Physics of closed drift thruster

Article *in* Plasma Sources Science and Technology · January 1999

DOI: 10.1088/0963-0252/8/1/021

Harold Kaufman
Kaufman & Robinson, Inc.

Raymond S. Robinson
Colorado State University

Plasma Sources Sci. Technol. **8** (1999) R1–R20. Printed in the UK PII: S0963-0252(99)00084-5

REVIEW ARTICLE

Physics of closed drift thrusters

V V Zhurin†, H R Kaufman‡ and R S Robinson§

† Front Range Fakel, Fort Collins, CO 80524, USA
‡ Front Range Research, Fort Collins, CO 80524, USA
§ Colorado State University, Fort Collins, CO 80523, USA

Received 13 April 1998, in final form 3 December 1998

Abstract. Closed drift thrusters are reviewed. The publications on these thrusters constitute a large body of information. This article can therefore include only the most prominent theoretical and experimental features of closed drift thrusters. In some regards, this article is also an attempted synthesis of the differing views of these thrusters found in literature, as well as in our own work.

In a closed drift thruster, the electric field that accelerates the ions is established by an electron current that passes through and is impeded by a magnetic field. The precessing electrons in this magnetic field follow a closed drift path giving this thruster its name. Closed drift thrusters are divided into magnetic layer and anode layer types, based both on the geometrical and material differences in the discharge channels of the two types, and on the different physical processes that take place within the discharge plasma.

Considered as a whole, the publications on closed drift thrusters constitute an impressive body of information that, for the most part, was generated in Russia independently of US research on electric thrusters.

1. Short historical review

Electric propulsion permits the reduction in propellant mass for a given space propulsion mission by generating higher exhaust velocities than are possible with chemical rockets. One type of electric thruster is the closed drift thruster. The study of thrusters with closed electron drift was initiated independently in the USSR and the US during the early 1960s [1–6]. In the US, and sometimes in the USSR, they were also variously called Hall-current thrusters and plasma thrusters—or accelerators.

The earliest devices clearly related to closed drift thrusters were axially symmetric designs introduced about 1960. The configurations investigated included both radially and axially accelerated beams. The thruster efficiencies, however, were poor.

By the late 1960s, there were efforts in both the US and the USSR on closed drift devices with efficiencies approaching 50% and design features clearly related to present designs. Some of these features were: steady-state operation at moderate power levels, external sources of electrons and externally applied magnetic fields.

In the US the effort on closed drift devices was smaller than that in the USSR, was directed primarily toward electric space propulsion (thrusters) [6] and stopped about 1970 due to a lack of progress compared to other types of electric thruster. The US electric propulsion programme continued after 1970, but emphasized other propulsion devices. As a measure of programme size in the US, there were a maximum of perhaps 200 engineers and scientists working on electric thrusters of all types by 1970 [7]. As the programme on electric space propulsion evolved, the efforts on other system components increased, so that the direct effort on electric thrusters decreased.

The effort on closed drift devices in the USSR not only continued, but was directed at ion accelerators in general, as well as the more narrow goal of thrusters for electric space propulsion. As a measure of the size of this effort, 2000–3000 engineers and scientists worked on closed drift devices in the USSR in the late 1980s [8]. It is significant that the effort in the USSR was more than an order of magnitude greater than that in the US. As a result of both the continuity and the size of the effort in the USSR, the present technology of closed drift accelerators and thrusters is primarily indebted to their efforts.

The best documentation for closed drift technology in the USSR during the 1970s and 1980s is in the proceedings of the *All-Union Conferences on Accelerators and Ion Injectors* [9]. The references for the theory given herein are almost all in the Russian language. Further, almost all of these references describe work conducted within Russia—formerly a part of the USSR and now the Russian Federation, or Russia. It is therefore proper to say that the development of the closed drift thruster is primarily a Russian achievement.

As shown by the articles presented at these conferences, the effort on closed drift thrusters in the USSR evolved into two major competing groups. The first group studied the thruster with closed electron drift and an extended acceleration zone, also called the stationary plasma thruster, and, more recently, the thruster with a magnetic layer. The leading scientist in this group was A I Morozov, and substantial work was carried out at the Kurchatov

Atomic Energy Institute (Moscow), the Moscow Aviation Institute, the Fakel Design Bureau (Kaliningrad, formerly Königsberg, in the Baltic region of the USSR), the Moscow Institute of Radioelectronics, the Moscow Research Institute of Thermal Processes, the Dnepropetrovsk State University (Dnepropetrovsk, Ukraine) and Kharkov Aviation Institute (Kharkov, Ukraine), and at other locations.

The second group studied a thruster with a shorter acceleration channel, called the anode layer thruster. The leading scientist in this group was A V Zharinov. Although the R&D effort on this device was smaller than on the magnetic layer type, considerable work was carried out at the Moscow Bauman Technical University, the Central Institute of Machine Building (Kaliningrad, a Moscow suburb now called Korolev), the Tbilisi Institute of Physics of the Georgian Academy of Sciences (Tbilisi, Georgia) and some other locations.

The initial operation of a magnetic layer thruster in space (the SPT-60) took place in February 1972 on the Meteor spacecraft [10, 11]. Following this initial operation, approximately 100 magnetic layer thrusters have been used on operational satellites. In comparison, the dominant US thruster technology has been the gridded electron-bombardment thruster. Although there have been space tests of this thruster (SERT-I and SERT-II) [12, 13] there have been no operational applications on satellites.

There appear to be two reasons for the relative success of the closed drift thrusters in space. First, the closed drift thrusters were (and are) much simpler than the US gridded thrusters. Second, at the time that closed drift thrusters were first used in space, high-energy storable chemical propellants were less developed in the USSR, thus the alternatives to electric propulsion were perhaps less attractive than they were in the US.

2. Types of closed drift thruster

There are many different configurations of closed drift thrusters. However, it is generally helpful from both a theoretical and experimental viewpoint to consider them as being either of the magnetic layer type or of the anode layer type.

Although most closed drift thrusters are of the one stage type, it is also necessary to recognize that considerable work has also been done on two stage thrusters.

Finally, the intent in this section is only to distinguish between the broad general categories of closed drift thrusters. Some of the rich variety of devices described in the literature will be indicated in later sections.

2.1. Operation of a closed drift thruster

One stage closed drift thrusters are shown in figures 1 and 2. Each of these thrusters has a magnetic circuit that generates an axisymmetric and generally radial magnetic field between the inner and outer poles. As shown, this magnetic circuit usually employs one inner magnet winding and several outer magnet windings, with the magnet windings powered either by a separate power supply or by connecting the magnet windings in series with the discharge supply. Although this

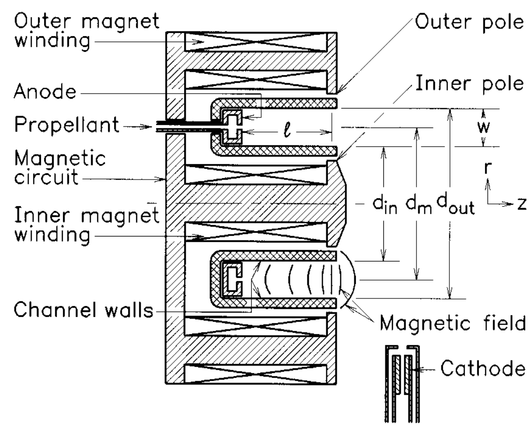

Figure 1. Closed drift thruster of the magnetic layer type.

configuration of the magnetic circuit is most common for space propulsion thrusters, other numbers and locations have been used for the magnet windings, and permanent magnets have occasionally been used in place of electromagnets.

The discharge results from a potential difference, V_d, being applied between the anode and cathode, called the cathode-compensator in Russian literature. This potential difference is generated by the discharge power supply (not shown). There can also be one or more power supplies associated with the hollow cathode, but these power supply circuits are generally similar to those used for hollow cathodes in gridded thrusters, and will not be discussed further.

In operation, an electric discharge is established between the anode and cathode. The electrons flowing from the cathode to the anode interact with the magnetic field and generate the accelerating electric field within the discharge plasma. These electrons also generate ions in collisions with neutral atoms of propellant. In addition to the electrons that go to the anode, some of the electrons from the cathode go to the ion beam and both charge and current neutralize the ions in that beam.

2.2. Magnetic layer thruster

A one stage magnetic layer type of closed drift thruster is shown in figure 1. Although multiple stage thrusters of the magnetic layer type have been tested, such attempts have been rare [14]. Almost all literature on this type of thruster is concerned with the one stage type. This thruster type is also known as a stationary plasma thruster and as a thruster with closed drift and extended acceleration region or zone. The distinguishing features of this type of thruster are ceramic walls for the discharge channel and a length of that channel, l, that is long compared to the channel width, w. The channel width in this case indicates both the width between the walls and the width of the beam of plasma that is accelerated.

The ceramic wall plays an important role in the discharge. The collisions of electrons and ions with the wall generate low energy secondary electrons. These secondaries tend to keep the electron temperature low in the discharge plasma. This low electron temperature in turn results in a more extended and gradual acceleration process. The latter

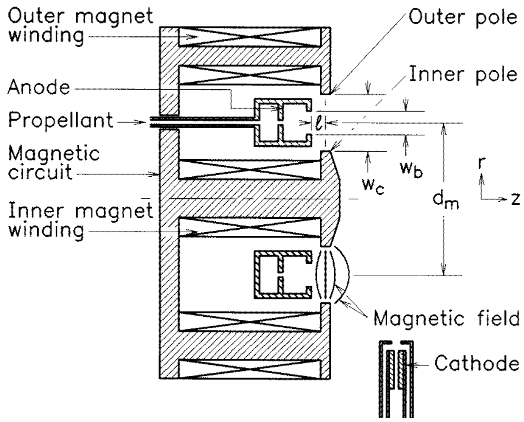

Figure 2. Closed drift thruster of the one stage, anode layer type.

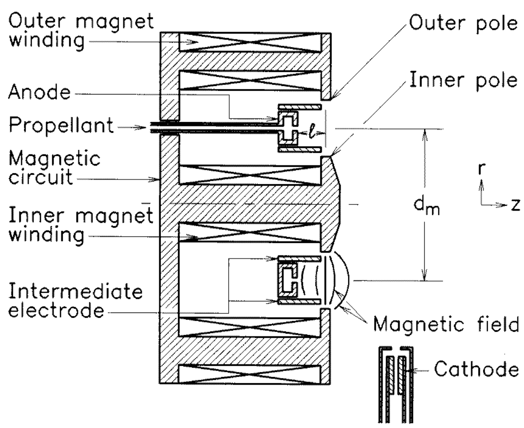

Figure 3. Closed drift thruster of the two stage, anode layer type.

effect is the basis of the use of 'extended acceleration zone' in one of the alternate names of this type of thruster.

2.3. Anode layer thruster

A one stage anode layer type of closed drift thruster is shown in figure 2. This type has also been called a thruster with short acceleration region or zone. The distinguishing features of this type of thruster are conducting walls for the discharge channel and a length of that channel, l, that is short compared to the channel width. In figure 2, the walls of the discharge channel might be considered the inner and outer poles, so that the channel width, w_c, is the width between these poles. The erosion of these poles is minimized by confining most of the accelerated beam of ions to a narrower beam width, as shown by the width, w_b, in figure 2.

With no energy-reducing exchange process to limit the electron temperature, the electrons flowing from the cathode to the anode increase in temperature. This increase in temperature results in a sharp increase in plasma potential as the anode is approached, so that much of the ion generation and acceleration takes place in a thin layer near the anode, which is the origin of the name 'anode layer'.

A two stage anode layer thruster is shown in figure 3. The intermediate electrode is maintained at a potential intermediate of the cathode and anode. The first stage between the anode and intermediate electrode is usually called the ionization stage, while the second stage between the intermediate electrode and the cathode is usually called the acceleration stage. In the configuration shown in figure 3, the width of the discharge channel is defined by the inner surfaces of the intermediate electrode. Because of the generally low ion energy in the ionization stage, collisions of ions with the intermediate electrode are less serious from an erosion viewpoint than collisions with the magnetic poles, which occur at much higher ion energies. Anode layer thrusters with one and two stages are both widely known and described in literature, although almost all present devices designed for space propulsion have one stage [15].

2.4. Basic closed drift theory

The general theoretical foundation of closed drift thrusters is presented in this section. This foundation applies to both magnetic layer and anode layer types of closed drift thruster. Although much of this theory applies to both one stage and multiple stage thrusters, some of it is limited to one stage versions, which are almost exclusively used for space propulsion. The brief review of theory presented in both this section and following sections was drawn primarily from a number of books on closed drift thrusters [16–25]. Appropriate page numbers are given with the specific items of theory. Because of the quantity of material covered, the theoretical derivations in the following presentation are often minimal and sometimes omitted. SI (rationalized mks) units are used throughout.

2.5. General operation

Most of the ions produced in closed drift thrusters are singly charged, and only singly charged ions are considered in this section. The reason for the bulk of the ions being singly charged is fairly straightforward. As soon as an atom loses an electron, there is usually enough accelerating electric field to rapidly remove that ion from the discharge plasma before another collision with another electron can further ionize it. Multiply charged ions are therefore mostly the result of single collisions of electrons that were sufficiently energetic to remove two or more electrons from a neutral atom. In addition to requiring electrons with sufficient energy, the cross sections for multiple ionization in a single collision are small compared to the single ionization cross section.

The efficient operation of closed drift thrusters, figures 1–3, is based upon the reduced mobility of plasma electrons across a magnetic field. The magnetic field between the pole pieces of the assumed axisymmetric thruster configuration is predominantly in the radial direction. The distribution of radial magnetic field and the resulting axial potential distribution, together with the circumferential motion of electrons in a closed drift thruster is indicated in figure 4. The ions enter the closed drift region from the anode side and are accelerated into the ion beam (from left to right in figure 4).

The axial variation in the strength of the radial magnetic field (figure 4(a)) has a bell-shaped distribution, reaching a maximum near the pole pieces and decreasing both near the anode and at the exit end of the thruster. In the resulting

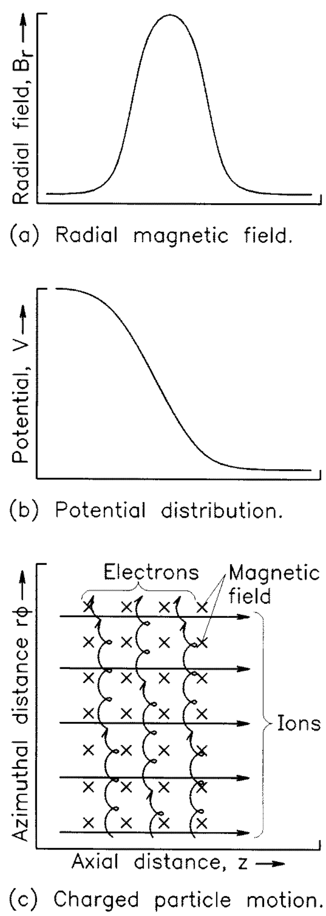

Figure 4. Potential distribution and charged particle motion for a given distribution of radial magnetic field.

potential distribution (figure 4(b)) most of the potential variation (the accelerating electric field) is near the region of maximum magnetic field strength. The reader should not, however, assume a direct relationship between local magnetic field strength and the axial electric field. There are significant departures from such a relationship, which are different for magnetic layer and anode layer thrusters. These departures are discussed in the theory sections on those thrusters.

There is an azimuthal electron drift shown in figure 4(c). This drift is normal to both the applied electric field, $\boldsymbol{E}_z$, and the magnetic field, $\boldsymbol{B}_r$, (the $\boldsymbol{E} \times \boldsymbol{B}$ direction) and therefore constitutes a Hall current. The axial electron current density, j_{ez}, is the result of collisions of electrons with other electrons, ions, neutrals, the walls of the channel and potential fluctuations in the plasma. Because of the reduced electron mobility normal to the magnetic field, it is possible for the plasma to withstand a substantial strength of electric field while conducting only a small electron current density. Thus

$$j_z \approx j_{iz}. \tag{1}$$

Under these conditions the electric field supplies energy mainly to the ions, increasing their directed kinetic energy.

If the electron drift of figure 4(c) is obstructed, a secondary electric field will be generated. This secondary electric field will result in a component of the electron drift parallel to the applied electric field, and therefore an increased electron conduction. To achieve efficient operation of a closed drift thruster it is therefore important that the electron drift motion takes place without obstacles; that is, in a closed drift path. In addition to this drift path having a closed shape, there should be a high degree of uniformity in both the plasma density and the strength of the magnetic field. The required uniformity is usually achieved with an axisymmetric configuration, although it is possible with sufficient care to use other shapes—for example, an elongated 'race track'.

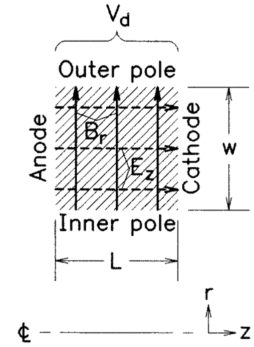

Figure 5. Simplified closed drift region (shown crosshatched).

Electrons are trapped inside the closed drift region, where most of the accelerating electric field exists. The rate of their departure from this layer is low enough that they are continually replaced by electrons supplied by the cathode and by secondary electrons from the ionization of neutrals. The condition of quasineutrality,

$$n_e \approx n_i \tag{2}$$

is thus satisfied within the closed drift region, as well as within the ion beam outside the thruster.

There is, however, an important part of the closed drift region in the anode layer thruster in which quasineutrality is *not* satisfied. This region is discussed in the theory section on the anode layer thruster.

2.6. Simplified model

A simplified model of the closed drift region is used for many of the calculations presented in this article. This simplified model is indicated in figure 5. The closed drift region is approximated with an annular volume having an axial length, L, and a radial depth, w. The magnetic field is radial, with a uniform value of B ($B = B_r$) within this region and a negligible value outside it. Mean values of neutral density and velocity, n_0 and v_0, ion density and velocity, n_i and v_i, and electric field, E, are assumed to exist throughout the region. To achieve uniformity in the radial direction, the radial depth, w, is often assumed to be small compared to the mean radius. The ion current, ion velocity and electric field are all in the axial direction ($j_i = j_{iz}$, $v_i = v_{iz}$ and $E = E_z$), and all parameters are circumferentially uniform. The electric field outside this region is negligible, so that the axial electric field, E, equals the discharge voltage divided by the length, V_d/L. In the literature, this region may be called the acceleration region, or the ionization and acceleration region, or the closed drift region or zone.

The use of this simplified model is justified by the useful results obtained by using it, and in no way is intended to contradict those theoretical and experimental results that depend on the detailed variations of parameters within the closed drift region.

2.7. Strength of the magnetic field

The strength of the magnetic field in the closed drift region must satisfy the following conditions:

$$\omega_e \tau_e \gg 1 \tag{3}$$

$$\omega_i \tau_i \ll 1 \tag{4}$$

where ω is the angular cyclotron frequency, τ is the mean time between collisions and the subscripts e and i indicate electrons and ions.

In the magnetohydrodynamic approach the plasma is accelerated by the Ampere force, $j_\phi B_r$. The Hall electron current density, $j_{\phi e}$, is in agreement with the electron density and the drift velocity in crossed electric and magnetic fields. Because the magnetic field influence on the ions is small, the ion azimuthal velocity is significantly less than this drift velocity.

$$|\boldsymbol{v}_{\phi i}| \ll |\boldsymbol{E} \times \boldsymbol{B}/B^2|. \tag{5}$$

It also follows that the length of the closed drift region, L, is significantly less than the ion cyclotron radius, r_{ic}.

$$L \ll r_{ic} = m_i v_i / eB. \tag{6}$$

However, because a condition for thruster operation is the existence of an electron azimuthal drift, the length, L, cannot be less than the electron cyclotron radius,

$$L > r_{ec} = (2eV_d/m_e)^{1/2}/\omega_e \tag{7}$$

where V_d is the applied potential. In other words, the length of the closed drift region is in the range

$$r_{ec} < L \ll r_{ic}. \tag{8}$$

2.8. Thermalized potential

Within the discharge plasma, a 'thermalized potential' can be defined,

$$V_{th} = V_p - (kT_e/e)\ln(n_e/n_{e0}) \tag{9}$$

where V_p is the plasma potential, k is the Boltzmann constant, T_e is the electron temperature in K, n_e is the electron density and n_{e0} is the reference electron density at the reference plasma potential, V_{p0}. The electron conduction is both small and mostly normal to the magnetic field lines, so that the conduction along a field line can be neglected. With this assumption, it follows that the thermalized potential is a constant along a magnetic field line.

It therefore also follows that magnetic field lines are plasma equipotentials within an accuracy of the order of kT_e/e, that is, within an accuracy in V of the order of the electron temperature in eV. This approximate relationship between magnetic field lines and plasma equipotentials is a valuable design tool for controlling the ion trajectories and plasma flow that was described first by Morozov [26, 27]. It should be kept in mind, however, that the electron temperature in a closed drift thruster can be quite high, so that the plasma equipotentials can depart significantly from the magnetic field lines, as shown in figure 6. Note further that the departure is greatest near the anode ($z = 0$), where the magnetic field is relatively weak.

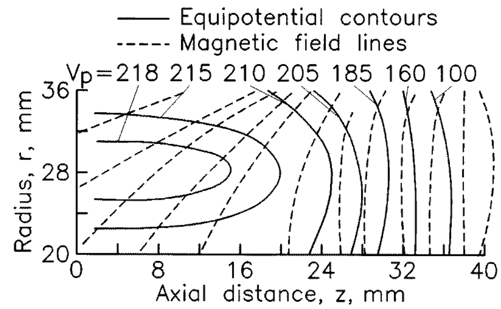

Figure 6. Comparison of equipotential contours of plasma potential with the shape of magnetic field lines for a magnetic layer thruster. Xenon flow, 2 mg s^{-1}; discharge voltage, 220 V, magnetic field strength, 150 Gauss. (After [33], with permission.)

2.9. Shape of the magnetic field

As described above, the shape of the magnetic field is important because this shape controls the ion trajectories.

For reasons that will be discussed in the theory sections on magnetic and anode layer thrusters, the most important part of the magnetic field is between the anode and the axial location near the magnetic poles where the maximum magnetic field strength, B_{max}, is reached.

Experiments have shown that this magnetic field between the anode and the maximum field location should have a nearly radial field direction at the mean diameter of the discharge chamber [28]. This shape is consistent with accelerating the ions in a nearly axial direction and minimizing their impingement on the inner and outer walls of the discharge channel.

An additional desirable feature for the magnetic field would be a continuous increase in magnetic field strength from the anode to the location of maximum strength near the exhaust plane. From a practical viewpoint, this feature is more important for magnetic layer thrusters, because the short discharge channel in the anode layer thruster does not permit much variation in its distribution of field strength.

Achieving a desirable shape for the magnetic field can be a task with various levels of difficulty. If the magnetic poles are well removed from both the inner and outer permeable paths, a desirable field shape can be obtained in a simple and straightforward manner by adjusting the relative strengths of the inner and outer magnet windings.

If a compact thruster is required, however, the inner and outer permeable paths will be close to the inner and outer magnetic poles and therefore affect the shape of the field between the anode and the magnetic poles. Achieving a desirable shape for the magnetic field can then require the use of a more complex pole structure employing multiple poles of varying strength near the inside and outside diameters.

2.10. Ion energy

From an energy viewpoint, the maximum ion velocity is

$$v_i = (2eV_d/m_i)^{1/2} \tag{10}$$

where V_d is the discharge voltage. There are various losses, the largest of which are associated with ion production. Experimentally, the mean ion energy in well developed thrusters corresponds to 70–90% of V_d.

2.11. Propellant utilization and the density of neutrals and ions

The utilization coefficient of neutral atoms in a closed drift thruster is of the order of [29].

$$\eta_u \approx n_i v_i/(n_i v_i + n_0 v_0). \tag{11}$$

Experimentally, $\eta_u \approx 1$. With dissipationless acceleration $v_i \gg v_0$. Both experimental observations and theoretical calculations support the additional conclusion that $n_0 \gg n_i$. In comparing these two relative relationships, however, it is found that for xenon propellant, $v_i/v_0 \gg n_0/n_i$, which is consistent with the experimental result that $\eta_u \approx 1$. (Note that it is generally *not* true that $\eta_u \approx 1$ if a light gas is used as the propellant in a typical closed drift thruster.)

As a result of the difference in densities in the closed drift region, ionizing collisions of electrons with neutrals dominate over ionizing collisions of electrons with ions. This result is important in understanding processes in the closed drift region.

2.12. Hall current

Assuming an $\boldsymbol{E} \times \boldsymbol{B}$ drift velocity for electrons, the Hall current per unit radius, J_H, is [30]

$$J_H \approx en_e \int_0^L (E/B)\,\mathrm{d}z \approx en_e V_d/B. \tag{12}$$

For the quasineutral condition of equation (2),

$$j_i \approx en_e v_i. \tag{13}$$

Solving equation (13) for n_e and substituting that value in equation (12),

$$J_H \approx j_i V_d/Bv_i \approx j_i(m_i V_d/2e)^{1/2}/B. \tag{14}$$

With a quasineutral plasma, then, the Hall current varies as $j_i V_d^{1/2}/B$. If J_H and j_i are both assumed to remain constant, the magnetic field, B, would have to vary as $V_d^{1/2}$ to satisfy equation (14). It should be kept in mind that an efficient operating condition is also assumed so that equation (1) can also be satisfied and equation (10) can be approximately satisfied.

2.13. Maximum ion current density

Using the one-dimensional magnetohydrodynamic approximation and Maxwell's equations, the maximum density of the momentum acquired by ions after their transit of the closed drift region is [30].

$$j_i v_i M_i/e = (B_{max}^2 - B^2)/2\mu_0 + (p_{e,max} - p_e) \tag{15}$$

where p_e is the electron pressure and the subscript, max, for B or p_e denotes the maximum value. The neutral gas pressure is even smaller than the electron pressure and has therefore been ignored. The electron pressure can be neglected in many cases, as well as the minimum magnetic field strength in the closed drift region, B. With these changes, equation (15) becomes

$$j_i v_i M_i/e = B_{max}^2/2\mu_0. \tag{16}$$

Equation (16) can be used to estimate the necessary value of magnetic field which, for xenon propellant and reasonable operating parameters, is usually in the range of $1\text{–}2 \times 10^{-2}$ T. The ion current density can thus have a very large value, limited from the theoretical viewpoint only by the strength of the magnetic field used. From a more practical viewpoint, however, it is necessary to consider the temperature limits of the closed drift hardware in setting current density and power density limits.

2.14. Length of the closed drift region

The time that an electron spends in passing through the closed drift region from the low-potential cathode boundary to the high-potential anode boundary is determined by the electron mobility transverse to the magnetic field, $\mu_{e\perp}$,

$$\tau_{eL} \approx L/v_{ez} \approx L/\mu_{e\perp}E_z \approx L^2/\mu_{e\perp}V_d \tag{17}$$

where $\mu_{e\perp} = \mu_{e0}/(\omega_e\tau_e)^2$. The electron mobility in the absence of a magnetic field (or parallel to it) is $\mu_{e0} = e/m_e\nu_e$, where ν_e is the total electron collision frequency.

The electron depletion from the closed drift region to the anode side is balanced in the stationary (steady state) regime by the addition of electrons from the cathode side and the appearance of new electrons due to ionizing collisions. The electron addition rate from the cathode side is much less than the rate of appearance of new electrons at typical operating conditions. The ionization frequency for electrons, ν_{ei}, must therefore satisfy the approximate relationship,

$$\tau_{eL}\nu_{ei} \approx 1. \tag{18}$$

Using equation (17) to substitute for τ_{eL}, the length of the closed drift region is found to be

$$L \approx (\mu_{e\perp}V_d/\nu_{ei})^{1/2}. \tag{19}$$

From equation (19) it can be seen that the length of the closed drift region can be changed by the selection of operating conditions. With substitution for $\mu_{e\perp}$ in equation (19), it can be shown that the length must be of the order of several electron cyclotron radii [31].

$$L \approx r_{ec}(\nu_e/\nu_{ei})^{1/2} \tag{20}$$

with r_{ec} defined as $m_e(2eV_d/m_e)^{1/2}/eB$. As an example, if $V_d = 500$ V and $B = 0.02$ T, $r_{ec} \approx 0.4$ cm. With the additional assumption of $\nu_e/\nu_{ei} \approx 10$, $L \approx 1$ cm.

If the frequencies ν_e and ν_{ei} are both assumed to be proportional to the density of neutral atoms, n_0, the length of the accelerating layer length does not in the first approximation depend on n_0, and, because the electron and ion densities, n_e and n_i, do not appear in equation (20), the length, L, also does not depend on the ion current density, j_i.

As shown in the above example, the estimated value for the length of the closed drift region is quite small, which has both positive and negative consequences. It means that, in principle, the discharge channel can be made very short because all physical processes associated with the ionization and acceleration of particles can be realized in this short region. However, the magnetic field must be well defined and localized in this short region, with, as described previously, a high degree of uniformity around the closed drift path. In addition, for high power thrusters, a great deal of power will be released in a small volume, which can result in overheating problems.

Having shown the general magnitude of the length, L, means of controlling or modifying this length can be considered. An important relationship is the dependence of the region length on the electron transverse mobility $\mu_{e\perp}$. If the plasma has sufficiently developed oscillations or 'turbulence', the alternating electric fields will sharply increase the electron collision frequency and the electron transverse mobility. From equation (20), this increased electron collision frequency will result in a proportional increase in length of the closed drift region. Also, as will be shown in the following section on magnetic layer thrusters, the effective transverse mobility of electrons, $\mu_{e\perp}$, can be increased by collisions with the wall, which causes the phenomenon of increased near wall conductivity [32, 33].

Another wall effect that can affect the acceleration length is the net electron emission. An effective total electron generation rate can be defined,

$$\nu_{et} \approx \nu_{ei} + [\langle j_{e,emi}(z) - j_{e,col}(z)\rangle]/en_e w \qquad (21)$$

where $j_{e,emi}(z)$ and $j_{e,col}(z)$ are the emission and collection current densities at the discharge channel walls. Using the equation of continuity for the electron current density in the closed drift region, another expression for the length of this region can be obtained [34].

$$L \approx r_{ec}(\nu_e/\nu_{et})^{1/2}. \qquad (22)$$

This equation is similar to equation (20), except that ν_{ei} is replaced by ν_{et}. From equation (22), it can be seen that the length of the closed drift region can be modified by changing the net electron emission from the discharge channel walls.

However, the importance of the electron emission from and collection by the walls goes beyond the result of equation (22). In that equation, the net difference of electron collection and emission is represented as an effective electron generation. If the emission and collection distributions are equal, so that there is no net electron generation, the electron exchange with the discharge channel walls can still have an effect on the electron temperature, and thereby change the characteristics of the discharge.

2.15. Electron conduction to the anode

Normal operation requires that electrons be transported to the anode at a rate sufficient to sustain the discharge. The preferred process for this arrival is by thermal motion of the electrons [35]. If the density and thermal velocity of the electrons are more than sufficient to conduct the discharge current, a normal sheath forms at the anode and the plasma potential is greater than the anode potential. This condition is described in literature as having a near anode potential jump of $\Delta V_a < 0$. If the density and thermal velocity are just sufficient to support the discharge, $\Delta V_a = 0$.

If the density and thermal velocity of the electrons are *insufficient* to conduct the discharge current, a reverse sheath forms with a near anode potential jump of $\Delta V_a > 0$. This condition can be caused by too low a propellant flow. When this condition exists, the power $J_d \Delta V_a$ is added to the electrons as they are accelerated toward the anode and ultimately appears as heat added to the anode. In addition to the inefficiency of having $\Delta V_a > 0$, this condition can result in the discharge easily becoming extinguished.

It should be noted that the ion density can be affected by the choice of propellant. In the same environment of electric fields, heavy ions will move more slowly, and therefore have a higher density. Through quasineutrality, the electron density will also be higher. The high atomic weight of xenon, the usual propellant, thus tends to facilitate electron conduction to the anode.

2.16. Geometric scaling

Various levels of scaling have been considered, but the scaling here will be limited to the effects of changing the width of the discharge channel, w, and the mean diameter of the discharge channel, d_m. In addition, it will be assumed that $d_m \gg w$, so that variations of parameters in the radial direction are small. The operating potential difference, V_d, will be held constant, and the propellant, typically xenon, will not be changed.

In establishing similarity, it is assumed that if the geometric ratios, l/w, r_{ec}/w, r_{ic}/w, λ_e/w, λ_i/w and λ_0/w are the same for two configurations of a closed drift thruster, then the operation of the two thrusters will be similar. (λ_e, λ_i, and λ_0 are the mean free path lengths of electrons, ions and neutrals.)

To maintain the same values of r_{ec}/w, r_{ic}/w, it is necessary that

$$Bw = \text{constant} \qquad (23)$$

or, alternatively, that B varies inversely with w. Because it is also assumed that l/w is held constant, it should be evident that it is also true that

$$Bl = \text{constant}. \qquad (24)$$

For the rest of this scaling discussion, it will be assumed that the magnetic field is varied to satisfy equations (23) and (24).

If the channel width, w, is varied while keeping the ratios l/w, λ_e/w, λ_i/w and λ_0/w constant, it is necessary for

$$n_e w = \text{constant} \qquad (25)$$

$$n_i w = \text{constant} \qquad (26)$$

$$n_0 w = \text{constant}. \quad (27)$$

That is, the electron current per unit of channel circumference ($n_e w$) is unaffected by a change in channel width, w. In a similar manner, the ion current and propellant flow per unit of channel circumference are also unaffected by a change in channel width.

The effect of variations in mean channel diameter, d_m, can be considered next. Because variations in channel width, w, were found above to have no effect, the channel width will be held constant. It should be apparent that, if w, j_i and j_0 (the equivalent current density of the neutral flow) are held constant, all the parametric ratios will also be unchanged. For changes in mean channel diameter, then, similarity corresponds to

$$J_i/d_m = \text{constant} \quad (28)$$

$$\dot{m}/d_m = \text{constant} \quad (29)$$

where J_i and $\dot{m}$ are the total ion current and total propellant flow respectively. That is, similarity is obtained when the ion current and propellant flow are varied with the mean diameter of the discharge channel.

Summarizing the effects of geometric scaling, magnetic field, B, must vary inversely with w (or l), and the discharge current and propellant flow must vary with the mean channel diameter, d_m. Variations in channel width, w, are relatively unimportant. There is an upper limit for the value of w that results in the radial variation in parameters becoming excessive and the assumption of $d_m \gg w$ not being valid. There is also a lower limit on w where the dimensions become too small for fabrication or the power densities become too large.

3. Magnetic layer theory

A magnetic layer type of closed drift thruster is shown in figure 1. The features that distinguish this thruster from an anode layer thruster are the relatively long discharge channel and the presence of dielectric walls in the discharge channel.

The presence of the dielectric walls has a significant effect on the operation of this type of closed drift thruster. The continuous exchange of high energy electrons from the discharge for low energy secondary electrons from the walls tends to limit the electron temperature within the discharge, generally resulting in a discharge that is, compared to the discharge in an anode layer thruster, more tolerant of departures from optimum conditions.

For the purposes of discussing the operation, it is useful to divide the discharge channel of a magnetic layer thruster into three regions: (1) the near anode region, (2) the ionization region and (3) the ion acceleration region. The ionization and acceleration regions together approximate the volume represented by the simplified model of the closed drift region presented in the previous section. The near anode region should be considered as external to the volume of the simplified model because of its relatively low magnetic and electric field strength.

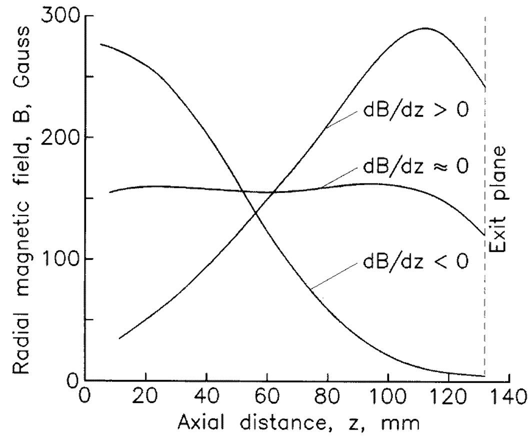

Figure 7. Different axial variations in magnetic field strength. (After [37], with permission.)

3.1. Stability criterion

In a theoretical study of the stability criterion [36], it was assumed that a constant ion current density in the axial direction, j_i, was neutralized by electrons and passed through a radial magnetic field, B, of varying strength. For the magnetic field to vary in strength and still be essentially radial, the radial thickness of the flow was assumed to be small compared to the radius. Further, the ion flow was conservative in energy and a function of the axial electric field, E_z.

For the ion flow to be stable to sinusoidal potential disturbances, it was found necessary that

$$\mathrm{d}(B/n_i)/\mathrm{d}z \geqslant 0. \quad (30)$$

This stability criterion is usually employed in the more restricted form,

$$\mathrm{d}B/\mathrm{d}z > 0. \quad (31)$$

Stated simply, a plasma flow will be more stable in regions of increasing magnetic field strength in the direction of ion flow, and more unstable in regions of decreasing magnetic field strength. This means that, in a typical magnetic field with regions of both $\mathrm{d}B/\mathrm{d}z > 0$ and $\mathrm{d}B/\mathrm{d}z < 0$, the potential fluctuations resulting from instability in the region with $\mathrm{d}B/\mathrm{d}z < 0$ will facilitate the diffusion of electrons across the magnetic field in that region, so that the accelerating potential difference will appear mostly across the region with $\mathrm{d}B/\mathrm{d}z > 0$.

There was also an experimental study of the effect of $\mathrm{d}B/\mathrm{d}z$ on the operation of magnetic layer thrusters [37]. A thruster was constructed with three magnetic coils. By adjustment of the relative currents in the different windings, various distributions of radial magnetic field could be obtained. The three distributions that were investigated are shown in figure 7. The ratio of ion-to-total current was measured along the discharge channel and found to be a maximum of 0.85 with $\mathrm{d}B/\mathrm{d}z > 0$, about 0.5 with $\mathrm{d}B/\mathrm{d}z \approx 0$ and only 0.35 with $\mathrm{d}B/\mathrm{d}z < 0$. The decreasing values of $\mathrm{d}B/\mathrm{d}z$ thus resulted in an increasing electron content in the discharge current and corresponded to an increasing electron diffusion across the magnetic field.

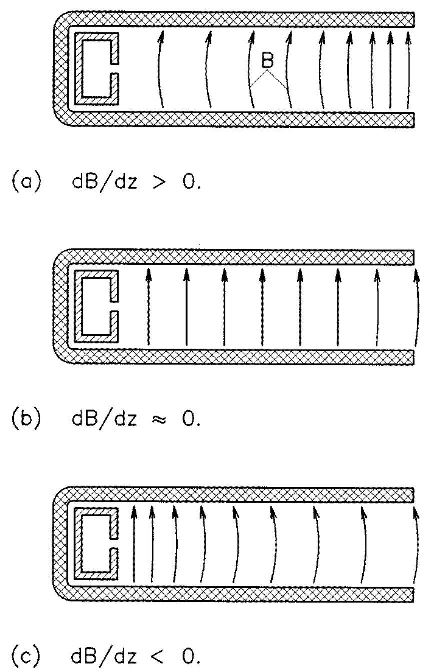

Figure 8. Magnetic field shapes for different axial variations of field strength.

The magnetic field external to the exhaust plane meets the opposite condition of $\mathrm{d}B/\mathrm{d}z < 0$, which accounts for little of the ion acceleration taking place external to the discharge channel, even though a considerable fraction of the total magnetic field may be in that location.

3.2. Magnetic field shape

The stability criterion is a theoretical basis for the general requirement given in the preceding section for a continuous increase in magnetic field strength from the anode to the maximum field location near the exhaust plane.

In addition to the effect on plasma stability, there is also an effect of $\mathrm{d}B/\mathrm{d}z$ on the focusing of ions within the discharge channel. Magnetic field shapes for three different values of $\mathrm{d}B/\mathrm{d}z$ are shown in figure 8. The field directions are radial at the mean radius to facilitate the escape of ions from the discharge channel without striking the channel walls. But the magnetic field cannot vary in strength along the channel and still be radial everywhere. Consideration of Laplace's equation will show that a varying field strength in the axial direction will result in the curvatures of field lines shown in figures 8(a) and 8(c).

In the basic closed drift theory presented in the previous section, equipotentials in the plasma were described as approximately following the shapes of magnetic field lines. In figure 8(a), with $\mathrm{d}B/\mathrm{d}z > 0$, there will be a tendency of ions to be focused away from the channel walls, so that more of the ions that are formed can be expected to leave the channel without striking a wall. In figure 8(b), with $\mathrm{d}B/\mathrm{d}z \approx 0$, there will be no such focusing effect. In figure 8(c), with $\mathrm{d}B/\mathrm{d}z < 0$, the focusing effect will actually be to direct ions against the walls. This adverse focusing effect was shown for $\mathrm{d}B/\mathrm{d}z < 0$ by the maximum in the experimental ratio of ion-to-total current being found near the upstream end of the channel and falling to about one-third of that value at the exhaust plane, thereby indicating that at least two-thirds of the ions formed strike the walls before reaching the exhaust plane. In contrast, the maximum ratio of ion-to-total current for $\mathrm{d}B/\mathrm{d}z > 0$ was much closer to the exhaust plane and the drop from the maximum value at the exhaust plane was less than 30% [37].

The combined effects of greater plasma stability and improved ion focusing should explain why most magnetic layer thrusters are designed with a magnetic field shape generally similar to figure 8(a).

In practice, the ion acceleration in magnetic layer thrusters is found to be concentrated where the magnetic field strength is high. Having a radial magnetic field at the mean radius is therefore most important in this high field strength region.

3.3. Isodrift regimes

The $\boldsymbol{E}\times\boldsymbol{B}$ drift of electrons results in a rotation of the electron cloud relative to the thruster axis of symmetry. There is a tendency for this cloud to rotate as a whole, which is called the 'isodrift regime' in Russian literature [38]. This rotation as a whole can be explained by assuming the opposite case, which will result in 'friction' between the separate parts of the electron cloud rotating at different angular velocities. Such relative rotation would lead to oscillations in the electron population, which would tend to synchronize the angular rotation.

3.4. Plasma sheaths

In the usual plasma sheath there is a potential difference, ΔV_s, equal in V to several times the electron temperature in eV. This potential difference serves to reflect most of the electrons that arrive at the sheath and reduce their loss rate to approximately that of the ions.

Plasma sheaths, called Debye layers in Russian publications, behave differently in the discharge channels of magnetic layer thrusters. The electrons arriving at the dielectric channel wall have energies in the range of 15–20 eV. For most ceramics there are two electron energies at which the secondary electron coefficient from an energetic electron is unity. Between these energies, the coefficient is greater than unity. If the sheath voltage plus electron energy (in eV) equals more than the energy required for the lower of these two energies for unity coefficient, but less than the higher, the wall will have a net loss of electrons and become more positive. Because the electron energy is already large enough to approximately give this lower value all by itself, the sheath voltage must be small. This is why a potential difference of the order of one volt is assumed in most of the wall-effect calculations in Russian magnetic-layer literature, instead of several times the arriving electron energy of 15–20 eV that one would normally expect.

3.5. Near wall conductivity

The small value of the potential difference at the plasma sheath in the discharge channel of a magnetic layer thruster

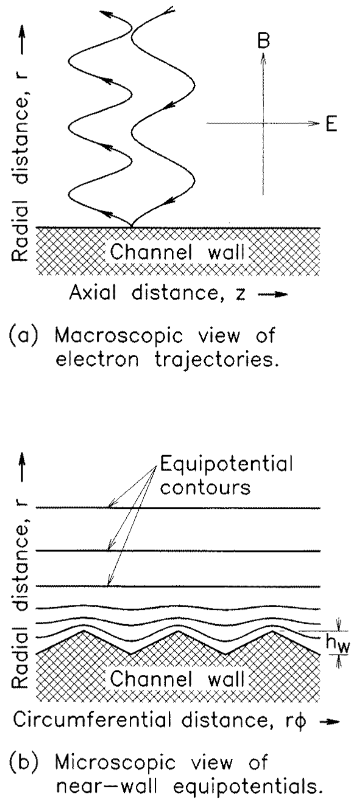

Figure 9. Near wall conductivity. (After [39] and [40], with permission.)

leads to a large number of electrons approaching closely or reaching the channel walls. In collisions of electrons with the wall, the wall plays the role of a 'large molecule', resulting in additional diffusion of the electrons across the magnetic field.

A collision of an electron with the wall is indicated in figure 9(a). The macroscopic view shown in figure 9(a) is in the r–z plane, which passes through the axis of symmetry. An incoming electron follows a spiral trajectory due to the magnetic field, collides with the wall and leaves following another spiral trajectory, which is usually displaced toward a more positive potential.

The dominant electron velocity is the $\boldsymbol{E} \times \boldsymbol{B}/B^2$ drift velocity, which is normal to the r–z plane shown in figure 9(a). The surface roughness that is important for this drift velocity is shown in the microscopic view of figure 9(b), in the r–ϕ plane. As indicated, the plasma equipotential contours near the wall increasingly reflect the roughness of the wall as the wall is approached. The roughness of the wall will thus be felt only by those electrons that approach the wall closely enough for the equipotential contours to be influenced by the wall roughness. As an approximate indication of sheath thickness, the Debye length in a discharge channel is of the order of 0.1 mm, or less.

The saw-like wall profile shown in figure 9(b) was justified by measurements of discharge channel walls, with angles of $\pm 20^\circ$ from the ideal surface felt to represent the actual roughness [39]. The equipotential contours near the wall were then approximated with sinusoids of varying amplitude. With this representation, the effect of the wall roughness was found to vary significantly with the value of sheath potential difference, ΔV_s.

For ΔV_s equal to five to seven times the electron temperature in eV, the effect of wall collisions was calculated as being negligible. For ΔV_s equal to 2.5 times the electron temperature, it was estimated that about 10% of the electron conduction was due to collisions with the wall. For the small values of ΔV_s at the dielectric channels walls in magnetic layer thrusters, the near wall conductivity is believed to be the dominant cause of electron conduction in normal operation [40]. Supporting evidence for the importance of near wall conductivity was found in the radial distributions of axial electron current, which were found to have maximum values near the walls [40].

3.6. Neutral transit time

The neutral transit time is given by

$$\tau_{0L} \approx L/v_0 \tag{32}$$

where L is the length of the closed drift region and v_0 is the neutral acoustic (thermal) velocity. For a typical length of roughly one centimetre, using xenon at 500 °C as the neutral propellant, the transit time should be of the order of 34 μs. Disturbances involving the transit time of neutrals should therefore have frequencies of the order of several tens of kHz. If the disturbance should penetrate into the near anode region, the transit time would be longer and the frequency lower.

3.7. Ion transit time

The ion transit time is given by

$$\tau_{iL} \approx L/v_i. \tag{33}$$

Using the maximum velocity for a 300 eV xenon ion and the same one centimetre length for a closed drift region, the ion transit time is found to be 8.2 μs. Disturbances involving the transit time of ions should therefore have frequencies of the order of 100 kHz.

3.8. Axial distribution of discharge parameters

The experimental distribution of the magnetic field in a magnetic layer thruster is shown in figure 10(a), with the corresponding distribution of electric field shown in figure 10(b) [35]. Most of the electric field, E, is concentrated in the region where $0.6B_{r,max} \leqslant B_r \leqslant B_{r,max}$. Upstream of this region ($z < 26$ mm), there is a small but significant *negative* electric field. In figure 10(c), the ion current, J_i, rises rapidly in the same region where $0.6B_{r,max} \leqslant B_r \leqslant B_{r,max}$, showing that both the ionization of the propellant and the ion acceleration are concentrated in this same region, which can be identified with the simplified model of the closed drift region.

Upstream of this ionization and acceleration region, however, the ion current is actually slightly negative, showing that ions from the upstream end of the ionization and acceleration region flow backward toward the anode [35]. In addition to the general upstream flow of ions, detailed probe

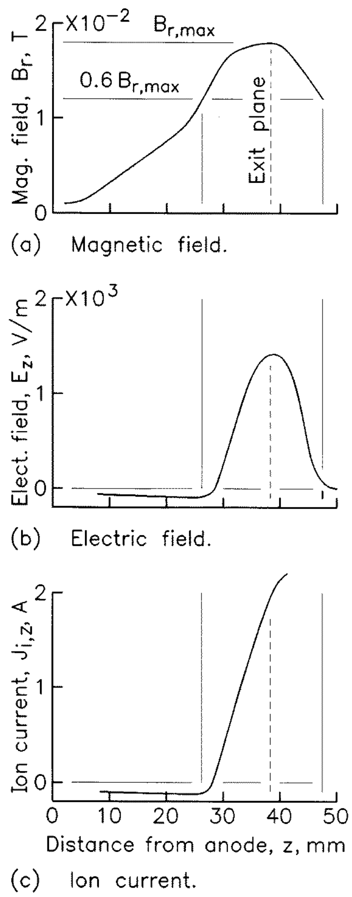

Figure 10. Axial distribution of discharge parameters. (After [35], with permission.)

measurements of the ions near the inner and outer walls of the discharge channel have velocity components toward those walls. Many of the backward flowing ions thus strike the walls of the discharge channel, become neutrals and increase the neutral density in the near anode region.

3.9. Near anode region

The near anode region in the magnetic layer thruster provides electrical contact between the anode and the ionization and acceleration regions farther downstream. Electron conduction to the anode is usually not a problem with this thruster type because of the very small electric fields, hence greater plasma densities, in the near anode region.

The energy losses in the near anode region of a magnetic layer thruster are small. At typical discharge operating conditions of several hundred volts and several amperes, the losses per beam ion in the near anode region were found to be $\leqslant$40 eV [41]. Further, much of this energy appears at the walls of the discharge channel in the near anode region, further decreasing the energy that arrives at the anode. It is consistent with the low energy losses in this region that the anode placement is not very critical in the magnetic layer thruster.

The near anode region has been observed to be ‘noisy’ from an electrical viewpoint, that is, to have many different types of oscillation [41]. The electrical oscillations generated in the near anode region propagate through the thruster and contribute to the overall electrical noise that is observed during normal operation. However, as long as the magnetic field is low near the anode, a fairly wide range of anode and discharge channel configurations may be used without significantly departing from normal operating parameters for a magnetic layer thruster. The electrical oscillations in the near anode region can thus be considered a part of normal operation.

4. Anode layer theory

Anode layer thrusters are shown in figures 2 and 3, with figure 2 showing a one stage type and figure 3 showing a two stage type. The features that distinguish this thruster from a magnetic layer thruster are the relatively short discharge channel and the presence of conducting walls in the discharge channel. Because of the shortness of the discharge channel, the ion impingement with the channel walls is usually reduced by concentrating the ion flow near the centre of the channel and away from the walls.

In the anode layer thruster the regions of ionization and acceleration practically coincide, and there is almost no space for the near anode region.

4.1. Acceleration in an anode layer thruster

In the preceding discussion of the stability criterion for acceleration in a magnetic layer thruster, that acceleration is implicitly assumed to be continuous process, which is substantially correct for that type of thruster. In contrast, the acceleration in an anode layer thruster is concentrated in a thin layer.

The acceleration process in a closed drift thruster results from the potential distribution established by electrons diffusing from the cathode to the anode. This electron diffusion is driven by two gradients, the potential gradient and the electron temperature gradient.

In a magnetic layer thruster, the secondary electrons that are emitted from the collisions of energetic electrons with the dielectric discharge chamber walls tend to limit the electron temperature in the plasma to a value (in eV) that is small compared to the total accelerating potential difference (in V). This results in the electron diffusion being primarily driven by the potential gradient.

In an anode layer thruster, due to both the short discharge chamber length and the large plasma sheath voltages that result from the conducting nature of the walls, with corresponding low secondary emission, the electrons experience a substantial increase in temperature as they flow from the cathode to the anode. The electrons gain energy from the potential difference between the cathode and anode and this energy is randomized into temperature by collisions with other electrons and collective waves in the plasma. At some point in the discharge, the increasing temperature results in an electron diffusion in the cathode direction that balances the electron diffusion in the anode direction due to the potential gradient. This balancing of electron diffusion in the two directions results in a limit for calculations based on the diffusion equation.

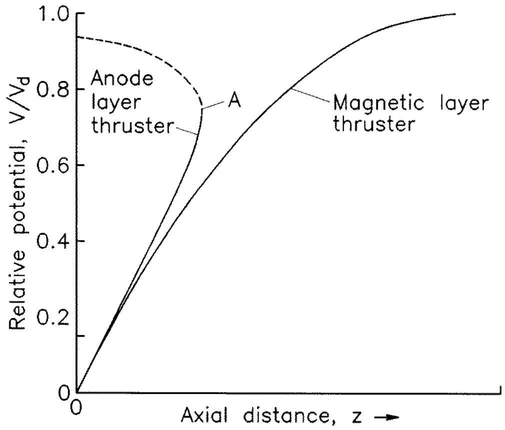

Figure 11. Comparison of the potential variations for the discharge channels of anode layer and magnetic layer thrusters. The axial distance shown is measured *upstream* from the exit plane. (After [42], with permission.)

The potential distributions in anode layer and magnetic layer discharges are indicated in figure 11 [42]. These potential distributions were calculated by assuming the same diffusion due to potential gradient for both types of closed drift thruster, and differ only in the effect of the increase in electron temperature as the anode is approached in the anode layer type. The effect of the increasing temperature on electron diffusion is balanced by the effect of potential gradient at point A in figure 11, where the slope becomes infinite.

It is possible to calculate the potential distribution in an anode layer thruster beyond point A (the dashed line in figure 11), but the potential distribution becomes double valued and physically unrealistic. What actually happens is that there is a near-discontinuous jump to anode potential in a single, or at most several, electron cyclotron radii. This near-discontinuous potential jump, with a substantial amount of the total ion acceleration taking place in a thin layer near the anode, is the basis of the name, ‘anode layer’. The analysis described above was first carried out assuming classical $1/B^2$ diffusion of electrons across a magnetic field [43]. A later analysis used the $1/B$ anomalous diffusion of electrons [42]. The results of both analyses were qualitatively similar, with the major difference being the required strength of the magnetic field.

The anode layer curve shown in figure 11 assumes zero initial electron temperature, and the conservation of electron energy as a constant current density of electrons flows from the cathode to the anode. A non-zero initial electron temperature, some loss in electron energy in flowing from the cathode to the anode or a variation in electron current density would all result in different value of V/V_d where the near discontinuous jump in potential takes place. For the magnetic layer curve shown in figure 11, the electron temperature was assumed to be negligible (zero) throughout the channel. Slightly different curves can be obtained by assuming different constant values for this electron temperature.

It may be of interest to note that a small potential jump of the type shown for the anode layer thruster will always be found near the anode for the magnetic layer thruster if a constant non-zero electron temperature is assumed. This small potential jump is related to the minimum ion velocity required for a stable sheath, and is not related to the larger jump described above for an anode layer thruster. For a magnetic layer thruster, the electron temperature in eV should still be small compared to the total potential difference, V_d, in V, so that the potential jump should be small compared to V_d.

4.2. Hall current

There is a significant departure from quasineutrality in the closed drift region of an anode layer thruster in the vacuum regime of operation. In normal closed drift operation, there is quasineutrality and the difference between n_e and n_i is small compared to either n_e or n_i. In the vacuum regime the plasma is dilute enough that $n_e \gg n_i$ in the closed drift region. This vacuum regime is described below. The approach taken generally follows that in Russian literature [44].

From Gauss’s law, the strong axial electric field in the closed drift region must be generated by the unneutralized electron charge per unit of cross section, $n_e L$,

$$E = e n_e L/\epsilon_0. \tag{34}$$

The electric field can be approximated by V_d/L, so that the electron density can be written as

$$n_e = \epsilon_0 V_d/eL^2. \tag{35}$$

Substituting this electron density into equation (12),

$$J_H \approx \epsilon_0 V_d^2/BL^2. \tag{36}$$

For the length of the closed drift region, L, equation (20) can be used. With this substitution and the further substitution for the electron cyclotron radius, equation (36) becomes

$$J_H \approx \epsilon_0 e V_d (\nu_{ei}/\nu_e) B/2m_e. \tag{37}$$

For the maximum value of this Hall current (per unit radius), $(\nu_{ei}/\nu_e) = 1$ and

$$J_{H,max} \approx \epsilon_0 e V_d B/2m_e. \tag{38}$$

This result shows that the Hall current is proportional to $V_d B$ in the vacuum regime. Note that this result differs from that of equation (14) for the quasineutral regime.

4.3. Ion current density

The momentum density can be calculated from the Lorentz force [44].

$$j_i m_i v_i/e = j_i (2m_i V_d/e)^{1/2} = J_H B. \tag{39}$$

Substituting $J_{H,max}$ for J_H and solving for j_i,

$$j_i = \epsilon_0 e^{3/2} V_d^{1/2} B^2/2^{3/2} m_e m_i^{1/2}. \tag{40}$$

From equation (40), the ion current density is shown to be proportional to $V_d^{1/2} B^2$ in the vacuum regime.

4.4. Transition between quasineutral and vacuum regimes

Whether the operation of an anode layer will be in the quasineutral or vacuum regimes can be estimated by comparing the quasineutral Hall current of equation (14) with the vacuum Hall current of equation (37). If the vacuum Hall current is larger, then the required Hall current will not be supplied by a quasineutral closed drift region and operation will be in the vacuum regime. Conversely, if the quasineutral Hall current is larger, the operation will be in the quasineutral regime.

Comparing equations (14) and (37) for the effects of different parameters will show that operation in the vacuum regime is favoured by: a large magnetic field, a low ion current density, a large discharge voltage and a low electron collision frequency (a low neutral density in the closed drift region).

The approximate transition between the vacuum and quasineutral regimes can be found by equating the vacuum Hall current of equation (37) with the quasineutral Hall current of equation (14). The transition voltage is

$$V_d \approx 2 j_i^2 m_e^2 m_i (\nu_{ei}/\nu_e)^2 / \epsilon_0^2 e^3 B^4. \qquad (41)$$

It has been generally helpful up to this point to distinguish between the magnetic layer and anode layer types of closed drift thruster by the relative lengths and wall materials for the discharge chambers. The transition between quasineutral and vacuum regimes for the anode layer thruster, however, presents another basis for distinguishing between types of closed drift thruster, one that can blur the geometric and material distinction.

4.5. Magnetic field shape

The axial variation in strength of the radial magnetic field in an anode layer thruster again has a bell-shaped distribution, reaching a maximum near the pole pieces and decreasing both near the anode and at the exit end of the thruster. The anode of a single stage anode layer thruster is typically located at, or slightly upstream (to the left in figure 2) of the maximum in magnetic field strength. There are apparently no successful anode layer thrusters in which the anode is located *downstream* of the magnetic field maximum. Further, the need for circumferential uniformity of the magnetic field is greater for the anode layer thruster than for the magnetic layer thruster.

Experimentally, the maximum strength of the magnetic field for an anode layer thruster is about twice that of an otherwise similar magnetic layer thruster. This result is consistent with the above discussion of the transition between quasineutral and vacuum regimes as well as the utilization of a smaller portion of the magnetic field volume between the magnetic poles in a magnetic layer thruster.

Because of the very compact nature of the anode layer discharge, it has been more difficult to make probe investigations of the detailed variations of parameters within that discharge region than within the discharge region of a magnetic layer thruster. The relationship between the magnetic field distribution and the operation of an anode layer thruster is therefore not as well known as this relationship in a magnetic layer thruster. It is still possible to draw a few conclusions.

Experimentally, the location of the anode has been found to be more critical when the anode is located at the maximum in magnetic field, and less critical when the anode is located slightly upstream of the maximum. But in either location, the location of the anode in an anode layer thruster is usually more critical than the anode location in a magnetic layer thruster. In anode layer thrusters that perform well, the magnetic field at the anode of an anode layer thruster is typically in the range of 90–100% of the maximum value of the magnetic field [45].

A possible implication of this upstream anode location is that the near discontinuous anode layer forms at approximately the maximum in magnetic field, and that the anode location becomes less critical when it is upstream of this maximum because its location is not directly affecting the anode layer.

4.6. Plasma sheaths

The walls of the discharge channels in anode layer thrusters are conductors, with relatively low secondary electron emission coefficients—compared to those of the dielectric walls of the magnetic layer thruster. The plasma sheaths that form adjacent to these conducting channel walls thus have a potential difference, ΔV_s, typically equal in V to several times the electron temperature in eV.

There are two consequences of these large potential differences in the plasma sheaths. The most important is the sharp increase in electron temperature as the electrons flow from the cathode to the anode. This increase in electron temperature leads to much of the ion acceleration taking place in a thin layer near the anode, as described above.

The other consequence concerns near wall conductivity. As described in the section on near wall conductivity for the magnetic layer thruster, the effect of the roughness of the discharge channel wall decreases as the potential difference at the plasma sheath increases. With the large potential differences that would be expected at the channel walls of an anode layer thruster, the near wall conductivity is assumed to be negligible.

4.7. Near anode region

The near anode region in an anode layer thruster is very short compared to the same region in a magnetic layer thruster. The small size of this region is believed to be responsible for some of the operating characteristics and problems associated with the anode layer thruster.

The short length of the near anode region affects the electrical contact of the plasma to the anode. In the near anode region upstream of the anode layer, the electron density is limited by quasineutrality to approximately the density of the ions. In turn, the ion density is limited by the rapid removal of ions due to the axial electric field in that region. Because the near anode region is short in the anode layer thruster, the axial electric field is high, and the density of electrons available to conduct the discharge current to the anode is limited. The reduced conduction to the anode tends, in turn, to cause increased losses near the anode.

The general overheating problem mentioned in the section on basic closed drift theory tends to be more common with the shorter channel length and closer spacing of parts in the anode layer thruster [46]. Not only are the losses in this region generated close to the anode, but, in the case of a hollow anode, some of the losses are generated inside the anode. The result is that more of the losses appear as anode heating in the anode layer thruster [41].

There is also a localized anode overheating problem, in which the anode temperature becomes circumferentially nonuniform. The resulting variation in neutral density interacting with the discharge results in this nonuniform temperature distribution being sustained and slowly rotating around the thruster axis. Because of the departure from circumferential uniformity, this localized overheating also results in a decrease in thruster efficiency.

It has been found experimentally that the operation of an anode layer thruster is usually improved when a hollow anode is used [47]. It appears likely that this improved operation results from the additional contact area between the anode and the plasma and the reduced electric field available to remove the ions within the hollow anode.

5. Operation of closed drift thrusters

The input parameters that characterize the operation of a closed drift thruster are: the discharge voltage, V_d; the discharge current, J_d; the propellant flow, $\dot{m}$, and the maximum value of the magnetic field, B_{max}, measured at the mean channel diameter. Each of these parameters can be varied over some range, but interactions between them prevent their completely independent variation.

The major output parameter is the thrust, F. The thruster efficiency is based on this thrust and is

$$\eta_{th} = F^2/2\dot{m}P \tag{42}$$

where $\dot{m}$ is the total propellant flow to the thruster and P is the total power supplied to the thruster. If the magnet windings are energized by connecting them in series with the discharge supply and the cathode requires no steady state heating or discharge power, the power supplied to the thruster can equal $V_d J_d$.

Many other definitions of thruster efficiency can be found in Russian literature, but the need for these other definitions usually results from incomplete information about F, $\dot{m}$, or P. Most often the lack is the absence of a measured thrust, so that a variety of other parameters such as the ion beam current, the fraction of doubly charged ions, and the cosine losses must be incorporated in the calculation of thruster efficiency. When the proper information is available, equation (42) is a fundamental and valid definition of thruster efficiency.

Starting is accomplished by establishing propellant flow and emission capability for the cathode and applying discharge voltage. Establishing emission capability for the cathode can be a one or two step process. In the two step process, a discharge is first established between the cathode and a keeper, and the electron emission for the main discharge (V_d and J_d) is established in a subsequent step. In the one step process, these two discharges are established simultaneously.

Once started, an essentially constant specific impulse (exhaust velocity divided by the gravitational constant) is maintained during normal operation by keeping the discharge voltage constant. The propellant flow is then regulated to maintain a constant discharge current. Because the discharge current approximately equals the ion beam current, the thrust is also held nearly constant.

Starting is ensured by increasing the discharge voltage and propellant flow to higher than normal values before starting. Both of these increases are easy to incorporate into the control procedure described above prior to initiation of the discharge current. For example, if there is no discharge current, the control will normally regulate the propellant flow to a higher than normal value.

It should be kept in mind that only the magnetic layer thruster has been used in space. As a result, that type of closed drift thruster has been subjected to a greater development effort and more is known about it. Many of the details of operation given below for a magnetic layer thruster will therefore be given with greater precision and assurance than similar details of operation for an anode layer thruster.

5.1. Propellant

Xenon is the only propellant that has been used for closed drift thrusters in space, and is also the propellant generally used in ground tests of closed drift thrusters intended for use in space. The reasons for this choice are the same for both gridded and closed drift thrusters: (1) xenon is an inert gas and therefore minimizes both spacecraft and environmental contamination, (2) xenon has a low pressurized tank mass, due to a high density at ambient temperature with, compared to other inert gases, a moderate pressure and (3) xenon has a low ionization energy per unit propellant mass, due to both a moderate ionization energy and a high atomic weight.

Other inert gases (argon, krypton and neon) have been used in laboratory experiments and may be practical choices for propellant in space if: (1) high specific impulses are required so that the relatively higher ionization energy per unit mass is not a serious problem, and (2) the amount of propellant required and the duration of the mission permit cryogenic storage to be used. Closed drift thrusters tend to operate better on propellants with low ionization potentials and high atomic weights. That is, at similar discharge voltages the thruster efficiencies are higher, the propellant utilizations are higher, the operating ranges are broader and the amplitudes of oscillations are smaller. These characteristics also tend to make xenon the preferred propellant, despite its high cost.

5.2. Anode

The propellant is normally introduced into a closed drift thruster through a hollow anode, although other means of propellant introduction have occasionally been used. The propellant is stored in a propellant tank on the spacecraft and reaches the anode through a feedline and an electrical isolator. Circumferential uniformity of the propellant is usually assured by using multiple apertures that are uniformly distributed around the circumference of the anode. For a magnetic layer thruster, the number of apertures required to assure uniformity is of the order of 20 or more. For an anode layer thruster, with its greater sensitivity to circumferential nonuniformity, a larger number of apertures might be required.

Modern anode layer thrusters are made with hollow anodes. ‘Hollow anode’ here does not refer to the cavity for circumferentially distributing propellant, as shown in figure 1. Instead, it refers to a cavity which the discharge plasma can and, in optimum operation, does penetrate—as shown in figure 2. In such a hollow anode, the downstream edge area of the anode is too small to provide adequate electrical contact with the plasma, and the electrical contact is augmented by the plasma contacting the internal area of the cavity.

5.3. Discharge channel

The discharge channel in a magnetic layer thruster is fabricated of ceramic. A variety of ceramics have a sufficiently high coefficient of secondary electron emission to provide normal operation. The choice of ceramic for space propulsion, however, also requires a low sputter coefficient for long life, sufficient mechanical strength to survive the launch environment, and good thermal shock resistance to survive startups and shutdowns. Considerable effort has been applied to the development of ceramics that simultaneously satisfy these diverse requirements [48, 49].

An anode layer thruster has a shorter discharge channel with conducting walls. Sufficient operating lifetime requires a low sputter coefficient for the conductor selected, but also depends on controlling the plasma flow so that the direct impingement of energetic ions on the channel walls is minimized, that is, by making $w_b < w_c$ (figure 2).

5.4. Cathode

The function and operation of a hollow cathode for a closed drift thruster are quite similar to the function and operation of a hollow cathode for a gridded thruster. However, the configuration used at present for closed drift thrusters differs substantially from that presently used for gridded thrusters. In gridded thrusters, the typical hollow cathode uses a tungsten orifice plate welded to a tantalum tube. Inside the tantalum tube and adjacent to the tungsten orifice plate, there is an oxide impregnated insert to supply the electron emission. The electron emission and the propellant flow required for operation leave the hollow cathode through the small orifice in the tungsten plate. The usual hollow cathode for a closed drift thruster uses a refractory metal tube, but the insert is of lanthanum hexaboride [10]. There is no separate orifice plate, and the electrons and required propellant flow escape through an aperture in the lanthanum hexaboride insert.

The above differences in the two types of hollow cathode result in some differences in operating characteristics. The exposed end of the aperture is where the wear takes place in both cathode types. But lanthanum hexaboride appears to have less resistance to sputtering due to ions falling back on the hollow cathode, so that a cathode using lanthanum hexaboride can be expected to have a somewhat shorter operating lifetime than one with a tungsten orifice plate. This shorter lifetime may *not* be a problem, though, because closed drift thrusters usually operate at lower specific impulses and higher thrusts for shorter operating lifetimes than would be required for gridded thrusters selected for the same mission. In practice multiple (redundant) cathodes are also more common on closed drift thrusters than on gridded thrusters.

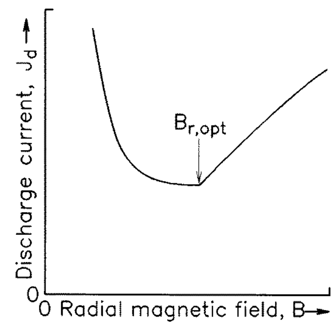

Figure 12. Discharge current as a function of magnetic field for a typical magnetic layer thruster at constant discharge voltage and propellant flow.

There is another difference in operating characteristics. A lanthanum hexaboride insert appears to be more resistant to contamination than the usual oxide impregnated insert [50]. This difference can be significant when prior ground testing of the flight hardware is required, followed by a long storage before launch. In the oxide impregnated type, the testing prior to launch converts a carbonate into the active oxide, but in the storage before launch the oxide can degrade into a less effective hydroxide. There appears to be no similar chemical conversion for lanthanum hexaboride during the storage prior to launch.

5.5. Optimum magnetic field

The experimental procedure for the selection of the optimum magnetic field requires both the adjustment of the overall field strength to minimize the discharge current and the relative adjustment of inner and outer magnet windings to minimize the cosine loss of the accelerated ion beam, with both of these adjustments made at a constant discharge voltage and a constant propellant flow.

Initially, both of these adjustments can be carried out in an iterative manner to achieve the optimum magnetic field. The minimum discharge current is optimum because the discharge current consists of the ion current (which is nearly constant if the propellant flow is constant) and the electron current to the anode. This electron current represents a loss, and the thruster efficiency is a maximum when this electron current is minimized. The typical variation of discharge current at constant discharge voltage and propellant flow is shown in figure 12 for a magnetic layer thruster. If operation is expected over a range of discharge voltage, testing should be carried out at several constant voltages to determine the compromise optimum magnetic field that will be used.

The cosine loss can be inferred by measuring the ion beam profile, but there is the uncertainty of the measured profile differing from the thrust-generating profile by an unknown amount of charge exchange. The direct measurement of thrust at a low enough background

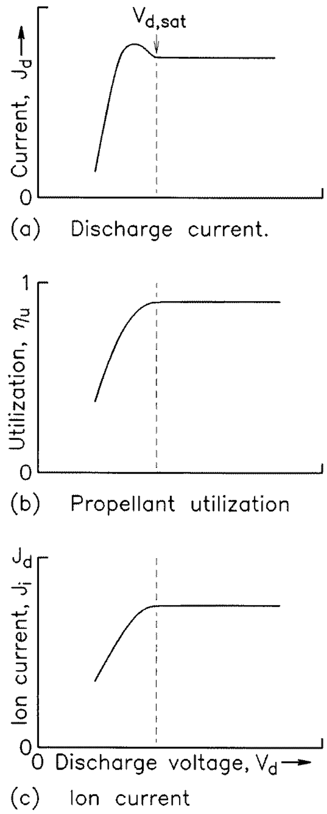

Figure 13. Discharge characteristics of a typical magnetic layer thruster at constant propellant flow.

pressure to approximate operation in space provides a better measurement of the cosine loss.

It was mentioned in the basic theory section that the optimum configuration of magnetic field has a nearly radial field direction at the mean diameter of the discharge chamber. This is essentially the magnetic field configuration obtained when the relative strengths of inner and outer magnet windings are optimized in the manner described above.

Once the optimum magnetic field is determined, the relative numbers of turns in the inner and outer windings can be adjusted so that the minimum cosine loss is obtained with the same currents in the inner and outer windings. If the magnet windings are to be energized by connecting them in series with the discharge supply, the absolute number of turns in the inner and outer magnet windings must also be adjusted to give the optimum magnetic field strength when the magnet windings carry the discharge current.

Typical optimum values of maximum magnetic field strength for magnetic layer thrusters (SPT-50, 60, 100 and 140) are in the range of 0.012–0.025 T. For anode layer thrusters (D-55, D-100 and TM-50) operating at comparable conditions the optimum values of maximum magnetic field are higher by a factor of two, as was mentioned above. The above magnetic fields are for specific impulses in the range of 1200–1600 s. From the discussion of equation (14), the magnetic field strength should be expected to vary approximately as the square root of discharge voltage for variations of the latter.

5.6. Discharge characteristics

Once an optimum magnetic field has been obtained, the operation of a closed drift thruster can be further defined by its discharge characteristics, which are shown in figure 13 for a typical magnetic layer thruster [35, 51]. Starting from a low discharge voltage, increasing that voltage initially results in an increasing discharge current. After sufficient increase in voltage, the discharge current reaches a maximum, falls slightly and then remains constant at higher discharge voltages. The region of constant discharge current is called the saturation current or optimal regime of operation, and extends upwards in voltage from $V_{d,sat}$.

The propellant utilization, η_u, and the ion-to-discharge current ratio, J_i/J_d, are also shown in figure 13. Both of these parameters are constant in the saturation region above $V_{d,sat}$. Propellant utilization of a magnetic layer thruster can approach 0.9 with the neutralizer included, the ion-to-discharge current ratio can be about 0.8 and the mean cosine value can be 0.95. All of these values assume xenon propellant and a discharge voltage of several hundred volts.

The mean ion energy corresponds to about 80% of V_d, increasing slightly at higher values of discharge voltage and decreasing at lower values. At a propellant flow sufficient to assure good propellant utilization, the mean ion energy is essentially unaffected by changes in the propellant flow. To the first approximation, the thrust is thus proportional to the product of $\dot{m}$ and $V_d^{1/2}$.

There is a minimum propellant flow necessary for the initiation of the discharge, although the thruster can operate at a lower flow after the discharge is started. Both the minimum starting and the minimum operating flows will vary approximately with the mean diameter of the discharge chamber, as indicated by the scaling relationships presented in the basic theory section. For similar sizes of thrusters, these minimum values will usually be smaller for magnetic layer thrusters than for anode layer thrusters. For anode layer thrusters, operation may only be possible for discharge voltages equal or greater than that necessary for the maximum in discharge current [52].

5.7. Oscillations of discharge parameters

There have been many theoretical and experimental studies of oscillations in closed drift thrusters. In general, oscillations can exist over a wide range of frequencies depending on values of parameters such as the discharge voltage and current, the magnetic field strength, the propellant flow, the number and location of the cathodes, the operating time since the thruster was last started, the total operating time of the thruster, the dynamic characteristics of the discharge power supply and the background pressure in which the thruster is operated. At small amplitudes, the oscillations can be considered a part of normal operation with no significant effect on operation. At large amplitudes, the oscillations can severely and adversely affect operation.

There are several types of oscillation that are frequently found in closed drift thrusters. Because oscillations have been studied more extensively in magnetic layer thrusters, the descriptions given below are drawn mostly from research on that type of thruster. The typical oscillation types are as follows.

5.7.1. Spoke type. At low discharge voltages, below $V_{d,sat}$ in figure 13, a spoke type of instability can be observed to rotate in the circumferential direction with a constant velocity,

$$v_\phi \approx c_v E_z / B_r \tag{43}$$

where c_v is a constant in the range 0.4–0.8 [53].

The study of this oscillation has shown that the spoke has an increased concentration of cold electrons and is surrounded by a blanket of high-temperature electrons.

5.7.2. Contour oscillations. Contour oscillations are longitudinal oscillations with frequencies in the range of 1–30 kHz, and therefore correspond approximately to the transit time for a neutral propellant atom. This oscillation is connected with an instability in the location of the ionization region. Contour oscillations can have a very large amplitude. In operating regimes with well developed contour oscillations, there can be an almost 100% modulation of the discharge current and a 10-20% modulation of the discharge voltage.

Contour oscillations depend significantly on the parameters of the discharge power supply circuit. Scientists studying magnetic layer thrusters have carried out extensive research on the possibility of controlling and minimizing these oscillations with a variety of filtering devices in the discharge circuit [54, 55]. Contour oscillations are observed in the vicinity of the optimum magnetic field, at $B < B_{opt}$ and $B > B_{opt}$. However, they become much smaller in amplitude, almost nonexistent, at $B \approx B_{opt}$.

5.7.3. Ionization oscillations. Ionization oscillations have frequencies in the range of 10–100 kHz. These oscillations are caused by ionization instabilities that result from the ionization front propagating irregularly around the circumference of the discharge channel [26, 53, 56]. One type of ionization oscillation is found in the saturation region and is caused by an azimuthal ionization wave travelling in the direction of electron drift. The other type of ionization oscillation is found in the low-voltage part of volt–ampere characteristics, at voltages below $V_{d,sat}$, and corresponds to the spoke type of instability discussed above.

Under the proper conditions, this type of oscillation can reach 15–20% of the discharge voltage at low values of V_d. In the saturation region, though, the intensity of this oscillation is relatively small. The ionization oscillation is similar to the oscillation observed in the positive column of a discharge in the presence of a magnetic field, where the onset of this oscillation was found to depend on reaching a minimum value of an instability parameter, $IB/(\mathrm{d}\dot{m}/\mathrm{d}t)$ [57].

5.7.4. Flight oscillations. Flight oscillations have characteristic frequencies from about 100 kHz up to 10 MHz and correspond approximately with the transit time for an ion [56]. These oscillations can be quite intense.

The analysis of flight oscillations is based on the concept that plasma particles are delayed in being transferred from one region to other. For example, neutral atoms are delayed in being delivered into the ionization region, ions are delayed in moving from the ionization region into the acceleration region and electrons are delayed in moving from the acceleration region into the ionization region. This approach is based on the general theoretical concept of such mechanisms, and is not intended to be tied to specific mechanisms. These oscillations are also called ionization-flight oscillations, because they are determined by the change of ionization rate due to the delay of particle appearance, from one region to another. This hypothesis was suggested by Kim [58]. However, there are criticisms of this approach [59], primarily on the lack of evidence for specific delay mechanisms.

5.7.5. High frequency oscillations. High frequency oscillations are typically in the range of 1–100 MHz [35]. These are hybrid azimuthal waves generated near the exit part of the thruster, in the region where the gradient of the magnetic field is negative. The amplitude of these oscillations is significantly smaller than the other types of oscillation described above.

5.7.6. Super high frequency oscillations. Super high frequency oscillations are in the range of several GHz [35]. These oscillations correspond to Langmuir frequencies with electron densities of about 10^{10}–10^{11} cm^{-3}. Appearance of these oscillations is connected with the development of electron layers in the plasma and the formation of flows of fast overheated electrons directed along as well across the magnetic field. These oscillations have the smallest amplitude, and have so far been measured only under carefully controlled laboratory conditions.

5.7.7. Summary of oscillations. There have been numerous Russian studies of oscillations and instabilities which had, at first, an academic character. With the present plans to use Russian closed drift thrusters on US spacecraft, recent studies have become more practical. In addition to the obvious motivation of reducing electrical noise, each improvement in suppressing oscillations of discharge parameters has the potential of improving thruster efficiency. In the studies to date the following general conclusions have been reached [53, 55].

(1) The average oscillation intensity decreases with increasing oscillation frequency.

(2) There are always random outbursts of high amplitude oscillations superimposed on the average background.

(3) The character of oscillations for a magnetic layer thruster has been compared with the same configuration when metal walls are substituted for the dielectric walls. The oscillations are similar for some types of oscillation, and different for others, with the more prominent oscillations usually found with the thruster having dielectric walls.

(4) Magnetic layer thrusters and anode layer thrusters have very similar types of oscillation, although there are some differences. There is also much more information available about oscillations in magnetic layer thrusters than in anode layer thrusters.

(5) Utilization of propellants with low ionization potentials such as xenon, or lithium and caesium reduces the intensity of oscillations, especially super high frequency

and some other oscillations. However, for propellants such as argon and nitrogen, the amplitude of super high frequency oscillations increases by two to three orders of magnitude.

In practice, both types of closed drift thruster have extensive oscillations in almost all ranges of operation. The presence of oscillations, which usually increase with total operating time, leads to the situation in which the conductivity across the magnetic field is determined less by normal plasma diffusion processes, and more by additional powerful mechanisms such as oscillations and increased near wall conductivity.

The utilization of Morozov's concept for the stabilization of the ion acceleration process with a positive longitudinal gradient of magnetic field permits the stabilization of certain plasma disturbances. There are some other ways for controlling oscillations, such as the use of additional electrodes in the discharge channel with the potentials of these electrodes actively controlled to suppress the oscillations [55].

In general, oscillations in closed drift thrusters constitute a complex and difficult problem that requires further theoretical and experimental study.

6. Trends in closed drift thrusters

As mentioned earlier, the magnetic layer thruster has been subjected to considerable development. It is true that a wide range of configurations has been studied, but, probably due to its use in space flight, there is also a clearly identifiable main path of this development. As a result of this development, the magnetic layer thruster has been modified in recent years, but, for the most part, not fundamentally changed from earlier versions.

Some modifications have been detailed changes in the anodes to improve reliability. Other modifications have been directed at concentrating the magnetic field closer to the exhaust plane. The earlier versions used what might be called broad poles. The later versions use narrow poles, or even multiple inner and outer poles, to concentrate the zone of ionization and acceleration closer to the exit plane. This concentration reduces the impingement of energetic ions on the dielectric walls, which increases both thruster efficiency and operating lifetime.

Viewed as a whole, the magnetic layer thruster is well understood and readily scalable [60], with a high level of efficiency and a long lifetime [61].

The anode layer thruster has a more varied background. The initial successful versions had two stages. Later, after improvement of the magnetic field configuration and the introduction of the hollow anode, one stage versions were developed that were suitable for operation in space. More recently, an extended anode version has been developed where the downstream end of the anode is extended to be flush with the downstream faces of the inner and outer poles [46].

From the discussion of the closed drift region for an anode layer thruster, it should be evident that the ion acceleration in superficially similar anode layer thrusters can occur with different processes. At one extreme, this acceleration takes place in a very thin, well defined anode layer. At the other extreme, it takes place in a more extended closed drift region that is perhaps similar to a magnetic layer thruster.

The definition of an anode layer thruster has become even more blurred in some recent thruster designs. These designs were essentially the same as magnetic layer thrusters, except that the dielectric walls of the discharge channel were replaced with metal walls. Because the walls were electrically 'floated', such thrusters might be called multistage anode layer thrusters. But the length of the discharge channels in these designs have been greater than their width, similar to magnetic layer thrusters, and their operation has also been generally similar. These designs are clearly closed drift thrusters, but it is not clear whether they should be called either magnetic layer or anode layer types.

7. Concluding remarks

The Russian publications on closed drift thrusters constitute a large body of information. For that reason, this article has only included the most prominent theoretical and experimental features of those publications.

The omissions of this article should also be indicated. Disagreement is part of any growing body of scientific information, and is certainly present in the publications on closed drift thrusters. For this review, the authors felt it was more appropriate to emphasize that information upon which there was the least disagreement, but regret the loss of 'flavour' in the omission of much of the disagreement.

There were also subjects that were omitted because they were too detailed to be included in a general review. A few examples of these subjects are: the azimuthal rotation of ions, the azimuthal nonuniformity of the discharge, the distribution of ion velocities, ion optics aberrations and a variety of radial variations and effects.

A partial omission has been the theoretical depth included in the publications on closed drift thrusters. Compared to US publications on electric thrusters, theory plays a larger role in Russian publications. It has been possible to include only a few of the main features of this theory.

It was stated at the beginning of this article that the development of the closed drift thruster is primarily a Russian achievement. The authors also believe that this achievement is an important one and sincerely hope that some of that importance has been conveyed in this review.

Acknowledgments

The authors wish to thank Professors A I Bugrova and A I Morozov for their assistance.

References

[1] Morozov A I 1993 Stationary plasma thruster (SPT), development steps and future perspectives *Proc. 23rd Int. Electric Propulsion Conf. (Seattle, WA, 1993)* (Worthington, OH: Electric Rocket Propulsion Society) IEPC-93-101 pp 945–9

[2] Morozov A I 1995 Electric propulsion thrusters and plasmadynamics *Proc. 24th Int. Electric Propulsion Conf. (Moscow, 1995)* IEPC-95-05, pp 41–53

[3] Janes G S, Dotson J and Wilson T 1962 Momentum transfer through magnetic fields *Proc. 3rd Symp. on Advanced Propulsion Concepts (1962)* vol 1 (New York: Gordon and Breach) pp 153–76

[4] Ellis M C Jr 1962 Survey of plasma accelerator research *Proc. NASA–University Conf. on the Science and Technology of Space Exploration (1962)* vol 2 (Washington, DC: NASA) pp 361–81

[5] Zharinov A V and Popov Yu S 1967 Acceleration of plasma by a closed Hall current *Sov. Phys.–Tech. Phys.* **12** 208–11

[6] Meyer R X 1967 A space-charge-sheath electric thruster *AIAA J.* **5** 2057–9

[7] Estimated from the authors and organizations represented at the *AIAA Electric Propulsion Conferences* in the US during this period.

[8] Estimated from the authors and organizations represented at *All-Union Plasma Accelerators and Ion Injectors Conferences* in the USSR during this period.

[9] The *All-Union Conferences on Plasma Accelerators* were held in 1971 (*Moscow*), 1973 (*Minsk*) and 1976 (*Minsk*). The subsequent *All-Union Conferences on Plasma Accelerators and Ion Injectors* were held in 1978 (*Moscow*), 1982 (*Moscow*), 1986 (*Dnepropetrovsk*) and 1989 (*Kharkov*) (in Russian)

[10] Artsimovich L A, Andronov I P, Esipchuk, Iu V, Morozov A I, Snarsky R K and Kozubsky K N 1974 development of a stationary plasma thruster (spt) and its testing on the earth artificial satellite ‘meteor’ *Kosmicheskie Issledovania* **12** 451–68 (in Russian)

[11] Sheremetjevsky N N *et al* (eds) 1978 Main results of space tests of an electric rocket device with SPT (EOL-2) on earth artificial satellite ‘meteor-priroda’ *Proc. 4th All-Union Conf. on Plasma Accelerators and Ion Injectors (Moscow, 1978)* (Moscow: Nauka) pp 317–21 (in Russian)

[12] Cybulski R J, Shellhammer D M, Lovell R R, Domino E J and Kotnik J T 1965 Results from SERT-I ion rocket flight tests *NASA Technical Note* D-2718

[13] Kerslake W R, Goldman R G and Nieberding W C 1971 SERT-II: mission, thruster performance and in-flight thrust measurements *J. Spacecraft Rockets* **8** 213–24

[14] Grishin S D, Leskov L V and Kozlov N P 1983 *Plasma Accelerators* (Moscow: Mashinostroenie) p 80 (in Russian)

[15] Garner C E, Brophy J R, Polk J E, Semenkin S, Garkusha V, Tverdokhlebov S and Marrese C 1994 Experimental evaluation of Russian anode layer thrusters *30th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. (Indianapolis, IN, 1994)*

[16] Artsimovich L A, Grishin S D, Grodzovsky G L, Leskov L V, Morozov A I, Porotnikov A A, Dorodnov A M, Padalka V G and Pergament M I (eds) 1973 *Plasma Accelerators* (a collection of papers from the *1st All-Union Conf. on Plasma Accelerators*) (Moscow: Mashinostroenie) (in Russian)

[17] Morozov A I (ed) 1974 *Physics and Application of Plasma Accelerators* (a collection of papers from the *2nd All-Union Conference on Plasma Accelerators*) (Minsk: Nauka i Tekhnika) (in Russian)

[18] Grishin S D, Leskov L V and Kozlov N P 1975 *Electric Rocket Thrusters* (Moscow: Mashinostroenie) (in Russian)

[19] Morozov A I 1978 *Physical Basics of Space Electroreactive Thrusters* (Moscow: Atomizdat) (in Russian)

[20] Grishin S D, Leskov L V and Kozlov N P 1983 *Plasma Accelerators* (Moscow: Mashinostroenie) (in Russian)

[21] Kozlov N P and Morozov A I (eds) 1984 *Plasma Accelerators and Ion Injectors* (a collection of papers from the *5th All-Union Conf. on Plasma Accelerators and Ion Injectors)* (Moscow: Nauka) (in Russian)

[22] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian)

[23] Belan N V, Kim V P, Oransky A I and Tikhonov V B 1989 *Stationary Plasma Thrusters* (Kharkov: Kharkov Aviation Institute) (in Russian)

[24] Morozov A I and Semashko N N (eds) 1990 *Ion Injectors and Plasma Accelerators* (a collection of papers from the *7th All-Union Conf. on Plasma Accelerators and Ion Injectors)* (Moscow: Energoatomizdat) (in Russian)

[25] Petrosov V A (ed) 1991 *Rocket-Space Techniques* (a collection of papers on electric propulsion, especially the magnetic layer type thruster) (Moscow: Research Institute of Thermal Processes) (in Russian)

[26] Morozov A I 1973 Plasma accelerators pp 5–15 in [16]

[27] Morozov A I 1973 On equilibrium and stability of flows in accelerators with closed electron drift and extended acceleration zone pp 85–92 in [16]

[28] Belan N V, Kim V P, Oransky A I and Tikhonov V B 1989 *Stationary Plasma Thrusters* (Kharkov: Kharkov Aviation Institute) (in Russian) pp 163

[29] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian) p 106

[30] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian) p 105

[31] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian) p 107

[32] Morozov A I 1968 Effect of near-wall conductivity in well magnetized plasma *Sov. J. Appl. Mech. Tech. Phys.* no 3, 19–22 (in Russian)

[33] Bugrova A I and Morozov A I 1991 Peculiarities of physical processes in aced (accelerator with closed electron drift and extended acceleration zone) pp 42–56 in [25]

[34] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Maslinostroenie) p 108 (in Russian)

[35] Bugrova A I and Kim V 1984 Modern state of physical studies in accelerators with closed electron drift and extended acceleration zone pp 107–28 in [21]

[36] Morozov A I 1973 On equilibrium and stability of flows in accelerators with closed electron drift and extended acceleration zone pp 85–92 in [16]

[37] Morozov A I, Esipchuk, Yu V, Kapulkin A M, Nevrovskii V A and Smirnov V A 1972 Effect of the magnetic field on a closed-electron drift accelerator *Sov. Phys.–Tech. Phys.* **17** 482–7

[38] Morozov A I 1984 Volumetric electrostatic fields in the plasma pp 82–106 in [21]

[39] Belan N V, Kim V P, Oransky A I and Tikhonov V B 1989 *Stationary Plasma Thrusters* (Kharkov: Kharkov Aviation Institute) pp 156–7

[40] Bugrova A I and Morozov A I 1984 Near wall conductivity pp 189–200 in [21]

[41] Egorov V V, Kim V, Semenov A A and Shkarban I I 1990 Near wall processes and their influence on operation of accelerators with closed electron drift pp 56–68 in [24]

[42] Kaufman H R 1984 Theory of ion acceleration with closed electron drift *J. Spacecraft Rockets* **21** 558–62

[43] Zharinov A V and Popov Yu S 1967 Acceleration of plasma by a closed Hall current *Soc. Phys.–Tech. Phys.* **12** 208–11 (Engl. transl.)

[44] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian) pp 109–11

[45] Belan N V, Kim V P, Oransky A I and Tikhonov V B 1989 *Stationary Plasma Thrusters* (Kharkov: Kharkov Aviation Institute) (in Russian) p 142

[46] Garkusha V I, Lyapin E A, Semyenkin A V and Tverdokhlebov S O 1993 Anode layer thrusters, state-of-the-art and prospectives *Proc. 23rd Int. Electric Propulsion Conf. (Seattle, WA, 1993)* (Worthington, OH: Electric Rocket Propulsion Society) IEPC-93-228 pp 2120–4

[47] Ljapin E A and Semenkin A V 1989 Accelerator with extended anode layer *7th All-Union Conf. on Plasma Accelerators and Ion Injectors* (Kharkov: TSNIIAtominform) pp 210–11 (in Russian)

[48] Berkov V I, Kozintseva M V, Razikov E V, Sapelkina V P and Trofimov A V 1986 Properties of ceramics in the flow of accelerators with closed drift and extended acceleration *Proc. 6th All-Union Conf. on Plasma Accelerators and Ion Injectors* ed A I Morozov(Dnepropetrovsk: Dnepropetrovsk State University) p 32

[49] Semenov A A and Shkarban I I 1991 Erosion of surfaces of construction elements by ion flows from ion–plasma sources pp 42–53 in [25]

[50] Kresanov V S, Malakhov N P, Morozov V V, Semashko N N and Shljuko V 1987 *Ia. High Efficiency Emitters of Electrons Based on Lanthanum Hexaboride* (Moscow: Energoatomizdat) (in Russian)

[51] Belan N V, Kim V P, Oransky A I and Tikhonov V B 1989 *Stationary Plasma Thrusters* (Kharkov: Kharkov Aviation Institute) (in Russian) pp 162–3

[52] Grishin S D, Leskov L V and Kozlov N P 1983 *Plasma Accelerators* (Moscow: Mashinostroenie) p 83 (in Russian)

[53] Esipchuk, Yu B, Morozov A I, Tilinin G N and Trofimov A V 1974 Plasma oscillations in closed-drift accelerators with an extended acceleration zone *Sov. Phys.–Tech. Phys.* **18** 928–32

[54] Abramkov V V, Izmailov A A and Shishkin G G 1989 Influence of external circuit on characteristics of accelerator with closed electron drift and extended acceleration zone *Proc. 7th All-Union Conference on Plasma Accelerators and Ion Injectors (Kharkov, 26–28 September, 1989)* pp 72–3 (in Russian)

[55] Vakhnjuk S P, Kapulkin A M and Prisnjakov V F 1990 Stabilization of plasma instabilities in accelerators with closed electron drift by boundary system of feedback pp 78–86 in [24]

[56] Morozov A I 1973 The study of plasma systems with closed electron drift and distributed electric field pp 75–84 in [16]

[57] Grishin S D and Leskov L V 1989 *Electric Rocket Thrusters of Space Apparatus* (Moscow: Mashinostroenie) (in Russian) p 126

[58] Kim V 1982 Main physical features of operational processes in modern accelerators with closed electron drift and extended acceleration zone *Proc. 5th All-Union Conf. on Plasma Accelerators and Ion Injectors* ed N P Kozlov (Moscow: Nauka) pp 39–40 (in Russian)

[59] Baranov V I, Nazarenko Yu S, Petrosov V A, Vasin A I and Yashnov Yu M New conceptions of oscillation mechanisms in the accelerator with closed drift of electrons *Proc. 24th Int. Electric Propulsion Conf.* IEPC-95-44, pp 344–51

[60] Bober A S and Maslennikov N A SPT in Russia—new achievements *Proc. 24th Int. Electric Propulsion Conf. (Moscow)* IEPC-95-06 pp 54–60

[61] Arkhipov B A, Bober A S, Gnizdor R Y, Kozubsky K N, Korakin A I, Maslennikov N A and Pridannikov S Y The results of 7000-hour SPT-100 life testing *Proc. 24th Int. Electric Propulsion Conf. (Moscow)* IEPC-95-39, pp 315–21