# Parameters of D-80 Anode Layer Thruster in One- and Two- Stage Operation Modes

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## ABSTRACT

One- and Two-stage modes of TAL D-80 are studied in detail. Optimal discharge (first stage) voltage from the thruster efficiency and the ion current fluctuation level point of view in Two-stage mode has been determined. The thruster efficiency and ion current fluctuation level in One- and Two-stage modes have been compared and the areas of preferable One-stage mode and Two-stage mode application have been found.

NOMENCLATURE

| | |
|---|---|
| $V_d$ | Discharge voltage (1st Stage) |
| $I_d$ | Discharge current |
| $V_a$ | Acceleration voltage |
| $I_a$ | Acceleration stage current (2nd stage) |
| $m_a$ | Anode mass flow (Xe) |
| $V_f$ | Floating potential voltage |
| $T_b$ | Thruster body temperature |
| $I_{inn}$ | Inner coil current |
| $V_{inn}$ | Inner coil voltage |
| $I_{out}$ | Outer coil current |
| $V_{out}$ | Outer coil voltage |
| N | Input discharge power |
| $V_{sum}$ | Total Voltage Drop ($V_d + V_a$) |
| $I_{sp}$ | Specific impulse |
| F | Thrust |
| $d_a$ | Average diameter of the thruster anode |
| $p_k$ | Chamber residual pressure |
| $V_{ac}$ | Alternating voltage, characterizing alternating ion current part |
| $V_{dc}$ | Direct voltage, characterizing direct ion current part |
| $\eta$ | Efficiency |

## STATEMENT OF PROBLEM.

Under the NASA Glenn Research sponsorship TsNIIMASH-Boeing team has developed a Hall thruster with increased performance and reduced mass, complexity and cost compared to state-of-the-art (SOA) gridded ion propulsion. Approach made use of key Thruster with Anode Layer (TAL) technologies specifically associated with a two-stage or multi-mode Hall thrusters [1].

Developed multi-mode thruster is called D-80 (its average diameter is equal to 80 mm) and it has an ability to operate both in One-stage mode and Two-stage mode.

The difference between One-stage and Two-stage modes is in the following:

- In a one-stage mode, the propellant ionization and ion acceleration occur within a single anode layer.
- In the two-stage mode, two discharges are arranged sequentially within one current channel. The first discharge or stage serves as a propellant ionizer, while the second stage provides acceleration of the newly generated ions.

As experimentally demonstrated at TsNIIMASH, the functional separation of ion production and acceleration zones provides a benefit when high $I_{sp}$ is required. The two-stage TALs demonstrate performance characteristics that are superior to all other Hall thrusters for $I_{sp}$s greater than 3000 s.

Existing One- and Two-stage TAL parameter range is given in Figure 1.

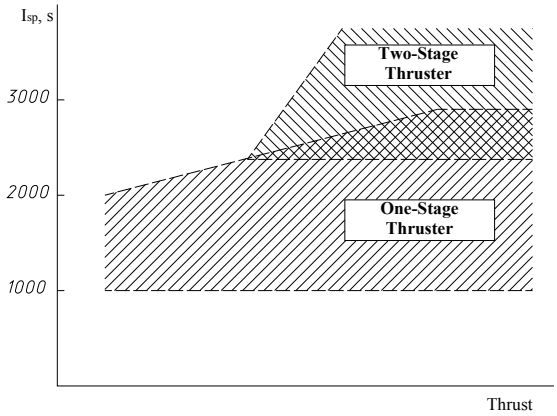


**Figure 1. Existing One- and Two-stage TAL Parameter Range.**

Obtained D-80 operating envelope is given in Figure 2.

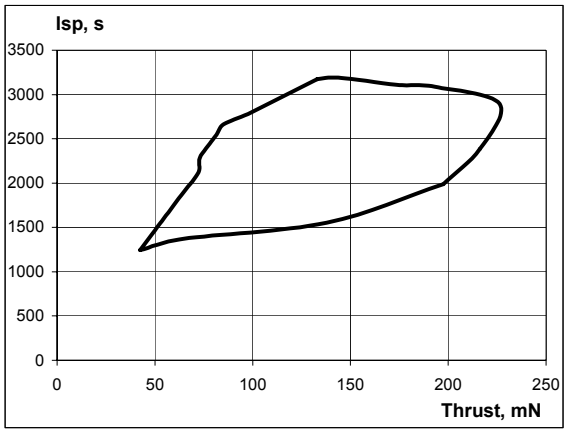


**Figure 2. D-80 operating envelope.**

The envelope includes One- and Two-stage modes. As one can see due to a multi-mode ability the thruster can efficiently operate both in low voltage mode, where Thrust/Power ratio is maximal, and in high voltage mode with maximal specific impulse.

As it was stated in [2] this ability allows to use the thruster for orbit transfer missions where maximal thrust is required (One-stage mode) as well as for station keeping missions where high specific impulse is needed (Two-stage mode).

The main purpose of the paper is to determine preferable One-stage mode and Two-stage mode application areas of D-80 operating envelope.

## DETERMINATION OF AREAS OF PREFERABLE ONE-STAGE MODE AND TWO-STAGE MODE APPLICATION.

One- and Two-stage modes can be compared by two criteria:

I. Thruster efficiency shall be maximal.
II. Ion current fluctuation level shall be minimal.

### One- and Two-stage modes comparison by thruster efficiency criterion.

It is obvious that the areas of preferable One- and Two-stage mode application are somehow limited by mass flow and summary voltage boundaries.

Two different experiment series have been carried out.

1. The first one was directed to mass flow boundaries determination.
2. The second one – to summary voltage boundaries determination.

Before characteristics of efficiency versus mass flow for One- and Two-stage mode obtaining, Two-stage mode has been preliminary optimized for given mass flow range, i.e. optimal from efficiency point of view discharge voltage has been found (see Figure 3).

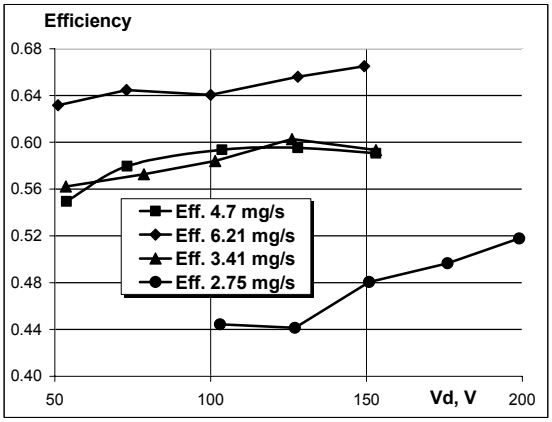


**Figure 3. Efficiency vs. $V_d$, $V_{sum}$ = 700 = const.**

Four different mass flow have been studied. For each mass flow first stage (discharge) voltage and second stage (accelerating) voltage were being changed in such a way that the summary voltage applied was the constant and equal to 700 V.

In discharge voltage range 100...150 V efficiency is approximately constant for mass

flows 3.41 mg/s and 4.7 mg/s. It can be explained by fact that the ionization effectiveness growth in the first stage is fully compensated by accelerating effectiveness decrease in the second stage

For large enough mass flow – 6.21 mg/s one can see that efficiency continues to grow with discharge voltage increasing, i.e. ionization effectiveness grows faster than accelerating effectiveness decreases.

At the smallest mass flow with discharge voltage lower than 150 V the thruster operated in unstable mode and acceptable efficiency level was obtained at discharge voltage equal to 200 V.

For each mass flow approximate discharge voltage values providing maximal thruster efficiency have been already known. Hence it is possible to compare One- and Two-stage modes (see Figure 4).

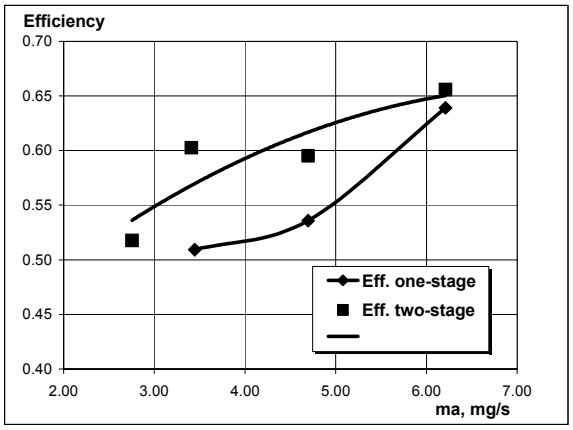


**Figure 4. Efficiency vs. mass flow, One- and Two-stage modes, $V_{sum}$ = 700 V.**

The figure shows that due to Two-stage application the essential gain is reached at mass flow smaller than 6 mg/s. And stable One-stage mode at mass flow smaller than 3 mg/s can not be obtained. Therefore the conclusion can be made – the Two-stage mode provides higher efficiency at small and average mass flows than One-stage mode and also it slightly expands thruster operating envelope to the smaller mass flows direction.

For the second experiment series average mass flow – 4.8 mg/s has been selected.

The mass flow selection explained by two reasons:

- The thruster has an acceptable ionization effectiveness in the One-stage mode at this mass flow.
- Two-stage mode has an essential advantage over One-stage mode at high summary voltage.

Preliminary detailed Two-stage mode studying and optimization for the given mass flow have been carried out.

Three different summary voltages have been studied – 600, 700 and 800 V. As in previous series for each summary voltage first stage voltage and second stage voltage were been changed in such a way that these summary voltages applied were the constant (see Figure 5).

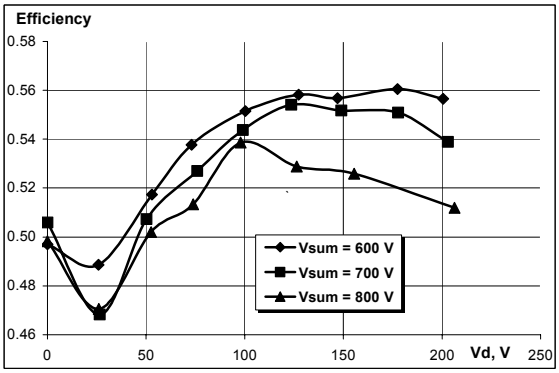


**Figure 5. $V_{sum}$ = const, Va и Vd = var, $m_a$ = 4.8 mg/s.**

While analyzing obtained characteristics efficiency versus $V_d$ (Figure 5), three pronounced zones can be seen:

1. The first one – $V_d \cong 0…25$ V. The zone is characterized by efficiency decreasing. The voltage value is too small to ionize the propellant and whole input power is spent to additional heating of discharge chamber elements. It causes efficiency decreasing.
2. The second zone – $V_d \cong 25…125$ V – is characterized by ionization effectiveness step-by-step growth. The thruster efficiency grows correspondingly.
3. The third zone – $V_d \cong 125…200$ V. Ionization effectiveness has reached its upper limit or its growth rate is very low. Another effect becomes apparent – at equal ionization effectiveness the mode with smaller discharge voltage will provide better efficiency (see the formula below).

$$\eta = \frac{F^2}{2 \bullet (I_a + I_d \bullet (V_d / V_a))} \quad (1)$$

For considered mass flow required discharge voltage value is about 125 V.

Let us determine summary voltage boundaries characterizing the areas of preferable One- and Two-stage mode application for given mass flow.

In the figure below the thruster efficiency versus summary voltage applied for One- and Two-stage modes are given.

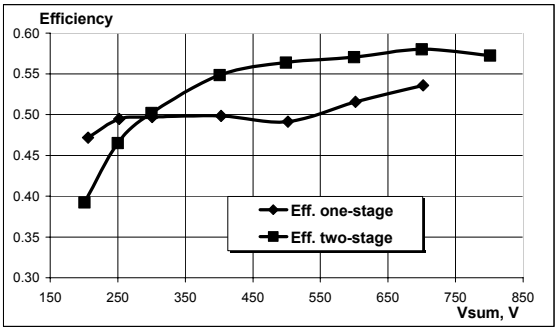


**Figure 6. Efficiency vs. $V_{sum}$, One- and Two-stage modes, $m_a$ = 4.8 mg/s.**

In Two-stage mode discharge voltage was constant and equal to the optimal value – 125 V.

For One-stage mode operating point with summary voltage applied higher than 700 V can not be obtained due to the thruster overheating.

Comparison showed that boundary voltage value is about 300 V and Two-stage mode application provides real gain at voltages higher than 400 V.

During D-80 tests stationary thermal modes data permitting comparison between One- and Two-stage modes have been obtained. Temperature has been measured at the thruster pole piece outer (see Table 1).

As one can see, from the thermal mode point of view the thruster in Two-stage high voltage mode can consume more power and provide better performance than in One-stage high voltage mode.

**Table 1. Stationary thermal modes.**

| $m_a$ | $V_d$ | $I_d$ | $V_a$ | $I_a$ | $V_{sum}$ | $I_{inn}$ | $V_{inn}$ | $I_{out}$ | $V_{out}$ | F | N | $I_{sp}$ | η | $T_b$ | $p_k$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mg/s | V | A | V | A | V | A | V | A | V | G | W | s | | °C | torr |
| 4.65 | 104.4 | 4.15 | 702 | 3.90 | 806 | 0.90 | 6.60 | 0.70 | 6.90 | 13.51 | 3171 | 2902 | 0.59 | 299 | 1.5E-04 |
| 4.65 | - | - | 702 | 3.97 | 702 | 0.90 | 6.60 | 0.72 | 7.10 | 11.76 | 2787 | 2527 | 0.51 | 297 | 1.5E-04 |

**Estimation of the ion current fluctuation level in One- and Two-stage mode.**

Let us set up a hypothesis – ionization and acceleration processes separation not only effects the thruster efficiency but influences on ion generation process stability.

To rebut or to prove the hypothesis ion current fluctuation level shall be estimated at One- and Two-stage modes, and Two-stage mode shall be preliminary optimized by minimal ion current fluctuation level criterion.

For ion current fluctuation level studying the following scheme is used:

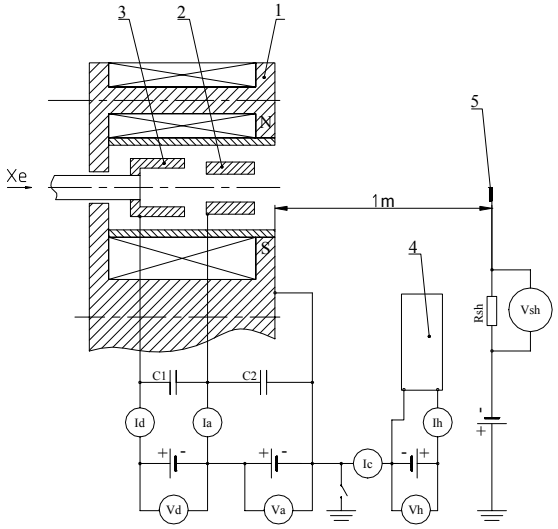


**Figure 7. Ion current fluctuation level measurements principle electric scheme.**

In the Figure 7 the following elements are shown:

1. Magnet system;
2. Second stage anode;
3. First stage anode;
4. Cathode-neutralizer.
5. Probe located at the thruster axis of symmetry at one meter distance.

To exclude the electron plasma component, constant negative potential bias equal to 20 V was applied to the probe.

Ion current fluctuation level was estimated with help of active resistance – R ≅ 1 kOm – connected in series with the probe.

Viewing oscilloscope was measuring alternating and direct voltage drops on the resistance (see Figure 7).

Ion current fluctuation level was determined as a ratio between alternating and direct voltages.

Before One- and Two-stage mode comparison Two-stage mode shall be optimized by ion current fluctuation level criterion.

The same procedure as in the previous chapter has been applied (see Figure 8). The thruster efficiency is given for reference. As one can see at the discharge voltage value equal to 125 V both maximal efficiency and minimal ion fluctuation level are provided.

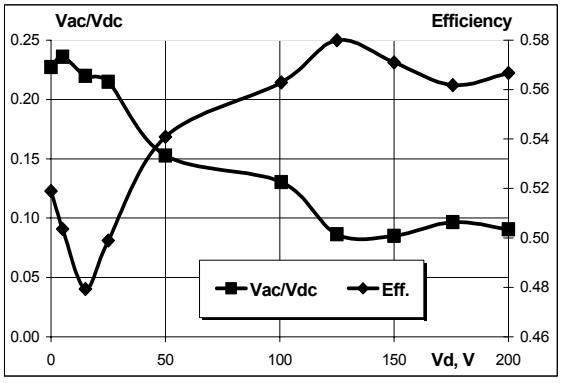


**Figure 8. $V_{ac}/V_{dc}$ and efficiency vs. $V_d$, $V_{sum}$ = 700 V, $m_a$= 4.8 mg/s.**

After finding of the discharge voltage value providing ion current minimal fluctuation level One- and Two-stage modes can be compared by this criterion. Obtained characteristics are given in Figure 9.

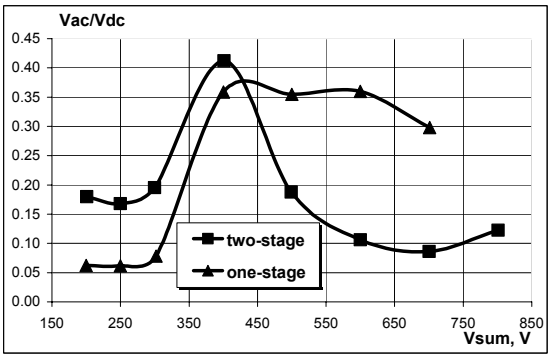


**Figure 9. $V_{ac}/V_{dc}$ vs. $V_{sum}$ in One- and Two-stage modes, $m_a$= 4.8 mg/s.**

At the voltages higher than 450 V Two-stage mode provides significantly lower ion current fluctuation level than One-stage mode.

## CONCLUSION

Studying One- and Two-stage modes the following tendency can be observed – efficiency gain due to Two-stage mode application decreases with mass flow increasing and increases with summary voltage applied increasing.

Area of preferable Two-stage mode application has an upper mass flow limiting value ≅ 6 mg/s and lower summary voltage limiting value ≅ 400 V.

For mass flow studied in detail (4.8 mg/s) at the voltages higher than 450 V Two-stage mode provides significantly lower ion current fluctuation level than One-stage mode. Two-stage mode optimization carried out for the given mass flow showed that discharge voltage value equal to 125 V simultaneously provides maximal efficiency and minimal ion current fluctuation level.

## REFERENCES

1. AIAA 2000-3254 Multi-Mode, High Specific Impulse Hall Thruster Technology.
G.W. Butler and J.L. Yuen
*The Boeing Company Canoga Park, California*

S.O. Tverdokhlebov, A.V. Semenkin, A.V. Kochergin and Solodukhin
*TsNIIMASH Korolev, MoscowReg., Russia*

R.S. Jankovsky
*NASA Glenn Research Center Cleveland, Ohio.*

2. AIAA 2001-3779 Current Status of Multi Mode TAL Development and Areas of Potential Application.

S. Tverdokhlebov, A. Semenkin and A. Solodukhin
*TsNIIMASH Korolev, MoscowReg., Russia.*