DESIGN AND TEST OF NITROUS OXIDE INJECTORS FOR A HYBRID ROCKET ENGINE

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Abstract

An injection system for the Helios hybrid rocket engine is designed by ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG). Within three years German students design and launch their own hypersonic rockets with self-made rocket engines within Studentische Experimental-Raketen (STERN) program of German Aerospace Center (DLR).

The quality and homogeneity of an atomized fluid and therefore the stability and efficiency of hybrid rocket engines are basically determined by the oxidizer injection system. The Helios hybrid rocket engine uses nitrous oxide as oxidizer. Evaporation and combustion of the atomized nitrous oxygen droplets need to be completed inside the combustion chamber, which is less than one meter long. The pressure drop over the injector protects the feed and tank system against backflow of the hot combustion gas. To respect this amount of requirements the most important equations and design rules of several injector designs are summarized shortly. Furthermore the design of the special test bench, which was built to validate the design of different injectors, is presented. An acrylic glass chamber was used for the experiments. Moreover the acrylic glass chamber provided a field of view into the injection of nitrous oxide, which was recorded by high-speed camera pictures. The quality and homogeneity of the injectors are rated directly by these pictures.

1. INTRODUCTION

ExperimentalRaumfahrt-InteressenGemeinschaft e.V. (ERIG) student group gets professional support by Studentische Experimental-Raketen (STERN) program from German Aerospace Center (DLR). Within this program German students design and launch their own hypersonic rockets with self-made rocket engines. One objective of this program is to top the European altitude record for non-professionals of 12.55 km. ERIG e.V. is also supported by the Institute of Aerospace Systems at Technische Universität Braunschweig.

For the expansion of experience with hybrid rocket engines ERIG e.V. established the Leonis project to construct their own Helios hybrid rocket engine for the STERN program. The oxidizer injection system of this paper is designed for the Helios hybrid rocket engine of ERIG e.V. The advantage of hybrid rocket engines in comparison to solid motors is the controllability. The advantage in comparison to high-performance liquid oxygen and hydrogen engines is the easier and safer handling of the propellant. Nitrous oxide is used for the Helios hybrid rocket engine as the oxidizer, because it liquefies at a pressure of about 50 bar at environmental temperatures. In that condition nitrous oxide has a considerably higher density and needs less tank volume for storage as at lower pressures. During the feeding of the oxidizer from the tank to the injection system the nitrous oxide pressure declines and thus a liquid-gas mixture is injected. The flow coefficient C_D for this liquid-gas mixture, which is estimated for new injector designs by previous experimental research, is validated by test runs at an injector test bench. Moreover the different nitrous oxygen injectors are filmed by a high-speed camera through the acrylic glass of the injector test bench chamber. Finally the most efficient, simple and stable injection system is selected for the Helios hybrid rocket engine.

2. GENERAL REQUIREMENTS FOR HYBRID ROCKET ENGINE INJECTORS

The injection system of a rocket chamber determines the atomization and homogeneity of the injected fluid as well as the efficiency and stability of the combustion. Therefore some basic rules and requirements for the design of hybrid rocket engine injectors are summarized briefly at this chapter.

2.1. Atomization and homogeneity

For a fast and efficient combustion of the injected fluid at hybrid rocket chambers a homogeneous injection of many atomized droplets is required. The injection of small droplets enlarges the area for the propellant mixing process and therefore accelerates the combustion process. The atomization of a fluid, which is injected through orifices, can be described by three nondimensional numbers. The first nondimensional number is the Reynolds number Re:

(1) $$Re = \frac{\rho v d}{\eta}$$

This nondimensional number describes the ratio of the inertia force to the viscous force. The velocity v of the injected fluid can be calculated using the massflow and the density ρ of the oxidizer. The diameter d of the orifices is used as a characteritic length of the injector and η is the dynamic viscosity of the oxidizer. For typical orifices this number need to be clearly larger than 2300 [1] to archive turbulent flow and therefore to enhance the mixing process of the injected fluid with the hot combustion gas. The limiting factor for the orifice diameter is the attachment of the flow, which is only guaranteed if the depth in comparison to the diameter of the orifices is larger than about 4 [2]. The second nondimensional number is the Ohnesorge number Oh:

(2) $$Oh = \frac{\sqrt{We}}{Re} = \frac{\eta}{\sqrt{\rho \sigma d}}$$

This nondimensional number compares the influence of the viscosity to the forces of the droplet deformation. An adequate Ohnesorge and Reynolds number out of an Ohnesorge-Reynolds number diagram ensure the atomization of the injected fluid directly after the injection. This is guaranteed by the high friction force in comparison to the low inertia and surface forces of the fluid. The third nondimensional number is the Weber number We:

(3) $We = \frac{\rho v^2 d}{\sigma}$

It compares the inertia force to the surface forces between the liquid and gaseous phase in the chamber. Therefore the value of the surface tension σ of the injected fluid is needed. Because of the interaction between the fast liquid and the surrounding gas in the chamber this number needs to be greater than 50 [3] to create small droplets. With an estimated flow coefficient C_D or the experimental results of a test run the Sauter Mean Diameter (short SMD) x_{23} of an injection can be calculated by equation 4

(4) $x_{23} = \frac{5.54}{C_D^2} \cdot \frac{\sigma}{\Delta p} \cdot \frac{\rho_{liquid}}{\rho_{gas}}$

This diameter is the equivalent diameter of a droplet averaged by the surface of the injected spray. Typical values for SMDs are less then 1 µm. Beside an accurate atomized injected fluid a homogenous distribution of the liquid propellant in the hybrid rocket engine chamber is required for a homogenous combustion of the solid propellant. Thus the orifices of the injection system are usually arranged according to the shape of the solid propellant. However for a new designed injector a test run is always required to ensure an adequate atomization, homogeneity and functionality.

2.2. Efficiency and stability

After the ignition of the hybrid rocket engine, the flow on the surface of the solid propellant is equivalent to an entrance region of a usual boundary layer. Some of the injected droplets of the non-evaporated propellant get even through this boundary layer at the entrance region and erode solid propellant particles. Simultaneously the liquid propellant and the solid propellant evaporate and react above the surface of the solid propellant. Furthermore unburned propellant diffuses through the boundary layer. This reacting area is called flame zone. More and more droplets evaporate with the proceeding flow so that only a diffusion flame exists further downstream. Therefore a uniform distribution of the orifices for a liquid propellant achieves close to the surface of the solid propellant a fast and efficient combustion. However it is important that not too many non-evaporated droplets touch the surface because an extinction of the flame or an unstable combustion may result. Consequently the angle between the orifices and the solid propellant does not need to be perpendicular. The prevention of instabilities is an important objective of the injector design because strong pressure oscillations can damage the whole rocket engine. Especially when a spontaneous decomposition propellant as nitrous oxide is used pressure oscillations can lead to a backflow of hot combustion gas to the liquid propellant tank. Therefore injection systems need to be designed with an adequate pressure drop to prevent hot gas from backflow. Usually some areas next to the orifices are left blank for the recirculation of hot gas for the stabilization of the flame around the orifice. However for a new designed injector a test run is also required to ensure an adequate stable combustion.

3. DESIGN OF THE DIFFERENT INJECTORS

For the overmatch of the European altitude record within STERN program, the oxidizer massflow needs to be about 1.1 kg/s. In combination with the mixture ratio (O/F) of the propellants and the exit velocity of the combustion gas v_{ex} at the end of the nozzle the oxidizer massflow determines directly the thrust F of the engine.

(5) $F = \dot{m}_{ox} v_{ex} \frac{O/F+1}{O/F}$

Four different designs for the arrangement of the orifices are considered:

1) Perpendicular orifices
2) Self-impinging
3) Self-impinging with bezels
4) Inclined orifices

The characteristic facts of the four injector design are summarized in table 1.

Injector design	1)	2)	3)	4)
Diameter	1.3mm	1.3mm	1.3mm	1.3mm
# of orifices	60	45	42	60
Re	467k	539k	577k	467k
We	237	274	315	237
Oh	0.0035	0.0033	0.0033	0.0035

TAB 1. Key values of the four injector designs

Previous injector designs of ERIG e.V., which are similar to the first design, had smaller diameters for the orifices. Due to broad cost reductions of the manufacturing, the diameters were enlarged. Hence an accurate atomization of the new orifices has not been experimental ensured by ERIG e.V. before. A second design with self-impinging oxidizer jets is constructed to reduce the size of the oxidizer droplets. This design is shown in figure 1.

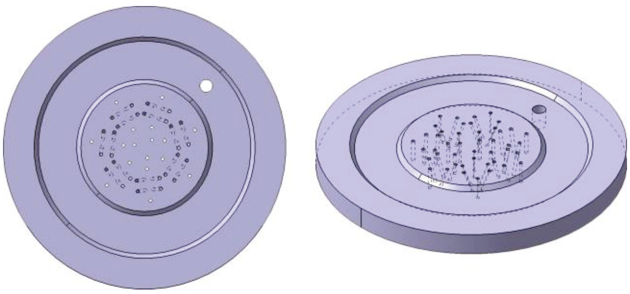

FIG 1. Top and isometric view of injector design 2)

Two self-impinging orifices are placed together at each part of the star shaped fuel geometry of the prospective solid fuel. At both sides of the impinging oxidizer fan a perpendicular orifice is placed to prevent a strong surface abrasion by the impinging fan. Initially a third injector system is designed to show a supposed pressure loss reduction by bezels at the orifices. A high manufacturing uncertainty is the disadvantage of this design due to the necessity of precise production of the high amount of small bezels. However, a pressure loss reduction is nonrelevant because a similar minimum pressure drop is needed during the injection for the prevention of oxidizer backflow at all injector designs. Concerning to this reason the pressure loss is regulated by the amount of orifices.

Furthermore previous hybrid engine hot run tests at ERIG e.V. showed that the fuel solid fuel regression rate at the combustion chamber increases with the chamber length. Thus less fuel is burned with perpendicular orifices than with the slightly inclined orifices as figure 2 shows. This results in a lower efficiency and a smaller utilization of the chamber volume for injector design 1. For this reasons, design 1 is no more taken into account in the following. The fourth design with 10 degree inclined orifices is shown at figure 3. Furthermore the arrangement of the orifices at all injector designs is adapted accordingly to the star shaped geometry of the solid fuel for a homogenous distribution of the oxidizer in the combustion chamber. Four circles of orifices with an offset of 5 mm each are used.

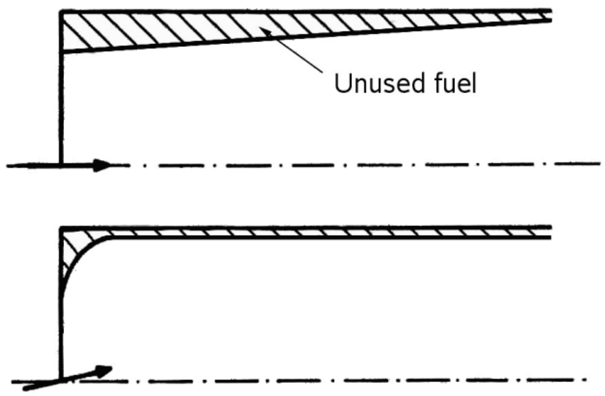

FIG 2. Perpendicular and inclined injection of the rocket chamber with partly burned fuel shape

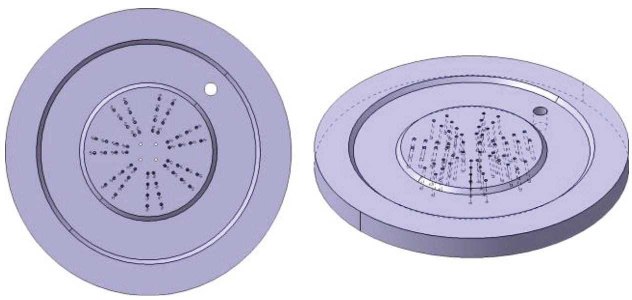

FIG 3. Top and isometric view of injector design 4)

Smaller diameters for the orifices were used by ERIG e.V. at previous injector designs. All in all only the second and the fourth injector design are manufactured out of stainless steel 1.4307 for the experimental validation with the injector test bench.

4. INJECTOR TEST BENCH

For the experimental determination of the flow coefficient and for the check-up of the atomization process an injector test bench with transparent acrylic glass is constructed. This test bench simulates the prospective chamber pressure of the hybrid rocket engine and therefore uses a nozzle at the end of the chamber. In comparison to a real hybrid engine hot run test, the oxidizer nitrous oxide is just used without an ignition. So the following material properties of nitrous oxide at environmental temperature of the prospective rocket range are used for the construction of the injectors and the test bench:

Temperature T	273.16 K (0°C)
Density (liquid) ρ_l	907.02 kg/m^3
Dynamic viscosity (liquid) η_l	0.07912 mPas
Surface tension σ	5.01 mPam

TAB 2. Material properties of nitrous oxide

The injection angles and a raw impression of the atomization process are filmed by a high speed camera. A Canon EX-F1 was used for the high-speed pictures with 1200 fps and a resolution of 336 x 96 pixels. The camera is placed 1 m away from the injector with a view angle of 60 degree. Thus the injection process and the orifices behind the flange can be filmed. The acrylic glass of this test bench, which has a similar geometry in comparison to the prospective hybrid rocket engine, is fixed together with the injector and the nozzle between two aluminum flange conjunctions and fixed with four threaded rods for a fast and easy assembly and disassembly. The inner radius of the acrylic glass tube is 61.5 mm, the thickness is 5 mm and the length 500 mm. The test bench is fixed on a steel plate for a safe and simple handling. The gas supply system consists of a nitrous oxide tank, a nitrous oxide gas bottle and a nitrogen gas bottle. Before a test run the liquid nitrous oxide is filled from the gas bottle into the 7 l nitrous oxide tank. Then the tank is pressurized with nitrogen to about 50 bar to keep the nitrous oxide liquid. During a test run the nitrogen keeps the oxide tank pressure nearly constant. Under this steady condition the nitrous oxide flows from the tank through a tube to the injector. With a full nitrous oxide tank a test runs lasts about 3 seconds. Furthermore all data is automatically collected over the test run time span by a controlling system. Instead of a massflow sensor the force sensor LCB120 from ME-Meßsysteme GmbH for the weight of the nitrous oxide tank is used for the measurement of the massflow. For the measurement of the pressure three identical piezoelectric pressure transducers are used, see table 3 for detailed information. One transducer measures before and after the injector and one measures at the nitrous oxide tank.

Manufacturer	Fischer
Type	ME6111C87AH90V00
Measuring range	0..60 bar
Electric output	0..20 mA
Operational voltage	24V DC

TAB 3. Datasheet of the piezoelectric pressure transducer

Explanations of the test bench in figure 4:

1: Injector	7: Injector flange
2: Nitrous oxide connection	8: Nozzle flange
3: Acrylic tube	9: Stabilization rings
4: Nozzle	10: Threaded rods
5: Injection pressure connection	11: Inner ring
6: Chamber pressure connection	

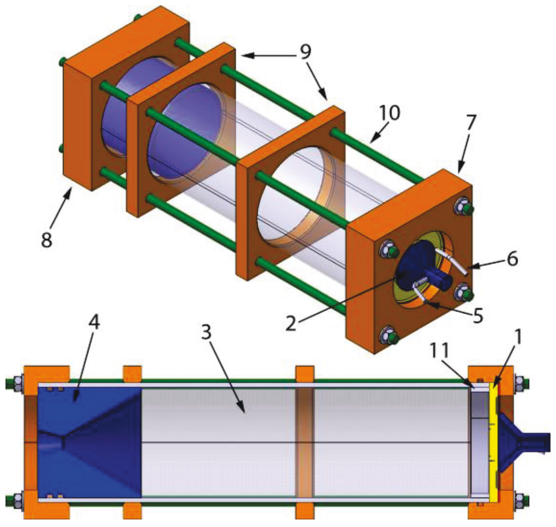

FIG 4. Test bench isometric and half-section view

5. INJECTOR TESTS RESULTS

In this chapter the test results of the injector design 2) and 4) are summarized and compared. Due to the fact that the physical state of nitrous oxide depends on the environmental temperature, the pressure of the filled nitrous oxide tank was measured to determine the material properties of the oxidizer before the nitrogen pressurization. The pressure of the nitrous oxide tank was determined to 29.90 bar. This leads to a temperature of 271.48 K (-1.68°C) of the liquid nitrous oxygen. Thus the discrepancies in comparison to the temperature approximation 273.16 K (0°C) during the evaluation of the injectors is neglected in the following. The flow coefficient C_D is calculated as equation 6 shows.

(6) $C_D = v_{inj} / \sqrt{\frac{2\Delta p}{\rho_{liquid}}}$

Whereas v_{inj} is the theoretical injection velocity of nitrous oxide for the assumption that only a liquid nitrous oxide massflow passes all orifices of the injector with the liquid density ρ_{liquid} which is listed in table 2. Furthermore a constant velocity is assumed over the cross section of all these orifices.

5.1. Injector with self-impinging jets

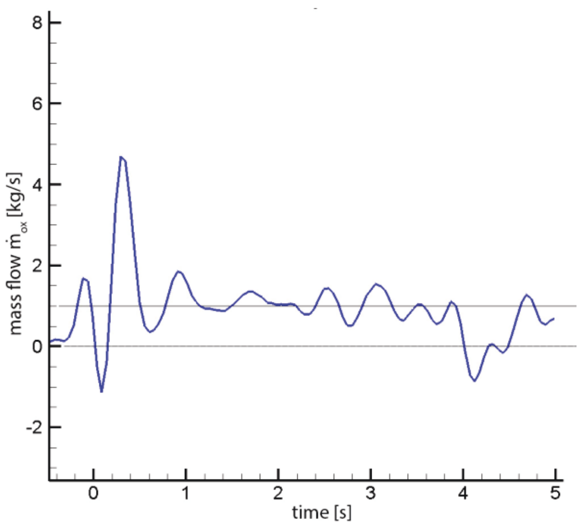

FIG 5. Nitrous oxide mass flow of design 2)

The mass flow rate for the test run period of the self-impinging injector test is shown at figure 5. This figure shows a decrease of the massflow after approximately 4 s. Thus the average mass flow is determined at this test run between 1 s and 4 s to $\dot{m}_{ox}$ = 1.02 kg/s. The mass flow is determined by the force sensor at the oxidizer tank. The nitrogen mass flow rate is already subtracted. The oscillations at the beginning occur also as a result of the nitrogen pressurization of the nitrous oxide tank. In figure 6 the pressure distribution over the test period is shown. The averaged pressure drop over the injector is determined between 1 s and 4 s to Δp = 13.15 bar.

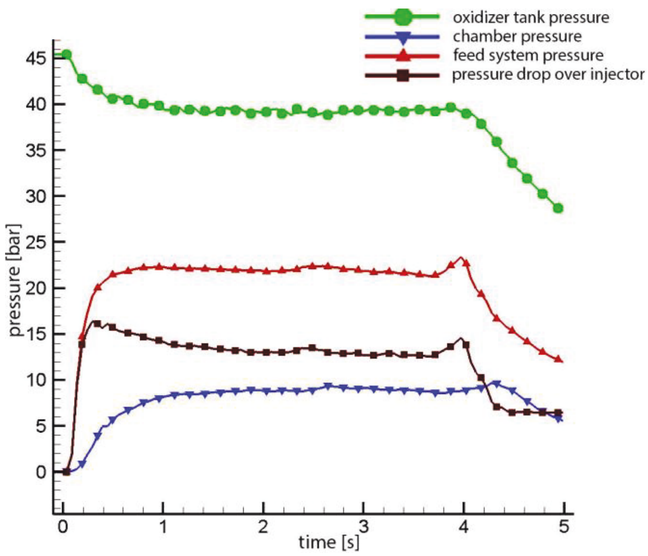

FIG 6. Pressure graph of the injector test of design 2)

In figure 7 the flow coefficient C_D over the test run period is shown. The average flow coefficient between 1 s and 4 s is C_D = 0.256. The shape of the injected nitrous oxide is shown in figure 8 after a period of 0.025 s. The angle of the injected nitrous oxide is about 45° there. The homogenous injection and atomization process of the injected nitrous oxide is also visible. Therewith this design shows a good functionality for the prospective hybrid rocket engine.

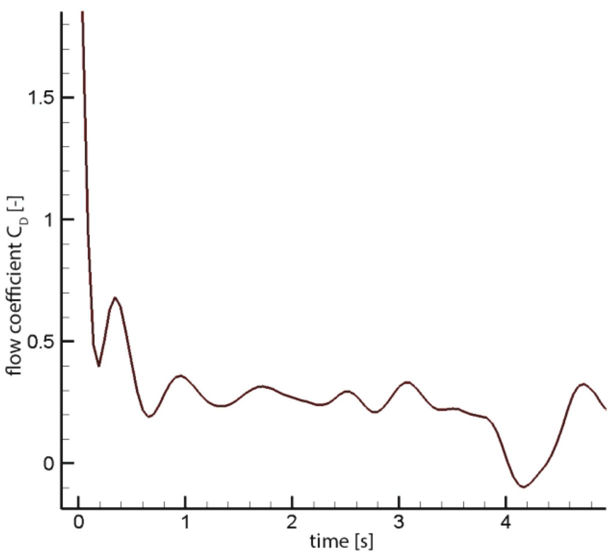

FIG 7. Flow coefficient of design 2)

FIG 8. Nitrous oxide jets after 0.025 s

5.2. Injector with inclined orifices

At figure 9 the distribution of the massflow rate over the test period is shown. The test run with the self-impinging injector was made before the one with the inclined injector. The pressure loss at the fluid system was slightly higher than expected at this test. Therefore the nitrogen pressure was increased, which leaded to a slightly higher massflow and pressure loss. The oscillation at the beginning occurs because of the inflowing nitrogen. According to figure 10 there is no more liquid oxidizer in the tank after 3.6 s. Thus the nitrogen pressure declines afterwards. The averaged mass flow is determined between t = 1 s and t = 3.6 s. This $\dot{m}_{ox}$ = 1.08 kg/s is very close to the designed value.

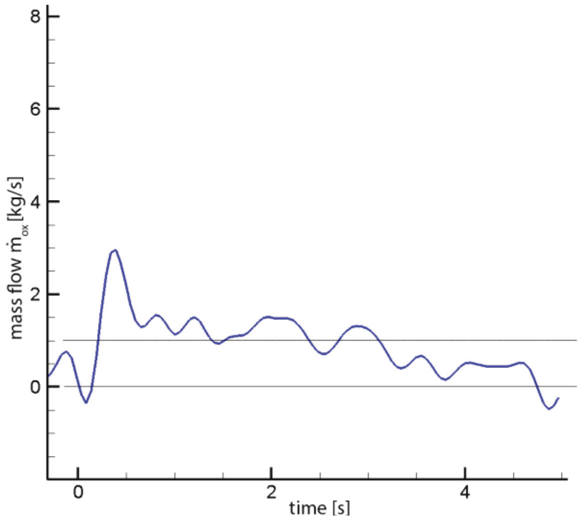

FIG 9. Nitrous oxide mass flow of design 4)

The average pressure drop over the injector of about Δp = 15 bar is shown at figure 10.

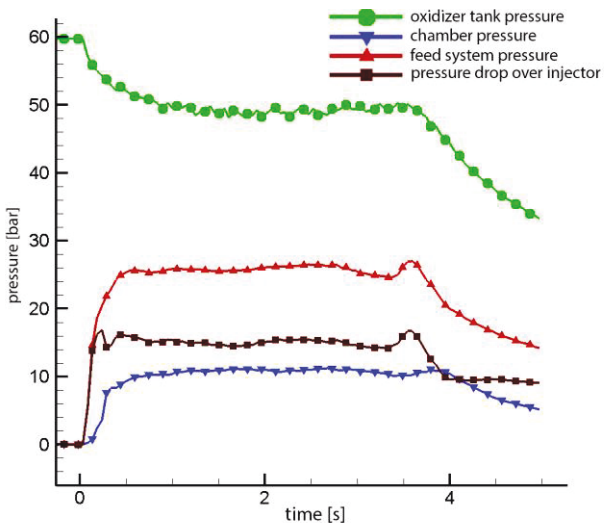

FIG 10. Pressure graph of the injector test of design 4)

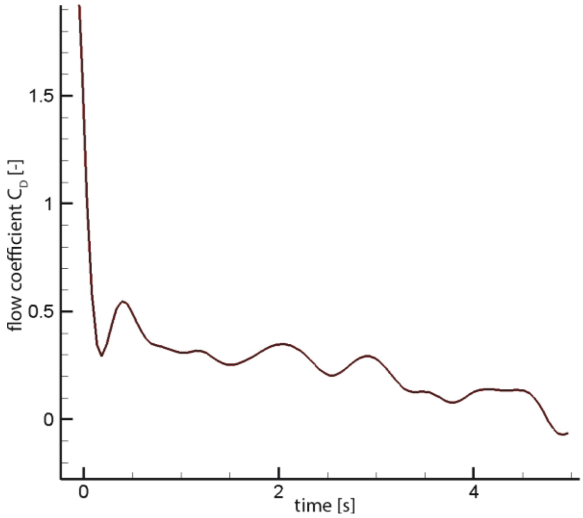

FIG 11. Flow coefficient of design 4)

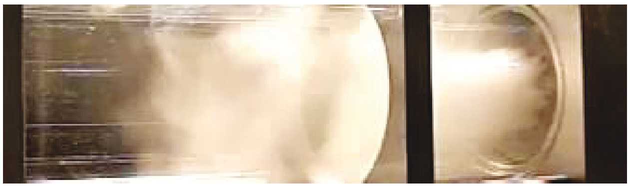

FIG 12. Nitrous oxide jet after 0.018 s

The flow coefficient C_D is also averaged between t = 1 s and t = 3.6 s with a value of C_D = 0.259. At figure 12 the nitrous oxide jet after 0.018 s is shown. The homogeneous injection and atomization process of the injected nitrous oxide is clearly visible. Therewith this design shows a good functionality for the prospective hybrid rocket engine as well as design 2). It is also visible that the angle of the injected nitrous oxide is similar to the test of the inclined injector of figure 8.

6. CONCLUSION

Table 4 summarizes the results of both injector designs.

	Design 2)	Design 4)
Pressure drop Δp	13.15 bar	15 bar
Mass flow rate $\dot{m}_{ox}$	1.02 kg/s	1.08 kg/s
Flow coefficient C_D	0.256	0.259
Jet angle θ	≈45°	≈45°
SMD x_{23}	0.32 µm	0.28 µm

TAB 4. Summary of the test results

Table 4 shows that higher flow coefficients cause directly a higher mass flow rate. The difference between design 2) and 4) is just 0.06 kg/s. In comparison to the design value of 1.1 kg/s this are just 5%. Figure 13 shows a comparison for the injection of both injector designs. In consideration of the results of both mass flows the chamber is even filled faster by nitrous oxide in the second test. This results maybe from the higher amount of orifices which induce a more homogenous distribution of the oxidizer in the chamber. Thus a more homogenous burn of the prospective solid fuel of the chamber is expected. To produce the same effect with the self-impinging design a greater distance between the impinging orifices is needed which leads to a larger nitrous oxide connection of the injection system. Therewith the design 4) is slightly advanced. The nitrous oxide is atomized to very thin droplet by both designs. Although the droplets size cannot be measured at this test bench at present, Figure 13 shows similar small atomized nitrous oxide jets. Besides the fact that the nitrous oxide distribution of design 4) is slightly better, former injector test campaigns showed that self-impinging are more often unstable during rocket engine hot runs [6]. Therefore the inclined injection system is chosen for the prospective Helios hybrid rocket engine. Nevertheless an extension of the injector test bench with a droplet size measurement system is desirable to validate the calculated droplet size of nitrous oxygen.

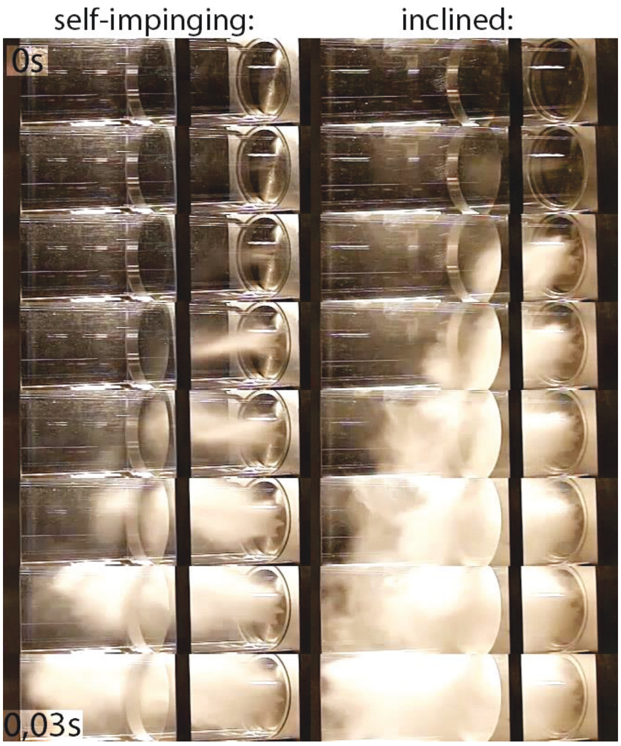

FIG 13. Spray of injector design 2) and 4)

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