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Atomization and hypergolic reactions of impinging streams of monomethylhydrazine and dinitrogen tetroxide

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ABSTRACT

Impinging liquid jets of monomethylhydrazine (MMH) and MON3 (i.e. dinitrogen tetroxide containing 3 wt% NO) were observed with high-speed cameras in order to explore fluid and flame behaviors in the impinging region. At the beginning of the impingement, a portion of the fluids that turned yellow in the impinging region was considered the NO_2 and N_2O_4 vapors or chemical condensate, while the white fogs were regarded mainly as the spreading MMH vapor. Auto-ignition occurred less than 5 ms after impingement, followed by the propagation of orange flames. Due to hypergolicity, orange and blue–white flames were held near the rim of the liquid sheet of the impinging jets. The orange flames tended to exist near the MON3 jets, while the blue–white flames spread on the side of the MMH jets. When atomization was so weak that a long liquid sheet was formed, the MMH and MON3 jets were separated by the orange flames. The atomization performance significantly affected the ignition delay time, as well as combustion efficiency and stability. However, even under strong atomization conditions, the liquid MMH and MON3 jets at a steady state are regarded as the impinging immiscible fluid jets.

1. Introduction

Bipropellant chemical thrusters, which are used for the attitude control and orbit maneuvering of spacecraft, are operated using a steady-state and pulse firing mode. The orders of firing time are about 10^1–10^3 s and 10^{-2}–10^{-1} s, respectively. The combustion chamber, injector and propellant are carefully designed and selected to obtain high combustion efficiency in the steady-state mode and fast ignition response in the pulse mode. Most bipropellant thrusters employ hydrazine (N_2H_4) or its derivatives (i.e. monomethylhydrazine (MMH, CH_3NHNH_2), unsymmetrical dimethylhydrazine (UDMH, $(CH_3)_2NNH_2$)) as a liquid fuel and dinitrogen tetroxide (N_2O_4) or nitric acid solution containing a certain amount of N_2O_4 (i.e. red fuming nitric acid (RFNA), white fuming nitric acid (WFNA)) as a liquid oxidizer. The combination of these fuels and oxidizers exhibits a unique and characteristic chemical reaction called “hypergolicity” [1,2] whereby a fuel and oxidizer spontaneously auto ignite upon contact with each other, even at low temperatures and low pressures. Therefore, the cyclic process of ignition and quenching in the pulse mode can be operated without an igniter and catalyst. To take advantage of hypergolicity, the bipropellant thrusters generally employ unlike-impingement type injectors [1] as shown in Fig. 1. The fuel and oxidizer streams impinge on each other near the injector, and make a liquid fan that eventually disintegrates into droplets.

Experiments on the hypergolic propellants require special equipment for safety as such propellants are often highly toxic and explosively reactive. Thus, the fundamental experimental data on the combustion of impinging hypergolic-propellants streams such as the atomization, ignition process and flame structure are limited. Thruster manufacturers still screen many trial products of the thrusters through the time and money consuming firing tests. In such a trial-and-error design process, designing a new chamber and injector outside the conventional thrusters is difficult. The fundamental experimental data on hypergolic propellant combustion is also necessary to develop less- or non-toxic propellants [3–8] because such propellants must possess ignition response and combustion efficiency comparable to hypergolic propellants.

NASA and its contractors [9–18] conducted many firing tests to observe the combustion flows of hypergolic propellants in 1960 s and 1970 s. The ignition process was divided into three sequential stages. In the first stage, the fuel and oxidizer react in the liquid phase and yield vapors due to the heat release of the liquid phase reactions. Next, the gas phase reactions of the vapors begin. Finally, thermal ignition occurs. Past studies [9–13,16,17] also reported that the unlike-impinging hypergolic streams mainly exhibit two modes

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Nomenclatures

x, y and z	coordinates fixed at the injector elements
D	diameter of the orifice
D_{ref}	reference diameter, equal to D_f of practical-size element
θ	impingement angle
T	temperature
P	pressure
ρ	density
V	injection velocity
Re_D	Reynolds number based on the orifice diameter and liquid properties
We_D	Weber number based on the orifice diameter and liquid properties
J	momentum flux ratio of the MON3 and MMH jets, $(\rho V^2)_o/(\rho V^2)_f$
MR	mixture ratio of the MON3 and MMH jets, $(\rho VD^2)_o/(\rho VD^2)_f$
t_V	time after the main valves open
t_I	time after liquids impingement

Subscripts

f	fuel, MMH
o	oxidizer, MON3
c	combustor

Table 1
Dimensions of the injector elements.

	Poor-atomization element	Practical-size element
D_f [mm]	1.0	D_{ref}
D_o [mm]	1.0	$1.4D_{ref}$
θ [°]	10	30

Table 2
Injection conditions of hot-fire tests.

		Poor-atomization element	Practical-size element
MMH	V (m/s)	12.0 ± 0.5	15.0 ± 0.8
	ρ (kg/m^3)	875	875
	T (K)	299	298
	Re_D (–)	1×10^4	8×10^3
	We_D (–)	4×10^3	3×10^3
MON3	V (m/s)	10.3 ± 0.8	10.8 ± 0.9
	ρ (kg/m^3)	1440	1440
	T (K)	299	298
	Re_D (–)	4×10^4	3×10^4
	We_D (–)	6×10^3	5×10^3
MR [–]		1.4	2.4
J [–]		1.2	0.9

of combustion as illustrated in Fig 1. One is the mix mode where the liquid fuel and oxidizer are well-mixed near the impinging point and form a spray combustion of the mixtures downstream. In another mode called the reactive stream separation (RSS) mode, the fuel and oxidizer separate instead of mixing due to the fast chemical reactions. Both combustion efficiency and stability in this mode are generally lower than in the mix mode because the fuel and oxidizer are not uniformly distributed in the chamber. To avoid the RSS mode, some correlations between the combustion mode and injection conditions were proposed based on firing tests and theoretical studies of the liquid and gas reactions [9–13]. Such correlation models use the combustion pressure, injection temperature, injection Reynolds number and other factors to predict the combustion mode. These models showed that the RSS mode likely occurs when the combustion pressure, injection temperature and injection Reynolds number are high. However, these models cannot always predict the combustion mode with various injector geometry because the experiments in each study were conducted with only a couple of injector elements. Notably, the picture qualities of past studies were not high enough to reveal the behavior of the impinging streams including the three-dimensional liquid fan, atomization and flames.

Since understanding the fluid behavior and reactions near the fuel-oxidizer interface is necessary, recent studies on hypergolic and less-toxic propellants explored such characteristics by using a micro reactor and drop tests [3–6,19,20]. Wang and Thynell [20] suggested a schematic model of the ignition of the MMH and RFNA system on the basis of the drop test, FTIR and ToFMS tests. They reported that neutralization occurs in the liquid phase to release a significant amount of heat and MMH/HNO_3 vapors, and then the vapors start reacting in the gas phase while an aerosol cloud of monomethylhydrazinium nitrate (MMH·HNO_3) forms at temperature below 280 °C. Dennis et al. [21] visualized the impinging MMH–RFNA jets by using a high-speed camera and observed the RSS mode under certain conditions. However, the image qualities near the impinging point were still not high enough to confirm that phenomena similar to those of the Wang's model [20] occurred in the impinging region. Only limited experimental data on MMH–NTO, which is the mostly used combination for spacecraft, has been recently published. Yuan et al. [22] observed the unlike-impinging streams of MMH and NTO at atmospheric pressure and various mixture ratios. They suggested that the induction distances from the impinging point always exist from the impinging point to the ignition position. However, the photographs were not clear enough to discuss fluid and flame behaviors near the impinging point. Matsuura et al. [23] investigated the combustion stability of MMH–MON3 (NTO containing 3 wt% NO) impinging jets by changing the void fraction of MON3, and reported higher flame intensity as the two streams strongly impinged.

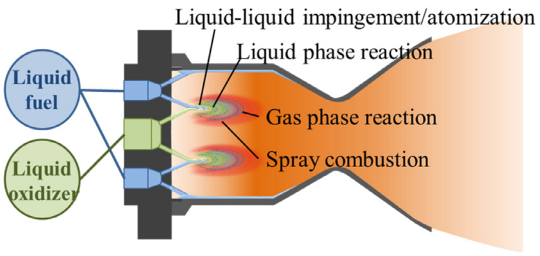

Fig. 1. Schematics of atomization and combustion in bipropellant thrusters with unlike-impinging type injection.

The present study aimed to obtain high-quality photographs of the MMH–MON3 impinging streams in order to explore the behaviors of liquid propellants and flames near the fuel-oxidizer interface. The correlation between such local phenomena and the combustion mode was also discussed. As the impinging jets with a practical unlike-impinging type element are not suited for visualization near the impinging points, another element that intentionally has less atomization performance by design was also used.

2. Experimental method

2.1. Unlike-impingement hot-fire apparatus

Two injector elements were used: one is the “practical-sized element” similar to the element of a practical thruster; the other is the “poor-atomization element” that was intentionally designed to perform worse atomization. Figure 3 and Table 1 show the configurations and dimensions of the elements, respectively. Table 2