INITIAL DESIGN OF A 1N MULTI-PROPELLANT RESISTOJET DUR-1

K.J.A. Rycek, B.T.C. Zandbergen
Delft University of Technology (DUT), Faculty of Aerospace Engineering,
Delft, The Netherlands

Abstract

The Delft University Resistojet-1 (DUR-1) uses electrical energy to heat a gas to a high temperature after which the gas is expanded to supersonic velocity in a 'De Laval' nozzle. Heating takes place using the direct heating method. The heater is a coiled tube of small inner diameter. This allows a small size of the resistojet while still attaining high gas temperatures.

This paper first gives a brief introduction to the need of non-chemical thermal propulsion systems as well as an overview of earlier resistojets and their characteristics. This is followed by a discussion of resistojet studies and analysis performed for DUR-1, focussing on electrical and heat transfer properties and thruster geometry. Next, the DUR-1 design is presented and discussed. Finally, some conclusions are drawn.

1. Introduction

An important performance parameter of rocket systems is the specific impulse (I_{sp}); The higher I_{sp}, the lower the propellant consumption and hence propellant mass. Increasing specific impulse thus may lead to an increase in payload mass or propellant load or a decrease in spacecraft mass. Hence, this may increase satellite lifetime or reduce launch costs [22].

For a thermal rocket engine I_{sp}, which is about proportional to the exhaust velocity v_e, depends on propellant or chamber temperature (T_c), and molar mass (M):

$$I_{sp} \sim v_e \sim \sqrt{\frac{T_c}{M}} \qquad (1)$$

The most common thermal rocket is the chemical rocket. However, it has some distinct disadvantages including the hazardous nature of most of the chemical propellants used and a specific impulse limited to about 450s. Alternative thermal propulsion systems, using a separate non-chemical energy source, may overcome these limitations as they allow non-hazardous propellants and/or propellants with low molar mass. Such systems include laser, microwave, solar and nuclear thermal propulsion, resistojets and arcjets [7, 10, 27]. However, an important limiting factor for these systems is the high mass of the required electrical power supply (EPS) [10, 21].

Since the early 1990's DUT is investigating low-thrust, non-chemical, thermal propulsion for spacecraft propulsion. Goal is to identify ways to heat the propellant to high temperatures in an efficient way.

Based on earlier studies at DUT [7, 8, 24] it has been decided to focus on resistojets as a first step. Reason is that resistojets are mechanically simple, compact, reliable, have high overall efficiencies (up to 90% [21]), are applicable with a variety of power sources and have uncharged plumes [5, 7, 25]. It has been decided to study low-thrust (<1N) multi-propellant resistojets with specific impulse higher than cold gas thrusters (>50s [6]). This has led to some preliminary DUR-1 studies and analysis and development of a first DUR-1 laboratory model.

2. Dur-1 preliminary studies

Development of resistojets commenced in the 1960's [17]. Since then a large number of experimental and operational resistojets have been flown, Table 1.

Table 1: Space-proven resistojets, (1965-1999) [2, 7, 13, 15, 18].

First launch	Vehicle type or experiment	Gas used	Watt	Thrust [mN]	Isp [s]
Experimental					
1967	ATS-2 & ATS-3	Ammonia	3,6	18	150
1968-1969	ATS-4 & ATS-5	Ammonia	3,6	18	150
1971	Sol Rad-10	Hydrazine	<10	-	-
1999	UoSAT-12	Nitrous Oxide	100	125	127
Geosynchronous stationkeeping					
1980	INTELSAT-V	Hydrazine	300-660	223-490	280
1983	Satcom-1R	Hydrazine	450	178-356	298
1994	GOMS	Ammonia	450	-	-
Other orbit adjustments					
1965	Vela	Nitrogen	92	187	123
1965	U.S. Navy satellite	Ammonia	30	89	132
1967	Advanced Vela	Nitrogen	30	89	132
1971	U.S. Navy satellite	Ammonia	3	44-356	235
1981	Meteor 3-1	Ammonia	450	-	-
1988	Gstar-3	Hydrazine	600	-	-
1997	Iridium	Hydrazine	500	-	-

For resistojets, material properties are an important limitation in obtaining high exhaust velocity. They limit maximum attainable gas temperatures to 2000~2700K [13, 21].

To maximize the attainable gas temperature, various heater/heat exchanger configurations have been studied in the past [10, 14, 16]. These studies show that two different heating methods exist: indirect and direct heating. In the indirect method two components are involved to transmit heat to the propellant: a heater and a heat exchanger. This allows for isolating the propellant from direct contact with the heater and hence increases heater lifetime [7, 16].

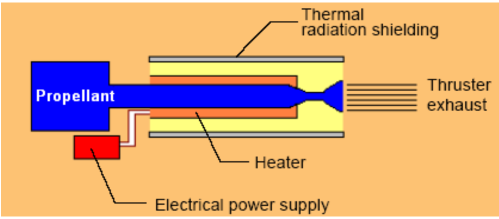

Fig. 1. Direct heating method

The direct method combines both functions in a single element, Fig. 1, where the propellant is in direct contact with the heater. This allows a relatively simple design.

At DUT an indirect heating resistojet has been proposed by Giacobone [7], and a direct one by Hoole [8]. For DUR-1, the direct heating method has been selected. Reason is that, under condition of same power input level, higher thermal efficiencies can be reached and as such a shorter distance is needed to heat the gas to a desired temperature. Moreover, the direct method incorporates a simpler design, allowing shorter lead-time and therefore reduced costs.

However, a drawback of direct heating is the material and propellant compatibility limitation due to possible corrosion/erosion effects.

Material limitations induce a maximum gas temperature of 2700K and as such a maximum exhaust velocity, dependant on the gas. Exhaust velocity as function of gas temperature has been calculated for different propellants using ideal rocket theory [21, 27]. Some results are depicted in Figure 2.

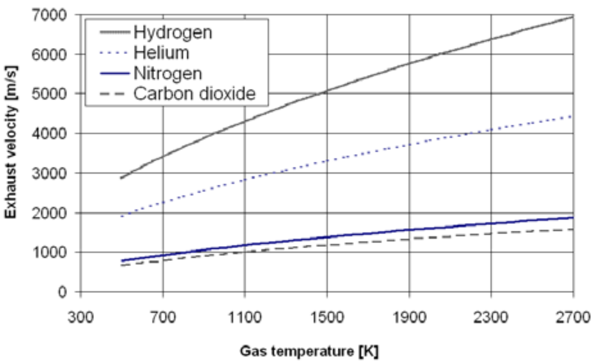

Fig. 2. Calculated exhaust velocity versus gas temperature for different propellants @ 20bar chamber pressure and ideal expansion at sea level

This figure shows that v_e increases with increasing T_c. Given a maximum propellant temperature and using this figure, the maximum achievable I_{sp} and corresponding mass flow $\dot{m}$ for low-thrust (<1N) thermal thrusters can be determined. This is tabulated in **Table 2** for various propellants for a maximum achievable gas temperature of 2700K.

Table 2: Mass flow and maximum specific impulse for different propellants for a 1N thruster @ 20bar chamber pressure and ideal expansion at sea level. (for 2700K).

	$I_{sp,max}$ [s]	$\dot{m}$ [g/s]
He	451	0.23
N_2	191	0.53
CO_2	161	0.63

The heat input rate required to raise propellant temperature, at constant pressure, is governed by:

$$P_{heat} = n\Delta H^0 = \dot{m}E \tag{2}$$

Where:
P_{heat}: required power for heating [W]
n : moles per second [mol/s]
ΔH^0 : change in total enthalpy [J/mol]
E: specific energy [J/kg]

The energy needed to heat unit propellant mass, also referred to as specific energy, is given in **Fig. 3** for several propellants.

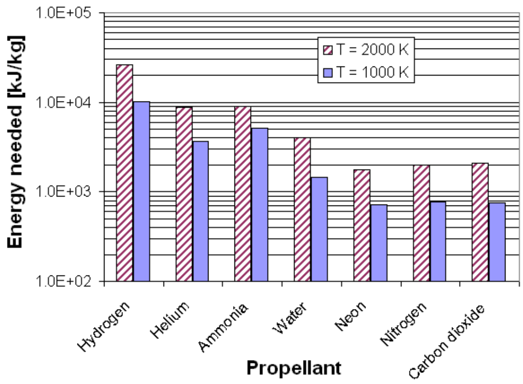

Fig. 3. Required energy to heat propellants from 298K to 1000K and 2000K for mass flow of 1kg/s

From this figure and using the above relation, it follows that to heat a nitrogen mass flow of 0.53g/s to 1000K, 408W is required for heating the propellant.

Propellant heating and its effectiveness largely depends on heater/heat exchanger geometry. The geometry affects both electrical and thermal properties. Therefore, this relation has been studied in more detail for direct heating.

3. Analysis

3.1. Electrical analysis

The electrical energy added to the heater is transformed into heat. This is defined as the Joule heating effect:

$$Q = P_{el}\,\Delta t \tag{3}$$

Where:
Q : heat developed in heater [J]
P_{el} : electrical power added to heater [W]
Δt : time span [s]

And:

$$P_{el} = RI^2 \tag{4}$$

With:
R : heater resistance [Ω]
I : heater current [A]

For ideal heating, P_{el} equals P_{heat}. In this ideal case, for a given supply voltage (e.g. determined by the satellite bus) the required heater current and resistance can be determined once the required power for heating, P_{heat}, is known. This is depicted in Figure 4 where the solid lines represent constant electrical power and the dashed and dotted lines indicate constant voltage levels.

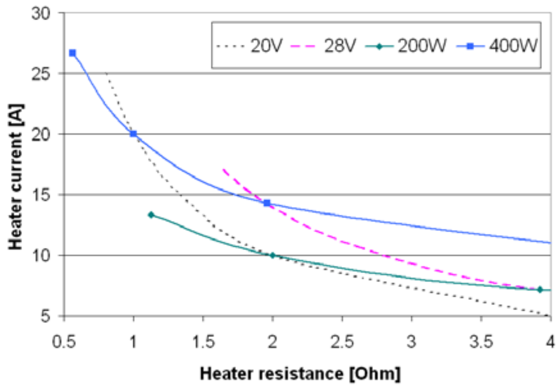

Fig. 4. Heater resistance and current determined by supply voltage and required heating power

Once the required heater resistance is known, heater geometry and material can be selected using:

$$R = \rho \frac{L}{A_{cs}} \quad (5)$$

Where:

ρ : electrical resistivity [Ωm]
L: heater length [m]
A_{cs} : cross sectional area [m^2]

Choosing an appropriate length, cross sectional area and electrical resistivity (a material property, see Table 3) the heater can be designed for the intended resistance. A complicating factor is that heater resistance depends on its temperature [3, 4, 11].

Table 3: Electrical resistivity @ 293K for different materials [1,12]

	Stainless steel	Copper	Platinum	Nickel	Tungsten	Aluminum	Brass
Electrical resistivity [10^{-8} Ωm]	76.5	1.68	10.72	8.54	5.51	2.83	6.2

3.2 Thermal analysis

In the actual non-ideal case, the electrical power needed for a steady-state chamber temperature depends on the required power for heating and the power losses:

$$P_{el} = P_{heat} + P_{loss} \quad (6)$$

Where:

P_{loss} : power losses [W]

In the initial thermal analysis, two heater geometries have been implemented: a coiled tube and a straight tube. First tests have shown that modelling the coil as a simple straight tube with a length equal to that of the unwounded coil gives more accurate results than modelling the coil as a simple cylinder of dimensions identical to the coil dimensions. Therefore, further elaborations of the thermal modelling have been performed for a simple straight tube but hold both for straight and coiled tubes.

Forced convection

In the analysis of the heat transfer in DUR-1's coiled tube, propellant heating by radiation has been neglected. Only heat transfer by means of forced convection is taken into account. This heat transfer can be calculated using [26]:

$$P_{focv} = hA\Delta T_{lm} \quad (7)$$

Where:

P_{focv} : forced convection heat transfer [W]
h : heat transfer coefficient [W/m^{2}K]
A : heat transfer surface [m^2]
ΔT_{lm} : logarithmic mean temperature [K]

Based on the practical method for forced convection described in [26], for fully developed turbulent flow in tubes (Re>2000) the Nusselt number, Nu, is calculated using:

$$Nu = 0.023 \mathrm{Re}_d^{0.8} \mathrm{Pr}^{0.4} \quad (8)$$

Where:

Pr : Prandtl number [-]

Re_d : Reynolds number related to inner tube diameter [-]

Analysis has been performed to investigate effect of heater length and diameter on gas temperature. Some results are shown in **Fig. 5**.

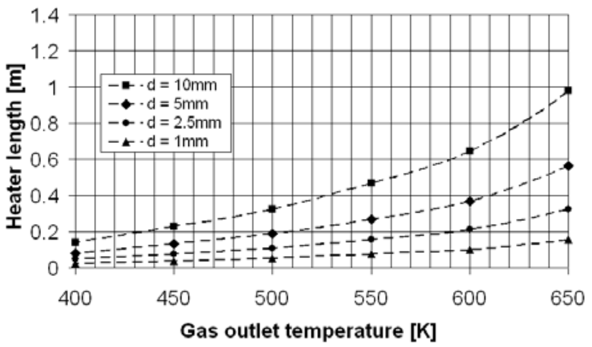

Fig. 5. Variation of gas temperature with heater length and inner tube diameter (@ constant heater temperature of 700K and a nitrogen mass flow of 0.8g/s)

The heater length needed to reach a desired gas temperature at heater outlet is depicted for different inner tube diameters (*d*). It can be concluded that heat transfer within the heater improves with decreasing *d*. However, by choosing a smaller inner diameter, the velocity in the tube increases and as such incorporates higher pressure losses. Analysis, furthermore, shows that for a fixed tube diameter heater length can be shorter with higher heater temperature and/or lower mass flow.

Heat losses

Besides heat transfer to the propellant, also heat losses should be taken into account. In the heat-loss analysis conduction losses have been neglected. The in-space radiative heat losses for DUR-1 have been modelled treating thruster environment as black and assuming the outer heater surface to be gray. The radiative net loss $P_{rad,loss}$ can then be calculated from [26]:

$$P_{rad,loss} = \sigma \varepsilon A_{Ho} \left(T_H^{\ 4} - T_\infty^{\ 4} \right) \qquad (9)$$

Where:
σ: Stefan-Boltzmann constant [W/m^{2}K]
ε: emissivity of outer heater surface [-]
A_{Ho} : outer heater surface [m^2]
T_H : heater temperature [K]
T_∞ : thruster environment temperature [K]

In Figure 6, the required power for heating the gas to a desired T_c (dotted line), the corresponding radiative losses (dashed line) and total EPS-power needed (solid line) are plotted.

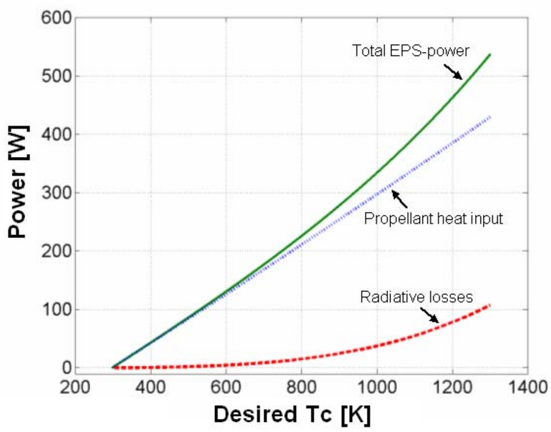

Fig. 6. Power versus desired gas temperature (propellant: nitrogen; mass flow = 0.8g/s)

This shows that P_{heat} increases proportionally with desired gas temperature T_c. Radiative losses increase faster (to the fourth power) for higher temperatures and as such more EPS-power is needed to reach a desired T_c. Thus, heater efficiency decreases. This decrease can be attenuated by radiation shielding.

4. Dur-1 laboratory model

To verify the heat transfer models and to improve DUR-1's efficiency a first laboratory resistojet has been developed. Main requirements for this model are:

- low cost
- safe operation
- multi-propellant
- low-thrust (<1N)

- heater temperature >600K
- short development time (<1yr)
- modular design (to allow implementation of different heaters and different thermal insulation concepts)

In order to keep costs low, the DUR-1 laboratory model has been designed for and tested in a non-vacuum environment.

The final design of the DUR-1 laboratory model is depicted in **Fig. 7** and shown schematically in **Fig. 8**. The arrows indicate the direction of the mass flow.

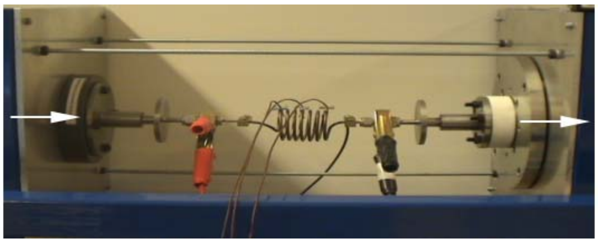

Fig. 7. DUR-1 laboratory assembly

The heater essentially is a coiled tube through which the propellant flows. This allows reducing the heater length while maintaining high heat transfer. The tube's inner diameter is 2.5 mm with a wall thickness of 0.25 mm. Its total unwounded length is 0.95m. Coil length and diameter are 42mm and 37 mm, respectively.

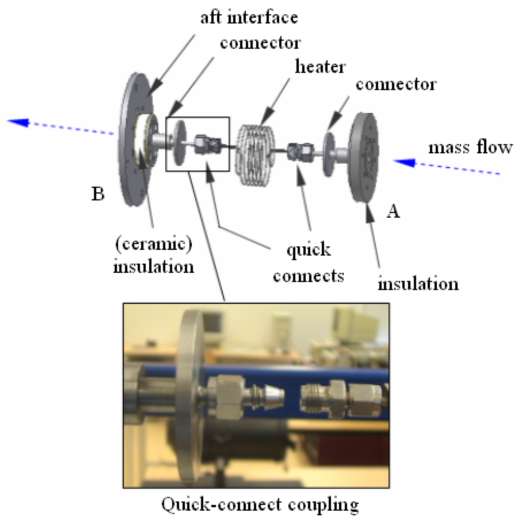

Fig. 8. DUR-1 main components in assembly

Bolts and quick connects, see **Fig. 8**, are used for assembly and allow different heater configurations to be included in the design, thus ensuring modularity.

DUR-1 also allows implementation of different nozzles, which can be fixed at end B. A scheme of a typical nozzle used is depicted in Figure 9 [24].

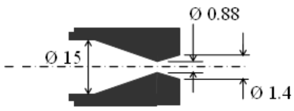

Fig. 9. DUR-1 nozzle (dimensions in mm)

To efficiently operate DUR- 1 with a given EPS and based on the safety requirement, electrical insulation at both ends of the heater is applied. At end B a ceramic insulator, which is by far the most expensive component of the resistojet, provides both electrical and thermal insulation. The electro-thermal insulator at end A (entrance) is made of polyvinyl chloride (PVC). The rationale behind this choice is to keep costs low. At the entrance, the incoming propellant flow is under ambient temperature and flows away from end A. This retards conduction towards end A due to active cooling of the connector. Time needed to reach the melting point of PVC through conduction has been calculated and is accounted for in the first tests.

Both connectors provide connections for shielding and housing of the resistojet and a gradual transition of the flow towards the heater at end A and towards the chamber at end B.

For heater material, low specific heat capacity, high specific resistivity and high melting point are desired. In addition, the material selected should allow the use of different propellants. Based on these properties and on 'off the shelf' availability at DUT, stainless steel has been selected as heater material.

Currently, materials used for DUR-1's electro-thermal insulation limit gas temperatures to 1100K [24, 19]. This limits the resistojet's performance. DUR-1 performances at 1100K for a 1N thrust are given in Table 4.

Table 4: DUR-1 mass flow and maximum specific impulse for different propellants for a 1N thrust level @ 10bar chamber pressure and with nozzle of Figure 9. (Non-ideal expansion in vacuum; 1100K).

	$I_{sp,max}$ [s]	$\dot{m}$ [g/s]
He	340	0.30
N_2	129	0.79
CO_2	111	0.92

To achieve low cost and short development time, 'off the shelf' technology and materials have been used where possible. As a result, the DUR-1 laboratory model has been developed in less than one year with total costs less than 1000 euro. However, the current laboratory thruster has been designed without shielding. This causes high radiative and convective losses during laboratory tests under atmospheric conditions.

5. Conclusions

A modular, multi-propellant, low-thrust laboratory resistojet has been developed using the direct heating method. The current lay-out allows gas temperatures up to 1100K.

The modular build-up of this thruster will allow future enhancements to achieve higher I_{sp}. The laboratory resistojet theoretically meets all the design requirements but has neither been optimised for efficiency nor for mass.

Future work includes implementation of different heaters and shielding and refined heat transfer study. Test data will be used to increase DUR-1's thermal efficiency and improve the theoretical modelling.

6. References

[1] Bejan A. *Heat Transfer.* John Wiley & Sons Inc., 1993.

[2] Braunscheidel E. Performance Characte-rization and Transient Investigation of Multipropellant Resistojets, *AIAA/ASME/ SAE/ASEE 25th Joint Propulsion Conference*, Monterey, CA, AIAA-89-2837, 1989.

[3] Bueche F and Hecht E. *Theory and problems of college physics*. 9th edition, Schaum's outline series – McGraw-Hill. 1997.

[4] Buijze W and Roest R. *Introduction to Electricity and Magnetism (in Dutch) 2nd edition,* Delftse Universitaire Pers, 1995.

[5] Chute F et al. Electric Propulsion in Space, *Canadian Aeronautics and Space Journal*, pp 381-388, 1970.

[6] Fortescue P, Stark J and Swinerd G. *Spacecraft Systems Engineering*. 3rd edition, John Wiley and Sons Ltd., 2003.

[7] Giacobone A. *Low thrust propulsion system research (MSc thesis),* Delft University of Technology., 2003.

[8] Hoole R. *Resistojet demonstration model (in Dutch, MSc thesis).* Delft University of Technology, 1990.

[9] Humble R, Henry G and Larson W. *Space Propulsion Analysis and Design*. 1st edition, McGraw-Hill Companies Inc., 1995.

[10] Jahn R. *Physics of Electric Propulsion*. McGraw-Hill Inc., 1968.

[11] Klompé A. *An introduction to the techniques of measuring.* Delft University of Technology, November 2000.

[12] Leijendeckers P. et al. *Polytechnical pocketbook (in Dutch).* 49th edition, Elsevier, 2002.

[13] Martinez-Sanchez M. Spacecraft Electric Propulsion – An Overview. *Journal of Propulsion and Power*, Vol. 14, No. 5, pp 688-699, 1998.

[14] Messerschmid E and Fasoulas S. *Raumfahrtsysteme*. Springer, 2000.

[15] Morris J. In-flight UOSAT-12 Resistojet Calibration. *AMSAT-UK Proceedings of the 17th Colloquium*, University of Surrey, pp 107-117, 2002.

[16] Pugmire T and Cann G. A 10,000 Hour Life Multipropellant engine for Space Station Applications, *AIAA/ASME/SAE/ASEE 22nd Joint Propulsion Conference*, Huntsville, Alabama AIAA-86-1403,1986.

[17] Pugmire T and Shaw R. Applied resistojet technology, *AIAA 8th Aerospace Sciences Meeting*, New York, AIAA-70-211,1970.

[18] Pugmire T et al. ATS-III Resistojet Thruster System Performance, *Journal of Spacecraft and Rockets*, Vol. 6, No. 7, 1969.

[19] Rycek K. *Initial Design of a 1N multipropellant resistojet DUR-1 (MSc thesis)*. Delft University of Technology, 2005.

[20] Stuhlinger E. *Ion Propulsion for Space Flight*. McGraw-Hill Inc., 1964.

[21] Sutton G and Biblarz O. *Rocket Propulsion Elements*. 7th edition, John Wiley and Sons Inc., 2001.

[22] Szabo J et al. Advances in electrostatic propulsion: ion and Hall thrusters at the Aerospace Corporation, AIAA 95 –3544.

[23] Turner M. *Rocket and Spacecraft Propulsion.* Springer-Praxis, 2000.

[24] Van Bolhuis M. *Delft Aerospace Space Propulsion Test Facility (MSc thesis)*. Delft University of Technology, 2004.

[25] Wertz J and Larson W. *Space Mission Analysis and Design*. 2nd edition, Microcosm Inc. Press, 1999.

[26] Wong H. *Heat transfer for engineers.* 1st edition, Longman Inc., 1977.

[27] Zandbergen B. *Thermal Rocket Propulsion.* 2nd edition, Delft University of Technology, December 2003.