Analysis of surrounding gas temperature influence on thermocouple measurement temperature

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Abstract. When thermocouple is used to measure high temperature gas flow, the measured temperature, i.e., the thermocouple bead temperature is not exactly the gas temperature. The bead temperature results from the bead energy balance including the convection with the gas flow, the radiation with the environment and the gas, the conduction with the thermocouple wire near the bead. The wire temperature is determined by its own energy balance relating to the gas temperature contacting the wire. Through the wire conduction, the bead temperature is related to the gas temperature around the wire near the bead. The one-dimensional thermocouple heat transfer simulation code was developed and validated by the elaborate experiment. In the current study, this code is used to study the influence of the surrounding gas temperature on the bead temperature. Of course, the gas temperature far away from the bead will not influence the bead temperature. The size of the surrounding region which could influence the bead temperature is identified and its relation with the flow condition and the thermocouple size is analyzed. The quantitative bead temperature variation with the temperature gradient inside this region is studied.

1. Introduction
Temperature measurement is often an indispensable step in many engineering fields [1]. For example, in the aerospace industry, temperature measurement of high temperature gas in power systems plays a crucial role in material selection and structural design [2]. The existing temperature measurement methods for high temperature gas mainly include non-contact type and contact type. The former includes laser measurement and infrared spectrum analysis. Currently, the more advanced non-contact measurement technologies include Raman laser diagnostic technology [3], Rayleigh laser measurement technology [4], and CARS laser measurement [5]. They have the advantages of high measurement accuracy, wide temperature range, small measuring point size, fast dynamic response and no interference with the flow field to be measured. But the non-contact measurement method often has the limitations
of high cost, long construction time of the whole measurement system, high requirements on the operator, and strict restrictions on the flow field environment. The most common measurement method in contact measurement is direct measurement by a thermocouple. The method is easy to use and less expensive, and is widely used in various scenarios of temperature measurement. However, in the field of high-temperature gas measurement, direct thermocouple temperature measurement will have a large error because the thermocouple bead conducts heat transfer with the external environment. The thermocouple bead will conduct convection and radiation heat transfer with the high temperature gas, radiation heat transfer with the external environment, and conduct heat conduction with the thermocouple wires, so the temperature of the thermocouple bead, that is, the measured temperature, is not equal to the gas temperature. Daniels [6] proposed a polynomial fitting correction method for steady-state temperature measurement. De [7] proposed a formula correction method that is applicable for steady state measurements. Bradley and Mathews [8] used a one-dimensional numerical method which discrete the thermocouple bead and wires into multiple grid points to correct the heat loss during steady-state temperature measurement. This method establishes discrete energy conservation equations for each grid and solves them numerically and it can comprehensively consider different heat transfer modes and perform high-precision correction. Nevertheless, in the implementation process, quite accurate thermocouple surface emissivity data and convective heat transfer coefficient data are needed. Luo [9] also developed a one-dimensional numerical code for temperature correction. Through the CFD numerical simulation, more accurate convective heat transfer coefficients for cross flow over a sphere and a cylinder are developed and they are used in the one-dimensional code. This further improved the accuracy of one-dimensional numerical method.

In the actual measurement process, the temperature of the thermocouple bead is not only affected by the temperature of the fluid surrounding the bead, but also the temperature of the fluid around the thermocouple wires which have influence on the temperature of the wires. Therefore, it is necessary to study the influence range (reflected in its length) of the high temperature flow field (HTFF) around the thermocouple on the bead temperature.

In this paper, the one-dimensional numerical program developed by Luo [9] is used to study the influence range of the flow field around the thermocouples of different sizes, that is, the determined length whose increase will no longer cause changes in the bead temperature. The influence of the bead size on the length is also studied. In addition, the effect of the length of the transition region between the high temperature flow field and the low temperature flow field (ambient temperature 300K) on the temperature of the thermocouple bead is also studied.

2. One-dimensional Numerical Simulation

The CFD method can accurately simulate the temperature of the thermocouple bead, but geometric construction, meshing, model setting and calculation are needed. The whole process takes a lot of time. Therefore, it is not convenient to use the CFD method to calculate the temperature of the bead for every measurement. Since the thermocouple wires is usually slender, its internal temperature gradient mainly exists in the axial direction, the temperature of the thermocouple bead is uniform. Since the size of the thermocouple is small relative to the flow field, the existence of the thermocouple has little interference with the flow field. It can also be considered that the convective heat transfer of a node of the
thermocouple only depends on the local flow field conditions, so the one-dimensional (axial) heat transfer assumption of the thermocouple wire is reasonable. After adopting the one-dimensional heat transfer assumption, the thermocouple wire and the bead are subjected to one-dimensional discretization, and the local convective heat transfer coefficient is input, and the surface emissivity and the ambient temperature are given for numerical calculation. One-dimensional thermocouple numerical simulation requires no mesh and is fast (several seconds to a few minutes) for fast thermocouple bead temperature calculations. In this paper, the one-dimensional numerical simulation program is used to study the influence range of flow field on bead temperature. The accuracy of this program is verified in the literature with experimental data [9].

Luo [9] established the steady-state energy balance equation of the thermocouple. Different from the previous studies, the gas radiation heat transfer between the thermocouple and the high-temperature gas was added for the first time in the equilibrium equation; usually, this heat transfer is small and negligible. However, for a high-pressure or large-sized combustion chamber, the gas radiant rate is high, and the heat transfer effect is very obvious and cannot be ignored. In the Matlab program, the heat balance equation is one-dimensionally discrete and solved. Compared with the three-dimensional CFD calculation method, the calculation speed can be greatly improved while ensuring the calculation accuracy.

In the steady-state flow field, the thermocouple reading does not change with time, and the energy conservation analysis of the bead is shown in Figure 1.

![Figure 1. Thermocouple bead heat transfer model](image)

$\mathcal{Q}_{\text{radb}}$ is the radiative heat transfer between the bead surface and the environment; $\mathcal{Q}_{\text{conv}}$ is the convective heat transfer between the bead and the high temperature gas; $\mathcal{Q}_{\text{radg}}$ is the high temperature gas radiation absorbed by the bead; $\mathcal{Q}_{\text{cond}}$ is the heat conduction between the bead and thermocouple wires; $\mathcal{Q}_{\text{cat}}$ is the absorbed portion by the bead of the surface catalytic reaction heat, it is neglected in this paper.

\[
\mathcal{Q}_{\text{cond}} + \mathcal{Q}_{\text{radb}} + \mathcal{Q}_{\text{radg}} + \mathcal{Q}_{\text{conv}} + \mathcal{Q}_{\text{cat}} = 0 \quad ; \quad \mathcal{Q}_{\text{cond}} = kA \frac{\partial T}{\partial x} \quad ; \quad \mathcal{Q}_{\text{radg}} = \sigma A \varepsilon \varepsilon_g T_g^4 \quad ;
\]

\[
\mathcal{Q}_{\text{conv}} = hA(T_g - T_b) \quad ; \quad \mathcal{Q}_{\text{radb}} = -\alpha A \varepsilon (T_b^4 - (1 - \alpha_g)T_g^4)
\]

Where \(k\) is the thermal conductivity of the corresponding material; \(h\) is the convective heat transfer
coefficient, $A$ is the corresponding heat transfer area; $T_\infty$ is the ambient temperature; $T_b$ is the bead temperature; $T_g$ is the gas temperature, and $\varepsilon$ is the surface emissivity of the thermocouple; $\varepsilon_g$ is the volumetric emissivity of the gas; $\alpha_g$ is the absorption coefficient of the gas to the environmental radiation.

The diameter of thermocouple bead is usually small (the largest thermocouple bead used in this paper is 0.750 mm in diameter). Since the thermal conductivity of the thermocouple material is large, and the internal temperature difference of the bead is very small, the bead temperature distribution can be considered to be uniform. The discrete process of the thermocouple bead and the thermocouple wires is shown in Figure 2.

Figure 2. Schematics of discrete equation (a) Thermocouple Bead (b) Thermocouple Wire

Discrete equation for energy balance of thermocouple bead:

\[
\begin{align*}
&k_1 \frac{\pi d^2}{4} \left( \frac{T_{i-1} - T_b}{\Delta x} \right) + k_2 \frac{\pi d^2}{4} \left( \frac{T_{i+1} - T_b}{\Delta x} \right) + \sigma \varepsilon (\pi D^2 - \pi d^2 / 2) \cdot \\
&[1 - \alpha_g] T_g^4 + \varepsilon_g T_g^4 - T_b^4] + h_g (\pi D^2 - \pi d^2 / 2)(T_g - T_b) = 0
\end{align*}
\]

Where $k_1$ and $k_2$ are the thermal conductivity of the first discrete point of the thermocouple wire A and B; $d$ is the wire diameter of the thermocouple; $D$ is the diameter of the thermocouple bead; $T_i$ represents the thermocouple wire temperature at the discrete point $i$; the gas radiation emissivity $\varepsilon_g$ is a function of the gas temperature, the gas composition and the size of the high temperature gas zone. The
absorption coefficient of environmental radiation $\alpha_g$ is a function of gas temperature, gas composition, high temperature gas zone size, and ambient temperature; $h_b$ is the convective heat transfer coefficient between the bead and the gas, using the formula of Luo [9]:

$$\text{Nu}_b = 2 + 0.24 \text{Re}^{0.7} \text{Pr}^{0.35}$$  \hspace{1cm} (3)

The physical properties of the formula are calculated using the film temperature.

The energy balance analysis of the thermocouple wire is similar to the bead energy equation. The energy balance discrete equation is:

$$k_i \frac{\pi d^2}{4} \left( \frac{T_{i+1} - T_i}{\Delta x} \right) + k_i \frac{\pi d^2}{4} \left( \frac{T_{i-1} - T_i}{\Delta x} \right) + \sigma \varepsilon \pi d \Delta x \cdot \left[ (1 - \alpha_g)T_{\infty}^4 + \varepsilon_g T_g^4 - T_i^4 \right] + h_w \pi d \Delta x (T_g - T_i) = 0$$  \hspace{1cm} (4)

Where $h_w$ uses the forced convection formula of Luo [9]:

$$\text{Nu}_w = 1.02 \text{Re}^{0.35} \text{Pr}^{0.35}$$  \hspace{1cm} (5)

The physical properties of the formula are calculated using the film temperature.

3. HTFF model and Boundary Conditions

In the calculation, the S type thermocouples are chosen. The incoming gas flow is set to atmospheric combustion product. The mixture properties include specific heat, density, viscosity, conductivity, and the temperature, pressure, and concentration of each gas component are calculated accurately with mass fraction weighted averaging rule. The emissivity of the thermocouple wire and thermocouple bead is set to 0.55. The thermocouple wire length is 85 mm, and the thermocouple wire end is set to the ambient temperature 300K.

The thermal conductivity of S type thermocouple wire A (pure platinum) [10] is

$$k_{Pt} = 0.0198T + 64.141, \quad T(\text{K})$$  \hspace{1cm} (6)

The thermal conductivity of S type thermocouple wire B (90%Pt/10%Rh) [10] is

$$k_{90\%Pt/10\%Rh} = 0.006T + 28.385, \quad T(\text{K})$$  \hspace{1cm} (7)

The thermal conductivity of the thermocouple bead takes the arithmetic mean of the thermocouple wire A and the thermocouple wire B.

3.1 HTFF model

The high temperature gas flow is the equilibrium combustion product of a H₂/Air near-adiabatic laminar flame with an equivalent ratio 0.6 produced by a one-inch Hencken burner [11]. The incoming temperature, velocity and gas mole fraction are shown in Table 1.
Table 1. H₂/Air Flame Temperature, Velocity and Composition

| EQR | Temperature (K) | Velocity (m/s) | N₂ mole fraction | H₂O mole fraction | O₂ mole fraction | OH mole fraction |
|-----|----------------|----------------|------------------|-------------------|-----------------|-----------------|
| 0.60| 1837           | 6.93           | 7.01E-01         | 2.23E-01          | 7.45E-02        | 1.14E-03        |

3.2 Step incoming gas temperature distribution

Two types of gas temperature distribution shown in Figure 3 are used to study the influence length of surrounding gas temperature on bead temperature. The first one is the step temperature distribution. The second one is the linear temperature distribution. In the step incoming temperature distribution, the gas temperature is set to 1837K, and the gas temperature is suddenly decreased to the ambient temperature 300K as shown in Figure 1a. In the linear incoming temperature distribution, the temperature is linearly decreased from 1837K to 300K.

Figure 3. Schematics of incoming temperature field (a) Step Decerase (b) Linear Decrease

This paper studies the range of temperature influence, so the velocity and composition of the flow field are set to certain constants which are shown in Table 1.
4. Effect of the length of HTFF on bead temperature

In the actual flame temperature measurement process, since the thermocouple has a small diameter and a long length, it cannot support the shape and positioning, and must be used in a ceramic tube. If the length of the thermocouple extended out of the ceramic tube is short, the presence of the ceramic tube will affect the thermocouple wire temperature distribution, thereby affecting the heat transfer between the bead and the wires, so affecting the temperature of the thermocouple bead. Therefore, it is necessary to study the influence range of the high temperature flame corresponding to different types of thermocouples, so as to select the appropriate extension length and reduce the influence of the ceramic tube on the bead temperature. The S type thermocouples by Omega are taken as examples to study, P10R-002 (wire diameter: 0.050 mm, bead diameter: 0.093 mm), P10R-003 (wire diameter: 0.075 mm, bead diameter: 0.163 mm), P10R-005 (wire diameter: 0.125 mm, bead diameter: 0.399 mm), P10R-010 (wire diameter: 0.250 mm, bead diameter: 0.750 mm). The range of influence provides a reference for the choice of extension length.

When the length $L$ of the high-temperature flow field shown in Figure 3 increases by 1 mm and the bead temperature does not change by more than 0.02% of the former bead temperature, that is, $(T_L-T_{L-1})/T_L \leq 0.02\%$, it is considered that the high-temperature flow field length no longer affects the bead temperature. The calculation results are shown in Table 2. The variation of bead temperature at which the extension length is stable with $L$ is shown in Figure 4.

**Table 2. The Length of HTFF of different types of thermocouples**

| Thermocouple types | Diameter of Wires(mm) | Diameter of Bead(mm) | Length of HTFF(mm) | Temperature of Bead(K) |
|--------------------|-----------------------|----------------------|--------------------|-----------------------|
| 002                | 0.050                 | 0.093                | 7.0                | 1726.2                |
| 003                | 0.075                 | 0.163                | 8.0                | 1697.4                |
| 005                | 0.125                 | 0.399                | 10.0               | 1641.1                |
| 010                | 0.250                 | 0.750                | 15.0               | 1572.7                |

![Figure 4. Bead temperature variation with $L$](image)

It can be seen that as the bead size and wire diameter increase, the influence range of the high temperature flow field also increases, but the bead temperature decreases. Therefore, the larger the
thermocouple size, the longer the length extended out of ceramic tube is required. For the Type 002 thermocouple, the extension length must exceed 7 mm, for the Type 010 thermocouples, the length of the extended ceramic tube must be at least 15 mm.

5. Effect of the length of transition zone on bead temperature

In the above study, the transition from high temperature (1837K) to low temperature (ambient temperature 300K) was a step transition. In this section of the study, we set the temperature field to a linear transition from high temperature to low temperature (shown in Figure3). Taking the four types of thermocouples as examples, the influence range of the linear transition region on the bead temperature is studied, and the reference extension length is provided. Consistent with the above, when the length L of the linear transition region increases by 1 mm and the temperature change of the bead does not exceed 0.02% of the former bead temperature, i.e. \( \frac{T_L - T_{L+1}}{T_L - 1} \leq 0.02\% \), the length of the linear transition region is no longer considered to affect the bead temperature. The calculation results of the influence of the transition region on the bead temperature are shown in Table 3.

Table 3. The Length of Linear Transition of different types of thermocouples

| Thermocouple types | Diameter of Wires (mm) | Diameter of Bead (mm) | Length of Linear Transition (mm) | Temperature of Bead (K) |
|--------------------|------------------------|-----------------------|----------------------------------|------------------------|
| 002                | 0.050                  | 0.093                 | 44.0                             | 1712.1                 |
| 003                | 0.075                  | 0.163                 | 49.0                             | 1681.5                 |
| 005                | 0.125                  | 0.399                 | 55.0                             | 1624.3                 |
| 010                | 0.250                  | 0.750                 | 68.0                             | 1552.6                 |

It can be seen that as the bead size and wire diameter increase, the influence range of the Linear Transition also increases, but the bead temperature decreases. It is similar to the conclusions reached in Section 4. However, by comparing Table 2 and Table 3, the influence length of the linear transition region is significantly larger than those of the step transition, and the length of the 002 thermocouple is more than six times that of the latter. In addition, for the same type of thermocouple, when the temperature no longer changes significantly, the temperature of the linear transition is lower than the temperature of the step transition, and the temperature difference of the bead for the 010 type is 20.1K.

6. Conclusion

Based on the calculation results of the one-dimensional numerical program, it is found that the influence range of the high temperature flow field on the bead temperature of different types of thermocouples is different. The increase of the thermocouple size leads to the increase of the influence range of the high temperature flow field, and the larger thermocouple needs a longer extension length extended from the ceramic tube. Similarly, the linear transition region has different influence range on the bead temperature of different types of thermocouples. The increase of the thermocouple size leads to an increase in the influence range of the linear transition region, and the range is much larger than the influence range of the step transition.
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