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THE LAST ACHIEVEMENTS IN THE DEVELOPMENT OF A ROCKET GRADE HYDROGEN PEROXIDE CATALYST CHAMBER WITH FLOW CAPACITY OF 1 KG/S

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ABSTRACT

Worldwide, the hybrid rocket propulsion technology gained in importance recently. A new innovative hybrid rocket engine concept is developed at the German Aerospace Center (DLR) within the program "AHRES". This rocket engine is based on hydroxyl-terminated polybutadiene with metallic additives as solid fuel and rocket grade hydrogen peroxide (high test peroxide: HTP) as liquid oxidiser. Instead of a conventional ignition system, a catalyst chamber with a silver mesh catalyst is designed, to decompose the HTP to steam and oxygen at high temperatures up to 615 °C. The newly modified catalyst chamber is able to decompose up to 1.3 kg/s of 87,5% HTP. Used as a monopropellant thruster, this equals an average thrust of 1600 N.

The catalyst chamber consists of the catalyst itself, a mount for the catalyst material, a retainer, an injector manifold and a casing. Furthermore, a pressure sensor, a mass flow sensor and a thermocouple can be attached to measure the properties of the decomposition products. With the described catalyst chamber a number of tests under steady conditions are carried out using 87.5 %wt hydrogen peroxide with different flow rates and constant amount of catalyst material. The chamber is mounted on a test-bed, which comprises attachment, peroxide storage, feed system, valves, data acquisition and control. By determination of the decomposition temperature the integrity of decomposition is verified and compared to theoretical prediction.

The catalyst chamber is designed using the self-developed software tool SHAKIRA. A short description of the tool features is given. The applied kinetic law which determines catalytic decomposition of HTP within the catalytic chamber is also given and commented. Several calculations are carried out to determine the appropriate geometry for complete decomposition with a minimum of catalyst material. The experimental results show good agreement with the results generated by the design tool.

The developed catalyst chamber provides a simple, reliable ignition system for hybrid rocket propulsion systems based on hydrogen peroxide as oxidiser. The system is capable for multiple re-ignitions without the need to meet an optimal ignition point. Such a system behaves like a hypergolic engine in terms of ignition, but no hazardous substances are required. The developed hardware and software can be used to design full scale monopropellant thrusters based on HTP and catalyst chambers for hybrid rocket engines. Both concepts are under considerations within DLR.

ABBREVIATIONS

AHRES	Advanced Hybrid Rocket Engine Simulation
H_2O	Water
H_2O_2	Hydrogen peroxide
O_2	Oxygen
HRE	Hybrid Rocket Engine
HTPB	Hydroxyl-terminated Polybutadiene
HTP	High Test Peroxide
LRE	Liquid rocket engine
NTO	Dinitrogen Tetraoxide (N_2O_4)
SHAKIRA	**S**imulation of **H**igh test peroxide **A**dvanced (**K**)Catalytic **I**gnition system for **R**ocket **A**pplications

NOMENCLATURE

Symbols (Latin)

c_p	J/(kg K)	Specific heat capacity at constant pressure
c_v	J/(kg K)	Specific heat capacity at constant volume
c^*	m/s	Characteristic velocity
$\dot{m}$	kg/s	Mass flow
p_c	bar	Pressure inside the catalyst chamber
R_i	J/(kg K)	Specific gas constant
T	K	Temperature

Symbols (Greek)

Γ	-	Vandenkerckhove function
Δp	bar	Pressure drop
ΔT	K	Temperature difference
$\eta_{\Delta T}$	-	Temperature efficiency
η_{c^*}	-	Characteristic velocity efficiency
κ	-	Heat capacity ratio
τ	-	Process time interval

Subscripts

ad	=	adiabatic
CB	=	catalyst bed
env	=	environmental
exp	=	experimental value
FL	=	feed line
mean	=	average value
max	=	maximum value
theo	=	theoretical value

I. INTRODUCTION

In the last 15 years a number of companies, research institutions, and universities worldwide have investigated catalytic and combustion properties of HTP and applied it to different rocket propulsion systems (e.g. Rocketdyne (USA), NASA – J. Stennis (USA), Purdue University – W. Lafayette (IN, USA), General Kinetics (CA, USA), Herakles – Safran (F), ONERA (F), DLR – AS Braunschweig (D); ALTA S.p.A., Pisa (I), University Road - Southampton (UK), Defence Agency for Technology - Seoul, (South Korea), and a number of universities and research institutions in China). Rocket engines based on HTP as oxidizer can be used for satellite propulsion (in mono- or liquid bi-propellant systems), as a thruster for LRE launcher booster and HRE/LRE upper stages, moon landers, sounding rockets, rocket airplanes for space tourism or for investigation of the upper Earth atmosphere layers. One additional HTP application recently investigated by several institutions in last time is a catalytic HTP ignition system for LRE and HRE, which represents a cheap and reliable solution. The use of HTP for hybrid rocket engines [16] has several positive aspects:

- A separate ignition system is not necessary,
- the structure/propellant mass ratio is lower than for other propellant mixtures,
- the regression rate of the solid fuel grain is higher compared to large number of known propellant mixtures, which enables higher thrust,
- the throttling of the engine can be efficiently realised by mass flow control of the HTP oxidizer,
- the specific impulse for 92% HTP based propellant mixtures are equal or superior to corresponding mixtures with NTO and only 8% lower than for corresponding mixtures with oxygen.
- By observing the basic rules of handling and HTP compliant design rules, the risk of fire, explosion, or personal injuries is lower than for other high energy propellant combinations.

These arguments delivered the basics for the start of the DLR program “AHRES”. This program also includes development and tests with a hybrid rocket engine demonstrator, based on hydroxyl-terminated polybutadiene with metallic additives as solid fuel and high concentrated hydrogen peroxide (HTP) as liquid oxidiser [16]. Instead of a conventional ignition system, a catalyst chamber with a silver mesh catalyst is designed to decompose the HTP to steam and oxygen at a very high temperature. The catalyst chamber is able to decompose currently up to 1.1 kg/s of 87.5% HTP. Used as a monopropellant thruster, this results in a theoretical thrust of 1605 N at sea level. The preliminary test results achieved with this catalyst chamber are presented in this paper.

With the self-developed DLR simulation code SHAKIRA the design of a catalyst chamber for decomposing HTP is carried out. The effective length of the designed catalyst chamber is 0.13 m. In Figure 1, the mass fraction of H_2O_2 vs. the distance from the inlet for a mass flow of 0.7 kg/s, 1.0 kg/s and 1.3 kg/s is plotted. The simulation shows clearly that a higher HTP mass flow up to 1.3 kg/s could be completely decomposed within the designed catalyst chamber. In the current project step, the capacity of 1,1 kg/s is tested and used. In the forthcoming project steps the maximum catalyst chamber capacity will be also tested.

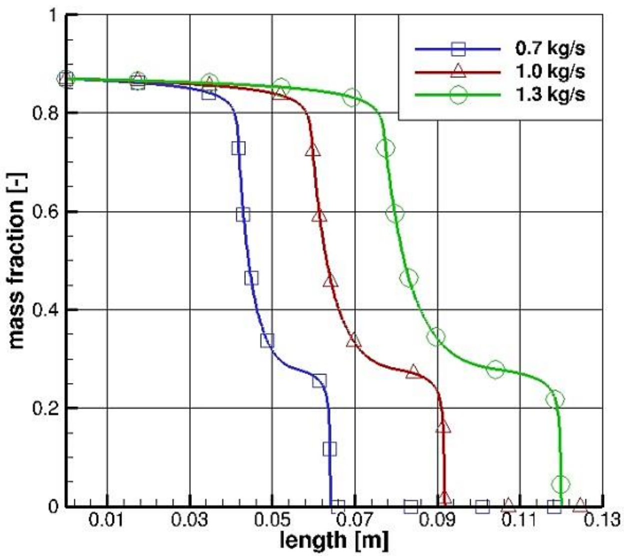

Figure 1: Mass fractions of H_2O_2 vs length for different mass flows

II. CONSTRUCTED CATALYST CHAMBER

Within the AHRES program the developed catalytic chamber is a modular robust solution which enables tests with different catalyst bed solutions for high HTP chamber pressures up to 70 bars. The presented design is primarily intended as pre-heated steam/gas generator with the aim to supply the discussed hybrid rocket engine demonstrator with gasified oxidizer and to enable multiple ignition of the engine without a separate ignition system. The established and proved catalyst chamber solution could also be upgraded to a HTP mono-propellant thruster for different purposes, with moderate effort [10], [11], [13].

The catalyst chamber housing is made out of Inconel 718 alloy to meet all future investigation requirements, which is rated for HTP concentrations up to 98 %wt. At the left and right ends of the housing, flange connectors are incorporated (Fig. 2) to enable a good sealing and more security for repeated connection/ disconnection of design elements as is common during research activities. On the oxidiser inlet side (in direction of the HTP feeding line) a flat sealing gasket, made out of Teflon based plastic, is mounted. To reduce the number of connection elements, which again reduces the security risks through bad sealing under dynamic operational conditions, the catalyst chamber is designed as monoblock construction with an injector in form of truncated cone for the HRE combustion chamber. The catalyst mount, formed as cylindrical tube with an inner diameter of 100 mm, is inserted into the casing. It serves as mechanical protection for the catalyst bed. The catalyst bed consists of high purity silver meshes. Depending on the required HTP mass flow, up to 200 silver screens can be embedded within the catalyst mount. In current tests up to 172 catalyst silver screens were used. To prevent mesh deformation or break-up due to pressure pulses on the upper side (flow feeding side), a distribution plate is attached. On the bottom side, a support plate with a large number of holes is installed.

Between the catalyst mounting and the catalyst chamber housing is a cylindrical gap. During the tests this gap contributes to the reduction of heat transfer to the housing. This reduces the ramp-up time until steady state working conditions are reached. The implemented design enables flexible handling with catalyst beds composed of heterogeneous structures or different catalyst materials. This is especially attractive for HTP applications with concentrations higher than 87.5%wt.

tank by means of a volumetric dosing pump. On the second lateral connection, a multi-branched manifold (pipe crossing) is mounted to connect one further solenoid valve for pressure discharge (V5), one mechanical ball valve for manual emergency pressure blow off (V12), as well as one solenoid valve for tank pressurization with nitrogen up to 100 bar (V3). The necessary nitrogen flow of 0.33 m_n^3/s for the tank supply is assured using a battery of nitrogen bottles with 300 bars. The system pressure can be adjusted by means of a dome pressure regulator and a pressure controller.

On the third lateral tank connection one further solenoid valve (V7) is attached, which enables flushing and purging of the tank and the feed system with high purity water before and after the tests. The permanent supply of filtered high purity water (on demand) is assured by one ion exchanger attached on the fourth lateral tank connector. The ion exchanger is connected to the water supply grid. The manually controlled ball valve (V13) allows the extraction of high purity water for

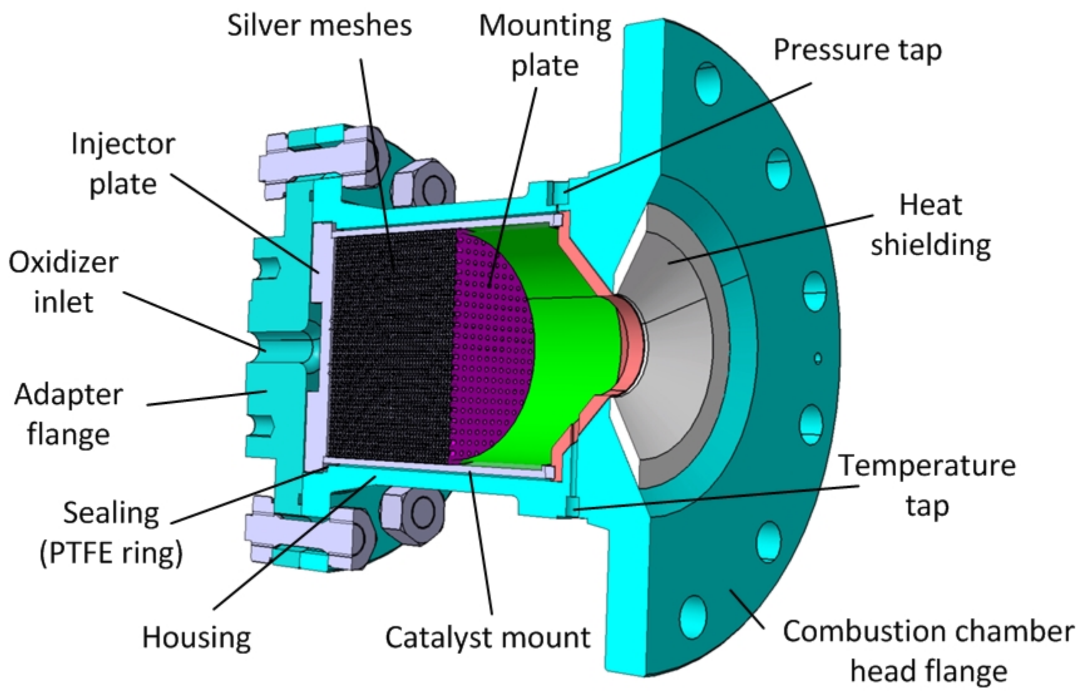

Figure 2: Catalytic chamber for the AHRES hybrid rocket engine

III. DESCRIPTION OF THE FEED SYSTEM

The main part of pressure feeding system of the oxidiser HTP is the high-pressure tank (s. Fig. 3). It is mounted on a stainless steel plate equipped with four force sensors, which enables the measurement of instantaneous HTP filling weight. As a redundant system, the filling level can be determined by means of an ultrasonic probe mounted at the base of the pressure vessel. The HTP tank is equipped with six flange connectors: four on the lateral side and one each on the top cover plate and the bottom tank side.

On one of the lateral connection a solenoid valve (V9) is attached, which in the open state allows the charging of the cleaning of the transport canister, the catalyst chamber and the hybrid rocket engine parts after the tests. On the fourth flange connector, a T-fitting is fixed for housing two thermocouples and one pressure sensor for the supervision of the HTP pressure vessel. An excess pressure valve is attached on the tank cover plate, which opens at pressures higher than 120 bars to prevent tank from bursting. Safety tests show that the tank can withstand pressure loads up to 180 bars without stress or deformation overloads. The tank base includes the operation port for HTP extraction. On the port flange a T-fitting is mounted, which enables attachment of a manually controlled discharge valve (V11) and a solenoid valve (V1) which permits HTP feeding in open state in direction of the catalyst chamber. In emergency cases, the discharge valve (V11) enables the HTP to be directed over one specially designed high-pressure discharge nozzle (D1) in the dump basin.

At the main pipeline for HTP feeding between the valve (V1) and the catalyst chamber several control elements and measurement sensors and instruments are attached. Behind the valve (V1) in the pipeline a pneumatically driven control valve (V10), a Coriolis flow meter, a check valve (V15), and a 3/2-way valve (V2) are installed. The combination of the control valve (V10) and the Coriolis sensor enable a precision HTP flow setting.

The check valve (V15) prevents pressure shock spreading from the catalyst/engine chamber in the direction of the feed line and tank. Between the valves (V15) and (V2) a T-fitting is attached. On its third free connection a solenoid valve (V4) is installed. In the open state the valve (V4) enables feeding nitrogen with a pressure of 50 bar into the catalyst or engine chamber, and thus drying or clean-up of catalytic chamber or extinction of the HRE combustion chamber (if attached).

After completion of the test the valve (V2) guides the flow in the direction of the dump basin. This enables the system to be cleaned of accumulated waste HTP. The spraying of HTP in the dump basin is prevented by a discharge nozzle (D1). All solenoid valves, which are in direct contact to the HTP, are of the coaxial type.

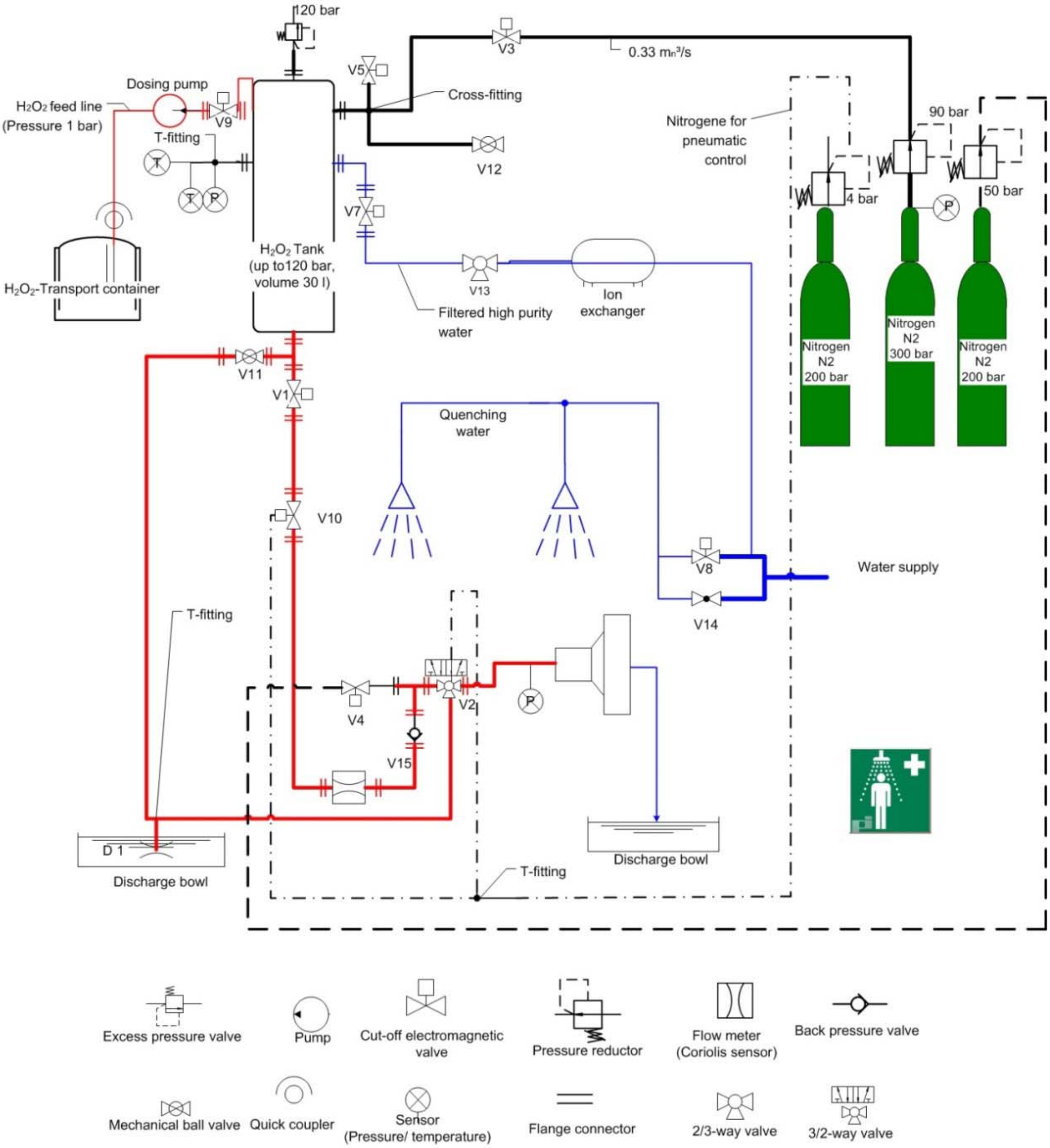

Figure 3: H_2O_2 – Flowchart (HRE Test bed)

IV. APPLIED MEASUREMENT TECHNIQUE

Two pressure sensors are connected in the oxidizer feed line, one in front of the catalytic chamber and one at the catalytic chamber housing – in front of catalyst injector (s. Fig. 4). The difference of these two pressure values equals the pressure loss across the catalyst chamber. Both pressure sensors (KTE6000), delivered from "Sensortechnics", are of the membrane type and have a measurement range of 0-150 bar and 0-100 bar respectively. On the back side of the catalyst bed and in front of the chamber injector a shielded thermocouple of type N with a measurement range of 1200°C is attached. Despite of the fact that the catalytic chamber has no classic convergent-divergent nozzle, but rather a truncated subsonic cone on the exit, it was possible to measure the thrust force on the test bed. With a system of four photo and video cameras, the form and length of the exhaust steam/oxygen jet is optically registered. The concentration of hydrogen peroxide vapour in the ambient air is measured with a HTP gas detector of type Dräger X-am 5100 with the sensor XS H_2O_2 for a measurement range of 0-20ppm. Concentration of liquid HTP is controlled indirectly by density measurement. The temperature of liquid HTP before inflow in the catalyst chamber is also measured with type J thermocouple. The HTP mass flow measurement is realized with a Coriolis flow meter OPTIMASS 8000 obtained from KROHNE (measurement range 0 – 1.5 kg/s HTP).

Trauen (s. Fig. 5) in July 2013. Five experiments were successfully conducted and post-analysis and evaluation was done. Emission of HTP vapour outside the catalyst chamber during all experiments was not observed and it can be concluded that the decomposition process was finished.

Evaluation of the HTP catalyst chamber efficiency is carried out by means of the characteristic velocity efficiency η_{c^*} and the temperature efficiency $\eta_{\Delta T}$. The characteristic velocity efficiency η_{c^*} is an important criterion for estimating the energetic efficiency of the catalytic chamber. It can be given with the following expression:

$$\eta_{c^*} = \frac{c^*_{exp}}{c^*_{theo}} \quad (1)$$

The experimental value of characteristic velocity c^*_{exp} is determined with the expression:

$$c^*_{exp} = \frac{\sqrt{R_i \cdot T_{exp}}}{\Gamma} \quad (2)$$

In equation (3) T_{exp} is the measured temperature of the decomposed gas mixture behind the catalyst bed in the catalyst chamber. In gas dynamic theory, the value Γ is known as the Vandenkerckhove function:

$$\Gamma = \sqrt{\kappa}\left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2(\kappa-1)}} \quad (3)$$

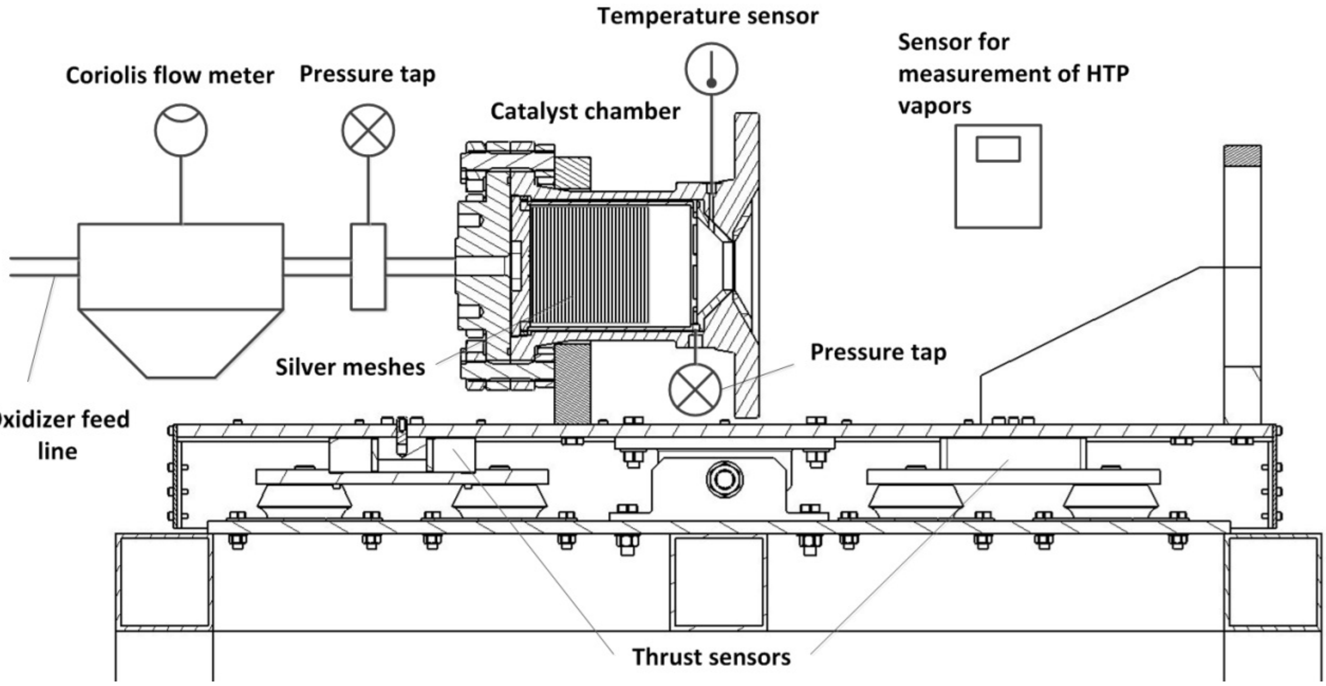

Figure 4: Arrangement for the testing of the HTP catalytic chamber

V. PRELIMINARY TEST RESULTS

The presented preliminary results were attained during a measurement campaign carried out at the DLR test range

The catalyst bed is well isolated from the housing by means of a gap between the housing and the catalyst mount (s. Fig. 2). Due to this fact, the polytrophic constant $n = (c_p/c_v)_{diabatic}$ in the first approximation can be taken as equal to the ratio κ and can be used for calculation of expressions (3) and (4). The alternative calculation of c^*_{exp} using the equation

$$c^*_{exp} = p_{c,exp} \cdot A_t/\dot{m}_{exp} \qquad (4)$$

is not suitable, because the applied catalyst chamber has no convergent-divergent nozzle on the exit, as it is usual for monopropellant HTP rocket engines. The flow conditions within the catalyst chamber in vicinity of measurement sensors do not correspond well with the throat conditions in a nozzle.

Figure 5: Test facility for hybrid rocket engines at DLR Trauen, Fassberg, Germany

The theoretical values of decomposition temperature T_{ad} and c^*_{theo} are determined with the Gordon-McBride CEA2 Thermochemistry code [17]. In the code, the relationships between named variables are also based on the formulation:

$$c^*_{theo} = \frac{\sqrt{R_i \cdot T_{ad}}}{\Gamma} \qquad (5)$$

For the HTP PROPULSE 875 (Evonik, Deutschland) with a H_2O_2 concentration of 87.5 %wt, the adiabatic decomposition temperature is T_{ad} = 968.46 K and the theoretical characteristic velocity is c^*_{theo}=913 m/s. With the CEA code, the calculated values for T_{ad} and c^*_{theo} do not show any change with pressure increase, but in reality discrepancies of few percent, dependent of pressure level in the chamber, are possible [18]. The measured temperature T_{exp}, as well as the corresponding value c^*_{exp} are lower (s. Table 1) than the calculated theoretical values. This can be explained with the losses due to the cooling in the injector and the chamber head area downstream the catalyst bed and the discrepancy between ideal 1D-expansion/real expansion of decomposed gas products in the convergent injector cone.

One additional indicator for estimating the efficiency of the catalytic chamber is the temperature efficiency

$$\eta_{\Delta T} = \frac{T_{exp} - T_{env}}{T_{ad} - T_{env}} \qquad (6)$$

The two further important operational criteria for characterisation of a catalytic chamber are the pressure drop across the catalyst bed Δp_{CB} and the total pressure drop across the feed line Δp_{FL} (between oxidizer tank and injector on HRE combustor head). They have important influence on decomposition process stability and structure weight (catalyst chamber and whole oxidizer feeding system).

The results of the measured efficiency criterions are given in table 1. The mean temperature efficiency $\eta_{\Delta T,\ mean}$ is in the range of 79,5 to 93,6%. Maximum temperature efficiency $\eta_{\Delta T,\ mean}$ is in the range of 82,72 to 94%. During all tests, the mean characteristic velocity efficiency $\eta_{c*,mean}$ exceeds 92% and maximum characteristic velocity efficiency $\eta_{c*,\ max}$ (%) is in the vicinity of 98%. All these parameters are realized by a mass flow load of the catalyst chamber in the range between 54 and 78% of the designed capacity. The conducted tests and analysis indicate that for high loads of the catalyst chamber with a HTP mass flow in vicinity of 1.0 kg/s the process shows good efficiency.

Table 1: Estimated efficiency of the catalyst chamber during carried tests

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Mass flow – measured $\dot{m}_{exp}$ [kg/s]	0,702	0,745	1,037	1,01	0,994
Process time τ [s]	6,6	10,8	5,4	3,5	3,2
Mean char. velocity $c^*_{exp,mean}$ [m/s]	845,93	870,16	894,45	858,41	879,89
Max char. velocity $c^*_{exp,max}$ [m/s]	894,74	895,78	895,23	858,41	879,89
Chamber pressure p_c [bar]	4,82	5,24	7,51	7,64	7,46
Mean temperature efficiency $\eta_{\Delta T,\ mean}$ [%]	79,05	86,22	93,61	82,72	89,15
Max. temperature efficiency $\eta_{\Delta T,max}$ [%]	93,74	94,01	93,88	82,72	89,15
Mean char. vel. efficiency $\eta_{c*,\ mean}$ [%]	92,46	95,1	97,76	93,82	96,17
Max. char. vel. efficiency $\eta_{c*,max}$ [%]	97,81	97,9	97,85	93,82	96,17
Total pressure drop across the catalyst bed Δp_{CB} [bar]	7,45 5,5	9,63 6,52	12,9	13,16	12,64
Pressure drop across feed line Δp_{FL} [bar]	85 88,6	81,4 86,8	76,7	76,18	77

The reported tests with the catalyst chamber are carried out in the transient and steady regime. By application of relatively high HTP mass flows, the transition from start point to steady state need a period of up to 4 s. The same transition time is necessary to shut off the process from the moment when the control valve is closed. This is a consequence of accumulated HTP mass within the catalyst bed which must be exhausted. The maximum mass flow achieved in the presented test results (s. Fig. 6 to 10) is an indicator for possible steady state flow. This conclusion should be confirmed by forthcoming long duration steady state tests with test times up to 30 s. The mean values of efficiency criteria during test 1 and test 4 are more representative for the catalyst chamber under transient working conditions. Tests 2, 3 and 5 could be regarded as quasi steady.

The properties of the exhaust jets (s. Figures 11 and 12) are dependent on the mass flow value. At lower mass flows (generally under 120 g/s) exhaust jets cool faster and saturated water steam will be generated. That makes the jet clearly visible and non-transparent. For higher mass flows, the exhaust jet comprises sufficient energy to deliver water steam in overheated condition and the jet remains transparent and rarely visible. During tests in mass flow range between 700 and 1037 g/s the jet is fully transparent.

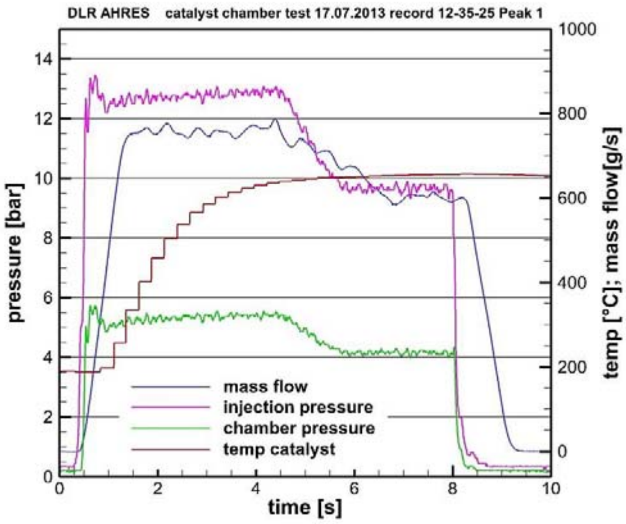

Figure 6: H_2O_2 catalytic chamber test 1 (peak 1) with main mass flow 702.4 g/s

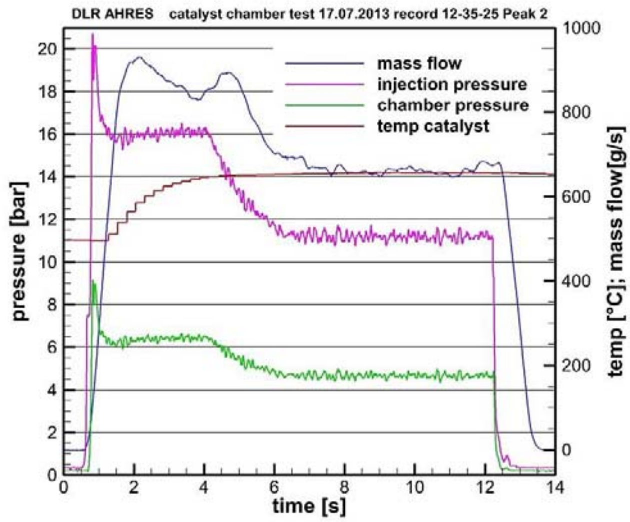

Figure 7: H_2O_2 catalytic chamber test 2 (peak 2) with main mass flow 745.2 g/s

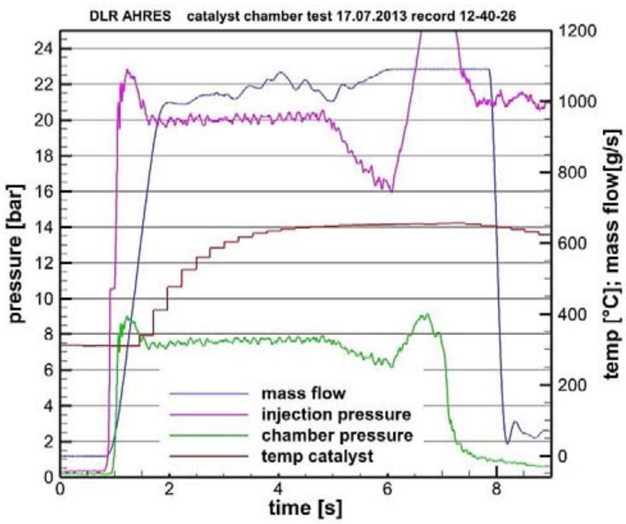

Figure 8: H_2O_2 catalytic chamber test 3 with main mass flow 1037 g/s

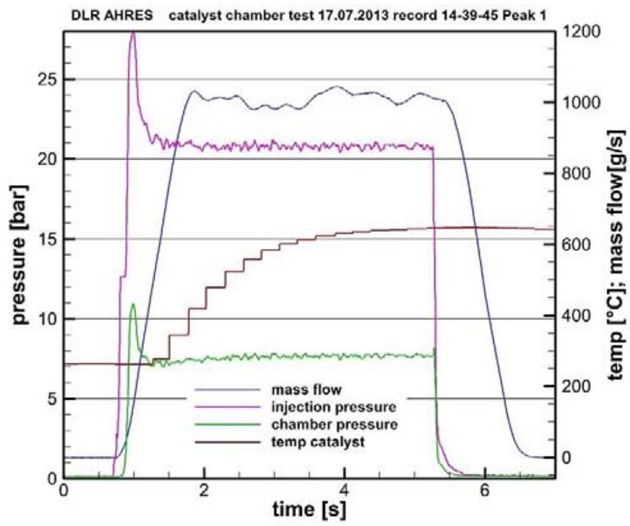

Figure 9: H_2O_2 catalytic chamber test 4 with main mass flow 1010 g/s

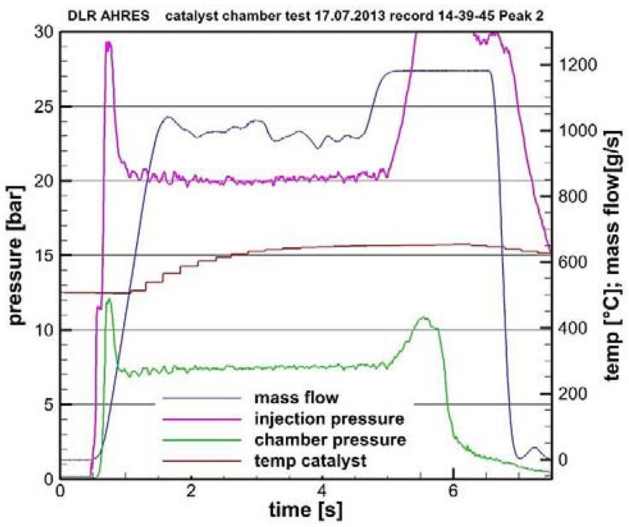

Figure 10: H_2O_2 catalytic chamber test 5 with main mass flow 993.83 g/s

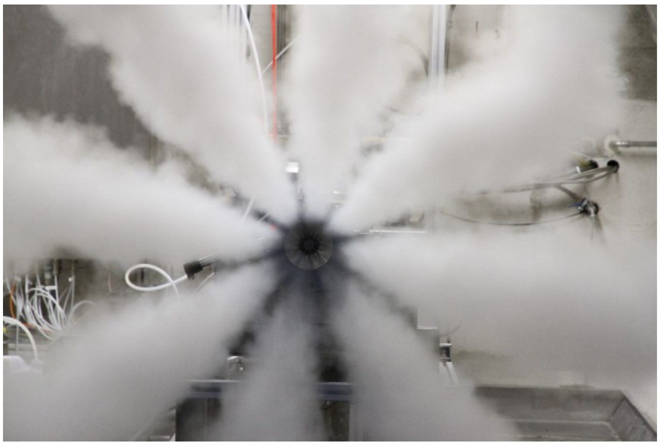

Figure 11: Test with HTP catalyst chamber carried out in March 2013 (mass flow 120 g/s)

Figure 12: Test with HTP catalyst chamber carried out in July 2013 (mass flow 745 g/s)

The diagrams on Figures 6 to 10 and table 2 show the appearance of low-frequency instabilities with frequencies between 8.8 and 13.6 Hz and amplitudes between 0.4 and 1.3 bar during the tests. The measured amplitudes are low and can be regarded more as hydraulic roughness than as instabilities. The driving force due to coupling between feed system and vaporisation delay also has some influence on instabilities during decomposition in the catalyst chamber. The degree of influence due to this coupling cannot be estimated without further and more detailed tests.

Table 2: Properties of low frequency instabilities within catalyst chamber during tests

	Test 1	**Test 2**	**Test 3**	**Test 4**	**Test 5**
Mass flow – measured $\dot{m}_{exp}$ [kg/s]	0,702	0,745	1,037	1,01	0,994
Chamber pressure p_c [bar]	4,82	5,24	7,51	7,64	7,46
Frequency [Hz]	8,79	6,76	8,51	10,86	13,64
Total Amplitude [bar]	0,3815	0,6378	1,31	0,38	0,57
Positive Amplitude [bar]	0,1299	0,3113	1,5677	0,0144	0,1931
Negative Amplitude [bar]	0,2516	0,3265	n/a	0,3731	0,3837

VI. CONCLUSIONS

The conducted tests confirm the design functionality and flexibility of the catalyst chamber. Also, design requirements (e.g. HTP steady mass flow up to 1000 g/s, complete decomposition of HTP to water steam and oxygen without remaining hydrogen peroxide vapors, ignition temperature for HTPB exceeded) are achieved. An activated silver mesh catalyst pack operates well with HTP PROPULSE 875. The decomposition temperature was approx. 300 °C below the melting point of silver. Furthermore, silver is cheap compared to platinum and is known for good commercial availability.

In this paper the preliminary results of a test campaign carried out in summer 2013 are presented, with the goal to estimate the properties and the thermal efficiency of the catalyst chamber for a HRE developed within the DLR AHRES research program. Further tests with higher mass flow up to 1200 g/s under steady conditions are in preparation. The instabilities within catalyst chamber and HRE combustion chamber observed in earlier tests carried in March 2013 are eliminated successfully due to modification of chamber construction. The achieved characteristic velocity efficiency is satisfying, but it is expected that it will rise under steady-state working conditions.

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