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Schlieren Imaging of Microthruster Exhausts for Qualitative and Quantitative Analysis

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Abstract. Schlieren imaging is a method used to visualize differences in refractive index within a medium. It is a powerful and straightforward tool for sensitive and high-resolution visualization of, e.g., gas flows. Here, heated cold gas microthrusters were studied with this technique. The thrusters are manufactured using microelectromechanical systems technology, and measure $22 \times 22 \times 0.85$ mm. The nozzles are approximately 20 μm wide at the throat, and 350 μm wide at the exit. Through these studies, verification of the functionality of the thrusters, and direct visualization and of the thruster exhausts was possible. At atmospheric pressure, slipping of the exhaust was observed, due to severe overexpansion of the nozzle. In vacuum (3 kPa), the exhaust was imaged while feed pressure was varied from 100 to 450 kPa. The nozzle was overexpanded, and the flow was seen to be supersonic. The shock cell period was linearly dependent on feed pressure, ranging from 320 to 610 μm . With activated heaters, the shock cell separation increased. The effect of the heaters was more prominent at low feed pressure, and an increase in specific impulse of 20% was calculated. It was also shown that schlieren imaging can be used to detect leaks, making it a valuable, safe, and noninvasive aid in quality control of the thrusters.

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1. Introduction

During operation, spacecraft generally need some type of on-board propulsion system [1]. The size and mass of the satellite, as well as the desired manoeuvres will determine what type of thrusters are required, and how much fuel is needed for the mission. The desire to reduce the mass of the spacecraft, while maintaining attitude control, is driving the development of very small and low-thrust propulsion systems [2]. Low-thrust propulsion systems are also key components in missions with larger spacecraft, where extremely accurate attitude adjustments are required, such as the LISA [3] and Darwin [4] missions. Microelectromechanical systems (MEMS) technology not only allows for miniaturization of the components themselves, but also for true integration with electronics and other components, such as valves, filters, etc. [1]. This renders MEMS devices particularly attractive for mass-critical applications [5].

Cold gas microthrusters are commonly fabricated using lithographic patterning and deep reactive ion etching (DRIE) of silicon wafers [6]. DRIE results in smooth side walls, making it particularly suitable for micronozzles [7], Figure 1. In these thrusters, heaters are embedded in the stagnation chamber to improve the specific impulse (efficiency).

The small scale of the thrusters, and low quantities of gas in the exhaust place high demands on magnification and sensitivity of the flow visualization and quantification methods [8].

When the gas exits the nozzle, pressure differences between the expelled gas and its surroundings will cause shock waves in the exhaust, which, reflected in the boundary layer, appear as periodic features in the jet. These features can be made visible using schlieren imaging [9].

In this paper, an in-line lens schlieren system using a high-resolution digital camera is designed, set up, and tested, and an effective post-processing technique is demonstrated. The exhaust from MEMS-based heated cold gas thrusters is visualized to study the behaviour at different flow rates, ambient pressures, and with different numbers of heaters activated. Measurements of the shock cells in the resulting images, together with simultaneous measurements of pressure and mass flow, are used to estimate the temperature in the stagnation chamber, the fully expanded Mach number, thrust, and specific impulse of the thruster.

2. Materials and Methods

2.1. Schlieren imaging

Schlieren photography, or schlieren imaging, is a method of visualizing inhomogeneities in transparent media. Gas exiting a nozzle is different from its surrounding in composition, pressure and temperature which leads to differences in refractive index, n_D . This will cause refraction of light rays passing through the gas, enabling visualization of the flow

Figure 1: Interior of micronozzle manufactured using DRIE. Gas exits to the left.

itself. By directing collimated light at the exhaust, and then focusing the beam onto a *cut-off*, which filters the refracted light from the beam, an image of the exhaust is created [9]. Simplified, the schlieren setup consists of a light source and a collimating lens, a schlieren lens, followed by a cut-off and a lens for focusing the image on a screen or camera sensor, Figure 2.

In order to achieve adequate collimation, a condensing lens is often used to focus light from the source onto an aperture or slit, which will then emulate a point-like (aperture), or extended point-like (slit) light source. By using variable apertures or slits, the degree of collimation can be tailored to the disturbance to be visualized. It is desirable to have long and matched focal lengths for the collimating lens and the schlieren lens.

The contrast and sensitivity is adjusted by moving the cut-off to filter unrefracted light to a desired degree. Light refracted away from the cut-off will pass unobstructed, but light refracted into it will be blocked. For many applications, a razor blade will serve very well as a cut-off, though graded cut-off filters may be used at high magnification, to reduce diffraction [11]. With a straight edge as cut-off, visualization of refraction in different directions is accomplished by rotation of the sample around the optical axis of the setup.

2.2. Experimental setup

In this work, the light source was a 1 kW quartz-tungsten-halogen (QTH) lamp (Oriel, Newport, USA) with a water-cooled infrared filter (Newport, USA), and an ultraviolet filter (Hoya Corporation, Japan) mounted on the focusing barrel. A 300 mm $f/5.9$ lens was used to focus the beam from the lamp onto a variable slit, mounted on two 1" manual translation stages for X-Y adjustment. After the slit, an identical lens, mounted on a single translation stage for X adjustment, collimated the light through the test area.

Figure 2: Schlieren setup in simplified schematic (top) with ϵ_y denoting angle of refraction of a light ray, and Δa the resulting displacement at the cut-off. Bird's eye view of actual setup (bottom), from left to right: light source, mirror, lens, variable slit, collimating lens, vacuum chamber with thruster, schlieren lens, cut-off, and camera. The cardboard is to block stray light from the lamp.

The schlieren lens is a 400 mm $f/7.9$ achromatic doublet, placed 800 mm from the thruster/samples.

The cut-off consisted of a razor blade mounted on an X-Y-positioning fixture, to ensure accurate positioning in the focal point of the schlieren lens, as well as enabling very precise lateral adjustment. A cut-off of 95-99% was used to maximize sensitivity and contrast of the images, while maintaining a full measuring range. Except for the lamp and filters, all optical components, as well as mounts and translation stages are from Thorlabs Ltd, UK.

Image acquisition was achieved with a digital camera ($\alpha 350$, Sony Corporation, Japan), and a 50 mm $f/1.8$ lens (Canon Inc, Japan) mounted on a bellows (Canon Inc, Japan). At the maximum magnification, the lens and bellows combination magnified the live image approximately 3.6 times, imaging an area of 4.5×7 mm.

For studies in vacuum, a cylindrical vacuum chamber with an inner diameter of 150 mm, and an internal height of 125 mm, was manufactured. The bottom plate was designed to include an electrical feedthrough with an external female 25-pin RS232 connector, as well as $1/16''$ NPT connections for the vacuum pump and the propellant

gas. The chamber had two opposing 40-mm KF flanges fitted with sight glasses (Pfeiffer, Germany). A mechanical manometer (Svenska Manometerfabriken, Sweden) on the chamber lid enabled pressure read-out. The chamber was evacuated using a vacuum pump (EDM 6, Edwards, UK). Xenon propellant gas was supplied to the thruster from a high-pressure gas cylinder. In order from gas connection to thruster, a 15 μm particle filter (Swagelok, USA), a pressure transducer (Standard industrial 0-1 MPa, Swagelok, USA) and a mass flow sensor (0-1000 sccm, Honeywell International Inc, USA) were connected. Both the pressure transducer and flow sensor were read by a multifunction DAQ (U2356A, Agilent Technologies, USA) at a sampling rate of 10 Hz. The mass flow sensor was calibrated for nitrogen, and the xenon flow rate was calculated using a conversion factor for calorimetric flow sensors [12].

2.3. Sample preparation

Three prototype cold gas microthrusters from the company NanoSpace were studied [13]. These are all designed to use xenon gas as propellant, and contain internal heaters in the stagnation chamber. Thruster #1 has six heaters, thrusters #2 and #3 have three each. The microthrusters measured $22 \times 22 \times 0.85$ mm, and the nozzles are approximately 20 μm wide at the throat, and 350 μm wide at the exit, etched to a depth of 350 μm . The microthrusters were mounted in an aluminium fixture (NanoSpace, Sweden) which provided connections for heater power and gas. Figure 3. A groove was milled from the top edge of the fixture down to the edge of the thruster nozzle, to enable imaging of the exhaust. The entire setup was mounted on a 3×1.5 m optical table top (CVI Melles Griot, USA), Figure 2.

The thrusters were manufactured from silicon using conventional UV lithography, thin film deposition, deep reactive ion etching and fusion bonding [14]. The nozzles and their connections were contained in one wafer, whereas the second wafer was left unstructured. Processing of helical diamond-like carbon heater elements was made with the more exotic laser-assisted CVD technique [14]. After oxidizing the nozzle wafer to prevent short-circuiting, three individually manufactured heaters were mounted manually, with connection arms in six through vias in each nozzle's stagnation channel. Electrical connection to thin film contact pads and leads on the other side was facilitated with silver glue, before the two wafers were bonded together.

2.4. Imaging and measurements

The jet exhaust from Thruster #1 was photographed in atmospheric ambient pressure with feed pressure ranging from 50 to 350 kPa. Images were captured with exposure times from 1/60 s (ISO 100), to minimize sensor noise, to 1/1000 s (ISO 1600), to enable better time-resolved visualization of the gas. The exhaust was photographed with the flow parallel to, as well as perpendicular to, the cut-off. Tests with and without the (vented) vacuum chamber in place were also conducted in order to determine any effects the vacuum chamber and its sight glasses could have on the images.

Figure 3: Thruster chip #1 (22×22 mm) in opened fixture. A spacer and eight alignment pins surround the silicon chip. The thruster exhausts into the milled u-shaped recession facing down and to the left in the picture. Here, 12 gold pads are used for connection to the six heaters, gas inlet is at the top right of the chip.

In vacuum (approximately 3 kPa) the feed pressure was adjusted from 50 to 450 kPa (relative to the vacuum chamber) in steps of 50 kPa. Feed pressure and flow rate were logged with 10 Hz sampling rate at each pressure level. Images of the exhaust from all three thrusters were acquired with different shutter speeds and the exhaust parallel to, as well as perpendicular to, the cut-off.

Studies were also conducted with Thruster #3 to determine the effects of the heaters on the exhaust in vacuum. Images of the exhaust were captured with no heaters active, each heater activated individually, the two heaters closest to the nozzle active, and all heaters active, with propellant at 200 kPa and 400 kPa feed pressure. When activated, Heater 1 (closest to the nozzle) was supplied with 71.9 mA at 13.6 V, Heater 2 with 90 mA at 12.8 V, and Heater 3 with 90 mA at 13.0 V. Limits were set to 90 mA or 13.6 V, whichever was reached first, and heaters were only activated when gas flow was present. The supplied power was calculated to 0.98 W, 1.15 W, and 1.17 W, respectively, for the three heaters.

The images acquired were 4592×3056 pixel RGB channel JPEG images, processed using MatLab (Mathworks, USA). As only the intensity data was of interest when using the razor blade cut-off, the three colour channels were added together to create a greyscale image. In stationary cases, noise and the effects of dust particles in the beam could be reduced by calculating the pixel-wise median of several images. In order to compensate for uneven background illumination, and dust particles on the lenses, mirrors, sight glasses, etc., a reference image (without propellant fed to the system) was captured and subtracted from the signal images. The resulting image was adjusted with respect to brightness and contrast in Gimp (GNU Image Manipulation Program).

3. Results

Images of the exhaust from Thruster #1 at atmospheric ambient pressure and with 100, 200, and 350 kPa feed pressure, Figure 4, depict the exhaust parallel to the cut-off. At the lowest of the feed pressures, the exhaust is seen to stick to one side. As the pressure increases, the exhaust straightens and narrows.

With the shorter shutter speeds, turbulence in the flow could be visualized. In images of Thrusters #1 and #2 at atmospheric ambient pressure with the flow perpendicular to the cut-off, Figure 5, the edges of the exhaust were less distinct. The appearance was similar in the two images, except for a darker area closest to the nozzle of Thruster #1, Figure 5(a).

In vacuum, the exhaust was straight and narrow even at the lowest pressure studied, and only became more distinct as the feed pressure increased, Figure 6. Exhaust from Thruster #2 was also studied in vacuum, both parallel with and perpendicular to the cut-off, Figure 7. In vacuum, pressure differences in the exhaust appeared to be stationary and could be photographed with relatively long exposure times. When photographed with the exhaust perpendicular to the cut-off, a periodic shock cell pattern in the exhaust was visible, Figure 7(b).

The period of the shock cell pattern changed with feed pressure, but also with the number of heaters active in the thruster. By plotting the intensity level of the image along a line through the centre of the exhaust and measuring peak-to-peak distances, the separation between the intensity maxima can be determined. A 50-point moving average was calculated in order to reduce noise in the image, Figure 8. The lighter grey line in the graph in Figure 8 is the intensity level along the centre of the exhaust in the image, with the uniform intensity of the fixture to the left, and the periodic intensity fluctuation of the exhaust slowly fading to a smooth line.

During the studies, the pressure and mass flow rate were logged, Figure 9. Measurements of the periods in the shock cell pattern were plotted both as a function of feed pressure, Figure 10, as well as as a function of the number of active heaters, Figure 11. Mass flow rates of Thruster #3 at feed pressures of 200 and 400 kPa, with different numbers of heaters active, are listed in Table 1. Using equations (1), (4), (6), (7), and (8), physical quantities relating to thruster performance were calculated, Table 2.

(a)

(b)

(c)

Figure 4: Exhaust from Thruster #1 at atmospheric ambient pressure, photographed with exhaust parallel with cut-off and with (a) 100, (b) 200, and (c) 350 kPa feed pressure. Field of view is 21×14 mm.

(a)

(b)

Figure 5: Exhaust photographed at high ISO with exhaust perpendicular to cut-off, at atmospheric ambient pressure. (a) Thruster #1. Shutter speed is 1/1000 s (b) Thruster #2. Shutter speed of 1/400 s. Field of view is 21×14 mm.

Figure 6: Exhaust from Thruster #1 in vacuum at 400 kPa feed pressure, with exhaust parallel with cut-off. Field of view is 7×4.5 mm.

(a)

(b)

Figure 7: Jet exhaust from Thruster #2 in vacuum, at 400 kPa feed pressure. (a) exhaust parallel with the cut-off. Field of view is 12.5×8.3 mm, (b) with exhaust perpendicular to the cut-off. Field of view is 6.5×4 mm.

Figure 8: Variation of grey scale intensity (bottom) along centre line of exhaust (top) with vertical dotted lines indicating periodic intensity peaks. The dark line is a 50-point moving average. Cropped image with a field of view of 7×1.5 mm.

Table 1: Average flow rates of Thruster #3 in vacuum for different combinations of active heaters and total power, with feed pressures of 200 and 400 kPa. Heater #1 is closest to the nozzle, σ is the standard deviation of 10 s measurements at 10 Hz sampling rate.

Active heater	Total heater power (W)	200 kPa feed pressure		400 kPa feed pressure	
		Flow rate (sccm)	σ	Flow rate (sccm)	σ
none	0	223	0.2	444	5.9
#1	0.98	185	1.4	402	5.0
#2	1.15	193	0.2	401	5.1
#3	1.17	190	1.2	403	5.3
#1 & 2	2.13	174	1.1	376	5.0
#1, 2 & 3	3.30	155	1.1	356	4.8

Figure 9: Mass flow versus feed pressure, from 0 to 450 kPa, with least squares fitted linear curves.

4. Discussion

4.1. Schlieren imaging

Traditionally, the challenge with schlieren photography is to maximize the field of view. Here, though, only a small field of view was required. For high magnification, the

Table 2: Calculated stagnation chamber temperature, exhaust temperature, exhaust speed, thrust, and specific impulse for 200 and 400 kPa feed pressure and different numbers of active heaters.

		Number of active heaters	T_i (K)	T_e (K)	v (m/s)	F (mN)	I_{sp} (s)
Feed pressure (kPa)	200	0	293	55	276	6.0	28.1
		1	353	67	303	5.5	30.8
		2	376	71	312	5.3	31.8
		3	422	79	331	5.0	33.7
	400	0	293	42	283	12.3	28.8
		1	324	46	297	11.7	30.3
		2	346	49	308	11.3	31.3
		3	365	52	316	11.0	32.2

Figure 10: Shock cell period versus feed pressure, with least squares fitted linear curves. Error bars indicate standard deviation of 6 measurements.

amount of available light is what limits the sensitivity. Increased sensitivity requires a narrower slit or aperture before the collimating lens, which will reduce the amount of transmitted light. Sensitivity can also be increased at the expense of measuring range, by increasing the level of cut-off, reducing the light transmitted to the imaging device even further. High magnification also means a smaller part of the beam is used.

If different propellants, smaller gas quantities, or even smaller nozzles are to be studied, a more powerful light source may be necessary. Arc discharge lamps are capable of over 100 times higher illuminance after collimation (due to the smaller source). Thus, much higher magnification is absolutely possible. Lasers, which offer a small source, are, however, unsuitable due to interference caused by the coherent light.

The studies at atmospheric pressure provided a suitable basis for development of the schlieren setup, and understanding of the effects of the vacuum chamber on the

Figure 11: Shock cell period versus number of active heaters, for 200 and 400 kPa feed pressure. Error bars indicate standard deviation of 6 measurements.

images. The sight glasses of the vacuum chamber were found to be of sufficient quality. However, using them, four additional surfaces that could collect dust were introduced. While this was fairly easily mitigated, either physically or in post processing, this should be an incentive to minimize surfaces in the beam, regardless of their optical quality.

Schlieren imaging is a general tool, like micrographing and conventional photography. Its use is by no means limited to microthruster exhausts. Due to its capability of resolving differences in refractive index, it can be used for the study of mixing chemicals, temperature changes, pressure waves, homogeneity within materials, etc [15]. As long as the media is transparent, and the setup is properly adjusted to resolve the differences in refractive index, the magnification is easily adapted for resolution down to micrometers, making it a suitable tool for microfluidics.

Various techniques are available to enhance the result, such as normalizing the image [10], or, as in this study, subtracting a reference image. By using standard photographic equipment, high-resolution images were captured, and noise was reduced by calculating the pixelwise median of several images.

4.2. Exhaust visualization

The exhaust flow was very fast, and the details, unless stationary, were generally lost due to motion blur. At atmospheric pressure, the speed of the exhausted gas was still low enough that shorter exposure times did resolve more detail, but because of the higher ISO required to maintain the same exposure value, more noise was introduced, Figure 5.

The background illumination in Figure 4 was very unstable, and indicated that there was a leak in Thruster #1. Comparison with Thruster #2, Figure 5, suggested the leak was from the thruster rather than from the fixture or fittings. In vacuum, the

leak was visible as a faint secondary exhaust to the left of the main exhaust, Figure 6. Measurements of mass flow versus feed pressure, Figure 9, also indicated an excess flow that may have been caused by the leak.

While some types of defects can be detected by other means, some anomalies in the jet behaviour would likely go unnoticed without visualization of the flow. For example, slipping of the exhaust, Figure 4(a), is caused by severe overexpansion of the nozzle when operated at atmospheric ambient pressure. Differences in design as well as in fabrication technique may also cause differences in the appearance of the exhaust.

As these were prototype thrusters, the schlieren technique was particularly useful, as it was able to visualize flaws, e.g. leakage, that could easily have gone unnoticed without this method, or a large number of reference thrusters. The relative ease with which this apparatus is set up, the relatively low cost compared with the manufacturing cost of the devices, and the very low risk acceptance due to the very high total cost of the missions, makes this a very useful method for tests of the thrusters.

In vacuum, the jet exhausts were observed to be supersonic. This was confirmed by the occurrence of shock cells, Figure 7(b).

4.3. Thruster theory

Assuming isentropic flow conditions and the ideal gas law being applicable, several parameters can be quantified [16].

The temperature in the stagnation chamber of the thruster, T_i , can be calculated through

$$T_i = T_{\text{RT}} \frac{\dot{m}_{\text{RT}}}{\dot{m}_h}, \quad (1)$$

where T_{RT} is the ambient temperature (here 293 K), $\dot{m}_{\text{RT}}$ is the mass flow rate for the unheated case, and $\dot{m}_h$ is mass flow rate for the heated case. For choked flow, the Mach number in the throat is 1, and the pressure in the throat of the nozzle, p_t , can be calculated using

$$p_t = p_i \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma-1}}, \quad (2)$$

where p_i is the inlet pressure (assumed to be the same as the feed pressure), and γ is the heat capacity ratio for xenon, 1.66 [17].

The temperature in the throat, T_t , is calculated through

$$T_t = T_i \left(\frac{p_t}{p_i} \right)^{\frac{\gamma-1}{\gamma}}, \quad (3)$$

and, similarly, the exhaust temperature, T_e , is calculated from

$$T_e = T_t \left(\frac{p_e}{p_t} \right)^{\frac{\gamma-1}{\gamma}}, \quad (4)$$

where p_e is the pressure of the fully expanded jet, here the vacuum chamber pressure of 3 kPa. The speed of sound in the exhaust can be expressed as

$$a = \left(\frac{\gamma R T_e}{M} \right)^{\frac{1}{2}}, \quad (5)$$

where M is the molar mass of xenon, 131 g/mol, and R is the universal gas constant, 8.314 J/Kmol. Finally, the speed of the exhaust, v , can be calculated through

$$v = a M_j = \frac{2a}{\gamma - 1} \left[\left(\frac{p_i}{p_e} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{\frac{1}{2}}, \quad (6)$$

where M_j is the fully expanded jet Mach number. Hence the thrust

$$F = \dot{m}v, \quad (7)$$

and the specific impulse, a measure of the efficiency of the thruster,

$$I_{sp} = \frac{v}{g_0}, \quad (8)$$

can be calculated, where g_0 is the gravitational acceleration at the surface of the Earth.

4.4. Quantification

Previous work [18] has suggested a formula for calculating the shock cell period based on the nozzle diameter and fully expanded jet Mach number (M_j), which are both design parameters. The ability to measure the shock cell period could thereby be used to solve for M_j , and, e.g., evaluate design and operating conditions. However, the presented formula does not take into account the effect of the heaters.

The difference when activating the heaters could be observed by a decrease in mass flow, Table 1, as well as an increased shock cell separation, particularly at lower feed pressure, Figure 11. Simulations [19] and studies with unheated micronozzles [20] have shown that the Reynolds number decreases with increased temperature, and flow visualization [11] has shown that chock cell separation for overexpanded nozzles increases with decreasing Reynolds number. When heating the gas, Table 1, the Reynolds number of the exhaust decreases. Hence, the shock cell separation increases, Figure 11. An increased number of active heaters will increase the effect. The biggest change was obtained when going from zero to one active heater, and with decreasing impact from then on. At higher flow rates, the heat transfer per volumetric flow unit is less, and the increase in average temperature of the gas is smaller. This is thought to be due to the heaters being approximately the same temperature. In the 200-kPa case, the third heater has less influence as the gas temperature has already saturated, whereas in the 400-kPa case, each heater raises the temperature about the same amount. This leads to the increased shock cell separation also with the third heater.

As the inlet pressure, p_i , is assumed to be equivalent to the feed pressure, it follows from Equation (6) that the Mach number does not change with the number of active heaters. However, the exhaust speed and shock cell period, Figure 12, do, which shows

Figure 12: Shock cell period versus calculated exhaust speed. The unheated case is indicated by connected dots, with shock cell period increasing with feed pressure from 100 to 450 kPa in steps of 50 kPa. The heated cases are represented by diamonds and squares for series of 200 and 400 kPa fixed feed pressure, respectively, with increasing number of active heaters (0, 1, 2 and 3) from left to right.

Figure 13: Calculated specific impulse and exhaust speed versus number of active heaters, for 200 and 400 kPa feed pressure.

that the model proposed by Phalnikar, et al. [18] is not applicable when the gas is heated. Furthermore, both the exhaust speed and specific impulse, Equation (8), increase up to 20% with increasing number of active heaters, Figure 13. The decrease in mass flow rate will, despite the increased exhaust speed, lead to reduced thrust, Table 2.

5. Conclusions

Schlieren imaging was shown to be a powerful technique capable of visualizing micrometre-scale xenon exhaust from microthrusters measuring 20 μm at the throat

and 350 μm at the exit, under various conditions in vacuum and air.

Studies either at atmospheric pressure or in vacuum can be used to identify and locate leaks in the thrusters.

Active heaters in the stagnation chamber will increase shock cell separation.

Measurements of the shock cell spacing in the jet exhaust, can be used to estimate the temperature in the stagnation chamber, temperature and pressure in the throat and exhaust, as well as exhaust speed, thrust and specific impulse of the thruster.

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