Pergamon

Int. J. Hydrogen Energy, Vol. 23, No. 6, pp. 491–497, 1998

0360–3199/98 $19.00+0.00

PII: S0360–3199(97)00034–7

IMPROVED COMBUSTION EFFICIENCY OF A H_2/O_2 STEAM GENERATOR FOR SPINNING RESERVE APPLICATION

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Abstract—Within the last ten years, DLR has proposed, developed and tested an alternative to conventional control methods for spinning reserve, such as life steam throttling and/or low pressure preheater shut-down, the spontaneous generation of additional steam formed by chemical reaction from stoichiometric mixtures of hydrogen and oxygen. In the so-called H_2/O_2 steam generator, the temperature of the reactant, in the ideal case pure steam, is reduced by injection of preheated feed water to correspond exactly with the temperature level of the steam condition at the point of injection into the power plant process. Initially, at DLR the main emphasis was laid on the development of the device, i.e. the closed loop control of all mass flow rates, steam quality and temperature, ignition and optimized start-up behavior of pressure and temperature. During 1994, DLR and Dasa carried out an experimental program at Lampoldshausen to improve the combustion efficiency of the device by applying Dasa's state-of-the-art rocket engine technology for design and fabrication of the propellant injection system.

The experimental results achieved through combining the experimental version of the steam generator and the closed loop control system from DLR and the modified propellant injection system from Dasa clearly show that the technical problems in establishing a spinning reserve system based on a H_2/O_2 steam generator can be overcome.

NOMENCLATURE

A	Cross section
c	Weight fraction
C_d	Flow coefficient
$\dot{m}$	Mass flow rate
p	Pressure
p_c	Pressure in the combustion chamber
R	Universal gas constant
R_{of}	Mass flow ratio oxidizer/fuel
R_{wg}	Mass flow ratio water/gas
t_{EQ}	Reaction rate (characteristic time to reach chemical equilibrium)
t_{QE}	Quenching rate
T_c	Steam temperature
T	Temperature
T[?]	Time constant for response functions
U	Voltage
Δp_{CV}	Differential pressure along control valves
κ	Isentropic exponent
Ψ	Stream function
des.	Subscript for desired values (closed loop regulation)
st	Subscript for stoechiometric mixtures
t	Subscript for stagnation quantities at an inlet

INTRODUCTION

Interconnected electrical grids have an almost negligible storage capacity of their own. Therefore, suitable measures have to be taken to match continuously the generation of electrical energy to the consumption within the network. For modern networks such as UCPTE (Union for Coordination of Production and Transportation of Electrical Energy), suitable requirements have been specified for the operators of power plants. Typically, each power plant unit must possess a spinning reserve of at least 5% of its design capacity, which should be activated within a few seconds.

Compared with conventional methods of spinning reserve such as live steam throttling or preheater shut-down, the direct steam generation has two advantages. First, the economic advantage is that capital and operating costs of such a device could be lower. Second, the ecological advantage is that the overall output of exhaust gases is reduced. Both advantages result from the fact that a spinning reserve based on the steam generator allows the power plant to be operated closer to its optimum design value and no power plant capacity is blocked to provide spinning reserve. DLR has proposed, developed and tested such alternative control methods [1–5].

STEAM GENERATOR DESIGN

The basic design of the DLR H_2/O_2 steam generator is shown in Fig. 1. The propellant injection part with coaxial injection elements at the entrance is followed by the regeneratively-cooled combustion chamber, the water injection part where the hot gases are cooled to the desired temperature, and finally the vaporization zone which is long enough to ensure mixing and vaporization of the injected water. The most severe constraints for the design of the steam generator are its desired start-up time which is of the order of about one second and the limiting boundary conditions for coolant mass flow rate and temperature. Both require all geometrical lengths in the system to be as short as possible.

The manufacturing precision of the injector head and especially of the injection elements is one of the key technologies with regard to the efficiency of the complete device. Propellant mixing and combustion, and hence the efficiency of the complete device, are mainly dominated by the propellant supply system in the injection part. Any geometrical inhomogenity in an injection element will cause a local deviation from the stoichiometric mixture and leads to insufficient thorough mixing of the propellants in the combustion chamber. Residence times of the propellants in the combustion chamber in the order of milliseconds make it obvious that mal-fabricated injection elements are a major source for efficiency deficits.

The main problem of the combustion part is the cooling of chamber walls. Typical mean heat loads are between 15 and 20 MW/m^2. It should be noted that the coolant mass flow rate cannot be chosen independently but is determined by the desired steam mass flow rate and temperature. Additionally, in a power plant pressure and temperature of the cooling water are determined by the plant itself. Since the mean temperature inside the chamber is above 3500 K heat transfer by radiation cannot be neglected. It is also worth mentioning that the recombination of dissociated species is an additional heat source in the wall boundary layer. Taking all this into account, cooling methods are necessary which normally are only used in rocket propulsion devices.

The purpose of the water injection system is to cool the hot gases of the combustion chamber to a temperature convenient for the IP turbine. This cooling process has to be as smooth as possible to avoid quenching of the hot gases which will cause non-tolerable high concentrations of unburned propellants in the exhaust steam. Furthermore, the complete cross section of the steam generator has to be filled with a specific amount of water to reach a homogeneous temperature distribution thus avoiding hot and cold spots in the steam, a source of possible turbine blade damage. The boundary conditions of the water injection system (mean velocity, 100 m/s: mean temperature, 3500 K; pressure, 4 MPa) require a carefully designed injection system, especially in respect of the nozzle diameters and their spatial distribution.

The final vaporization part of the steam generator has two tasks: first, to enhance the turbulence to promote mixing of the two-phase flow, and second, to increase the residence time to ensure complete vaporization of big droplets. The outlet of this part is designed to hold sensors for temperature and steam quality to allow for an on-line control of the steam properties.

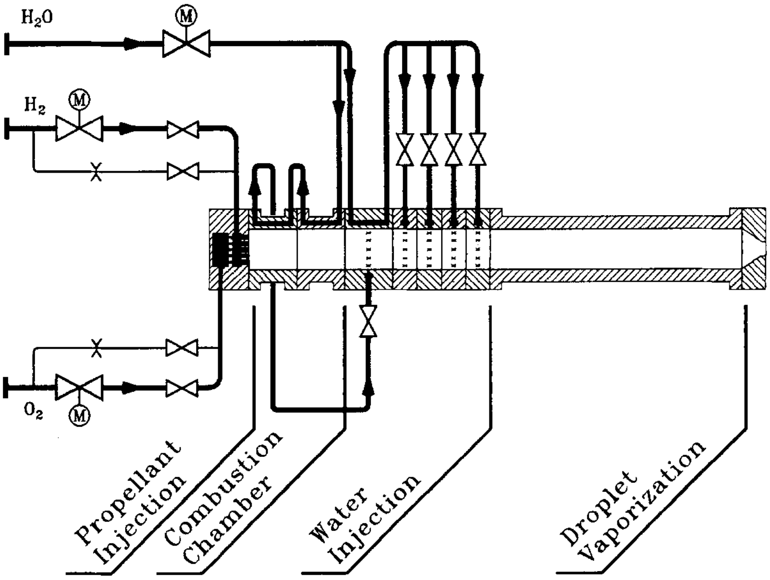

Fig. 1. Sketch of the H_2/O_2 steam generator.

COMBUSTION EFFICIENCY

Two groups of efficiency deficit sources can be identified. The first group summarizes all types of mechanisms which cause inhomogenities of the gas mixture at the combustion chamber entrance, while the second group covers all sources for incomplete chemical reaction of the propellants in the combustion chamber.

Mixing inhomogenities

The mixing of the propellants may be enhanced by turbulence promoters such as swirl elements in the oxygen line or a recess of the oxygen post inside each injector element. Nevertheless, mixing inhomogenities are caused by deviations from the stoichiometric values of the flow rates through individual injection elements. Each coaxial injection element has its individual mass flow ratio $\{R_{\text{of}}\}_i = \{\dot{m}_{\text{O}_2}\}_i/\{\dot{m}_{\text{H}_2}\}_i$ and a deviation $\{\Delta R_{\text{of}}\}_i$ from the stoichiometric value ($\{R_{\text{of,st}}\} = 7.936$) which is given by equation (1).

$$\{\Delta R_{\text{of}}\}_i = \frac{\partial\{R_{\text{of}}\}_i}{\partial\{\dot{m}_{\text{O}_2}\}_i}\cdot\partial\{\Delta\dot{m}_{\text{O}_2}\}_i + \frac{\partial\{R_{\text{of}}\}_i}{\partial\{\dot{m}_{\text{H}_2}\}_i}\cdot\partial\{\Delta\dot{m}_{\text{H}_2}\}_{\text{i}} \tag{1}$$

Assuming these deviations $\{\Delta R_{\text{of}}\}_{\text{i}}$ from the stoechiometric value to be small leads to:

$$\frac{\{\Delta R_{\text{of}}\}_i}{R_{\text{of,st}}} = \frac{\{\Delta\dot{m}_{\text{O}_2}\}_i}{\dot{m}_{\text{O}_2,\text{st}}} - \frac{\{\Delta\dot{m}_{\text{H}_2}\}_i}{\dot{m}_{\text{H}_2,\text{st}}}. \tag{2}$$

These $\{\Delta R_{\text{of}}\}_i$ cause concentration inhomogenities in the combustion chamber even if the sum of them is zero, corresponding to an overall stoichiometric propellant mass flow rate. The flow through each injection element can be modelled by the mass flow rate $\dot{m}_i$ and the stream function Ψ_i to:

$$\{\dot{m}\}_i = \{C_{\text{d}}\}_i\{A\}_i\{p\}_i\{\Psi\}_i\sqrt{\frac{2\kappa}{\kappa-1}\,\frac{1}{R\{T_{\text{t}}\}_i}}, \tag{3}$$

$$\{\Psi\}_i = \sqrt{\left(\frac{p_c}{\{p_{\text{t}}\}_i}\right)^{2/\kappa} - \left(\frac{p_c}{\{p_{\text{t}}\}_i}\right)^{\kappa+1/\kappa}}. \tag{4}$$

with $\{C_{\text{d}}\}_i$ the flow coefficient, $\{A\}_i$ the flow cross section, $\{p_{\text{t}}\}_i$ and $\{T_{\text{t}}\}_i$ the total pressure and total temperature at the upstream end of each injection element. Deviations from the stoichiometric mass flow in each individual injection element and for the species H_2 and O_2 can be written as:

$$\left\{\frac{\Delta\dot{m}}{\dot{m}}\right\}_i = \left\{\frac{\Delta C_{\text{d}}}{C_{\text{d}}}\right\}_i + \left\{\frac{\Delta A}{A}\right\}_i + \left\{\frac{\Delta p_{\text{t}}}{p_{\text{t}}}\right\}_i + \left\{\frac{\Delta\Psi}{\Psi}\right\}_i - \frac{1}{2}\left\{\frac{\Delta T_{\text{t}}}{T_{\text{t}}}\right\}^i. \tag{5}$$

A discussion of the right-hand terms in equation (5) identifies possible sources for incomplete mixing. Another effect which has an impact on the mixing process is thermal blocking. The heat transfer from the combustion chamber to the injection head leads to a unequal rise in the temperatures of the H_2 and O_2 flow channels.

QUENCHING

Neglecting species with minor quantities, the reaction of hydrogen and oxygen may be written as:

$$4\text{H}_2\text{O} \overset{p,T}{\leftrightarrow} 2\text{H} + 2\text{OH} + 2\text{H}_2 + \text{O}_2. \tag{6}$$

Three different types of quenching mechanisms can be identified as responsible for incomplete reaction in the steam generator. First, quenching at the relatively cold walls of the combustion chamber. Assuming that only the hot gases of the developing wall boundary layer are cooled yields of mass of about 5% of the total mass in the combustion chamber are subject to this quenching process. Further, considering that significant quenching occurs for $t_{\text{EQ}}/t_{\text{QE}} \geqslant 1$, this would result in mass fractions of unburnt propellants in the steam of about 0.006% for hydrogen and 0.04% for oxygen, respectively. The second quenching mechanism is dilution caused by the injection and vaporization of water. The mass flow rate of the injected water is considered to be about 3.5 times the mass flow rate of the propellants. Third, quenching by the fast reduction of temperature due to the injection of that large amount of relatively cold water. In our investigation it is impossible to distinguish between the influence of the last two effects, because in the system the injected water is not an inert species.

As an example, a temperature reduction of steam from 2500 K to 800 K by quenching with steam at 375 K leads, according to equation (6), to about 90% of the high temperature equilibrium hydrogen mass remaining in the low temperature mixture [6]. For an illustration, the equilibrium mass fractions of the system at 4.0 MPa are shown as a function of temperature in Fig. 2. Note that

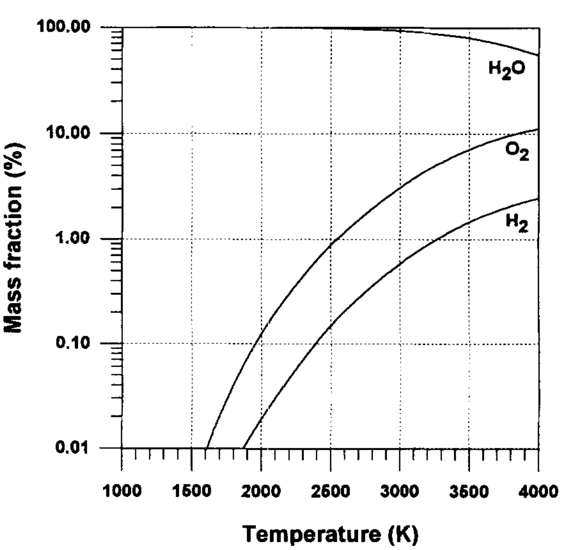

Fig. 2. Equilibrium mass fraction distribution of steam at 4 MPa.

the maximum tolerated mass fraction of hydrogen in the effluent is 0.01% and that of oxygen is 0.3%. An overall quenching rate in the steam generator, based on the mean hot gas velocity, the temperature difference and the length of the water injection and vaporization system, is of the order of 10^5 K/s.

The rate constants of the system $H_2/O_2/H_2O$ are below the millisecond level only for temperatures above 2500 K. Hence, the water injection system has to be optimized to reduce this source of un-recombined propellants.

The estimations in this paper are based only on order of magnitude assumptions of quenching processes in the steam generator. For detailed information, the interaction between cold water droplets and the hot gas mixture has to be investigated and the process of condensation of steam on the cold droplet surface taken into account. Using a Lagrangian code to follow each droplet and its boundary layer over the droplet life time, it should be possible to study this interaction effect and its impact on the incompleteness of the reaction in detail. To do this, the process has to be considered to be dominated by different time and length scales such as the total life time of droplets, turbulent time scale of the flow, mean residence time of the flow in the steam generator, droplet diameter, boundary layer thickness and the characteristic length scales of the steam generator.

Control of stoichiometric propellant supply

An operating point of the steam generator is well defined through three variables: combustion chamber pressure p_c, steam temperature T_c and oxygen/hydrogen mass flow ratio R_{of}. These three variables are regulated in a closed loop digital control process where any deviation from the set point is compensated by modification of the mass flow rates for oxygen, hydrogen and water using electrical driven control valves. The output from the control unit to the valves are linearly related to the rate of the motors' revolution, i.e. the speed of the valve pistons.

Because of the non-linearities in the system and the coupling between the controlled properties, standard algorithms for PID control failed to give acceptable results. Thus, a control algorithm has been developed which describes the relation between the required motion of the control valve inserts and the differences between desired and actual values of the controlled variables, assuming a damped system of first order for p_c, T_c and R_{of}. The first derivation in time for the controlled variables are given by equation (7). The T_i are time constants for the controlled variables.

$$\dot{p}_c = \frac{p_{c\,\text{des.}} - p_c}{T_{pc}}, \quad \dot{T}_c = \frac{T_{c\,\text{des.}} - T_c}{T_{Tc}}, \quad \dot{R}_{\text{of}} = \frac{R_{\text{of des.}} - R_{\text{of}}}{T_{R_{\text{of}}}} \tag{7}$$

The calculation of the required motion of the control valves (linear to voltage U) results from the relation between pressure loss and mass flow rate in the supply system considering all coupled conditions. The overall result can be found in equation (8).

$$U = \text{C} \cdot \begin{cases} \left(\dfrac{p_t - p_c}{\Delta p_{\text{CV}}} \dfrac{\ddot{m}}{\dot{m}} - \dfrac{1}{2} \dfrac{\dot{p}_t - \dot{p}_c}{\Delta p_{\text{CV}}} \right) & \text{for liquid media} \\ \left(\dfrac{\ddot{m}}{\dot{m}} - \dfrac{\dot{p}_t}{p_t} + \dfrac{1}{2} \dfrac{\dot{T}_t}{T_t} - \dfrac{\dot{\Psi}}{\Psi} \right) & \text{for gaseous media} \end{cases} \tag{8}$$

with some constant C depending on the geometrical properties of the control valves, the tank pressures and temperatures p_t and T_t, the stream function Ψ, and the pressure difference over the control valves Δp_{CV}.

From consideration of the energy and mass balance, the derivations of the mass flow rates for hydrogen, oxygen and water can be written as a relation of the derivation of the controlled variables (see equation (7)), and some parameters A, B, and Z that represent the actual status of the system. A detailed description of the closed loop control process can be found in [4, 5].

Since the most important problem during the operation periods of the H_2/O_2 steam generator is the exact control of the stoichiometric propellant supply (to avoid residual gases caused by a deviation from the set point) the measurement of either mass flow rates or mass flow ratio has to be done with maximum accuracy.

Two different principles of R_{of} on-line detection have been implemented for the tests with the experimental steam generator. First, R_{of} calculation by measurement of the mass flow rates in the supply system using calibrated orifices and, second, on-line determination of the (related to stoichiometric mixture) surplus component either of oxygen or hydrogen in the steam with a modified zirconia sensor.

Since the minimum overall accuracy of mass flow measurement with standard orifices and pressure/temperature sensors is about $\pm 0.7\%$ the mean geometric accuracy for the mass flow ratio would be $\Delta R_{of}/R_{of} < \pm 1.0\%$. By comparison, the detection of R_{of} with a calcia-stabilized zirconia sensor system has shown a significantly better accuracy ($\Delta R_{of}/R_{of} < \pm 0.2\%$). Though the operating range of this sensor is limited with $7.7 < R_{of} < 8.28$ through the maximum amount of detectable hydrogen or oxygen in steam, this device covers the desired operating range of the steam generator ($7.95 < R_{of} < 8.07$) very well. For details about the capabilities of a calcia-stabilized zirconia sensor [2, 3].

Figure 3 presents the results of a probe calibration for oxygen (left) and hydrogen (right). The time constant of such a measurement system is basically fixed by the geometric conditions of the supply for the ZrO_2 probe, in this case < 100 ms.

Since the probe is able to detect either oxygen or hydrogen in steam (not both propellants at the same time), a well insulated supply line with defined length is used to ensure the complete reaction of unburned hydrogen and oxygen at stoichiometric mixture in the steam which result from mixing inhomogenities in the steam generator.

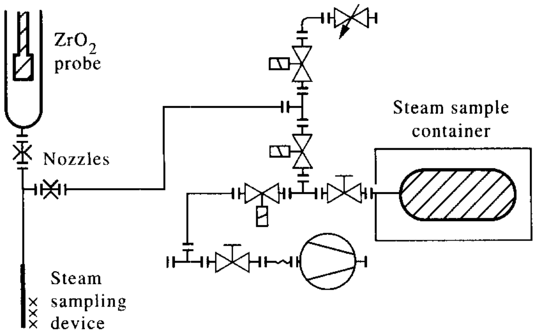

Fig. 3. Calibration results for measurement of H_2 and O_2 concentration with a modified calcium oxide-stabilized zironia sensor.

Residual gas detection

Since the on-line measurements of the residual gas concentration with the modified zirconia sensor would only provide valid results for the surplus component and hide stoichiometric residuals, a device for sampling of a representative amount of the produced steam (<50 g gathered over 5 s test time) had been used. A retrospective calculation by using the results of a gas chromatographic analysis of the sample leads to the residual gas concentration in the tests. Fig. 4 shows the set-up for gathering the steam sample. The steam sample container has to be evacuated before the test to avoid pollution. For reliable results a sample mass of 20–30 g, gathered over 5 s test time under steady state conditions, has been sufficient. Both effectivity and mass flow ratio as mean values over the sampling time are additional results from the gas chromatographic analysis of the steam sample.

Propellant purity

The purity of the propellants and the feed water have an important effect on the purity of the steam. By using mass balance for the steam generator the concentration of pollutants c_i as weight fraction can be written as shown in equation (9).

$$\frac{P_{O_2/i}R_{of}}{(R_{of}+1)(R_{wg}+1)}+\frac{P_{H_2/i}}{(R_{of}+1)(R_{wg}+1)}+\frac{P_{H_2O/i}R_{wg}}{(R_{wg}+1)}=c_i \qquad (9)$$

with the oxygen:hydrogen mass flow ratio ($R_{of}=\dot{m}_{O_2}/\dot{m}_{H_2}$) and the water:gas mass flow ratio ($R_{wg}=\dot{m}_{H_2O}/[\dot{m}_{H_2}+\dot{m}_{O_2}]$) and the weight fraction of the pollutants in the original media $P_{j/i}$. The purity of standard technical oxygen, as delivered from factory, is better than 99.5%, which means that up to 0.5% (based on the oxygen amount) of non-condensable gases (mainly Ar and N_2) will remain in the steam. With $R_{wg}=3.6$ and $R_{of}=7.94$ for example, the weight fraction of non-condensable gases in the steam amounts to 0.1%.

IMPROVED PROPELLANT INJECTION SYSTEM

The injector is the key component of a H_2/O_2 steam generator in terms of the quality of the produced steam. Any residual concentrations of hydrogen and/or oxygen result mainly from an uncompleted mixing and combustion of the two gases.

The high requirements for design and manufacturing of the injector result from the necessity to keep the concentrations of hydrogen and oxygen in the produced steam below 0.01% and 0.3%, respectively. These values correspond to a combustion efficiency of 99.8%. State-of-the-art cryogenic rocket engines are typically working with a combustion efficiency of 99.5%.

The electronic control of the feed valves is only able to guarantee an overall stoichiometric ratio of oxygen and hydrogen. In order to meet the high requirements it is therefore necessary to design the injector head and the injector elements in such a way that the desired mixture

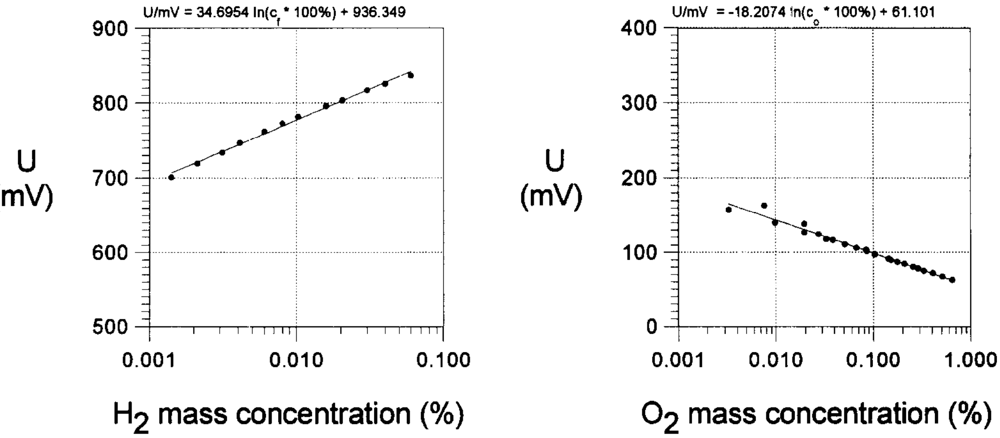

Fig. 4. Experimental set-up for steam sampling and on-line measurement of the mixture ratio.

ratio is obtained at each of the approximately 50 injection elements.

The required know-how and manufacturing technology is available at Daimler–Benz Aerospace as a result of its activities in rocket engine development, testing and production.

Injector head design and flow checks

Based on the design of the Ariane HM7 engine, an injector head for stoichiometric combustion of gaseous hydrogen and oxygen has been designed and manufactured that is suitable for the experimental version of a H_2/O_2 steam generator developed by the DLR.

This injector head has a diameter of 100 mm and an integrated ignitor and 58 coaxial injection elements. The overall nominal mass flow is 400 g of hydrogen and 3170 g of oxygen. Each element is equipped with one throttle for oxygen and four throttles for hydrogen. The oxygen throttles are replaceable in order to compensate manufacturing tolerances. The selected materials are chrom–nickel alloys and copper.

The completely integrated injector head, which is shown in Fig. 5 has been tested in flow checks with nitrogen in order to proof the mixture ratio at each of the 58 elements and if necessary to replace some of the oxygen throttles. These flow checks have already indicated that the injector head has to be further optimized in order to meet the high combustion efficiency requirements.

Injector head testing

The idea of the test campaign at the DLR test facilities in Lampoldshausen was to identify the influence of the injector head and the potential to improve it by state-of-the-art rocket engine technology. Therefore, the original experimental version of the DLR had been reactivated and the originally obtained results had been confirmed in an additional set of tests. The hydrogen and oxygen concentrations obtained in the produced water vapor are much higher than the target values as illustrated in Fig. 6.

For a better comparison only the injector of the experimental version has been replaced by the Dasa injector head. All other components including the closed loop control were unchanged.

The tests of the so modified experimental version have been conducted successfully. Samples of the water vapor produced have been analyzed by a gas chromatograph and the resulting values are shown in Fig. 6. These values are much better than those obtained with the unmodified experimental version, but are still higher than the target concentrations of 0.3% by weight of oxygen and 0.01% by weight of hydrogen.

CONCLUSION AND OUTLOOK

In a joint effort, DLR and Dasa have achieved major improvements of the combustion efficiency of the steam generator and shown that there are margins for the further improvements which are necessary to meet the requirements for power plant applications. First, an optimized injector head design is feasible but requires a product development phase where several design parameters have to be optimized experimentally. Second, the closed

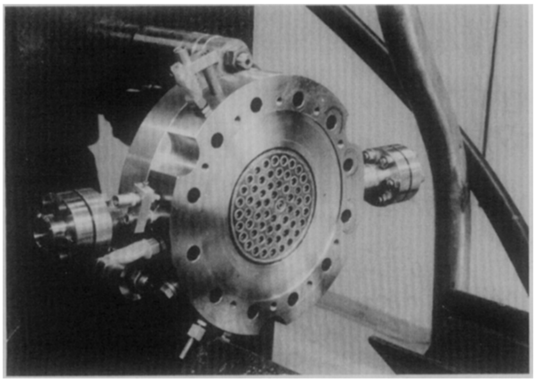

Fig. 5. Dasa injector head with 58 injection elements with a diameter of 100 mm.

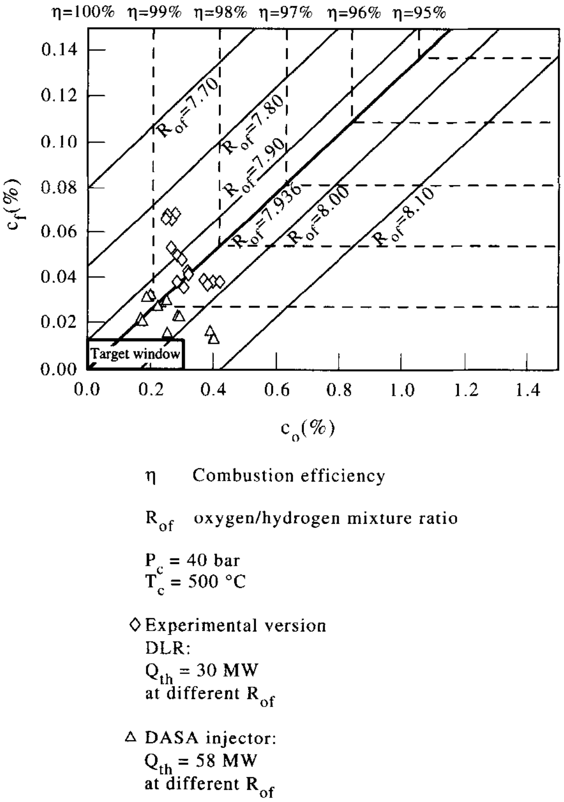

Fig. 6. Gas concentrations obtained with the original DLR experimental version and the Dasa injector head.

loop control system offers a significant potential to reduce the residual gas concentrations, since the results so far have been achieved without any fine tuning of the control parameters. Hence, especially the start-up phase has a great potential for optimization.

The technical specifications of a H_2/O_2 steam generator for power station applications do not allow any margins for the residual gas concentrations. Therefore, the potential for improvements described have to be fully implemented in a prototype version to keep the concentrations of hydrogen and oxygen below the target values.

The effort for a product development phase including experimental testing, manufacturing of a large scale prototype and the testing of this prototype in a suitable power station costs approximately DM 10 million. The technical risks of such a development program are, as well as the residual gas concentration, the lifetime of the combustion chamber, the start-up phase of the steam generator and the interface to the power station. Nevertheless, no "knock-out" criteria have been identified.

Dasa is willing to develop such a H_2/O_2 steam generator and will take over all technical risks provided that there is a significant market potential documented by a fixed order of at least 20 units. For any further activities concerning steam generators, DLR is offering its P6.1 test facility which has been in use during the development phase and is equipped with all necessary instrumentation for data acquisition and control as well as its know-how in closed loop control systems for this kind of devices.

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