

Analyses on and Applications of Thermocouples Used for Airflow Temperature Measurements in Aircraft Engine Compressor

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Abstract: The current status of thermocouple temperature measurement technology and development is reviewed, the applications of the thermocouples in temperature measurements of aircraft engine compressor are introduced, and ways to improve the accuracy of temperature measurement are analyzed by looking at sources of measurement error. It is found that the effect of thermal inertia on temperature measurement accuracy and other shortcomings can be overcome by using temperature measurement method of multi-thermocouples; thermocouple accuracy is the main factor affecting the measurement accuracy of the compressor and the development of a high accuracy thermocouple is an effective way to improve temperature measurement accuracy; Au/Pt thermocouple is a kind of high-precision thermocouple with the best thermoelectric properties currently known, and can be applied to the aircraft engine temperature measurements. Copyright © 2014 IFSA Publishing, S. L.

Keywords: Thermocouple, Compressor, Temperature measurement, Error.

1. Development Status of Thermocouples

Temperature is a main measurement parameter in aircraft engine tests. Temperature measurements of an aircraft engine compressor, an important part of aircraft engines, include inlet, inter-stage and outlet gas temperature measurements, of which the measurements of inter-stage temperature and outlet temperature commonly use thermocouples. The inter-stage gas temperature reflects power generating capability of a single blade and can be used to validate the compressor blade design, and the outlet gas temperature is directly related to the overall performance of the compressor along with the design

of the combustion chamber, therefore, accurate temperature measurements contribute to the development of aircraft engines. Among temperature measurement sensors, thermocouples are widely used in aircraft engine temperature measurements due to their simplicity and high accuracy. The principle of thermocouple temperature measurement is the conductor thermoelectric effect. As shown in Fig. 1, the closed loop would produce thermoelectric power, if there exists a temperature difference between the ends of the different conductors, which can be translated to a temperature measurement based on the relationship between electric potential and temperature. Thermocouple development has been

ongoing for over 200 years ever since Thomas J. Seebeck discovered the thermoelectric effect in 1821. With developments in scientific research and industrial technology, thermocouple structure, materials, etc. have also been further developed and is relatively mature.

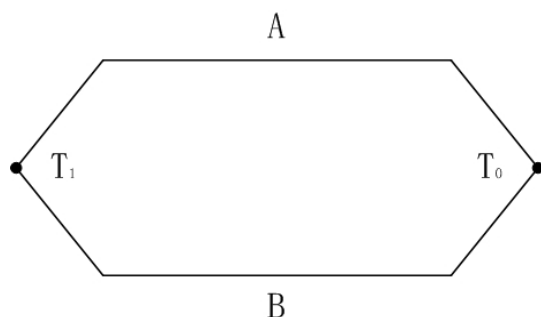


Fig. 1. Schematic diagram of a thermocouple.

All of the thermocouples and Resistance Temperature Detectors (RTDs) produced in China from 1988 onwards follows the International Electrotechnical Commission standards. These standards specify S, B, E, K, R, J, T types as the seven standardized unified design thermocouples in China while tungsten-rhenium and iridium-rhodium thermocouples are the main non-standardized thermocouples. The standardized thermocouples are divided into two groups, cheap metal thermocouples which include E, K, J, T types and noble metal thermocouples consisting of S, B, R types. Thermocouples are either grade I or grade II depending on whether the allowable error is $\pm 1.5\text{ }^{\circ}\text{C}$ or $\pm 2.5\text{ }^{\circ}\text{C}$, respectively. Inhomogeneity has a great impact on thermocouple accuracy. Therefore, the US, Australia, South Korea, Germany, Egypt, and other countries have performed research on inhomogeneity and have achieved some progress. Elemental thermocouples with wires made of one element instead of alloy materials might solve the problem of inhomogeneity. Au/Pt Thermocouple is a typical representative of elemental thermocouples, with good thermoelectric properties. Dean C. Ripple [2] detailed the remarkable property of Au/Pt thermocouples to maintain a temperature drift of under $15\text{ m}^{\circ}\text{C}$ after

1000 hours of use at temperatures up to $1000\text{ }^{\circ}\text{C}$. In 2003, Egyptian researchers [1] studied the thermoelectric properties of the Au/Pt thermocouple with results showing temperature reproducibility degrees is $\pm 4\text{ m}^{\circ}\text{C}$ in temperature range of $0\text{ }^{\circ}\text{C}$ - $900\text{ }^{\circ}\text{C}$, and less than $5\text{ m}^{\circ}\text{C}$ in silver fixed point ($961.78\text{ }^{\circ}\text{C}$). In 2010, F. M. Megahed of the National Institute for Standards in Egypt evaluated the properties and temperature characteristics of noble metal thermocouples (which include Au/Pt, Pt/Pd, and S-type thermocouples), and recommended Au/Pt thermocouples are the most optimal thermocouples to use after a comparison of factors that included repeatability, Seebeck coefficients, thermocouple drift, and other characteristics (Table 1) [9].

Table 1. Inhomogeneity, repeatability, Seebeck coefficients values for Au/Pt, Pt/Pd and type S thermocouples.

Properties	Inhomogeneity	Repeatability	dE/dt
Au/Pt	$19\text{ m}^{\circ}\text{C}$	$6.5\text{ m}^{\circ}\text{C}$	$24.94\text{ }\mu\text{V}/^{\circ}\text{C}$
Pt/Pd	$23\text{ m}^{\circ}\text{C}$	$35\text{ m}^{\circ}\text{C}$	$19.2\text{ }\mu\text{V}/^{\circ}\text{C}$
S-Type	$219\text{ m}^{\circ}\text{C}$	$33\text{ m}^{\circ}\text{C}$	$11.4\text{ }\mu\text{V}/^{\circ}\text{C}$

Due to the corrosive factors of fluid and other factors, thermocouples are often put into the thermocouple protection tubes to extend service life. The tube material and thermocouple type changes depending on the measurement requirements. Thermocouple temperature drift occurs with usage which needs to be corrected through regular calibration, heat treatment, or replacement. To reduce the time period of thermocouple calibration and disassembly, researchers have developed the fixed point thermocouple. Fixed point thermocouples (Fig. 2) have a ceramic fixed-point crucible and a miniature heating element in the periphery that a traditional thermocouple lacks which gives the thermocouple the function of simple fixed-point calibration. Fixed point thermocouples can be periodically tested and also corrected based on the drift from the fixed point. The reliability of fixed-point thermocouples have been proven [2] during long term practical use.

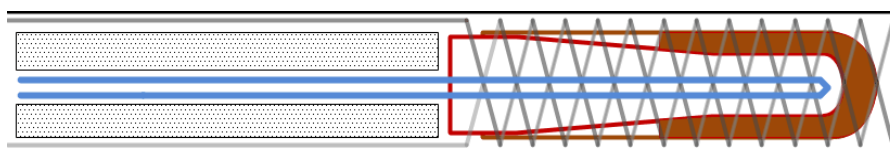


Fig. 2. The tip of a fixed-point thermocouple.

For temperature measurements in special environments, such as high temperature or high speed gas environments, shielding cover or the stagnation

cover is used to reduce measurement error. Thermal shielding cover shown in Fig. 3, has the effect of being a barrier to direct radiation heat transfer

between the high temperature thermocouple and low temperature wall, reducing the effect of heat radiation on the measurement. Ignoring heat conduction, the heat balance equation for the thermocouple junction is:

$$h(T_g - T) = \sigma \varepsilon (T^4 - T_w^4), \quad (1)$$

where T_g is the actual air flow temperature, T_w is the wall temperature and T is the thermocouple temperature, $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2\text{K}^4)$ is Stefan-Boltzmann constant, ε is emissivity. The smaller the radiation heat transfer, the closer the thermocouple measurement is to the actual air flow temperature. The structure of stagnation cover, shown in Fig. 4, cause isentropic stagnation of high-speed airflow so that the measured temperature value is close to the total temperature, T^* . Complete stagnation is difficult to achieve so the total temperature recovery coefficient, r , is proposed as:

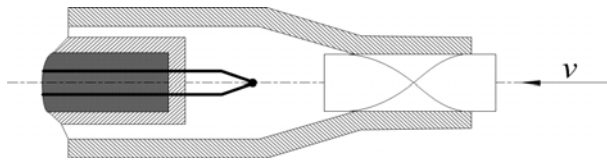


Fig. 3. The structure of shielding cover.

The thermal inertia of thermocouples restricts its application in dynamic temperature measurement. To reduce the thermal inertia of thermocouples, traditional method is to reduce thermocouple size and increase thermocouple surface area, but the measurement results have shown that these methods are not sufficient to meet the requirements of some fast dynamic temperature measurements. Using two or more thermocouples can compensate for thermal inertia on the measurement. Research on multi-thermocouple methods mainly focus on two-thermocouple methods, using time constants or relative expressions from theoretical calculations to compensate the measured value [6-8]. A first-order expression is usually used to establish a mathematical model of the thermocouple.

$$T_{g,1} = T_{m,1} + \tau_1 \frac{dT_{m,1}}{dt}, \quad (3)$$

$$T_{g,2} = T_{m,2} + \tau_2 \frac{dT_{m,2}}{dt}, \quad (4)$$

where T_m is the temperature measured by the thermocouple, τ is the time constant, and subscripts 1 and 2 represent thermocouple 1 and thermocouple 2 respectively. Combined with the actual measurement data, first-order model is discretized in order to

$$r = \frac{T_g - T}{T^* - T} = \frac{T_g - T}{v^2 / (2c_p)}, \quad (2)$$

where v is the air flow velocity and c_p is the specific heat at constant pressure.

It can be seen that the total temperature recovery coefficient is close to 1 when the measuring gas temperature is close to the total temperature. When Mach number, Ma , is greater than 0.2 ($Ma > 0.2$), the temperature error caused by gas speed cannot be ignored generally.

Research on the thermal and stagnation shields, such as information on the dual shielding cover, the dual stagnation cover, crisscross thermocouple, other cover designs, and the empirical formula for the general stagnation cover is provided in references [3-5].

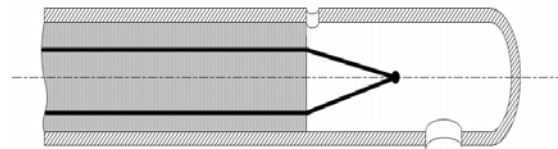


Fig. 4. The structure of stagnation cover.

provide the equivalent difference equation that describes the model:

$$T_{m,1}(j) = a_1 T_{m,1}(j-1) + (1-a_1) T_{g,1}(j-1), \quad (5)$$

$$T_{m,2}(j) = a_2 T_{m,2}(j-1) + (1-a_2) T_{g,2}(j-1), \quad (6)$$

where a_1, a_2 are the expressions related to the time constants, j is the sequence number of the measured temperature data samples. Assuming the actual air flow temperature where two thermocouples located is the same, Eq. 5 and Eq. 6 can then be combined to give

$$T_{m,2}(j) = a_2 T_{m,2}(j-1) + \frac{1-a_2}{1-a_1} T_{m,1}(j) - \frac{a_1(1-a_2)}{1-a_1} T_{m,1}(j-1), \quad (7)$$

Using the least squares method, parameters a_1, a_2 can now be identified by minimizing the deviation between $T_{m,2}$ calculated by Eq.7 and the real temperature measured by thermocouple 2. The actual air flow temperature can be obtained by substituting the time constant into Eq.3 or Eq.4. Ignore the thermal conduction error, the heat balance equations of three thermocouples are established:

$$T_g - T_{m,1} = \frac{\varepsilon \sigma}{h_1} (T_{m,1}^4 - T_w^4), \quad (8)$$

$$T_g - T_{m,2} = \frac{\varepsilon\sigma}{h_2} (T_{m,2}^4 - T_w^4), \quad (9)$$

$$T_g - T_{m,3} = \frac{\varepsilon\sigma}{h_3} (T_{m,3}^4 - T_w^4), \quad (10)$$

where h is the convective heat transfer coefficient, subscript 3 represents the third thermocouple. By convective heat transfer criterion equation, the ratio of the convective heat transfer coefficient of each thermocouple is:

$$\frac{h_1}{h_2} = \left(\frac{d_2}{d_1}\right)^{1-n}, \quad \frac{h_1}{h_3} = \left(\frac{d_3}{d_1}\right)^{1-n}, \quad (11)$$

where d is the thermocouple junction diameter and n is an experimental index. The actual air flow temperature can be obtained by simultaneously calculating the above equations.

Zero diameter extrapolation is the main method used in China to measure the transient temperature while reducing radiation errors [9-11]. Additional development of the thermocouple also includes thin film thermocouple [12], wireless thermocouple [13, 14], new thermocouple materials [15], signal processing techniques [16-18] etc.

2. Thermocouples and Other Temperature Sensors in Temperature Measurements of an Aircraft Engine Compressor

Temperature is one of the most important measurement parameters of the compressor and its measurement accuracy will have a direct impact on compressor performance. Analysis show that temperature measurement errors account for more than 80 % of efficiency errors. It is necessary to understand more aspects of the compressor temperature measurement and improve temperature measurement methods. Due to the temperature of compressor being usually less than 600 °C and requiring higher measurement accuracy, compressor temperature measurements are mainly based on contact measurement which makes the thermocouple method and thermal resistance method most appropriate. RTDs have the benefits of high accuracy, stable performance, repeatability but has a lower upper temperature limits and a larger structure size compared to thermocouples. RTDs are mainly used in inlet temperature and fuel temperature measurements of the aircraft engine and atmospheric temperature measurements in the compressor test. Thermocouples are used in the measurement of compressor inter-stage gas temperature and the outlet gas temperature. Many connection methods of the

thermocouple, such as temperature difference thermocouple method and series thermocouple method, are used to improve measurement accuracy. A diagram of airflow temperature measurement thermocouple placement in a compressor can be seen in Fig. 5.

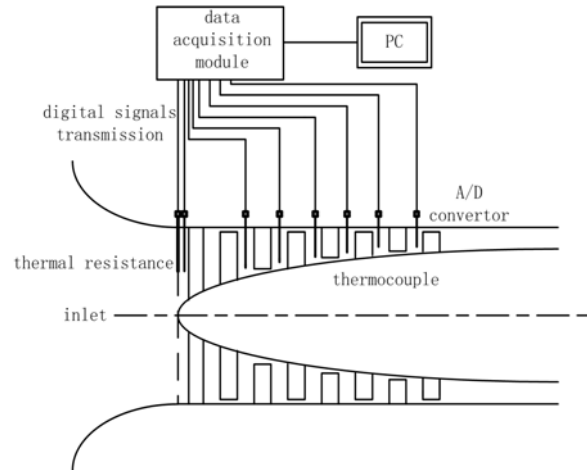


Fig. 5. Compressor temperature measurement schematic.

In order to achieve multi-point measurement and small structure size, China Gas Turbine Research Institute [20, 21] developed a leaf shape foil thermocouple but this method needs further research and promotion. For other special cases, such as inlet temperature distortion measurements, sheet thermocouples are used to measure inlet temperature with a time constant of around 0.05 s [22].

Data acquisition (DAQ) devices are the terminal part of the measurement system and are used in conjunction with the computer for data processing. The analog signal generated by the thermocouple needs to be converted into a digital signal and then inputted to the data acquisition device. Considering the influence on the analog signal from interference during transmission, the A/D (Analog to Digital) converter is arranged at the front of the whole system. When selecting a DAQ, interface number, error, range and other parameters should be taken into consideration and will ultimately affect the price. Temperature monitoring system, NEFF470 measurement and control system, is one of main early data acquisition devices. Currently commonly used brands include instruments from Keithley, Agilent, Fluke, Omega, NI and products.

Engines used in testing should not be brand new engines nor engines with too long of operation time. Ideally, the operation time should be in the range of 50-100 hours in order to make sure the engine complies with the design requirements. Normal engine testing procedures should include the following: 1) Temperature measurement requirements should be outlined in an official document, which include the component to be measured, location of the temperature measurement,

environmental conditions, and engine operating conditions. 2) Temperature measurement process of the engine test should be determined by fully considering the characteristics of temperature measurement techniques. 3) Engine tests usually start by bringing engine slowly from the idling state to a stable intermediate state for 5-10 minutes before slowly returning to the idle state and finally turning the engine off. After the engine has shut off, thermocouples should measure for 10-15 minutes. 4) The temperature range of engine components is very large. Relevant design parameter must be consulted and a thermal analysis must be completed prior to testing in order to determine the types of thermocouple to be used. 5) Refitting of the engine for measurement purposes should not affect engine performance and must fulfill the temperature measurement requirements. 6) Disassemble of the engine in accordance with the test requirements, and install thermocouples. Test the modified engine in order to test the operating condition and the applicability of the thermocouples. 7) Testing the engine and collecting the measurement results in accordance with the test requirements. 8) Organizing temperature measurement results.

3. Thermocouples and Other Temperature Measurements

Thermocouple measurement error is mainly produced in the sensor, transmitters, and data acquisition device. Sensor errors include thermocouple error, velocity measure error, heat transfer error, dynamic response error, etc. The main error of the transmitter is the noise introduced during transmission, the compensation conductor error and A/D conversion error. The data acquisition device generally includes a cold junction compensation circuit, which is the main source of error. Thermocouple error is mainly produced by materials and long-term use. Stress and lattice unevenness during wire material production along with thermoelectric property changes, such as instability or drift, from use. Grade I thermocouples are used in the compressor with an allowable error standard of ± 1.5 °C. With constantly improving production technologies, the allowable error has already been decreased to ± 1.0 °C. Considering the low airflow velocity at the compressor inlet in ground tests, the compressor inlet gas flow Mach number can be assumed to be 0.4 using the following formula:

$$\Delta T_v = T^* - T_g = (1-r) T^* \left(\frac{\frac{k-1}{2} Ma^2}{1 + \frac{k-1}{2} Ma^2} \right), \quad (12)$$

where ΔT_v is the thermocouple velocity error, Ma is Mach number and k is the ratio of constant pressure specific heat and constant volume specific heat. When the total temperature recovery coefficient, r , is

0.97, the velocity error is about 0.5 °C. Due to the low temperatures and large length-diameter ratio of the compressor along with the protective casing pipe that has a thermal shield effect, radiation error is very small. Dynamic error is negligible as measurements in the compressor are almost static measurements. If the velocity error is corrected, the error will be further reduced and be within the error range of ± 1.5 °C. In the engine tests, the thermocouple output signal will be converted to a digital signal directly thus eliminating the error introduced by wire compensation. According to a survey of data acquisition instruments, such as Omega, NI, the total error is about ± 0.5 °C~ 1.0 °C. When measuring the inter-stage gas temperature of an aircraft engine, the above analysis shows that the total measurement system error is about ± 2.0 °C. If using the temperature difference thermocouple method, the total system error is about ± 3.5 °C. When measuring the inlet temperature, the distortion of the compressor with dynamic errors cannot be ignored and the data acquisition device error will be larger. In addition, there are many errors in the system like the error introduced by the strong magnetic field and thermocouple electric leakage. In order to reduce the errors, various measurement factors needs to be considered. As can be seen from the sources of error, research to increase the accuracy of temperature measurement should emphasize the development of high-precision thermocouples and other sensors.

4. Summary

The thermocouple has been widely used in the aircraft engine testing and many other temperature measurement applications. This paper outlines the current status of thermocouple measurement technology and development along with an analysis of sources of air compressor temperature error. It is found that 1) thermocouples have distinct advantages and its technology has undergone extensive development. The effect of thermal inertia on temperature measurement accuracy and other shortcomings can be overcome by using the multi-thermocouples method; 2) thermocouple accuracy is the main factor affecting the measurement accuracy of the compressor and the development of a high accuracy thermocouple is an effective way to improve temperature measurement accuracy; 3) Au/Pt thermocouple is a high-precision thermocouple with the best thermoelectric properties currently known, and can be applied to the aircraft engine temperature measurement.

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