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Catalytically promoted green fuel with hydrogen peroxide: Effect of hypergolic combustion on atomization and flow characteristics using impinging jets

Gabriel Silva Dias ^{a,b,*}, Fábio Antônio da Silva Mota ^{a,c}, Lihan Fei ^a, Mingyang Liu ^a, Chenglong Tang ^{a,*}, Fernando de Souza Costa ^b

^a State Key Laboratory of Multiphase Flows in Power Engineering, Xi'an Jiaotong University, Xi'an, Shanxi 710049, PR China
^b Combustion and Propulsion Laboratory, National Institute for Space Research (INPE), Cachoeira Paulista, São Paulo 12630-000, Brazil

^c Department of Aerospace Engineering, Federal University of ABC (UFABC), Santo Andre, São Paulo 09210-580, Brazil

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ABSTRACT

This study explores the jet impingement of a catalytically promoted hypergolic green fuel with High Test Peroxide (HTP). Experimental investigations were conducted using simultaneous high-speed visible, infrared and backlight imaging. Two major aspects were investigated. First, a study exploring the potential of decoupling the combustion phenomenon through the utilization of the fuel without a catalyst as a simulant, enabling a comparative analysis of the atomization process with the authentic hypergolic pair undergoing combustion. A Reynolds versus Weber numbers diagram was obtained for jets with equal momentum in the steady-state flow regime, and a novel breakup mode was observed. The named Reactive Foamy Segregation mode was found as a two phenomenological regime, where a reacting foam exists together with a segregation stream. An analysis of the liquid film velocity formed by impinging jets indicated that the hypergolic pair exhibited significantly lower speeds and corroborates with the introduced breakup mode. Second, an analysis about the transient and steady-state jet flow effects, revealing the existence of separate planes for the reacting foam and plumes, regions with different oxidizer to fuel ratios. This natural effect was intensified by the force generated from the exothermic reaction of hydrogen peroxide decomposition. Notably, the central region of the sheet exhibited the lowest temperature, indicating that the liquid-phase mixture and propellants' residence time were insufficiently effective in decomposing the peroxide. These findings contribute to a deeper understanding of the complex fluid dynamics involved in catalytically promoted hypergolic reactions applied in liquid rocket engines.

1. Introduction

Hydrazine-based fuels (monomethyl hydrazine — MMH, and unsymmetrical dimethyl hydrazine — UDMH) burning with Nitrogen Tetroxide (NTO), or the NTO/Nitric Oxide (NO) blends are well known hypergolic propellants that present high toxicity and can detonate. Several aspects of hypergolic combinations have been studied, including chemical kinetics, physical and chemical properties, stability, toxicity, storability, and propulsive parameters. In recent years, there has been increasing interest in green hypergolic propellants which exhibit lower toxicity and less environmental impact compared to conventional hypergolic propellants, especially with the use of High Test Peroxide (HTP) as an oxidizer [1–5]. Most studies on catalytically promoted green hypergolic fuels have focused on the development of new compounds and analysis of ignition performance using drop tests, where the ignition delay time (IDT) is determined along with combustion characteristics [1-3,6,7]. In hypergolic liquid propulsion systems, an impinging jets apparatus can be used to simulate conditions closer to real applications and can provide data related to atomization, vaporization, mixing, and combustion of propellants.

The fluid dynamics of non-reactive impinging jets, Newtonian or non-Newtonian, under different temperatures and under different configurations, is reported by many authors [8–10]. A pair of jets at

* Corresponding authors. *E-mail addresses:* gabriel.dias@inpe.br (G.S. Dias), chenglongtang@mail.xjtu.edu.cn (C. Tang).

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relatively low velocities impinging each other with the same jet momentum form a collision sheet in a plane perpendicular to the plane containing the momentum vectors of the jets. Waves are formed on the sheet surface and grow until the sheet is fragmented into ligaments at a certain breakup length. The ligaments eventually break up into droplets [8,11,12].

Compared to collision sheets of simulant propellants, collision sheets formed by hydrazine hypergolic propellants have received significantly less research attention recently [12,13], although it was widely studied in the past [14–16]. A few recent studies on liquid green hypergolic propulsion systems adopting HTP have conducted hot tests employing impinging jet injectors [4,17]. However, there is a lack of experimental and fundamental data regarding the formation and disintegration of hypergolic propellant sheets promoted by catalysts. This gap in the literature highlights the need for further research in this area for a better understanding of the atomization and burning processes of hypergolic propellants.

Understanding the atomization process of hypergolic propellants is challenging because the phenomenon is coupled with the liquid phase mixing reaction, followed by evaporation and subsequent ignition, as soon as the fuel ignition temperature is reached [18]. After ignition, the atomization process continues in the complex combustion environment.

This work employs a decoupling technique to study the atomization of hypergolic propellants. It uses HTP 85 wt% itself in both hot and cold tests, and a green fuel without a catalyst is used as a surrogate for cold tests. This ensures high similarity in density, viscosity, and surface tension properties with the real hypergolic pair (HTP/Fuel with catalyst), which is important for mimicking the sheet development and breakup process [19]. A remarkable characteristic of the employed fuel is its capacity to promote hypergolic reactions with as little as 1 wt% of catalyst. Additionally, it has similar theoretical performance compared to the highly toxic MMH/NTO, as evidenced by the density specific impulse of approximately 438 s g/cm³ and a specific impulse of 348.2 s [6].

Synchronized high-speed cameras were used to comparatively analyze the atomization of a catalyst-promoted hypergolic propellant to its non-reactive counterpart using a Reynolds (Re) versus Weber (We) diagram, followed by an analysis of velocities over the atomization field, and finally, an analysis of the reactive flow after ignition in different flow regimes is conducted.

2. Materials and methodology

2.1. Materials

In this work, an 85 wt% HTP solution was used as the oxidizer in both cold and hot tests. For the hot tests, the PAHyp0 fuel used in the present work is described by Mota et al. (2023) [6], composed of Tetramethylethylenediamine/Dimethylaminoethanol/ Methanol (TMEDA/DMEA/MeOH), 1:1:1 vol% with 1 wt% of CuCl₂·2H₂O as a catalyst. Two simulants were used for the fuel: one (S1) is a 93.2 wt% H₂O/MeOH solution, and the other (S2) is TMEDA/DMEA/MeOH (1:1:1 vol%), which differs from the fuel by removing the catalyst. Values of density, dynamic viscosity, and surface tension of the employed propellants and simulants, as well as the adopted acronym, are shown in Table 1.

The green fuel surrogate (S2) density was measured by using a calibrated volumetric glassware and an analytical balance. The dynamic viscosity was measured by a Lichen NDJ-5S viscometer and the surface tension was determined by the stalagmometric method [20].

2.2. Experimental apparatus

Two syringe pumps Lead Fluid model TYD02-01 were used to inject the propellants through Teflon 1/4'' tubes. Two injectors of 0.6 mm exit diameter and 6.67 length/exit diameter ratio were used to appropriately eject the propellants. The pre-impingement distance was 4 mm, and the impingement angle was 60°. A water-filled tank was used under the impingement point to collect products and non-burned material. To record backlight and visible images, a Phantom V2021 camera and a Phantom T3610 camera were used, respectively. The exposure time was adjusted for 1.5 µs for backlight and 50 µs for visible. The sample rate was set for 2000 frames per second for both cameras. A timeresolved infrared camera, InfraTec ImageIR8855hp, was set to 100 FPS, to analyze the sheet side view, as depicted in Fig. 1. Since the emissivity values and concentrations of all participating species along the mixing, ignition, and combustion processes were not accurately known, infrared imaging can only provide qualitative temperature information. In a combustion environment, when the temperature clearly exceeds the infrared camera upper limit (300 °C), only a qualitative temperature bar is provided. The hot tests were performed in open air during a short period of time with appropriate safety precautions.

During the experiments, the average value of 1.3 for the oxidizer to fuel ratio (O/F \approx 1.3) resulted from selecting the same jet momentum (*mv*) for both jets, $\dot{m}_f v_f / \dot{m}_o v_o = 1$, where \dot{m} is the jet mass flow rate, v is the jet velocity, the subscript f designates fuel or fuel simulant (surrogate), and the subscript o designates oxidizer. The average jet velocities of HTP, Fuel, S1, and S2, considering steady-state regime for a given jet momentum in millinewton, are depicted in Table 2. Detailed information about infusion and mass flow rates is given in *Supplementary material S1*.

A syringe pump, similarly to other infuse systems [23], takes a certain time to achieve its steady-state flow regime, and three regions can be distinguished, as depicted in Fig. 2. By using a DG645 delay generator connected to both syringe pumps, the experiments ensured a fuel lead infusion configuration, that means the fuel infusion was initiated firstly once the oxidizer infusion was delayed from 10 to 100 ms, as illustrated in Fig. 2. After a certain time, the two propellants are in steady-state flow rate, detectable by the constant maximum sheet width, and then, as the fuel injector was about to deliver the programmed volume, its flow rate started decreasing until zero.

The maximum relative uncertainties related to the measured quantities of density, dynamic viscosity and surface tension are $\pm 0.60\%$, $\pm 2.00\%$ and $\pm 0.50\%$, respectively. The calculated parameters mass flow rate, jet velocity, and jet momentum have relative uncertainties of $\pm 0.69\%$, $\pm 0.93\%$ and $\pm 1.16\%$, respectively. The uncertainties ultimately propagate to the dimensionless parameters, resulting in $\pm 2.02\%$ and $\pm 2.29\%$ for Weber and Reynolds numbers, respectively.

2.3. Atomization field velocity by imaging

In conventional Particle Image Velocimetry (PIV) methods, particles are seeded to the flow and lasers sources are applied for measurement of field velocities in turbulent flows and flames [24]. Schlieren and Shadowgraphy are low-cost methods that can also yield good velocimetry results, especially in non-reactive sprays [25]. However, as far as the authors know, this is the first time that an attempt has been made to perform velocimetry analysis in sprays where, due to the evaporation and combustion process, the particles are decreasing in size until their complete burning.

In the present experimental study, backlight visible imaging was employed to differentiate the droplets, ligaments, and liquid sheet from the background. On steady-state regime, the droplets and ligaments served as the main traceable particles for the open-source code PIVlab [26]. No particles were seeded to the flow.

At least one hundred sequential images were employed to determine the field atomization velocity, for both non-hypergolic and hypergolic

Table 1

Properties of	f	simulant	and	l propel	lants.
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Acronym — Simulant/Propellant	Density [kg/m ³]	Dynamic viscosity [mPa s]	Surface tension [mN/m]	Ref.
HTP — HTP 85 wt% solution	1370	1.26	79	[21]
Fuel — Green Fuel PAHyp0	830	1.45	24	[6]
S1 — Ethanol/water 93.2 wt% solution	820	1.60	23	[22]
S2 — Green Fuel PAHyp0 surrogate	820	1.31	23	-

Table	2
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Test conditions for different jet momentum (*mv*). Jet velocities in [m/s].

<i>mv</i> [mN]	v_{HTP}	v_{Fuel}	$v_{S1=S2}$
0.79	1.43	1.83	1.84
1.58	2.02	2.59	2.61
3.15	2.85	3.67	3.69
6.30	4.03	5.18	5.21
12.60	5.70	7.33	7.33



Fig. 1. Workbench.

pairs. The analyzed images were 720×720 pixels, with a scale of 20 pixels/mm. The interrogation window was set to 120 pixels, with horizontal and vertical offsets of 60 pixels. Uncertainties related to the referenced technique are discussed in Wieneke's (2015) work [27].

3. Results

This section is divided into three main subsections. In the first subsection, the analysis focuses on the impingement outcome of S1 and S2 (surrogates) with HTP, without hypergolic ignition. In the second subsection, a comparison is made in terms of sheet breakup analysis and sheet velocity between HTP/S2 and the hypergolic pair HTP/Fuel. In the last subsection, only HTP/Fuel hot tests are analyzed.

3.1. Outcome of non-hypergolic HTP/S1 and HTP/S2 pairs

The outcomes of both non-hypergolic pairs, HTP/S1 and HTP/S2, considering transient and steady-state flow regimes are shown in Fig. 3 for the 12.6 mN experimental jet condition.

Given the similarity between S1 and S2 in terms of density and surface tension (Table 1), the differences rely on dynamic viscosity. It is well known that viscosity plays a crucial role in the atomization process; the higher the viscosity, the more difficult and delayed the breakup process. In this sense, as S2 has lower viscosity, it was supposed to atomize more easily if a pair of S2 jets were compared to a pair of S1 jets. However, driven by propulsion applications, this work adopts the impingement of two different fluids (oxidizer and fuel/simulants).

It was experimentally observed, as shown in Fig. 4, that the outcome of HTP/S2 impingement presented significant heat release. Liu et al.



Fig. 2. Schematic of different flow regimes and experimental mass flow rate ranges, with transient flow regimes in regions 1 and 3 and steady-state flow regime in region 2.



Fig. 3. Sheet front view of non-hypergolic pairs HTP/S1 and HTP/S2, both in transient and steady-state flow regimes, inv = 12.6 mN.

(2023) [28], reported different effects of temperature on atomization characteristics, depending on fluid viscosity and flow rates. The experimental observed increase in temperature is an indication of a chemical reaction, with subsequent formation of new chemical substances. The authors believe that, once there are no bubbles in Fig. 3, the most probable chemical reaction is the primary oxidation of TMEDA by HTP, forming some oxidized intermediates, releasing heat and with no detectable gas products. As the new and transient substance has unknown physical properties, the atomization process of reacting HTP/Simulants is difficult to predict.

Sequenced images of the steady-state regime were analyzed using ImageJ algorithms [29] to create average atomization field images. As a result, for low values of jet momentum, the maximum film width reached 3.49 mm and 2.85 mm for HTP/S1 and HTP/S2, respectively. Additionally, the breakup length was tracked for 50 ms at higher jet momentum, resulting in average values of 14.75 mm for HTP/S1 and 9.13 mm for HTP/S2. The overall analysis indicates that, despite



Fig. 4. Sheet side view of non-hypergolic pairs with $\dot{m}v = 6.3$ mN: (a) HTP/S1 and (b) HTP/S2, with significant heat release.

HTP/S1 having a larger maximum width for low We and Re, the HTP/S2 film is slightly more advanced in the breakup regime for a given jet momentum. More information about batch image processing and breakup analysis is provided in *Supplementary material S2*.

The authors believe that, given the feasibility and the good match in physical properties, using real fuel to create a simulant (surrogate) by removing the catalyst is the best option for studying the atomization process of hypergolic propellants. Besides that, hypergolic reaction promoted by the catalyst is the only configuration that allows this option. The next section takes advantage of this feature, decoupling the combustion process in order to analyze the atomization/breakup of hypergolic propellants sheets promoted by a catalyst.

3.2. Comparison between non-hypergolic and hypergolic collision sheets

3.2.1. Breakup regimes

Reynolds (Re) and Weber (We) are important dimensionless numbers in fluid dynamics; they relate inertia to viscous forces and inertia to surface tension forces, respectively. Fig. 5 depicts Re versus We for a relatively low value range. All the pictures in Fig. 5 were taken in steady-state flow regime (region 2 on Fig. 2). For the hypergolic pair (HTP/Fuel), steady-stage was reached after ignition, i.e., in a combustion environment. Backlight imaging suppressed the visible flames, making the sheet analysis possible.

Analyzing the non-hypergolic sheet for a certain jet momentum and comparing to the hypergolic sheet in the same condition, the hypergolic reaction accelerates the atomization process, as already mentioned in literature [18].

A new breakup regime is proposed for catalytic hypergolic propellants: the Reactive Foamy Segregation regime (RFS). It is a two phenomenological regime, where a reacting foam exists together with a segregation stream. This regime was found in the hypergolic propellant sheets while the non-hypergolic collision sheets showed a closed rim regime and a transition to an open rim regime, where surface tension forces are in a certain equilibrium with inertial forces. However, due to hydrodynamic instabilities, small droplets appear at the non-hypergolic sheet edge. This mode is absent in the hypergolic sheet, since its edge is taken over by a reacting foamy region, resulting from the liquid phase interaction between the HTP and the catalyst present in the fuel. Besides that, while the non-hypergolic sheets under low Re and We values are mostly contained in a plane, the hypergolic ones showed a segregated stream, as depicted in Fig. 6. In other words, in a side view, a reacting foam appears close to the bisector line, and a segregated stream is formed, inclined on the fuel jet injection side (Fig. 6). It is possible to imply that the expelling force due the exothermic decomposition of HTP is stronger than the aggregating surface tension force, causing segregation.

Previous studies indicated penetration, well-mixed and separation regimes as a function of jet velocity, impingement angle and chamber pressure, using hydrazine as fuel [14–16,30]. In the case of RFS, the HTP concentration is probably also a sensible parameter to be explored.

The rimless mode for the non-hypergolic pair takes place with intermediate values of Re and We. The sheet becomes relatively unstable with formation of holes and appearance of sudden sheet disintegration, indicating a transition to wave regime, together with a larger number of droplets on the sheet side, while for the hypergolic propellants at the same injection condition just a few detached reacting foams were present ($\dot{m}v = 6.3$ mN).

The wave regime occurs in the higher Re and We value for the nonhypergolic pair while for the hypergolic counterpart the wave regime appears earlier, for intermediate values of Re and We. The flow in the collision sheet becomes turbulent, due to the more intense impact waves. The ligaments and the reacting foams in this regime present a round shape, surrounding the unstable liquid sheet. On the wave regime, the reacting foam is not the dominant breakup mechanism anymore, once they are already detached from the rim at a shorter breakup length, as shown in Fig. 7.

The IDT for the hypergolic HTP/Fuel case is also shown in Fig. 5. A plateau of around 32.5 ms was observed for *mv* values ranging from 0.79 mN to 6.30 mN, while for mv = 12.6 mN, a higher average value of 56.5 ms was reached. In hypergolic ignition events, the first portion of mass exiting the injectors, which occurs in a highly transient flow condition, matters. Given a hypergolic pair being experimented with by an impinging jets apparatus, it is believed that two main parameters contribute to IDT: the contact residence time between the propellants and the level of mixing. Whether a high residence time would be desirable for sufficient local heat release, leading to higher evaporation rates and subsequent ignition, such a condition would be easily reached with a relatively low jet velocity, which in turn would lead to poor mixing. It is expected that an optimum balance between the two parameters would lead to the lowest IDT value. Naturally, HTP solution concentration also plays a role in IDT. A decrease in IDT from 32.5 ms to 14.8 ms on average was observed when the HTP concentration was increased from 85 wt% to 93 wt%. Data with both HTP concentrations is given in Supplementary material S3.

3.2.2. Velocity field in the atomization region

Fig. 8 shows the atomization velocity field from the experimental case shown in Fig. 7.

As the analysis was made under steady-state flow regime (Fig. 2), the HTP, Fuel and S2 jet momenta are expected to be the same, leading to a sheet formed in a plane parallel to the camera field of view plane. Is important to mention that the adopted analysis has no means to properly count particles with spatial (3D) movements. However, by adopting the same jet momenta configuration and considering the impinging jets nature, the spray particles (ligaments and droplets) that originate from the liquid sheet are expected to have mostly 2D movement, with exception from the particles moving through RFS, in the hypergolic case. The maximum velocity for the non-hypergolic pair was around 5 m/s in the center-line position downstream the impingement point, while for the hypergolic propellants the maximum was around 4 m/s in a more disperse region near the impingement point.

Atomization of non-reactive fluids is already a complex phenomenon, with aggregative and disruptive forces competition, where the velocity fields of sheet and subsequent droplets are still studied nowadays. The velocity field shown in Fig. 8a is a result of the aforementioned complex phenomena added by the complication factor



Fig. 5. Reynolds versus Weber breakup regimes diagram for hypergolic and non-hypergolic pairs based on HTP jet properties. Ignition Delay Times (IDT) are indicated. Please refer to Supplementary material S3 for lower IDT values corresponding to a higher HTP solution.



Fig. 6. Segregated stream phenomena by (a) Infrared camera, \dot{mv} 0.79 mN and (b) Visible camera, \dot{mv} 1.58 mN.



Non-Hypergolic - HTP/S2 Hypergolic - HTP/Fuel

Fig. 7. Ligaments and reacting foam of non-hypergolic and hypergolic pairs under wave breakup regime, $\dot{m}v$ 12.6 mN.



Fig. 8. Atomization field velocity of (a) HTP/S2 and (b) HTP/Fuel. Both for mv = 12.6 mN.

of liquid-phase mixing followed by chemical reaction (detected by heat release, Fig. 4), originating new chemicals formation. An even more complex environment is shown in Fig. 8b, with liquid mixing followed by evaporation and combustion, where the atomization process takes place in an ambient with combustion product gases, intermediate species and gradient pressures.

In the hypergolic case, the gas expansion of reaction products plays a role in atomization process. The gas expansion probably affects the velocity of the still liquid ligaments and droplets in the spray by creating pressure gradients. The pressure gradients may decelerate or accelerate particles to all directions (x, y and z). However, it was observed that the hypergolic atomization field under steady-state flow seems to be confined in a central plane (Fig. 10) for the experimental case of 12.6 mN, unlike the case with a jet momentum of 1.58 mN, where a RFS takes place (Fig. 6).

The aforementioned observation led the authors to assume that the deceleration of the HTP/Fuel atomization field compared to HTP/S2,



Fig. 9. Dimensionless velocity over a center-line for different jet momentum (*mv*), for both hypergolic (HTP/Fuel) and non-hypergolic (HTP/S2) pairs.

specifically in the case of 12.6 mN (without RFS), is due to an additional drag force produced by the evaporation process of reacting/foamy droplets and ligaments. This deceleration is possibly added by deceleration caused by a complex gradient pressure field. Fig. 9 shows a graph of dimensionless velocity as function of dimensionless distance from the jet impingement point. The obtained velocity fields were used to extract a velocity-over-line parameter, V_{PIV} , located in the center of the velocity field, aligned to the impingement point (the line of higher velocity). The V_{PIV} was non-dimensionalized by the HTP jet velocity, $v_{j,HTP}$. The distance from the impingement point, D_{IP} was non-dimensionalized by jet diameter, d. In the dimensionless analysis, the HTP/S2 cases showed similar velocity profiles, while the hypergolic HTP/Fuel velocity profiles differ in respect to the breakup regimes proposed in the previous section. Considering the hypergolic HTP/Fuel case, the lowest *mv* presented RFS and a shorter evaporation distance, as a consequence, its velocity along center-line decreased.

In the transition, when inv = 3.15 mN, the velocity profile reached its maximum at a longer distance from the impingement point. It was noted by imaging analysis that the inv = 3.15 mN case also presented longer breakup distance. The velocity after the breakup length seemed to decrease for all hypergolic cases, probably due to an absent liquid sheet driving force acting downstream, together with an increase in drag due to an accelerated evaporation process, once the recently detached particles have more available area to evaporate. The slope change in velocity profile for hypergolics cannot be considered as a measurement of breakup length, but is related, due to the decrease in velocity after foam detachment.

Once the wave regime was reached ($\dot{mv} = 12.6$ mN), the velocity profile of HTP/S2 is similar to the HTP/Fuel, just differentiated by a velocity decrease.

3.3. Impinging jets of hypergolic propellants under different flow regimes

In this section, a single shoot experiment is analyzed under three different flow regimes (Fig. 2).



Fig. 10. Synchronized images of hypergolic reaction under different flow regimes, mv = 12.6 mN. Please see Supplementary material S4.

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Declaration of competing interest

The flow regime 1 took place at the shoot beginning, still in a transient state. After ignition, two planes were observed, as depicted on the schematic of Fig. 10. Slightly different from the result in Section 3.2.1, where the segregation stream was observed in steady-state regime, the phenomenon in this section is believed to be an intensification of the existing separation stream of non-reactive impinging jets, caused by the transient difference in jet momentum, added by the effect of the segregation stream phenomenon described in Section 3.2.1. The plume dispersed around the center-line, observed in backlight imaging, is believed to be formed mostly by fuel, due to the momentarily higher jet fuel inertia (fuel lead configuration), leading to an O/F < 1.3 region. As a consequence, the region named reacting foam has O/F ratio closer to stoichiometry, which may lead to a higher temperature comparing to the plume region. The visible image in Fig. 10 (flow region 1) corroborates the description given to this phenomenon, as the plume around the center-line takes longer to burn, probably due to poor mixing and poor atomization, leading to large fuel droplets.

In the flow regime 2, both fuel and HTP jets are in steady state, an optimum mixture is achieved. No plume region was observed, as all regions on the sheet seems to be evaporating equally.

In flow regime 3, when the fuel jet was decreasing its volume flow rate, a plume appeared on the edges instead of the center-line. By analyzing the images, the most probable explanation is that the plume is again composed mostly by fuel (O/F < 1.3). Differences in jet inertia, together with reactive stream separation, plays a role here, as in flow regime 1.

The central HTP/Fuel hypergolic sheet region, especially for the higher jet momentum, was similar to non-hypergolic pairs. This similarity indicates that the propellants' residence time was not sufficient to lead to significant HTP decomposition. Significant chemical reactions only occurred at the edge of the sheet, detectable by the formation of foam. For that reason, a lower temperature is expected in the inner sheet region compared to the reacting foam.

4. Conclusion

Hypergolic collision sheets formed by the jet impingement of a catalytically promoted green fuel with hydrogen peroxide were experimentally studied and compared to non-hypergolic sheets by simultaneous high-speed visible, infrared and backlight imaging analysis. The possibility of decoupling the combustion phenomenon by using the fuel without catalyst as a simulant was explored, allowing interesting comparative analysis of the atomization process with the real hypergolic pair involving combustion. A Reynolds versus Weber diagram for impinging jets with equal momentum was obtained and a new breakup mode for catalytic promoted hypergolic propellants was identified: the Reactive Foamy Segregation, corroborated by the dimensionless velocity analysis. The effects of transient and steadystate jet flows were also analyzed. It was found that in the transient flow regime, the reacting foam and plume exist in separate planes, a natural effect intensified by the force caused by the exothermic reaction of hydrogen peroxide decomposition. In the steady-state regime, good mixing resulted in similar evaporation across the sheet, except for the center region closest to the impingement point. In this region, the liquid-phase mixing and residence time of propellants were not sufficiently effective in decomposing the hydrogen peroxide.

CRediT authorship contribution statement

Gabriel Silva Dias: Designed research, Collected data, Performed research, Analyzed data, Wrote the paper. Fábio Antônio da Silva Mota: Designed research, Collected data, Performed research, Analyzed data, Revised the paper. Lihan Fei: Designed research, Analyzed data, Revised the paper. Mingyang Liu: Collected data. Chenglong Tang: Designed research, Analyzed data. Fernando de Souza Costa: Analyzed data, Revised the paper.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Please see Supplementary materials S1, S2, S3, and S4.

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