Experimental Investigation of the Effect of Channel Material on Hall Thruster Characteristics

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Abstract

The operation of an experimental Hall thruster with two channels of identical geometry made from different materials, glass and boron nitride ceramics, was compared. Higher current ratio and efficiency values were obtained with the boron nitride ceramic channel. The differences in thruster behavior between the two channel materials became more appreciable as the discharge voltage was increased. These results indicate the significant role of near wall processes in determining the magnitude of the axial electron current. Since larger axial electron currents were obtained with the non-sintered ceramic, it is suggested that even though near wall process may depend on the surface roughness or the porosity of the channel, they are affected by other channel material properties, e.g. the dielectric constant.

1. Introduction

As is well known, Hall thrusters are characterized by a large specific impulse as compared to chemical and conventional thrusters and larger thrust density than ion engines. An additional characteristic is the ability to modify the jet velocity and/or the thrust by varying the mass flow and/or the discharge voltage [1]. This flexibility enables, in principle, to operate Hall thrusters under various conditions at constant or variable power levels [1-4]. However, the practical realization of this potential depends on the ability to maximize the thruster efficiency at the various operating modes.

The thruster efficiency can be written as the product of the propellant utilization and the power efficiency. As for the propellant utilization, it depends on the mass flow rate and can be affected by the channel geometry [3,7,8]. Experiments with a Soreq built Hall thruster indicated that the propellant utilization and, as a result, the specific impulse and the efficiency tends to degrade as the mass flow rate is reduced at a given discharge voltage [3-7]. By modifying the channel length and profile, improvements in the propellant utilization and thruster performance at small mass flow rates were achieved [3,4,6].

As for the power efficiency, it is proportional to the ion to discharge current ratio, I_i/I_d, at the thruster exhaust [1]. Operating the Soreq experimental thruster at relatively low mass flow rate values, it was observed that there is a limited range in which the current ratio is almost not affected by the discharge voltage [7]. At larger discharge voltages, the current ratio and, as a result, the thruster efficiency drop significantly. Near wall processes of some kind leading to an increased axial electron current, were suggested as a possible explanation for this behavior [7].

Near wall processes in Hall thrusters were intensively investigated, both experimentally and theoretically [1,9-11]. Nevertheless, their mechanisms are far from being understood. Some experimental results have indicated that the material structure of the channel do affect the axial electron current and its radial distribution [9,10]. For example, measured axial electron current amplitudes in a quartz channel were found to be lower than those obtained with a channel fabricated from a hot pressed boron nitride (BN) ceramic at similar thruster operating conditions [9]. The granular structure of the BN ceramic was suggested as a possible explanation for this result [9].

In our previous works mentioned above the experimental thruster was operated with a channel fabricated from a non-sintered machinable glass ceramic (GC). In order to investigate the dependence of thruster behavior on channel material, a set of thruster operating experiments was performed with a BN ceramic channel. As it is described in section 2, GC and BN materials have different mechanical, thermal and electrical properties. A sample of results of the experiments performed with the BN channel

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and their comparison with those obtained with a GC channel are described in section 3. In general, higher values of the current ratio were obtained with the BN channel and, as a result, also higher efficiencies. Also, the voltage range in which the current ratio is almost constant is extended in the BN case. These results indicate that other material properties than those suggested in [9] may play a role in the near wall processes and thus in determining the magnitude of the axial electron current.

2. Machinable glass vs. boron nitride ceramics

A schematic drawing of the Hall thruster is shown in Fig. 1. An experimental Hall thruster was used as a research tool to characterize the thruster operation under various conditions [5], with two identical geometry channels made of two different ceramic materials, BN and GC. Table 1 bellow compares some properties of these materials. Although a firing procedure is not required for both ceramics, a GC channel can be machined with a higher precision due to its better mechanical properties. Moreover, having a higher density and zero porosity, the problem of outgasing in vacuum is lower for GC. An additional advantage is its relatively low price which makes the GC material attractive for use in the laboratory. On the other hand, the lower thermal expansion of BN and its higher thermal conductivity result in a reduced level of undesired thermal stresses in the channel during thruster operation. Additional advantages of BN are its higher usage temperature and, most probably, its lower dielectric constant, which is almost not changed in the usage temperature range.

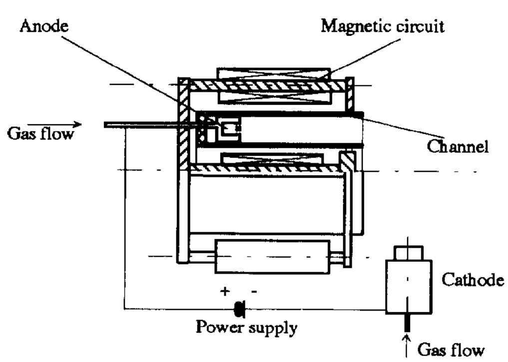

Fig. 1 A schematic drawing of the Hall thruster.

Table 1: A comparison of some properties of machinable glass (GC) and boron nitride (BN) ceramics.

Ceramic:	GC	BN
Shear strength, MPa	$26\cdot10^3$	29.86
Porosity, %	0	15.27
Maximum usage temperature, ° C	1000	1800
Thermal expansion, $\times10^{-6}$ 1/° C at room temp. to 800 ° C	12.3	≈ 0.7
Dielectric constant : at room temp. at 400° C	5.68 10	4.02 ≈5

3. Results and discussions

The experiments we shall now describe were performed with BN and GC channels of the same channel length, L = 40 mm, where L is taken from the anode to the thruster exhaust. The thruster was operated in the discharge voltage range of 100 - 500 V using a 500 V laboratory voltage regulated power supply, and at two xenon gas mass flow rates, 1.2 mg/s and 1.7 mg/s. As the aim of this work was to study the effect of channel material on Hall thruster operation, the value of the mass flow rate, in all the results described below includes only the anode mass flow rate and a correction for the background pressure in the chamber, while the cathode mass flow rate is not included.

The experiments took place in the vacuum facility at Soreq [5]. The following diagnostics were used in these experiments: a high sensitivity (0.5 mN) thrust stand, discharge voltage and current, coils current and mass flow rate measurements, and a planar Langmuire probe setup for jet plume measurements [3,5].

Discharge characteristics

The influence of the magnetic field on the thruster operation was observed with both ceramic channels. However, with the BN channel it was somewhat different from that with the GC channel. For example, Fig. 2 compares the discharge current versus the coils current at a constant discharge voltage of 250 V for both BN and GC channel cases at a mass flow rate of 1.7 mg/s. In the GC case, when the coils current is varied at a given mass flow rate, there is a value of the coils current, I_c*, for which the discharge current is minimal, a behavior which was already described in Refs. 5 and 7. Since in such operating points with the GC channel, the thruster efficiency was found maximal [5], for all the relevant results presented bellow, the coils current was at the corresponding I_c*.

With the BN channel, instead of I_c* at which the discharge current is minimal, there is a range of the coils current in which the discharge current is almost not changed (See Fig. 2). As explained in Ref. 2, the increased discharge current, which was usually observed with the GC channel at $I_c > I_c$*, was found to be associated with an appearance of large amplitude discharge oscillations. Oscillations of the same frequency range were also measured with the BN channel. Here, their amplitude was found also to increase with the coils current even though the discharge current was unchanged. In any case, the value of the coils current above which the discharge current is unchanged, while the amplitude of oscillations is minimal, was taken as an equivalent I_c* at each operating point for all the subsequent results related to the BN channel.

Figs. 3 and 4 show illustrative curves of I_c* versus the mass flow rate, obtained at a constant discharge voltage of 250 V, and the dependence of I_c* on the discharge voltage for two values of the mass flow rate, 1.2 and 1.7 mg/s, respectively, for the BN and GC channels. For the BN channel, as in the case of the GC channel, I_c* is almost proportional to the mass flow rate (See Fig. 3). In addition, a behavior of $I_c^* \propto V_d^{1/2}$ [1], which according to Ref. [7] is a characteristic of a constant current ratio at a given mass flow rate, was also observed with the BN channel for both mass flow rates, as the discharge voltage was increased from 150 to 300 V (See Fig. 4). However, in contrast to the GC channel case, a sharp increase in I_c* at larger discharge voltages was not observed with the BN channel. Here, at 1.2 mg/s, I_c* increases slower with the discharge voltage as the discharge voltage is increased from 300 V to 500 V, while at 1.7 mg/s, I_c* is almost unchanged, up to 470 V.

A possible explanation of these results is that in the BN channel case, near wall processes affect less the thruster operation than in the GC case. Fig. 5 shows a sample of illustrative curves of the measured ion to discharge current ratio, I_i / I_d, versus the discharge voltage at two mass flow rates of 1.2 mg/s and 1.7 mg/s, for the two channel material cases. As could be expected from the above results of I_c* versus the discharge voltage, the current ratio measured with the BN channel for both the mass flow rate values is almost not changed when the discharge voltage is increased from 150 to 400 V. Some insignificant reduction of the current ratio appear at larger discharge voltages. In general, lower values of the current ratio and consequently larger values of the axial electron current are observed with the GC channel for both mass flow rates.

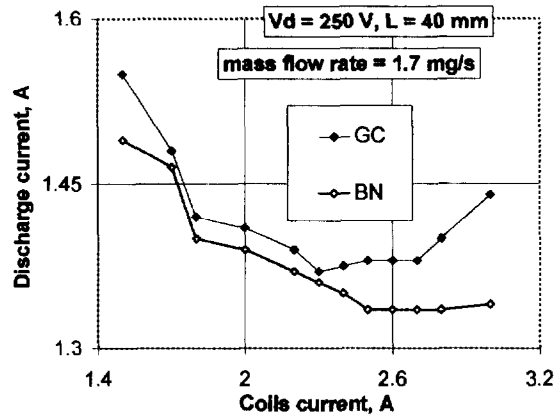

Fig. 2 The discharge current versus the coils current obtained at constant values of the discharge voltage, 250 V, and the mass flow rate, 1.7 mg/s, with BN and GC channels of the same channel length, 40 mm.

The above results appear to be in some contradiction to the conclusions of Ref. [9], where Hall thruster operation with quartz and BN channels was investigated. According to this reference, the granular structure of the sintered BN contributes mainly to an increased axial electron current at large discharge voltages. Since GC is a non-sintered material, it seems that there are also other factors, which may be caused by differences in other physical properties of the channel materials, for example the dielectric constant (See Table 1), and which affect strongly the axial electron current, and, as a result, the current ratio.

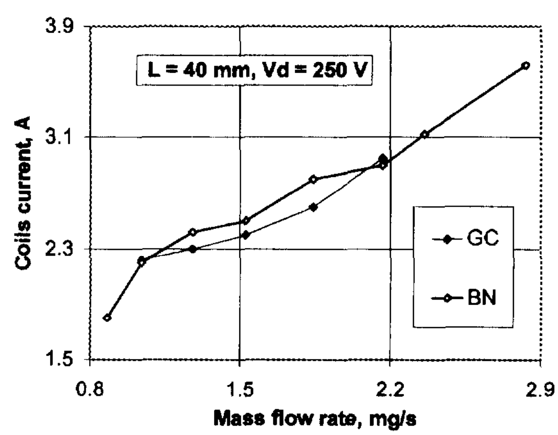

Fig. 3 I_c* versus the mass flow rate at a constant discharge voltage of 250 V for two channels made from GC and BN, respectively, with the same channel length, L = 40 mm.

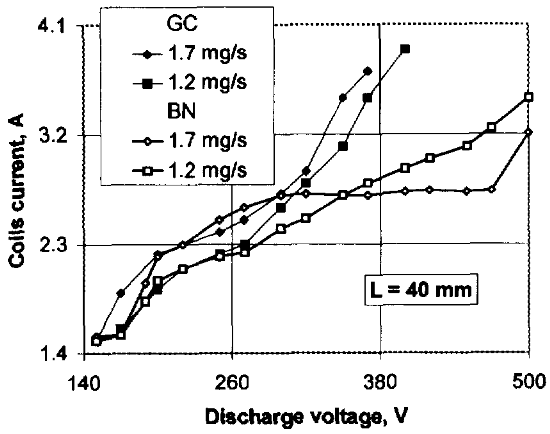

Fig. 4 I_c* versus the discharge voltage for two channels made from GC and BN, respectively, with the same channel length, L = 40 mm, and for two mass flow rates, 1.2 mg/s and 1.7 mg/s.

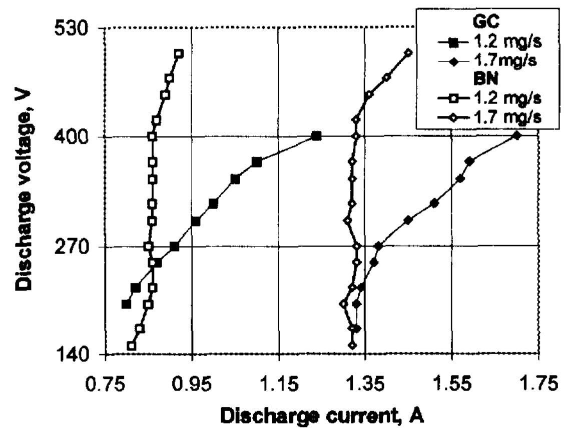

Fig. 6 The V-I characteristics measured at two mass flow rates $\dot{m}$ = 1.2 and 1.7 with the channels made from two different materials, BN and GC, of the same channel length L = 40 mm.

Fig. 6 demonstrates the V-I characteristics measured with the BN and GC channels at the two mass flow rates. It has to be noted here that the thruster operation with the GC channel at $V_d > 400$ V was usually unstable and sometimes associated with a significant heating of the thruster parts. Therefore, in contrast to the BN channel, where the thruster behavior was very stable almost at all the measured range of the input parameters, it was almost impossible to perform measurements at this discharge voltage range with the GC channel. As could be expected, a different behavior was obtained with the BN channel. Here, the discharge current is almost not changed with the discharge voltage from 150 V to 500 V.

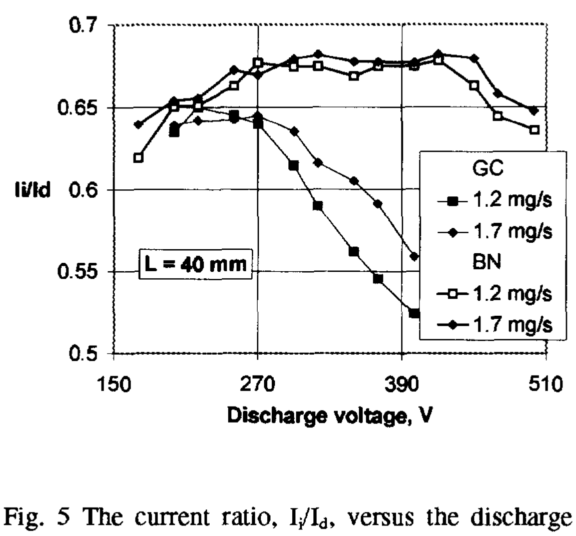

Fig. 5 The current ratio, I_i/I_d, versus the discharge voltage at two mass flow rates of 1.2 mg/s and 1.7 mg/s and at a channel length of 40 mm, for the GC and BN channel material cases.

Propellant utilization

Illustrative results of the propellant utilization, $\frac{m}{e}\frac{I_i}{\dot{m}}$, [1], versus the discharge voltage obtained for both channel material cases at two mass flow rates, 1.2 mg/s and 1.7 mg/s, are shown in Fig. 7. e and m are the electron charge and the atomic mass, respectively. As can be seen, in most cases of given values of the mass flow rate and the discharge voltage, larger propellant utilization was obtained with the GC channel. At discharge voltages larger than 270 V, this result could be attributed to an increased electron flux density, which is caused by near wall processes, leading to an increase of ionizing collisions in the channel.

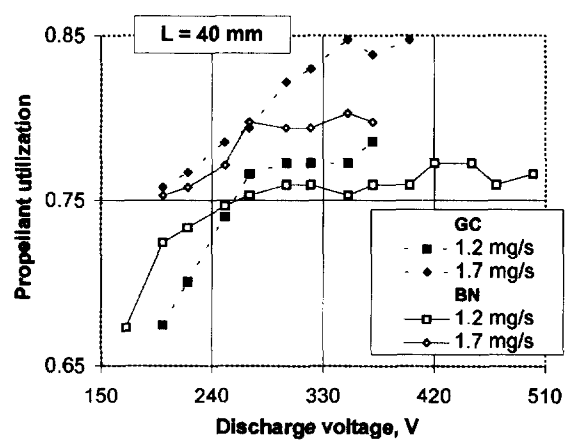

Fig. 7 The propellant utilization versus the discharge voltage obtained with the BN and GC channels of the same channel length, L = 40 mm, at two mass flow rate values: 1.2 mg/s and 1.7 mg/s.

On the other hand, it follows from the corresponding V-I characteristics and the current ratio versus the discharge voltage (See Figs. 5 and 6), that the resulted increase in the ion current is smaller than the increase in the axial electron current and therefore, lower thruster efficiency could be expected for the channel made from GC.

Thruster performance

It follows form the V-I characteristics shown in Fig. 6 that at a given mass flow rate the input power increases with the discharge voltage. The thruster performance versus the input power measured for the same operating conditions is shown in Fig. 8. Generally speaking, at both mass flow rates, 1.2 mg/s and 1.7 mg/s, the better thruster performance was obtained with the BN channel. As can be seen from Fig.8c, the behavior of the efficiency reflects that of the current ratio at small mass flow rates. For example, in the case of the BN channel, at $\dot{m}$ =1.2 mg/s the efficiency reaches about 40 % at 215 W (V_d = 250 V), and remains almost the same as the voltage is increased. On the other hand, the efficiency with the GC channel has a maximum of about 35 % at 246 W (V_d = 270 V) and then drops for higher voltage values. These results indicate that Hall thruster operation in a variable thrust mode [3], or large Isp operating modes [3,4] can be more efficient with the BN channel.

3. Conclusions

In this paper we compared the operation of an experimental Hall thruster with two identical geometry channels made from different materials, glass ceramic and boron nitride ceramic. In general, higher values of the current ratio and, as a result, better thruster performance were obtained with the BN channel. These differences became more appreciable as the discharge voltage was increased. These results indicate that ion and electron losses in the thruster depend on some properties of the channel material. It seems that a near wall mechanisms of some kind plays a significant role in the physical processes taking place inside the Hall thruster during its operation. This supposed mechanism, whose magnitude could depend on the dielectric constant, the secondary emission yield or the surface roughness or porosity of the channel material, is a matter for further investigations, both experimental and theoretical. For that purpose, thruster operation with channels made from additional materials is planned.

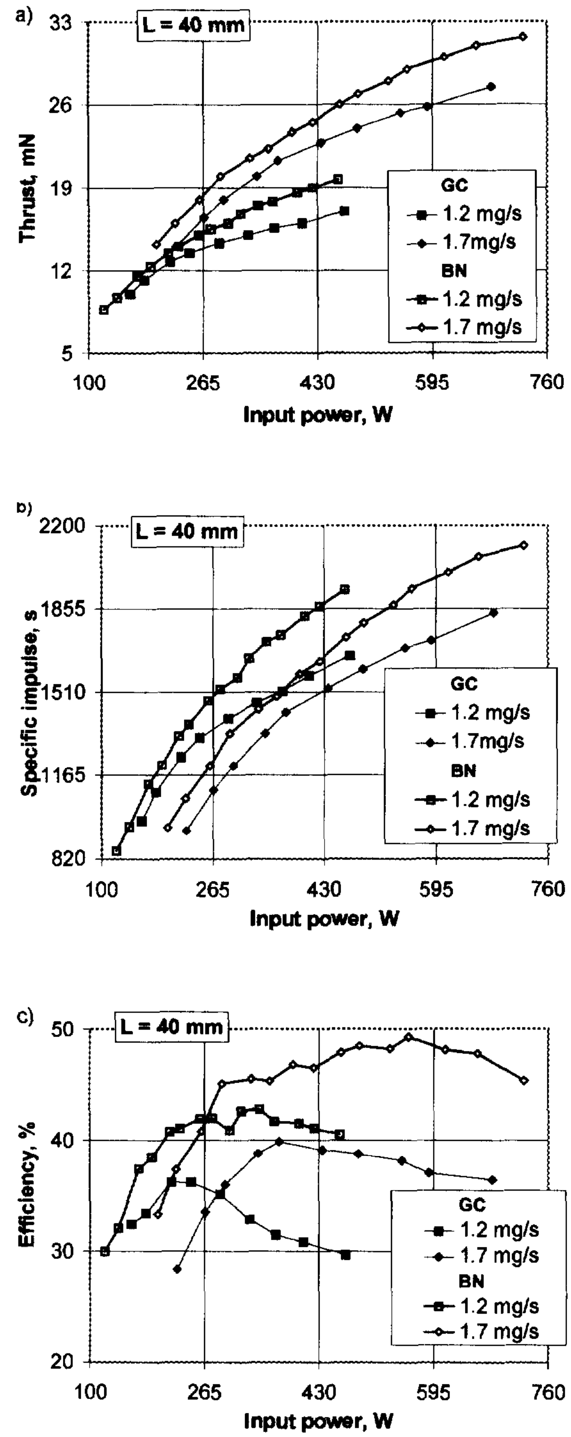

Fig. 8 A comparison of the thruster performance obtained with the GC and BN channels for the same channel length of 40 mm at two mass flow rates, 1.2 mg/s and 1.7 mg/s. a) Thrust b) Specific impulse and c) Thruster efficiency versus the input power.

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