

Decomposition of Ionic Liquid Ferrofluids for Multi-Mode Spacecraft Propulsion

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Ionic liquid ferrofluids based on mixtures of [Emim][EtSO₄] and [Bmim][NO₃] fuels and hydroxylammonium nitrate oxidizer were synthesized by adding iron oxide nanoparticles. The resulting propellants were then tested for decomposition capability. Spot plate testing indicated that the temperature required to initiate rapid decomposition dropped from 115 °C to 75 °C with a 30% by weight addition of iron oxide for the [Bmim][NO₃] propellant. Adding more iron oxide resulted in an increase in onset temperature. The [Emim][EtSO₄] propellant had a much lower decrease in onset temperature, bottoming out at 90 °C. Batch reactor tests under vacuum showed that 10% addition of iron oxide results in the greatest increase in decomposition rate for both propellants. Since most ionic liquid ferrofluids do not exhibit the Rosensweig instability below 50% iron oxide by weight, it is unlikely this will be of use in a multi-mode system. However, adding a small amount of iron oxide to ionic liquid monopropellants could be beneficial as it will reduce power requirements, while only reducing specific impulse by roughly 2.5%.

I. Introduction

MULTI-mode spacecraft propulsion systems utilizing a high-thrust chemical monopropellant thruster in combination with a high-specific impulse electric electro-spray thruster have the potential to greatly improve spacecraft mission flexibility. The greatest gain in mission flexibility would be a system that utilizes a single propellant for both monopropellant and electro-spray modes.^{1,2} The challenge is then to identify propellants that offer acceptable performance and successful operation in both modes. Previous research has identified several ionic liquids or mixtures of ionic liquids that theoretically can achieve high performance in both modes.^{3,4} Work presented in this paper extends the previous work on ionic liquid multi-mode propellants to ionic liquid ferrofluids, which have the potential to reduce system hardware complexity and power requirements in both chemical and electro-spray propulsive modes.

The benefit of a multi-mode propulsion system is increased spacecraft mission flexibility through the availability of both high-thrust and high-specific impulse modes, enabling a large mission design space.^{1,2,5,6} This technology has the potential to allow for greater changes to the mission plan during the mission as needs arise since a variety of maneuvers are possible using the same propulsion system. A multi-mode system utilizing a single ionic liquid propellant for both chemical monopropellant or bipropellant propulsion and electric electro-spray propulsion has been shown to be a potentially beneficial type of multi-mode system, as it could function well in both modes. Further, results have shown that a dual-mode system with shared hardware and propellant still provides better propellant utilization and enhanced mission flexibility even if each mode does not perform as well as the current state-of-the-art in each mode considered separately.^{2,6} Furthermore, the most flexible configuration includes a monopropellant thruster, as utilization of a bipropellant thruster in this type of system would inherently lead to unused mass of stored oxidizer since some of the fuel is used for the electrical mode.

Ionic liquids are essentially salts that maintain liquid state at room temperature or even well below room temperature. Ionic liquids have garnered more attention over the last decade due to their potential application as environmentally benign industrial solvents.⁷ While they are considered environmentally benign, recent

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investigations have shown certain ionic liquids undergo autoignition as they approach decomposition temperature.⁸ Furthermore, current research has aimed at synthesizing and investigating ionic liquids as potential propellants and explosives.^{9, 10} This opens the possibility of utilizing ionic liquids as an earth-storable spacecraft chemical propellant.

Typically, hydrazine has been employed as a spacecraft monopropellant because it is earth-storable and easily decomposed to give good propulsion performance.¹¹ Because it is also highly toxic, recent efforts have focused on finding an alternative “green” monopropellant. Binary or ternary mixtures including the energetic salts hydroxylammonium nitrate (HAN), ammonium dinitramide (ADN), or hydrazinium nitroformate (HNF) have been proposed as potential replacements.¹²⁻¹⁶ Since all of these ionic compounds have melting points above room temperature, they are typically stored as an aqueous solution. A compatible fuel component such as methanol, glycerol, or triethanolammonium nitrate (TEAN) is typically also added to provide increased performance.

Imidazole-based ionic liquids are of particular interest to this study due to their already proven electro-spray capabilities. The ionic liquid 1-ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ([Emim][Tf₂N]), or [Emim][Im]) represents the propellant planned to be used in a future colloid, or electro-spray, thruster flight application.¹⁷ Due to their favorable electrochemical properties, several other imidazole-based ionic liquids are currently the subject of research in the field of electro-spray propulsion.¹⁸ Previous research has shown that these types of ionic liquids will not perform well as monopropellants due to the large amount of carbon contained within their cation. However, considering the heavy ionic liquids as a fuel component in a binary mixture with an oxidizing salt, such as HAN, shows promise as a monopropellant. This may offer high performance as both a monopropellant and electro-spray propellant if the favorable electrochemical properties are retained along with the high molecular weight of the mixture.³ Additionally, previous research has shown that these mixtures are stable at room temperature and may be decomposed catalytically or thermally.¹⁹

Ignition is a transient process in which reactants are rapidly transitioned to self-sustained combustion via some external stimulus. Nonspontaneously ignitable propellants, such as monopropellants, must be ignited by some external means before self-sustained decomposition or combustion can begin. For practical applications, the amount of energy needed to provide ignition must be minimal, and the ignition delay time should be small.¹¹ The most reliable methods of monopropellant ignition on spacecraft include thermal and catalytic ignition, in which the monopropellant is sprayed onto a heated surface or catalyst. Hydrazine monopropellant is typically ignited via decomposition by the commercially manufactured iridium-based catalyst S-405. For optimum performance, the catalyst bed is typically heated up to 200°C, but can be ‘cold-started’ with no preheat in emergency situations.¹¹ The Swedish ADN-based monopropellant blends require a catalyst bed preheat of 200°C. They cannot be cold-started, which is a major limitation presently.¹⁶ Additionally, recent efforts have placed greater emphasis on smaller satellites, including cubesats.²⁰ Since these satellites must be small in both volume and mass, any additional mass imposed by the propulsion system heating or power requirements is especially disadvantageous.

Recent efforts have focused on reducing the propulsion system complexity and thus overall mass and volume for small satellite propulsion systems. For the electro-spray system, efforts have included reducing or simplifying the emitter hardware. Meyer, et. al. have investigated ionic liquid ferrofluids as means of eliminating the need for emitter hardware entirely.^{21, 22} This was accomplished by adding iron oxide nanoparticles to ionic liquids such as [Emim][Tf₂N] that have been used previously for electro-spray propulsion. The iron oxide nanoparticles create what is known as a ferrofluid, which when exposed to a magnetic field creates the so-called Rosensweig instability that functions as self-forming emitter tips in the liquid itself. Particularly intriguing from a multi-mode propellant perspective is that iron oxide has been used as a catalyst in solid rocket motors, including those using ammonium perchlorate, which is an ionic compound.¹¹ If then the iron oxide could function both as an enabler of the Rosensweig instability formed electro-spray emitter tips as well as a catalyst for thermally induced or catalytically induced chemical propulsion, it would be beneficial in both modes of a multi-mode propulsion system.

The following sections present an experiment to assess the thermal or catalytic ignition feasibility of imidazole-based ionic liquid ferrofluid monopropellants. Specifically, iron oxide particles were added to two propellants we have synthesized in a previous study,¹⁹ and their effect on chemical decomposition was quantified. This was done by studying the decomposition of propellants injected onto preheated catalyst material. Section II describes the experimental setup used in this study as well as the propellants. Section III describes results of the experiments. Section IV presents a discussion of the results. Section V presents the conclusions.

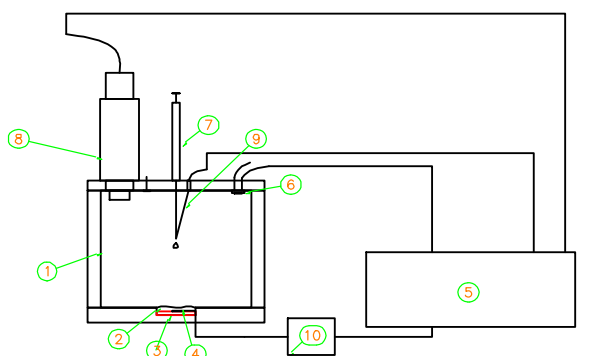
II. Experimental Setup

The role of the igniter in operation of a monopropellant rocket engine is to provide an initial pressurization of the thrust chamber such that self-sustained decomposition, and subsequent combustion, can begin. Ideally the igniter

provides a short ignition delay with minimal preheat temperature so that less power is required from on-board power systems. Our experiment is designed to provide quantitative measurements of ignition delay and pressure rise characteristics for monopropellants injected onto a heated surface or catalyst acting as the igniter. A variety of setups have been employed in other studies,²³ but a micro-reactor was selected because it provides the most robust analysis. This type of setup does not capture the actual ignition delay times and pressure rises that can be achieved through careful catalyst bed design in actual thrusters, nor does it determine if the decomposition results in self-sustained combustion. The goal of these experiments is to determine if the propellants can be decomposed readily and which catalyst materials are most effective in doing so. This setup provides a means of comparison of the ignition capabilities of already proven, high-performance monopropellants, and represents the first step in verification of reaction initiation prior to more expensive and time consuming thruster testing.

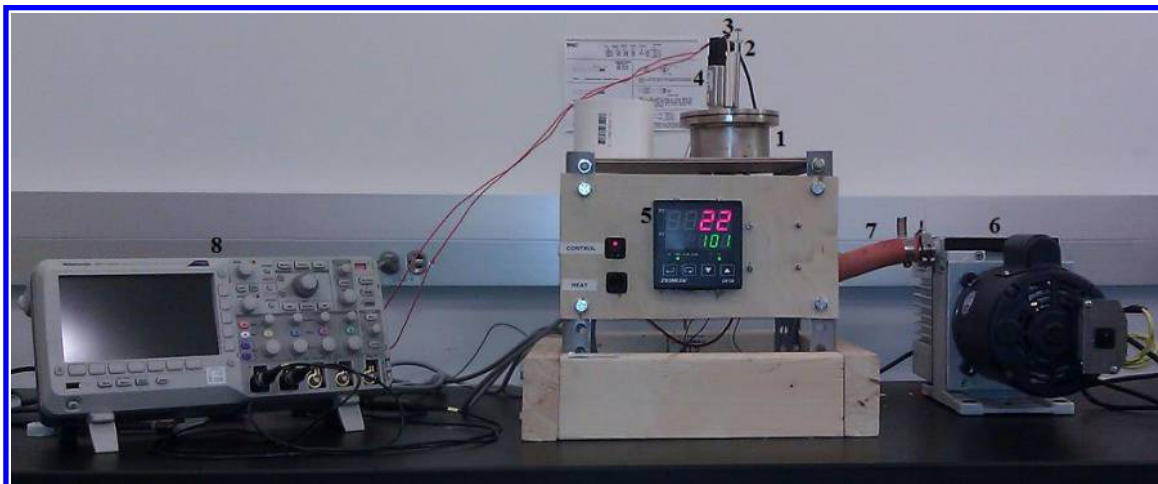
A. Experimental Setup

The experimental setup is a micro-reactor for study of thermal and catalytic decomposition based on previous designs, as is the same one used in the previous study on multi-mode ionic liquid propellants.^{15, 19, 24} The reactor vessel itself consists of a stainless steel tube with stainless steel plates for the bottom and top plates of the reactor. The total internal volume of the reactor is 440 mL. The bottom plate has a 1" by 1" square machined to a depth of 1/4" to accommodate the thermal and catalyst bed. The catalyst bed consists of a small stainless steel plate on top of a Kapton heating element capable of reaching preheat temperatures up to 232°C. A catalyst can be placed on the bed or left empty to evaluate thermal ignition. A type-K thermocouple is used to monitor the bed preheat temperature, as well as the catalyst bed temperature during the ignition process. A process controller is used to set preheat temperatures. The top plate is removable and contains the majority of the instrumentation. An o-ring groove accommodates a proper static seal when the top plate is bolted to the reactor. A stainless steel, fast response (2 ms typical) pressure transducer capable of 0-2.5 bar pressure measurements is located on the top plate. This is used to evaluate pressure rise and ignition delays for each propellant-catalyst combination. Additionally, a type-K thermocouple is secured to the top plate to monitor the internal atmosphere temperature. A photodiode of 400-1100 nm measurement range is also located on the top of the plate. It is used as redundancy in the ignition verification and delay measurement and may provide a measure of ignition delay more accurate than solely the pressure transducer. An oscilloscope is used to monitor all of the aforementioned instrumentation and record the data. Finally, a mechanical pump is used to create a vacuum in the reactor to a pressure of roughly 10^{-2} torr. The entire experimental setup is shown in Figs. 1 and 2.



1 Reactor	5 Oscilloscope	8 Pressure transducer
2 Catalyst Bed	6 Photodiode	9 Liquid sensor
3 Resistance Heater	7 Microsyringe	10 Temperature controller
4 Thermocouple		

Fig. 1 Instrumentation schematic.



1 Reactor	4 Pressure transducer	7 Vacuum hose
2 Microsyringe	5 Temperature controller	8 Oscilloscope
3 Liquid sensor	6 Vacuum pump	

Fig. 2 Photograph of the entire experimental setup with numbered components.

The feed system of the micro-reactor is a 100 μL Hamilton micro syringe. To evaluate ignition delay, the precise moment at which propellant is introduced into the reactor must be known. This is accomplished through a custom-designed liquid probe, shown in Fig. 5. The probe consists of a piece of copper wire and a separate electrical connection to the syringe needle. The copper wire is bent and carefully positioned so that when propellant is introduced through the syringe, its viscosity causes it to form a droplet between the tip of the syringe and the wire. When the propellant leaves the tip of the syringe, it opens a circuit between the syringe needle and the probe wire. The circuit is capable of activating a 5 V relay with liquids of conductivity at minimum equal to pure water. Since all of the propellants tested are ionic liquids that are highly conductive, this is more than adequate. Finally, since the distance from needle tip to catalyst bed is known, the propellant density and volume are known, and the propellant is in a vacuum environment, the fall time can be easily calculated and subtracted from the overall ignition delay.

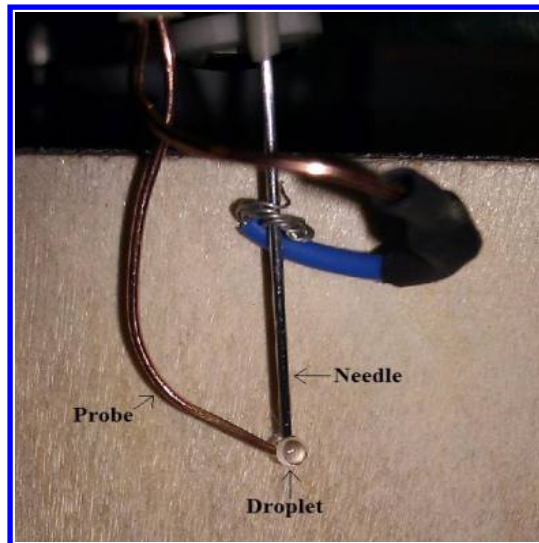


Fig. 3 Liquid probe.

B. Uncertainty Quantification

Uncertainty in the pressure measurements analyzed hereafter can be traced to two instruments: the pressure transducer and the microsyringe. According to the manufacturer's calibration data, the total uncertainty in the pressure measured by the transducer is ± 3 mbar. In terms of the microsyringe, the actual volume injected may vary from the intended value due to the fact that measurements are read directly from physical markings on the syringe. The smallest graduation is 1 μL , and it is therefore reasonable to assume a worst case scenario of ± 1 μL . This uncertainty is important in terms of the theoretical pressure rise calculations, since an exact volume is assumed. This translates into an error of ± 3 mbar in the theoretical calculations. The effect of both uncertainties on the conclusions will be discussed in a later section.

C. Propellants

The primary goal of this study is to quantify the effect of adding iron oxide particles to previously synthesized ionic liquid propellants on the thermal or catalytic decomposition characteristics of the propellant. The previously synthesized multi-mode specific propellants consist of hydroxylammonium nitrate (HAN) oxidizer mixed with either 1-butyl-3-methylimidazolium nitrate ([Bmim][NO₃]) or 1-ethyl-3-methylimidazolium ethyl sulfate ([Emim][EtSO₄]) in the mass ratios given in Table 1.¹⁹ These ratios were chosen based on the best compromise between both theoretical chemical and electrospray performance.³ The chemical structure of each ionic liquid used in this study is shown in Fig. 4. Three chemicals are therefore used in this study: [Bmim][NO₃] (≥ 95% purity, Sigma Aldrich), [Emim][EtSO₄] (≥ 95% purity, Sigma Aldrich), and HAN solution (24% wt. in H₂O, Sigma Aldrich). Solid HAN is produced by removing water from the 24% HAN solution at high vacuum (~10⁻⁵ torr) for 8h. [Bmim][NO₃] and [Emim][EtSO₄] are also exposed to vacuum for roughly 8 hours to remove any volatile impurities. Iron oxide nanoparticles (50-100nm, Sigma Aldrich) are then added to the propellants. Notationally, the mixture will be referred to in reference to the mass percent of iron oxide, i.e. a 50% iron oxide mixture means there is 50% iron oxide by weight and 50% of either Propellant A or Propellant B by weight.

The synthesis of these liquids was completed in two parts: the combining of the binary ionic liquids, and the addition of iron oxide particles. The [Bmim][NO₃] and [Emim][EtSO₄] ionic liquids and the HAN oxidizer were reduced in a vacuum chamber for 24 hours in order to boil off water and crystallize the HAN, then combined in the mass ratios according to Table 1. The mixtures were set to rest overnight to dissolve the HAN. These mixtures formed the base liquids for the ILFFs, and were the beginning mixtures for the spot plate testing. The mixtures were brought close to a magnet to see if they would exhibit the Rosensweig instability. The mixtures synthesized do not fully exhibit the Rosensweig instability, but this may be due to the overwhelming strength of the magnets used. Another possible cause to consider is the size of the particles used in this experiment. The particles have diameters of 50-100nm and are larger than the particles used in research for electrospray engines (~10 nm).²¹ However, the purpose of this experiment was to determine whether addition of iron oxide particles to the ionic liquid propellants would cause a reduction in the temperature required to start rapid decomposition. Consideration of the electrospray capabilities are beyond the scope of this study.

Table 1. Mass percent of fuel and oxidizer in binary HAN-IL mixtures.

Propellant	IL Fuel	%Fuel	%Oxidizer
A	[Bmim][NO ₃]	44	56
B	[Emim][EtSO ₄]	41	59

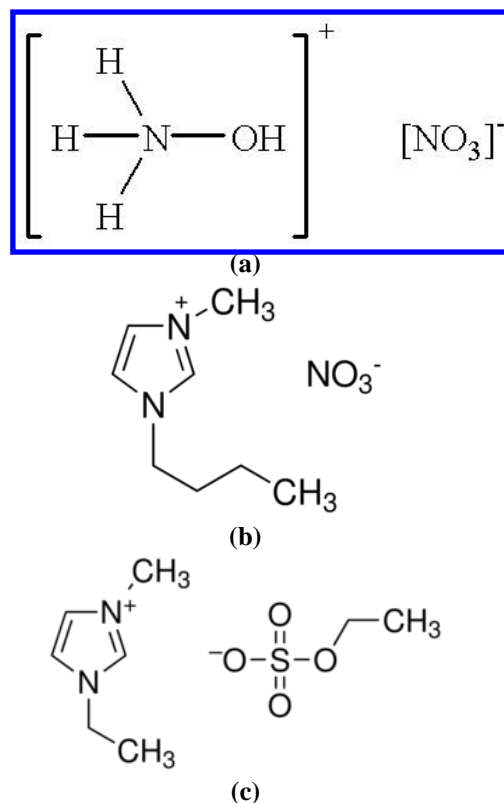


Fig. 4 Structural formula for a)HAN, b) [Bmim][NO₃], and c) [Emim][EtSO₄].

III. Results

Results in this section include theoretical performance calculations to determine the effect of iron oxide addition on the expected chemical thruster performance of the ionic liquid propellants. The ionic liquid ferrofluid mixtures are then spot plate tested in open atmosphere to gather qualitative data and ascertain relevant trends. Finally, the ionic liquid ferrofluids are tested in the batch reactor to quantitatively deduce the effects of iron oxide addition on the ionic liquid propellants.

A. Theoretical Performance of Ionic Liquid Ferrofluid Propellants

The NASA Chemical Equilibrium with Applications (CEA)²⁵ code is used to estimate the theoretical chemical performance of the monopropellants with iron oxide addition. The specific impulse is shown in Fig. 5, and the combustion products are shown in Fig. 6. For each calculation, a chamber pressure of 300 psi and expansion ratio of 50 is assumed. These represent values typical of chemical monopropellant spacecraft thrusters.²⁶ Fig. 5 shows that as

iron oxide is added to the propellant mixture, the theoretical specific impulse drops significantly, from about 260 seconds with no iron oxide to 170 seconds with 50% iron oxide. Both the propellant mixtures suffer decreases in specific impulses, ~15-16% decrease for 0-25% iron oxide, and at 25% iron oxide the specific impulse is 213 seconds for Propellant A and 205 seconds for Propellant B. However, the combustion temperature also decreases. At 25% iron oxide the combustion temperature decreases to roughly 1450 K. Fig. 6 shows that the product species do not change significantly, indicating that perhaps much of the iron oxide will not be consumed in the reaction, but may act more as a catalyst, as presumed.

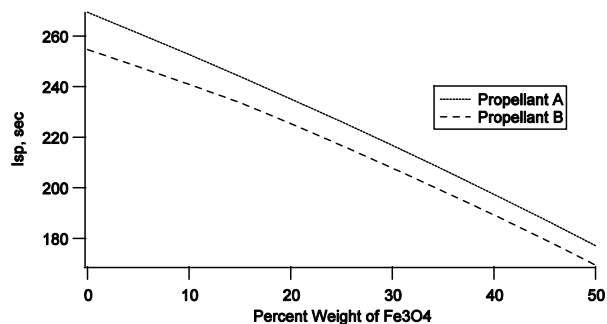


Fig. 5. Specific Impulse of Propellants as a Function of Percent Weight Iron Oxide.

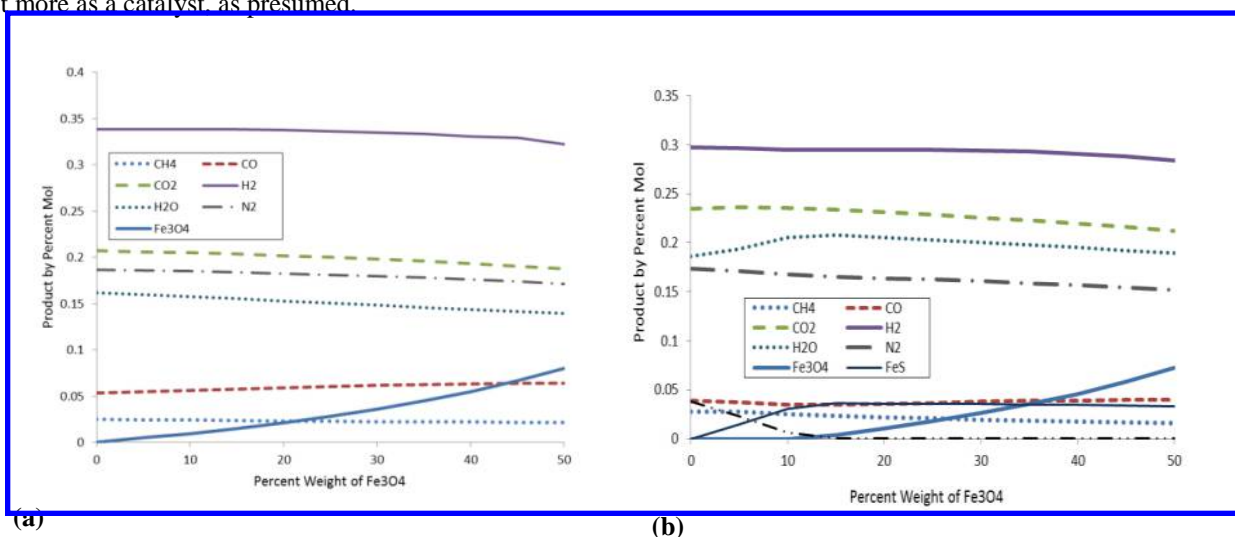


Fig. 6 Product Species Mole Fraction as a Function of Percent Weight Iron Oxide for a) Propellant A and b) Propellant B.

B. Spot Plate Test Results

The spot plate test was performed to establish if the ILFFs would decompose. A summary of all results is shown in Table 2. The onset temperature reported in the table is the temperature at which the propellant fully decomposed in less than about 5 seconds, with the event being initiated less than one second after propellant was injected onto the heated plate. Both Propellant A and Propellant B an onset temperature of about 115 °C without particles. Typically as the weight percent of iron oxide increased, the onset temperature decreased. Propellant A had a minimum onset temperature of 75 °C at 30% iron oxide and Propellant B had a minimum of 90 °C at 40% iron oxide. It became increasingly difficult to pick up the mixtures with the hypodermic needle at 50% iron oxide in Propellant A and at 40% iron oxide in Propellant B due to an increase in viscosity, so it was not possible to do spot plate testing at these weight percentages or above. Similar to previous results, decomposition of the propellants with no iron oxide addition left a yellow residue on the plate.¹⁹ However, propellants with iron oxide left a dark brown paste on the plate.

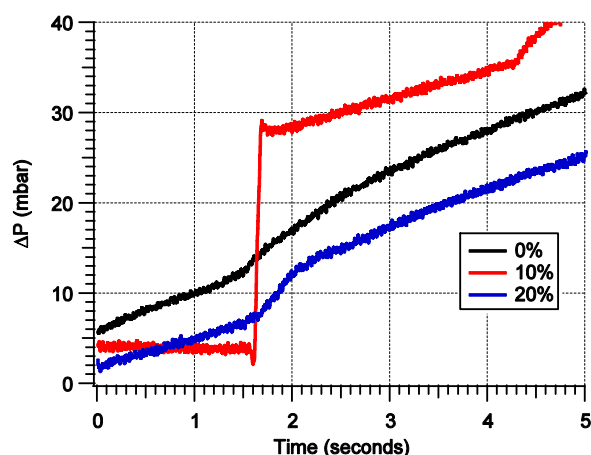
Table 2. Results of Spot Plate Tests.

<i>Propellant A</i>					
% Iron Oxide	0	10	20	30	40
Onset Temp, °C	115	90	80	75	85
Residue	yellow liquid	brown paste	brown paste	brown paste	brown paste
<i>Propellant B</i>					
% Iron Oxide	0	10	20	30	40
Onset Temp, °C	115	100	95	90	n/a
Residue	yellow liquid	brown paste	brown paste	brown paste	n/a

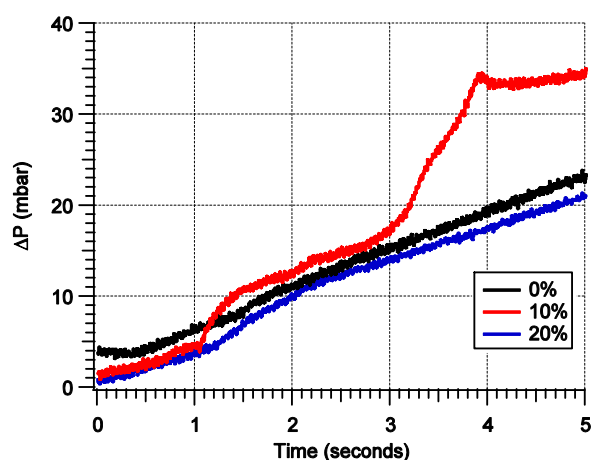
C. Batch Reactor Results

Pressure rise versus time from injection into the batch reactor and onto a heated plate was measured to quantitatively compare the rate of decomposition of the propellants. In each case, the volume of propellant injected was 30 μL . Testing was conducted starting at a 60°C preheat temperature, but no significant effects were observed until the temperature was raised to at least 120°C. Results at 120°C for Propellants A and B with iron oxide composition of 0%, 10%, and 20% are shown in Fig. 7. From the figure, when the propellants had 0% and 20% iron oxide a constant 4 mbar/s pressure rise was measured. Interestingly, when the propellants had 10% iron oxide increased activity was detected. After a 1.6 second delay, Propellant A decomposed rapidly at a rate of 120 mbar/s. Propellant B had a similar delay, but only decomposed at a rate of 30 mbar/s. Propellant B shows a second rapid pressure rise event at around 3 seconds. This will be discussed in a later section.

Results with a preheat of 160°C are shown in Fig. 8. Propellant A shows a rapid decomposition event almost immediately after injection onto the heated plate, with a pressure rise rate of 120 mbar/s for the case with no iron oxide. For the 10% and 20% iron oxide cases, the pressure rise rate is greater at roughly 220 mbar/s. The 10% iron oxide case has the highest pressure rise after initial injection of 24 mbar. Again, there are some secondary events at later times which will be addressed in the next section. Propellant B shows less intense activity than Propellant A. For the case of no iron oxide, there is a decomposition event after 0.4 seconds with a pressure rise rate of 80 mbar/s. The total pressure rise and pressure rise rate are roughly the same for the 10% iron oxide case, but occurs 1.1 seconds after injection. The case with 20% iron oxide has a longer delay and much less intense decomposition event, occurring at 1.6 seconds after injection with a pressure rise rate of 20 mbar/s.

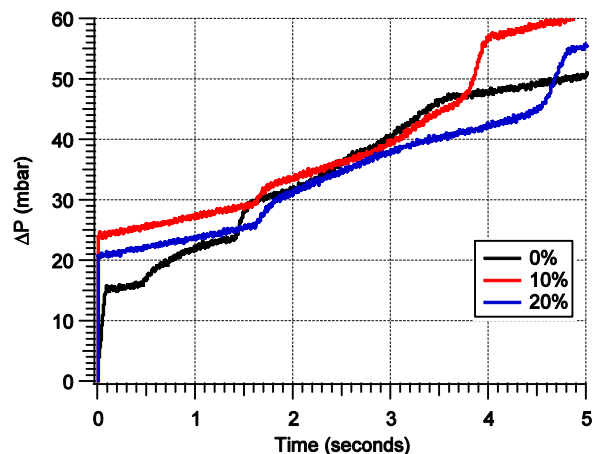


a)

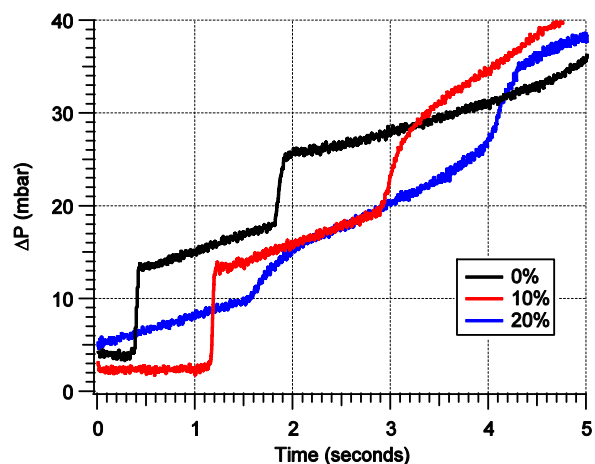


b)

Fig. 7. Pressure Rise Versus Time from Injection into Batch Reactor for a) Propellant A and b) Propellant B with 0, 10, and 20% Weight Iron Oxide on a 120°C Plate.



a)



b)

Fig. 8. Pressure Rise Versus Time from Injection into Batch Reactor for a) Propellant A and b) Propellant B with 0, 10, and 20% Weight Iron Oxide on a 160°C Plate.

IV. Discussion

Results indicate that adding iron oxide to the ionic liquid propellants does have an effect on the spot plate temperature required to achieve rapid decomposition. Spot plate testing indicates that as more iron oxide is added to the propellant mixture, the temperature at which rapid decomposition occurs decreases. These tests also indicate that there is a limit to this positive effect as the onset temperature for Propellant A decreased up to 30% iron oxide by weight, but then increased with additional iron oxide. The additional iron oxide content caused the onset temperature to decrease 13% more for Propellant A compared to Propellant B. This suggests that the benefit of adding iron oxide to ionic liquid propellants in terms of reduced decomposition onset temperature is dependant on the formulation of the propellant. It is unclear from these results whether the effect is due to additional HAN oxidizer content in Propellant B compared to Propellant A, or the difference in fuel choice. It is likely that the fuel choice plays a significant role since the difference in oxidizer content is only 3% by weight, but this should be investigated further. The residue post-decomposition is also notable in that the dark brown ‘paste’ seems to indicate that much of the iron oxide is not consumed in the reaction. This result is in agreement with and strengthens the predictions made by the chemical equilibrium calculations in Fig. 6.

The results of the batch reactor tests are less conclusive to the overall outlook, but some trends can be commented upon. At 120 °C preheat temperature, Propellant A exhibits a sharp decomposition event, but only for a

10% iron oxide mixture composition. This is interesting as the trend does not continue for mixtures above 10% iron oxide as was the case in spot plate testing. Rather, the minimum decomposition onset temperature appears to have moved to 10% iron oxide by weight rather than 30% by weight. This could perhaps be explained by the lack of oxygen in the atmosphere of the batch reactor compared to the open atmosphere spot plate testing. Iron oxide absorbs oxygen, so it is possible that during the decomposition the extra oxygen absorbed by the iron oxide could be a major contributor in the reaction. A similar trend is seen in the results for Propellant B at this temperature, but as seen in the previous research the rate of decomposition is much slower for the [Emim][EtSO₄] fuel.¹⁹ At 160 °C preheat temperature, the decomposition rate of Propellant A is virtually indistinguishable as a function of iron oxide content. This is likely due to the fact that, based on spot plate testing and results of tests at 120 °C, this is well past its onset temperature. Propellant B shows a more interesting trend. The rate of decomposition is virtually the same for no iron oxide content compared to 10% iron oxide by weight, but the delay is roughly one second longer. This suggests that the iron oxide content has decreased the thermal conductivity of the propellant since the reaction rate is the same, but the time required to achieve the onset temperature is increased. It should also be noted that the secondary events are essentially propellant leftover from the initial ‘burst’ of decomposition and are not repeatable or significant for analysis. This was discussed in detail in the previous research on ionic liquid propellant decomposition and for brevity is not included here.¹⁹

The fact that iron oxide decreases the onset temperature could benefit spacecraft monopropellants utilizing ionic liquid propellants. Since a lower preheat temperature will be required, less power will be required to operate the thruster. Since there seems to be the most significant benefit around 10% iron oxide composition by weight, the performance penalty is not that severe. As seen in Fig. 5 the performance (specific impulse) decrease is roughly 10 seconds (~6%). For systems where inert mass or volume reduction is especially important, this could result in a net reduction of mass for the entire system if the power requirements are such that the propellant mass penalty due to lower specific impulse is negated. This, of course, depends on the type of mission, satellite, thruster, and system architecture and full determination of this effect is beyond the scope of this study. For multi-mode systems, these results seem to indicate that ferrofluids may not be ideal because the chemical performance decreases significantly, and there does not appear to be a benefit to adding more than 10% iron oxide by weight, and most ionic liquid ferrofluids do not exhibit the Rosensweig instability at mixtures lower than 50% iron oxide by weight.

V. Conclusion

Ionic liquid ferrofluids were synthesized from ionic liquid propellants based on mixtures of fuels [Emim][EtSO₄] and [Bmim][NO₃] and HAN oxidizer by adding iron oxide. Spot plate testing indicates that the iron oxide effectively reduces the temperature required to initiate decomposition of the propellant. Additionally, the brown residue left over from the decomposition indicates that the iron oxide was not consumed in the reaction. Testing the propellants in a batch reactor showed that the benefit of reduced decomposition onset temperature peaks at roughly 10% iron oxide by weight. Because most ionic liquid ferrofluids do not exhibit the Rosensweig instability below 50% iron oxide by weight, their use in a multi-mode system involving a chemical monopropellant thruster and an electrospray thruster involving emission sites formed from the Rosensweig instability does not appear to be an ideal choice. However, adding iron oxide in small amounts to ionic liquid monopropellants could be beneficial as a reduction in decomposition temperature would also result in reduced thruster power requirements.

Acknowledgements

The authors would like to thank the Missouri Space Grant Consortium for partially funding this work.

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