HiSST: 3rd International Conference on High-Speed Vehicle Science Technology
14 -19 April 2024, Busan, Korea

Experiments on High Speed Air-Breathing Propulsion for Sustainable Supersonic Flight

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Abstract

This publication presents first results of an ongoing investigation into combustion processes and environmental impacts of Ramjets and Scramjets at the German Aerospace Center (DLR) within the European MORE&LESS project. It summarizes the first extensive test campaigns within the project with gaseous hydrogen and liquid hydrocarbon-based fuels. In summary more than 100 hot runs have been performed so far in order to generate an emission and combustion data base for validation purposes of CFD simulations and for the simulation of environmental and atmospheric impacts of supersonic flight. Sustainable combustion and combustion measurement data could be obtained for different boundary conditions and hydrogen and n-heptane as a fuel. First NOx measurements in the exhaust gas plume show a strong directional and uneven distribution of this type of emission in the flow. An outlook on additional experiments using different types of fuel (e.g. bio fuels) and improved measurement techniques is also presented. Further research requirements and subsequent changes in the test setup are discussed.

Keywords: *Ramjet, Ground Testing, More&Less, Thermodynamics, Gasdynamics*

1. Introduction

Internationally, research on sustainable and efficient alternatives to current aerospace propulsion systems has increased demand for replacement of toxic propellants and for the modernization of existing systems through greater efficiency. These drivers along with national security challenges have brought Ramjets with supersonic combustion (Scramjets) and other systems back into focus (see e.g. [1], [2], [3]). The main challenges of high-speed air-breathing propulsion (HSABP) systems like Ramjets and Scramjets are short fuel residence times, controlled mixing and combustion, and efficient /sufficient cooling of the engine's components exposed to very high heat loads. However, in their practical application especially for future sustainable supersonic flight, the focus is also on the emissions generated by the propulsion system. This is a so far mostly neglected aspect of HSABP research and needs increasing attention. Thus, the project *MDO and REgulations for Low boom and Environmentally Sustainable Supersonic aviation (More&Less)* features a combination of high-fidelity simulation / modelling activities and test campaigns that merge into the multi-disciplinary optimization framework to assess the holistic impact of supersonic aviation onto environment. This ultimately leads to recommendations to shape European and global regulations for sustainable supersonic aviation. DLR Lampoldshausen is participating in the project with its unique high-speed air-breathing propulsion testing capabilities to provide the necessary experimental testing data on Ramjet propulsion. This publication presents the first results of the ongoing investigation of the More&Less experiments conducted at the German Aerospace Center (DLR) and the first more than 100 test runs. Further research requirements and subsequent changes in the test setup are discussed.

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2. Experimental Setup

The Institute of Space Propulsion of the German Aerospace Center (DLR) Lampoldshausen has developed and established a research test bench (M11.1) to investigate high speed air-breathing propulsion (HSABP) and to collect data on its application in sustainable supersonic flight. The test bench (see [4], [5], [6] for details and performance) consists of a hydrogen / oxygen air vitiator (Fig. 1) with 11 hydrogen / oxygen burners that heat up the pressurized air fed through them. They can be interconnected in different burner patterns to adjust the mass flow, pressure, and temperature of the vitiated air as required. A multi-stage combustion process including the introduction of makeup oxygen adjusts the vitiated air mixture to an atmospheric composition before being introduced into an experimental setup.

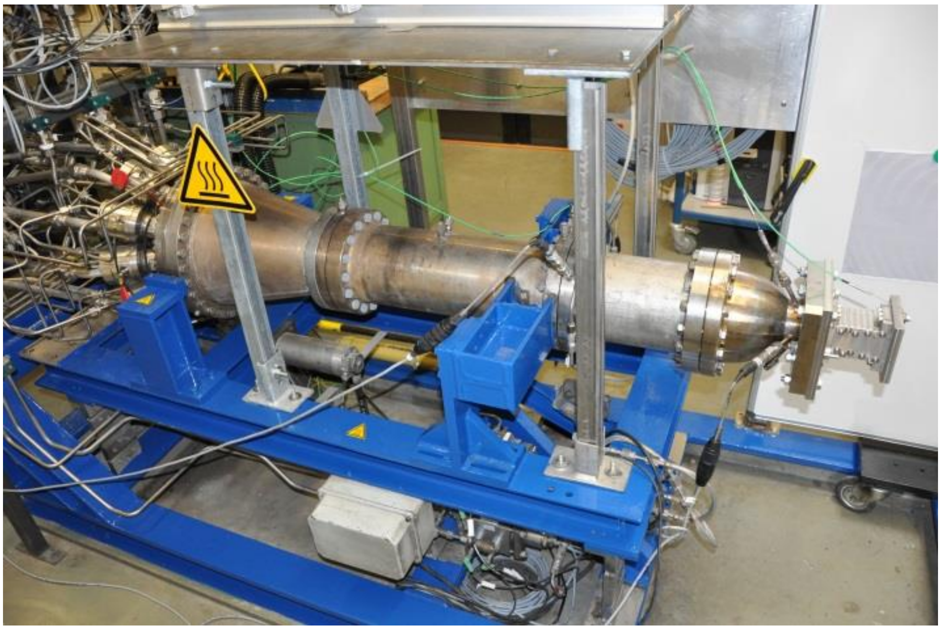

Fig 1. Air Vitiator

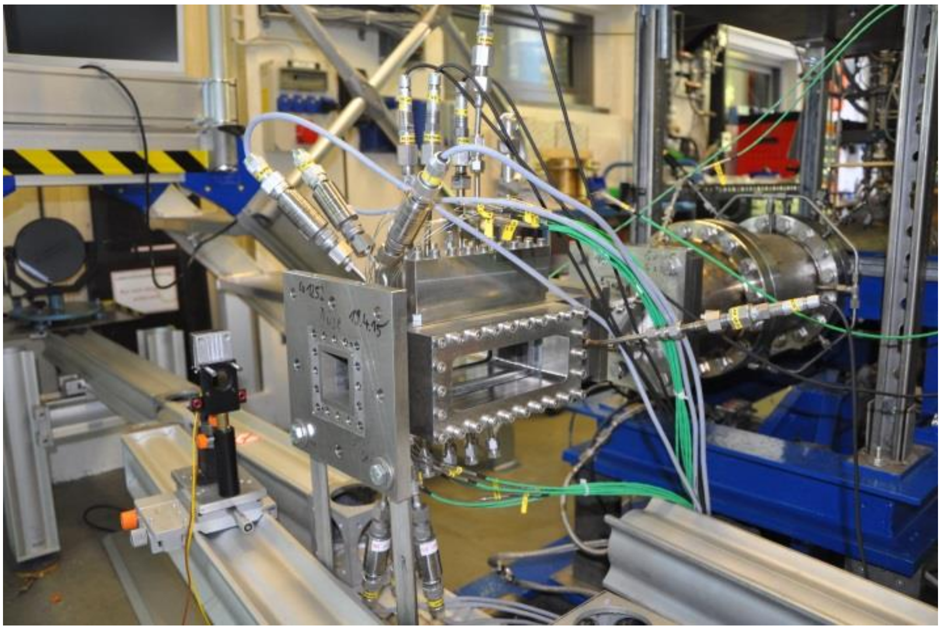

Fig 2. Ramjet / Scramjet Model Combustion Chamber

It is possible to reach stagnation temperatures up to 1500 K, stagnation pressures of 25 to 30 bars and mass flows of 5,0 kg /s maximum with the air vitiator with testing time reaching from several seconds to several minutes, depending on the requirements of the experiment. Connected to the air vitiator is a geometrical transition section that converts the round cross-section (diameter 135 mm) into a rectangular cross-section (45 by 45 mm) with minimal influence on the boundary layer.

For the More&Less project a model combustion chamber is connected to the previously mentioned transition section (Fig. 2). This versatile model combustion chamber (length 300 mm) can accommodate different injector configurations and various types of measurement equipment. It can be operated either as a Ramjet or as a Scramjet. Details on the standard intrusive and non-intrusive measurement equipment of the model combustion chamber can be found in [7]. The experiments for More&Less were performed mainly in the Ramjet configuration, whereas the Scramjet configuration was used for reference experiments at selected boundary conditions only. Two quartz glass windows provided optical access and allowed the use of a Background Oriented Schlieren (BOS) system [4], [8]. This system features detailed Schlieren imagery and was shown in previous HSABP experiments to be less affected by changes in the refractive index of the quartz glass windows due to strong heating [4] as it is caused by combustion processes. Two sophisticated gas sampling systems were installed to measure the chemical gas composition and the water vapor content of the gas. The first sampling port is located at the air vitiator in the settling section downstream of the burner cans. It provides data on the initial water vapor content of the vitiated gas. This can be used in comparison to reference samples of the pressurized air supply to calculate the water vapor generation by the vitiation process. The second sampling station is located downstream of the model combustion chamber in the exhaust plume (Fig. 3). It consists of a water-cooled sampling probe that can be moved in three directions within the exhaust gas stream via a positioning system. Gas samples collected with the probe initially pass through a sampling chamber where NOx measurements are performed in-line by an off-the-shelf industry-grade sensor. This probe also features the option to perform solid mater measurements with a filter in order to determine an indication for the Smoke Number [9]. After passing the NOx measurement chamber the sample is collected in evacuated gas sample cylinders for further analysis at the physic-chemical lab of DLR Lampoldshausen. The system is automatically flushed with fresh sampling gas before a sample is routed to one of the sample cylinders and it can acquire multiple samples during a single air vitiator run, if required.

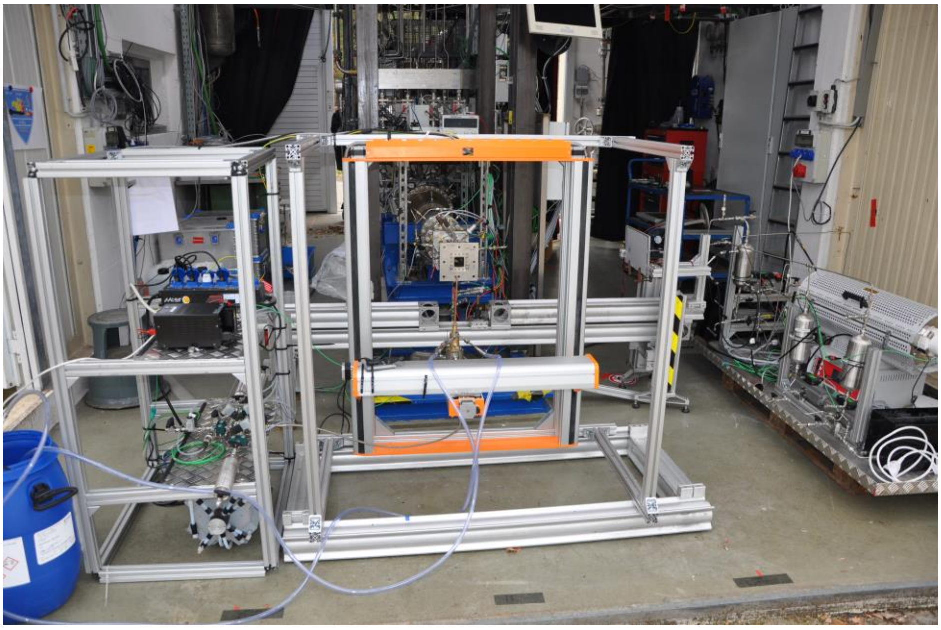

Fig 3. M11.1 Test Bench with Exhaust Gas Sampling System Installed

3. Experimental Methodology

In the combustion experiments, a cavity style injector developed by DLR Lampoldshausen was used with a single injection element located parallel to the hot gas main flow. The cavity with the dimension 84 mm x 30 mm is located at the bottom wall of the combustor and 125 mm downstream of the combustor's inlet plane. A 20° ramp directs the secondary cavity flow into the hot gas main flow. To force ignition outside of auto-ignition boundaries or of less reactive fuels, a glow plug is located 20 mm downstream of the injector element.

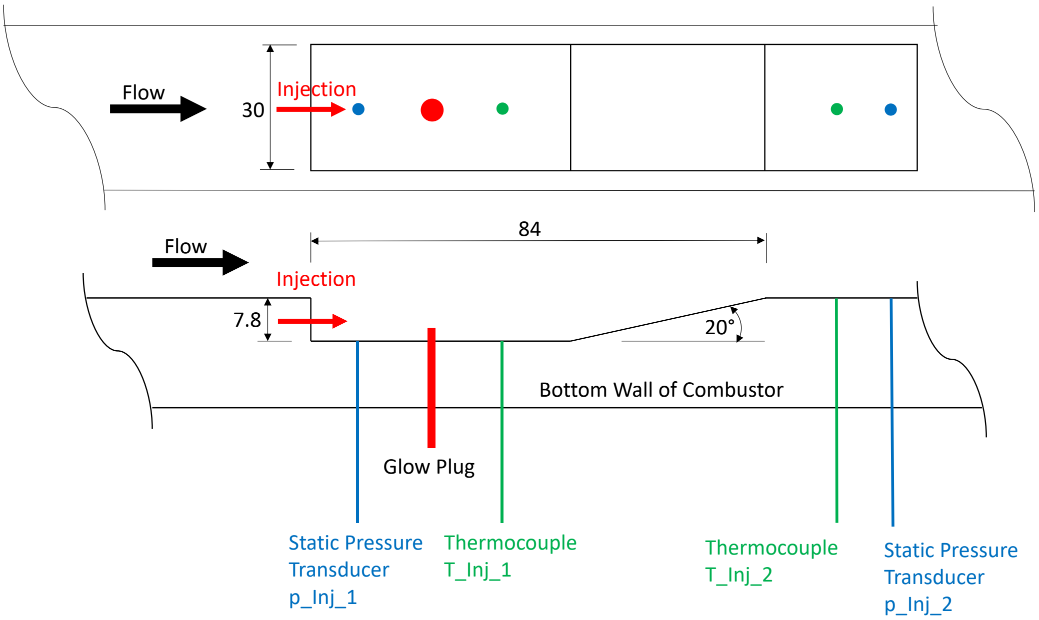

Fig 4. DLR cavity injector schematic

The injector is equipped with two type-K thermocouples located in the cavity (35 mm downstream) and at the end of the ramp (94 mm downstream). Pressure measurements are obtained via two static pressure ports located within the cavity (5 mm downstream, *Measurement Specialities Type P913-G003, 0-10 bar abs*) and at the end of the ramp (79 mm downstream, *Measurement Specialities Type P913-G003, 0-10 bar abs*). Additionally, pressure, temperature and mass flow rate of the fuel are measured in the supply line right before entering the injector head by a type-K thermocouple, a static pressure sensor and a Coriolis mass flow meter (*Micro Motion ELITE CMF010M*). The injector element can be exchanged in order to adapt the injector head to gaseous or liquid fuels respectively. Additionally, the model combustion chamber is equipped permanently with eight type-K thermocouples and three static pressure ports with pressure sensors on the upper wall, downstream of the cavity injector. The stagnation boundary conditions at the air vitiator and the static boundary conditions at the inlet plane of the model combustion chamber are monitored by sensors accordingly (see [4]-[7] for details). Experiments have been performed using gaseous hydrogen and n-heptane as fuels (see e.g. Fig 5). Those fuels were injected at various fuel mass flow rates and at different air vitiator boundary conditions. For gaseous hydrogen, the initial test duration was set to 10 seconds. The initial design of the injector for the first tests featured a removable ramp in order to change the ramp angle, if needed. It was found that this option introduced survivability issues for the hardware (see section 4) during longer runs (10-20 s test time) due to very high heat loads at the ramp's leading edge. A design evolvement to an integral design as a single piece of hardware without the option to exchange the ramp solved this issue. Additionally, the test run time was limited to 5 seconds for most of the subsequent tests in order to limit the introduced amount of heat.

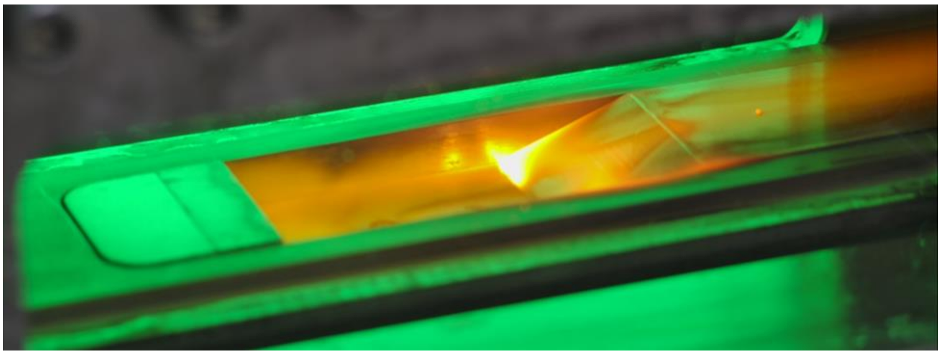

Fig 5. Combustion of gaseous hydrogen fuel in DLR Cavity Injector

Table 1. Selected hydrogen ramjet test conditions with sustainable combustion

TestDuration [s]	Stagnation Temperature [K]	Designated Stagnation Pressure [bar]	Hot Gas Mass Flow Rate [g/s]	Fuel Mass Flow Rate [g/s]
5	1200	3	700	0.56
5	1200	3	700	1.22
5	1200	3	700	1.53
5	1200	7	1600	0.56
5	1200	7	1600	0.77
5	1200	7	1600	0.99
5	1200	7	1600	1.21
5	1200	7	1600	1.34
5	1200	7	1600	1.50
5	1200	9	2100	0.77
5	1200	9	2100	0.79
5	1200	11	2600	1.03
5	1200	15	1135	0.35
5	1200	15	1135	0.56
5	1200	15	1135	0.77
5	1200	15	1135	0.98
5	1200	15	1135	1.21
5	1200	15	1135	1.52

The hydrogen experiments were conducted at air vititator stagnation temperatures of 900 K and 1200 K. Whereas a sustainable combustion was achieved at 900 K only for certain boundary conditions, the 1200 K test point proved to support a wider variety of boundary conditions with continuous combustion (see Table 1). Thus, the main focus of the hydrogen experiments for the first More&Less hydrogen campaign was put on the 1200 K boundary condition after initial investigation of the 900 K test point. The 1200 K test condition also provided the most promising validation point for the numerical simulation within the holistic framework.

As a preparation for the upcoming bio-fuel / SAF tests designated for the project More&Less, injection and combustion experiments were conducted with the cavity injector and n-heptane as a pure hydrocarbon without the additives of typical aviation-grade fuel blends. In close collaboration with the other project partners of the numerical simulation work packages, two stagnation temperatures were selected for the initial experiments: 900 K and 1200 K. During the test campaign it was found that 900 K is not a suitable boundary condition because only a short ignition during the air vitiator start-up could be achieved without any sustainable combustion (see Table 2). Thus, the experiments were focussed on the 1200 K stagnation temperature condition in combination with different stagnation pressures, hot gas mass flow rates and fuel mass flow rates. The 1200 K stagnation temperature test point provided sustainable ignition and combustion of the n-heptane fuel at most fuel mass flow rates (see Fig. 6).

Table 2. Selected n-heptane ramjet test conditions with sustainable combustion

Test Duration [s]	Stagnation Temperature [K]	Designated Stagnation Pressure [bar]	Hot Gas Mass Flow Rate [g/s]	Fuel Mass Flow Rate [g/s]	Combustion
5	1200	5	1140	1.18	Yes
5	1200	5	1140	1.22	Yes
5	1200	5	1140	1.26	Yes
5	1200	5	1140	1.58	Yes
5	1200	5	1140	1.62	Yes
5	1200	5	1140	1.64	Yes
5	1200	5	1140	1.81	No
5	900	7	1842	1.06	No
5	900	7	1842	1.12	No
5	900	7	1842	1.38	No
5	1200	7	1600	0.63	Yes
10	1200	7	1600	0.73	Yes
5	1200	7	1600	0.76	No
10	1200	7	1600	0.79	Yes
5	1200	7	1600	0.83	Yes
5	1200	7	1600	0.92	Yes
5	1200	7	1600	0.93	Yes
5	1200	7	1600	1.03	Yes
5	1200	7	1600	1.05	No
5	1200	7	1600	1.54	Yes
5	1200	7	1600	2.25	Yes
5	1200	7	1600	2.54	Yes
5	1200	7	1600	8.78	Yes
5	1200	7	1600	8.82	Yes
5	1200	7	1600	8.97	Yes
5	1200	9	2100	1.38	Yes
5	1200	9	2100	1.45	Yes
5	1200	9	2100	1.50	Yes
5	900	9	2368	1.54	Yes

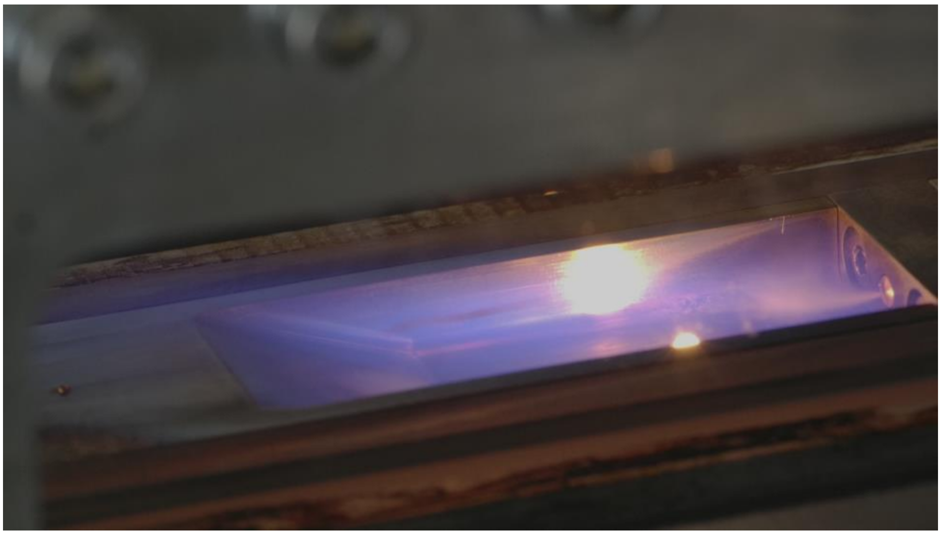

Fig 6. Combustion of n-heptane liquid fuel in cavity injector for More&Less project

4. Preliminary Results

During the experiments a detailed understanding of the limits of air to fuel mixtures and limits of ignitability was obtained. Some testing points showed self-sustaining combustion, others needed the constant help of a glowing plug as a heat source in order to push the limits of ignitability further.The initial design concept of the cavity injector featuring a removable and interchangeable ramp proved to be only an option for the run-in tests due to its limited heat resistance. The very sharp and thin leading edge of the ramp section was bent under the heat accumulation during combustion resulting in an intrusion of hot gases underneath the ramp part.

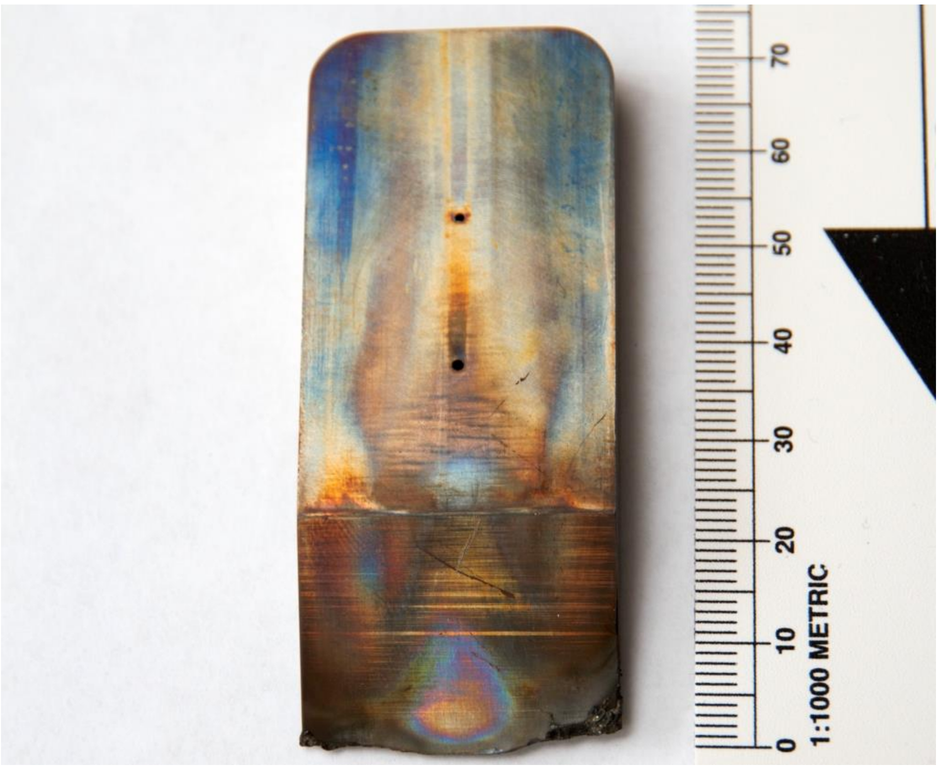

Fig 7. DLR cavity injector ramp with thermal damage at the leading edge

Especially the test runs with high fuel mass flow rate led to an increasing mechanical damage of the Inconel leading edge (see Fig. 7). The improved, integral design of the cavity injector turned out not to be prone to this issue and was used for the subsequent test campaigns.

For the emission measurements the sampling probe was positioned 0.416 m from the exit plane of the model combustion chamber. This position was determined in pre-test and found to provide a sufficient stagnation pressure to fill and pressurize the gas sample cylinders properly for further processing in the lab. If the stagnation pressure and thus the fill pressure of the gas sampling cylinders would be too low, the chemical lab might not able to run multiple gas chromatography runs or different analyses as required Additionally, this sampling position complies as close as possible with the ICAO requirements for in-situ emission measurements of regular turbo jet engines in [9], scaled down appropriately. In order to quantify the distribution of NOx within the exhaust gas plume, three different sampling probe positions were defined for detailed measurements. All positions were located in the middle plane of the combustion chamber without lateral extension. The first sample was drawn at the centreline of the combustion chamber, the second sampling position was initially deflected -70 mm (n-heptane) and then changed to -40 mm below the centreline (hydrogen). The third sample position was initially deflected +70 mm (n-heptane) and then changed to +20 mm above the centreline (hydrogen). It was determined in pre-tests that the exhaust plume is not fully symmetrical with a deflection angle to the bottom due to the combustion process and the introduced secondary flow. Thus, a sample pressure high enough for analysis could not be obtained at the upper side at a position deflected further than 20 mm from the centreline with hydrogen fuel.

Table 3. Selected NO_x emission measurements for hydrogen ramjet experiments

Stagnation Temperature [K]	Designated Stagnation Pressure [bar]	Hot Gas Mass Flow Rate [g/s]	Fuel Mass Flow Rate [g/s]	Sampling Probe Position	NO_x Mean Value [ppm]
1200	3	700	0.56	+20 mm	40
1200	3	700	0.56	0 mm	50
1200	3	700	0.56	- 40 mm	40
1200	3	700	1.50	+20 mm	50
1200	3	700	1.50	0 mm	45
1200	3	700	1.50	- 40 mm	40
1200	5	1140	0.56	+20 mm	80
1200	5	1140	0.56	0 mm	100
1200	5	1140	0.56	- 40 mm	55
1200	5	1140	1.50	+20 mm	90
1200	5	1140	1.50	0 mm	125
1200	5	1140	1.50	- 40 mm	55
1200	7	1600	0.56	+20 mm	170
1200	7	1600	0.56	0 mm	190
1200	7	1600	0.56	- 40 mm	125
1200	7	1600	1.50	+20 mm	140
1200	7	1600	1.50	0 mm	180
1200	7	1600	1.50	- 40 mm	110

The same applies for n-heptane, where only NO_x values could be obtained at the 70 mm positions. Table 3 shows selected emission measurements for different boundary conditions and hydrogen as a fuel. The results show a strong accumulation of NO_x emissions at the centreline of the exhaust plume.

The highest values were obtained at this position over the different boundary conditions except the 1200 K, 3 bar condition with 1.50 g/s fuel mass flow rate, where the maximum is located at the +20 mm position. With increasing hot gas mass flow rate, the NO_x emissions increase. This is caused by two effects: Firstly, the combustion process of the air vitiator consumes more hydrogen if a higher air mass flow rate needs to be heated up and secondly the intrusion depth of the hot gas main flow into the cavity increases with a higher stagnation pressure. An increased intrusion depth mixes more oxydator into the combustion and thus increases the combustion temperature. The same observation can be made if n-heptane is used as a fuel (see Table 4). For conditions with a similar fuel mass flow rate compared to the hydrogen case (1.40 g/s and 1.60 g/s n-heptane vs. 1.50 g/s hydrogen), the NOx emissions are slightly higher for n-heptane than for hydrogen. Despite the larger distance of the sampling points to the centreline compared to hydrogen, the values show the same asymmetricity of the exhaust plume. As for hydrogen, the deviance increases with an increasing stagnation pressure of the hot gas main flow. The highest NOx emission in the campaign so far was measured for 1200 K and 9 bar stagnation pressure with a fuel mass flow rate of 1.40 g/s.

Table 4. Selected NO_x emission measurements for n-heptane ramjet experiments

Stagnation Temperature [K]	**Designated Stagnation Pressure [bar]**	**Hot Gas Mass Flow Rate [g/s]**	**Fuel Mass Flow Rate [g/s]**	**Sampling Probe Position**	**NO_x Mean Value [ppm]**
1200	5	1140	1.20	+70 mm	30
1200	5	1140	1.20	0 mm	170
1200	5	1140	1.20	- 70 mm	25
1200	5	1140	1.60	+70 mm	30
1200	5	1140	1.60	0 mm	150
1200	5	1140	1.60	- 70 mm	25
1200	9	1140	1.40	+70 mm	110
1200	9	1140	1.40	0 mm	280
1200	9	1140	1.40	- 70 mm	75

5. Conclusions

DLR Lampoldshausen has modified its M11.1 chemical air vitiator test bench in order to conduct the hydrogen and hydrocarbon Ramjet test campaigns within the European project More&Less. The upgrades include the development of a cavity style injector which can use gaseous fuels such as hydrogen and liquid fuels such as hydrocarbons. For the required emission measurements, the bench is now equipped with a sophisticated gas sampling system, which can sample multiple gas samples per test run at different locations of the exhaust plume and simultaneously measure NO_x emissions. The first more than 100 hot test runs showed a good, sustainable combustion at some selected boundary conditions for hydrogen and the pure hydrocarbon n-heptane. Initial survivability issues connected with the cavity injector design could be solved during the test campaign. NO_x measurements of the exhaust plume show a higher concentration at the middle axis of the flow with a drop at the outer regions of the flow. Generally, the NO_x concentration above the exhaust flow's middle axis is higher than below it. The test runs enabled a large data base which helps to validate the numerical models within the project.

6. Outlook

Additional experiments with gaseous hydrogen and different hydrocarbons are performed at the moment in order to increase the already large data base for numerical simulation validation purposes. This includes further gas sampling of the vitiated air and the exhaust gases as well as NO_x measurements. For selected boundary conditions and sampling positions Smoke Number measurements are planned. Future publications will include detailed cross-analyses of the combustion data obtained. In the course of the project an extensive test campaign addressing bio-fuels / sustainable aviation fuels (SAF) will be conducted. This will help to collect unique data on Ramjet combustion processes and emissions using bio-fuels / SAF. Future publications are planned to include a detailed comparison between numerical simulation data and experimental data to gain a better understanding of the combustion and emission processes.

Acknowledgements

The work presented in this paper is funded by the Horizon 2020 Program of the European Commission under Grant Agreement GA-101006856. This support is greatly appreciated by the authors.

References

1. Sholto, F., Smart, M. K., Kearney, M. P., Jahn, I.: Flyback of the SPARTAN Scramjet-Powered Launch Vehicle. AIAA- American Institute of Aeronautics and Astronautics, AIAA 2018-2177 (2018). https://doi.org/10.2514/6.2018-2177
2. Kerst, A., Gross, K. C., Oren, E. P., Komives, J. R., Rhoby, M., Ombrello, T.: Preliminary Investigation of a Scramjet Flowfield with Hyperspectral Imaging. AIAA- American Institute of Aeronautics and Astronautics, AIAA 2017-4646 (2017). https://doi.org/10.2514/6.2017-4646
3. Speier, R., Nacouzi, G., Lee, C., Moore, R.: Hypersonic Missile Nonproliferation - Hindering the Spread of a New Class of Weapons. RAND Corporation, RR-2237-CC (2017). https://doi.org/10.7249/RR2137
4. Strauss, F., General, S., Manfletti, C., Schlechtriem, S.: Flow Visualizations with Background Oriented Schlieren in a Transpiration-Cooled Model Scramjet Combustor. Int. J. of Energetic Mat. and Chem. Prop. 18(2), 133-155 (2019). https://doi.org/10.1615/IntJEnergeticMaterialsChemProp.2019028003
5. Strauss, F., Manfletti, C., Lieberwirth, R. and Schlechtriem, S.: Experimental Setup on Transpiration Cooling in Supersonic Combustion Ramjets (Scramjets). 5th Space Propulsion Conference, 2nd to 6th May 2016, Rome, Italy, (2016).
6. Strauss, F., Manfletti, C., Freudenmann, D., Witte, J., Schlechtriem, S.: Preliminary Experiments on Transpiration Cooling in Ramjets and Scramjets. AIAA- American Institute of Aeronautics and Astronautics, AIAA 2016-4968 (2016). https://doi.org/10.2514/6.2016-4968
7. Strauss, F., General, S., Cragg, P., Schlechtriem, S.: Wall Pressure Stability and Cooling Efficiency Analysis in a Transpiration-Cooled Scramjet Model Combustor. HiSST:2nd International Conference on High-Speed Vehicle Science Technology, 11-15 September 2022, Bruges, Belgium. HiSST-2022-0007 (2022)
8. Settles, G. S., Hargather, M.: A Review of Recent Developments in Schlieren and Shadowgraph Techniques. Meas. Science and Techn. 28, 042001 (2017). https://doi.org/10.1088/1361-6501/aa5748
9. International Civil Aviation Organization (ICAO): Annex 16 to the Convention of International Civil Aviation, Environmental Protection, Volume II - Aircraft Engine Emissions, Fourth Edition. (2017). ISBN 978-92-9258-314-9.