Influence of afterburning suppression on the combustion of solid propellants: Recent progress and outlook

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Abstract. The exhaust gas, CO and H₂, occupy about a half amount of combustion products, and they make the oxidative reaction with oxygen in the ambient air entraining into the plume during the combustion of solid propellants, producing shock wave, visible flash and increased infrared radiation. In order to inhibit the afterburning plume of solid rocket motors, one of the best ways is to utilize potassium salts as suppression in the propellant formulation. This review discussed and summarized the influence of a great number of potassium salts including inorganic (K₂SO₄, KHCO₃, KCl, KNO₃, KBF₄, and K₂Co(NO₃)₆ etc.) and organic (K₂C₂O₄, Potassium biphthalate, KD, energetic K(NNMPA) and ADNPK) compounds on the decomposition kinetics, flame structures and temperature, burning rate, combustion wave structures, quenched surface of solid propellants, especially the plateau burning effect. The equipment of plume tests involves in the pressure differential scanning calorimetry, infrared (IR) radiation signature, afterburning flame length and nitrogen-filled pressure-regulating burner etc. The mechanism by which chemical inhibition occurs when certain powders are added to fuel-air flames was shown and discussed. Moreover, the exhaust properties and electron density of solid propellants were modeled and calculated. Finally, future research trends are suggested from different perspectives involving the KOH testing inside the solid rocket motors, plume signature testing and novel insoluble K compounds.

1. Introduction

The exhaust plumes of the rocket motor can generate visible, IR and ultraviolet radiation signature, and it is due to that exhaust gas CO and H₂ in rocket plumes are oxidized during the combustion of the solid propellants, resulting into the increase of flame temperature and the formation of CO₂ and H₂O [1-6]. The oxidative reaction in the ambient air is called afterburning (figure 1) [7]. The signature may be detected and identified by the high-speed tracked vehicles. Currently, the solid rocket motor for the precision strike and stealth of tactical missile and drone is favorably loaded with low exhaust plume signature propellants [8-10].

The low signature solid rocket propellants have been developed and applied for over 60 years
[11-15]. Compared with other propellant types, the low signature propellant not only emphasis the increasing of performance but also cover the minimum smoke, low radiate energy and visible primary, and more environmental properties [9,11,16-21]. Among these performances, the problems involving in the secondary smoke and visible primary have been solved by removing the ammonium perchlorate oxidizer in the propellants [22]. However, high radiate energy produced from the afterburning of the solid propellants has not been explored fully, and its damages have not been inhibited efficiently. Afterburning will bring many hazards, which involve in several aspects below: 1) the elevated plume temperature will easily expose the launch position of the missile and itself, affecting the survivability of the missile weapon system, 2) It can produce a high-temperature, high-speed plasma non-uniform flow field, which causes serious electromagnetic wave attenuation and affects the normal working of the guidance system, 3) Increasing the noise of the rocket motors resulted into the easier detection of plume signature, 4) It generates strong visible light, causing brief visual impairments for launchers, etc [23-26].

![Figure 1](image)

**Figure 1.** Definition of the flame length of rocket plume.

In order to inhibit the afterburning plume of solid rocket motors, several methods have been considered below [27-30]. The first one is that increasing the oxygen balance of the propellant formulation and reducing the sum P value of the molar fractions of the reducing gases CO and H₂, but it will reduce the energy of the propellant, and the method is therefore greatly limited. Additionally, adding more nitramines or high-nitrogen energetic compounds will increase the number of N₂ moles and decrease the number of CO and H₂ moles in the combustion products. This will not only keep the energy, but also inhibit the afterburning [31-33]. The method of chemical inhibition was used by adding appropriate amount of flash suppressors. It is well known that potassium salts have been used successfully for inhibiting the gun muzzle flash and the afterburning rocket plume.

The potassium salts to inhibit the plume afterburning can be only applied for DB and RDX-CMDB propellants without AP oxidant, because potassium salts can react with HCl produced by the combustion of AP to generate stableKCl, and destroy the flame inhibition effect of potassium salts [23]. In the review, we discussed and summarized the influence of a great number of potassium salts including inorganic and organic compounds on the decomposition kinetics, flame structures and temperature, burning rate, combustion wave structures, quenched surface of solid propellants, especially the plateau burning effect. The equipment of plume tests involves in the infrared (IR) radiation signature, afterburning flame length and TDLAS etc. The mechanism by which chemical inhibition occurs when certain powders are added to fuel-air flames was shown and discussed. Moreover, the exhaust properties and electron density of solid propellants were modeled and calculated. Finally, future research trends are suggested from different perspectives involving the
KOH testing inside the solid rocket motors, plume signature testing and novel insoluble K compounds.

2. Effects of Potassium salts on the thermal behaviors of solid propellants

Combustion of solid propellant is a complex multi-stage process based on condensed phase and gas-phase chemical reaction [34]. The thermal decomposition of condensed phases is to evaluate the premise of combustion and detonation performances of propellants, and the several parameters of thermal properties including the thermal stability, peak temperature, activation energy (Ea), thermolysis chemical pathways and heat of decomposition is essential to explore and understand [35]. As mentioned above, addition of potassium salts in the solid propellants can inhibit the afterburning of plume, so using differential scanning calorimetry (DSC) analyze the the thermal decomposition of solid propellants with flame suppressors, in order to reveal the effect of suppressors on the combustion performance of propellants.

2.1. Thermal behaviors of low-sensitive propellants

For the energetic materials, high energy and low sensitivity is the main research and developed directions. However, there is a direct contradiction between both properties. In recent studies, in order to obtain the low-sensitive double base propellants, 2-methyl-2-[(nitrooxy)methyl]propane-1,3-diyl dinitrate (TMETN) was used to replace the Nitroglycerin (NG).

Zhao et al. studies the the interaction of potassium salt flame suppressors (organic phase KD, KNO3 and K3AlF6) with TMETN and burning catalyst used in NC/TMETN insensitive propellants during thermal decomposition by using the pressure differential scanning calorimetry (PDSC) [36]. As shown in table1, the data from thermal analyses show that there is an obvious interaction during thermal decomposit ion of the mixtures of potassium salt with Pb-Cu-CB catalyst (lead phthalate/copper adipate/ carbon black ratio of 10/3/2) and TMETN. Among three kinds of potassium salts, KD not only decreased the peak temperature and increase the heat releases, but also does not affect the catalytic function of Pb compounds. However, KNO3 can not promote the decomposition of TMETN and reduce the burning rate. K3AlF6 has a destructive action for catalyst lead phthalate decomposing into active component PbO. This may be one of the reasons that K3AlF6 make the propellant plateau effect disappear.

Moreover, the group further explored the effect of potassium salts on the thermal decomposition of the combustion catalysts [37]. The results show that the organic potassium salt KD has the minimal influences on the thermal decomposition process of lead phthalate (Φ-Pb), as depicted in the table1. K3AlF6 badly effects the decomposition characteristics of Φ-Pb. Finally, the relations between the effect of different potassium salts on the thermal decomposition of the burning catalysts and the burning plateau effect of solid propellant are analyzed. The thermal decomposition products of different potassium salts affected the functions of catalysts.
### Table 1. A summary of DSC parameters of solid propellants under the effect of potassium salts.

| Composition                  | Exothermic peaks (10 °C⋅min⁻¹), under 4 MPa in N₂ flow | References |
|------------------------------|----------------------------------------------------------|------------|
|                              | $T_o$/°C | $T_{p1}$/°C | $ΔH$/J⋅g⁻¹ | $T_{p1}-T_o$/°C | $T_{p2}$ | $T_{p3}$ |           |
| TMETN                        | 190.1   | 207.5      | 2550       | 17.4            | 247.3   | na       | [36]      |
| TMETN/ Pb-Cu-CB (3/1)        | 180.6   | 203.2      | 2777       | 22.6            | 301.6   | 325.0    | [36]      |
| TMETN/KD (3/1)               | 185.3   | 204.5      | 3571       | 19.2            | 293.4   | na       | [36]      |
| TMETN/ Pb-Cu-CB/KD (3/1/1)   | 181.4   | 204.5      | 3566       | 23.1            | 252.3   | 302.7    | [36]      |
| TMETN/KNO₃ (3/1)             | 186.3   | 206.5      | 2481       | 20.2            | na      | na       | [36]      |
| TMETN/ Pb-Cu-CB/ KNO₃ (3/1/1)| 187.7   | 207.6      | 3541       | 19.9            | 325.4   | na       | [36]      |
| TMETN/K₃AlF₆ (3/1)           | 182.3   | 209.6      | 3452       | 27.3            | 323.4   | na       | [36]      |
| TMETN/ Pb-Cu-CB/ K₃AlF₆ (3/1/1)| 179.3 | 202.8      | 2736       | 23.5            | 292.7   | 425.0    | [36]      |
| A-Cu/KD (1/1)                | 245.3   | 256.6      | na         | 11.3            | 303.5   | 414.9    | [37]      |
| Φ-Pb/KD (1/1)                | 202.7   | 232.2      | na         | 29.5            | 299.1   | 358.0    | [37]      |
| Pb-Cu-CB/KD (1/1)            | 213.5   | 232.2      | na         | 18.5            | 267.8   | 302.0    | [37]      |
| A-Cu/ KNO₃ (1/1)             | 225.1   | 260.0      | na         | 34.9            | 293.6   | 309.5    | [37]      |
| Φ-Pb/ KNO₃ (1/1)             | 210.3   | 235.4      | na         | 25.1            | 257.7   | 301.3    | [37]      |
| Pb-Cu-CB/ KNO₃ (1/1)         | 204.3   | 225.8      | na         | 21.5            | 313.0   | 449.2    | [37]      |
| A-Cu/ K₃AlF₆ (1/1)           | 218.2   | 249.4      | na         | 31.2            | 305.2   | 313.1    | [37]      |
| Φ-Pb/ K₃AlF₆ (1/1)           | 216.7   | 217.6      | na         | 0.9             | 242.2   | 309.1    | [37]      |
| Pb-Cu-CB/ K₃AlF₆ (1/1)       | 214.9   | 216.7      | na         | 1.8             | 247.5   | 307.8    | [37]      |

Notes: $T_o$, onset temperature of the peaks; $T_{p1}$, the first peak temperature of thermal events; $ΔH$, heat releases, in J⋅g⁻¹; $T_{p2}$, the second peak temperature; $T_{p3}$, the third peak temperature; na, not available; respectively.
2.2. The thermal behaviors of nitramine modified double base propellants

The nitramine modified double base propellants have been used for the rocket motors. Qi et al. explored the influence of energetic potassium salt (KE) on the thermal decomposition performance of nitramine modified double base propellants [34]. In figure 2, The KE appeared a exothermic peak of about 201.2 °C, while K2SO4 has no significant change with the increase of temperature, which indicates that KE is easier to decompose and releases heat compared to the K2SO4.

Even though potassium salts including KE and K2SO4 results into the decrease of the heat release of propellants in table2, the thermal decomposition reaction products of KE during the heating process can promote the thermal decomposition of NC/NG double-base components and RDX, and have a more obvious effect on the thermal decomposition of RDX compared to the K2SO4. Therefore, the two factors, the greater heat release and the catalytic effect of NO2 on the propellant, may be the reason why KE for reducing the burning rate of propellant is smaller than that of K2SO4.

![Figure 2. DSC curves of propellants and flame suppressors additive.](image)

**Table 2.** A summary of DSC parameters of solid propellants under the effect of potassium salts.

| Composition | Exothermic peaks (10 °C·min⁻¹) under 0.1 MPa in N₂ atmosphere | References |
|-------------|-------------------------------------------------------------|------------|
|             | $T_o/°C$ | $T_p/°C$ | $\Delta H/J·g^{-1}$ | $T_p-T_o/°C$ | $T_{p2}$ | $T_{p3}$ |          |
| CM          | 152.5    | 205.1    | 856.62              | 52.6         | 236.9    | na       | [34]      |
| CM/2% KSO₄ | 152.5    | 205.0    | 768.76              | 52.5         | 237.0    | na       | [34]      |
| CM/2% KE    | 152.5    | 203.4    | 827.01              | 50.9         | 232.3    | na       | [34]      |

CM: The composition is composed mass fraction of 55% NC and NG, 35% RDX, 10% combustion catalysts and other auxiliary.

2.3. Effects of flash suppressors on decomposition kinetics

The thermal decomposition of low signature propellants with flash suppressors is essential to understand and analyze their combustion and detonation performances. In the previous works,
inorganic (KNO$_3$, KSO$_4$, and K$_3$AlF$_6$), organic (KD) and energetic (KE) potassium salts have been investigated and added into the low-sensitive and nitramine modified double base propellants, and the thermal decomposition kinetics of propellants and effects of potassium salts to catalysts and other energetic materials also have been analyzed and summarized.

Most of flash suppressors have a obvious disadvantage of reducing burning rates, but energetic flash suppressors could provide NO$_2$ and release heat, favoring to improve the burning rate of propellants. Compared to the inorganic potassium salts, the decomposition products of organic salts have the minimal influences on the catalysts and other components of propellants. Therefore, energetic potassium salts keep the burning plateau effect of propellants, which could have larger potential application than other potassium salts. Improving the kinetic analysis of the thermal decomposition is challenging and a popular topic to study the solid propellants.

3. Influence of potassium salts to the combustion of solid propellants

In order to study and explore the influences of potassium salts to the combustion of solid propellants, various aspects have been considered, which contain flame structures and temperature, burning rate, combustion wave structures, quenched surface of solid propellants, especially the plateau burning effect. The plateau burning effect of the solid propellants can keep the stableworking of rocket motors. Currently, the burning rate of propellants can evaluate and obtain the plateau burning effect and pressure exponents, and the burning rates were measured normally by strand burner method.

The burning rate can be particularly sensitive to the value of the pressure exponent, $n$, which is the slope of the log $(u)$ vs. log $(p)$ curve. High values of $n$ can produce large changes in the burning rate with relatively small changes in chamber pressure but with potentially catastrophic consequences [38]. Moreover, a high pressure exponent can result in a difficult start for the rocket motor [35].

3.1. Effects of inorganic potassium salts

Inorganic potassium salts were studied and used first for inhibiting the afterburning of the propellant plume. Yim et al. discussed the selected method of afterburning suppressants for NEPE minimum smoke propellant and several factors including potassium compounds with higher potassium content, melting point and hygroscopic characteristic were used to select inorganic afterburning suppressors [7]. K$_2$SO$_4$, K$_2$CO$_3$, and KNO$_3$ are known to effectively suppress the afterburning of double base propellants, while KClO$_4$, KClO$_3$, and K$_3$AlF$_6$ are not applicable to minimum smoke propellant because chlorine or fluorine in these compounds could induce secondary smoke. Further, the afterburning flame length and mid-range IR intensity were measured for HMX/RDX propellant with 1.1% potassium sulfate, and results show that the total IR irradiance was reduced to about 23% compared to the propellant without afterburning suppressant in table 3.
Table 3. Selected formulations and infrared irradiance reduction in minimum smoke propellants.

| Flash suppressors | Composition of propellant | Preparation method/condition | Total IR irradiance of rocket plume | References |
|-------------------|---------------------------|------------------------------|-------------------------------------|------------|
| none              | 37.1% PEG binder, 2.9% Additives, 34% RDX, 24.4% HMX, 1% ZrC | mixed in a vertical planetary mixer, cured in an oven heated by hot water for 10 d at 323 K. | Irradiance ($10^2 \text{Wcm}^{-2}$) | IR rate (%) | |
| none              | 37.1% PEG binder, 2.9% Additives, 27.9% RDX, 30% HNIW, 1% ZrC |  | | |
| 0.6% K$_2$SO$_4$ | 37.1% PEG binder, 2.9% Additives, 34% RDX, 24.4% HMX, 1% ZrC |  | 3.679 | 100 | [39] |
| 0.8% K$_2$SO$_4$ | 37.1% PEG binder, 2.9% Additives, 27.9% RDX, 30% HNIW, 1% ZrC |  | 1.921 | 52.22 | [39] |
| 1% K$_2$SO$_4$   | 37.1% PEG binder, 2.9% Additives, 27.9% RDX, 30% HNIW, 1% ZrC |  | 1.671 | 45.42 | [39] |
| 1.1% K$_2$SO$_4$ | 37.1% PEG binder, 2.9% Additives, 34% RDX, 24.4% HMX, 1% ZrC |  | 1.024 | 27.83 | [39] |
| 1.1% K$_2$SO$_4$ | 37.1% PEG binder, 2.9% Additives, 27.9% RDX, 30% HNIW, 1% ZrC |  | 0.883 | 22.64 | [39] |
| 1.1% K$_2$SO$_4$ | 37.1% PEG binder, 2.9% Additives, 34% RDX, 24.4% HMX, 1% ZrC |  | 2.453 | 66.68 | [39] |

Zhao’s group did lots of works to study the effect mechanism of flash suppressors. As shown in table 4, the combustion properties of insensitive nitrocellulose based propellant containing potassium inorganic compounds have been explored [40]. The burning rate of solid propellants decrease by using TMETN to replace NG and pressure exponents increased under low pressure condition, but the plateau burning effect appeared above 10 MPa. KNO$_3$ reduces the burning rate of the propellant over the entire measured pressure range, the plateau burning effect are still preserved within the range of 10 to 14 MPa, but the burning rates in plateau area decrease, the pressure exponents becomes larger. However, addition of K$_3$AlF$_6$ badly destroys the plateau burning effect of insensitive propellant. Additionally, chlorine or fluorine in these compounds could induce secondary smoke.
Table 4. Combustion performance of solid propellants under the effects of flash suppressors.

| Flash suppressor | Composition of propellant | Preparation method | Combustion Properties | References |
|------------------|---------------------------|--------------------|-----------------------|------------|
|                  |                           |                    | Burning rate at plateau area (mm/s) | Pressure exponents | Plateau burning effect (MPa) | |
| none             | 59% NC, 30% NG, 2.5% TEGDN, 4.5% other auxiliary, 1% combustion stabilizer, 2.0% (Φ-Pb), 0.6% | 13.05 | 0.062 (8~14MPa) | Above 8 | [40] |
| none             | Low sensitive propellants: 59% NC, 30% TM ETN and NG, 2.5% TEGDN, 4.5% other auxiliary, 1% combustion stabilizer, 2.0% (Φ-Pb), 0.6% A-Cu, 0.4% CB | Solvent-free screw pressing process | 13.20 | 0.113 (10~14MPa) | Above 10 | [40] |
| 2% KNO₃         |                           | 9.50               | 0.194 (10~14MPa)      | 10~14       | [40][41] |
| 2% K₃AlF₆⁻      |                           | none               | na                    | none        | [40][41] |
| 2% organic KD   |                           | 9.65               | 0.063 (6~12MPa)       | 6~12        | [40][41] |

By using similar propellants, the researcher presented the flame structures of NC/TMETN insensitive propellant containing different potassium salts by means of the single frame amplification photography [41]. As shown in figure 3, various potassium salts enable the flame structure of the propellant to be different. Addition of KNO₃ presented similar flame structure with the no flash suppressor propellant, while brightness of flame become weaken obviously. The propellant containing K₃AlF₆⁻ possesses completely different flame structure.

The study on the quenched surface characteristics of NC/TMETN propellant with potassium salt have been performed by using scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) [42]. Addition of KNO₃ reduced the carbon content on the quenched surface and increased the size of Pb ball, which decreased the active materials and weakened the catalytic performance. Because K₃AlF₆⁻ reacted with the Pb oxide to form PbF₄, the catalysis function of Pb compound was destroyed completely.
Figure 3. (a) Flame photographs of plateau double base propellant, and flash suppressors including KD (b), KNO₃ (c), and K₂AlF₆(d) were adding into the propellant.

Table 5. Effect of eliminated-flame additive on combustion performance of propellants.

| Flash suppressors | Composition of propellant | Preparation method | Burning rates (mms⁻¹) | Pressure exponent $n_{15-23}$ |
|-------------------|---------------------------|--------------------|------------------------|-------------------------------|
| none              | Nitramine modified double base propellant: 55% NC+NG, 35% RDX, 10% catalysts and other auxiliary | Slurry casting process | 29.67, 30.18, 30.18, 30.28, 30.36 | 0.05 |
| 2% K₂SO₄         |                           |                    | 29.07, 29.41, 29.33, 29.47, 30.07 | 0.08 |
| 2% energetic compound KE |                       |                    | 29.50, 29.56, 29.70, 29.91, 30.18 | 0.05 |

Qi et al. has studied the influence of K₂SO₄ on the combustion performance of nitramine modified double base propellant [34]. Addition of K₂SO₄ reduced the burning rate of propellant and increased the pressure exponent, as shown in table 5. Compared to the double base propellant without flash suppressors, K₂SO₄ reduced the diameter of the plume at the engine nozzle of the propellant, but the afterburning still exists in figure 4. The addition of the flash suppressors greatly reduces the radiation temperature of the engine plume. K₂SO₄ can reduce the radiation temperature of the propellant from 1353 to 1082 °C in figure 4.
Two inorganic salts (LiF and KA) as flash suppressors have been used for nitramine modified double base propellant [44]. Addition of two plash suppressors decreased the burning rates of propellants and increased the pressure exponent in table 6. The propellant samples were placed into the motor with the diameter of $\Phi 50$. The flame of propellant without plash suppressor has the width of 0.174 m and the length of 1.91 m in figure 6. Compared to LiF, addition of KA resulted into the disappearance of afterburning.
3.2. Effects of organic potassium salts

Compared to inorganic potassium salts, organic potassium compounds as flash suppressors have good compatibility with the other component of propellants, and the combustion products of organic suppressors don’t affect the function of catalysts. In table 4, although addition of organic potassium compound KD for NC/TMETN insensitive propellants reduced the burning rate, the pressure exponents and plateau burning effect were kept. Additionally, the burning rates and the plateau range of the propellant containing KD can be adjusted by means of the composite catalysts. The propellant containing an organic potassium salt (KD) maintains the flame structure characteristics of plateau double-base propellant, as shown in figure 3 [41]. Moreover, the quenched surface characteristics of the NC/TMETN propellants indicated that addition of KD resulted into the decrease of Cu content on the quenched surface and weakened the cooperation between Pb and Cu [42].

Two organic potassium salts including C₄O₆H₄K₂ and KD have been studied on the combustion performance of the nitramine modified double base propellant by Li et al [43]. Addition of these flash suppressors decreased the burning rates of propellants and increase the pressure exponent in table 6. Addition of C₄O₆H₄K₂ reduced the afterburning of plume, but addition of KD resulted into the disappearance of afterburning. After adding 1.5% flame suppressors, the infrared transmittance and visible light transmittance of the propellant plume have little effect, and the laser transmittance increases, as shown in table 6.

| Flash suppressors | Composition of propellant | Preparation method | Burning rates (mms⁻¹) | Pressure exponent | IR permeation rate (%) | Visible permeation rate (%) | Laser permeation rate (%) |
|------------------|--------------------------|--------------------|----------------------|-------------------|------------------------|----------------------------|--------------------------|
| None             | Nitramine modified double base propellant: 60% NC+NG, 30% RDX, 5% catalysts, 3% stabilizer and 2% ballistic modifier | Slurry casting process | 10.60 11.80 12.27 12.83 13.10 13.89 | 0.17 | 97.4 | 96.6 | 77.4 |
| 1.5%LiF          | Nitramine modified double base propellant: 60% NC+NG, 30% RDX, 5% catalysts, 3% stabilizer and 2% ballistic modifier | Slurry casting process | 8.86 10.32 11.21 11.99 12.54 | 14.61 | 0.31 | 97.7 | 96.1 | 85.9 |
| 1.5%KAK          | Nitramine modified double base propellant: 60% NC+NG, 30% RDX, 5% catalysts, 3% stabilizer and 2% ballistic modifier | Slurry casting process | 9.08 10.66 11.56 12.28 12.82 | 14.44 | 0.29 | 97.5 | 96.6 | 84.3 |
| 1.5%KD           | Nitramine modified double base propellant: 60% NC+NG, 30% RDX, 5% catalysts, 3% stabilizer and 2% ballistic modifier | Slurry casting process | 7.88 9.21 10.05 10.81 11.42 | 14.08 | 0.36 | 97.0 | 95.4 | 88.9 |
3.3. Effects of organic energetic potassium salts

In 2013, Qi et al. explored the influence of organic energetic potassium salts KE on the inhibiting afterburning of plume. As depicted in table 5, addition of KE reduced a bit of burning rate compared to the propellant without flash suppressors, while the pressure exponent has no influence. Compared to \( \text{K}_2\text{SO}_4 \), organic energetic potassium salts KE contain nitro group (\(-\text{NO}_2\)), producing \( \text{NO}_2 \) gas during heating, and \( \text{NO}_2 \) gas can make the catalytic decomposition of NC, NG and RDX [44]. The flame of the engine with the KE propellant has a discontinuous cylindrical shape in figure 4. It is a typical primary combustion flame, and the secondary combustion flame has basically disappeared. Addition of KE reduced the radiation temperature from 1353 to 913 °C in figure 5.

Compared to the inorganic potassium salts such as \( \text{K}_2\text{SO}_4 \), organic salts KE is more easily decomposed and releases heat at high temperature [34]. On the one hand, it is conducive to the improvement of propellant energy; on the other hand, a larger heat releases, which will cause higher heat to be fed back to the surface of the condensed phase and promote the thermal decomposition rate of the condensed phase. The thermal decomposition reaction products of KE during the heating process can promote the thermal decomposition of NC / NG double-base components and RDX, and have a more significant effect on the thermal decomposition of RDX. In summary, The two factors, the large thermal decomposition heat and the catalytic effect of \( \text{NO}_2 \) on the propellant, may be the reason why KE reduces the burning rate of the propellant to a small extent compared to \( \text{K}_2\text{SO}_4 \).

For the equal mass of KE and \( \text{K}_2\text{SO}_4 \), the K content of the former (25.9%) is less than that of the latter (27.5%), but compared with an inorganic potassium salt \( \text{K}_2\text{SO}_4 \), KE is more easily decomposed under high temperature conditions, and the number of K\(^+\) participating in the flame suppression is larger, and "effective" K\(^+\) content is higher, and this may be the reason why the flame suppression effect of KE is stronger than \( \text{K}_2\text{SO}_4 \).

Several energetic potassium compounds, 2,3-dihydro-4-nitro-3-(dinitromethylene)-1H-pyrazol-5-amine potassium salt [K(NNMPA)] [45], 4-amino-3, 5-dinitropyrazole potassium salt (ADNPK) [46] and 4,4-azo-1,2,4-triazol-5-one potassium salt [K(ZTO) \( \cdot \) H\({}_2\text{O}\)]\(_n\) [47], have been synthesized by Xu’s group, and the crystal structures, sensitivity and thermal behaviors of these compounds have been obtained and analyzed. However, the studies on the influences of these compounds to the thermal decomposition and combustion performance of propellants were not explored yet.

Other inorganic and organic potassium salts as flash suppressors also have been reported in the past.
The method of coating pretreatment were also used to eliminate the destructive effect of flame suppressors on the combustion of nitramine modified double base propellant. Results show that the coating method can reduce the pressure exponent of the propellant from 0.79 to 0.35, but it cannot completely restore the Plateau burning effect destroyed by the flame retardants [48].

4. Predictions of afterburning inhibition by potassium

In 1975, Mchale explored and computed the mechanism of chemical inhibition by potassium compounds for the exhaust gas, as shown in table 7 [51]. The principal feature to note in the complete lack of inhibition exhibited by KBF4 compared with the strong inhibiting effect found for the other three potassium salts. In table 7 all the species are gaseous unless indicated as liquid. The common product species among the effective inhibitors are K and KOH, but potassium metal vapor is ruled out as a chemical flame inhibitor.

Table 7. Effect of flash suppressors additive on combustion performance of exhaust gas

| Flash suppressors | Composition of exhaust gas (mole percent) | Radiant intensity (J/lb/sr) | Calculated exhaust temperature (ºC) | Reaction products | Mole % |
|-------------------|------------------------------------------|---------------------------|-------------------------------------|------------------|-------|
| none              |                                         | 203                       |                                    |                  |       |
| 3% K2SO4         | 26.6% CO, 17.8% H2, 22.8% N2, 14.4% CO2, 18.2% H2O | 16                       | 1312                                | K                | 0.115 |
|                   |                                          |                          |                                    | KOH              | 0.734 |
| 3% KHCO3         |                                          | 16                       | 1291                                | K2CO3(l)         | 0.009 |
|                   |                                          |                          |                                    | K                | 0.091 |
|                   |                                          |                          |                                    | KOH              | 0.623 |
| K2C2O4           |                                          | 14                       | 1295                                | K2CO3(l)         | 0.059 |
|                   |                                          |                          |                                    | K                | 0.101 |
|                   |                                          |                          |                                    | KOH              | 0.665 |
| KBF4             |                                          | 244                      | 1285                                | KF               | 0.053 |
|                   |                                          |                          |                                    | HF               | 2.23  |
|                   |                                          |                          |                                    | KBO2(l)          | 0.119 |
|                   |                                          |                          |                                    | KBO2             | 0.403 |
Predicted extents of afterburning in fuel-rich exhausts of metal-modified, double base propellant rocket motors have been investigated by using means of a plume prediction code by Jensen et al [52]. The influences of a number of metals, including potassium, iron, molybdenum, tungsten, barium, tin, and chromium, on afterburning have been examined for a 300 N thrust motor. Li et al [53] have explored the influence rule of potassium salt flame suppressors (KNO$_3$, K$_3$AlF$_6$ and organic potassium salt KD) on the plume electron density of modified double base propellants with different solid fillers, energetic additives, oxygen coefficients, catalysts and Al powder content. The potassium salt flame suppressors possess the maximum influence on the plume electron density, and its value is higher than the basic formulation by 4 orders of magnitude. The KNO$_3$ can increase the plume electron density of the formulation, but the KD and K$_3$AlF$_6$ can reduce the plume electron density of the formulation.

Recently, Babushok et al. developed a kinetic model of inhibition by the potassium-containing compound, and the kinetic model includes reactions with the following gas-phase potassium-containing species: K, KO, KO$_2$, KO$_3$, KH, KOH, K$_2$O, K$_2$O$_2$, (KOH)$_2$, K$_2$CO$_3$, KHCO$_3$, and KCO$_3$ in figure 6 [54]. However, flame equilibrium calculations demonstrate that the main potassium-containing species in the combustion products are K and KOH on the inhibition of hydrocarbon-air flames.

![Equilibrium volume fraction of potassium-containing species in the combustion products of a methane-air flame as a function of equivalence ratio (initial conditions: 298 K, 101.33 kPa, KHCO$_3$(s) mole fraction of 0.25%).](image)

**Figure 7.** Equilibrium volume fraction of potassium-containing species in the combustion products of a methane-air flame as a function of equivalence ratio (initial conditions: 298 K, 101.33 kPa, KHCO$_3$(s) mole fraction of 0.25%).

5. **The mechanism of combustion inhibition by potassium**

The rocket exhaust plumes producing the afterburning is due to the combustion occurring of CO and H$_2$. Afterburning takes place when the sequence of chain-branching chemical reactions: [23]

\[
\begin{align*}
\text{Initiation of chain:} & \quad 2\text{H}_2 + \text{O}_2 \rightarrow \text{H}_2\text{O} + \text{OH}^- + \text{H}^+ \\
\text{Grow of chain:} & \quad \text{H}^- + \text{O}_2 \rightarrow \text{OH}^- + \text{O}^+ \\
& \quad \text{O}^- + \text{H}_2 \rightarrow \text{OH}^- + \text{H}^+ 
\end{align*}
\]
Propagation of chain: \( \text{OH}^- + \text{H}_2 \rightarrow \text{H}_2\text{O} + \text{H}^- \) \hspace{1cm} (4)
\( \text{CO} + \text{OH}^- \rightarrow \text{CO}_2 + \text{H}^- \) \hspace{1cm} (5)

In previous work, researchers have conducted detailed and in-depth studies on the flame inhibiting mechanism of potassium salts. It is generally believed that the flame inhibiting effect of potassium salt is due to the decomposition of the flash suppressors generates KOH, and the H and OH radicals in the gas react with KOH, and following the reaction formula:
\[
\text{KOH}(g) + \text{H}^- \rightarrow \text{K}'(g) + \text{H}_2\text{O} \hspace{1cm} (6)
\]
\[
\text{K}'(g) + \text{OH} \rightarrow \text{KOH}(g) \hspace{1cm} (7)
\]
(6) and (7) can accelerate the termination of chain-branching chemical reactions, and hence combustion is suppressed [52]

However, combustion inhibiting by potassium salts have some disadvantage. For example, 1) addition of potassium salts results into the decrease of specific impulse for solid propellants. 2) Potassium salts reduced the burning rate of propellants and reduce the pressure exponent, and they affects or destroyed the plateau burning effect. 3) Addition potassium salts tend to produce excessive secondary smoke. Therefore, new potassium flash suppressors are essential to explore and study for solid propellants.

6. Conclusions and future work suggestions
The review discussed and summarized the influence of a great number of potassium salts including inorganic, organic and energetic compounds on the decomposition kinetics, flame structures and temperature, burning rate, combustion wave structures, quenched surface of low-sensitive and nitramine modified double base solid propellants, especially the plateau burning effect. The studies favor to weaken and eliminate the afterburning of the exhaust plumes on the rocket motors.

In the future works, novel potassium salts should be explored firstly, especially organic or energetic organic potassium salts. Currently, metal-organic frameworks (MOFs) with special crystal structures are popular for the combustion catalysts, and MOFs with potassium cations could have multi-functional properties such as flash inhibiting and catalysts. Other compounds (K\text{PbCo(NO}_2)_n, K\text{PbCu(NO}_2)_n) could have similar application. Additionally, new methods should be used for the measurement and analyze of plume. Tunable Diode Laser Absorption Spectroscopy (TDLAS) can check the OH' radicals, and developing the equipment for the measurement of gaseous KOH during the combustion process of solid propellants. Lastly, in order to eliminate the disadvantage of flash suppressors, coating potassium salts or avoiding the contact between potassium salts and catalysts are very important and should be studied further.

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