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RESEARCH ON RECONSTRUCTION TECHNOLOGY
OF TEMPERATURE FIELD IN ENGINE COMBUSTION
CHAMBER BASED ON IMAGE THERMOMETRY

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Abstract

In order to make up for the defects of traditional temperature measurement methods, image temperature measurement technology is gradually applied to the measurement of temperature field of high-temperature objects. By analysing and demonstrating the feasibility of three-dimensional temperature field reconstruction in engine combustion chamber, the algorithm of temperature field reconstruction was put forward in this paper, the model between flame radiation energy and temperature field in engine combustion chamber was established, and the application of radiation imaging temperature measurement technology in aero engine annular combustion chamber test was preliminarily realized.

Key words: aero engine, radiation imaging, temperature field measurement, outlet section, combustion chamber

Introduction. The temperature distribution at the exit of the combustion chamber is one of the most important parameters of the aero engine combustion chamber, which directly affects the life and reliability of the first stage turbine guide vanes and working blades. With the development of aero engine towards

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higher thrust to weight ratio, the exhaust temperature of combustion chamber is also getting higher and higher. The average temperature at the outlet of the high-temperature combustion chamber has reached 2000 K [1], and the hot spot temperature has even reached more than 2500 K [2,3], that is to say, in the development of high-power aero engine, ultra-high temperature measurement has been a difficult problem that we have to face. For aircraft engines, the combustion state of the fuel largely determines the thermal energy conversion efficiency of the engine. If the combustion state in the combustion chamber is unstable, it will lead to the coking of the fuel nozzle, and the generation of various pollutants discharged will also increase [4]. In short, measuring the temperature distribution in the engine combustion chamber is an insurmountable gap in the development of high power-to-weight engines, and can also provide data support for optimizing engine design and improving combustion efficiency of the combustion chamber. Therefore, the research on the reconstruction of temperature field in the aero engine combustion chamber is of great practical significance.

Image-based temperature field measurement technology is a new non-contact measurement technology, and has been widely studied in recent years. In the late 1980s, VISKANTA and MENGUC [5] gave the radiation heat transfer equation of the combustion system, and calculated the internal parameters of the combustion system, such as radiation parameters, temperature field and boundary conditions, by using the thermal radiation intensity of the system. In recent years, researchers have conducted a lot of research on radiation transfer, the solution of ill conditioned equations, the model between radiation energy imaging and temperature, and obtained good results. They can achieve the three-dimensional temperature field distribution data and real-time display of more than 1000 discrete units in the furnace. The refresh cycle of the three-dimensional temperature field is less than 5 seconds, and the relative error is within 5% [6-11]. At the same time, image temperature measurement technology is also slowly introduced to the aviation field [12], and flame image temperature measurement technology has been applied to the tail end of combustion chamber, single/multi head combustion chamber, etc. However, there is almost no relevant research on the application of image temperature measurement technology to the interior of full ring combustion chamber. With the increasing demand for high power weight ratio engines, ultra-high temperature measurement will inevitably become one of the urgent problems in engine development. The introduction of image temperature measurement technology will help to solve the problem of ultra-high temperature measurement.

Experimental. The combustion area in the engine combustion chamber is divided into: M units in the space area and N units in the wall area; I units in total. The radiation information in the furnace is obtained by CCD camera. The CCD camera is placed at the outlet of the engine combustion chamber, and its field of view angle is required to cover the combustion area of the combustion chamber as much as possible. The radiation imaging model established the quan-

titative relationship between the flame radiation image and the three-dimensional temperature distribution in the furnace:

$$(1) \quad I_{\lambda, CCD} = A_{\lambda} I_{b\lambda}.$$

Among them, the elements of matrix A are determined by the radiation emitted by the i -th grid cell and the share received by the j -th CCD pixel cell, which is mainly calculated by the Ratios of Energy Scattered by the medium or Reflected by the boundary surface (DRESOR) number. Although there is such a relationship between the flame radiation image and the three-dimensional temperature distribution in the combustion chamber, it is still difficult to calculate the temperature from the radiation image information. Therefore, the new radiation imaging model established the quantitative relationship between the two-dimensional temperature image of the flame and the three-dimensional temperature distribution in the furnace:

$$(2) \quad T_{\lambda, CCD} = A_{\lambda} I_{b\lambda}.$$

Among them, $T_{\lambda, CCD}$ is the two-dimensional temperature image of the flame, which is the cumulative result of the flame radiation information in three-dimensional space on the CCD target surface, and $T_{\lambda, CCD}$ is directly proportional to the flame radiation energy information E . The reference point temperature is calculated by colourimetry based on the three primary colours of colour images R , G and B :

$$(3) \quad t_{CCD}(i_0) = C_2 \left(\frac{1}{\lambda_r} - \frac{1}{\lambda_g} \right) / \ln \left[\frac{r'(i_0)}{g'(i_0)} \cdot \frac{\lambda_r^5}{\lambda_g^5} \right].$$

The calculation formula of flame two-dimensional temperature image is as follows:

$$(4) \quad t_{CCD}^4(i) = t_{CCD}^4(i_0) \frac{G(i)/k'(i)}{G(i_0)/k'(i_0)}.$$

After the temperature image and A' are known, the modified Tikhonov regularization method applied to the linear problem can calculate the blackbody radiation intensity $I_{b\lambda}$, and then the combustion temperature field T can be obtained by Planck's Law:

$$(5) \quad I_{b\lambda} = \left(A_{\lambda}^{\top} A_{\lambda} + \alpha D^{\top} D \right)^{-1} A_{\lambda}^{\top} T_{\lambda, CCD}.$$

In addition, the flame radiation intensity is closely related to the flame temperature and radiation characteristic parameters, so the functional relationship between them can be established:

$$(6) \quad I_{\lambda, CCD} = f(\kappa_{\lambda}, \sigma_{s\lambda}, T),$$

where, $\kappa_\lambda, \sigma_{s\lambda}$ are absorption and scattering coefficients, respectively, and the equation can be differentiated as:

$$(7) \quad I_{\lambda, CCD} = I_{\lambda, CCD}^r + \left[\frac{\partial I_{\lambda, CCD}^r}{\partial \kappa_\lambda} \frac{\partial I_{\lambda, CCD}^r}{\partial \sigma_{s\lambda}} \right] [\Delta \kappa_\lambda^r, \Delta \sigma_{s\lambda}^r]^\top.$$

The least square solution of the equation is:

$$(8) \quad \begin{bmatrix} \Delta \kappa_\lambda^r \\ \Delta \sigma_{s\lambda}^r \end{bmatrix} = \left\{ \left[\frac{\partial I_{\lambda, CCD}^r}{\partial \kappa_\lambda} \frac{\partial I_{\lambda, CCD}^r}{\partial \sigma_{s\lambda}} \right]^\top \left[\frac{\partial I_{\lambda, CCD}^r}{\partial \kappa_\lambda} \frac{\partial I_{\lambda, CCD}^r}{\partial \sigma_{s\lambda}} \right] \right\}^{-1} \times \left[\frac{\partial I_{\lambda, CCD}^r}{\partial \kappa_\lambda} \frac{\partial I_{\lambda, CCD}^r}{\partial \sigma_{s\lambda}} \right]^\top (I_{\lambda, CCD} - I_{\lambda, CCD}^r).$$

Thus, the iteration amount of radiation characteristic parameters can be calculated. Combined with the solution process of temperature, the flame temperature and radiation characteristic parameters can be retrieved simultaneously from the flame radiation image not only by iteration.

Results and discussion. Since the optical lens can only withstand the temperature below 600° , while the temperature in the combustion chamber exceeds 2000° , the existing technology cannot obtain the three-dimensional flame image of the full ring combustion chamber through the CCD camera, so a system for testing the temperature field at the end face of the combustion chamber outlet is built to verify the feasibility and reliability of the radiation imaging temperature measurement technology. The hardware part of the system is mainly composed of imaging system (filter, pinhole high-temperature lens,), image sensing system (CCD camera, video cable), and image processing system (industrial computer, image acquisition and analysis software), as shown in Fig. 1.

The imaging system focuses the light information emitted from the surface of the object to be measured on the CCD photosensitive surface through the optical lens. The colour CCD camera of the image sensing system outputs three primary colour signals containing luminance information. The image acquisition card collects and converts the standard video image signals in real time to convert analogue signals into digital signals; the image processing system on the computer stores digital image signals, establishes a visualization system, and completes temperature measurement calculation and temperature field measurement reconstruction. The instrument electrical control box can ensure the safe operation of the equipment and avoid lens ablation and pollution. The temperature visualization system can read the flame image in the combustion chamber in real time, collect the image information at the frequency of 5S, establish the temperature distribution map of the image, and draw the two-dimensional temperature distribution plan, three-dimensional colour isotherm and cloud map, time temperature trend map, and regional temperature colour map of the combustion chamber.

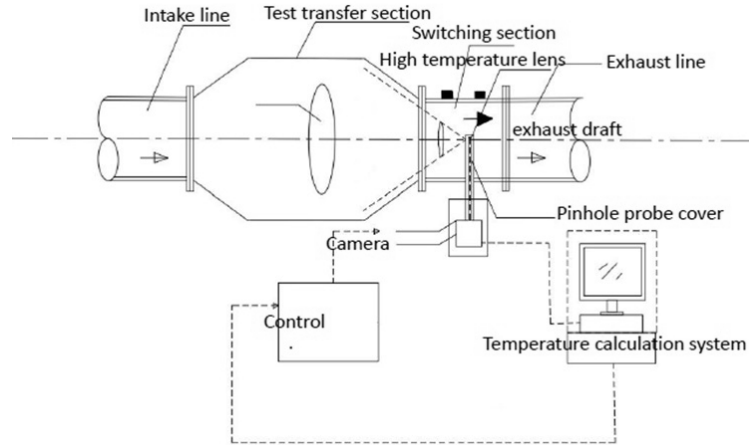


Fig. 1. System structure diagram

Taking the performance test of a direct combustion chamber of a certain type of aero engine as an example (inlet pressure is 1.03 MPa and inlet temperature is 294 °C), the flame imaging system (single camera) was installed at the downstream end of the combustion chamber test section to capture the internal flame image of the combustion chamber in real time before the performance test. When the inlet parameters of the combustion chamber reach the inlet temperature and pressure, the performance of the test parameters is recorded. The traditional way to record the performance results is to rotate an angle to collect the temperature once, stay for a few seconds and then rotate an angle to collect again, so as to obtain the temperature at the outlet end face of the combustion chamber (one cycle takes about 3 minutes). After collection, the results are processed as shown in Fig. 2. The highest temperature at the outlet of the combustion chamber is about 1161 °C and the lowest temperature is about 640 °C under this parameter. Since the camera system is installed at the rear end of the combustion chamber transfer section, the temperature that the camera faces reaches more than 1000°, and a camera can only obtain a flame image of one surface at a moment (as shown in Fig. 3), which cannot be three-dimensionally restored. Therefore, the flame image of a moment can be mirrored into three identical flame fronts with an angle difference of 120 °C for three-dimensional restoration of the flame image, and temperature calculation. As shown in Fig. 3, the highest and lowest temperatures of the exit cross-section at this moment are about 1300 and 600°, respectively.

From the above results, it can be seen that the thermocouple obtains the point surface temperature of the exit section, while the flame image is the surface temperature and the recording time of the results is much shorter. Although the difference at the high temperature is still within the acceptable range, and there is almost no difference at the low temperature, it can be seen that the image

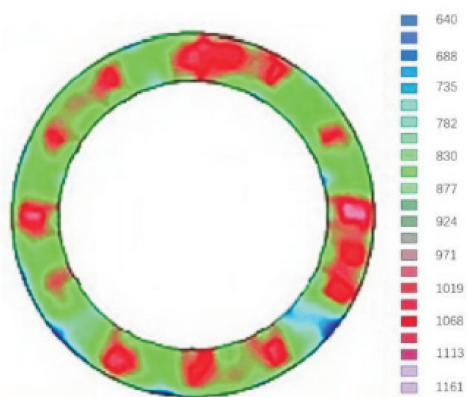


Fig. 2. Temperature distribution at the outlet of combustion chamber



Fig. 3. Flame diagram at the outlet of combustion chamber performance test

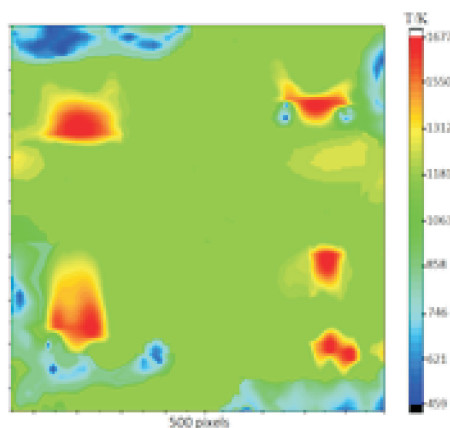


Fig. 4. Colour cloud diagram of combustion chamber outlet section temperature

temperature measurement technology can reflect the combustion situation of the combustion chamber to a certain extent.

Conclusions. The application of radiation imaging technology to the temperature measurement of aero engine combustion chamber can make up for the following defects of traditional measurement methods:

(1) In the aero engine combustion chamber test, the flame image temperature measurement technology is used to obtain the temperature field at the exit of the combustion chamber, which can make up for the defect of obtaining the point temperature by rotating mechanism.

(2) Using thermocouples to record the temperature field at the outlet of the combustion chamber is to record the temperature of a point every other time, which indicates that the hot spot couple temperature measurement cannot reflect

the temperature of all positions at the outlet of the combustion chamber at a certain time, that is, it cannot completely and accurately reflect the combustion situation.

(3) CCD image temperature measurement greatly shortens the time of performance acquisition, reduces the cost of combustion engine test, effectively protects the safety of test equipment, and reduces the test risk.

(4) Using CCD image temperature measurement can not only observe the flame combustion situation in real time, but also understand the performance of the combustion chamber more comprehensively, which will help to understand the suitability of combustion design more comprehensively and shorten the development cycle of the combustion chamber.

To sum up, if flame image thermometry can be well applied to the measurement of combustion chamber temperature field, it can not only solve the defect that the existing temperature measurement methods cannot obtain continuous temperature, but also reduce the test risk and cost. Due to the harsh and complex environment in the combustion chamber, it is difficult to completely replace the contact temperature measurement with the flame image method at present, but if it can be used together, it will greatly benefit the research of the engine and save the cost for the design of the engine.

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