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An Update on Surrey Nitrous Oxide Catalytic Decomposition Research

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Abstract. Nitrous oxide catalytic decomposition is an on-going research programme at Surrey. This research supports the development of novel multi-mode propulsion system concept for a small satellite. At present the efforts are concentrated on the issues supporting the development of restartable nitrous oxide monopropellant thruster. This thruster is considered suitable for small satellite station-keeping and phasing. The thruster's operational principle employing nitrous oxide catalytic decomposition is described. The thruster's catalyst pack sizing can be performed by application of the given loading factors and described axial temperature profile measuring technique. Ergun's equation is recommended for assessment of the pressure drop through the catalyst pack. The maximum flows supported by the self-pressurising nitrous oxide feed system are discussed.

Nomenclature

A – cross-sectional (frontal) area of catalyst pack, m^2

d_p – diameter of the packing, m

H°_{vap} – specific heat of vaporisation, J/kg

I_{sp} – specific impulse, s

LF – Loading factor, kg/s/m^2

$\dot{m}$ – propellant mass flow rate, kg/s

p – pressure, Pa

$Rate_{heat\ absorption}$ – rate of heat absorption, W

Re – Reynolds number

T_{max} , T_{min} – maximum and minimum temperatures respectively, °C

$UoSAT$ – University of Surrey satellite

V_s – superficial mean velocity of propellant, i.e. the velocity the fluid would have if the tube were empty, m/s

z – coordinate along the thruster axis of symmetry, m

ε – void fraction (porosity)

ρ – density, kg/m^3

Introduction

Nitrous oxide propulsion is one of the current research programmes at Surrey. This programme is to assist the development of multi-mode propulsion system for an "affordable access to space" small satellite. Due to unique properties of the propellant this system could be advantageous for application on mini- (500-100kg), micro- (100-10kg), and nano- (10-1kg) satellite platforms.

Nitrous oxide can be stored as a liquid onboard a spacecraft for long periods. Its high vapour pressure eliminates the need for an onboard expulsion system. Its non-toxicity and compatibility with common construction materials suggest inexpensive system design and exploitation. In its vapour phase it can be used for cold-gas and electrothermal propulsion. The ability of this chemical to exothermically decompose leads towards its use for restartable mono- and bipropellant thrusters. Its decomposition can be accelerated by catalyst. This suggests low electric power input for the propulsion system. Thus, nitrous oxide can be used in cold-gas, monopropellant, bipropellant, and resistojet thrusters. This covers all propulsion functions required for small satellites.

Since the whole range of propulsion functions can be covered by one self-pressurising propellant, multi-mode propulsion systems can be envisioned to satisfy a wide variety mission requirements. Such systems would employ different types of thrusters fed by nitrous oxide from a single, simply designed storage tank. Due to its efficient propellant management, this multi-mode propulsion system is very flexible to small satellite mission scenario change.

The nitrous oxide propulsion concept, its advantages, state-of-the-art, and the achievements in the area are presented in details in the earlier publications. [1-4] This paper gives the recent update on the status of the research.

Application

The upcoming constellation missions involve *UoSAT* micro-satellite platforms (60-100kg) injected into various Low Earth Orbits. Therefore, two primary propulsion functions that might be required are: station-keeping for compensation against air drag, and phasing for desired revisit time. Both functions are likely to be performed at low thrust (0.1-0.5N) since it imposes no challenging requirements on small satellite's Attitude Control and Determination System. Multiple thruster firings are essential for this type of missions.

Upon the consideration it was concluded that 0.15N nitrous oxide monopropellant thruster is suitable for these missions since:

- It is capable of providing the above thrusts repeatedly
- Specific impulse of about 160s can be achieved at input power requirements (30W for 5-7min.) that are feasible for the small satellite power system
- It offers overall propulsion system simplicity and low cost
- In the case of monopropellant mode failure, the thruster can be used in cold-gas mode (I_{sp} = 59s)

Monopropellant Thruster Concept

Schematics of the restartable nitrous oxide monopropellant is shown in Figure 1. In this device a flow of nitrous oxide is injected into the decomposition chamber. Upon injection, nitrous oxide starts to decompose on an electrically heated catalytic wire. The heat generated by decomposition activates the main catalyst, which in turn decomposes more nitrous oxide, and generates more heat. The process proceeds with increasing temperature until all of the catalyst is activated and the rate of decomposition reaches its maximum when steady state is achieved. This takes a few seconds. The products of the decomposition leave the chamber through the converging-diverging nozzle generating thrust. Once self-sustaining nitrous oxide decomposition is achieved, the electrical power input is no longer required.

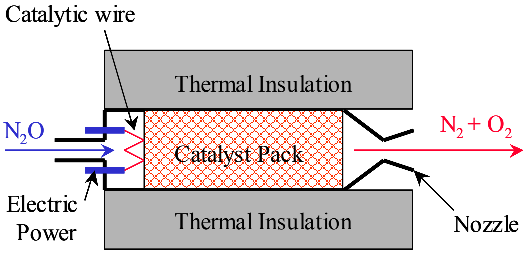

Figure 1: Nitrous oxide monopropellant thruster schematics.

The main catalyst in form of pellets or monolith is packed inside the thruster. Because of this it is referred later as a catalyst pack.

Catalyst Pack

Since nitrous oxide decomposition occurs inside the catalyst pack, its design determines the thruster's performance. For given mass flow rate the catalyst pack size and pressure drop are of primary concern.

Loading Factor

Loading factor is a catalyst pack design parameter. It informs that reactant (propellant) mass flow rates can be supported by the catalyst pack frontal area. The loading factor is defined as the reactant mass flux (Figure 2):

$$LF = \frac{\dot{m}}{A} \qquad \textbf{(1)}$$

During the tests loading factors supported for nitrous oxide ranged from 0.12 to 2.39kg/s/m^2. Since nitrous oxide is injected in catalyst pack in a gas phase its loading factors are lower than, for example, for hydrogen peroxide (60-236 kg/s/m^2). [5]

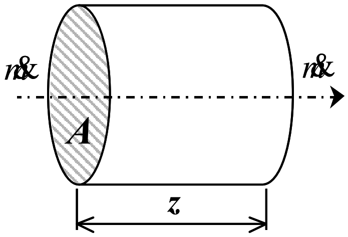

Figure 2: Catalyst pack geometry

Knowing the catalyst pack frontal area its diameter can be calculated. Therefore, catalyst pack length is the only size left to determine. This is discussed in the next section.

Axial Temperature Profile

Axial temperature profile measurement is used for determination of the optimum catalyst pack length.

During steady-state operation mode, nitrous oxide decomposes on its way downstream the catalyst bed towards the nozzle (Figure 3). Upon injection to the reaction chamber nitrous oxide starts to decompose on the catalyst. At the beginning, the decomposition occurs at a slow rate because in this "heat exchange" region the temperature increase is primarily due to heat transfer. Heat transfer upstream of the catalyst bed occurs by conduction through catalyst pellets. Heat transfer downstream, however, is due to gas flow convection. In other words, heat delivered by conduction through catalyst pellets and generated by the decomposition process is absorbed and transported downstream by flow of nitrous oxide. The heat absorbed warms up the flow. Flow and catalyst temperature increase. Since the decomposition is temperature dependent process the reaction rate increases. The contribution by heat generation increases primarily due to catalytic decomposition. The temperature curve climbs steeper. With temperature rising, however, thermal decomposition of nitrous oxide starts to play significant role in the decomposition process. At above 800°C, thermal decomposition starts to dominate. The major part of the nitrous oxide, however, is decomposed by this time. Therefore, the temperature curve slope becomes smoother. The flow (catalyst pack) temperature reaches its maximum when most of the nitrous oxide is decomposed. In the properly designed catalyst pack, therefore, maximum temperature corresponds to the down-stream end of the catalyst pack. If there is not enough catalyst in the catalyst pack, nitrous oxide will not decompose fully, and the energetic potential of the propellant will be wasted. If there is too much catalyst in the pack, when the part of the catalyst down-stream will not be employed in the decomposition process (wasted) but dissipates the heat. In the both of the cases of improper design, the temperature of the downstream end of the catalyst pack is lower than that of the proper one, and the performance suffers.

Two different catalyst pack lengths were tested. The axial temperature profiles were measured at the outside wall. The measurements are taken at steady-state operation condition. Nitrous oxide mass flow rates are almost the same.

Firstly, a 38-mm length bed was loaded with 4gm of catalyst (Figure 4). In the test the axial temperature profile corresponds to, strictly speaking, the situation described as "not enough" catalyst. However, the catalyst pack length is close enough to the "optimum" since the temperature at the end of the pack almost reaches its maximum. Loading factors for this catalyst loading are in the range from 0.12 to 0.55kg/s/m^2.

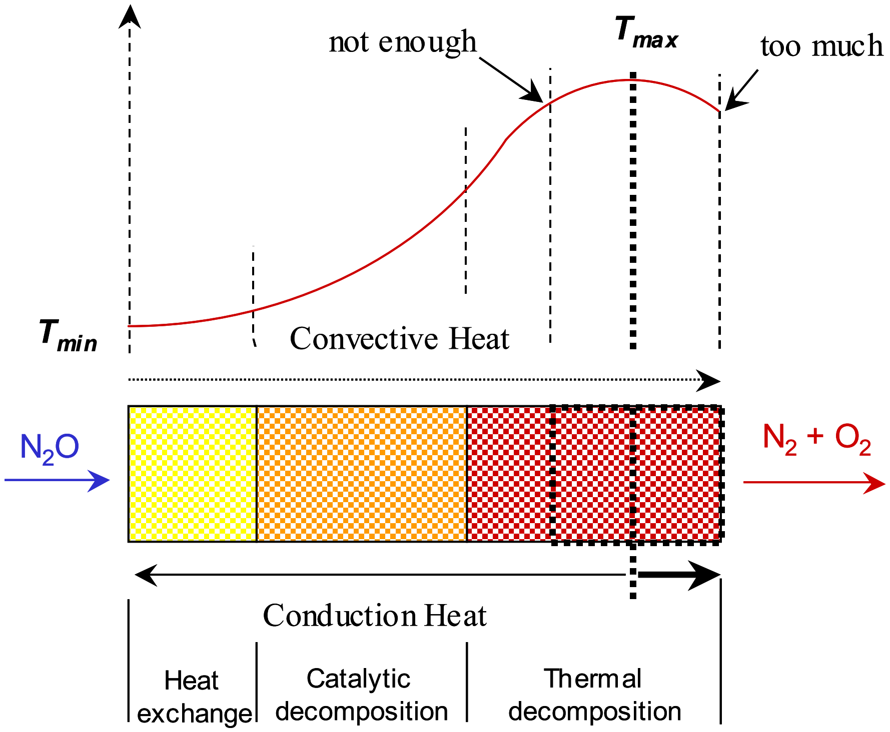

Figure 3: Schematics of axial temperature distribution in the catalyst pack

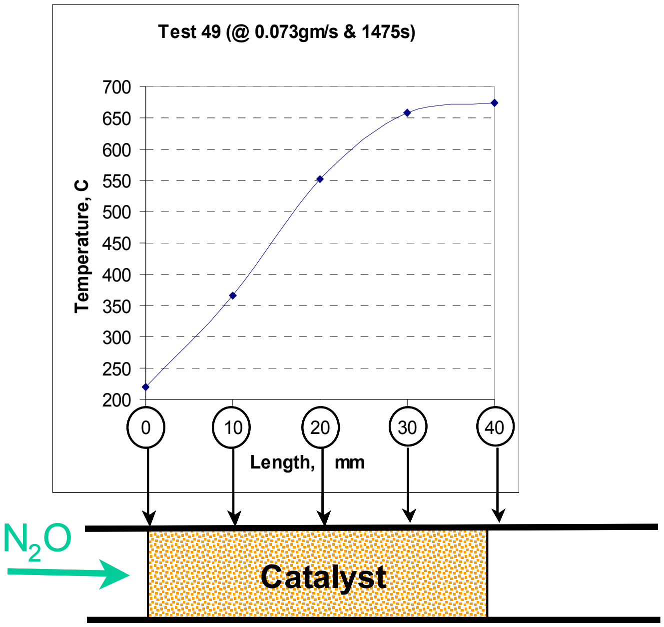

Figure 4: Axial temperature distribution. (Data are taken at 25th min. of the test. Mass flow rate is 0.073gm/s)

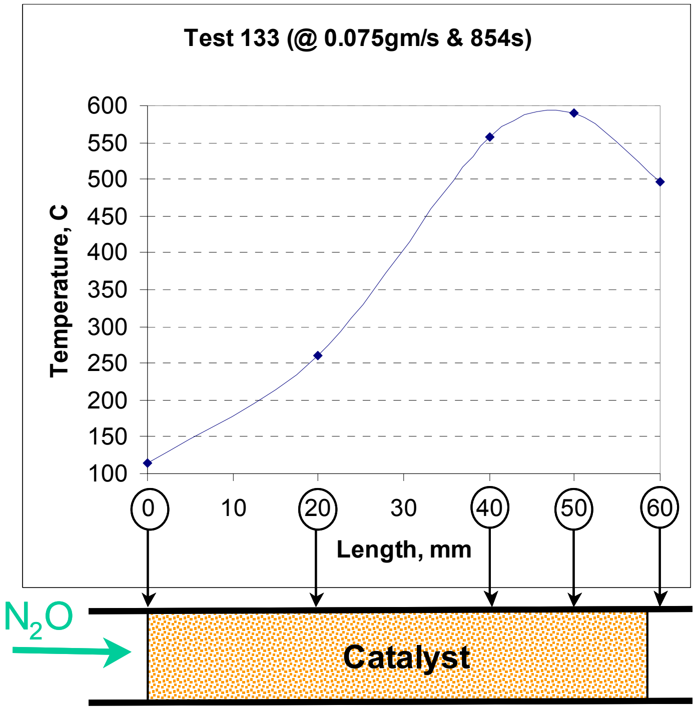

Figure 5: Axial temperature distribution. (Data are taken at 14th min. of the test. Mass flow rate is 0.075gm/s)

Secondly, 58-mm bed loaded with 6gm of the same catalyst (Figure 5). In the test the axial temperature profile corresponded to the situation when the test design is overloaded with catalyst. Loading factors for this catalyst loading are in the range from 0.12 to 0.67kg/s/m^2.

The negative effect of heat dissipation due to pack overloading with the catalyst is shown in Figure 6. The reaction chamber wall temperature in test 133 is lower than that of in test 49 due to non-optimal amount of catalyst loading. The optimum catalyst pack length is between 40 and 50mm (closer to 40mm).

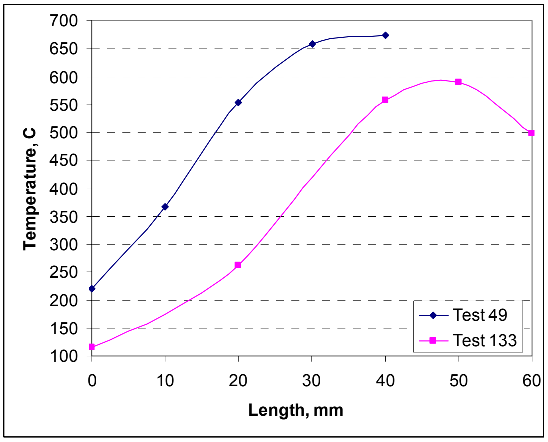

Figure 6: Comparison of the axial temperature profiles for the catalyst packs.

The determination of its length completes pack's sizing.

Another important design parameter is pressure drop through the catalyst pack.

Pressure Drop

Inside the nitrous oxide monopropellant thruster chamber, pressure drop is associated with resistance to flow while the gas is passing through catalyst pack. Pressure drop through the catalyst pack is used to predict thruster chamber pressure that determines the propellant mass flow rate necessary to achieve the required thrust.

For the case of pellet packing Ergun's equation was used for the pressure drop prediction. [6-9]

$$\frac{dp}{dz} = -\frac{\rho V_s^2}{d_p}\frac{1-\varepsilon}{\varepsilon^3}\left[\frac{150(1-\varepsilon)}{\mathrm{Re}} + 1.75\right] \qquad \textbf{(2)}$$

Comparison of experimental data to the ones predicted by the equation demonstrated that the results are in good agreement. Currently pressure drop through the catalyst pack is about 0.03bar.

Feed System

Self-pressurising feed system design was revised to assess its feasibility in supporting required nitrous oxide mass flow rates.

In general, self-pressurising feed systems are limited by maximum propellant flow rate. In the case of liquefied gases liquid-to-gas phase change is associated with heat absorption. In other words, heat must be added to vaporise the liquid. The quantity is called *latent heat* or *heat (enthalpy) of vaporisation*. Heat of vaporisation is a function of temperature (Figure 7).

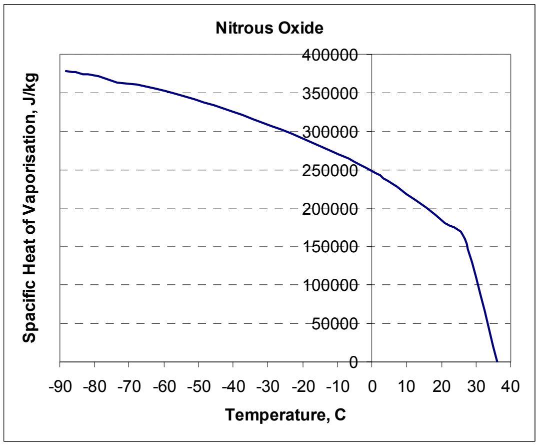

Figure 7: Specific heat of vaporisation.

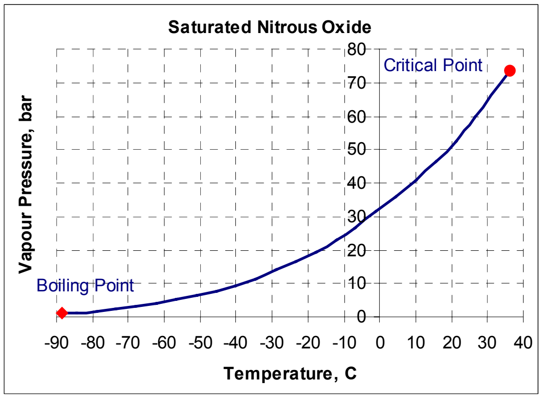

Figure 8: Vapour pressure.

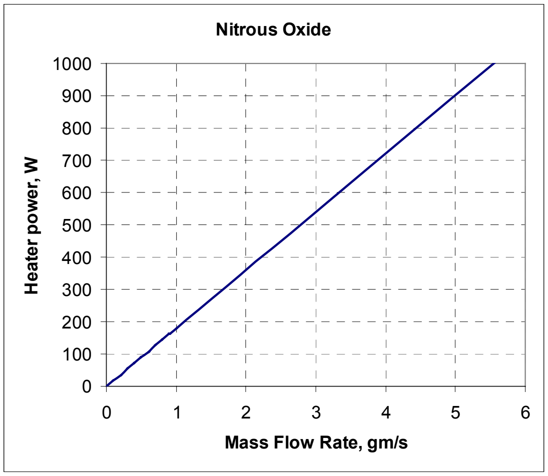

Figure 9: Heat required for absorption compensation.

When liquefied nitrous oxide is consumed out of the storage tank, the temperature inside the tank drops as a result of propellant vaporisation. The temperature drop will, in turn, cause a pressure drop inside the tank (see Figure 8), and vaporisation heat value rise. This will slow down the evaporation process, and cause drop of propellant consumption rate. The higher the initial consumption rate, the faster the temperature, pressure, and consumption rate drop inside the storage tank. As a first order approximation the rate of heat absorption can be calculated as:

$$Rate_{heat\ absorption} = \dot{m} H^{\circ}_{vap} \qquad \textbf{(3)}$$

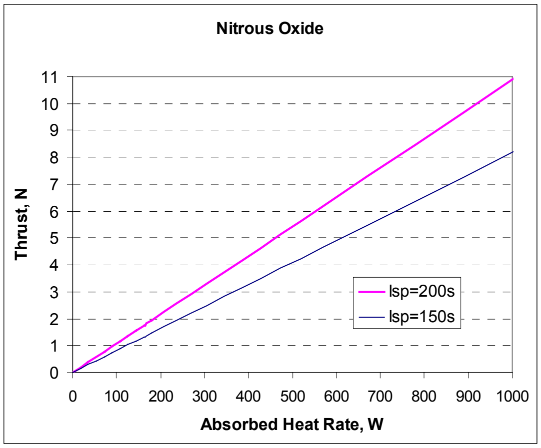

Figure 10: Heat rate required to support 0-11N thrusts. (nozzle expansion ratio =200)

Heat transfer from ambient to nitrous oxide compensates for heat absorption. If the rates for the both processes are the same ($Rate_{heat\ absorption} = Rate_{heat\ transfer}$) (the case of big tanks and small consumption rates), then no additional action is required. Often, however, rate of heat absorption exceeds that of heat transfer ($Rate_{heat\ absorption} > Rate_{heat\ transfer}$). In such a case, two scenarios are possible. If consumption time is short, then heat transfer might still be able to compensate during idle periods, and temperature and pressure will recover. Otherwise, additional heat is required to compensate for the performance drop.

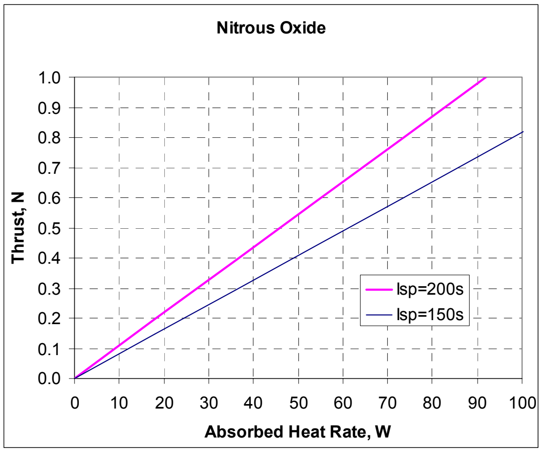

Figure 11: Heat rate required to support 0-1N thrusts. (nozzle expansion ratio =200)

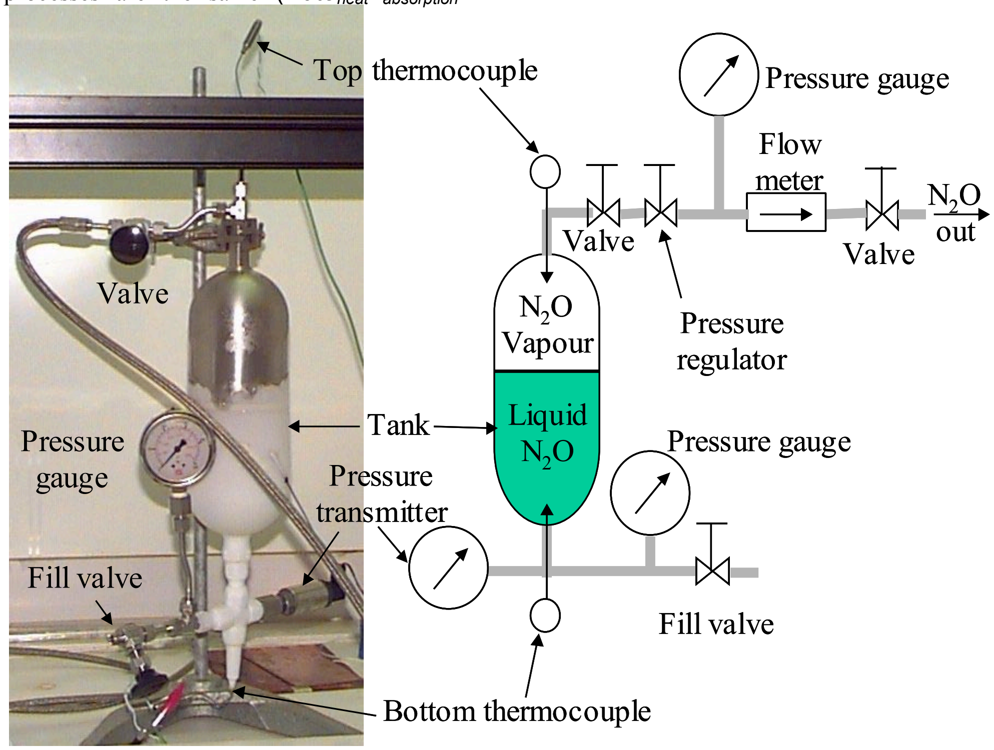

Figure 12: Schematics and set-up for the nitrous oxide bleeding test. The snapshot is taken at the end of the test when the pressure in the tank dropped to about zero (gauge).

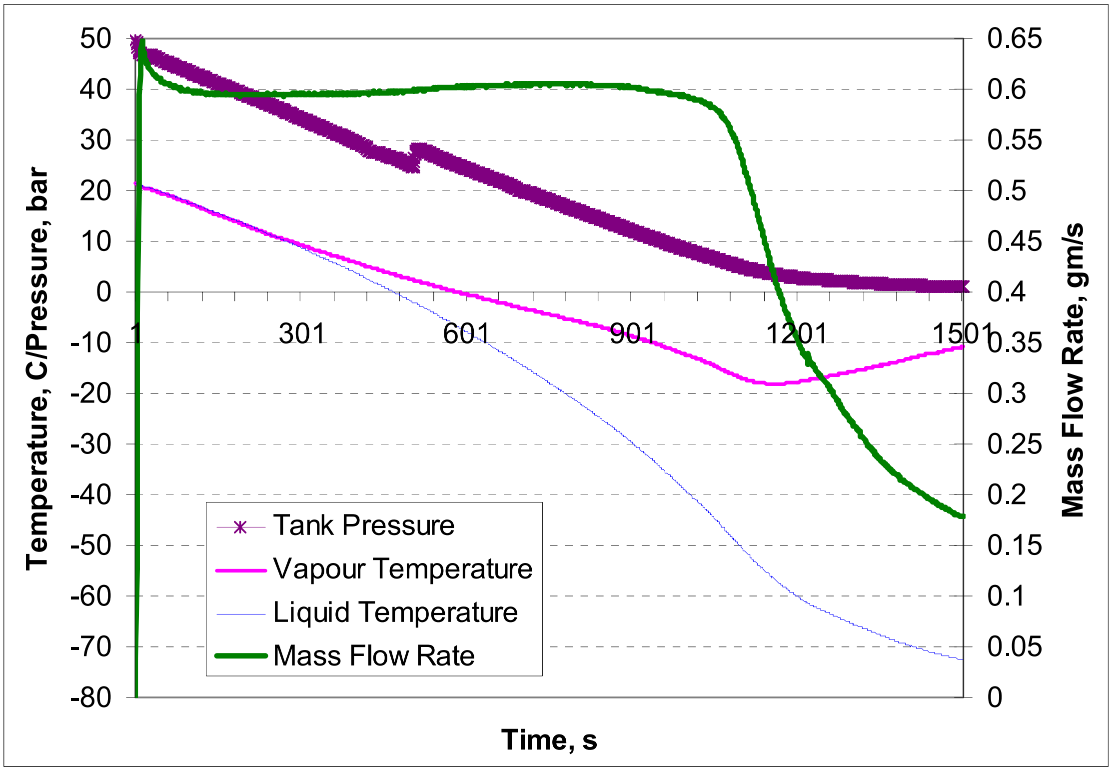

Figure 13: Nitrous oxide bleeding test.

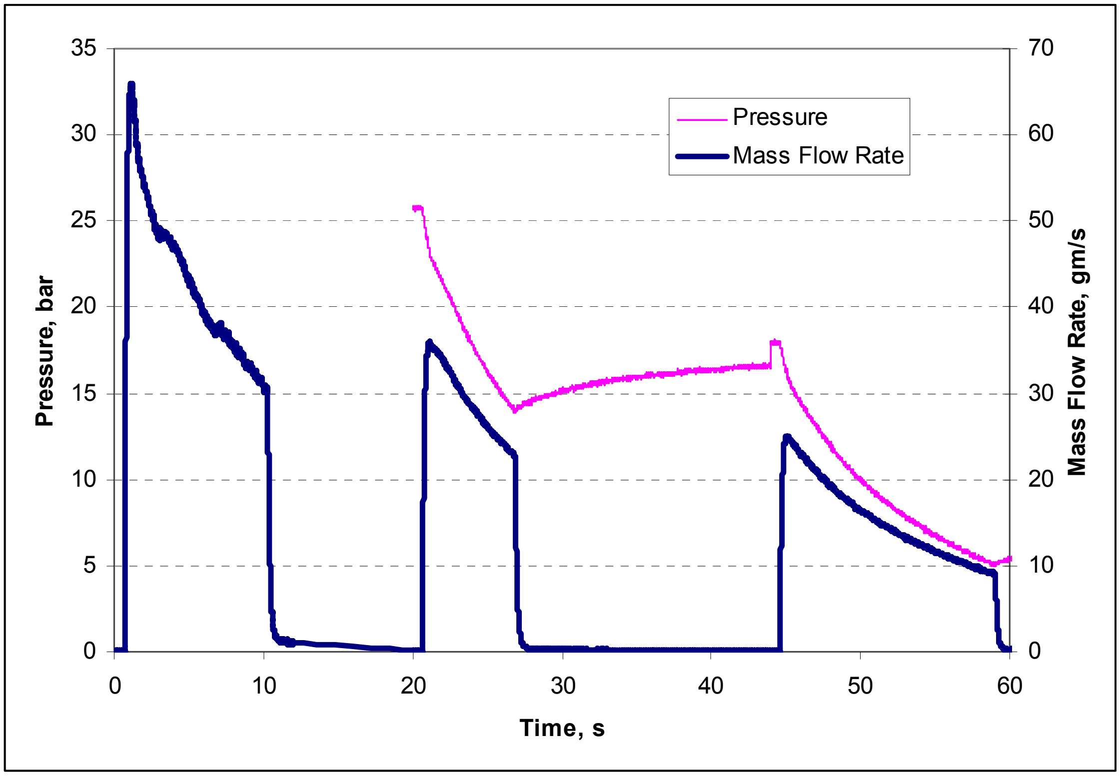

Figure 14: Nitrous oxide blow-down test.

The amount of heat required for compensation is calculated using the linear approximation above. This amount of heat is significant (Figure 9). Heat transfer will decrease the curve gradient; it is a function of design (geometry and materials), and therefore, is an attribute of a particular design.

Assessments of heat for nitrous oxide evaporation to support required thrusts are given in Figure 10 and Figure 11. Due to high latent heat of liquefied nitrous oxide, a self-pressurising feed system using this propellant would be difficult to scale for high consumption rates (thrusts >10N). For low thrust, (<1N) small satellite propulsion, the heat requirements are affordable. Since heat transfer hasn't been accounted for, these assessments are conservative, and give too pessimistic a forecast. Indeed, because heat transfer rates are higher for smaller systems, the heat requirements are lower than predicted.

Nitrous oxide bleeding was performed out of the tank to assess the practicality of self-pressurising feed system with no heating. Before the test, a 1 litre stainless steel tank was filled with liquid nitrous oxide. During the test, gaseous nitrous oxide was bled out of the top of the tank (see Figure 12). Nitrous oxide mass flow rate, liquid and vapour temperatures, and tank pressure were automatically recorded (see Figure 13). The initial value (~0.65gm/s) was determined by the maximum nitrous oxide mass flow rate the flow-meter could support. Opening the valve was followed by slight drop in nitrous oxide mass flow rate that soon stabilised at about 0.6gm/s. While the mass flow rate remained somewhat constant for 16 minutes, the nitrous oxide vapour pressure and temperature both steadily decreased. After the tank's pressure dropped below 10bar, the nitrous oxide mass flow rate finally decreased. The increasing difference in liquid and vapour temperatures (that were originally the same) was due to the liquid's level drop upon nitrous oxide consumption. The spike on the pressure curve is due to the heat released by the phase change (enthalpy of fusion) when moisture condensed on the tank's wall froze. The test demonstrated that monopropellant thrusts ≤ 0.9N could be supported by nitrous oxide feed system with no heating for total impulse ~ 900Ns.

In-orbit operation of the self-pressurising nitrous oxide feed system onboard *UoSAT-12* mini-satellite has proven that 0.13gm/s mass flow rate can be supported with no heating. For this reason ~0.15N monopropellant thrust resulting in lower mass flow rate (~0.1gm/s) is expected to impose no difficulty for a small satellite.

The practicality of the higher flow, self-pressurising nitrous oxide feed system with no heating was further assessed by Gary Haag for application in ~150N-thrust hybrid rocket motor. [10] During the field test liquid nitrous oxide was drawn out of 3 litre stainless steel tank. The test results for three consecutive runs are presented in Figure 14. These results demonstrate that mass flow rates ≥20gm/s cannot be supported by self-pressurising nitrous oxide feed system. In this case, efforts to increase heat transfer in the design are appreciated as well as heating. The engineering solutions of the problem can involve:

- Application of additional heating
- Regenerative cooling of nozzle or the whole thruster by nitrous oxide
- Application of heat exchangers
- Application of high thermal conductivity materials in the design
- Increase in heat transfer exchange surface area
- Application of nitrous oxide gas accumulators

The measures suggested above might still not be enough to support required high propellant flows. In such a case propellant expulsion system or pump-feed must be used.

This cooling property of nitrous oxide can be turned into a benefit. Active thermal control of the spacecraft can be performed by bleeding nitrous oxide out of the tanks.

Conclusions

Restartable nitrous oxide monopropellant thruster is a feasible option for small satellite station-keeping and phasing.

Recent experimental results of nitrous oxide catalytic decomposition research presented in this paper can be used for the monopropellant thruster catalyst pack design.

Although its phase change feature limits the maximum flows supported by self-pressurising nitrous oxide feed system the experience demonstrates that this would not be a problem within the operation range of the prospective monopropellant thruster (0.1-0.2N).

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