TOTAL TEMPERATURE RECOVERY CHARACTERISTICS TEST TECHNIQUE BASED ON TOTAL PRESSURE CALIBRATION WIND TUNNEL

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Keywords: *Subsonic Wind Tunnel, Total Temperature Recovery Factor, Influencing Factor Analysis, Total Temperature Probe Test*

Abstract

It is difficult to obtain the recovery characteristics of a total temperature probe due to limited number of dedicated wind tunnel for recovery characteristics calibration, complex test procedure, long test period and high cost. Feasibility study of calibrating recovery characteristics using ordinary total pressure calibration wind tunnel was conducted, including the test principle and procedure, the analysis of the major influencing factors and uncertainty estimation of the measurement, etc. The major influencing factors include the variation of air temperature surrounding the probe under test, the characteristics of the flow fields of the wind tunnel low speed section, heat loss of the wind tunnel flow nozzle, heat exchange between the nozzle free jet and the probe and the heat conduction along the support of the probe. On the basis of the feasibility study, a simple total temperature recovery test system was established based on the ordinary total pressure calibration wind tunnel. Several types of probes were tested using the system. Uncertainty analysis of recovery factor was carried out taking into account static calibrations curve of probe with data-acquisition channels fitted by least squares. The test results and analysis proved the common subsonic wind tunnel can be used to quantify the recovery characteristics of total temperature probe, which can be used in design verification to distinguish different probes design in terms of their recovery factors. The study explored a low cost technique to acquire recovery factors using ambient air total pressure calibration wind tunnel. Experience was gained in both theoretical investigation and application of the test. Valuable test data accumulated can also be used for comparison with the results from hot wind tunnel in the future to verify the accuracy of the method.

1 Introduction

The R&D of aeroengines or gas turbines is closely linked with the development of relevant engine measuring technique. Intrusive probes representing contact measurement methods are still widely used in the field of aeroengine measurement, which have experienced great changes in probe types and structures different from that of traditional probes. It is these changes that make the measuring accuracy of some total temperature probes harder to be inferred and assessed by design experience and theoretical calculation than before. Foreign countries have developed advanced measuring methods and test platforms and accumulated numerous fundamental data [1]. However, there are few hot wind tunnels available in domestic. What is worse, only a small proportion of them could be operated normally and provide affluent time for test. On the other hand, calibration tests in hot wind tunnels have numerous restricts, long preparation time and high cost [2]. These two factors lead to the imbalance of supply and demand which indirectly affects the technical development of total temperature probes. Therefore, there is a strong demand for more apparatus [3]. It has been increasingly desired by the professionals in related field that total temperature probes could be conveniently and effectively calibrated like pressure probes on the same platform. To solve this problem, it was put forward in this paper that wind tunnels for pressure probe calibration might serve for one important item of total temperature probe calibrations, total temperature recovery measurement. A total temperature measuring system established upon the existed subsonic open wind tunnel was to realize this test idea, which would be comprehensively considered including influencing factor on the whole probe test in many aspects. It was expected to achieve the goal of measuring of total temperature recovery factor finally.

2 Recovery Factor and Wind Tunnel Test System

The recovery factor was a core technical parameter indicator that could reflect the dynamic measuring characteristics of total temperature probes. The brief test principle of the recovery factor was as follows: reference probe was mounted in the low speed section and probe to be tested was placed in the air stream discharged from the nozzle. The temperature difference between the reference and the test probe was obtained, which was directly related to the recovery factor of the test probe. The wind tunnel provided for tests was an open subsonic wind tunnel and was not dedicated for total temperature calibration, but for pressure calibration. Now that the wind tunnel has been used for the pressure calibration, it should be reformed before determining the total recovery factor of a probe.

The basic structure of wind tunnel was shown in figure 1. The main parts of the wind tunnel consisted of the DC motor, the Roots blower, the diffuser, the setting chamber and the test section. Tests were performed in the test section and the other parts of the wind tunnel supplied the air stream tests needed. The air stream was generated from the Roots blower driven by the DC motor. The air flow was adjusted by the gas valve to change the stream Mach number. The air stream passed through the diffuser and setting chamber and the flow field became stable and uniform. An additional total temperature recovery factor test system was established upon the wind tunnel. The system (see figure 1) was composed of an industrial computer, data acquisition and zero calibration apparatus. The test data was acquired by Agilent 34970A, transferred and saved in the IPC finally. The HART SCIENTIFIC 9101 guaranteed the constant temperature condition for a thermocouple reference junction, needed by thermocouple probes except Pt resistance probes.

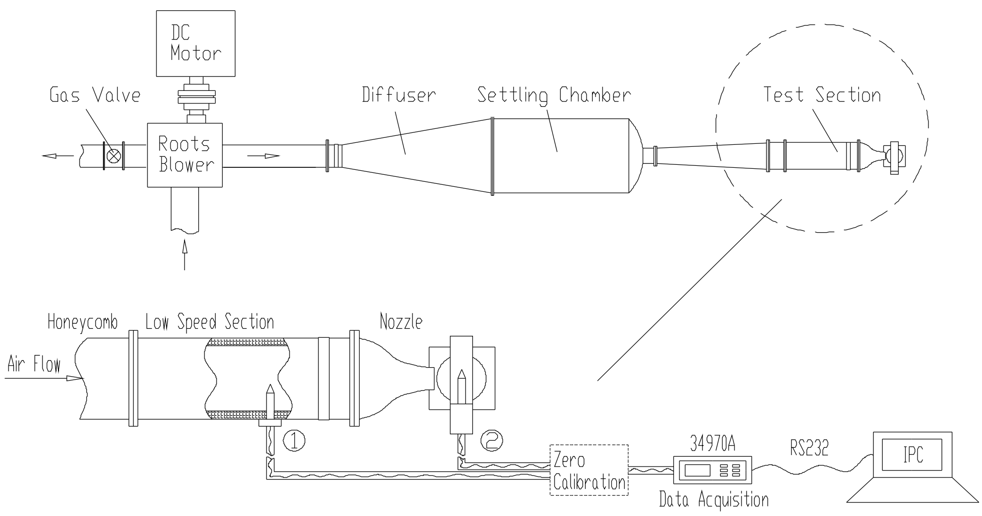

Fig.1 Schematic Diagram of Wind Tunnel and Total Recovery Factor Test System

The wind tunnel was prepared for pressure calibration in the beginning. Hence, flow

3 Evaluation of Influencing Factors on Test

velocity in the low speed section of test section should be known in advance to estimate its impact on the reference total temperature probe.

Tab.1 Flow Parameters of The Low Speed Section and The Entrance of The Nozzle

M	0.5	0.4	0.3	0.2	0.1
P(Pa)	18978	11840	6499	3069	1060
P_h(Pa)	100477	100481	100481	100485	100489
ρ_r	1.188	1.117	1.064	1.030	1.010
M	0.503	0.402	0.300	0.207	0.122
v' (m/s)	173.83	138.86	103.80	71.75	42.32
v(m/s)	7.638	6.490	5.093	3.637	2.188

In table 1, there were many parameters including directly measured ones and indirectly measured ones, which indicated the characteristics of the flow field. The nozzle total pressure P^* (gauge pressure) and static pressure P_h (absolute pressure) were acquired by sensors respectively. The Mach number M was calculated by the expression as [4]

$$M = \sqrt{\frac{2}{k-1}\left[\left(\frac{P^* - P_h}{P_h}\right)^{\frac{k-1}{k}} - 1\right]}, \qquad (1)$$

with P^* the total pressure of the wind tunnel, P_h the static pressure of the wind tunnel and k the air adiabatic index.

After M was derived, the velocity v' outside the entrance of the nozzle was calculated with M. Because the mass flow was constant at a certain M, the velocity v inside the entrance of the nozzle was calculated with v'. Air densities of the entrance of the nozzle inside and outside were calculated with the ideal gas state equation individually. Hereby, air density ration ρ_r was divided air density of the nozzle inside by that of the nozzle outside.

As to the data in table 1, v of this air stream was so small that the reference probe could be treated as in a static flow field. Thus, the impact on the total temperature of the reference probe could be ignored.

The wind tunnel's pipe in the test section was not designed with heat insulation layers. Accordingly, the location mounted reference probe should not be far from the entrance of the nozzle. But there would be also heat loss through the surface of the part of pipe downstream from the reference probe to the entrance of the nozzle. The quantity of the loss of this part of pipe was estimated through thermodynamic modeling.

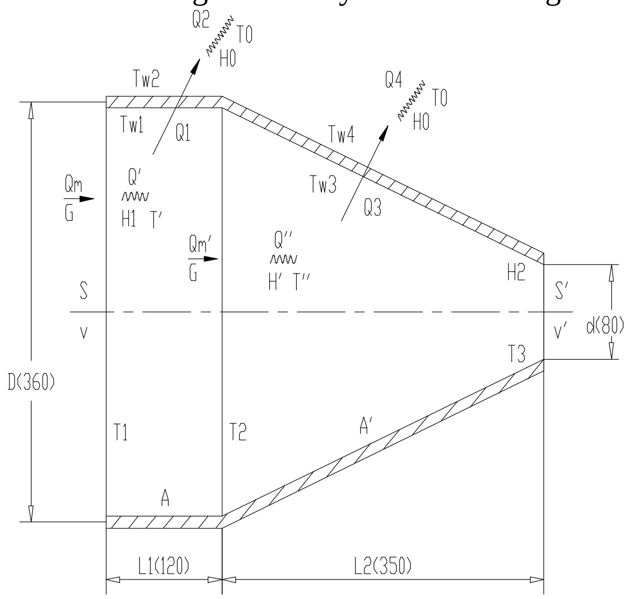

Fig.2 Heat Transfer Analysis of The Nozzle

According to heat transfer theory [5], heat-transfer-balance equations sets (a) and (b) about the two sections of L1 and L2 described in figure 2 were written respectively as

$$\begin{cases} Q_m = Q' \\ Q' = Q_1 \\ Q_1 = Q_2 \end{cases} \text{(a) and} \quad \begin{cases} Q_m' = Q'' \\ Q'' = Q_3 \\ Q_3 = Q_4 \end{cases} \text{(b)},$$

with Q_m the air stream heat loss during L1 part, Q_m' the air stream heat loss during L2 part, Q' the convective heat transfer during L1 part, Q'' the convective heat transfer during L2 part, Q_1 the heat conduction through L1 pipe wall, Q_3 the heat conduction through L2 pipe wall, Q_2 the surface convective heat loss of L1 part and Q_4 the surface convective heat loss of L1 part.

In the condition of 0.5 Mach number, provided that T_1, the entry temperature of L1, was 20℃ and ambient temperature T_0 was 0℃, T_{w1}, T_{w2}, T_{w3}, T_{w4}, T_2 and T_3 would be 9.95℃, 9.93℃, 17.83℃, 17.75℃, 19.97℃ and 19.83℃, where T_{w1} and T_{w2} were the internal and external wall mean temperature of L1, T_{w3} and T_{w4} were the internal and external wall mean temperature of L2 and T_2 and T_3 were the entry and exit mean temperature of L2.

Compared with each other, T_3 was close to T_0 obviously. It meant that the heat transfer loss was so small that it would not affect the test too much. The magnitude of loss in this procedure could be neglected.

As referred to the data in table 1, ***M*** of the wind tunnel was below 0.5. Meanwhile, the Reynolds number ***Re*** was larger than 30. Therefore, the nozzle free jet was uncompressed turbulent jet (see figure 3), of which the turbulent coefficient ***a*** was in the range of 0.066 to 0.071. Here the value of ***a*** was taken as 0.066 considering the turbulence intensity and its uniformity in engineering calculations [6]. The relationship of the four parameters nozzle inner diameter ***d***, jet initial length ***L***, jet falloff angle θ and turbulent coefficient ***a*** could be expressed as [7]

$$\tan q = \frac{r}{L} = 1.49a \, , \qquad (2)$$

with ***r*** the nozzle inner radius in millimeter. The relationship between jet diffusion angle α and turbulent coefficient ***a*** could be expressed as [7]

$$\tan a = 3.4a \, , \qquad (3)$$

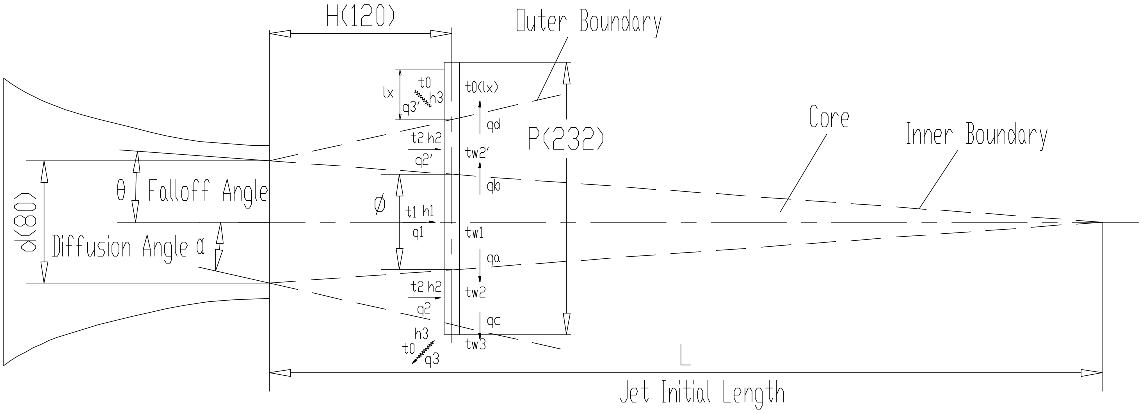

Fig.3 Shape of Free Jet from The Nozzle and Heat Transfer between Jet Flow and Probe Support

The size of the inner and outer boundary at the position ***H*** from the entrance of the nozzle, where the test probe was placed, could be calculated (see figure 3). Therefore, the heat conduction along the chosen probe support like figure 4 could be estimated, which was a typical probe support with more solid material 1Cr18Ni9Ti.

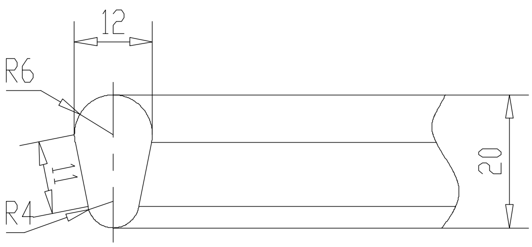

Fig.4 Profile and Size of The Chosen Probe for Heat Conduction Analysis

Combining the theory of jet flow [6] and the heat transfer theory [5], heat-balance could be written as equations sets (c) in the extreme case

$$\begin{cases} q_1 = q_a + q_b \\ q_2 + q_a = q_c \\ q_3 = q_c \\ q_2^{'} + q_b = q_d \\ q_3^{'} = q_d \end{cases} \qquad \text{(c)},$$

with q_1 the convective heat transfer in the jet center between the air stream and the support, q_2 and $q_2^{'}$ the convective heat transfer in the region between the inner and outer boundary of two sides, q_3 and $q_3^{'}$ the convective heat transfer in the region out of the outer boundary of two sides, q_a and q_b the heat conduction across the inner boundary along the support in opposite direction and q_c and q_d the heat conduction across the outer boundary along the support in opposite direction.

When a probe support was inserted into the jet flow and emerged from the opposite side, the middle sensing element was in center of the jet flow region as in figure 3. In this scenario, the support region surrounding the sensing element reached the lowest temperature.

Assuming the probe support was divided into five pieces (see in figure 3), t_{w1}, t_{w2}, $t_{w2'}$ and t_{w3} were the mean values of the temperature of each piece of support from bottom to top. Provided that t_1 was 19.2℃ at 0.5 mach number (considering the recovery factor of the support as 0.7, the temperature of the support was actually 15℃) and ambient temperature t_0 was 0℃. In this case, t_{w1}, t_{w2}, $t_{w2'}$ and t_{w3} would be 14.32℃, 13.03℃, 12.65℃ and 10.58℃.

From the above result, it came to the conclusion that even though the probe chosen was an extreme extraordinary example, the average temperature t_{w1} of the support in the free jet center approached 15℃. Thereby, it was considered that this test method would not vary the temperature value of the sensing element.

4 Probes, Recovery Factors and Uncertainty Analysis

On the basis of the analysis of the test feasibility, four kinds of probes were selected for the total temperature recovery characteristic test [8]. Figure 5 showed the structures of the probes tested respectively. The types of sensing elements mainly included RDT (Pt100) and thermocouple (type T). Among those probes, the Pt100 probe was a single-sensing-element probe and the type T thermocouple probes were multi-sensing-element probes. Each sensing element was denominated as *Yx-n* , where the *Y* indicated its probe type, the *x* which one of the same type of probes and the *n* which element on the probe support. Two probes of the same type were selected. One was used as reference probe and its *x* was defined as *1*, while the other as test probe and its x as *2*.

Sensing junction of *Probe A* was sheathed and the probe's stagnation zone was within the support. *Probe P'* had a separable stagnation cover and the sensing element was individual. When the sensing element was withdrawn from the stagnation cover, it became *Probe P*. Sensing junction of *Probe a* was bare and located in a stagnation cup welded to the support. All the probes had metal mounting flanges, which were not described in detail.

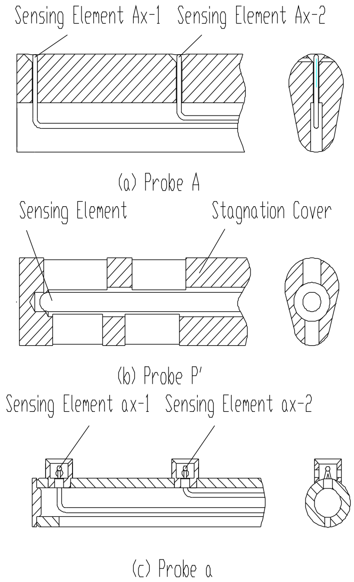

Fig.5 (a) Structure of *Probe A*; (b) Structure of *Probe P'* (*P* is the individual sensing element in the *P'*); (c) Structure of *Probe a*

The recovery factor *r* was mainly related to total temperature and Mach number, expressed as

$$r = 1 - \frac{T_r - T_t}{T_r}\left(1 + \frac{2}{(k-1)\,M^2}\right), \qquad (4)$$

with T_r the temperature of the probe mounted in the low speed section and T_t the temperature of the probe discharged out of the entrance of the nozzle. Relative combined standard uncertainties of *r* were derived by putting the uncertainties of M, T_r and T_t.into the equation as

$$\frac{u(r)}{r} = \left(\left[\frac{4(1-r)}{2M+(k-1)M^3}\right]^2\left[\frac{u(M)}{M}\right]^2 + \left[\frac{T_t(1-r)}{T_r(T_r-T_t)}\right]^2\left[\frac{u(T_r)}{T_r}\right]^2 + \left[\frac{1-r}{T_r-T_t}\right]^2\left[\frac{u(T_t)}{T_t}\right]^2\right)^{0.5}, \qquad (5)$$

The three uncertainties *u(M)*, $u(T_r)$ and $u(T_t)$ should be determined before the uncertainty of *r*. Relative combined uncertainties of *M* classified as B-type uncertainty was calculated from the equation as [9]

$$\frac{u(M)}{M}=\frac{2+(k-1)M^2}{2kM^2}\sqrt{\left[\frac{u(P^*)}{P^*}\right]^2+\left[\frac{u(P_h)}{P_h}\right]^2},(6)$$

where the uncertainties of total pressure P^* and ambient pressure P_h were depended on the transducer's accuracy.

Tab.2 Relative Combined Uncertainties *u(M)*/*M*

M	0.207	0.3	0.402	0.503
u(M)/*M*	0.5%	0.24%	0.13%	0.08%

The static calculations of these probes were performed and the calibration curves were fitted by least squares [10]. Uncertainties of corresponding temperature value produced by the least square fit were considered as each probe's measuring uncertainties estimation to be participated in calculation.

Probes' recovery factors at different *M* were given in table 3. Equipment aging of the wind tunnel resulted in the unsteady flow at low Mach number. Consequently, the uncertainties were deeply affected by the measuring error of probes. In conclusion, the uncertainty error was generally larger than that at high Mach number. Whereby, the results at low Mach number were not valuable for reference and use.

Tab.3 Recovery Factors of Probes' Sensing Elements *r*

M	0.12	0.2	0.3	0.4	0.5
r(*P2'*)	0.725	0.690	0.851	0.854	0.848
r(*P2*)	0.725	0.689	0.679	0.700	0.684
r(*A2-1*)	0.758	0.786	0.865	0.837	0.792
r(*a2-2*)	0.516	0.825	0.868	0.883	0.864

5 Conclusions

The total temperature measuring system upon the total pressure wind tunnel was easy and convenient for use, with which total temperature recovery factors of probes could be tested. During the process of test, the magnitude of the impact on temperature by influencing factors didn't cause interference with the results. The technical idea put forward in the paper was practiced smoothly.

It could be found that obvious distinctions among the measuring accuracy of four total temperature probes appeared at *M* above 0.3 by comparing the test results of the recovery factors of different probes, and the sequence from good to bad was *Probe a*, *Probe P'*, *Probe A*, and *Probe P*. Such test results matched their performances in their practical use ideally. The probes' measuring accuracy was achieved, and also reflected probes characteristics exactly.

Acknowledge

Gratitude to colleagues TIAN Jixiang and CHEN Yuefei's assistance in conducting tests.

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