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Research on 2D Temperature Field Measurement Method of Mg/CO_2 Combustion Flame Based on Color CCD

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Abstract. A new Mg/CO_2 powder rocket propulsion system is proposed for Mars exploration. Accurate measurement of Mg/CO_2 combustion flame temperature field has important reference value for understanding the combustion characteristics and operating conditions. In this paper, the two dimensional temperature field of the Mg/CO_2 combustion flame is obtained by building a Mg/CO_2 combustion device and colorimetric temperature measurement system based on the color charge coupled device (CCD). The influence of magnesium powder particle size, premixed Reynolds number, and CO_2/Mg oxygen fuel ratio on the flame temperature of Mg/CO_2 combustion are discussed. The results show that the maximum temperature of Mg/CO_2 combustion flame under different working conditions is between 2500K and 2900K, and it increases with the increase of magnesium powder particle size, premixed Reynolds number, and oxygen-fuel ratio.

Key words: Mg/CO_2; Colorimetric temperature measurement; 2D Temperature Field; CCD.

1. Introduction

Mars exploration is one of the hot topics of human deep space exploration. In order to reduce the cost of exploration, in situ resource utilization with magnesium as fuel and CO_2 in the Martian atmosphere as oxidant has been proposed [1-3], and it is an attractive prospect [4-5]. During the operation of the Mg/CO_2 rocket engine, the temperature field of the Mg/CO_2 powder combustion flame is one of the important parameters that reflect the powder combustion characteristics and operating conditions of engine. Therefore, accurate measurement of the Mg/CO_2 combustion flame temperature field has important reference value for understanding the working condition of the powder engine combustion chamber and evaluating the comprehensive performance of the powder engine.

For the study of Mg/CO_2 ignition and combustion temperature, many thermocouples [7-10] were used. The ignition experiment was carried out on magnesium particles and CO_2 in different pressure environments [11]. The results show that the ignition temperature is between 830K and 980K, and the ignition temperature decreases slightly with the increase of the ambient pressure. LI Fang [12] has experimentally studied the ignition and combustion performance of Mg/CO_2 by the self-designed ignition device, which showed that the ignition temperature of magnesium particle of medium sizes in CO_2 is about 960 K, and the ignition temperature would gradually increase with the increase of particle size. However, the thermocouple belongs to point measurement, it is not suitable for the measurement of the combustion temperature field of magnesium combustion.

At present, the steady combustion temperature field of Mg/CO_2 mainly depends on numerical calculation. LI Fang [13] calculated the performance of powder rocket engines theoretically from the aspects of its working performance and influencing factors, and found that the effective specific impulse of the powder rocket engines was higher than that of the traditional propulsion systems. Through the calculation and research of the combustion performance of magnesium powder and carbon dioxide, the influence law of the pressure, initial temperature, oxygen fuel ratio and other parameters is obtained. the two step combustion reaction process of gas phase reaction of Mg/CO_2 combustion and heterogeneous reaction on particle surface was taken into account, Li Junjie [14] calculated the Mg/CO_2 combustion by using 6 styles of combinations with gas phase and heterogeneous combustion models of laminar finite rate, eddy dissipation, King and the results shows that the combustion model with the combination of gas phase eddy dissipation model and heterogeneous King model has the highest accuracy comparing with the experimental result.

In addition, Mg/CO_2 ignition temperature was also measured by Colorimetric temperature, used the flame's own radiation for temperature measurement [15], which based on the color CCD is one of the radiation thermometry. It has the advantages of large measurement region. Wide temperature measurement range, high reliability, and can accurately obtain the flame temperature field and pseudo color display.

In this paper, Mg/CO_2 combustion experiments will be conducted by building a color CCD temperature measurement system for Mg/CO_2 two dimensional temperature field of different working conditions, and the influence of magnesium powder particle size, premixed Reynolds number, CO_2/Mg oxygen fuel ratio on the temperature field of Mg/CO_2 combustion flame will be analyzed for understanding the law of Mg/CO_2, ignition and combustion under the deferent magnesium powder particle size, premixed Reynolds number, CO_2/Mg oxygen fuel ratio

2. Temperature Measurement Principle based Radiation Image Method

According to the description of Planck's blackbody radiation law, when temperature is T, the relationship between the electromagnetic radiation force and the wavelength is:

$$E_{\lambda b} = \frac{c_1\lambda^{-5}}{e^{c_2/(\lambda T)}-1} \tag{1}$$

Where $E_{\lambda b}$ is electromagnetic radiation force (W/m^3), T is thermodynamic temperature (K), λ is electromagnetic wave length (nm), c_1 is first radiation constant ($c_2 = 3.7419 \times 10^{-16} W \cdot m^2$), c_2 is second radiation constant [16] ($1.4388 \times 10^{-2} m \cdot K$).

The radiant intensity of each pixel of the flame image captured by the color CCD can be decomposed into red component intensity R, green component intensity G and blue component intensity B, and the RGB intensity value can be expressed as:

$$\begin{cases} R = A\int_{380}^{780} L(\lambda,T)R(\lambda)d\lambda = k_R L(\lambda_R,T) \\ R = A\int_{380}^{780} L(\lambda,T)G(\lambda)d\lambda = k_G L(\lambda_G,T) \\ R = A\int_{380}^{780} L(\lambda,T)B(\lambda)d\lambda = k_B L(\lambda_B,T) \end{cases} \tag{2}$$

Where $R(\lambda)$, (λ), $B(\lambda)$ is the response characteristic function of CCD, $L(\lambda, T)$ is the theoretical radiation function of flame, k_R, k_G, k_B is the proportionality coefficient [17], obtained by the blackbody calibration experiment.

According to experience, R and G signals are always stronger than B signals in the radiation process of high temperature objects. In addition, in order to reduce the influence of camera's own factors, R and G signals are selected as colorimetric temperature measurement signals [18], which can be obtained

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$$\frac{L(\lambda_R, T)}{L(\lambda_G, T)} = \frac{Rk_G}{Gk_G} \tag{3}$$

Combination equation (1), and letting $c_g = ln(k_G/k_R)$, we can get the temperature function shown as equation (4).

$$T = \frac{c_2\left(\frac{1}{\lambda_g} - \frac{1}{\lambda_r}\right)}{\ln\frac{R}{G} + c_g + 5\ln\frac{\lambda_r}{\lambda_g}} \tag{4}$$

The measured temperature is the final actual temperature. Compared with the monochrome temperature measurement method, the colorimetric temperature measurement method based on the color CCD uses the mutual compensation of the two wavelength signals to reduce the influence of external factors on the radiation signal, and improve the temperature measurement accuracy and temperature measurement range.

3. Experimental System and Calibration

3.1. Experimental System

The experimental system for measuring the temperature field of Mg/CO_2 combustion flame is shown in the figure 1. The experimental system includes two parts: the metal powder combustion device and the color CCD temperature measurement system. The metal powder combustion device is composed of four parts: motor seat, powder box, fluidization zone and combustion chamber. The working process is as follows: the DC stepper motor drives the ejector rod upward, and the ejector rod pushes the piston at the bottom of the powder box to push the metal magnesium powder upward; powder is driven by CO_2 gas in the fluidizer, premixed airflow is formed and ignited in the combustion chamber.

Color CCD temperature measurement system includes imaging system, image sensing system, image processing system. Temperature measuring system working principle is as follows: radiation signal from Mg/CO_2 combustion flame radiation through the installation of attenuation in front of the camera and into the lens, the light on the CCD camera sensitive target, through the photoelectric conversion effect of CCD camera, the radiation optical signals into digital image signal and output by the data link to the computer to store. The digital signal was processed and calculated by computer image processing software, and the temperature field information of Mg/CO_2 combustion flame was obtained.

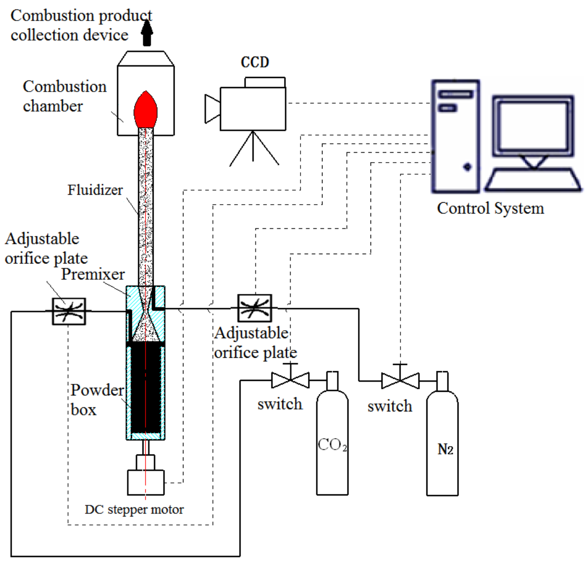

Figure 1. Schematic diagram of the experimental system

3.2. Calibration of Temperature Measurement System

As shown in Figure 2 is a color CCD camera calibration experiment system, mainly composed of a high-temperature blackbody furnace, a color CCD camera, a USB data transmission line, and a computer. By installing an attenuator with a transmittance of 1% in front of the lens, turning off the automatic gain and white balance, and setting the exposure time to obtain a radiation image that meets the image processing requirements

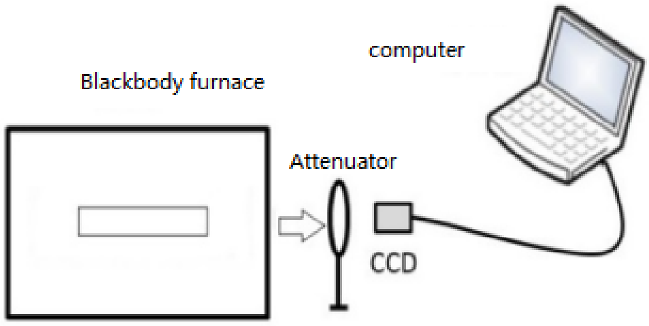

Figure 2. CCD calibration experiment system

The radiation temperature range of the blackbody furnace selected in the calibration experiment is 1323K~1483K, and the temperature interval is 20K. There are 9 sets of blackbody furnace radiation images captured. By reading the R, G, B values of each pixel in the fixed area of the radiation image, and calculating an average values for the calculation of the colorimetric temperature measurement formula, the calibration coefficient c_g is finally calculated.

Table 1. Flame radiation image date

T/K	R	G	B	Cg
1323	6.00	4.67	1.67	2.89
1343	8.67	6.00	2.67	2.70
1363	16.00	10.33	5.00	2.57
1383	20.00	13.33	7.67	2.54
1403	24.67	16.00	7.00	2.45
1423	30.67	19.67	7.67	2.39
1443	38.00	25.33	7.67	2.37
1463	47.33	32.00	6.33	2.33
1483	57.67	39.67	10.67	2.29

3.3. Verification of Calibration Results

In the verification and calibration experiment, the radiation image of the blackbody furnace was obtained by setting five known temperatures, and the R and G values of the radiation image were read by MATLAB. The corresponding values were obtained by the relationship between the calibration coefficient value and the temperature, and the calculated temperature value was obtained by the colorimetric temperature measurement formula. The temperature measurement accuracy of the calibration experiment of the blackbody furnace is verified by comparing the calculated temperature with the set temperature. It can be drawn from the data in Table 2 that there is a slight deviation between the calculated temperature and the set temperature in the acceptance experiment, but the relative deviation is small, about 0.5%-1.2%. Therefore, the colorimetric temperature measurement has a higher temperature measurement accuracy in the blackbody furnace calibration experiment, and it is more suitable for high temperature measurement.

Table 2. Calculate temperature and set temperature date

Setting temperature (K)	Calculating temperature(K)	Relative deviation (%)
1333	1349	1.20
1373	1377	0.29
1413	1406	0.50
1453	1437	1.10
1493	1478	1.00

4. Mg/CO_2 Combustion Flame Temperature Field Measurement

4.1. Experimental Conditions

The experimental conditions were designed for the three parameters of magnesium powder particle size, premixed Reynolds number, and CO_2/Mg oxygen fuel ratio, and studied the influence of Mg/CO_2 combustion flame temperature. Table 3 shows the all experimental conditions.

Table 3. General experimental conditions

Experimental conditions	particle diameter/d(um)	Reynolds number/Re	oxygen fuel ratio/a
1	5	2500	1.5
2	10	2500	1.5
3	20	2500	1.5
4	5	1589	1.5
5	5	1816	1.5
6	5	2043	1.5
7	5	2497	1.5
8	5	2678	1.5
9	5	2815	1.5
10	5	3019	1.5
11	10	2500	1.3
12	10	2500	1.5
13	10	2500	1.7
14	10	2500	1.9
15	10	2500	2.1

Magnesium particle size, premix Reynolds number and oxygen fuel ratio directly affect the ignition and combustion temperature field of Mg/CO_2 flame. The magnesium particles selected in the experiment were produced by Shanghai Shuitian Material Technology Co., Ltd. The diameter of magnesium particles selected were 5um, 10um and 20um.

The calculation formula of Reynolds number of mixed flow is as follows:

$$\mathrm{Re} = \frac{4KA}{\pi\mu D\sqrt{T^*}} P^* \tag{5}$$

Where, D is the diameter of the fluidized tube; K is the specific heat function of CO_2 gas, K=0.0482; P* is the total pressure of fluidized gas; T* is the total temperature of fluidized gas; A is the area of fluidized stomatal plate. In equation 5, D, K, T* and A is fixed, setting premixed Reynolds number by changing the total pressure P* of fluidized gas.

For the regulation of oxygen fuel ratio (A/F), since the Reynolds number and the mass flow rate of CO_2 is fixed, the oxygen fuel ratio can be changed simply by changing the Mg mass flow rate.

The calculation formula of magnesium mass flow is as follows:

$$q_{Mg} = \rho ANL \tag{6}$$

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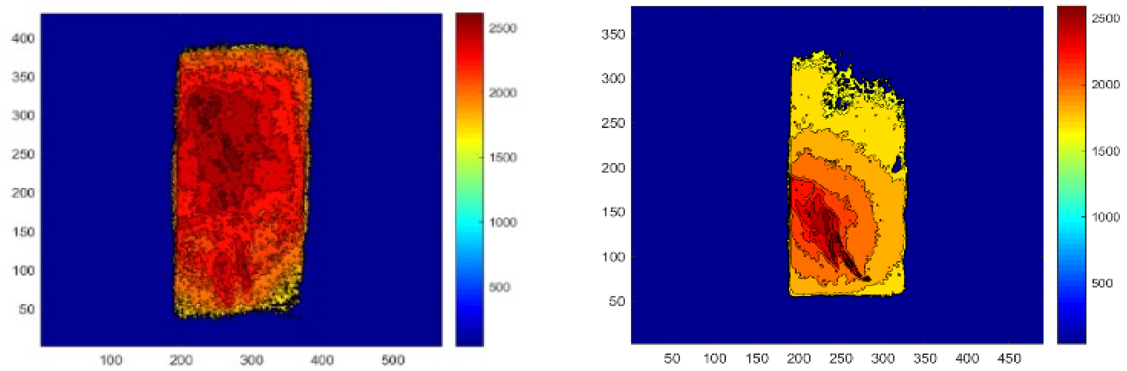
Where, ρ is the packing density of magnesium; A is the area of the contact surface between the piston and magnesium; N is the number of motor pulses; L is the displacement of the motor per pulse. In the equation (6), ρ, A and L are fixed. According to the selected motor parameters, setting different oxygen fuel ratios by calculating the number of pulses required for the total displacement to set different oxygen fuel ratios.

4.2. Experimental Results and Analysis

The thermal radiation image of Mg/CO_2 combustion flame was collected by color CCD, and the two-dimensional temperature field distribution of Mg/CO_2 combustion flame was obtained based on the colorimetric processing of radiation image, and a maximum temperature values in the whole stable combustion process was extracted. Figure 3 shows the pseudo color diagram of Mg/CO_2 combustion flame temperature field under different particle diameter conditions.



Experimental condition 1 Experimental condition 2

Figure 3. Pseudo-color image of combustion flame under particle diameter conditions

Figure 4 is the line chart of the change of the maximum temperature with the particle diameter, figure 4 shows that the maximum temperature of stable combustion is between 2613K and 2722K, The maximum temperature decreases with the increase of particle diameter. Experiments show that the smaller the particle diameter, the greater the surface area involved in the combustion reaction. In a high temperature environment, the mass of the magnesium vapor reacts with CO_2 will be greater, the faster the combustion reaction, the higher the combustion temperature.

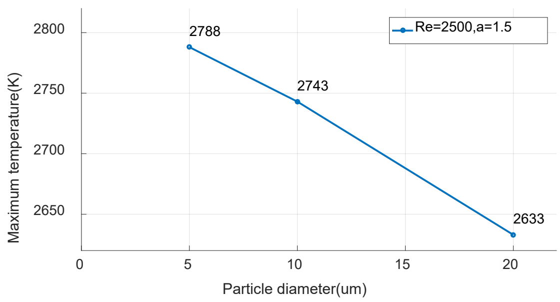
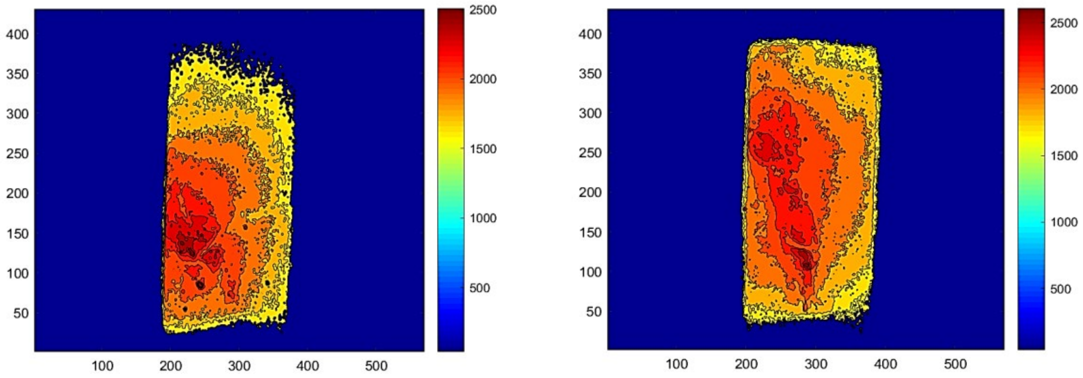


Figure 4. Polyline change of maximum temperature

Figure 5 is the pseudo color image of the burning flame under different Reynolds number conditions.



Experimental condition 4 Experimental condition 5

Figure 5. Pseudo-color image of Reynolds number combustion flame

Figure 6 is the line chart about the relation of the maximum temperature of Mg/CO_2 with the Reynolds number. Figure show that the maximum temperature varies between 2587K and 2893K, and the maximum temperature decreases with the increases of the Reynolds number. In addition, because of the Reynolds number increases, the velocity of the premixed airflow at the outlet of the fluidization tube becomes faster, excessively fast airflow may cause the premixed magnesium particles to participate in the combustion reaction for a shorter time, and it will be incompletely combusted and be taken out of the combustion chamber by the airflow.

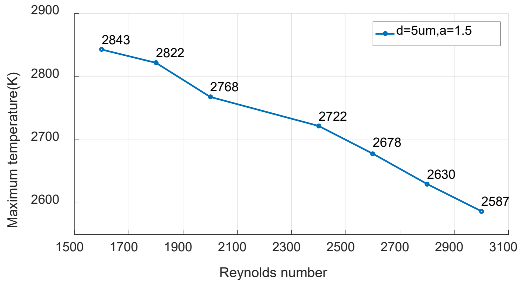
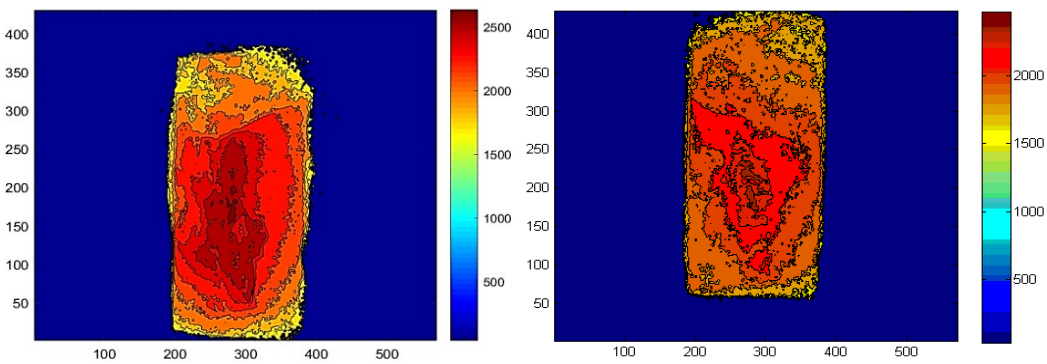


Figure 6. Polyline of change in maximum temperature with Reynolds number

Figure 7 is a pseudo color diagram of the temperature field of Mg/CO_2 combustion flames with different oxygen fuel ratios.



Experimental condition 13 Experimental condition 15

Figure 7. Pseudo-color image of combustion flame in oxygen-fuel ratio

Figure 8 is a line chart of the maximum temperature value of Mg/CO2 combustion with the change of oxygen fuel ratio. With two different particle diameters and Reynolds numbers, the maximum temperature value range is between 2525K and 2821K, the maximum temperature decrease with the increase of the oxygen fuel ratio. Experiment shows that the mass flow rate of magnesium decreases with the increase of oxygen fuel ratio, when the Reynolds number, the fluidizing gas pressure, and the CO2 gas mass flow rate is fixed. In the same time, the mass of magnesium powder ejected from the fluidized tube decreases, resulting in a decrease in the mass of magnesium involved in combustion and a decrease in the combustion flame temperature.

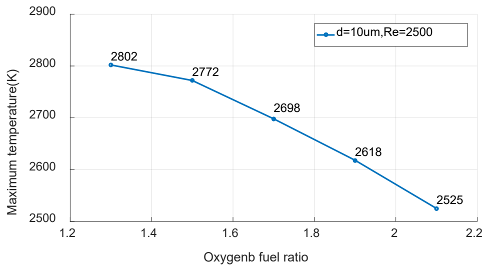


Figure 8. Line chart of the change of the maximum temperature with the oxygen fuel radio

5. Conclusion

(1) The two dimensional temperature field measurement method of Mg/CO_2 combustion flame based on color CCD colorimetric image temperature measurement method was proposed, and the color CCD temperature measurement system was calibrated by high temperature standard radiation blackbody furnace, and the relationship between CCD response coefficient Cg and radiation temperature was obtained. Using the black body furnace to carry out the verification experiment of the temperature measurement system, the colorimetric temperature measurement results were compared with the set value of the black body furnace, and the relative deviation was found to be less than 1.2%, which verified the accuracy of the temperature measurement of the high temperature object based on the color CCD radiation image method.

(2) The temperature field of Mg/CO_2 combustion flame under different working conditions was measured by using the color CCD temperature measurement system, and the temperature radiation image of the flame was obtained. The maximum temperature of steady combustion of the flame was between 2500K and 2900K When other factors are fixed, the maximum temperature decreases with the increase of particle diameter, decreases with the increase of the Reynolds number, decrease with the increase of the oxygen fuel ratio.

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