N_2O PROPULSION RESEARCH AT TSINGHUA: 2003

Vadim Zakirov[(1)], Luming Li [(2)], and Gong Ke[(3)]

[(1)] Associate Researcher, Ph.D., Tsinghua Space Center, Room 209, 12th Floor, Main Building, Tsinghua University, 100084, Beijing, P.R. China, Email: v.zakirov@tsinghua.edu.cn
[(2)] Professor, Ph.D., Tsinghua Space Center, Room 122, Welding Building, Tsinghua University, 100084, Beijing, P.R. China, Email: lilm@tsinghua.edu.cn
[(3)] Professor, Ph.D., Vice president, Tsinghua University, 100084, Beijing, P.R. China, Email: gongk@tsinghua.edu.cn

ABSTRACT

This paper describes research at Tsinghua University, P.R. of China, promoting development of sub-Newton thrust nitrous oxide monopropellant for application onboard small spacecraft. This research focuses on investigation of pressure effect on N_2O decomposition with respect to miniaturization of decomposer design and acceleration of reaction initiation. The experimental results demonstrate that by raising chamber pressure N_2O decomposer design can be scaled down and start-up transient of prospective monopropellant can be shortened. Based on these results it is concluded that prospective N_2O monopropellants can have size and mass competitive to existing hydrazine ones. Further research is suggested to improve the achieved performance.

1. INTRODUCTION

Application of nitrous oxide (N_2O) liquefied gas as propellant onboard small spacecraft offers a number of advantages. [1] Denser nitrous oxide (~745kg/m^3) onboard volume-constrained small "piggyback rider" suggests increase in propellant mass loading comparative to non-liquefied cold-gas propulsion typically using pressurized (~200bar) nitrogen (~200kg/m^3). High vapor pressure (~50bar at 20ºC) of this gas pushes it out of the storage tank eliminating the need in expulsion system typically used for hydrazine, thus, making small spacecraft propulsion system design simpler and lighter. N_2O exothermic decomposition implies low-power consumption propulsion system for power-constrained small spacecraft. Non-toxicity, non-flammability, and compatibility with common structural materials are the other properties of nitrous oxide beneficial for low-cost propulsion system. Variety of possible N_2O propulsion modes (cold-gas, monopropellant, bipropellant, and resistojet) covering all propulsion functions (attitude control, orbit maintenance and maneuvering) suggests development of multi-mode propulsion system for small spacecraft employing different types of thrusters fed by nitrous oxide from a single storage tank. In addition to being a moderate performance [1-3], low-power, and low-cost this system features advanced propellant management because it allows the propellant onboard be used by the propulsion mode of choice. This gives small spacecraft an important advantage – flexibility to mission scenario change.

To become feasible the multi-mode propulsion concept suggested above relies on development of advanced N_2O thrusters ensuring spacecraft velocity change performance competitive to that of alternative propulsion systems.

Research promoting development of advanced N_2O thrusters is on its way at Tsinghua University. Sub-Newton thrust nitrous oxide monopropellant for micro-satellite (10-100kg) is a focus of the present research.

2. THRUSTER CONCEPT

Monopropellant thruster concept suggested by the authors [1] takes advantage of N_2O catalytic decomposition. A catalyst lowers activation energy barrier so that reaction occurs at much lower temperature (>200°C) compared to thermal decomposition (>1000°C). [4]

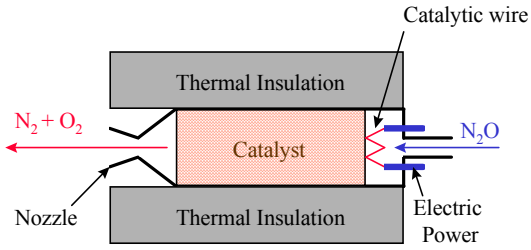

Fig. 1. Nitrous oxide monopropellant thruster schematics.

The schematics of a nitrous oxide monopropellant thruster employing catalytic decomposition is shown in Fig. 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

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steady state is achieved. This takes a few seconds. The products of the decomposition leave the chamber through the nozzle generating thrust.

Once balance between heat generation by decomposition and heat dissipation into surrounding is achieved the reaction becomes self-sustaining so that electrical power input is no longer required.

This concept offers significant electrical power savings because:

- It makes use of catalytic decomposition providing considerable input power savings for reaction initiation over thermal decomposition technique employed in a resistojet
- It takes an advantage of self-sustaining decomposition as zero input power main operation mode for a thrusters

Theoretical specific impulse performance for nitrous oxide monopropellant reaches 206s.

This N_2O monopropellant concept has been proven feasible at the University of Surrey, U.K. Self-sustaining N_2O decomposition was repeatedly initiated and successfully controlled during hundreds of hot firings (see Fig. 2). [1, 4-6]

Fig. 2. Surrey-3 N_2O monopropellant prototype design hot firing. (non-choked flow)

3. GOALS

Once the monopropellant concept was proven feasible the design of efficient N_2O decomposer has become a primary concern.

Proof-of-the-concept N_2O monopropellant prototype design designated as Surrey-3 (see Fig. 2) demonstrated that decomposer's internal diameter could be as small as 15mm, length ~ 40mm, it could support 0.03-0.1N thrusts, and specific impulse was assumed to be about 150-160s.

Existing 0.19-1.0N thrust hydrazine monopropellant thrusters (CHT-0.5 and MR-103G) developed by Astrium and Primex [7,8] are reported to have higher specific impulse (202-227s), smaller size chambers (about 8mm internal diameter and 35mm length), and weight about 120gm. However, fast specific impulse performance deterioration of hydrazine monopropellants for thrust level <0.19N suggests that in that range nitrous oxide monopropellant could be a competitive propulsion thruster option, especially, if its dimensions and mass are reduced to somewhat below the ones the hydrazine monopropellants have.

Short start-up transient is another important issue for thruster since during that time propellant is used inefficiently. Surrey-3 N_2O monopropellant prototype design featured 10-15min.-long start-ups that are non-feasible for practical applications.

Lack of the test data regarding choked flow hot firing of N_2O decomposer was responsible for poor understanding of pressure effect on catalytic decomposition.

However, because the Surrey's design served mainly as proof-of-the-concept for N_2O catalytic decomposition technique, testing ground for materials, it had a lot of potential for improvement.

Therefore, to make N_2O monopropellant feasible for space propulsion applications the following sub-sequent research goals at Tsinghua have been set:

- Minimize N_2O decomposer's size and mass while keeping thrust in 0.01-0.15N range;
- Shorten start-up transient period;
- Study pressure effect on decomposition inside N_2O decomposer.

These goals are interconnected: the last one is intended to serve the first two goals implying N_2O decomposer design optimization.

4. APPROACH

The approach taken at Tsinghua relies on increase in decomposer chamber pressure. This approach is a result of two main considerations.

Since for self-sustaining N_2O decomposition rate of heat generated by reaction in volume (V) balances the rate of heat lost through decomposer's wall (surface area, S), the relationship can be written as following:

$$\frac{\mu p}{RT}\frac{V}{t}\left(\Delta H + Q\Delta a\right) = hS\left(T - T_0\right) \qquad (1)$$

Fig. 3. Nitrous Oxide Monopropellant Prototypes

where μ – molar mass for gas mixture, kg/mol
p – chamber pressure, Pa
R – ideal gas constant, R = 8.314 J/mol/K
V – decomposer volume, m^3
t – stay time, s
Δa – relative N_2O concentration change
ΔH – specific enthalpy change, J/kg
T – gas temperature, K
T_0 – ambient temperature, K
Q – reaction specific heat, J/kg
h – heat transfer coefficient, $W/m^2/K$
S – decomposer heat transfer area, m^2

Eq. 1 suggests that upon scaling N_2O decomposer size down volume reduction can be compensated by increasing chamber pressure so that the balance is preserved.

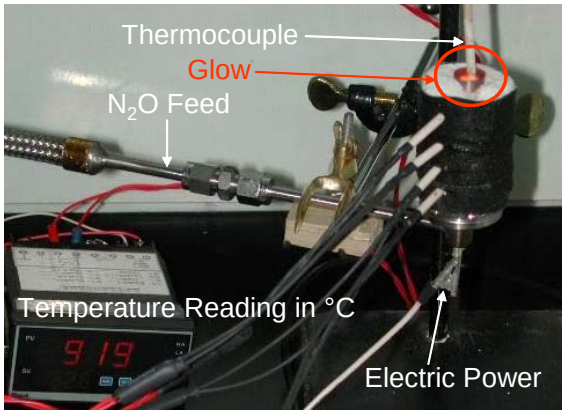

Fig. 4. NOMP-1 test firing (non-choked flow design).

The other consideration is that decomposition reaction velocity is directly proportional to chamber pressure (see Eq. 2).

$$W(a,T) = k(T)\, a \frac{\mu p}{RT} \qquad (2)$$

where a – relative N_2O concentration
R – ideal gas constant, R = 8.314 J/mol/K
μ – molar mass for gas mixture, kg/mol
p – chamber pressure, Pa
T – gas temperature, K
$k(T)$ – reaction rate, 1/s

N_2O decomposer operation at higher chamber pressure is, therefore, advantageous since higher reaction velocities can be achieved and are desirable for shorter start-up transient.

Following the above logic, choking N_2O flow with nozzle and raising chamber pressure would be the way to go.

5. RESULTS AND DISCUSSION

Although choking flow was a primary intention the first N_2O decomposer design at Tsinghua (see Fig. 3) designated NOMP-1 (Nitrous Oxide Monopropellant Prototype) was non-choked. It was done mainly to raise research funding quickly by fast demonstration of N_2O decomposition technique potential at low risk.

Proof-of-concept for N_2O catalytic decomposition technique application for monopropellant thruster was confirmed in NOMP-1 test firing (see Fig. 4).

During this test (see Fig. 5) nitrous oxide self-sustaining decomposition was initiated with heat input of ~10kJ. After that electric power was turned off and decomposition was controlled solely by N_2O flow. Recorded decomposition temperature exceeded 900ºC at steady state. So called "hot-restart" (when no pre-heating of catalyst bed is required – zero input electric power) was then demonstrated by switching N_2O flow off and turning it on. After the flow was turned on decomposition temperature restored its value. Then, test was terminated since all goals were achieved.

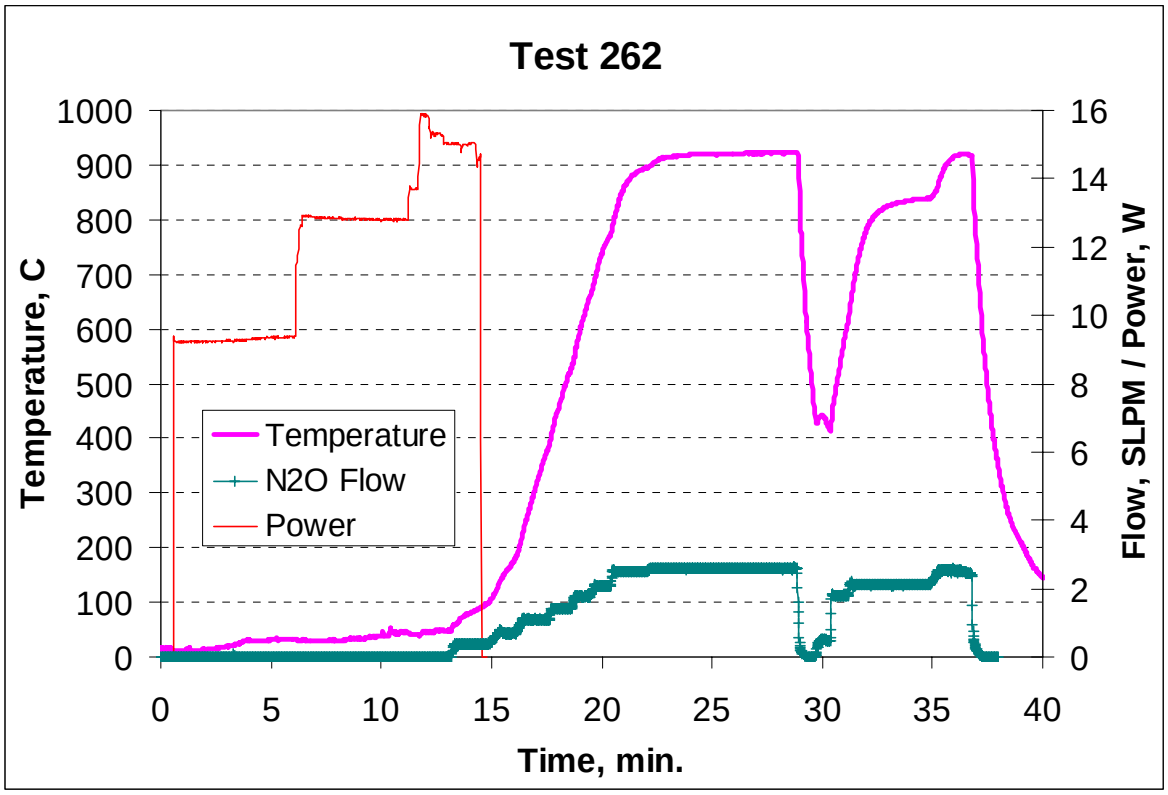

Fig. 5. NOMP-1 test firing results.

Table 1. Comparison of nitrous oxide decomposer designs.

Parameter	Surrey-3	NOMP-1	NOMP-2	NOMP-3
Diameter, mm	15	12	8	8
Volume, mm^3	6715	4072	1659	1508
Mass flux, $kg/m^2/s$	0.12-0.41	0.09-0.71	0.46-2.08	0.37-1.39
Choked flow	No	No	Yes	Yes
Pressure range (gauge), bar	0	0	5-25	1-24
Start-up transient time, s	~600	~600	~300	~50
Mass, gm	---	81	151	37

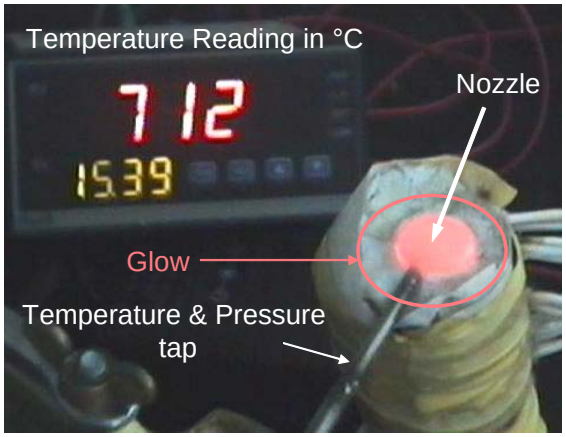

Fig. 6. NOMP-2 test firing (choked flow design).

For NOMP-1 decomposer's internal diameter was reduced by 20% (compared to Surrey's design, Fig. 2, and Table 1). Most importantly, NOMP-1 proved that self-sustaining N_2O decomposition can be successfully initiated in 39% smaller volume. This was, therefore, the first achievement in nitrous oxide monopropellant miniaturization.

During NOMP-2 test firing (see Fig. 6) the flow was choked by 0.18mm-diameter nozzle. Steady-state operation was observed for pressure above 5bar (gauge). For NOMP-2 exhaust temperature and N_2O mass flow rate were mapped over chamber pressure range. Later analysis of the test data revealed linear relationship between chamber pressure and mass flow rate (see Fig. 7). This result is in good agreement with the theory treating the both, nozzle and decomposer mass flow rates (Eq. 3 – continuity condition), as linear functions of chamber pressure:

$$\dot{m} = \frac{VQk_0 a\mu p e^{-\frac{E_a}{RT}}}{c(T)RT(T-T_0)} - \frac{hS}{c(T)} = \frac{\mu p}{RT} A_c \sqrt{\gamma \frac{R}{\mu} T \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (3)$$

where p – chamber pressure, Pa
k_0 – pre-exponential factor, 1/s
E_a – activation energy, J/mol, energy needed to initiate reaction
R – ideal gas constant, R = 8.314 J/mol/K
a – relative N_2O concentration
V – chamber volume, m^3
Q – specific heat for N_2O decomposition reaction, J/kg
c – gas mixture specific heat, J/kg/K, that is temperature dependent
γ – specific heat ratio
T – gas temperature, K
T_0 – ambient temperature, K
μ – molar mass for gas mixture, kg/mol
A_c – hydraulic area for nozzle throat critical cross-section, m^2
S – decomposer heat transfer area, m^2
h – heat transfer coefficient, $W/m^2/K$

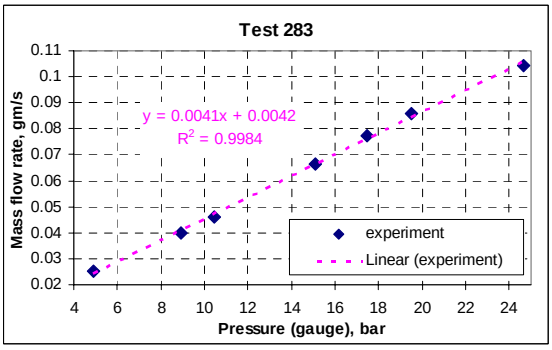

Fig. 7. Mass flow rate – chamber pressure relationship.

Later it was found that the same N_2O mass flow rates through the decomposer could not be supported by bigger nozzle (0.45mm in diameter).

On the whole, NOMP-2 decomposer's internal diameter was reduced by another 33% (see Table 1) that corresponded to 59% volume reduction compared to NOMP-1. This was, therefore, another achievement in nitrous oxide monopropellant miniaturization.

As it was expected higher chamber pressures make it possible to support significantly higher mass fluxes in comparison to previous designs mentioned above (see Table 1). Maximum mass flow rate supported by the design is about 0.1gm/s that correspond to 0.14N of calculated ideal thrust.

Due to manufacturing flaw nozzle for NOMP-3 design had been made too big (0.5mm in diameter) so that decomposition reaction was quenched by excessive mass flow rates through the nozzle. Blocking wire was used to restrict mass flow rates through the nozzle to appropriate values (see Fig. 8).

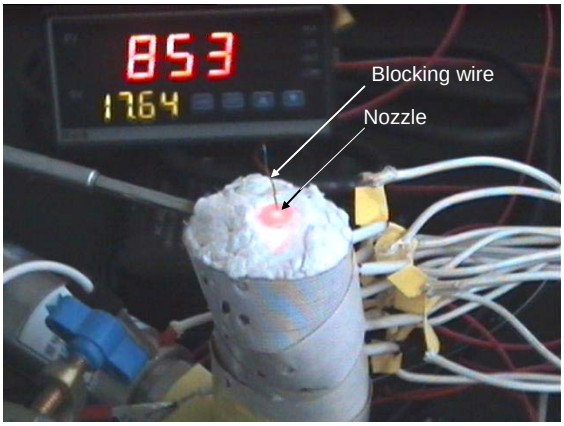

Fig. 8. NOMP-3 test firing (wire blocks the nozzle).

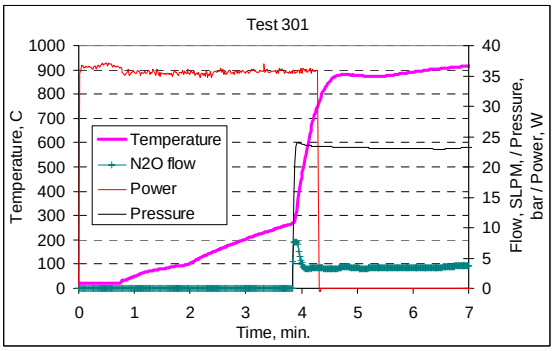

Fig. 9. Start-up transient for NOMP-3 (For this test the catalyst pack length was about 24mm that is of the size for hydrazine monopropellant.)

During NOMP-3 testing exhaust gas temperature exceeded 1108ºC (upper limit for thermocouple reader) demonstrating potential of N_2O decomposition technique in achieving 170 < Isp < 200s.

Start-up time as short as 52s was recorded (see Fig. 9). This is another significant practical achievement for NOMP-3 design. For example, someone fires prospective N_2O monopropellant thruster onboard small satellite passing over ground-station. The time when the satellite is in the direct view of ground-station is about 15min. If the prospective N_2O monopropellant thruster has start-up transient time of 10min. (earlier design at Surrey, see Table 1), when with additional 5min. thruster pre-heat time it is impossible task since by the time the thruster operates at full thrust the satellite will already be out of ground-station view. For the NOMP-3 case presented in Fig. 9 total time before the thruster gets to its full thrust is less than 5min. leaving another 10min. of full thrust operation before the satellite be out of ground-station view. For 60kg micro-satellite equipped with prospective N_2O monopropellant thruster delivering

0.1N thrust at Isp=155s for 10min. total velocity change for the satellite will be ~1m/s. This velocity change is significant for satellite orbit raising, station-keeping, and phasing propulsion functions.
Due to design improvement NOMP-3 is more than 2 times lighter than NOMP-1, and 4 times lighter than NOMP-2. Since most of its weight is accumulated in fittings and pressure tap, that are necessary only for testing and can be removed, the weight of flight qualified thruster is expected to be about 10-20gm (without thermal insulation).
NOMP-3's chamber diameter and length are about the same as that one for hydrazine monopropellant.
On the whole, current NOMP-3 design can be developed into flight qualified N_2O monopropellant thruster with performance practical for small satellite applications and competitive to hydrazine monopropellant for 0.01-0.15N thrust range.

6. CONCLUSIONS

- The approach taken for N_2O decomposer miniaturization by raising chamber pressure is successful.
- Decomposer's internal diameter and length are successfully reduced to almost a half of the Surrey's design, and currently are 8 (diameter) and ~24mm (length) that is the same size of existing hydrazine monopropellant thruster's one.
- Reaction chamber volume is successfully reduced to almost 4.5 times that of the Surrey's design, and currently is ~1500mm^3 that is almost the same value of existing hydrazine monopropellant thruster's one.
- Thrusts up to 0.14N were estimated, and are within desired range.
- Specific impulse values for nitrous oxide monopropellants are estimated to be in the range of 150-170s. Although it is lower than 202-227s specific impulse for existing hydrazine monopropellant thrusters (0.19-1N) such specific impulse can still be competitive for the thrusts <0.19N since currently there is no hydrazine monopropellant thruster for this thrust range. Non-toxicity and non-flammability on nitrous oxide are other advantages of prospective monopropellant comparative to toxic and flammable hydrazine for small satellite applications.
- N_2O decomposer design weight was reduced 4 times for choked design, and currently is as low as 37gm. It has potential to be further reduced to 10-20gm that is competitive with existing hydrazine monopropellant thruster's weight.
- Start-up transient has become 12 times faster, and currently is as short as 50s. This time is enough short for such small satellite propulsion functions as orbit raising, station-keeping, and phasing.

On the whole, current NOMP-3 design can be developed into flight qualified N_2O monopropellant thruster with performance practical for small satellite applications and competitive to hydrazine monopropellant.
Future research in the area of N_2O monopropellant is planned to further improve its size, mass, and start-up performance.

7. ACKNOWLEDGEMENT

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