Cesium Hollow Cathode with Internal Discharge and Gas Feed for Electric Propulsion Applications

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Abstract: Cesium has the lowest electron work function and ionization energy among all chemical elements. In this paper, a cathode design utilizing Cesium as a surface activator is discussed. The cathode operates at significantly lower temperatures (600-700˚C) than the most commonly used cathode types. Moreover, discharge ignition occurs at voltages below 15 V allowing to couple the power sources for preheating and internal discharge ignition, and hence leading to a simpler cathode operation with only one low voltage-power supply. Results both from the standalone and coupling tests with two different power Hall thrusters (developed in TUBITAK UZAY) show a stable cathode operation in the 1-8 A emission current range and a clear influence of the internal discharge and Xe mass flow on the Cesium cathode coupling with the Hall thrusters.

Nomenclature

I_{id}	=	internal discharge current
V_{id}	=	internal discharge voltage
T_r	=	Cesium reservoir temperature
TÜBİTAK	=	The Scientific and Technological Research Council of Turkey
UZAY	=	Space Technologies Research Institute
HALE	=	Hall Effect Propulsion System Development Project

I.Introduction

In the last couple of decades there is a distinctive interest to the development of space electric propulsion systems (EPS) in the world. The main reason for this interest is the significant advantages of EPS over chemical systems, including higher specific impulse and longer lifetime with thousands of ignition cycle. This particular interest to the technology continues to grow due to rapid progress in electronics, which allows for longer satellite lifetime, lighter payload, power budget wise better fit of EPS to the satellite, and hence increased payload mass fraction. To date, among a large variety of electric propulsion technologies, mostly Hall and gridded ion thrusters have space heritage on both scientific and commercial satellites in LEO and GEO orbits. When compared these two types of technology, the Hall thrusters have a higher thrust-to-power ratio, lower system complexity, and hence lower cost and better reliability over the latter type.

Operation of both Hall and gridded ion thrusters requires usage of electron sources or cathodes, main role of which is supplying electrons for bombardment ionization and ion beam neutralization. Hollow cathodes are considered to be

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the most viable choice as an electron source for space propulsion applications. Plasma discharge inside the cathode cavity, which is typically manufactured from highly efficient thermoemission materials, is the electron source in such devices. The hollow cathodes can have electron emission density up to 10^6-10^7 A/m^2 at comparably low power consumption levels of 10-25 W/A. Thrust efficiency, mass utilization, operation stability, and reliability of electric propulsion systems, especially at low powers, heavily depend on the hollow cathode parameters.

Most hollow cathodes utilize low work function inserts such as polycrystalline LaB_6, CeB or W matrix impregnated with oxides mixture. Working temperature of these inserts ranges from 900 to 1600 ˚C, requiring refractory metal utilization, high starting and operation power consumption, and a complex design with tens of heat shields and thermal dividers. Another problem of these inserts is the so-called “poisoning effect” leading to usage of high purity inert gas, strict storage and handling requirements, implementation of special starting procedures after exposure to atmospheric air, and reliability and lifetime deterioration after several air exposures. In addition, ignition procedure of the cathodes operating with the above mentioned inserts usually requires two different power supplies; one for preheating of the insert and one for high voltage discharge ignition.

Cesium activated hollow cathodes is a competitive alternative for electric propulsion applications. Utilizing Cesium as a surface activator reduces the work function to 1.3-1.4eV at much lower operation temperatures (600 °C) when compared to BaO (1.9 eV at 1000 °C) or LaB_6 (2.7 eV at 1600 °C) inserts, which in turn reduces total power consumption and increases reliability, having similar Volt-Ampere characteristics.

This paper presents a Cesium based cathode that is being developed in the scope of Hall Effect Propulsion System Development Project (HALE)[1] carried by The Scientific and Technological Research Council of Turkey - Space Technologies Research Institute (TUBITAK UZAY). Results from the standalone cathode experiments and Hall thruster coupling tests performed in the electric propulsion facility at TUBİTAK UZAY premises in Ankara are also presented.

II.Cesium cathode design

For a cathode design, the best insert material would be the one having both low electron work function (opportunity to have larger emission current at lower temperatures) and high ion work function at the same time (low activator depletion rate). However, because of the same and inseparable nature of these two characteristics, such a material is unattainable. One approach to solve the problem is to have all construction elements of the cathode made of a material with high ion work function, while enabling electron emission from a thin low electron work function activator layer on the surface of the construction element. This approach is used in the cathodes impregnated with BaO-CaO-Al_2O_3 mixture. In these cathodes, Ba covers the surface of cathode construction made of tungsten matrix, thereby enhancing electron emission from the low electron work function Ba layer while retaining the cathode cavity geometry by high sputtering yield tungsten matrix. Preservation of the high emission layer in this case is ensured by a constant replenish of the depleted Ba molecules (due to diffusion) from the impregnated tungsten pores.

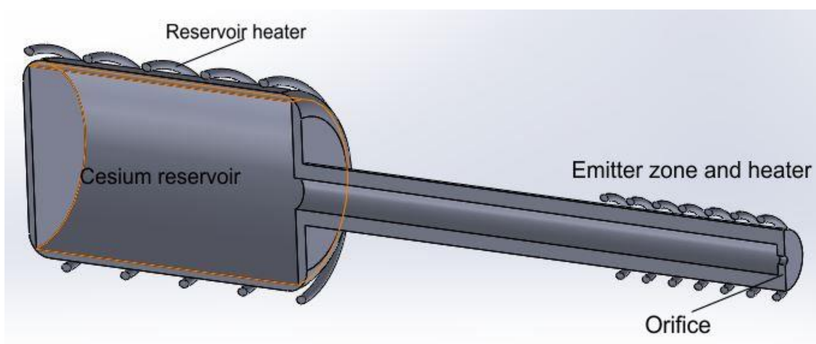

Figure 1. Cesium cathode model

At typical cathode operation temperatures, Cesium has two orders of magnitude higher vapor pressure and hence depletion rate than Ba. Therefore, usage of Cesium in a cathode requires a larger reserve and therefore implementation of an additional reservoir as depicted in Fig.1.[2]

In typical Cesium cathode designs[2] such as the one given in Fig. 1, the cathode consists of a reservoir filled with Cesium and a long tube enclosed by an orifice. In this design, emission occurs in the preheated region close to the orifice (emitter zone). The cathode has two separately controlled heaters. The reservoir heater regulates the Cesium vapor pressure, and thereby the mass flow rate of Cesium to the emitter zone. The emitter zone heater keeps the temperature sufficiently high for electron emission. Temperature difference between the emitter and reservoir region can reach up to 500 °C. For sustainable operation, the reservoir temperature at medium emission currents shall be below 200 °C, and therefore the emitter temperature can be in the range of 500-800 °C.[3]

In such cathodes, connecting the two heaters for a more compact and simpler design is desirable. However, coupling of the heaters or construction of the cathode to have only one heater in the emitter zone (where the reservoir is heated by conduction) is a complicated task. This can only be achieved experimentally for a narrow range of operation conditions.

The cathode that is designed in the scope of this work is presented in Fig. 2. It has a Cesium reservoir (1) enclosed by a porous orifice (2) and wrapped by a Tungsten heater (6). Two orifices (2, 3) and a ceramic insulator (5) form a cavity in front of the reservoir. In the current design, cathode operation with a low Cesium mass flow rate (or equally a low Cesium pressure inside the emitter zone) is desirable for a more compact structure. A keeper-like discharge can be applied to sustain stable operation under low pressure conditions (Cesium pressure of 10^{-5}-10^{-3} Torr). However, under such low pressures, Cesium cannot form a quasi-neutral plasma column and efficiently conduct electrons outside the cathode (In Cesium cathodes, typical pressure in the emitter zone for stable discharge and quasi-neutral plasma column formation is around 1 Torr). To overcome this problem, a supplementary gas cavity is added between the orifices 3 and 4 to the cathode design as shown in Fig. 2.

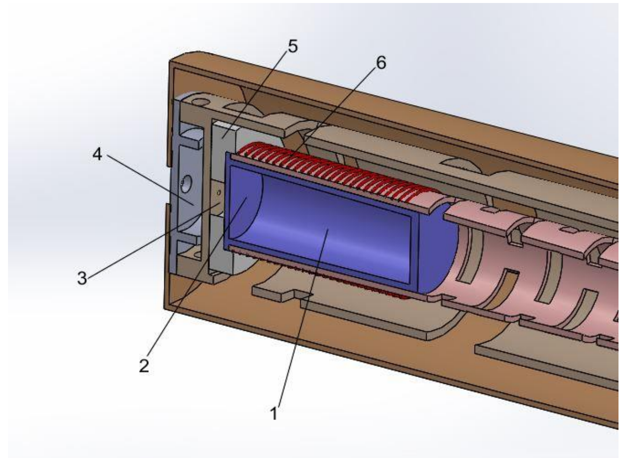

Figure 2. Cesium cathode with internal discharge and gas cavity

In our current design, a Cesium composition (more information is given below) is filled into the reservoir (1). The orifices 2, 3 and the ceramic insulator (5) form the necessary cavity for internal Cesium discharge. The orifices 3 and 4 form an additional gas cavity to create a positive plasma column, where the gas (e.g. Xenon, Argon, etc.) is supplied from the back of the cathode. The internal Cesium discharge is ignited by supplying a potential between the orifices 2 and 3. Main thruster discharge is connected to the orifice 4.

Analysis conducted in Ref. 3 leads to the fact that there is an optimal temperature of the emission surface for every pressure inside the cathode. As seen in Fig. 3, the optimal emission surface temperature lays in the interval of 650-700 °C (920-970 K) for a wide range of pressures. These temperatures are extremely high for a reservoir filled with pure Cesium (vapor pressure can exceed 600 Torr), making pure Cesium not applicable in a compact design like the one given in Fig.2.

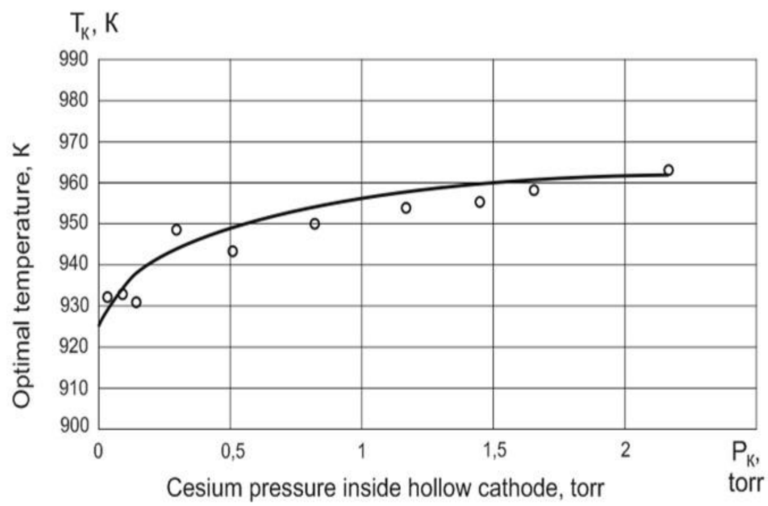

Figure 3. Dependency of optimal emission surface temperature on Cesium pressure in the discharge cavity

In the current design, instead of pure Cesium, its carbonate, Cs_2CO_3, that dissolves at temperatures close to emission surface optimal is used. At temperature levels above 610 °C, it dissolves and forms Cs_2O, which diffuses through porous orifice 2 to the internal discharge gap. Thermal dissociation continues forming pure Cesium and Oxygen atoms. An Oxygen layer forms on the porous metal surface together with a Cesium monolayer. It is well proven for thermos-emission electrical converters that coupled adsorption of electronegative elements with Cesium reduces the work function and increases the Cesium desorption energy.[4]

III.Keeperless starting approach

Starting procedure of the internal discharge in Cesium cathodes differs from ordinary hollow cathodes. Cesium offers an extremely low discharge ignition voltage, which led to the idea of implementing one power supply for both heating of Cesium reservoir and ignition of the internal discharge. In this approach, the heater (6) is connected in parallel with the internal discharge gap that is formed by the orifices 2 and 3. A voltage on the order of 15-20 V and a current on the order of 2 A are supplied to the heater together with the internal discharge gap. The Cesium reservoir is preheated until the pressure and temperature in the internal discharge gap reaches to a sufficient level for ignition. Typically, ignition starts at voltages even below 15 V. At the moment of ignition, the current that was flowing through the heater starts to flow through the arc discharge in the internal gap and the Cesium reservoir is maintained at the working temperature by the Cesium plasma discharge exclusively. The decrease of the reservoir temperature leads to a decrease in the Cesium pressure inside the cavity, subsequently resulting in an increase in the electrical resistance of the discharge gap. When the resistance of the discharge is increased, the voltage level, V_{id}, and hence the power deposited to the internal discharge increases. In that case, part of the current starts to flow through the heater, keeping the reservoir warm, and hence sustaining a stable Cesium pressure inside the cavity. This approach requires proper coupling of the Cesium composition chemical properties and the discharge and heater electrical properties together with the cathode geometrical sizes and thermodynamic properties.

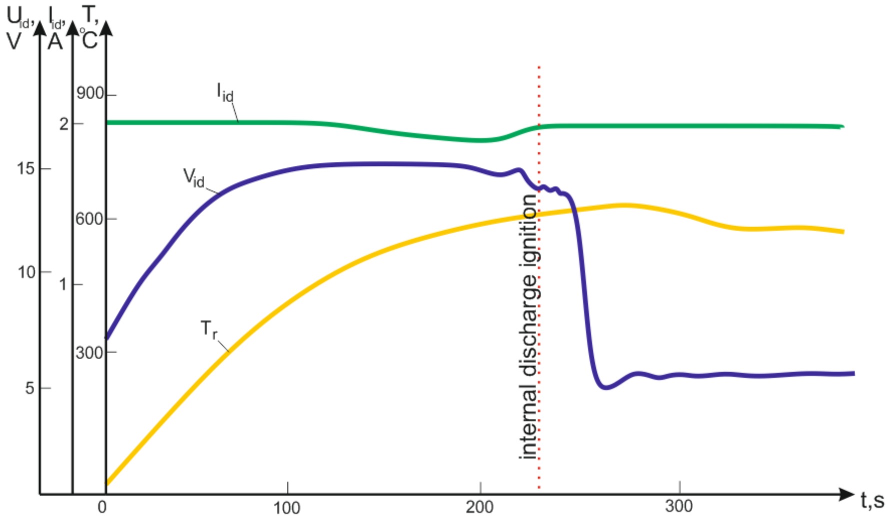

Figure 4. Time variation of the internal discharge voltage V_{id}, internal discharge current I_{id}, and Cesium reservoir temperature T_r at cathode startup

A typical starting procedure of the designed Cesium cathode is presented in Fig. 4. The graph shows time variation of the internal discharge voltage (V_{id}), internal discharge current (I_{id}) and the Cesium reservoir temperature (T_r) during the cathode startup. For the startup, the cathode is fed by a current and voltage limited-power supply (2 A and 15 V, respectively). On the graph before the internal discharge ignites at 225 s (typically starts somewhere between 200-300 s), all the current flows through the heater filament. In this time period, the voltage increases with temperature until the rise of the heater resistance ceases (before 90 s) and the power supply transfers into the voltage control mode and limits the voltage. Beyond this point, the current starts to fall gradually as the heater continues to increase the temperature. Close to the internal discharge ignition line, the temperature inside the Cesium reservoir reaches to a level enough for the start of thermos-dissociation of the Cesium carbonate resulting in an increase of the pressure inside the internal discharge gap. When the pressure reaches to a certain level, part of the current starts flowing through the gap, as the gap is electrically connected in parallel with the heater. Shortly after the initiation of internal discharge, Cesium low voltage arc discharge establishes in the gap. At this point, the power supply switches into a current control mode.

IV.Cesium hollow cathode coupling with Hall thrusters

In the scope of this work, in addition to cathode experiments, a series of coupling tests of the Cesium cathode with Hall thrusters are also performed. All cathode experiments reported in the previous section and the coupling tests with Hall thrusters that will be discussed in this section are performed at TUBITAK UZAY's electric propulsion test facility located in Ankara, Turkey. The vacuum chamber that is used in the experiments is 2.5 m in diameter and 4.3 m in length. The pumping system on the chamber utilizes three Oerlikon Coolvac 60000 cryopumps with an overall pumping speed of 180000 l/s and can reach an ultimate vacuum level of $2\ 10^{-8}$ mbar. This system is capable of keeping the pressure below $4\ 10^{-5}$ mbar under 50 sccm Xe load.

The cathode coupling experiments are performed with two different power Hall thrusters, which are also being developed in-house in the scope of HALE project. One thruster operates at a power of 200-300 W (called HALE-200 hereinafter) while the other one has a power level of 1-1.5 kW (HALE-1500). The HALE thrusters integrated with the designed HALE cathode are presented in Fig. 5

For the HALE-1500 thruster experiments, the thruster discharge voltage is varied in the range of 150-500 V while the discharge current is varied in range of 3-6 A. The firing experiments for the cathode coupled HALE-1500 thruster show an anode efficiency of 58% when the operating power is set to 1365 W and the cathode supplied 4.55 A at 4 sccm Xe mass flow. For the HALE-1500 thruster, the anode efficiency is increased up to 60.5% when it is fired at a non-nominal operation point, where the cathode supplies varying current between 5 and 12 A, and the power consumption reaches 1792 W.

Similar experiments are also performed for HALE 200 with anode and cathode mass flow rates of 10 sccm and 0.8 sccm of Xe, respectively. The results from the HALE-200 firing tests show an ultimate anode efficiency of 39% at 250 W power and 0.94 A discharge current.

More detailed analysis of the HALE 200 thruster operation is conducted for a better understanding of the influence of the internal discharge current (I_{id}) and Xe mass flow on the coupling. During these experiments, the cathode is insulated from the thruster structure while both the cathode and thruster are insulated from the chamber ground. Voltage drop between the cathode outer shell and Hall thruster body is measured under varying cathode mass flow rates and internal discharge currents (I_{id}) while keeping the anode voltage and anode mass flow constant at 200 V and 10 sccm Xe, respectively. Before collecting the data in Fig. 6, the thruster is allowed to operate for 40 minutes to avoid outgassing effects and sustain stable discharge current. (Please note that the time period required for the stabilization of the cathode is around 7-10 minutes as seen in Fig. 4.)

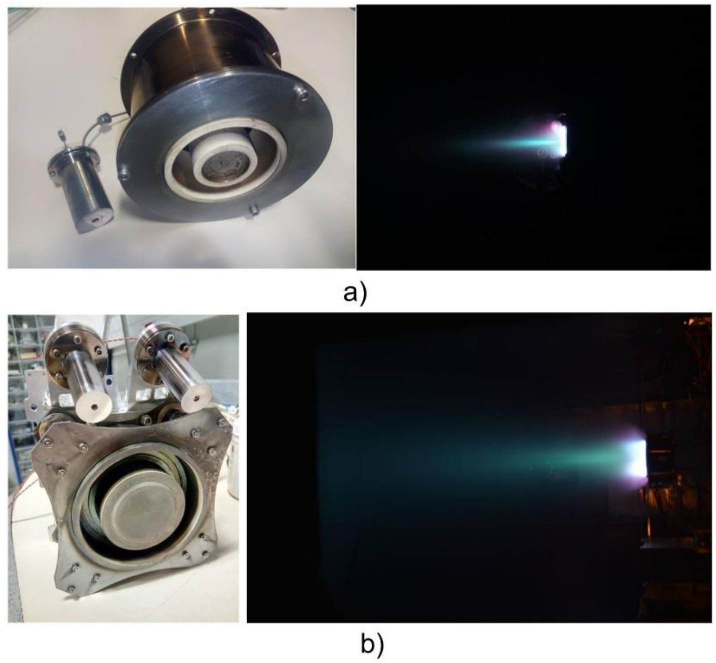

Figure 5. HALE Hall thrusters. *a) HALE-200; b) HALE-1500*

For the experiments, the cathode internal discharge is set to 2 A and 15 V, and the anode discharge is set to 200 V and 1 A. The cathode startup follows the pattern that is already described in section III. The cathode voltage and mass flow rate data are collected under varying internal discharge current by using a NI DAQ6211 and two MKS MF-1 mass flow meters, and plotted with respect to each other in Fig. 6. Even though the measured voltage is not directly correlated with the coupling voltage, it still provides some insight about the influence of the cathode parameters on the coupling.

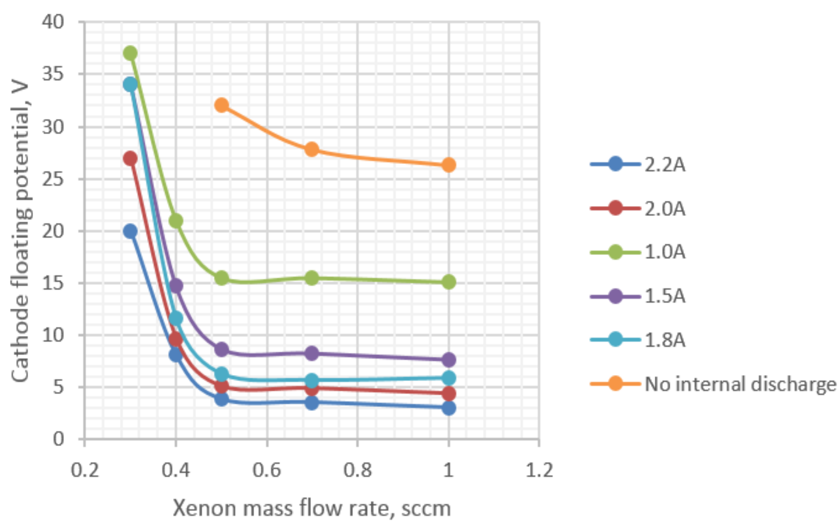

Figure 6. Cathode floating potential dependency on Xe mass flow and internal discharge current

As seen on the plot in Fig. 6, the cathode floating voltage sharply decreases with the Xe mass flow rate increase. Beyond 0.5 sccm, any additional Xe mass flow does not show a significant influence on the cathode floating voltage. This behavior is expected and related with the "plume to spot" mode transition of the cathode [5,6]. While supplying 1A to the thruster, this mode transition occurs at ~0.5 sccm Xe for the current design.

The results also show that the internal discharge current has an influence on the floating potential. As seen in Fig. 6, the cathode floating potential is significantly lower for the internal discharge currents greater than 1.5 A. Moreover, dependence of the cathode floating potential on I_{id} at constant mass flow rate is mostly linear, with a small slope change near 1.5 A. Results also show that the cathode can function without an internal discharge at voltages between 26 and 32 V in the cost of a significant power consumption (the orange curve). When the overall thruster efficiency is considered, power consumption due to both coupling and internal discharge is part of the loss in the system. Comparison of the curves in Fig. 6 implies that the increase in the internal discharge current between the curves is a lot slower than the decrease in the corresponding coupling voltage (note that the results in Fig 6 are obtained under a constant anode current of ~1 A and a cathode internal discharge voltage of ~5 V). As the coupling voltage does not benefit the thrust production,[5] supplying a couple of watts more power to the internal discharge should improve the overall thruster efficiency.

V.Conclusion

In this paper, the advantageous of Cesium cathodes over BaO-CaO-Al_2O_3 impregnated cathodes and cathodes with LaB_6 inserts are discussed by presenting a Cesium cathode design and its test results. In Cesium cathodes, low electron work function allows for receiving comparable electron emission currents with the other types of cathodes at low temperatures. Typical operation temperature of the designed cathode is below 700 °C. Moreover, high vapor pressure and low ionization energy of Cesium offers an internal discharge ignition without any additional gas feed and high voltage power supply, which also reduces the total power consumption in our design. Coupling of physical, chemical, and geometrical properties of this Cesium based cathode enables an easy and predictable starting procedure, which can be handled by only one low voltage, current stabilized-power supply. Cathode coupling tests with Hall thrusters conducted in the scope of this work show that minimum mass flow rate to ensure the spot mode operation of the cathode at 1 A emission current is 0.5 sccm Xe. Results also suggest that to improve the overall thruster efficiency, the internal discharge should be maintained all the time because of its significant influence on the cathode-thruster coupling properties. Future work will concentrate on the phenomenological model development for gaining more insight about the cathode operation and lifetime evaluation.

Acknowledgments

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