as follows.

2.2.1 The effect of the structure, dimension and material

The temperature recovery coefficient *r* of sonic thermocouples with different structures varies greatly. The temperature recovery coefficient *r* of the sonic thermocouple in which the air flow is parallel to the thermocouple wire is 0.86±0.09. However, it is 0.68±0.07 in the sonic thermocouple in which the air is perpendicular to the thermocouple wire. But for the specific thermocouple, the effects of the structure, material and dimension on the temperature recovery coefficient *r* are not considered because the structure and material are given and there is just a little change in the dimension.

2.2.2 The effect of the temperature and pressure

The influence of the variation of the temperature on temperature recovery coefficient can be ignored since the range of the variation of the atmosphere temperature is narrow in the normal temperature. The effect of the atmospheric pressure in the same area can also be ignored due to its little variation.

2.2.3 The effect of the Mach number of the air flow

Sonic thermocouple has two kinds of structures ,transverse and axial wiredrawing. The air flows through the measuring end of the thermocouple axially in the axial wire-drawing sonic thermocouple. The typical structure is shown in Fig. 1 as follows.

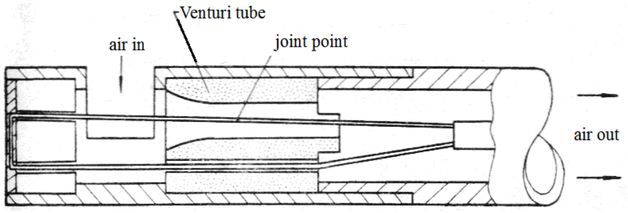

Fig. 1 The typical structure of the axial wiredrawing thermocouple

According to the test data [2], the temperature recovery coefficient *r* changes with Mach number *M* provided that the air passes through the thermocouple wire in the certain direction.

The temperature recovery coefficient *r* keeps constant when the speed of the air flowing through the throat of the sonic thermocouple reaches and exceeds the sonic speed, which is the typical characteristic of the sonic thermocouple. The relation between the temperature recovery coefficient *r* and Mach number *M* in the axial wiredrawing thermocouple with a cylinder measuring end can be seen in Fig. 2.

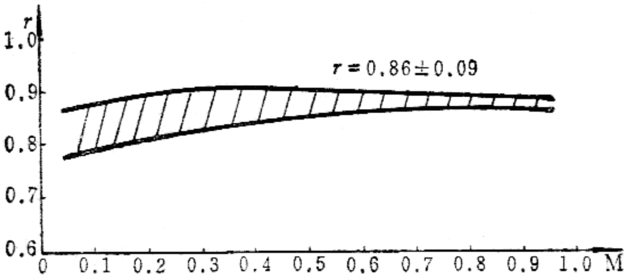

Fig. 2 The relation between *r* and *M* in the cylinder measuring end

As shown in Fig. 2, the value of *r* changes indistinctly with the increase of the Mach number and tends to be stable finally. So the effect of the variation of the Mach number can be ignored.

2.2.4 The effect of the flow condition (Reynolds number Re)

Reynolds number *Re* is a non-dimensional parameter, which determines the condition of the air flow. The air flow is generally classified into two conditions, laminar and turbulent flow. The effective temperature Tg in the turbulent flow is larger than that in the laminar flow since the viscosity shear work between the air in the boundary layer of the turbulent region is stronger. As a result, the temperature recovery coefficient r of the turbulent region is larger than that of the laminar region. According to the experiment data, r is not related to Reynolds number Re in the laminar and turbulent region.However, r increases with the rise of Reynolds number Re in the transition area.

If air flows through the thermocouple wire in parallel, when $Re < 5\times10^5$, it is laminar flow, r=0.845; when $Re > 1\times10^6$, it is turbulent flow, r=0.90; when *Re* is in the transition area between 5×10^5 and 1×10^6 , *r* goes up with the increase of the *Re*. *r* is irrelevant to Reynolds number *Re* in the laminar and turbulent region[2].

In the throat area of Venture tube of one sonic thermocouple, *r* has nothing to do with *Re* when *Re* of the air flows through the measuring end of the thermocouple wire is less than 2×10^4 and the air is laminar flow.

2.2.5 The effect of Prandtl number Pr and the adiabatic index k of the flow medium

Prandtl number *Pr* and the adiabatic index *k* can be considered as a constant for one certain gas. For example, air is usually seen as the ideal gas, Prandtl number *Pr* and the adiabatic index *k* are 0.7 and 1.4 respectively.

Prandtl number *Pr* and the adiabatic index *k* are related with the nature of the fluid medium, but there is a certain amount of water vapor in the real air, and the humidity of the air in the atmosphere will change the Prandtl number *Pr* and the adiabatic index *k*.

The lower specific humidity has a little effect on the temperature recovery coefficient *r* and the sonic correction coefficient *a* since the lower specific humidity has less impact on Prandtl number *Pr* and the adiabatic index *k*.

However, the conclusions in the following show the measure error and the sonic correction coefficient deviation caused by the variation of Prandtl number *Pr* and the adiabatic index *k* in the high humidity condition can not be ignored for the sonic thermocouple which has high accuracy demand in the normal temperature.

2.3 The analysis for the effect of humidity on *r* and *a*

2.3.1 The effect of the humidity on the adiabatic index k

The sonic correction coefficient *a* will be affected by the variation of the adiabatic index *k* since the temperature recovery coefficient of the sonic thermocouple is not 1. The adiabatic index *k* is related to the nature of the fluid and changes with the components of the fluid.

For the dry air, the adiabatic index *k* is 1.4. In the normal atmosphere, the specific humidity has direct effect on the adiabatic index [3], which will be discussed briefly as follows.

According to the definition of the relative humidity and the specific humidity of the air:

$$\varphi=Pv/Ps$$

$$d=622\,Pv/（B-Pv）$$

So $$d=622\,\varphi Ps/（B-\varphi Ps）$$

Here φ—relative humidity

Pv—the partial pressure of the vapor in the atmosphere

Ps—saturated vapor pressure relative to a certain temperature

B—atmospheric pressure

d— specific humidity (or humidity ratio)

The approximate relation between the adiabatic index *k* and the specific humidity *d* is:

$$k=1.4001.76\times10^{-4}d$$

It turns out that the adiabatic index   decreases with the rise of the air relative humidity and specific humidity.

2.3.2 The effect of humidity on the temperature recovery coefficient r

As the air is mainly composed of the diatomic molecules, generally Prandtl number *Pr* is 0.7. But Prandtl number of vapor or water is larger than 0.7, so the wet air has a larger Prandtl number than the dry air. According to the experimental results of the heat transfer theory [4], the increase of Prandtl number will lead to the increase of Nusselt number *Nu*. According to the definition of Nusselt number *Nu*:

$$Nu=\alpha L/\lambda$$

α—heat transfer coefficient(or heat release coefficient)

L—the diameter of the measuring end of the thermocouple wire

λ— heat conductivity coefficient of the fluid (air)

Since the geometrical parameters of thermocouple are given, the increase of Nusselt number Nu can enhance the convective heat transfer coefficient α between the fluid and the thermocouple wire which will then increase the temperature recovery coefficient r of the thermocouple.

2.3.3 *The effect of humidity on the sonic correction coefficient a*

According to the formula (2) and the conclusion in chapter 2.3.1, if the temperature recovery coefficient r is given, the decrease of adiabatic index k caused by the increase of the air humidity will lead to a relative decrease of the sonic correction coefficient a.

According to the formula (2) and the conclusion in chapter 2.3.2, the increase of the temperature recovery factor r caused by the increase of the air humidity will also lead to a relative decrease of the sonic correction coefficient a.

In summary, the increase of the air humidity will lead to a relative decrease of the correction coefficient a of the sonic thermocouple.

The consequences above are based on the qualitative analysis. However, the quantity value of the sonic correction coefficient affected by the humidity should be confirmed by experiment because the relation of the temperature recovery coefficient r and the sonic correction coefficient a is rather complicated.

3 Experimental results of the influence of humidity on the sonic correction coefficient *a*

The sonic thermocouple used to measure the total temperature of inlet air of an engine is a cylindrical measuring end and the axial wiredrawing sonic thermocouple. The main performance parameters are as follows.

The range of the operating temperature:

-77℃～+207 ℃

The pressure of air in the throat:

0.098～0.241 MPa

Sonic correction coefficient:

1.028 ±0.004

In order to study the influence of the air humidity on the sonic correction coefficient, a amount of acceptable thermocouples are tested in different humidity conditions. The test results have been shown in Table 1 and Fig. 4.

The first four sets of data in Table 1 show that there is a linear relationship between the specific humidity d and the sonic correction coefficient a, and the linear correlation coefficient is -0.971. The regression equation of the line in Fig. 4 is as follows:

$$a=1.0300 -3.084\times10^{-4}d$$

The fifth sets of data in Table 1 shows a mutation, and this is because when humid air flows through the throat of Venturi tube at a lower temperature and higher relative humidity, the vapor in the air liquefies due to the drop in temperature and the steam condensation and the gas-liquid (water) two-phase flow cause the increase of the heat transfer coefficient α, which combine and lead to a jump of temperature recovery coefficient r and a discontinuity reduction of the sonic correction coefficient a, near the dew point of the humid air. As a result, the sonic thermocouple may provide the significant indication error and conditional out-of-tolerance.

Due to the limitation of the test data, the above only shows the analysis of the primary experiments. The researches of the performance of the thermocouple in the high humid condition and near the dew point are to be done the next step.

Table 1 Test data of the sonic thermocouple

Number	Atmosphere temperature T^*/K	Measured temperature Tj/K	Relative humidity φ/%	Specific humidity d/（g/kg）	Sonic correction coefficient a
1	298.8	290.7	24	5.573	1.0277
2	286.3	278.2	32	3.420	1.0292
3	278.6	270.6	42	2.681	1.0294
4	296.9	289.4	67	14.092	1.0258
5	270.0	263.9	86	2.411	1.0230
Notes	Measured values	Measured values	Measured values	Calculated values	Calculated values

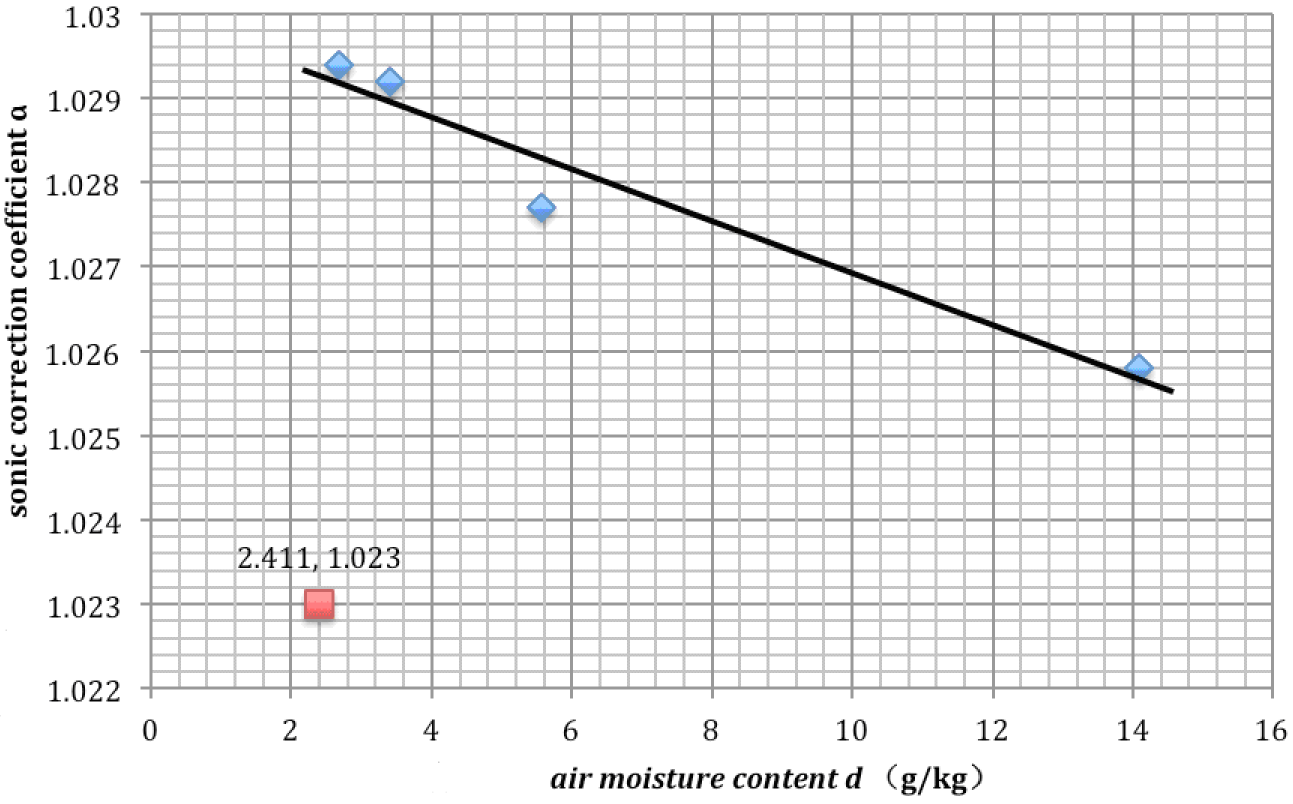

Fig. 4 The effect of the specific humidity *d* on the sonic correction coefficient *a*

4 Conclusion

- In the normal atmosphere, the air humidity is the main factor affecting the sonic correction coefficient of sonic thermocouple.
- In general, the rise of the air humidity leads to the decrease of the sonic correction coefficient, and the sonic correction coefficient keeps rather well linear regular with the specific humidity under the 67 percent of the relative humidity.
- In the higher relative humidity condition, there is a discontinuity reduction of the sonic correction coefficient a of the sonic

thermocouple if the air flowing through the throat of the Venturi tube condenses and liquefies. There will be a larger measure error provided that the sonic correction coefficient is constant.

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