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NANOALUMINIUM – WATER SLURRY: A NOVEL “GREEN” PROPELLANT FOR SPACE APPLICATIONS

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ABSTRACT

In the present work, a novel approach to the problem of hydrazine replacement is proposed. Aluminium/water slurries are suggested as potential substitutes for hydrazine. This slurry includes both the fuel (Al) and the oxidizer (H_2O), and has physical properties similar to those of a monopropellant. The specific impulse of the Al/ H_2O bipropellant is about 300 s. The proposed propellant includes only non-toxic components; this fact significantly facilitates preparation, storage, filling, and other operations. The results of preliminary experiments with single droplets of nanoAl – gelled water slurry are reported. A new research programme is presented, which is funded by INTAS and CNES and involves six teams from France, Italy, and Russia. The programme includes studies of nanoaluminium – water slurries in order to develop the best methods for their preparation, atomisation and combustion.

1. REASONS FOR USING NANOALUMINIUM/ WATER SLURRY IN SPACE PROPULSION

Various spacecraft and satellites normally use hydrazine as monopropellant for low-thrust engines, which are required for their stabilisation, orientation, and small manoeuvres. Unfortunately, hydrazine is a very toxic compound. The problem to replace hydrazine with “green” propellants is identified as the barest necessity by CNES and other space agencies. Typically, monopropellants, such as highly concentrated hydrogen peroxide, binary HAN-water mixtures, and nitrous oxide have been considered as potential candidates.

A novel and alternative approach is to consider aluminium/water slurries, which include both fuel (Al) and oxidizer (H_2O), and have physical properties similar to those of a monopropellant. Aluminium combustion with steam for underwater propulsion has been studied since 1940s [1]. Recently, it was proposed to use the combustion of Al with H_2O (the specific impulse of the Al/ H_2O bipropellant is about 300 s) in satellite propulsion [2]. Specifically, it was suggested to inject

separately Al nanoparticles and liquid water or to oxidise with steam Al in the form of grains or porous sponge, as in conventional rocket hybrid motors. Experiments on flame propagation in bulk samples of nano-Al/gelled water slurry [4, 5] imply that this slurry might be used as propellant in rocket engines. In this case, the Al/ H_2O system would possess bulk physical properties like a true monopropellant, which is attractive for applications where hydrazine is mainly used. The proposed propellant includes non-toxic components (Al, H_2O , and a small amount of gelling agent); this fact significantly facilitates preparation, storage, filling, and other operations. Also, the main combustion products are Al_2O_3 and H_2 .

It should be noted that combustion of slurry fuels (aluminium, carbon, or boron suspended in a liquid hydrocarbon; carbon suspended in water) in high-temperature oxidizing atmospheres was extensively studied for applications to propulsion and power plants [6]. Typically, combustion of single slurry droplets in the hot products of a gas burner was studied. It was found that during combustion of such droplets, the liquid fuel is rapidly vaporised, and then large agglomerates of particles form and burn that result in unexpectedly long burning times for applications.

However, in the case of the nanoAl/ H_2O slurry, the distinguishing feature is that the system includes both fuel (Al) and oxidizer (H_2O). This fact implies that droplets in such slurry may burn by a different mechanism. In fact, it is expected that under certain conditions, H_2O will react with Al particles inside the droplet (at least at the beginning of heating) and only part of the water vapour will leave the droplet before Al oxidation or droplet disintegration. This suggests that agglomeration of Al particles will not occur, or at least will become much less than in the fuel slurries mentioned above.

The experiments [5] have demonstrated that under some conditions, such as nano scale Al particles and gelling of water, combustion propagates steadily inside the Al/ H_2O slurry, with superheating of gelled water by 170-200 K and ignition of Al nanoparticles in the combustion front. This leads one to expect that there exist conditions for the complete combustion of Al/ H_2O

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droplets. Note that disintegration of the droplet is an appropriate event if the Al particles do not agglomerate and can burn rapidly in the H_2O -rich atmosphere of a combustion chamber. Moreover, such a scenario may be truly advantageous, since it may prevent agglomeration of the Al_2O_3 formed and hence decrease losses of specific impulse due to two-phase flow.

As mentioned above, the Al nanoparticles may provide necessary conditions for successful use of Al/ H_2O slurry in combustion applications. The Al nanoparticles are considered as a promising highly energetic ingredient for propellants, explosives, munitions, and pyrotechnical compositions. Today, over a dozen companies are developing and manufacturing nanoscale metal particles by different methods, such as electroexplosion of Al wires [7] and Al gas-phase condensation [8]. In particular, the Al nanoparticles with monomolecular and quasi-polymer chemisorbed organic, organosilicon and inorganic coatings [9] are of great interest for the proposed Al/ H_2O propellant. Indeed, the particles should not react with water during long periods of storage (normally at room temperature) but should be ignited easily at relatively higher temperatures. Of course, to compete with conventional propellants, such as hydrazine, the proposed nanoAl/ H_2O system should be sufficiently cheap. The cost of Al nanoparticles is rather high but the increasing interest in their use will definitely lead to increasing production and hence to decreasing the cost.

Thus, the nanoAl/ H_2O slurry propellant promises the higher specific impulse than hydrazine or other monopropellants, and at the same time, can be designed with physical properties that make it appropriate for using in satellite propulsion systems. Many scientific and technological problems, however, should be resolved before making the decision to develop industrially these propellants and relevant engines.

2. PRELIMINARY EXPERIMENTS ON Al/ H_2O DROPLET COMBUSTION

Analysis of the literature did not reveal any publications on combustion of Al/ H_2O slurry droplets. Thus, determination of the droplet combustion mechanisms for the Al/ H_2O slurry is urgently needed to evaluate the performance of this system as propellant.

The present paper reports the results of preliminary experiments with single droplets of nanoAl – gelled water slurry. The gelled water was prepared by adding 0.1 wt.% polyacrylamide and mixed with 15 wt.% nanoAl powder (mean size 50 nm). The droplets were suspended on the tip of a quartz fibre and ignited using

a hot Nichrome wire or an electric arc in air or argon atmosphere.

The experiments show that the droplets ignite and burn in air or argon with a stable spherical flame. Successful experiments in the inert atmosphere confirm that the combustion occurs due to the reactions between Al and H_2O . Replacement of nanoAl with coarser Al powder (6 μm) dramatically increases the ignition delay time in air and makes impossible the ignition in argon.

Thus, the preliminary experiments on ignition and combustion of single nanoaluminium/gelled water droplets lead to the conclusion that such droplets can burn steadily due to the reaction between Al and H_2O , and confirm that the nano scale of Al particles is required for the stable combustion.

3. RESEARCH PROGRAMME FUNDED BY INTAS AND CNES

A new research programme on preparation, atomisation and combustion of nanoaluminium – water slurries has started on April 1, 2004. The programme is funded by INTAS and CNES and supports a consortium of six teams (P.I. Gökalp):

- Laboratoire de Combustion et Systemes Réactifs (LCSR), Centre National de la Recherche Scientifique, Orleans, France
- University of Rome “La Sapienza”, Rome, Italy
- Institute of Chemical Kinetics and Combustion (ICKC), Siberian Branch of the Russian Academy of Sciences, Novosibirsk, Russia
- Tomsk State University (TSU), Tomsk, Russia
- Institute of High Current Electronics (IHCE), Siberian Branch of the Russian Academy of Sciences, Tomsk, Russia.
- Institute for Energy Problems of Chemical Physics (INEPCP), Russian Academy of Sciences, Moscow, Russia.

The research programme aims to validate the potential use of the nanoaluminium – water propellant as a substitute to hydrazine in space propulsion. The programme is composed of the following tasks:

- Identification of best methods for production of Al nanoparticles, including particles with non-oxide coatings, and for their storage and mixing with gelled water.
- Determination of the rheological properties of nanoAl/gelled water slurry and of its atomisation and ignition characteristics.
- Determination of single nanoAl/ H_2O slurry droplet combustion regimes and ignition/combustion characteristics under different experimental

conditions, such as particle size, mass fraction of Al, pressure of ambient gas, and heating rate.

- Determination of the combustion wave structure in bulk samples of Al/gelled water slurries and the completeness of its combustion depending on particle size (in both nano and micro scales) and on the level of water gelling.
- Development of mathematical models for combustion of Al nanoparticles in water vapour.

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