ON USE OF ALKALI METALS AS SPT PROPELLANTS

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ABSTRACT

In the present work a comparative analysis of various aspects of using alkali metals as electric thruster propellants was performed. In particular, the problems concerning discharge channel processes control system design and operation, the propellant storage and supply system and cathode-neutralize features are considered. Besides, the comparison of propulsion, power and weight characteristics is made, some technical, economic and ecological aspects of using alkali metals as thruster propellants are also considered.

INTRODUCTION

Electric thrusters (ETs), created on the basis of Hall-type plasma accelerators with the closed electron drift (ACDs), including stationary plasma thrusters (SPTs) and thrusters with the anode layer (TALs), have the highest performance in the range of specific impulse values (1500...2500 s), which is necessary for fulfilling most space transportation missions. Like for most ion thrusters, xenon is used as a propellant there. With increase of the scope of the problems to be solved with the help of ETs, the matter of replacement for xenon, which is currently used as a propellant for most practically utilized ETs, by an alternative propellant, becomes keener. Besides its high cost, the main xenon's disadvantage is its rarity in the Earth atmosphere and related to that complexity of its output. So it is practically unworkable to use xenon for solving the above problems when units and tens of tonnes of an on-board propellant are required.

ETs of the ACD type should meet some special requirements associated with space operation peculiarities. These requirements include, for example, high molecular mass values (more than 100 atomic units), low ionization potential, storage and supply systems with high performance, ground development simplicity, and minimum influence on spacecraft elements and systems.

From the above requirements, a list of possible candidates for ACD propellants with high parameters, related to the specific impulse, is not too long: caesium, mercury, bismuth and, possibly, cryptone, lead, tin and antimony. Cryptone, which is the only gas in this list, first, has an insufficient molecular mass, and second, its physical and chemical properties do not allow to create a storage and supply system, which would be efficient in terms of its mass. As to the metals, there is at least one objective factor, which favors the use of alkali metals as ACD propellants. We mean that alkali metals, and in particular caesium, have the lowest ionization potentials in comparison with the rest of the metals, i. e. they ensure the minimum energy expenditures for their ionization. Besides, among the above metals, caesium is the less harmful for the environment. For these reasons, the present paper contains a comparative analysis of various aspects of the use of alkali metals as ACD propellants instead of xenon utilized traditionally. In particular, differences in processes, taking place in a discharge channel, in operation and design of propellant storage and supply systems, and in cathode-neutralizer operation are considered. Besides, comparison of thrust, energetic and mass integrated characteristics is presented, as well as some engineering, economic and ecological aspects of the use of alkali metal ACDs are considered. Characteristics of both existing and future systems were taken into account when comparing.

1. ACD Operating Processes

As it was already mentioned at the beginning of ACD development (Ref. 1), the use of alkali metals as propellants was attractive because of as their low ionization potentials. Only this fact does contain a lot of advantages in comparison with other propellants. Below we shall compare xenon and caesium if it is not mentioned specially. Xenon and caesium are practically of the same atomic mass. It results in the same dynamics of ions when the accelerator operates. It may be considered with high accuracy, that ions move with no collisions and that the magnetic field effect on ions is negligible at normal interelectrode gap sizes, so the motion of one particle can be described by the following equation:

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M \frac{d\vec{r}}{dt} = e\vec{E}.
\]
Normally, the electric field configuration is of a relatively simple shape, and generated ions are of a zero velocity, so ion trajectories essentially coincide with electric field force lines. The discharge plasma electric field proper is a sum of a superpositioned external electric field and a self-conformed field, emerging in result of a plasma charged particles motion.

As experimental studies show, at the preset discharge voltage and flow rate values, the optimum accelerator operating regime (in terms of the maximum efficiency) is reached at the magnetic field magnitude corresponding to the minimum discharge current. At this regime, when operating on xenon, a measured electron temperature value $T_e$ (or, to be more exact, the average electron kinetic energy) is normally 10...15 eV, i.e. it is close to the xenon atom ionization potential ($E_{\text{xen}} = 12.13$ eV). As it is known, in crossing magnetic and electric fields, the average electron energy is defined by the energy, which it obtains when moving along the Larmor radius. Then it is quite probable, that when operating on caesium, whose ionization potential is lower by a factor of 3 ($E_{\text{caesium}} = 3.89$ eV), the optimum operating regime is expected to take place at the electron temperature that is lower than in the case of xenon, by a factor of 3. In this case, at the same discharge voltage, the optimum magnetic fields for caesium are expected to be 1.5...2 times higher. It means, that electrons are magnetized stronger, and, hence, undesirable longitudinal electron fluxes, resulting in energy lasses, must decrease. Furthermore, the decrease of the average electron energy can result in some decrease of heat fluxes into discharge channel walls and of heat ion sparse in terms of velocities at the exit due to the electron pressure ($p_e = n_e T_e$) decrease. However, the change of wall Debye layers operating regime can turn out to be a more important consequence of the $T_e$ decrease.

The following discharge ignition voltage values were obtained when studying ACD discharge ignition (Ref. 2): 50 V for caesium, 150 V for xenon and 250 V for argon. Thus, normal operation on caesium is already possible at discharge voltage values of about 100 V, which corresponds to 1000...1200 s specific impulse values, which is practically unachievable in the case of xenon. In other words, for ballistic missions, where low outflow velocities, and, hence, low discharge voltages are required, this alkali metal is more effective.

Estimates show, that because of their collisions with walls, atoms are ionized in the channel, on the average, two times, so the xenon ion discharge or radiation rate is 40...50 eV. The ionization process, occurring in the accelerating channel, may be either direct or in steps. Spontaneous radiation processes in lines play an important part at the step-by-step ionization. Ref. 3 describes an experimental study of the radiation in lines from a xenon ACD. In this work, total radiation energy was estimated in the vacuum ultraviolet zone in the wavelength range between 50 and 200 nm. It turned to be 15 % of the discharge input power. Similar evaluations were performed for alkali metals, too (Ref. 4). It was obtained, that the radiation rate for caesium was $\sim 20$ eV, and for lithium it was $\sim 30$ eV. Experimental investigations of caesium plasma sources showed a good agreement between measured and evaluated ion rates (20...25 eV). So it may be inferred, that in comparison with xenon, alkali metals ensure smaller losses due to radiation and ion creation energetic rates.

Thus, evaluation of ion creation and plasma acceleration processes in ACDs, utilizing on caesium as a propellant, shows that its use is justified and in some cases more profitable that the use xenon.

During ACD experimental development, the use of caesium resulted in better thrust performance in a wide range of specific impulse values in comparison with xenon.

The investigations conducted allow to make a conclusion that alkali metals are potentially better than inert gases in terms of their thrust and energetic efficiency.

2. Propellant Storage and Supply System and Thruster Dynamic Characteristics

Propellant storage and supply system characteristics primarily depend on propellant properties. Low-boiling propellants, to which xenon refers, are usually stored at uprated pressures.

Storing xenon under pressure determines a propellant storage and supply system, which should contain strong tanks and pressure reduction units. Xenon may be supplied relatively easily, as a pressurized gas has sufficient internal energy and can be arranged to flow into the thruster. Solenoid-operated pneumatic valves are utilized as regulators, which have sufficiently high dynamic characteristics (their blow-off time ranges between units and tens of milliseconds). So xenon thruster preparation ranges from less than a second (when using a filamentless cathode-neutralizer) to 150...200 s (when using a pre-heated cathode). It determines rather high characteristics of xenon thrusters, used for orbit correction and spacecraft orientation systems.

High-boiling propellants, such as alkali metals, are normally stored in their liquid state. If metals are used, their storage temperature must be kept higher than their melting point (which is $\sim 60^\circ$C for caesium), or they must be stored as solids, for example, as wires. If metals are stored as liquids, the tanks, used for their storage, are not practically loaded with pressure and have relatively small mass. In this case less restrictions are imposed on the tank shape, and it can be selected from design considerations. To arrange normal thruster operation, it is necessary to convert the propellant from
its liquid phase into the vaporous one with the help of a vapor generator. It is not easy to attain a constant evaporation rate to ensure a stable propellant flow rate in weightless. To eliminate propellant condensation on cool parts, the duct, within which the propellant is supplied from the vapor generator to the thruster, and some thruster elements must be of sufficiently high temperature. So the propellant duct should be pre-heated. Besides, very high caesium chemical activity should be accounted, which limits the selection of structural materials. In general, it may be concluded, that alkali metals storage and supply systems are more complicated than ones for gases in terms of their design. Dynamic characteristics of thrusters, using caesium or other metals, are also worse than those of gas-propellant thrusters, as it is necessary to ensure vapor generation and the pre-heating of thruster units. However, it is unlikely that these disadvantages could be important for the following reason. The change-over from xenon to caesium is justified only if a big propellant load is required, which is typical for a sustaining thruster. In this case a number of thruster switches-on is restricted, and a characteristic operation time would be of hundreds and thousands of hours for each switch-on. That is why even if the preliminary preparation time is about one hour, it would be quite acceptable.

3. Cathode-Neutralizer Operation

As a rule, gas discharge electron sources of the hollow cathode type are used as ACD cathodes, which contain an electron thermoemitter, having a cavity, through which a propellant flows. Sufficiently high temperature of the emitter is supported due to ion bombardment of the cavity surface. The initial heating is ensured either by an additional discharge, or an external heater.

Caesium cathodes-neutralizers (CNs) differ from CNs based on lanthanum hexaboride and barium and strontium mixtures, which are presently used, by reduced operating temperature levels (~800 °C). The use of caesium in CNs allows to create a cathode potential drop with a voltage which does not exceed the threshold of CN material cathode sputtering.

When operating on gases, the increase of the current density above 500 A/cm² results in the increase of cathode material entrainment. In the case of operation on alkali metal vapors, this undesirable effect arises at higher current densities (800...1000 A/cm²). Cathode material entrainment defines thruster lifetime.

At the present time, CNs are developed for xenon thrusters on the base of caesium combinations (carbonates, alunomates and combinations of introduction into graphite). Being heated up to 600...700 °C, they decompose with formation of a pure alkali metal, which satisfies the CN emission temperature range (Ref. 5). The use of caesium allowed to reduce the cathode operating temperature and unproductive xenon flow rate, resulting in the thruster efficiency increase. Doing so, there is an insignificant xenon flow rate, corresponding to the erosion CN material entrainment, made of refractory metals without activators, and exceeding a lanthanum hexaboride or barium aluminate flow rate (if a CN is made of these thermoemission materials) by an order or two. Combined tests of a CN based on caesium aluminate with a xenon ACD demonstrated service-ability of this system at activator consumption of about 10⁻⁸ kg/s. The use of caesium as the basic propellant almost completely removes the CN problem due to very high emission properties of caesium and its combinations. These properties ensure low temperatures of CN elements, respectively low flow rates and design durability.

4. Lifetime and Ground Development Problems

The missions, for which caesium is supposed to be used as an ET propellant, will require thruster lifetime of thousands and, possibly, tens of thousands of hours. So the problem of ensuring thruster lifetime and its confirmation under the ground conditions requires to be considered separately.

As to thrusters of the ACD type, a discharge chamber insulator wall (for SPTs) or pole piece (for TALs) wear rate and CN lifetime are the parameters, determining its lifetime (Ref. 6 and 7). As investigations conducted show, when operating on caesium, the insulator wear did not exceed that in the case of xenon. If to consider, that xenon thruster lifetime of several thousand hours is presently attained, then it can be expected, that, when using caesium, the lifetime will not be less than this amount, as xenon and caesium ions are of about the same destroying capability. The caesium CN lifetime is higher than the xenon one, as caesium allows to attain the same current densities, but at essentially lower cathode temperatures. As practice shows, long-time thruster operation in space (about several years) requires to perform thorough lifetime tests, as some effects are not revealed during short-time tests (less than a year). This is especially urgent when using alkali metals as propellants due to their high chemical aggressivity. For the same reason, the presence of alkali metals can enhance design element corrosion when leakage emerges. These notes primarily concern a caesium storage and supply system. This problem is a little simplified by a fact that most system elements have moderate temperatures, whereas only a propellant supplying duct, placed after a vapor generator, and a thruster proper are of uprated temperatures.

Space environment imitation is very important during ground development of powerful xenon thrusters, as it is necessary to keep sufficiently high vacuum at reasonably...
high gas flow rates. Besides, so called oilless pumping-out is required in most cases, that can be ensured only with the help of very expensive (in terms of their price and operation) cryogenic vacuum systems. Caesium thruster development of practically any power does not require a power vacuum station, as caesium itself can be a getter. Yet, if there is a closed cycle, the total amount of caesium may be very small, so the test facility will be ecologically safe. Therefore, caesium thruster ground development may turn out to be much cheaper and more extensive, as it will not be hard to arrange the necessary quantity of jobs for conducting tests.

CONCLUSION

Alkali metals are much cheaper than xenon, and, which is the most important, their reserves and Earth-output capabilities are much bigger. This factor may be crucial when planning and realizing global projects involving ETs, such as a Mars mission.

In this work, a comparative analysis has been performed of various characteristics and parameters of plasma accelerators with the closed electron drift, operating on xenon and alkali metals. The investigations, conducted in this work, allow to make certain conclusions relating to expediency of the use of alkali metals as stationary plasma thruster propellants. Comparison of xenon and caesium ACD energetic efficiencies turns out the latter to be more preferable. In particular, caesium provides lesser heat fluxes and losses due to radiation from discharge plasma. In principal, a caesium ACD allow to attain the same thrust as a xenon one, but at smaller energy expenditures.

In summary it should be noted, that we did not consider caesium plasma jet effect on spacecraft elements and systems. The goal of our work was to consider possibilities of creation and application of ACDs on alternative propellants. The problem of their effect on a spacecraft does exist and is rather complicated, however, it does not command any pessimism, and, in our opinion, deserves to be considered separately.

REFERENCES