

Probe design for measuring total temperature of combustor outlet based on water cooling

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Abstract: To obtain the outlet temperature of combustor, a kind of high-temperature and water cooling thermocouple was designed. The main factors affecting the results of thermocouple measurement were analyzed after numerical simulation. Results showed that the high-temperature water cooling thermocouple can achieve high temperature measurement under the condition of 2 400 K. With the increase of the distance between the water cooling structure and the stagnation cover, the temperature measurement result was more accurate, and the increase in the area ratio of the inlet and outlet of the stagnation cover within a reasonable range can make the measurement results more accurate. The surface emissivity of the measuring point had a great influence on the radiation error. The pressure and flow rate of cooling water can be effectively reduced after adding zirconia coating onto the surface of the rake body.

Key words: probe; total temperature; combustion chamber; water cooling; thermocouple

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The outlet temperature of aero-engine combustor is a very important parameter, and the accurate measurement of outlet temperature can provide important reference data for the optimization design of engine inlet and outlet nozzle^[1]. There are two kinds of methods for temperature measurement: contact and non-contact. At present, the direct measurement method using the thermocouple is widely used^[2-5]. To measure the temperature of the high-speed and high-enthalpy gas, the sensor is usually combined with the stagnation cover to form a total temperature probe in order to make the temperature of the sensor much more close to the true temperature of airflow. Considering these, domestic and foreign scholars have conducted a lot of research^[6-11]. The total temperature water cooling

probe is mainly used for the high temperature measurement in the engine test presently^[12]. Its advantage is that the thermocouple shell can withstand high temperature and high speed flow, which can meet the request of the total temperature measurement under high temperature conditions, but the radiation error and velocity error influence on the measurement accuracy should not be ignored^[10-11]. By optimizing the structure parameters and selecting the appropriate area ratio of the inlet and outlet of the stagnation cover, the error can be reduced to improve the accuracy of the temperature measurement^[15-17].

In this paper, a thermocouple based on water cooling for the high temperature measurement is researched mainly. Under the premise of the cooling water is not boiling and the strength

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of the main body of the sensor meets the requirements, the thermocouple is deeply studied. This paper analyzes the main factors that affect the temperature measurement of the thermocouple and provides technical support for the design of the thermocouple for measuring the temperature of the outlet gas flow in the combustion chamber under the high temperature environment.

1 Probe design

1.1 Design idea

The difficulty of measuring the temperature in the high temperature flow field mainly comes from the high temperature resistance of the thermocouple. Therefore, it is necessary to cool the thermocouple while measuring. The influence of the high temperature makes the cooling of probe more difficult. The high temperature of the gas in the combustion chamber outlet presents a great challenge to the conventional contact total temperature measurement. In order to ensure the reliability and accuracy of the total temperature measurement, it is necessary to make a comprehensive consideration of the thermocouple material, probe structure and fabrication process. Besides, the thermocouple is usually made into a total temperature probe style with a stagnation cover in order to make the temperature measured by the thermocouple close as the actual total temperature of the high-enthalpy and high-speed airflow.

The design goal of the total temperature probe is to achieve the temperature measurement in the flow field with the highest temperature of 2400 K, the highest total pressure of 9 MPa, the

maximum flow rate of 23.707 kg/s and the inlet velocity of 199.9 m/s. The following problems should be considered in the design of probe.

①Cooling problem of probe: it is very likely that the material of the probe will be melted in such a high temperature when the total temperature of the flow field is about 2400 K. Therefore, it is necessary to cool the probe effectively. The protection of the probe can be achieved by selecting materials with high thermal conductivity and water cooling technology.

②The influence of the probe structure parameters on the temperature measurement accuracy: the influence of the distance between the water cooling structure and the stagnation cover as well as the area ratio of the inlet and outlet of the stagnation cover are mainly considered;

③The effect of radiation error and velocity error on the temperature measurement results;

④The influence of the thickness of the thermal protective zirconia coating on temperature measurement results.

1.2 Temperature measurement principle

Figure 1 shows a typical temperature probe structure with a stagnation cover^[18]. The measuring principle is that when the high-speed airflow passes through the stagnant cover, its speed is reduced to a very low level, so that the air temperature is close to the total temperature. By measuring the thermoelectric potential generated by a thermocouple placed at the end of the stagnation shield, the temperature of the airflow after stagnation is obtained. The stagnation cover can avoid the lateral impact of turbulent flow and reduce the dynamic load of the thermocouple wire, prolong the service life of the thermocou-

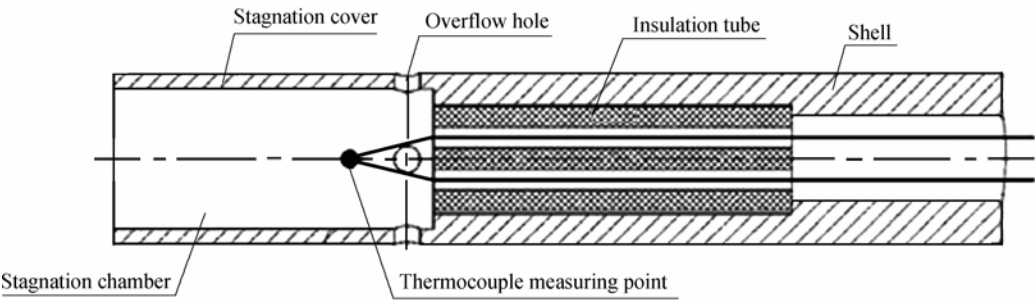


Fig. 1 Schematic diagram of the total temperature probe with a stagnation cover

ple wire. In order to compensate for the temperature loss caused by heat conduction and thermal radiation, an appropriate overflow hole is arranged at the back end of the cover to continuously update the stagnant gas of the probe head. An insulating ceramic tube is used for the isolation of the connecting rod and the lead wire of the thermocouple.

1.3 Structure design

The structure of the high temperature water cooling thermocouples temperature rake is shown in Fig. 2. It is mainly composed of a stagnation cover, a thermocouple, an insulating tube and a shell, etc. According to the working environment of testing engine, water cooling is used

to cool the rake body, and lCr18Ni9Ti is chosen as the shell material of the total temperature sensor. A zirconia material stagnation cover is designed in front of the thermocouple wire, which can effectively stop the flow, and has the advantages of good heat exchange performance in the stagnation cover, so that the sensor can respond quickly. The material of thermocouple wire is WRe5-WRe26, which is shielded by an aluminum oxide ceramic tube and separated from the cooling water. Table 1 shows physical properties of material for temperature rake.

In the table, ρ is the density, c is the specific heat, λ is the thermal conductivity, and ϵ is the emissivity.

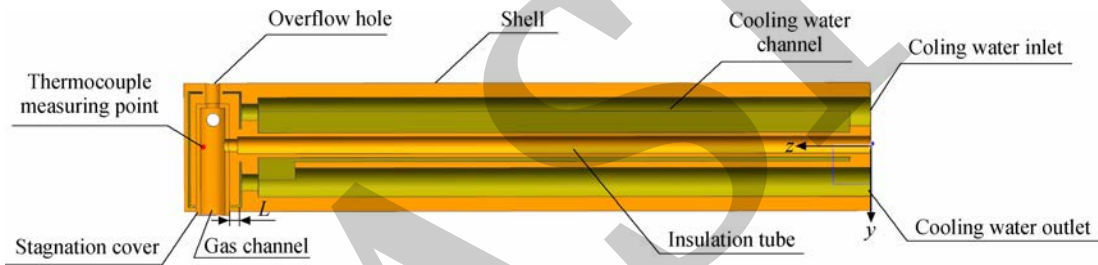


Fig. 2 Structure of water cooling thermocouple temperature rake

Table 1 Physical properties of material for temperature rake

Material	$\rho/(\text{kg}/\text{m}^3)$	$c/(\text{J}/(\text{kg} \cdot \text{K}))$	$\lambda/(\text{W}/(\text{m} \cdot \text{K}))$	ϵ
Zirconia	5 890	800	2.09	0.45
Stainless steel	7 930	500	21.5	0.95
Tungsten rhenium alloy	19 700	134	75	0.32
Corundum	3 970	1 888	0.62	0.95

1.4 Numerical calculation

1.4.1 Governing equation

The law of conservation of mass, conservation of momentum and the law of conservation of energy can be described by the following general mathematical expressions:

$$\frac{\partial(\rho\varphi)}{\partial t} + \text{div}(\rho u\varphi) = \text{div}(\Gamma_\varphi \text{grad}\varphi) + S_\varphi \quad (1)$$

As the dependent variable, it can be used as velocity, momentum, temperature, enthalpy, turbulent kinetic energy and so on.

The turbulence model is based on the Real-

izable $k-\epsilon$ two equation turbulence model, and the radiation model is based on the P-1 radiation model. The standard wall function is adopted for the near wall treatment.

1.4.2 Computational domain

The numerical calculation is based on the general fluid dynamics software Fluent, and the physical models of the three physical models are established and the grids are divided respectively in order to calculate the coupling between temperature rake, airflow and water. The heat conduction, convection and radiation are calculated

by the method of coupling between flow and heat. The grid was set up as a thermocouple point (simplified as a small ball), and the grid was placed in the flow channel of the stagnation cover to simulate the steady temperature of the measured point. The insulating porcelain tube is equivalent as a circular wall with a thickness of 150 mm, and it has not drawn in the domain. The wall boundary conditions are given to calculate the heat transfer from the airflow to the insulating ceramic tube. Due to the small diameter of the wire attached to the ball in the airflow, it has little influence on the airflow parameters. And the thermal conductivity error can be ignored when the ratio of length to diameter of the thermocouple wire is greater than 10. Therefore, in order to simplify the mesh division, the wire part is omitted. The Computational domain is shown in Fig. 3.

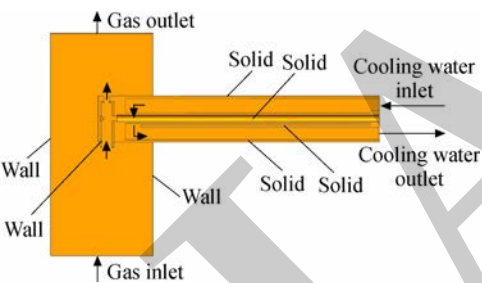


Fig. 3 Computational domain

The boundary conditions of the calculation are as follows: taking the half of the measured rake as the research object, the inlet is selected as the pressure inlet, the outlet is the pressure outlet, the periodic boundary is periodic, and the other solid walls are all selected as wall. To calculate the temperature between the three rake, airflow and water, the physical model is established and the grid is divided. The heat transfer, convection and radiation between them are calculated by the heat and heat coupling method, The entire computational domain uses an unstructured grid for meshing. In order to improve the accuracy of the solution, the small grid of the measuring point is locally encrypted. Finally get the overall quality of the better grid.

After grid-independent solution verification, the total number of meshes in the calculation area is about 1.5 million. There are some assumptions about the model: ① incompressible fluid; ② the physical property of fluid does not change with the change of temperature and pressure, always hold constant; ③ the influence of gravity is ignored; ④ the flow and heat transfer has reached a steady state, and the parameters do not change with time; ⑤ the fluid is without inner heat source.

2 Results and analysis

This paper focuses on the influence of the distance between the water cooling structure and the stagnation cover and ratio of the area inlet and outlet in the stagnation cover in order to analyze the influence of different structural parameters on the temperature measurement of the total temperature probe. The effects of velocity error and radiation error on the measurement results are also considered. In the calculation, the total air temperature is 2 400 K, the total pressure is 9 MPa, the maximum flow rate is 23.707 kg/s, and the inlet velocity is 199.9 m/s. Calculation condition is showed in Table 2. In Table 2, L is the distance between the water cooling structure and the stagnation cover; $A_i : A_o$ is the ratio of the inlet and outlet area on the stagnation cover; δ is the thickness of the zirconia coating on the surface of the harrow; ϵ is the surface emissivity of measuring points. T_{air} is the inlet airflow total temperature; P_{air} is the inlet airflow total pressure; u_{air} is the inlet airflow velocity. p_{cw} is the cooling water inlet total pressure; T_{cw} is the cooling water inlet temperature.

The velocity error is calculated by Eq. (2)

$$\Delta T_v = T^* - T_{effective} \tag{2}$$

where ΔT_v is the velocity error, T^* is the total temperature of the airflow, and $T_{effective}$ is the effective temperature of the airflow. The effective temperature of the airflow increases with the increase of the cooling water pressure, and the velocity error decreases with the increase of the cooling water pressure.

Radiation error is calculated by Eq. (3)

$$\Delta T_r = \frac{\varepsilon \sigma (T_j^4 - T_w^4)}{h}$$

(3)

where ΔT_r is the radiation error, ε is emission

rate, σ is Stefan-Boltzmann constant, T_j is indicating temperature, T_w is the average wall temperature of visible stagnation cover, and h is the coefficient of the convective heat transfer.

Table 2 Calculation condition

Case	<i>L</i> /mm	<i>A</i> _i : <i>A</i> _o	δ /mm	ε	<i>T</i> _{air} /K	<i>p</i> _{air} /MPa	<i>u</i> _{air} /(m/s)	<i>p</i> _{cw} /MPa	<i>T</i> _{cw} /K
1		1.24	0	1	2400	9	199.9	2	300
2	7		0	0.32	2400	9	199.9	2	300
3	7	1.24		0.32	2400	9	199.9	2	300

2.1 Influence of distance *L* between water cooling structure and stagnation cover on thermocouple temperature measurement

Based on the software Fluent, the temperature distribution of the central section of the rake is obtained when the distance between the water cooling structure and the stagnation cover *L* is 5, 7 and 10 mm, respectively. Fig. 4 is the temperature profile of the central section of the temperature rake in which *L* is 7 mm.

According to the case 1 in Table 2, the calculation results shown in Table 3. The results of the simulation calculation of the thermocouple temperature measurement are shown respectively when the distance between the water cooling structure and the stagnation cover *L* is 5, 7, 10 mm, respectively. As can be seen from Table 3, with the increase of the distance between the water cooling structure and the stagnation cover, the radiation transfer heat is reduced. The thermocouple indicates that the temperature increases towards the true value 2400 K. The velocity error and the radiation error decrease, and the average wall temperature of the stagnation cover increases gradually. The increase of the distance between the water cooling structure and the stagnation cover can make the measurement result more accurate. The temperature rise of wall temperature and the supporting cover stagnation may lead to burn out the rake. Therefore, the appropriate distance between the water cooling structure and the stagnation cover taking into account the above two points must be selected.

For safety reasons, the *L* value of 7 mm is selected finally.

In Table 3, *Q_r* is the radiation heat transfer, *T_i* is the indicating temperature, ΔT_v is the velocity error, ΔT_r is the radiation error, and *T_{ave}* is the average wall temperature on the hysteresis shield.

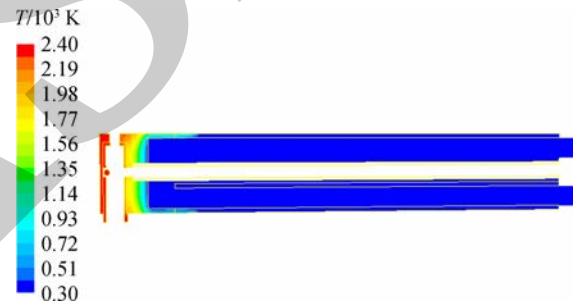


Fig. 4 Temperature distribution of the central section of the temperature rake(*L*=7 mm)

Table 3 Simulation results of thermocouple temperature measurement with different *L*

<i>L</i> /mm	<i>Q_r</i> /W	<i>T_i</i> /K	ΔT_v /K	ΔT_r /K	<i>T_{ave}</i> /K
5	0.8467	2357.197	4.735	38.066	2310.461
7	0.6627	2365.520	4.682	29.797	2329.573
10	0.4912	2373.253	4.659	22.086	2347.032

2.2 Influence of ratio of inlet and outlet area of stagnation cover on temperature measurement

The area ratio of the inlet and outlet of the stagnation cover determines the Mach number of indoor airflow, and the measurement error in the process of speed is a function of Mach number

on the flow. To obtain the appropriate measurement results, the Mach number of the inner flow should be as small as possible to minimize the velocity error. Keeping the inlet area unchanged, it can be adjusted by changing the outlet area. The influence of area ratio of the inlet and outlet of the stagnation cover on the thermocouple temperature measurement is shown in Table 4 according to the case 2 in Table 2. As

can be seen from Table 4, with the increase of the area ratio of the inlet and outlet of the stagnation cover, the temperature of the thermocouple is increased, and the sum of the velocity error and the radiation error decreases. Therefore, it is more accurate to increase the ratio of the inlet and outlet area within a reasonable range. In the direction of the airflow towards the entrance, the $A_i : A_o$ value of 1.24 is selected finally.

Table 4 Simulation results of thermocouple temperature measurement with different $A_i : A_o$

$A_i : A_o$	Q_r/W	T_i/K	$\Delta T_v/K$	$\Delta T_r/K$	T_{ave}/K
1.125	0.327	2378.34	6.961	14.698	2323.155
1.24	0.333	2379.91	5.127	14.962	2323.815
1.375	0.294	2382.24	4.543	13.216	2333.055

2.3 Influence of thickness of zirconia coating on surface temperature and thermal protection of rake body

The surface of the rake body is coated with zirconium oxide in order to strengthen the thermal protection of the rake body. The effect of coating thickness on the temperature distribution of the inner wall of the water chamber is studied. Fig. 5 shows the temperature distribution of the inner wall of the water chamber in the air-flow section, when the thickness of the zirconia coating on the surface of the harrow is 0, 0.5, 1, 1.5 mm. As can be seen from the graph, the surface temperature of the inner wall of the water chamber decreases gradually with the increase of the thickness of the zirconia coating on the surface of the rake. Without zirconia coating, the surface temperature of the water chamber is higher than 500 K while the surface tem-

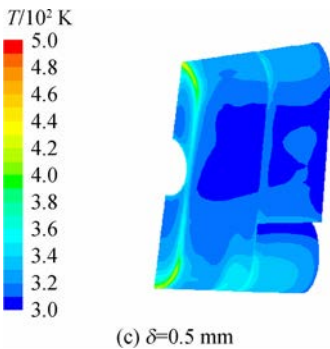
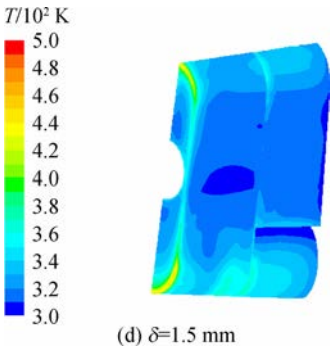
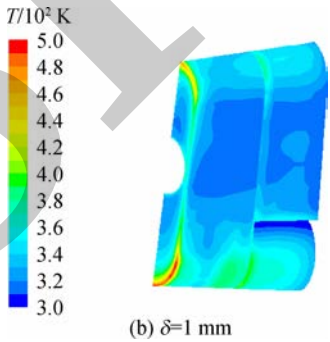
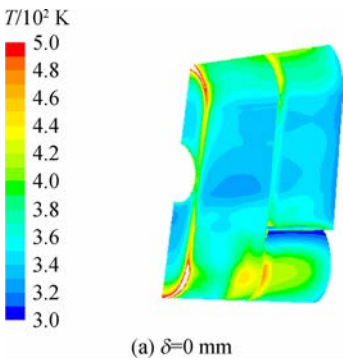


Fig. 5 Temperature distribution of the inner wall of the water chamber in the gas flow section

perature of the water chamber is lower than 500 K when coated with zirconia.

According to the case 3 in Table 2, the calculation results in Table 5 show the temperature measurement in different thickness of zirconia coating on the outside surface of the rake. As can be seen from Table 4, the temperature of the thermocouple is gradually reduced, and the velocity error is not changed with the increase of the thickness of zirconia coating on the external surface of the rake. But the radiation error is increased,

and the wall temperature of the stagnation cover is decreased. The results show that if the thickness of zirconia coating on the external surface of the rake increases, due to the decrease of wall temperature of the inner surface of stagnation cover, the amount of radiation between the measuring point and the visible surface increases, which leads to the increase of the radiation error, and finally leads to a lower temperature measurement as the results of the rake without zirconia coating.

Table 5 Simulation results of thermocouple temperature measurement

δ/mm	Q_r/W	T_i/K	$\Delta T_v/\text{K}$	$\Delta T_r/\text{K}$	T_{ave}/K
0	0.333	2379.91	5.127	14.962	2323.815
0.5	0.456	2373.93	5.566	20.503	2295.362
1	0.529	2371.31	5.679	23.810	2278.955
1.5	0.541	2370.02	5.753	24.326	2275.367

2.4 Selection of cooling water flow rate and pressure adding zirconia coating on outer surface of rake body

Table 6 shows the average-temperature calculation results when the inlet pressure of cooling water is 2 MPa and the thickness of zirconia coating on the outside surface of the rake is 0, 0.5, 1, 1.5 mm. As can be seen from the Table, the addition of zirconium oxide coating on the surface of the rake can significantly decrease the average temperature of the inner wall of the water chamber, which is helpful to avoid the boiling of the cooling water. The T_{iwave} in Table 6 represents the average temperature at the inner wall of the water chamber. When the thickness of zirconia coating on the outside surface of the rake are 0.5, 1, 1.5 mm, the average temperature were 367, 348, 338 K respectively, which is no greater than the boiling temperature of cooling water. The highest average temperature of the inner wall of the water chamber is 360 K and 352 K respectively when the thickness of the zirconia coating is 1 mm and 1.5 mm, and the temperature is no greater than the boiling temperature of the cooling water. It can be seen that after adding zirconia coating on the surface of the

rake body, the inlet water pressure of 2 MPa can meet the requirement of no boiling of the cooling water, and the inlet flow rate of cooling water is 1.1342 kg/s. In the case of a coating thickness greater than 0.5 mm, the average wall temperature of the water chamber is 367 K. Based on the fact that the cooling water does not boil and the maximum possible reduction in radiation error, finally, the coating thickness of 1 mm was chosen.

Table 6 Average temperature of the inner wall of the cavity into the water flow part

δ/mm	0	0.5	1	1.5
T_{iwave}/K	415	367	348	338

3 Calibration

To order to calibrate the influence of surface emissivity of actual measuring point, the surface emissivity of stagnation cover and surface emissivity of the support on the temperature measurement results, the results are calibrated by the following cases. The parameters of the airflow are given by: the inlet total temperature is 2400 K, the air inlet total pressure is 9 MPa (absolute pressure), and the inlet velocity is 199.9 m/s.

The parameters of the cooling water inlet total pressure are given; the inlet total pressure is 2 MPa (gauge), the inlet temperature is 300 K for case 4— case 8; the inlet total pressure is 5 MPa (gauge), the inlet temperature is 300 K for case 9. The surface emissivity of actual measuring point is 0.32, the surface emissivity of stagnation cover is 0.45, and the surface emissivity of support is 0.95.

In Table 7, the case 4 and case 6 show the temperature measurement results when surface emissivity of measuring point is 1.0 and the distance between the stagnation cover and the water cooling structure is 7 mm and 10 mm respectively. Case 5 and case 8 show the temperature measurement results when surface emissivity of measuring points is 0.32, surface emissivity of the zirconia on stagnation cover is 0.45, the surface emissivity of support is 0.95, the distance between the stagnation cover and the water cooling structure is 7 mm and 10 mm respectively. Case 7 shows the temperature measurement results when surface emissivity of measuring point is 0.32 and other solid internal emissivity is 1 and the distance between the stagnation cover and the water cooling structure is 10 mm. Case 9 shows the temperature measurement results when the inlet total pressure is 5 MPa (gauge),

surface emissivity of measuring points is 0.32, surface emissivity of the zirconia on stagnation cover is 0.45, the surface emissivity of support is 0.95 and L is 7 mm.

Compared with case 4 and case 5, it can be found that the surface emissivity has a great influence on the radiation error. The indicated temperature of the thermocouple obtained by the actual solid surface emissivity is higher than that of the solid surface when the emissivity is 1, therefore the radiation error is smaller, and the velocity error is not changed. The actual measurement results should be based on the calculation results of the case 5, and calibrated according to the actual emissivity of thermocouple surface material. The comparison between case 6 and case 8 is similar to that of numerical case 4 and case 5.

Compared with numerical case 5 and case 9, it can be found that the indicated temperature, the velocity error, the radiation error, and the average temperature of visible stagnation cover are unchanged when the inlet hydraulic pressure is 2 MPa and 5 MPa respectively. The results show that the effect of water pressure of the inlet on the indicated temperature, the velocity error, the radiation error, and the average wall temperature of visible stagnation cover is very small, which can be ignored.

Table 7 Effect of surface emissivity of actual measuring point on temperature measurement

Case	ϵ	Q_r/W	T_i/K	$\Delta T_v/K$	$\Delta T_r/K$	T_{ave}/K
4	1	0.66277	2365.520	4.682	29.797	2329.573
5	0.32	0.33281	2379.910	5.127	14.962	2323.815
6	1	0.49126	2373.253	4.659	22.086	2347.032
7	0.32	0.22904	2386.730	2.972	10.297	2348.897
8	0.32	0.24994	2383.730	5.032	11.237	2342.191
9	0.32	0.33370	2379.871	5.125	15.0028	2323.618

4 Summary

A thermocouple probe based on water cooling for high temperature measurement is designed when the flow field with the highest temperature of 2400 K, the highest total pressure of

9 MPa, the maximum flow rate of 23.707 kg/s and the inlet velocity of 199.9 m/s. The influence of different structural parameters on the temperature measurement of the total temperature probe is analyzed, and the conclusions are as follows;

- 1) The designed thermocouple can meet the

requirement of the total temperature measurement precision and thermal protection under the high temperature condition of 2400 K;

2) The increase of the distance between the water cooling structure and the stagnation cover makes the temperature measurement result more accurate, but the increase of the distance will cause the rise of temperature on the stagnation cover and the support cover body, which should pay attention to avoid temperature rake burned;

3) With the increase of the area ratio of inlet and outlet, the temperature of the thermocouple increases, and the sum of the velocity error and the radiation error decreases. As a result, the increase of the area ratio of the inlet and outlet of the stagnation cover in a reasonable range can make the temperature measurement result more accurate;

4) The emissivity of the surface has a great influence on the radiation error;

5) After adding zirconium oxide coating on the surface of the rake body, the pressure and flow rate of the cooling water can be effectively reduced under the premise of avoiding the boiling of the cooling water.

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