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High Speed Hydrogen Combustion Phenomena

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Hydrogen is regarded as one of the most promising energy carriers of the future. It shows a high specific energy density and the exhaust gases from a combustion with air, with H_2O as the main reaction product, contain nearly no toxic parts and do not contribute to the greenhouse effect. Furthermore hydrogen can be generated simply by the electrolytical dissoziation of water. However, the complex interactions of fluid mechanics, gasdynamics and reaction kinetics involved in the combustion process are not yet understood. Therefore the authors' institute is involved in hydrogen combustion research for nearly a decade with two major aspects. For one there are safety considerations with regard to accidental combustion in hydrogen facilities with storage tanks and distribution systems or in nuclear power plants in the course of a loss-of-coolant-accident. The other aspect is the optimization of combustion chambers.

The major safety problem in hydrogen facilities in case of an unintentional ignition of hydrogen/air mixtures beside the release of large amounts of thermal energy are possible strong deflagrations or even detonations. The propagation rate of an initially slow deflagration can be increased by turbulent flame acceleration up to supersonic speeds or even undergo transition to detonation [1, 2]. Since fast flame fronts are connected with strong overpressures, reaching values of more than thirty times the initial pressure in the case of a detonation, they are capable of damaging inventory parts of a facility. Therefore detailed knowledge of the mechanisms of turbulent flame acceleration and the transition from deflagration to detonation is necessaray for safety analysis.

While for unintentional ignitions of large hydrogen/air mixtures the resulting combustion rate should stay as low as possible, the aims pursued in the design of optimized combustion chambers are quite contrary: high energy release, small geometrical dimensions and high efficiency of the reaction. To reach those goals, one basic questions is, how the reaction rate and the stability of a flame can be influenced by means of induced turbulence. The degree of turbulence can both increase the reaction rate at lower degrees but also decrease the reaction rate due to quenching effects at high degrees of turbulence [3, 4]. Therefore the combustion process in a combustion chamber should be organized so that the degree of turbulence is as high as possible but below the level at which quenching effects reduce the reaction rate. The mechanisms involved are similar to the ones responsible for turbulent flame acceleration.

For the investigation of turbulent combustion behaviour of various hydrogen/air mixtures an explosion tube (6 m long, 66 mm inner diameter) equipped with opto-electronical sensors to detect the flame front velocity was used. Arrays of orifices with different blockage ratios and distances between two successive orifices were placed inside the explosion tube to study the effect of turbulence on the general combustion behaviour. *Fig 1* shows typical flame front velocities recorded along the axis of the explosion tube when an array of orifices with a blockage ratio of 69% and a spacing value of 490 mm, representing a multichamber geometry, is installed [5]. The blockage ratio is defined as the ratio of the area blocked by the orifices in the detonation tube to the area of the unblocked tube. Flame acceleration is mainly caused by a turbulent jet of hot gases emerging through the opening of the orifice into the next chamber. Depending on the hydrogen concentration different maximum burning velocities connected with different combustion modes are reached. In the mixture with 11% hydrogen the flame propagates as a normal deflagration. Its velocity increases rapidly at the beginning of the obstacle array, but quenching effects cause the velocity to drop after a distance of about 1.5 m and the flame is finally quenched completely before it reaches the end of the tube. At 14% hydrogen the flame is accelerated strongly to proceed as a supersonic flame through the obstacle array. Pressure losses prevent further flame acceleration to speeds near the detonation velocity. At the end of the obstacle region the velocity decreases again due to decreasing turbulence. The flame in the mixture with 24% hydrogen accelerates very fast to speeds close to the detonation speed and eventually

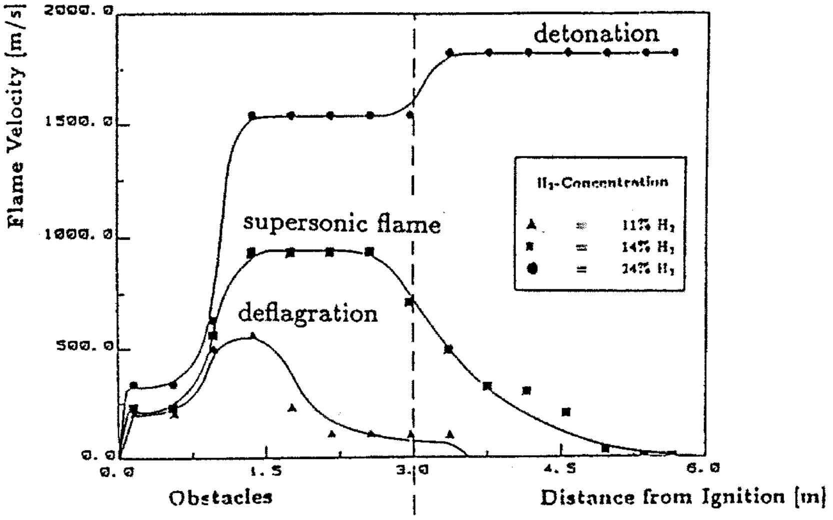

Fig.1 Flame velocity in detonation tube; obstacle distance 490 mm, blockage ratio 0.69

undergoes transition to detonation at the end of the obstacle array. A significant difference was observed in the combustion behaviour when the multichamber arrangement described above was replaced by an array of orifices with a blockage ratio of only 32%. Here the flame is accelerated by turbulence induced by the obstacles. *Fig. 2* shows the maximum flame front velocities reached within the obsatcle array for both blockage ratios used [5].

Due to the motion of the unburnt gas ahead of the flame the velocities obtained in the explosion tube are the added values of the velocity of the unburnt gases and the actual burning velocity. However, the burning velocity is the key parameter for stationary combustion. Therefore LDV measurements of the gas velocity are currently conducted in the explosion tube. The burning velocity can both be calculated from the difference of the gas velocity in front of and behind the reaction zone by applying the conservation laws of mass, momentum and energy as well as from the difference between the gas velocity ahead of the flame and the total flame front velocity as it is obtained from the opto-electronic sensors. Although these measurements are very difficult due to the extremely fast processes involved, first results indicate, that during the transition to detonation the burning velocity reaches values close to the critical burning velocity.

To investigate stationary hydrogen combustion phenomena, two combustion chambers had been installed. One is designed as a tube-type subsonic burner equipped with removable turbulence promoting obstacles for the investigation of the structure of turbulent flames as they appear behind such obstacles [6]. The other setup is a transsonic wind tunnel in which high speed hydrogen/air flames are examined [7].

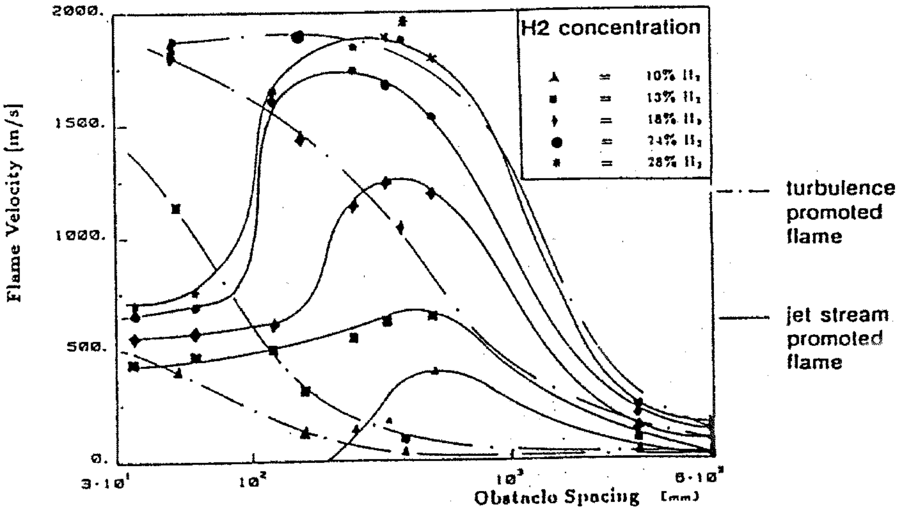

Fig.2 Maximum flame velocity as function of turbulence (represented by distance between obstacles)

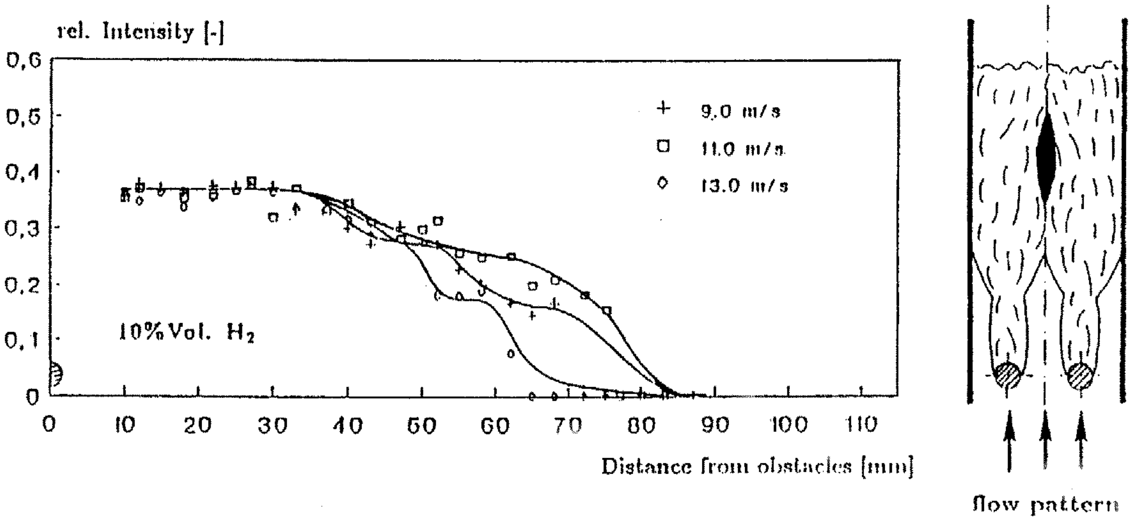

Fig.3 Hydrogen concentration profiles downstream of obstacles

The subsonic burner can be operated at various hydrogen concentrations and main stream velocities and the obstacle configuration can also be changed. Depending on the flow field induced by the obstacles the process of combustion varies. The method of raman scattering was used to simultaneously measure the concentration of H_2, N_2, O_2 and H_2O along the main stream axis of the burner. This simultaneous measurement of all species is achieved by the employment of a pulsed excimer laser as a high energy light source and an intensified diode-array detector as a highly sensitive detector. *Fig. 3* shows the profiles of the hydrogen concentration at main gas velocities of 9, 11 and 13 m/s when the burner is equipped with two parallel obstacles and the hydrogen content is set to 10% [6]. Each flame exhibits distinct non-reactive regions which are assumed to be caused by quenching effects within the flame. The number and position of these region is determined by the flow field which varies with the main gas velocity. This setup should also be suitable for future examinations to optimize combustion in a stabilized recirculation area at higher main gas velocities.

In the transsonic wind tunnel both the mixing of hydrogen and air as well as the stabilization of flames by induced recirculation zones are investigated over a wide range of main air flow velocities up to the transsonic region and different injection systems for hydrogen [7]. The distribution of hydrogen in air is detected by holographic interferometry. This measurement technique allows large regions to be examined with a single measurement. The stabilization of the flames is achieved by either one or two reward facing steps inducing recirculation zones. Like in the subsonic burner the method of raman scattering is employed to investigate the structure of the combustion zone. However, by using a pulsed dye laser and an intensified CCD-camera the obtained species distribution will be one dimensional instead of point measurements. First results of these investigations expected within the next few months.

References:

[1] Strehlow R.A.: *Combustion Fundamentals*; McGraw-Hill, New York ; 1984

[2] Bartlmä F.: *Gasdynamik der Verbrennung*; Springer Verlag, Berlin; 1975

[3] Brehm N.: *Ein Beitrag zum Phänomen des Übergangs Deflagration-Detonation*; Dissertation; TU München; 1987

[4] Brehm N., Mayinger F.: *Turbulent Flame Acceleration: The Transition from Deflagration to Detonation*; Proc. of Second Int. Symp. Heat Transfer; Peking; 1988

[5] Haibel M., Mayinger F., Strube G.: *High Speed Hydrogen Combustion: Former and Future Research Activities*; R & D-Support Group Aerothermodynamics of Combustion Chamber and Nozzles in the FRG Hypersonic Technology Programme; Internal Report; Aachen; 1990

[6] Mayinger F., Strube G.: *Struktur und Brenngeschwindigkeit hochturbulenter Wasserstoff-flammen*; BMFT- Abschlußbericht RS 1 500 769; FIZ Karlsruhe; 1990

[7] Haibel M., Mayinger F.: *Hochgeschwindigkeits-Wasserstoff-Luft-Verbrennung*; Annual Meeting of the SFB-project 255 in Munich; TU Munich; 1990