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INTERNATIONAL COOPERATION ON HYDROGEN/OXYGEN HIGH PRESSURE COMBUSTION

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Abstract

DLR and DASA of Germany as well as CNES and SEP of France have decided to collaborate on oxygen/hydrogen high-pressure combustion. In order to promote and intensify a common program the novel research and test facility P8 for LO_2/GH_2 high-pressure rocket combustors is presently being built at the DLR in Lampoldshausen. It provides for combustion chamber pressures up to 30 MPa at a maximum total propellant mass flow rate of 9.5 kg/s. The P8 test bench will be jointly financed, operated and utilized. The paper describes the design of P8, its instrumentation and combustion diagnostics as well as the organization of this international cooperation. Finally, the currently planned research program on high-pressure combustion will be discussed.

Introduction

Development costs of future LO_2/LH_2 rocket engines can be reduced if powerful computer codes are available which describe the flow and combustion phenomena of appropriate oxygen/hydrogen rocket combustors. Another important aim in the field of rocket combustor technology is to increase engine performance by utilizing improved turbopump cycles such as advanced expander and staged combustion cycles. These closed cycles require higher combustion pressures. A detailed understanding of the physical processes involved in such combustors is necessary and calls for suitable experimental investigations. To broaden the basic knowledge of corresponding physical phenomena such as liquid jet break-up, propellant mixing, vaporization, combustion as well as heat and mass transfer an important research program on cryogenic LO_2/GH_2 combustion in rocket engines was undertaken in France, several years ago, by SEP and CNES in collaboration with CNRS and ONERA[1]. Within this framework numerous studies (numerical, theoretical and experimental) have already been performed in various laboratories. Furthermore, since the beginning of this year a small cryogenic test facility named MASCOTTE is at the disposal of the French scientific community at ONERA. This test facility allows the study of LO_2/GH_2 combustion at low and medium pressures ($\leq$ 1 MPa) for reduced mass flow rates ($\leq$ 0.1 kg/s).

The original intension of this research program was to build a rocket combustor test bench for elevated combustion pressures, called BCRT (Banc Combustion Recherche Technologie) at Vernon, France.

DLR, DASA and some German universities have focussed their interests on a similar research program. It was proposed in 1991 for funding to DARA, the German Agency for Space Affairs. Only recently, DARA has initiated a compound program on cryogenic combustor modelling. In 1991 the DLR put in operation its LO_2/GH_2 Micro Combustor Test Facility (MCTF) for combustion investigations up to 2 MPa. The DLR intended to intensify its research acitivities by building the P8 test bench for LO_2/GH_2 high-pressure combustion supported by funds from the State Government of Baden-Württemberg as well as by the Federal Ministry of Research and Technology.

Since the performance data for P8 covers most of the BCRT features, the DLR, SEP, CNES and DASA finally concluded to jointly design, build and operate the P8 test bench at the DLR research center in Lampoldshausen. P8 will be a complementary test facility allowing the study of combustion mechanisms at more realistic conditions and, in particular, at high pressures. The other interest for CNES, DASA and SEP in this new facility lies in its capacity to evaluate new concepts of combustion devices.

Organization of International Cooperation on P8 Test Bench

DLR, CNES, SEP and DASA have decided to cooperate in the field of hydrogen/oxygen high-pressure combustion. For this purpose the high-pressure rocket combustor test facility P8 will be jointly designed, operated and utilized. The international cooperation on the P8 test bench is based on a memorandum of understanding (MOU) which was signed on December 18, 1992 by DLR, CNES, SEP and DASA. The object of the MOU is to fix the responsibilities of its partners, the organization for controlling the construction, operation and utilization of the test bench, the cost sharing and other general contractual settlements.

For the construction phase a steering committee was formed comprising six members from DLR (2), CNES (2), SEP and DASA which confirms the project manager, checks the progress of work, accepts the detailed specifications and confirms the acceptance tests for the test bench. The project management which is devided into the sub tasks: civil work, fluid system, MCC, project control and quality assurance reports to the steering committee. For the operation phase a similar steering committee will have the following functions: approval of the annual financial plan and the annual experimental research program carried out on P8, as well as checking and approval of expenses for operation and maintenance. A scientific committee will be formed comprising three members each from DLR and CNES as well as two members each from DASA and SEP. The tasks of the scientific committee are the elaboration of a joint research program and a test program carried out at P8 for the following year.

The total calculated costs of the P8 test bench amount to 18 million DM. The investment costs are shared by the partners. For construction of P8 and an additional laboratory being built adjacent to P8, the DLR is supported with 10 million DM each from the State Government of Baden-Württemberg and the Federal Ministry of Research and Technology.

Time Schedule For Construction & Operation of P8

The project is divided into four phases:

Phase A: Basic Engineering

The purpose was to prepare a preliminary design file. It was finished on March 17, 1993 by the preliminary design review (PDR).

Phase B: Detailed Engineering

This phase includes the preparation of a detailed design file which finalizes the design of P8 according to the accepted requirements of PDR, prepares the build-up phase with calls for tender, and relevant associated technical specifications as well as elaborates a development schedule and cost estimation. Phase B has been accomplished with the critical design review (CDR) on July 27, 1993.

Phase C: Tender Specification and Bid Evaluation

Phase D: Procurement, Construction, Installation & Acceptance

This phase comprises procurement, fabrication, assembly, factory acceptance, delivery on site, integration and site acceptance. These activities will be followed by system acceptance stage R1 scheduled for February 1995 and R2 which will be accomplished in April of 1995. P8 will then be available for operation.

Relevant Parameters for LO_2/GH_2 HP Combustion Investigations

Presently the "Vulcain" LO_2/LH_2 rocket engine is being developed by the European Space Agency. To reduce technical risks as well as to achieve reasonable development costs, a gas generator turbopump cycle was selected featuring 10 MPa as the combustion chamber pressure and 5.1 as the overall oxidizer/fuel mixture ratio[2]. Several publications such as Ref. 3-7 have pointed out that payload capability of rocket propulsion systems can be increased significantly if (1) open turbopump cycles are replaced by closed cycles and (2) the combustion chamber pressure is raised.

For orbital transfer vehicles the expander cycle is a promising candidate if the combustion chamber pressure is raised from presently 3 MPa (as realized in the RL 10 motor) to 10 MPa or even higher. This can only be accomplished if the heat transfer rate from the combustion gas to the cryogenic hydrogen coolant is intensified and cryogenic oxygen is used as an additional coolant.

For very high-performance demands the staged combustion cycle is a suitable choice. In this case the combustion chamber pressure can be raised by increasing the turbine inlet temperature as well as preburner pressure and by reducing pressure losses in the cooling system. The latter can be achieved if the regenerative cooling is partly replaced by transpiration cooling[8].

For investigations of combustion related effects on propulsion performance, wide ranges of operating parameters should be considered. These include main combustion chamber pressures between 5 MPa and 27 MPa as well as oxidizer/fuel mixture ratios between 4 and 8. For experiments related to preburners the operating ranges of interest comprise preburner chamber pressures between 10 MPa and 50 MPa and mixture ratios between 0.5 and 1.0 for fuel-rich as well as from 60 to 100 for oxidizer-rich preburners, respectively.

Design of P8 Test Bench

The P8 high-pressure rocket test bench is being built at the northwestern edge of the DLR Research & Test Center in Lampoldshausen. The location was selected to ensure free access and operation of the test bench independent of the test program carried out for ESA's ARIANE-5 project at DLR's large rocket test facilities.

The principle requirements for P8 include the operation of combustion chambers supplied with cryogenic oxygen and precooled gaseous hydrogen. For tests of water-cooled thrust chambers a high-pressure cooling water supply system is foreseen. The option for an additional cryogenic hydrogen supply system is kept open.

The general arrangement of P8 is shown in Fig. 1. It is composed of two test cells, four diagnostic rooms and the tank and supply facilities for the propellants. The test cells are arranged in opposite directions to each other in order to reduce mutual restrictions. In between the two test cells are located the tank compartments for gaseous (and optionally for cryogenic) hydrogen and for cryogenic oxygen thus minimizing losses of the supply system due to short piping. To meet the safety requirements the storage facilities for hydrogen and oxygen are strictly separated and located on opposite sides of the P8 test site. For a rocket test bench it is a novel feature to have two diagnostic rooms arranged adjacent to both sides of each test cell, thus enabling the simultaneous use of at least two different laser based diagnostic systems for one

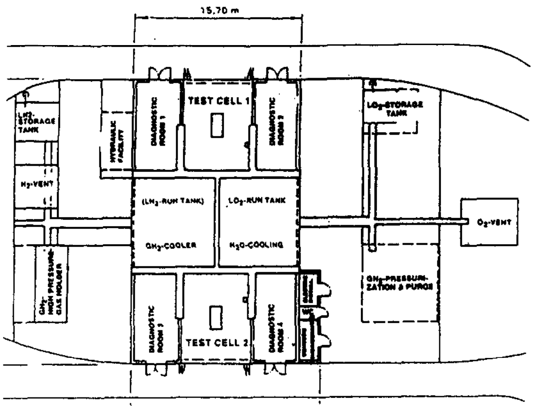

Fig. 1 General arrangement of P8 test bench for LO_2/GH_2-high pressure combustion.

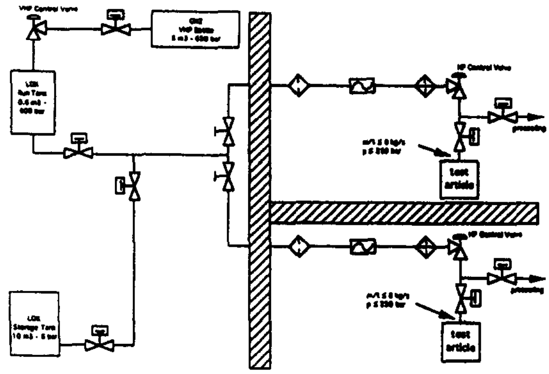

Fig. 2 Simplified flow diagram of LO_2-supply system at P8.

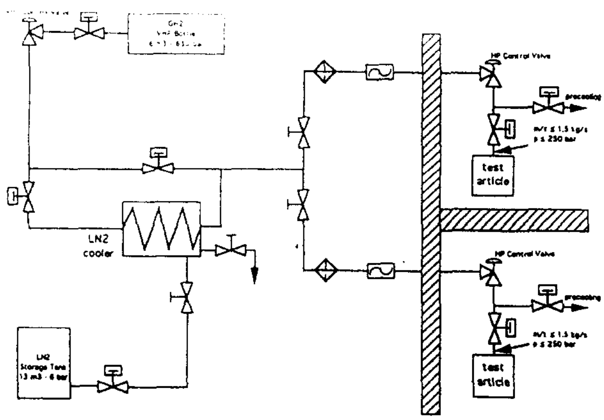

Fig. 3 Simplified flow diagram of GH_2 supply system at P8.

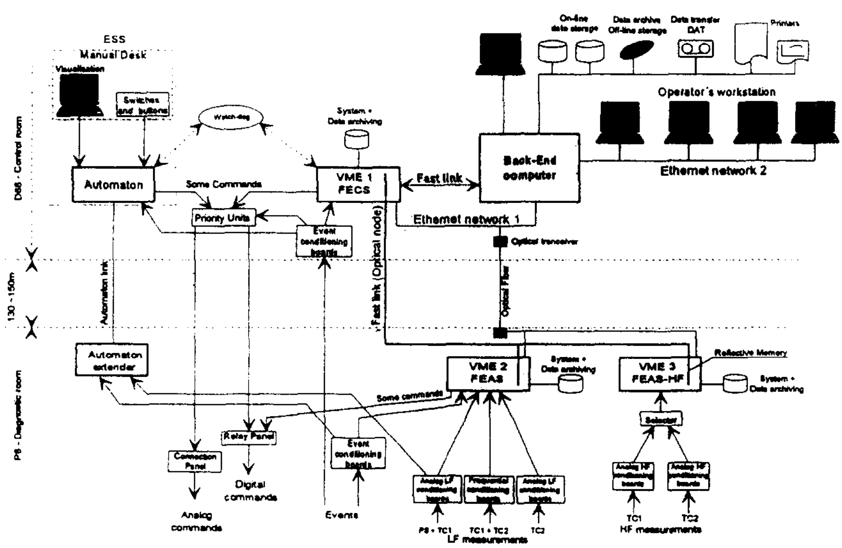

Fig. 4 MCC-system hardware architecture of P8.

combustion experiment. Each test cell is 6 m wide and 8 m long. The combustion chamber or test specimen will be mounted horizontally. Vibration transfer from the combustor to the laser diagnostic devices is reduced by a separate foundation for the combustor support structure. The roofs of the test cells are movable to provide for venting of the test cells during operation. Two rows of openings in the walls between the test cell and the diagnostic rooms, normally closed when not in use, allow optical access from the laser diagnostics to the combustor.

Due to the assumed maximum mass of liquid hydrogen which can be stored at the test bench a circular safety zone of 95 m in diameter was defined. The P8 test bench will be controlled from an operation building, denoted as D68, which is located outside of this safety zone. D68 contains the control room, a machine shop and compartments for test preparation as well as calibration.

Operating Parameters

The operating parameters of P8 can be characterized by the mass flow rates of the fluids and the fluid pressure at the interface to the combustion chamber or test specimen, respectively. Table 1 summarizes the main operating data of P8.

Table 1: Main Operating Parameters of P8

Fluid	Range of Mass Flow Rate, kg/s	Pressure at Interface, MPa
Liquid Oxygen	0.20 - 8.00	2.40 - 36.00
Gaseous Hydrogen	0.05 - 0.25 0.05 - 0.60 0.05 - 1.00 0.80 - 1.50	2.40 12.00 24.00 36.00
Cooling Water	0 - 50.00	0. - 20.00

The fluid temperatures at the interface to the combustion chamber amount to 92 - 120 K with a tolerance of ± 3 K for liquid oxygen and 100 - 150 K with a tolerance of ± 5 K for precooled gaseous hydrogen.

These operating data provide wide ranges of LO_2/GH_2 rocket combustor parameters. The operating conditions for closed cycle combustors are listed in Table 2.

Table 2: Achievable operating conditions at P8 for simulations of closed cycle combustors.

combustor type	combustion chamber pressure type MPa	mixture ratio r
main combustion chamber	5 - 27	4 - 7
fuel-rich preburner	20 - 30	0.6 - 0.9
oxidizer-rich preburner	20 - 30	60 - 100

Since flow visualization and application of laser-optical diagnostics are of particular interest, the diameters of the model combustors in general should not be smaller than roughly 50 mm. Assuming reasonable data for the chamber contraction ratio (A_c/A_t) leads to corresponding thrust levels (at the selected chamber pressure) between 2.5 kN (at 2.5 MPa) and 38 kN (at 30 MPa). Because the majority of experiments will require an optical access to the combustor flow, the test duration for these experiments is determined by the maximum allowable surface temperature of the windows. Depending on the combustion chamber pressure, temperature, and cooling method test runs are restricted typically to a few seconds. For heat transfer investigations the test durations are determined by the transitional period for the corresponding parameters. Necessary test durations can exceed 30 seconds.

Fluid System

The fluid system supplies the experimental combustor or test specimen with the propellants cryogenic oxygen (LO_2) and gaseous hydrogen (GH_2), precooled or at ambient temperature, as well as with cooling water. Consequently, the feed system comprises of the following sub-systems:

- high-pressure (HP) LO_2 supply system,
- HP GH_2 supply system,
- cryogenic storage and transfer facility,
- secondary system and,
- auxiliary system and very high-pressure (VHP) gas supply.

A simplified schematic of the HP LO_2 supply is shown on Fig. 2. It includes a LO_2 run tank with 0.6 m^3 useful capacity and 60 MPa maximum service pressure with evaporation losses less than 5 % per day. The tank volume provides for a test duration of 15 seconds at a maximum LO_2 mass flow rate of 8 kg/s. The LO_2 supply line, designed for 40 MPa and without insulation, connects the run tank with the test specimens. Two identical lines branch to the two test cells with each one equipped with filters, flowmeter, control valve, pre-cooling valve and main shutoff valve. The LO_2 run tank is pressurized by gaseous nitrogen stored in a 5 m^3 VHP bottle at 60 MPa maximum operating pressure. LO_2 is stored at 0.6 MPa in a 10 m^3 storage tank. Fig. 3 depicts the simplified schematic of the GH_2 supply system. Gaseous hydrogen is stored at 60 MPa maximum operation pressure in a 6 m^3 VHP bottle. For pre-cooling the hydrogen gas, it is fed through a gas cooler equipped with multiple parallel pipe coils which are submerged in a liquid nitrogen (LN_2) volume of 9 m^3. The LN_2 Dewar is supplied by LN_2 from a 13 m^3 storage tank. The GH_2 cooler is equipped with a LN_2 level indicator and automatic LN_2 filling-up equipment. For safety reasons all hydrogen waste gas of the test facility will be fed to the H_2 vent stack having 15 m in height. A main component of the auxiliary system is the cooling water supply system comprising a water tank of 2 m^3 volume and 32 MPa design pressure, a water feedline system as well as a pressurization system. The water tank is pressurized by gaseous nitrogen taken from a 3 m^3 VHP storage bottle with 60 MPa maximum operating pressure.

MCC & Combustion Diagnostics

Measurement, Control and Communication (MCC)

The MCC system is designed to provide for the following tasks:

- data acquisition at high (50 kHz) and low (1 kHz) frequencies for both the regulation and control of the fluid systems as well as the user defined measurements in the test cells,
- process control with either command output or digital control,
- emergency stop system (EES),
- video and communication, and
- test preparation as well as data treatment.

The general MCC design is shown schematically in Fig. 4. The backend computer is used for test preparation, test supervision and test data treatment, making use of several X-Terminals as the operator's interface as well as the standard peripherals. This system consists of an HP 9000/745-50 MHz computer with 64 Mbyte memory and HP 715 X-Terminals. The operating system in use is a HP-UX, the Unix of HP, with software developed in C. Data treatment is performed by the standard package Dynaworks by Interspace. The demanding realtime tasks are performed by 3 VME frontend systems:
FECS (frontend command system) equipped with 3 HP742rt CPUs located in the control building for safety reasons,
FEAS (frontend analog system) for on-line acquisition and storage of low-frequency analog data equipped with 3 HP742rt CPUs 16MB, located in the test stand in order to minimize electrical noise influence, and FEAS-HF (high-frequency) for on-line acquisition and storage of high frequency analog data equipped with 2 HP742rt CPUs, 128 MB, located in the test stand. The systems are interconnected by means of a high- speed reflective (shared) memory for real-time data exchange and standard Ethernet for less demanding purposes. A second Ethernet is used for connecting the X-Terminals to users. The safety concept is accomplished by an independent ESS. It consists of a Siemens S5-135U PLC which provides for a safe state of the test bench in

case of computer failure during a test.
The accuracy of the complete measurement chain is designed to be better than 1 % for the supply system and better than 0.5 % for the combustor related measurements. The signals have a resolution of 12 bit. Each test cell is provided with 104 low frequency channels having 1.000 samples/sec each, 3 frequency channels with 500 samples/sec, and 24 high frequency channels with a scanning rate of 50.000 sample/sec each. The maximum overall HF-sampling rate amounts to 1.28 Msamples and the maximum storing time to 30 seconds.

Diagnostics

A unique feature of the test bench is the provision of sophisticated laser-based diagnostics for visualization of the flow and combustion phenomena in combustors and for non-intrusive measurements of the state variables. At least two different laser diagnostics can be utilized simultaneously at one test specimen.

Methods which are based on Mie scattering such as laser-Doppler anemometry (LDA), particle image velocimetry (PIV), phase-Doppler particle analyzer (PDPA) and laser diffraction particle sizing yield information about local velocities as well as velocity distributions, turbulence characteristics, coherent structures, local particle size distributions and particle densities. The application of spontaneous Raman techniques provides for temperatures and densities of major species; coherent anti-Stokes Raman techniques (CARS) yield temperature and its fluctuation. From laser induced fluorescence (LIF) methods, information about concentration and temperature fields as well as locations of flame fronts are deducible.The application of conventional (Schlieren, laser light sheet) and more sophisticated (high speed video applying pulsed lasers or flash light) visualization techniques yields characteristic length or time scales of coherent structures and vortices in the flow. The knowledge of those is essential for both modelling and passive or active control of mixing and combustion. Although the range of possible application of these methods does not cover the entire flow field and pressure range which is of interest, a combination of these techniques allows detailed studies of the phenomena which exist in rocket engines.

For several years the partners have been utilizing various laser-optical diagnostics for combustion research[9-12]. These diagnostic methods are presently being adapted to the specific conditions of O_2/H_2 high-pressure combustion [13-15]. Flow visualization in windowed LO_2/GH_2 combustion chambers at moderate combustion pressures ($\leq$ 2 MaP) have been practised for several years at DLR's Micro Combustor Test Facility (MCTF) and since the beginning of 1994 at ONERA's "MASCOTTE" test bench. A few examples should illustrate the results obtained. Fig. 5 shows the spontaneous OH-emission from a LO_2/GH_2 combustor with a three-element coaxial injector operated at MCTF[16]. Fig. 6 depicts the laser induced OH-fluorescence image of a single-element coaxial injector utilized in a LO_2/GH_2 experimental combustion chamber at MASCOTTE[17].

Planned Research & Technological Program

The test program planned to be executed on the P8 test bench can be distinguished into three work categories:

- adaptation of non-intrusive measurement methods to the particular conditions of oxygen/hydrogen high-pressure combustion,
- basic research on LO_2/GH_2 high-pressure combustion, and
- technology studies related to cryogenic rocket combustion devices.

As far as the DLR is concerned, the following laser diagnostics are being adapted for utilization in high-pressure LO_2/GH_2 combustion:
2D-laser-Doppler-anemometry (LDA) for local velocity and flow turbulence measurements, particle image velocimetry (PIV) for measurement of velocity distributions, two wavelength hydrogen CARS for local temperature measurements, and UV-laser diagnostics for visualization of flame fronts and cryogenic spray phenomena. The first applications of these

techniques at P8 are scheduled for 1996 concerning LDA, PIV and CARS and for 1997 related to UV-laser diagnostics.

As a part of the French Research Program on LO_2/GH_2 cryogenic combustion SEP and CNES have contracted studies with CNRS and ONERA on advanced optical diagnostics. Various techniques such as: OH radical laser induced fluoresence (LIF), dye fluorescence, Raman scattering, or droplets measurement by PDPA have already been used for spray combustion on coaxial injectors at ambient pressure and with substitution fluids[11,12]. Presently, visualizations by LIF on OH radicals and temperature measurements by CARS are in progress at ambient pressure on the MASCOTTE test facility and tests at elevated pressures, up to 1 MPa, are planned before the end of this year.

In order to prepare measurements at high-pressure, (at least 10 MPa) which are intended to be implemented on the P8 test facility, theoretical and experimental studies on the spectroscopic behavior of H_2,O_2 and H_2O molecules at high-pressure have also been undertaken[13,14]. Validation of these studies are currently in progress for CARS applications in a gaseous oxygen/hydrogen burner at medium-pressure (4 MPa).

The basic research program on the P8 will be, as far as SEP and CNES are concerned, an extension of the program undertaken in France but with an emphasis on high-pressure and supercritical phenomena. The fields of interest are atomization, vaporization, and mixing with high density ratio and turbulent spray combustion. The goals of both these programs are the development of new physical models for rocket engine combustion and the validation of numerical codes such as the 3D Navier Stokes code named THESEE used by SEP for combustion device modelling[18,19].

The main objectives of DLR's basic research program for high-pressure combustion are to provide the corresponding industry with basic knowledge related to the flow and combustion phenomena in LO_2/GH_2 rocket combustion chambers and to contribute to the development of suitable computer models. Consequently, the experimental R&D program can be divided into the following topics:

- flow visualization within the combustor,
- local measurements of velocity, temperature and species concentration,
- operational research of main combustion chambers for closed cycle rocket engines (investigations of stable combustion range, start-transient during ignition, local heat transer data, experimental performance at partial load, transpiration cooling, operation range for expander cycle engines, regenerative cooling by cryogenic oxygen), and
- verification tests for computer models.

Presently, experimental combustion chambers with optical access are being developed. Phenomenological investigations of the jet break-up, mixing, vaporization and combustion process utilizing single and multiple element coaxial injectors are currently carried out at MCTF for combustion chamber pressures up to 2 MPa. These investigations will be carried on at P8 in 1995 for elevated pressures.The studies of local heat transfer from the combustion gas to the wall will begin in 1996. The numerical as well as experimental investigation of transpiration cooling has been started two years ago. Experiments for transpiration cooling with substitution fluids will be carried out at P8 beginning in 1996.

Concerning technological studies, the work to be performed by SEP on P8 will be first directed to the study of new concepts of injectors. Single element tests are planned first and then subscale chamber tests will be considered. Since the cooling water capacity at P8 is limited, it will not be possible to perform tests with high mixture ratios and pressures higher than roughly 10 MPa. For combustion chambers with few centimeters in diameter it should be possible to perform tests up to 25 MPa for mixture ratios not greater than 2. Even if the similitude conditions are not exactly conserved with respect to actual conditions the test conditions will be representative enough to extrapolate the results to actual conditions. The test specimen for single element tests is being designed at SEP. It is a modular test specimen so that the injector, the throat or the chamber body can be changed easily. Measurements will be of the conventional type such as pressure and temperature transducers or fiber optical detectors to locate and measure the length of the flame and its fluctuations. This test specimen will be available by the end of next year. Related tests should start at the beginning of 1996.

DASA will be the first user of the P8 test bench in 1995. Existing hardware from the Ariane 5 Vulcain motor subscale program will be used for these investigations. It is planned to perform high mixture ratio/high-pressure tests (O/F range 7 to 9, p_c range 10 to 15 MPa) with the Vulcain 19 element subscale injector and a water-cooled chamber, in preparation for Vulcain MKII pre-development tests. The first tests with the Vulcain MKI subscale hardware will be run in the existing operating box and will serve as hot fire demonstration tests to verify P8's operational characteristics. Technological studies for later DASA P8 test campaigns could be aimed at different cooling concepts such as regenerative, film and transpiration cooling. Further possible topics of interest are low cost injection element design, hot gas injection element design, and investigations dealing with the multiple ignition of LO_2/GH_2 thrust chambers.

In addition to these technology investigations DASA will work together with DLR to use local field data gained from special tests with advanced laser diagnostics obtained from chambers with optical access. These data will be used to better understand the governing physical phenomena in spray combustion and to validate numerical models intended for performance and heat transfer prediction.

Summary

DLR, CNES, DASA and SEP have decided to design, operate and utilize jointly a high pressure combustor test facility, denoted as P8, which is presently under construction at DLR's Research & Test Center in Lampoldshausen,Germany. The P8 rocket test bench will be ready for operation in May 1995. It provides for LO_2/GH_2 combustor tests with a maximum combustion chamber pressure of 30 MPa and wide ranges of oxidizer/fuel mixture ratios. The cryogenic oxygen mass flow rate can be varied between 0.20 kg/s and 8.0 kg/s and the mass flow rate of pre-cooled gaseous hydrogen between 0.05 kg/s and 1.50 kg/s. The measurement, control and communication system of P8 provides for more than 130 measuring channels per test specimen including low-frequency (1 kHz) as well as high-frequency (50 kHz) channels. A unique feature of P8 is the provision of sophisticated laser based diagnostics for visualization of flow and combustion phenomena and for non-intrusive measurements in combustors. The planned test program for P8 includes the adaptation and qualification of non-intrusive measurement methods for high-pressure applications, basic research on LO_2/GH_2 high-pressure combustion and technological studies related to rocket combustor components.

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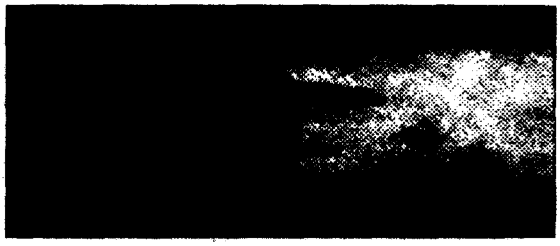

Fig 5 Spontaneous OH image of LO_2/GH_2 model combustor with 3-element coaxial injector[16].

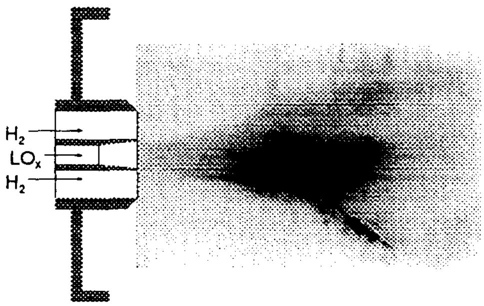

Fig. 6 Laser-induced OH-fluorescence image of LO_2/GH_2 model combustor with single-element coaxial injector[17].