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SELECTION OF IONIC LIQUIDS AND CHARACTERIZATION OF HYPERGOLICY WITH HYDROGEN PEROXIDE

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A theoretical screening and experimental characterization of the hypergolicy of different ionic liquids in combination with highly concentrated hydrogen peroxide was conducted. The aim of the investigation was to find a possible alternative hypergolic bipropellant, which substitutes the commonly used hypergolic propellant combinations of hydrazines and dinitrogen tetraoxide. Highly concentrated hydrogen peroxide was chosen as 'green' oxidizer, ionic liquids were chosen as alternative fuels. Ionic liquids offer very low vapor pressures compared to common fuels and this allows simplified handling procedures. The theoretical screening focused on commercially available ionic liquids. Criteria for the selection of ionic liquids included density, melting point, viscosity and theoretical performance calculations. By means of these results 1-butyl-3-methylimidazolium acetate (BMIM Ac) was chosen for further investigation. Pure BMIM Ac was tested with the so-called drop test method and did not show a hypergolic behavior with hydrogen peroxide. Hence catalytic transition metals like acetate salts were dissolved in the ionic liquid . With different concentrations of copper (II) acetate hypergolic ignition was archived. The ignition delay time is in the order of several 100 milliseconds.

KEY WORDS: *hydrogen peroxide, ionic liquids, hypergolic green propellant, catalytic fuel, 1-*

butyl-3-methylimidazolium acetate, BMIM Ac

1. INTRODUCTION

Hypergolic fuel-oxidizer combinations are the preferred choice as storable propellant of space propulsion systems for large spacecraft, for example the Automated Transfer Vehicle (ATV), Orion service module (MPCV-ESM) and many geostationary satellites (ArianeGroup, Orbital Propulsion 2017). Hypergolic propellants ignite when they come into contact. Therefore a separate igniter is not required. Hypergolic ignition assures reliable and repeatable operation. Since the middle of the 1960s hypergolic systems are flight proven and large knowledge is available. The fuel of hypergolic space propulsion systems are commonly based on hydrazine and its derivatives, such as unsymmetrical dimethyl hydrazine (UDMH) or monomethyl hydrazine (MMH). The oxidizer is based on dinitrogen tetraoxide N_2O_4 (NTO). NTO is available in solutions with nitric oxide. The solutions are named mixed oxides of nitrogen (MON-i), where i indicates the percentage of nitric oxide NO in N_2O_4 / NO_2.

Hydrazine is on the candidate list of substances of very high concern of the European REACH (Registration, Evaluation, Authorization of Chemicals) regulation because of its high carcinogenetic hazard potential (Malm 2011). It is possible that the use of hydrazine in the EU will be banned in the near future. UDMH and MMH are also highly toxic and they could be added to the list of substances of very high concern. NTO and other nitrogen oxides are toxic and corrosive. One of the main adverse physical properties of hydrazine and its derivatives and NTO is their high vapor pressure. This leads to contamination of the atmosphere if the substances are handled in open containers or if some of them are spilled accidently. Because of the negative health effects, extensive safety precautions are necessary during production, transportation, storage and handling of those substances which results in high costs. Less toxic, alternative fuels, which allow simplified handling procedures, could provide a significant cost reduction.

An alternative oxidizer for nitrogen oxides is highly concentrated hydrogen peroxide (HP). Hydrogen peroxide can be decomposed into water vapor and oxygen. The decomposition reaction is exothermic. For propulsive related applications, concentrations of HP diluted by water between 70% and 98% are used (Ventura and Garboden 1999). HP was used during the early days of spaceflight in the mid-1950s and beginning of the 1960s as monopropellant (D. Baker 2017). In these applications it was decomposed by a catalyst. It was also used as oxidizer of the British launcher “Black Arrow” in the 1970s (Ventura and Garboden 1999). There are two methods to use HP as oxidizer (Wernimont 2005): staged combustion and liquid-liquid combustion. With the first method, HP is decomposed by a catalyst and hot water vapor and gaseous oxygen are generated. The fuel is injected into the hot decomposition products and ignites due to the high temperature and the presence of oxygen. The second method uses a fuel which reacts with the HP when they come into contact. This is achieved either using a fuel that is hypergolic with HP or by adding additives to a non-hypergolic fuel. There are two types of additives: catalytic and reactive additives (Palmer and Rusek 2004). Catalytic additives can be transition metal salts, which are dissolved in the fuel. The transition metal ion catalyzes the decomposition of the HP. The fuel is then vaporized due to the heat produced by the decomposition reaction and after an ignition delay the mixture of produced oxygen and vaporized fuel ignites. The second group of reactive additives reduces the HP directly. The reduction reaction of HP releases more energy than the decomposition reaction (Palmer and Rusek 2004) and the ignition delay can be shortened.

An example of a catalytic hypergolic fuel with HP is the so-called ‘Block 0’ developed by the U.S. Navy in the 1990s. The fuel is a mixture comprising of methanol and the catalytic additive manganese acetate tetrahydrate (MAT). It has an ignition delay time (IDT) of 11 ms (Palmer and

Rusek 2004). In general, catalytically active ions for the decomposition of HP are for instance Co^{2+}, Co^{3+}, Cu^{1+}, Cu^{2+}, Fe^{2+}, Fe^{3+}, Mn^{2+} and Mn^{3+} (Melof and Grubelich 2001). However, catalytic additives with transition metal ions reduce the specific Impulse (Isp) due to the heavy metal components in the exhaust gases.

Further, reactive fuels can be used with strong reducing agents, such as metal- or borohydrides. For this purpose, the hydrides are dissolved in a suitable solvent (Palmer and Rusek 2004). After HP and reactive fuel come into contact, mixing takes place and spontaneous ignition in the liquid phase can be observed (Rarata and Florczuk 2016). This is similar to the ignition of common toxic hypergolic propellants. Handling of pure hydrides is challenging, because of their high reactive sensitivity to air and moisture (Sippel, et al. 2011). Groups in Korea (Kang, Lee and Kwon 2017), Poland (Florczuk and Rarata 2017) and the US (Kan, Heister and Paxson 2017) have tested liquid reactive hypergolic fuels recently in drop tests or combustion chambers.

Ionic liquids (ILs) are promising alternative fuels: ILs are salts which have a melting point below 100 °C and consist of anions and cations. Due to this ionic composition, ILs have very low vapor pressures, which facilitates handling compared to the hydrazine fuels with high vapor pressures.

In literature, it has been reported that some ILs are hypergolic with different oxidizers like white fuming nitic acid (WFNA), red fuming nitric acid (RFNA), NTO and HP (Sebastiano, et al. 2014) (Zhang and Shreeve 2014). Very low ignition delay times for WFNA have been reported in the order of 1 ms (Zhang, et al. 2016). Hypergolicy is mainly driven by the anion of an ionic liquid (Sebastiano, et al. 2014). Research by Sun et al. has shown that the cation has a great impact on the physical properties of the IL and the ignition delay time (Sun, Tang and Zhang 2017).

Hypergolic ionic liquids with HP were investigated by Schneider et al. of AFRL, USA (Schneider, et al. 2011), Kim et al. of Hannam University, South Korea (Kim, et al. 2015) and Weiser of ICT, Germany (Weiser, et al. 2017). Schneider et al. synthesized an IL consisting of the tetraethyl ammonium (TEA) cation and aluminum boron hydride ($Al(BH_4)_4^-$) anion. This IL showed hypergolic behavior with HP 90 % and 98 %. The ignition delay was below 30 ms (Schneider, et al. 2011). Furthermore Schneider et al. found catalytic ionic liquids with the iodide (I^-) or tetrachloroferrate ($FeCl_4^-$) anion. By dissolving these catalytic IL in an IL based fuel, ignition delay times in the order of 30- 50 ms were reached (Schneider, et al. 2014). Kim et al. investigated different anion and cation combinations on hypergolicy with HP (Kim, et al. 2015). They prepared different salts, which were solid and dissolved them in 2-hydroxyethylhydrazine, which is also toxic and carcinogenic. The most promising IL in terms of ignition delay time from drop tests between 8 and 33 ms were based on the 1-Ethyl-4-methyl-1,2,4-triazole cation and azide (N_3^-), cyanide (CN^-), iodide (I^-), tetrachloroaluminate ($AlCl_4^-$) anion. But the viscosities of the IL fuels are relatively high from 190 mPa s to 940 mPa s and toxic and carcinogenic substances were still used. Weiser et al. investigated 1-ally-3methylimidazolium dicyanamide (AMIM DCA), which is hypergolic with WFNA but not with HP. They dissolved copper based catalyst at an amount of 15 wt.% in the IL and reached ignition delay times down to 9 ms with 95% HP in an injection test setup (Weiser, et al. 2017).

This work concentrates on a new hypergolic liquid-liquid propellant combination based on hydrogen peroxide and a commercially available ILs. Therefore a theoretical screening was conducted first. Based on these results a fuel was chosen and hypergolic drop test were carried out.

2. THEORETICAL SCREENING

2.1 Fuel Requirements

The melting point of a potential fuel should be similar to hydrazine or below. Hydrazine has a melting point of 0.6 °C (E. Wernimont 2006), HP 98% melts at -3°C and potential IL fuels should also melt below 0°C. The density of a fuel should be higher than 1 g/cm³ to have an advantage with respect to the density specific impulse compared to hydrazine based bipropellant systems. Viscosity should be as low as possible to guarantee good mixing behavior of fuel and oxidizer (Zhang, et al. 2011). The sensitivity to air and moisture in the air must be low to ensure simple handling. A positive enthalpy of formation contributes to a high energy density and a high specific impulse. However, substances with high positive heat of formations tend to be sensitive. For handling and transportation the fuels should be insensitive to impact, friction and electro-static discharge. The decomposition temperature of the IL fuel should be high enough to ensure safe handling under ambient conditions.

2.2 Thermochemical Calculation

A theoretical screening with the NASA code ‘Chemical Equilibrium with Applications (CEA)’ (McBride and Gordon 2004) was conducted to estimate the performance of different ILs. As reference the ArianeGroup bipropellant thruster with a nominal thrust of 200 N was chosen. These thrusters were developed and qualified to be used as attitude control, maneuvering and breaking system of ESA’s ATV (ArianeGroup, Orbital Propulsion 2017). The nominal Isp is about 270 s, the nominal chamber pressure is 8 bar and the nozzle expansion ratio 50. MMH and MON-3 (mixture of NTO and 3% nitric oxide) are used as propellant. The enthalpies of formation ($\Delta_f H^0$) must be known to calculate the performance of a propellant. For hydrogen peroxide the enthalpy of formation is known and implemented in NASA CEA code. All of the enthalpies of formation mentioned in this work are available in literature.

2.3 Screening of IL

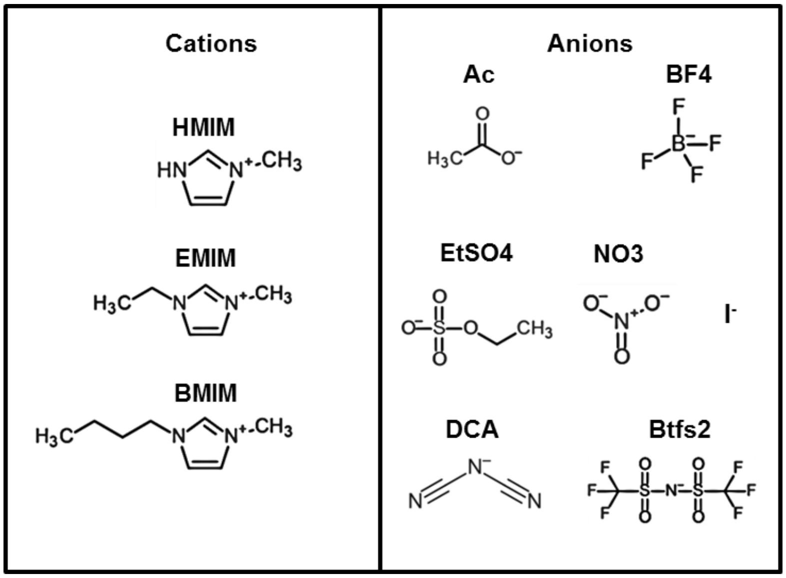

Figure 1 Cations and anions of ILs

In this work, fuel screening included only commercially available ionic liquids. Most of the hypergolic ILs mentioned in the introduction are tailored IL, which have been synthesized in volumes in the order of a milliliter. Commercially ILs are already available in larger amounts and therefore less expensive. This facilitates scaling from basic drop tests to more realistic combustor tests. For consideration in this screening the physical properties of the IL in question, especially the enthalpy of formation, viscosity and density had to be publicly available. Final screening for this investigation included nine different ionic liquids. The cation of all ILs is an imidazolium ring with different hydrocarbon side chains, 3-methylimidazolium ($HMIM^+$), 1-ethyl-3-methylimidazolium ($EMIM^+$) and 1-butyl-3-methylimidazolium ($BMIM^+$). The considered anions were acetate (Ac^-), bis(trifluoromethylsulfonyl)imide ($Btfs2^-$), dicyanamide (DCA^-), ethylsufate ($EtSO_4^-$), iodide (I^-), nitrate (NO_3^-) and tetrafluoroborate (BF_4^-). Structural formula of the different anions and cations are shown in Figure 1.

Equilibrium calculations were performed with 98% hydrogen peroxide as oxidizer. In TABLE 1 the necessary physical properties and results of the calculations are given. The conventional hypergolic combination consisting of MMH-NTO is also given. ILs with an Isp_{noz} lower than 305 s were not considered for further investigations, due to low performance. Except BMIM I the other IL were not known to be hypergolic with HP. Therefore a catalytic salt must be dissolved to obtain hypergolicy. Because of the heavy transition metal ions in the combustion exhaust the Isp is further reduced. The density Isp was chosen to be higher than 417 s kg/m³, which is an increase of 10 % compared to MMH-NTO. The viscosity at room temperature must also be as low as possible to ensure good mixing. The iodide IL has a high viscosity of 1180 mPa s and hence was not considered in this investigation. The $Btfs2^-$, $EtSO_4^-$ and BF_4^- ILs offer low Isp and were rejected. The BMIM NO_3 is solid at room temperature and not suited as fuel. The dicyanamide ion is reported not to be reactive with HP (Nichols, et al. 2016). Furthermore the cyanide ion and cyanide salts such as copper (I) cyanide are highly toxic. Therefore they were not considered for further investigation. The HMIM Ac has a low viscosity but a low Isp compared to BMIM Ac. The BMIM Ac offers an inconveniently high viscosity. The aforementioned manganese acetate salt (MAT) has been already used as catalyst in fuels with hypergolic behavior with HP. Salts and IL, which share the same anion, have a good solubility. BMIM Ac was selected as fuel for this investigation because of the high Isp of 308.3 s and the possibility that a catalytically active salt can be dissolved in the IL to promote the hypergolic ignition.

TABLE 1: Properties of ILs and results of screening with NASA CEA

Name	$\Delta_f H^0$ [kJ/mol]	η [mPa s]	ρ [g/cm^3]	ROF_{max} [-]	Isp_{noz} [s]	Isp_{Vac} [s]	ρ I_{sp} [kg s / m^3]
MMH NTO	**---**	**---**	**---**	**1,7**	**314,1**	**324,4**	**379,3**
HMIM Ac	**-425**[a]	**---**	**1,03**	**3,6**	**302,2**	**316,4**	**398,7**
EMIM DCA	**274**[b]	**17,7**[b]	**1,10**[b]	**4**	**310,4**	**325,4**	**416,0**
EMIM Et SO4	**-579**[c]	**94.2**[d]	**1,24**[d]	**3,2**	**301,6**	**316,1**	**410,8**
EMIM Ntfs2	**-1600**[a]	**39.4**[d]	**1,52**[d]	**1,6**	**285,8**	**298,6**	**411,1**
BMIM Ac	**-452**[a]	**208**[d]	**1,05**[e]	**4,6**	**308,3**	**323,1**	**422,5**
BMIM BF4	**-1221**[f]	**104**[d]	**1,30**[d]	**3,5**	**301,8**	**316,4**	**415,8**
BMIM DCA	**244**[b]	**29,5**[b]	**1,06**[b]	**4,6**	**326,5**	**326,5**	**437,2**
BMIM I	**-119**[a]	**1180**[d]	**1,48**[d]	**3**	**292,3**	**305,9**	**415,0**
BMIM NO3	**-261**[g]	**Solid (RT)**[d]	**1,16**[d]	**3,4**	**309,8**	**324,8**	**416,9**

with enthalpy of formation $\Delta_f H^0$, viscosity η, density ρ, ratio of oxidator and fuel ROF_{max} (at Isp_{max}), maximum specific impulse of the nozzle Isp_{noz}, maximum vacuum specific impulse Isp_{Vac}, density specific impulse ρ Isp (at ROF_{max})

[a] (Kabo, et al. 2010), [b] (Sun, Tang and Zhang 2017), [c] (Z.-H. Zhang, et al. 2006a), [d] (Iolitec

2017), [e] (Bogolitsyn, Skrebets and Makhova 2009), [f] (Z.-H. Zhang, et al. 2006b), [g] (Yermalayeu 2013)

3. EXPERIMENTAL SCREENING

3.1 Drop test: Method

Drop tests are a simple and fast approach to evaluate possible hypergolic fuel oxidizer combinations. In a typical experiment, a droplet of one component of the propellant is dropped into a pool of the other component. The components mix and the mixture ignites after an ignition delay. The time until ignition can be measured by analyzing high speed video recordings. In the presented experiments, a droplet of the oxidizer (HP) was dropped into the fuel pool. In case of a hypergolic combination, a flame could be observed, that was accompanied with a “pop” sound. The ignition delay time (IDT) is the major factor to evaluate the hypergolic performance of a propellant. The IDT is defined from the first contact of oxidizer and fuel until the first flame is observed. The IDT measured with drop tests depends on various environmental factors, so different laboratories often measure different ignition delay times of the same propellant. In order to avoid hard start phenomena in thrusters it is important to have a short ignition delay time. There are different accepted values for the duration of the ignition delay. In the 1940s, when the first hypergolic propellants were assessed, an IDT below 50 ms was accepted (Clark 1972). The conventional hypergolic propellant MMH-NTO has an ignition delay in the order of several milliseconds (Florczuk and Rarata 2015).

For this investigation, BMIM Ac was chosen and first hypergolic drop tests were conducted. The drop test setup is shown in Figure 2. 1 ml of the fuel was inside a test vial and the HP was released from the tip of a pipette. The drops had a volume of ca. 0.05 ml and fell from 80 mm height into the fuel. Drop tests were recorded by a Phantom SX2.1 high speed camera with a frame rate of 2000 fps. IDT was determined as time period between the first contact of oxidizer drop with the fuel and the first appearance of a flame. Due to safety aspects, drop tests were executed inside a fume hood. After each test, the vial was filled with water to suppress further reactions.

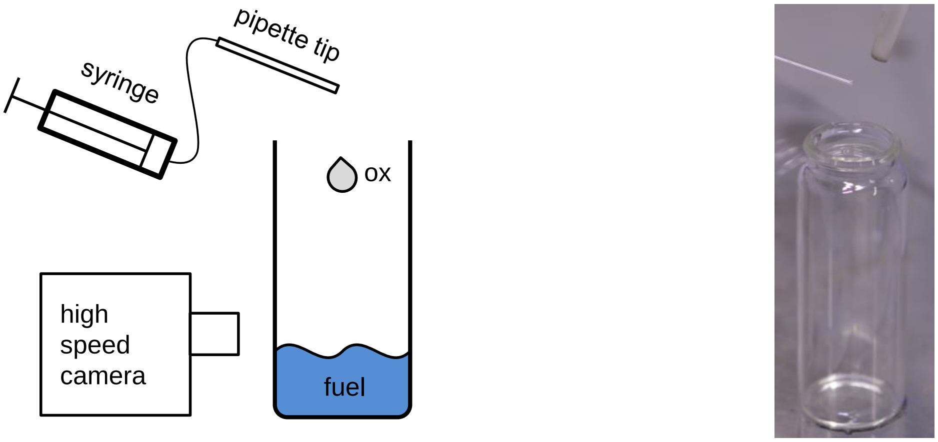

Figure 2 Drop test setup; left: schema, right: setup

3.2 Substances used

The chosen IL was purchased from Iolitec, Germany. BMIM Ac has a purity of 98 % and was used without further purification. HP (PROPUSLE®) was purchased from EVONIK, Germany and had a concentration of 95 %. Investigated catalytically active salts consisted of copper (II) acetate (CuAc) (99,999%) which was purchased from Alfa Aesar and manganese (II) acetate tetrahydrate (MAT) (>99%) from Acros.

3.3 Preparation of fuels

Four fuels with different concentrations of copper (II) acetate were prepared, 0.57 wt.%, 1.06 wt.%, 3.02 wt.% and 6.11 wt.%. The fuel and salt were weighed and stirred for about 1 h to dissolve the salts. In the case of 0.57 % and 3.02 % some crystals were not dissolved in the IL. Hence the concentrations used with 0.57% and 3.02 % CuAc were a lower than nominally. The final concentrations were not determined. Three different MAT promoted fuels were made with concentrations of 1.19 wt.%, 3.01 wt.% and 10.00 wt.%. The prepared fuels are shown in Figure 3. In the following the different catalytically activated fuels are referred as given in TABLE 2.

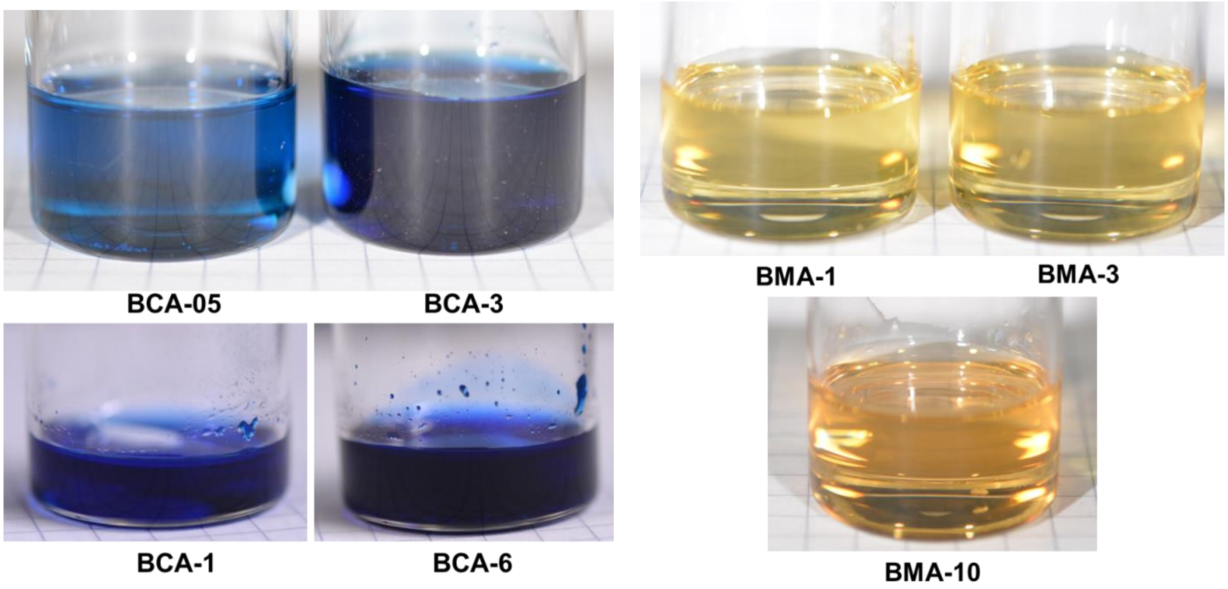

Figure 3 BMIM Ac with dissolved catalytic salts; blue: copper acetate; yellow: manganese acetate tetrahydrate

TABLE 2 Fuel identification

Ingredients	**Name**
1-butyl-3-methylimidazolium acetate	**BMIM Ac**
BMIM Ac + 0.57 wt.% copper (II) acetate	**BCA-05**
BMIM Ac + 1.06 wt.% copper (II) acetate	**BCA-1**
BMIM Ac + 3.02 wt.% copper (II) acetate	**BCA-3**
BMIM Ac + 6.11 wt.% copper (II) acetate	**BCA-6**
BMIM Ac + 1.19 wt.% manganese (II) acetate tetrahydrate	**BMA-1**
BMIM Ac + 3.01 wt.% manganese (II) acetate tetrahydrate	**BMA-3**
BMIM Ac + 10.00 wt.% manganese (II) acetate tetrahydrate	**BMA-10**

4. RESULTS & DISCUSSION

Pure BMIM Ac and pure copper (II) acetate were tested in the drop test with 95 % hydrogen peroxide. In both cases no reaction was observed. To introduce hypergolic behavior the BMIM Ac was prepared as described above with copper (II) acetate. Ignition occurred in all drop tests with BCA fuels.

TABLE 3 Results of drop tests BCA fuels

Substance	Result of drop test	Average IDT [ms]	Number of drop test	Standard deviation [ms]
BMIM Ac	**No reaction**	**-**	**3**	**-**
BCA-6	**Ignition**	**341.6**	**4**	**22.2**
BCA-3	**Ignition**	**335.4**	**4**	**61.9**
BCA-1	**Ignition**	**189**	**2**	**25.5**
BCA-05	**Ignition**	**963.3**	**4**	**53.5**

TABLE 3 summarizes the results of the drop tests with pure BMIM Ac and BCA fuels. The ignition delay time of BCA-1 was the shortest with an average of 189 ms. Figure 4 shows a series of snapshots of the high speed video during a drop test with BCA-1 and one drop of 95% HP. The first ignition occurred at 171.5 ms after contact of fuel and oxidizer in the vapor phase above the surface of the fuel. This first ignition propagated only in the vapor phase and was not able to ignite the mixture completely. The first ignition was quenched and after 193.5 ms and a second ignition occurred, which was quenched again. Finally the third ignition in the vapor phase was able to ignite the liquid mixture at 226.5 ms. Both of BCA-1 drop tests have shown the behavior that the initial ignition was not able to ignite the liquid mixture.

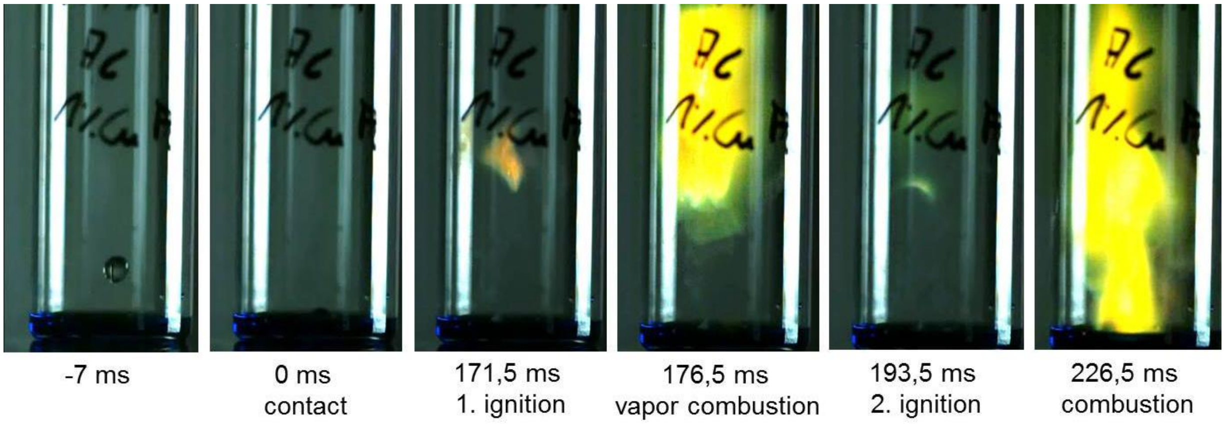

Figure 4 Drop test BCA-1

Figure 5 shows a series of snapshots of the high speed video during a drop test with BCA-3 fuel. 132 ms after impact vapor generation was observed. The generated vapor ignited 251 ms after initial contact. In contrast to BCA-1, the initial ignition propagated to the liquid mixture in less than 1 ms. All tests of the BCA-05, BCA-3 and BCA-6 fuels showed a sustained combustion directly above the surface of the liquid shortly after the initial ignition. BCA-05 had the longest ignition delay time due to the low concentration of the catalyst. The average IDTs of BCA-3 and BCA-6 were similar. BCA-1 had the shortest IDT but the energy release of the first ignition was not enough to ignite the mixture. The liquid mixture was ignited in the order of 50 ms after first ignition. The mixing of oxidator and the fuels after contact was poor because of the high viscosity of the BMIM Ac. After impact no backjets or crown formations were observed. The HP drop did not penetrate and break up the fuel’s surface. The decomposition reaction took place only at the boundary between HP and fuel.

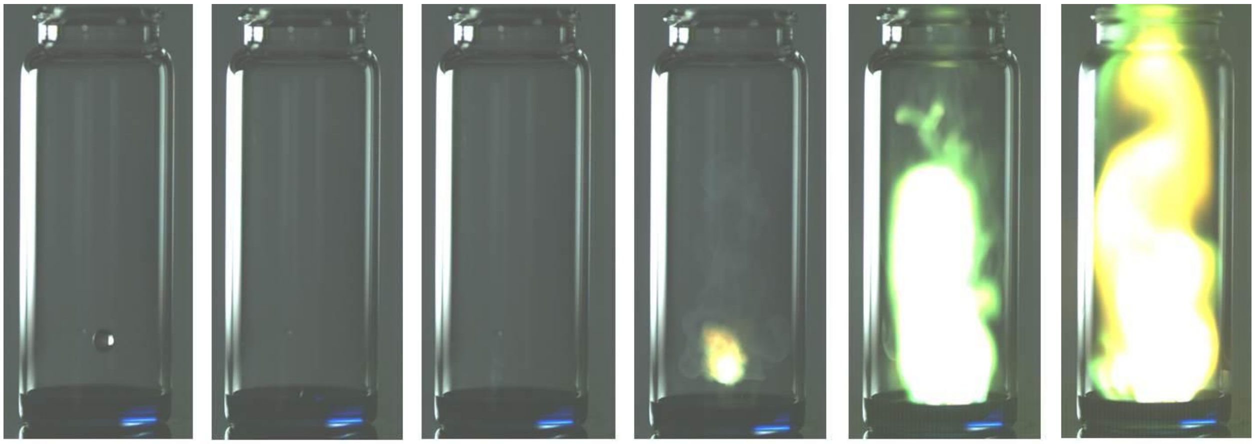
-8,5 ms | 0 ms contact | 132 ms vapor | 251 ms ignition | 254 ms combustion | 317 ms combustion

Figure 5 Drop test BCA-3

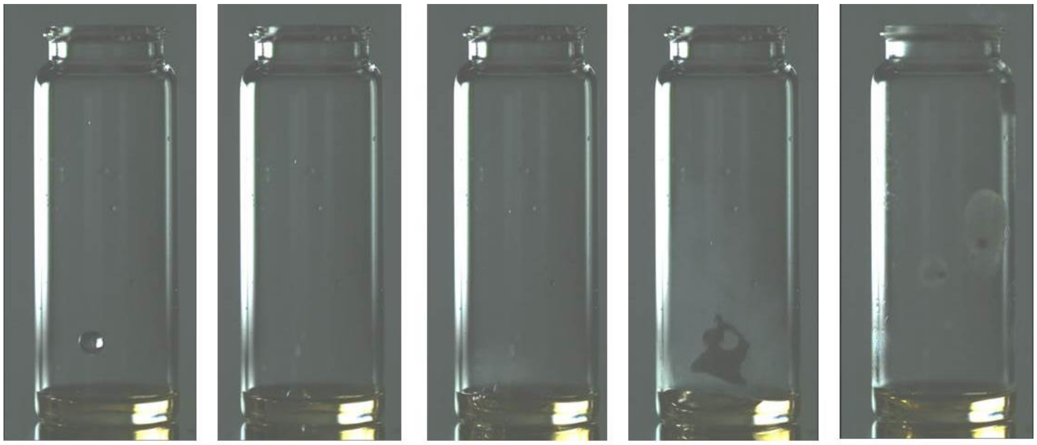
-8,5 ms | 0 ms contact | 10 ms vapor | 16 ms rebound | 78 ms

Figure 6 Drop test BMA-10

Overall 11 drop tests with BMA fuels were conducted. The results of these tests are given in TABLE 4. The BMA fuels showed a different behavior in the drop test compared to the BCA fuels. Figure 6 shows a drop test with the BMA-10. Within 10 ms vapor was generated and shortly after the HP drop rebounded from the surface of the fuel. The HP was decomposing and bubbling, but in most of the cases no ignition occurred. The drop was catapulted to the surface of the vial and decomposed there. The BMA-3 fuels showed the same behavior but the vapor generation and rebound of the drop started in average after 32.6 ms. The rebound effect was less violent compared to BMA-10. In case of BMA-1 no rebound of the drop was observed. The HP was floating on top of the fuel and decomposed. Vapor was generated in average after 103.4 ms and the drop moved on the fuel surface. Only during two tests (BMA-3 and BMA-10) ignition was observed, see Figure 7. But the ignition took place in the vapor phase and was not able to result in a sustained combustion. After 45 ms the flame was quenched and HP was decomposing. Like the BCA fuels, the mixing of HP and fuel was very poor. The HP was decomposed because of the MAT at the boundary between fuel and HP. The high decomposition rate and the produced hot gases on the surface boundary lead to the rebound of HP. The catalytic activity of MAT was higher than of CuAc, because of the earlier vapor generation. But due to the poor mixing and rebound effect a small amount of the fuel was vaporized and ignition was not achieved in most cases.

TABLE 4 Results of drop tests BMA fuels

Substance	Result of drop test	Average time to vapor generation [ms]	Number of drop test	Standard deviation [ms]
BMA-10	**Violent decomposition**	**9.7**	**3**	**0.6**
BMA-3	**Violent decomposition**	**32.6**	**4**	**2.6**
BMA-1	**Violent decomposition**	**103.4**	**4**	**5**

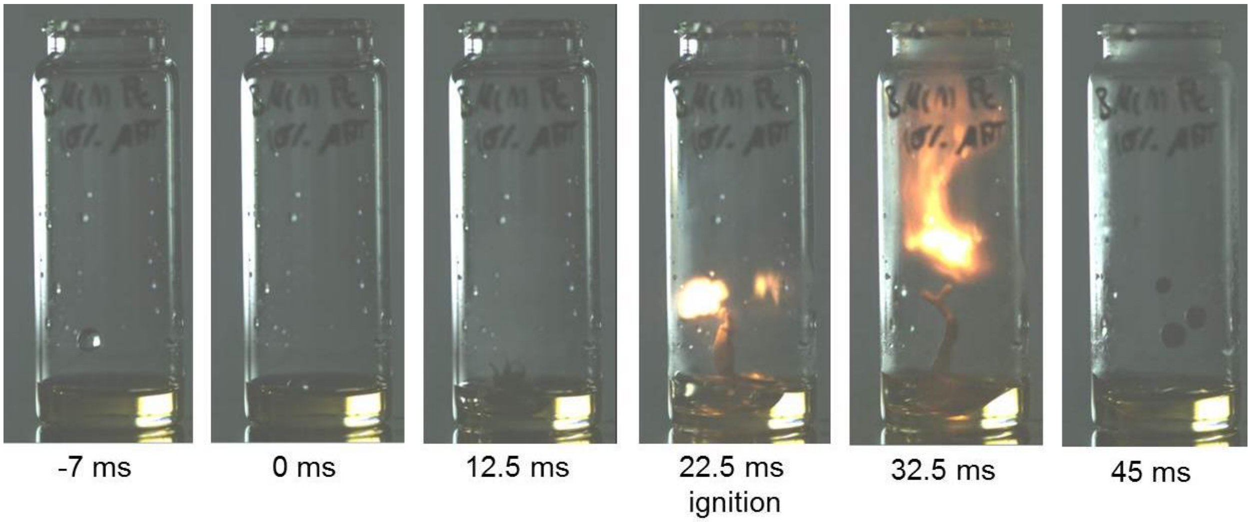

Figure 7 Drop test BMA-10 with ignition

5. CONCLUSIONS

Different ILs have been screened with NASA CEA code to obtain a survey on the performance data of different potential ionic liquid fuels. The IL 1-butyl-3-methylimidazolium acetate was chosen as potential fuel to be tested with regard to hypergolic behavior with HP in drop tests. Pure BMIM Ac is not hypergolic with 95 % HP. Catalytic transition metal salts, copper (II) acetate and manganese acetate tetrahydrate were dissolved in the BMIM Ac and tested in the drop test. Reliable hypergolic ignition was only achieved in case of copper (II) acetate. The shortest ignition delay was 171.5 ms with 1.06 wt. % copper (II) acetate, which is much longer compared to conventional hypergolic propellants. Manganese acetate tetrahydrate promoted fuels showed only violent decomposition of HP with vapor generation. Mixing behavior of fuel and oxidizer was poor because of the high viscosity of the BMIM Ac fuels.

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ABBREVIATIONS

Ac^-	Acetate
AFRL	Air Force Research Laboratory, Edwards, USA
ATV	Automated Transfer Vehicle
BF_4^-	Tetrafluoroborate
BMIM	1-Butyl-3-Methylimidazolium
Btfs2	Bis(Trifluoromethylsulfonyl)Imide
CEA	Chemical Equilibrium With Applications, thermodynamic code of NASA
CuAc	Copper (II) Acetate
DCA	Dicyanamide
DLR	German Aerospace Center
DT	Drop Test
EMIM	1-Ethyl-3-Methylimidazolium
ESA	European Space Agency
$EtSO_4^-$	Ethylsufate
HMIM	3-Methylimidazolium

HP	Hydrogen Peroxide
I^-	Iodide
ICT	Fraunhofer Institute for Chemical Technology, Pfinztal, Germany
IDT	Ignition Delay Time
IL	Ionic Liquid
Isp	Specific Impulse
MAT	Manganese Acetate Tetrahydrate
MMH	Monomethyl Hydrazine
MON	Mixed Oxides of Nitrogen (NO in N_2O_4/NO_2)
MPCV ESM	Multi-Purpose Crew Vehicle European Service Module
NASA	National Aeronautics and Space Administration
NO_3^-	Nitrate
NTO	Dinitrogen Tetraoxide (N_2O_4 in equilibrium with NO_2)
REACH	Registration, Evaluation, Authorization Of Chemicals
RFNA	Red Fuming Nitric Acid
RT	Room Temperature
TEA^+	Tetraethyl Ammonium
UDMH	Unsymmetrical Dimethyl Hydrazine
WFNA	White Fuming Nitic Acid