Fuel 111 (2013) 367–373

Contents lists available at SciVerse ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Experimental studies the burning process of gelled unsymmetrical dimethylhydrazine droplets under oxidant convective conditions

Songjiang Feng [a,*], Bo He [a], Haobo He [a], Lingyu Su [a], Zhiyong Hou [a], Wansheng Nie [a], Xihong Guo [b]

[a] Department of Space Equipment, The Academy of Equipment, Beijing 101416, China
[b] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

HIGHLIGHTS

- Oxidant convective conditions affect the burning behavior of gel UDMH droplets.
- The enveloped flame is converted to the escaped flame as convective velocity rises.
- The enveloped flame is more helpful to the burning process.
- Microexplosion intensity of enveloped flame rises with convective temperature.
- Microexplosions intensity of escaped flame is higher, but frequency was lower.

ARTICLE INFO

Article history:
Received 6 December 2011
Received in revised form 26 March 2013
Accepted 26 March 2013
Available online 9 April 2013

Keywords:
Organic gel propellant
UDMH
Burning behavior
Flame structure
Oxidizer convective environment

ABSTRACT

Gelled hypergolic propellants offer potential safety and performance improvements over conventional liquid and solid propellants. Understanding the combustion process of single gelled droplets is the first basic step to predict their behavior in the future combustion chambers. Experimental studies were performed to investigate the burning behavior of gelled unsymmetrical dimethylhydrazine (UDMH) droplets under oxidant convective conditions. The effects of oxidant convective conditions including velocity and temperature on the burning behavior were analyzed. The burning process was broken down into four stages: heating and swelling period, initial combustion period, violent combustion period, and stable and extinguished combustion period. Sometimes the droplet inside seemed to be porous or botryoidal. The microexplosion period lasted for a long time sometimes exceeding about 70% of the burning lifetime, and the phenomenon of gas jet combustion due to the burst steam from microexplosions was founded. The conversion of burning flame from a layered and enveloped flame structure to an escaped flame structure with increase in the convective velocity was observed. When the enveloped flame appeared, it was more helpful to the burning process, and the intensity of microexplosions and the burning rate constant were found to increase with the convective temperature. When the escaped flame appeared, it was disadvantageous to the burning process, and the intensity of microexplosions decreases with rise in convective velocity. Compared with the escaped flame, the intensity of microexplosions of the enveloped flame was lower, but the frequency was higher.

1. Introduction

The demand for high performance, high energy–density fuels has led to an ever increasing research of gel propellants [1]. Gel propellants potentially combine the advantages of liquid propellant operability and solid propellant storability [2]. The unsymmetrical dimethylhydrazine (UDMH)/nitrogen tetroxide (NTO) combination is one of the most common hypergolic propellants currently in use. In order to improve its storage stability and handing safety, the organic gellant is successfully used to gel UDMH. Because of the addition of gellant to UDMH, rheological characterization, atomization, and burning processes of gelled UDMH are different from those of pure UDMH. So before gels can be widely used, their atomization and combustion processes as well as the rheological characteristics must be well understood [3].

A lot of work has been carried out to understand the mechanism of gel propellants rheology and atomization. Natan and Rahimi [4,5] surveyed various aspects of the developing status of the gel propellants and the flow properties of gel fuels in tapered injectors. Teipel and Forter-Barth [6] examined the rheological behavior of the nitromethane/silicon dioxide gels and summarized the main rheological studies of selected, mostly metallized, gel propellants. Wei et al. [7] studied the rheological behavior of a polymer-gellant

* Corresponding author. Tel.: +86 10 66364480.
E-mail address: hnfengsj@163.com (S. Feng).

0016-2361/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.fuel.2013.03.071

gel propellants simulants. In the aspect of atomization of gel propellants, Jayaprakash and Chakravarthy [8] studied the spray droplet size distribution, the spray breakup length and the spray angle of metallized gelled fuel. In addition, Rahimi and Natan [9,10], Mueller and Turns [11], and Mordosky et al. [12] studied the atomization properties of gel fuel simulants, aluminum gel propellants, and gelled RP-1 propellants, respectively. Cai and Zhang [13] summarized the developing status of gelled propellants atomization research.

Studies of the combustion processes of gel propellants, especially of the gel propellant droplets, are scarce in comparison to the long term investigations of their rheology and atomization properties [14]. Gels are multi-component fuels, which burn similar to slurries [1,15]. The work on the droplet combustion characteristics of a varied range of multi-component fuels has been summarized in literature [1,15–17]. For understanding the mechanism of gelled droplet combustion, the Gelled Propellants Laboratory at Purdue University, the Israel Institute of Technology (Technion), Indian Institute of Technology, and so on, have carried out many experimental and theoretical studies. Firstly, Arnold et al. [2,3,18] recently detailed the droplet burning of hydrocarbon/silica and monomethylhydrazine (MMH)/hydroxypropylcellulose (HPC) gels. These studies are part of an ongoing Army Research Office project to further develop the fundamental science of gelled hypergol utilization in practical systems. The phenomena observed by them indicated that the amount of added gellant influenced the burning rates, temperature and size of gelled droplets. The burning characteristic of MMH/HPC gels showed different from that of hydrocarbon/silica gels. And the effects of diluents on ignition and on the dual flame structure were found to be considerable while the gelled MMH droplet burning in an environment of NTO (nitrogen tetroxide) diluted with nitrogen. Secondly, Natan et al. carried out some experimental and theoretical work on the burning characteristics of gel propellant droplets of water gels [19] and hydrocarbon based gels (kerosene [20], JP-5 [21,22], JP-8 [17,23]). Results indicated that the amount of the added gellant had a strong influence on the droplet burning behavior in comparison to the ungelled pure liquid. For example, their investigations illustrated that the typical d^2-law can be used for the pure hydrocarbon fuel droplets as well as for the gelled JP-5 droplets [21,22] and the gelled JP-8 droplets [17,23]. However, since the gellants may increase the latent heat of vaporization and also slightly the propellant density in comparison to the pure ungelled liquid, an increasing amount of gellant increases the droplet burning time. Besides a decreased burning rate with increased gellant amount, also a higher droplet burning temperature had been measured for increased gellant amounts [22]. As burning progresses, the phenomenon including an elastic gellant layer or shell formation about the droplet, bubbles accumulation within the shell of the droplet, droplet volume swelling, a rupture in the droplet, vapor jetting, microexplosions, and the remaining droplet collapsing. This phenomenon may be repeated several times over the lifetime of the droplet [17]. Their studies also indicated an increase in the burning rate constant with the pressure for a particular initial droplet diameter. Additionally, they also concentrated on the theoretical model of the combustion processes [16] and spray diffusion flames [24,25] of the organic gel droplet. Thirdly, Mishra et al. [1,15] experimentally investigated the effects of gellant concentration, initial droplet diameter and chamber pressure on the combustion of organic gel kerosene fuel droplets. The authors indicated that flame structure, burning rate constant, and microexplosion intensity were sensitive to these conditions. For example, the burning rate constant was found to decrease with increase in the gellant concentration, decrease in initial droplet diameter. And for a given range of diameters, the burning rate constant continued to increase with pressure. The flame exhibited a triple flame structure. Experiments were also carried out to study how the burning behaviors of gel droplets were affected by these conditions.

The spraying gelled droplets in the combustion chamber evaporate and burn within a convective environment. It is necessary and important to study the burning behavior of gelled droplets under this environment. However, previous investigations concentrated on the combustion processes of gelled hydrocarbon fuels and gelled monopropellants mainly like MMH droplets under static conditions. Research on burning behavior of gelled UDMH droplets especially within a convective environment has not been conducted. Therefore, the present study is focused on measuring the burning behaviors of gelled UDMH droplets within an oxidant convective environment. The main aim of this paper is to examine the effects of oxidizer stream velocity and temperature on flame structure, droplet shape and size, and burning lifetime of gelled droplets.

2. Materials and methods

2.1. Materials

The experiments were conducted on gelled UDMH propellant droplets because of the increasing practical importance of this class of propellants, which combine the advantages of both liquids as well as solids. UDMH was used here as the base fuel, and a gellant was used to gel UDMH. According to reports in Refs. [26,27], the gellant was a marketed reagent which was a type of organic high polymer mainly containing multiple chemical elements, including C, H, O, N, S, Cl, F, and Si, etc. The preparation techniques of UDMH gels were described in Ref. [28] in detail. Because the UDMH is a kind of volatile poisonous substance, the gel preparation experiment must be conducted in a sealed with high-speed stirring and cooling device in a reaction vessel. UDMH was joined into the reaction vessel and then was cooled to 283–293 K. The next step was to stir acutely for 10 min while adding gellant slowly. Then stir for 30–90 min once more and obtain the UDMH gel propellant.

2.2. Experimental methods

Fig. 1 shows a schematic diagram of the experimental setup mainly consisting of a high-pressure heat exchanger, an oxidant evaporator, a high-speed camera, a pressure sensor, and a temperature sensor. And the high-pressure heat exchanger and the oxidant evaporator had maximum pressure handing capacities of 0.5 MPa and 1 MPa, respectively. Liquid oxidant of N_2O_4 was loaded in the oxidant evaporator from an oxidant tank. And the quality of N_2O_4 was fixed by the maximum volume of the oxidant evaporator and enough not only to form various initial pressures in the oxidant evaporator by heating for different time but also to provide enough oxidant concentration for burning with gelled UDMH droplets. And fixed quality nitrogen was filled in the heat exchanger from a pressure vessel and heated for different time. The high-temperature nitrogen was then mixed with the liquid oxidant. The liquid oxidant was thus heated and evaporated to form high-temperature and high-pressure oxidant gas. Finally, the valve of the oxidant evaporator was opened and the high-temperature oxidant gas injected and formed the open oxidant convective environment. The initial temperature of the oxidizer stream was measured by the temperature sensor. The initial velocity of an oxidizer stream was controlled by adjusting the pressure inside the oxidant evaporator and especially the outlet valve opening of the oxidant evaporator.

With special concern to the reproducibility of the experiment, it is necessary to ensure that the droplets can be regenerated around