Research of high temperature redundant thin film thermocouple

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Abstract: Using the two-way flow-heat and one-way thermo-solid coupling simulation analysis methods, the designed thin-film thermocouple is analyzed by finite element, and the flow field, temperature field, and structural field inside the sensor are obtained. The high-temperature redundant thin-film thermocouple working simulation test shows that: The response time of the designed thin-film thermocouple is less than 2 seconds, and the stress and deformation are within the required range under the operating temperature load and wind load.

1. Introduction

At present, in the field of gas turbine\textsuperscript{[1,2]} exhaust temperature measurement, to prolong the service life of the temperature sensor, the temperature sensor is generally placed in a metal protection tube. During the temperature measurement process, due to the large volume of the protection tube, the temperature sensor and the measured The time for the medium to establish thermal equilibrium increases the response time of the sensor, resulting in that the sensor cannot sense the temperature change instantaneously and achieve effective tracking, and its output takes a long time to reach a steady-state. On the other hand, due to the hysteresis in the measurement of the sensor, the output signal detected by the sensor is different from the actual measured signal of the system. Only by truly improving the thermal response characteristics of the sensor can it be possible to meet the requirements of instantaneous dynamic temperature measurement.

This topic research the fast response of the high-temperature platinum rhodium\textsuperscript{[3,4,5]} 10 - platinum thin-film thermocouple, based on gas turbine exhaust temperature testing requirements as the background, to carry out high-temperature platinum-rhodium 10 - platinum thin-film thermocouple technology research, based on the theory of thin-film thermocouple, thermocouple reliability analysis by technology, structural design, the simulation analysis, the sensitive film deposition technology, and testing technology, Solve the problem of a slow response time of high-temperature detection in current engineering.

2. Construction and Geometrical Dimensions of Specimens
The redundant thin-film thermocouple developed in this subject is designed based on the sheet-like
structure. A redundant design method of platinum-rhodium 10-platinum thin-film thermocouple is proposed. And the thin-film thermocouple sensor chip is designed into a new triangular redundant structure, namely Two sets of thin-film temperature measuring electrodes are designed on the ultra-thin aluminum oxide ceramic substrate to form electrode redundancy, and the middle of the two sets of electrodes is a hollow part is shown in Figure 1. At the same time, this subject proposes an anti-current sandwich package structure, the schematic diagram of which is shown in Figure 2.

![Fig.1 Schematic diagram of chip redundancy structure](image1)

![Fig.2 3D simulation of sandwich structure](image2)

To achieve the miniaturization of the temperature measurement structure and reduce the response time of the thermocouple as much as possible, the width and thickness of the two sets of temperature measurement electrodes are designed to be 0.3mm and 1μm respectively, and the length of the electrode I is designed to be 14mm, the length of the thermal electrode II is designed to be 7mm, the size of the thermal junction 1 is designed to be Φ0.45mm, and the size of the thermal junction 2 is designed to be Φ0.35mm.

In the coupling analysis, the thermocouple chip is simplified to a 0.2mm triangular substrate, and the simplified thermocouple chip is imported into Fluent, and then the DesignModeler module is used to establish a fluid domain. The fluid domain is a cylinder with a radius of 8mm and a height of 50mm. Use the Mesh module to divide the fluid area mesh, and establish a finite element model for coupled analysis. The finite element model is shown in Figure 3.

In this paper, the internal flow field, temperature field, and structural field of the sensor are analyzed by two-way fluid-thermal coupling and one-way thermo-solid coupling methods, and the stress magnitude and temperature distribution on the thermocouple chip and the response time of the redundant thin-film thermocouple are solved.
3. Test Results and Discussions

3.1 Fluid field analysis results
After the exhaust gas discharged from the gas turbine enters the stagnation cover through the air inlet at a speed of 10m/s, it hits the sidewall of the stagnation cover, and generates a split flow at the sidewall, generating eddy currents on the left and right sides of the cavity, such as shown in Figure 4(a). From the streamlined cloud diagram of the internal flow field, it can be found that after the fluid enters the sensor at a speed perpendicular to the end face of the air inlet, it does not generate regular motion, but generates a large number of irregular motions, even on the surface of the chip. A certain eddy current puts forward high requirements on the strength of the chip. From the velocity vector program of the internal flow field on the chip plane, it can be found that the gas velocity increases significantly at the outlet position, and the gas flow rate is larger at the top position of the Al2O3 ceramic substrate, as shown in Figure 4(b). It also better proves the correctness of the temperature sensing node selection.

3.2 Temperature Field Analysis Results
When the fluid entering the sensor through the air inlet of the stagnation cover flows to the surface of the chip, the heat is transferred to the thermocouple chip by convection heat transfer. After the chip receives the heat of the fluid, its surface temperature rises rapidly. To further analyze the temperature distribution and response time on the chip, the temperature calculated in the flow field is introduced into the temperature field, as shown in Figure 5, at 0.2 seconds, the top of the chip substrate, that is, the thermocouple junction is seen. The temperature of the point is the highest, which is in good agreement with the correctness of our use of the thermocouple junction on the top of the chip as the temperature sensing junction.
To analyze the temperature change of the thermocouple chip more intuitively, import the temperature data of the thermocouple chip calculated in the flow field at different times into the Origin drawing software, and draw the temperature change curve of the thermocouple chip within 5s, as shown in Figure 6 shown.

![Temperature distribution cloud diagram of chip at 0.2s](image)

**Fig.5 Temperature distribution cloud diagram of chip at 0.2s**

It can be seen from Figure 6 that the temperature of the thermocouple chip continues to rise during the entire temperature measurement process, and the temperature of the entire thermocouple chip stabilizes within 5 seconds. Therefore, this paper only analyzes the temperature change of the chip within 5 seconds. The rising speed of the thermocouple chip in the first 2 seconds is significantly higher than that in the next 3 seconds, and the lowest temperature on the entire thermocouple chip has exceeded 700 °C in 2 seconds, exceeding 69% of the exhaust gas temperature of the gas turbine, just reaching the design target that the designed response time of the thermocouple is less than 2 seconds.

3.3 Structural Field Analysis Results

As mentioned above, the fluid entering the sensor transfers heat to the thermocouple chip through convection heat exchange, and also brings a certain fluid pressure to the chip. To analyze the chip in the process of convective heat exchange with the fluid pressure that the chip is subjected to, the fluid pressure calculated in the flow field is introduced into the structure field, and then in the transient statics module, the fluid pressure and change trend that the chip is subjected to within 5 seconds are calculated. Since the chip is in the first 0.2 seconds, the fluid pressure on the inside is very small, so this paper only analyzes the change curve of the fluid pressure from 0.2 seconds to 5 seconds, as shown in Figure 7.

![Temperature variation trend of chip in 5s](image)

**Fig.6 Temperature variation trend of chip in 5s**
Fig. 7 Fluid pressure variation trend of chip in 5s

From Figure 7, it can be seen that the fluid pressure on the chip basically increases in the first 2 seconds, but decreases in 2 to 2.8 seconds, and then increases continuously until 5 seconds. A state of equilibrium is reached. At about 1.2 seconds, the fluid pressure on the chip reaches its peak value, which is about 2837.1Pa, which is far less than the pressure that the chip can bear, and also far less than the yield strength of the alumina ceramic material, which verifies the feasibility of this design scheme. From the graph of the change of fluid pressure on the chip, it is obvious that the fluid pressure on the chip substrate tends to be stable after 5 seconds, about 2250.1Pa.

As mentioned above, the high-temperature fluid not only transfers temperature to the thermocouple chip but also transfers pressure to the thermocouple chip. Therefore, it is necessary to introduce the temperature load and fluid pressure calculated in the flow field into the structure field of the thermocouple chip and analyze the chip. The equivalent stress generated under these two loads can be seen from the above analysis that the fluid pressure and thermal load on the thermocouple chip tend to be stable after 5 seconds. Therefore, this paper only analyzes the stress distribution of the chip within 5 seconds. In general, it is only necessary to analyze whether the maximum stress value of the object is within the allowable stress range. Therefore, it is only necessary to analyze the maximum stress value of the chip at different times. The change curve is shown in Figure 8.

Fig. 8 Maximum stress variation trend of chip in 5s

As can be seen from Figure 9, the stress on the chip gradually increases until after 5 seconds, the stress on the chip reaches a peak value and tends to be stable. The equivalent stress distribution cloud diagram at 5 seconds is shown in Figure 9 shown.
4. Conclusion
In this paper, the finite element analysis software is used to analyze the flow field, temperature field, and structural field inside the redundant thin-film thermocouple within 5 seconds by using two-way flow heat and one-way thermo-solid coupling analysis methods.

The conclusions are as follows: the temperature of the thermocouple chip has reached 69% of the gas exhaust temperature within 2 seconds, and the temperature of the entire thermocouple chip is stable after 5 seconds, so the response time of the thermocouple can be considered to be less than 2 seconds; The fluid pressure on the thermocouple chip also tends to be stable at 5 seconds, with a maximum value of 2837.1Pa, which meets the strength requirements of the thermocouple chip, while the stress value at the root and corners of the chip is relatively large, with a maximum stress value of 108MPa. Within the allowable stress range of alumina ceramic materials, it meets the design and uses requirements.

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