Statistical model for combustion of high-metal magnesium-based hydro-reactive fuel*

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We investigate experimentally and analytically the combustion behavior of a high-metal magnesium-based hydro-reactive fuel under high temperature gaseous atmosphere. The fuel studied in this paper contains 73% magnesium powders. An experimental system is designed and experiments are carried out in both argon and water vapor atmospheres. It is found that the burning surface temperature of the fuel is higher in water vapor than that in argon and both of them are higher than the melting point of magnesium, which indicates the molten state of magnesium particles in the burning surface of the fuel. Based on physical considerations and experimental results, a mathematical one-dimensional model is formulated to describe the combustion behavior of the high-metal magnesium-based hydro-reactive fuel. The model enables the evaluation of the burning surface temperature, the burning rate and the flame standoff distance each as a function of chamber pressure and water vapor concentration. The results predicted by the model show that the burning rate and the surface temperature increase when the chamber pressure and the water vapor concentration increase, which are in agreement with the observed experimental trends.

Keywords: high-metal magnesium-based hydro-reactive fuel, water ramjet engine, combustion experiment, combustion model

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1. Introduction

Investigations on water ramjet engines, which simply utilize hydro-reactive fuel combusting with seawater to generate thrust, are being extensively conducted for their application in the cruise propulsion system of high-speed torpedoes currently.[1−3] As for the hydro-reactive fuel of the engine, the high heat releases of Al/H_2O and Mg/H_2O reactions have made aluminum and magnesium powders the most promising high energy additives.[4,5]

The idea of using metal to burn with seawater in underwater propulsion systems actually dates back to as early as the 1940s.[6] An experiment was conducted by Kuehl[6] on the ignition temperature of aluminum particles in a static water vapor atmosphere. Prachukho[7] and Ozerov[8] performed experimental investigations on the burning rate of magnesium particles in water vapor. Foote[9] conducted experimental investigations on the combustion behavior of aluminum powders with water vapor at ambient pressure. Miller[10] proposed a green rocket propulsion system using aluminum or magnesium powders as the fuel to combust with water in a vortex combustor.

As the VA-111 Shkval torpedo revealed in 1995, magnesium-based hydro-reactive fuels seem to be the most developed fuels due to their high combustion efficiency and ignition behavior.[11] The performance of water ramjet engines increases with the increasing metal content in the hydro-reactive fuel. The oxidizer content in the fuel decreases when the metal content increases which results in a seriously incomplete combustion and even flameout.[12]

A number of laboratories used high speed motion pictures in strand burners to obtain the combustion behavior of metallized solid propellants with regular amounts of metal additives (up to about 20%–50% mass).[13−15] Since the combustion characteristics of such propellants are different from those of the propellants with lower metal contents, the visualization of these phenomena is of great interest.[13] Chen[3] carried out research on the effect of the diameter of aluminum particles on the combustion of the hydro-reactive fuels with lower metal contents. Li[16] studied the combustion of the magnesium-based hydro-reactive fuels with a metal content of 50%, and obtained the effect of the components on the com-

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bustion characteristics of the fuels. However, to the best of our knowledge, investigations of the fundamental combustion behavior of hydro-reactive fuels containing large fractions (more than 60% mass) of metal additives have not been reported. Investigating these aspects is the main purpose of this study. A physical understanding of the combustion behavior is indispensable to formulate a mathematical description of the problem. The basic assumption of the analysis relies on the postulation that such a process is likely to be similar to that of the conventional solid composite propellant, where solid oxidizer particles burn with the binder forming a gaseous diffusion flame between the pyrolysis gases from the crystals of the oxidizer and from the binder fuel.[17] The recognition of a diffusion-dominated combustion process yields the classical granular diffusion flame (GDF) model.[17] In the 1970s the Beckstead–Derr–Price (BDP) model, which postulated multiple flames, provided a framework for almost all modeling efforts since its publication.[17,18] The BDP model has been further elaborated and extended by Glick,[19] King,[20] Miller,[21] and Cohen.[22] The assumptions and approximations made in the BDP model are the basis for the conversion of a complicated, unsteady, three-dimensional combustion process into a simplified steady state one-dimensional problem.[17] The same phenomena may be encountered in the present high-metal magnesium-based hydro-reactive fuels.

We investigate experimentally and analytically the combustion behavior of a high-metal magnesium-based hydro-reactive fuel under high temperature gaseous atmosphere. The specific objectives are 1) to determine the state of magnesium particles in the burning surface and 2) to characterize the combustion behavior by analyzing a steady-state combustion model.

2. Experimental approach

2.1. Experimental setup

The combustion of solid propellants containing large fractions (40 wt%–50 wt%) of metal additives is always studied by means of a high speed photography technique using a high pressure windowed strand burner.[13,23] Our experimental study uses a pressure-regulated test combustor and focuses on the combustion wave temperature measurement and the qualitative observation of the fascinating phenomena involved in the combustion of a high-metal magnesium-based hydro-reactive fuel strand. The experimental apparatus consists of a gas feed system and an experimental combustor. The gas feed system mainly consists of a high temperature water–vapor feed line and a high temperature argon feed line, which can help to provide different water–vapor concentrations for the combustion. The operating chamber pressure and gas content of the combustor are controlled by adjusting the mass flow rates and time of the argon and water vapor. The combustor is shown in Fig. 1. It is composed of a cylinder, an ignition base, a gas entering pipe, and windows. The cylinder is about 350 mm in length and 216 mm in diameter. The combustor can bear a pressure higher than 4 MPa. The thick glass windows allow observation and video recording of the burning process by means of a high-speed video camera.

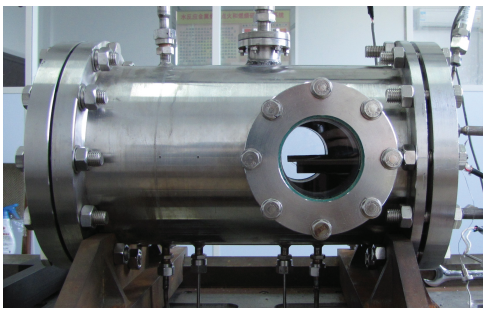


Fig. 1. Schematic diagram of an experimental combustor.

The 7 mm×7 mm×70 mm propellant strand is shown in Fig. 2, which consists of 19% ammonium perchlorate (AP) as the oxidizer, 8% hydroxy terminated polybutadiene (HTPB) as the binder, 73% magnesium as the high energy additive. An imbedded type K fine-wire thermocouple with a diameter of 0.5 mm is used to measure the temperature profiles in both the subsurface and the surface regions of the fuel strand. The strand ignition is achieved by using a hot nichrome resistance wire.



Fig. 2. The high-metal magnesium-based hydro-reactive fuel strand.

2.2. Experimental results and analysis

Experimental conditions and results are presented in Table 1. When the water–vapor concentration of the combustor is equal to zero, the combustion happens in an argon environment. Argon is a kind of inert gas, which do not react with the hydro-reactive

fuel. The combustion of the fuel in the argon environment is a self-sustaining behavior. The comparison of the results in the argon and the water–vapor environments is helpful to study the combustion mechanism of the high-metal magnesium-based hydro-reactive fuels. Figure 3 shows the combustion wave temperature profiles of the propellant strand during combustion, which are obtained from the thermocouples imbedded in the propellant strand. The burning surface temperature is deduced by using the same method used in Ref. [24]. During the strand combustion, the temperature increases from the initial temperature (T) to the burning surface temperature (T_s). The T_1 corresponds to the first peak point of the dT/dx–x curve, and the value in argon is mostly considered as the decomposition temperature of AP.

Table 1. Experimental conditions and results.

	No. 1	No. 2
Ambient pressure of combustor/MPa	2.23	1.80
Ambient temperature of combustor/K	287.5	322.8
Water–vapor concentration of combustor	0.0	0.211
Burning surface temperature of strand/K	1039.3	1080.4
Burning rate of strand/mm·s^{-1}	24.7	38.3

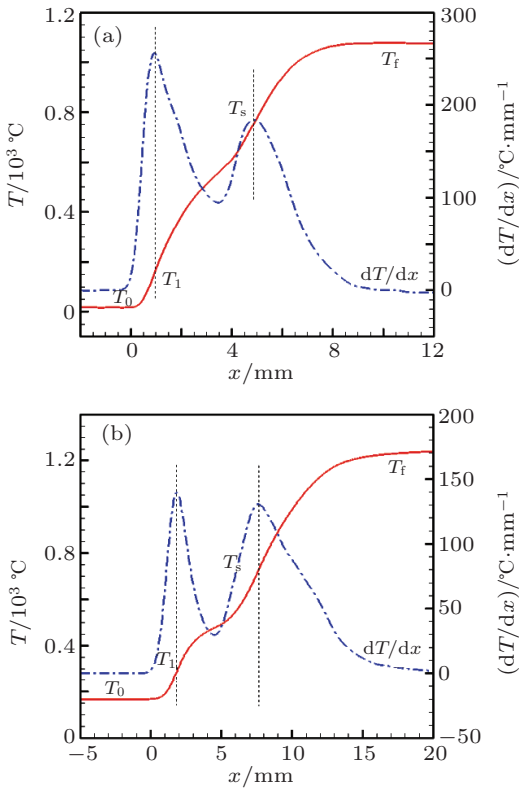


Fig. 3. (color online) Combustion wave temperature profiles during the strand combustions under experimental conditions (a) No. 1 and (b) No. 2.

It is shown that the burning surface temperatures of the propellant strand in argon and water vapor are both higher than the melting point of magnesium (923 K), which indicates a molten state of magnesium particles existing in the burning surface of the strand. The surface temperature and the burning rate of the propellant strand in water vapor are higher than those in argon. It suggests that the combustion in water vapor has a higher heat release than that in argon.

3. Theoretical modeling

3.1. Physical description of the combustion model

According to the experimental results of fuel combustion in argon and water–vapor atmospheres, the water–vapor atmosphere has seriously effects on the combustion characteristics of high-metal magnesium-based hydro-reactive fuel. The combustion process of the fuel can be deduced from the following description. The oxidizer, the binder, and the magnesium particles are preheated by conduction as the hydro-reactive fuel burns. With the heat feedback from the combustion zone, the temperature of the solid fuel increases without chemical changes before the decomposition of AP and HTPB, which can be defined as the inert heating zone. Then AP and HTPB begin to decompose when the decomposition temperature of the solid fuel is reached. At the propellant surface, the initial decomposition step of both the oxidizer and the binder is endothermic. However, either set of decomposition products can possibly undergo further condensed phase reaction, resulting in a less endothermic and possibly an exothermic process at the surface. These decomposition products then pass into the gas phase, mix, and react. Absorbing the released heat, the magnesium particles in the fuel begin to melt and evaporate. The combustion happens when the magnesium vapor meets the decomposition products from AP and HTPB. Because of the lack of an oxidizer, the magnesium vapor cannot combust completely near the fuel surface. The combustion would continue when the magnesium vapor meets the water vapor far away from the burning surface. And the releasing heat of the combustion partly feedbacks to the burning surface to maintain the decomposition of the fuel.

According to the above analysis, the combustion process of the high-metal magnesium-based hydro-reactive fuel can be divided into three zones: 1) in-

ert heating zone with no chemical reaction; 2) condensed reaction zone, where the decomposition of AP and HTPB, and the melt of magnesium particles occur; 3) gas reaction zone, where the reaction between decomposition gases of AP and HTPB, magnesium vapor, and water vapor occurs. Figure 4 shows the physical combustion model of the fuel.

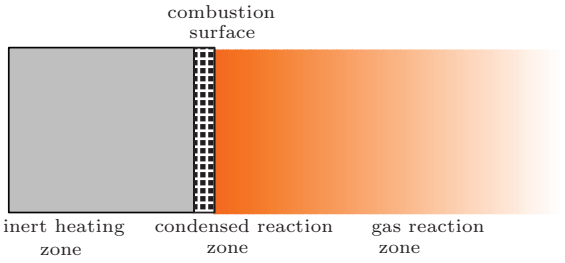


Fig. 4. (color online) Physical combustion model of the high-metal magnesium-based hydro-reactive fuel.

The high-metal magnesium-based hydro-reactive fuel is a kind of composite propellant, so the BDP model can be used for reference. The geometric relationship of the flame structures of the high-metal magnesium-based hydro-reactive fuel proposed here is sketched in Fig. 5. Four flames are considered in the model: AP premixed flame, AP/Mg/HTPB primary diffusion flame, AP/Mg/HTPB final diffusion flame, and Mg/H_2O diffusion flame. In the following section, the details of the equations describing these flames are presented along with a discussion of the results and the application of the model.

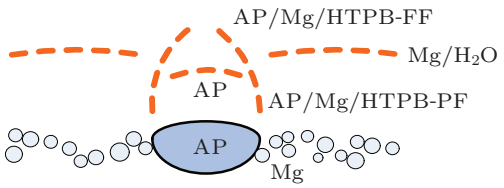


Fig. 5. (color online) Flame structure of the high-metal magnesium-based hydro-reactive fuel.

3.2. Basic equations of the combustion model

Based on physical considerations and experimental results, a mathematical one-dimensional model is formulated to describe the combustion behavior of high-metal magnesium-based hydro-reactive fuel.

3.2.1. Conservation of mass

The total mass flux emanating from the propellant surface is[17,18]

$$\begin{aligned}\dot{m}_0 &= \rho_c r_b \\ &= \dot{m}_{AP}\frac{S_{AP}}{S_0} + \dot{m}_{HTPB}\frac{S_{HTPB}}{S_0} + \dot{m}_{Mg}\frac{S_{Mg}}{S_0}, \end{aligned} \quad (1)$$

where $\dot{m}_0$ is the mass burning rate of the fuel; $\dot{m}_{AP}$ and $\dot{m}_{HTPB}$ are the decomposition rates of AP and HTPB, respectively, which can be expressed via the Arrhenius pyrolysis law; $\dot{m}_{Mg}$ is the burning rate of magnesium particles on the burning surface; ρ_c and r_b are the density and the burning rate of the fuel, respectively, $\rho_c = \sum_{i=1}^{3} \rho_i Y_i$, ρ_i is the density of the component; Y_i is the mass fraction of the component, i represents AP, HTPB, and Mg; and S_0 is the total surface area, S_{AP}, S_{HTPB}, S_{Mg} are the surface areas of the components, which can be calculated by using the geometrical relationship.

Thus, averaged over the entire propellant surface, the mass flux is[18,24]

$$\dot{m}_0 S_0 = \dot{m}_{AP}\frac{S_{AP}}{Y_{AP}} = \dot{m}_{HTPB}\frac{S_{HTPB}}{Y_{HTPB}} = \dot{m}_{Mg}\frac{S_{Mg}}{Y_{Mg}}. \quad (2)$$

It can be seen from Eq. (2) that the burning rate can be calculated from any of the three equalities. Due to the high content of magnesium, it is assumed that the burning rate of magnesium particles is the dominant characteristic of the combustion of the high-metal magnesium-based hydro-reactive fuel. Therefore, the third expression is used throughout the model.

3.2.2. Propellant surface geometry

The statistical approach is used to calculate the surface area of the magnesium particles at the burning surface. It is assumed that the portion of the particle which protrudes above or is recessed below the burning surface is spherical, but always joining the fuel at the planar fuel surface.[18] Thus, the surface area of the magnesium particles that is exposed to reaction can be calculated as

$$\frac{S_{Mg}}{S_0} = \frac{\zeta[6(h/d_{Mg})^2 + 1]}{[6\zeta(h/d_{Mg})^2 + 1]}, \quad (3)$$

where ζ is the volume fraction of the magnesium particles in the hydro-reactive fuel, and d_{Mg} is the average diameter of the magnesium particles before combustion. The geometric factor h/d_{Mg} represents the fraction distance that the magnesium particle protrudes above or is recessed below the burning surface, which can be deduced by the way used in Ref. [18].

The surface areas of AP and HTPB are[24]

$$S_{\mathrm{AP}} = n_{\mathrm{AP}} \cdot \pi \left(H^2 + d_{\mathrm{AP}}^2/6\right), \quad (4)$$

$$S_{\mathrm{HTPB}} = n_{\mathrm{AP}} \cdot \frac{\pi}{6}\left[\left(\frac{1}{\zeta_{\mathrm{AP}}} - 1\right) d_{\mathrm{AP}}^2 - \frac{n_{\mathrm{Mg}}}{n_{\mathrm{AP}}} d_{\mathrm{Mg}}^2\right]. \quad (5)$$

Equations (3), (4), and (5) permit the calculation of the surface areas of the components for the eventual use in Eq. (1).

3.2.3. Conservation of energy

In order to calculate the burning rate of the hydro-reactive fuel using Eq. (2), the burning rate of magnesium particles on the burning surface must be evaluated.[25] By considering the combustion model for combusting metal droplets in a gaseous medium, the burning rate of magnesium particles is calculated as

$$\dot{m}_{\mathrm{Mg}} = 4\pi \frac{d_{\mathrm{Mg}}}{2} \frac{K_{\mathrm{g}}}{c_{\mathrm{pg}}} \frac{Nu_T^0}{2} \ln\left[1 + \frac{c_{\mathrm{pg}}(T_{\mathrm{f}} - T_{\mathrm{b}})}{L + c_{\mathrm{pl}}(T_{\mathrm{b}} - T_0)}\right], \quad (6)$$

$$T_{\mathrm{f}} = T_\infty + \frac{\varepsilon Y_{\mathrm{OX},\infty}\left[Q_{\mathrm{mg,c}} - L - c_{\mathrm{pl}}(T_{\mathrm{b}} - T_0) - c_{\mathrm{pg}}(T_\infty - T_{\mathrm{b}})\right]}{c_{\mathrm{pg}}(1 + \varepsilon Y_{\mathrm{OX},\infty})}, \quad (7)$$

$$Nu_T^0 = 2 + 0.6\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33}. \quad (8)$$

Specific details about the equations may be found in Refs. [24] and [26].

It is assumed that the global kinetics adequately describes the decompositions of the oxidizer and the binder. Utilizing the Arrhenius expression, we can express the mass burning rate as[18]

$$\dot{m}_{\mathrm{AP}} = A_{\mathrm{AP}} \exp\left(-\frac{E_{\mathrm{AP}}}{RT_{\mathrm{s}}}\right), \quad (9)$$

$$\dot{m}_{\mathrm{HTPB}} = A_{\mathrm{HTPB}} \exp\left(-\frac{E_{\mathrm{HTPB}}}{RT_{\mathrm{s}}}\right), \quad (10)$$

where A_{AP}, A_{HTPB}, E_{AP}, E_{HTPB} are the Arrhenius frequency factors and the activation energies of AP and HTPB, respectively, T_{s} is the burning surface temperature, and R is the gas constant. From Eqs. (6) and (9), it can be seen that the surface temperature becomes a very critical factor in determining both the burning rate and the pressure dependence.

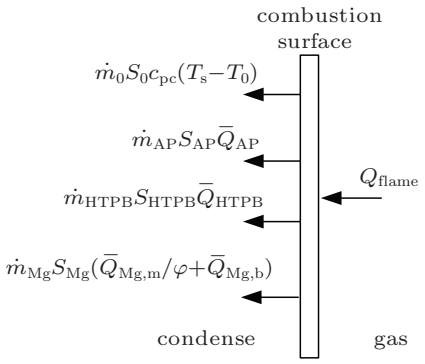


Fig. 6. Heat balance on the burning surface.

It is assumed that the oxidizer, the binder, and the magnesium particles are at the same temperature on the burning surface. In the present model, an overall averaged temperature is calculated, considering the energies of decomposition of both the oxidizer and the binder on the burning surface, the energy of evaporation of magnesium particles on the burning surface, and the energy feedback from the flames to the burning surface by conduction.[27,28] The heat balance on the burning surface is sketched in Fig. 6.

Using the model physical features and assumptions, the heat flux conservation equation is

$$\begin{aligned}&\dot{m}_0 S_0 c_{\mathrm{pc}}\,(T_{\mathrm{s}} - T_0) + \dot{m}_{\mathrm{AP}} S_{\mathrm{AP}} \bar{Q}_{\mathrm{AP}} \\ &\quad + \dot{m}_{\mathrm{HTPB}} S_{\mathrm{HTPB}} \bar{Q}_{\mathrm{HTPB}} \\ &\quad + \dot{m}_{\mathrm{Mg}} S_{\mathrm{Mg}} \left(\bar{Q}_{\mathrm{Mg,m}}/\varphi + \bar{Q}_{\mathrm{Mg,b}}\right) = Q_{\mathrm{flame}}, \end{aligned} \quad (11)$$

where $\bar{Q}_{\mathrm{AP}}$, $\bar{Q}_{\mathrm{HTPB}}$, $\bar{Q}_{\mathrm{Mg,m}}$, $\bar{Q}_{\mathrm{Mg,b}}$ represent the decomposition heat of AP, HTPB, and the melting heat and the evaporation heat of magnesium, respectively φ is the evaporation fraction of magnesium in the fuel, and Q_{flame} represents the heat transferred from various flame fronts to the propellant surface. Specific details about Q_{flame} may be found in Ref. [24], which includes the calculation of these flame standoff distances.

3.3. Modeling results

In the preceding equations, the burning rate appears in a transcendental form requiring an iterative solution.[29,30] The principal equations involved are Eqs. (2)–(6), (9), and (10) with the various terms defined appropriately. The equations are solved numerically at a given pressure and given gas contents of the combustor, which iterates on the burning surface

temperature.[31,32] After reaching a solution, the pressure and the gas contents are increased, and a new iteration begins.

3.3.1. Effect of chamber pressure

From the basic consideration of the model and the form of the equations, it can be seen that the surface temperature is lower for lower chamber pressure, which will reduce the burning rate of the high-metal magnesium-based hydro-reactive fuel. The calculated effect of chamber pressure is shown in Fig. 7. The experimental results are also sketched. It is shown that the burning rate and the surface temperature increase when the chamber pressure increases, and the results are coincident with the experiments. As the chamber pressure increases, the reaction rate of gas phase and the heat release rise up, and so does the heat feedback to the burning surface.

Modeling the microscopic flame structure of the statistically average magnesium particles introduces a detailed physical reality into the combustion model of the hydro-reactive fuel, which has not been attempted previously. Figures 8 and 9 respectively show the flame standoff distances and the heat feedbacks to the burning surface for various chamber pressures. The height of the Mg/H_2O diffusion flame is proposed to be the same as that of the AP/HTPB/Mg final flame. As the chamber pressure increases, the gas diffusion becomes difficult, and the height of the AP/HTPB/Mg diffusion flame increases. Reversely, the reaction rate increases when the chamber pressure increases, and the height of the AP premixed flame decreases.

All of these flames favor heat feedback to the burning surface when the chamber pressure is below 2.5 MPa, and the heat feedback mostly comes from the AP/HTPB/Mg primary flame and the Mg/H_2O diffusion flame. When the chamber pressure increases above 2.5 MPa, the height of the AP premixed flame is less than that of the AP/HTPB/Mg primary flame. If the oxidizer is consumed completely by the AP premixed flame, the AP/HTPB/Mg primary flame would disappear. The heat feedback from the AP premixed flame increases when the chamber pressure increases. The reaction of the AP/HTPB/Mg final flame becomes difficult, and the heat feedback to the burning surface decreases. More and more magnesium vapor reacts with water vapor, and the heat release from the Mg/H_2O diffusion flame increases.

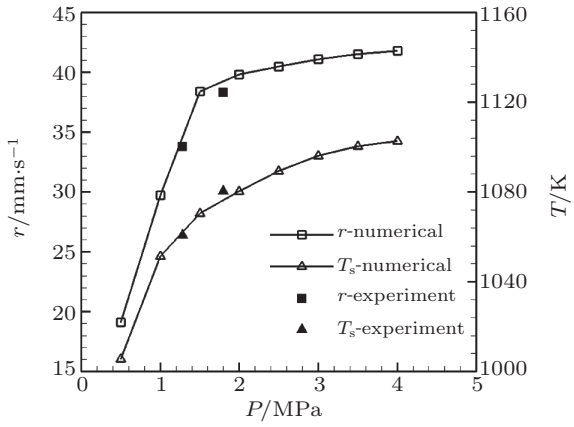


Fig. 7. Variations of burning rate and surface temperature with chamber pressure.

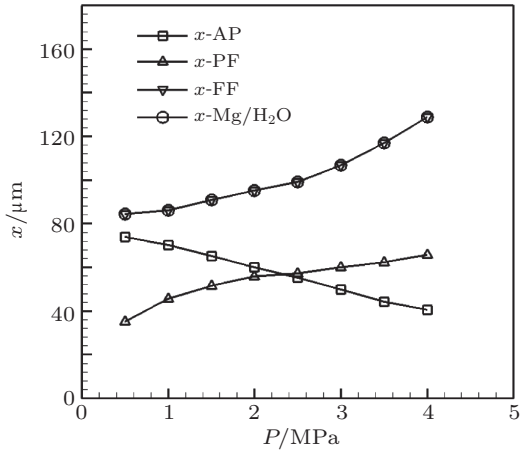


Fig. 8. Variation of flame standoff distance with chamber pressure.

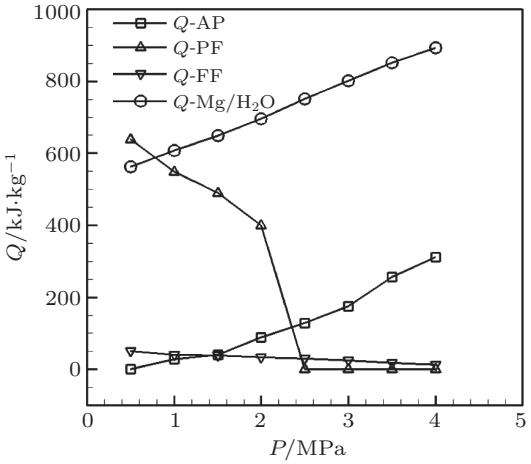


Fig. 9. Variation of heat feedback with chamber pressure.

3.3.2. Effect of water–vapor concentration

The effect of water–vapor concentration on the combustion characteristic of the high-metal magnesium-based hydro-reactive fuel is calculated.

The calculated effect of water–vapor concentration is shown in Fig. 10. The experimental results are also sketched. It is shown that the burning rate and the surface temperature increase when the water–vapor concentration in combustion atmosphere increases, which agrees with the experimental results.

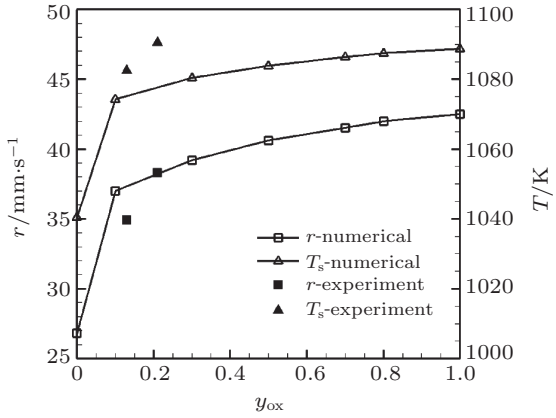


Fig. 10. Variation of burning rate and surface temperature with water–vapor concentration.

Figures 11 and 12 show the variations of the flame standoff distance and the heat feedback to the burning surface with the water–vapor concentration. The flame standoff distance increases slightly when the water–vapor concentration increases. The heat feedback to the burning surface mainly comes from the AP/HTPB/Mg primary flame when $y_{ox} = 0$. As y_{ox} increases, the Mg/H_2O diffusion flame becomes the main source of heat feedback.

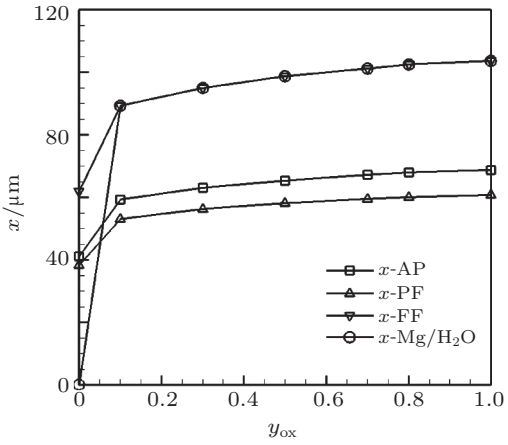


Fig. 11. Variation of flame standoff distance with water–vapor concentration.

Because the reaction rate of the Mg/H_2O diffusion flame and the combustion percentage of magnesium vapor increase when the concentration of water vapor increases, the burning rate and the heat release of the Mg/H_2O diffusion flame rise up. But the water–vapor concentration has less effect on the AP premixed flame and the AP/HTPB/Mg primary flame.

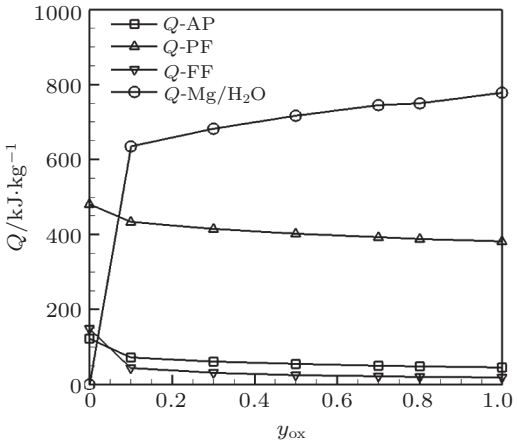


Fig. 12. Variation of heat feedback with water–vapor concentration.

4. Conclusion

This work provides an experimental study and a theoretical analysis of the fascinating features involved in the combustion of a high-metal magnesium-based hydro-reactive fuel under high temperature gaseous atmosphere. The fuel studied in this paper contains 73% magnesium powders, 19% AP, and 8% HTPB. The experimental study focuses on the combustion wave temperature measurement and the qualitative observation of phenomena involved in the combustion of a hydro-reactive fuel strand using a pressure-regulated test combustor. The comparison of the experimental results in argon and water–vapor environments is used to deduce the combustion mechanism of the high-metal magnesium-based hydro-reactive fuel, which helps to formulate a mathematical one-dimensional model based on the Backstead–Derr–Price model. The calculated results indicate that the model is capable of describing the various qualitative combustion characteristics observed in the high-metal magnesium-based hydro-reactive fuel. The model calculates the burning surface temperature, the flame standoff distance, and the burning rate. The results show that the calculated values are in agreement with the experimental results of the burning surface temperature and rate of the fuel.

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References

[1] Kiely D H 1994 *AIAA Paper* 1994-2837
[2] Hargrove J 2004 *AIAA Paper* 2004-0130
[3] Chen C, Wang Y H and Zhang F L 2010 *Journal of Solid Rocket Technology* **33** 670 (in Chinese)
[4] Owis F M and Nayfeh A H 2002 *AIAA Paper* 2002-0875
[5] Wu J H, Ye S, Hu D and Yang X D 2008 *Chin. Phys. Lett.* **25** 1138
[6] Kuehl D K 1965 *AIAA Journal* **3** 2239
[7] Prachukho V P, Ozerov E S and Yurinuv A A 1971 *Combustion, Explosion, and Shock Waves* **7** 195
[8] Ozerov E S and Yurinuv A A 1977 *Combustion, Explosion, and Shock Waves* **13** 778
[9] Foote J P, Lineberry J T and Thompson B R 1996 *AIAA Paper* 1996-3086
[10] Miller T F and Herr J D 2004 *AIAA Paper* 2004-4037
[11] Gan X S, He G Q and Wang J Y 2008 *Journal of Solid Rocket Technology* **31** 4 (in Chinese)
[12] Gao Y, He Z and Liu P A 2009 *Journal of Solid Rocket Technology* **3**2 17 (in Chinese)
[13] Laredo D and Gany A 1983 *Acta Astronautic* **10** 437
[14] Hsieh W H, Peretz A, Huang I T and Kuo K K 1991 *Journal of Propulsion and Power* **7** 497
[15] Arkhipov V A, Gorbenko M V, Gorbenko T I and Saveleva L A 2009 *Combustion, Explosion, and Shocks Waves* **45** 40
[16] Li S L, Zhang W and Zhou X 2009 *Journal of Solid Rocket Technology* **32** 197 (in Chinese)
[17] Pelosi A D and Gany A 2007 *Combustion Science and Technology* **179** 265
[18] Beckstead M W, Derr R L and Price C F 1970 *AIAA Journal* **8** 2200
[19] Glick R L 1974 *AIAA Journal* **12** 384
[20] King M K 1978 *AIAA Paper* 1978-0216
[21] Miller M 1982 *Combustion and Flame* **46** 51
[22] Cohen N S and Stand L D 1982 *AIAA Journal* **20** 1739
[23] Yang C H 2009 "Ignition and Combustion of Magnesium Particles in Water Vapor" (Ph. D. Thesis) (Hangzhou: Zhejiang University) (in Chinese)
[24] Han C 2011 "Research on Steady-state Combustion Mechanism in High-metal Magnesium-based Fuel Water Ramjet Engines" (Ph. D. Thesis) (Changsha: National University of Defense and Technology) (in Chinese)
[25] Yang T 2008 *Principle of Rocket Engine Combustion* (Changsha: National University of Defense and Technology) pp. 122–135 (in Chinese)
[26] Williams F A 1965 *Combustion Theory* (New York: Addison Wesley) pp. 37–44
[27] Huang L Y, Xia Z X, Hu J X and Zhu Q W 2011 *Sci. Chin.: Technol. Sci.* **54** 1
[28] He B, He H B, Feng S J and Nie W S 2012 *Acta Phys. Sin.* **61** 148201 (in Chinese)
[29] OuYang C, Chen L H and Mo J Q 2012 *Chin. Phys.* B **21** 050203
[30] Han X L 2004 *Acta Phys. Sin.* **53** 4061 (in Chinese)
[31] Wang X W, Cai G B and Jin P 2011 *Chin. Phys.* B **20** 104701
[32] Tahsini A M and Ebrahimi M 2006 *AIAA Paper* 2006-4959