INFLUENCE OF TURBULENCE ON THE DEFLAGRATIVE FLAME PROPAGATION IN LEAN PREMIXED HYDROGEN AIR MIXTURES

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SUMMARY

Within the scope of safety considerations for nuclear reactors due to the possible release of hydrogen in the course of a hypothetical severe accident considerable efforts are put on the investigation into the propagation of turbulent, premixed hydrogen air flames. The present paper gives a short introduction to the experimental and numerical investigation of the HYMI and VOASM projects inside the IV FWP of the EC. Emphasis is put on the physics of turbulent reacting flows, the unstable dynamics of lean hydrogen-air flames and the interaction of flame fronts with turbulent flow fields as expected during a severe accident. Experiments are carried out at three differently scaled combustion chambers to investigate the influence of stationary flow fields and containment-typical obstacles on the combustion process. The diagnostics of turbulent reacting flows, applied within the present work, is based on sophisticated optical methods in order not to disturb the physical process itself by the sensor. The results of the experiments lead to an improvement of a recently developed combustion model.

1. INTRODUCTION

Due to the release of a huge amount of hydrogen during a hypothetical severe accident in a nuclear power plant, violent hydrogen combustion might be considered as challenging the containment integrity in the early phase. The assessment of hydrogen risk mitigation concepts as catalytical recombiners, deliberate igniters and additional mixing requires a satisfactory understanding of turbulent flame propagation, covering slow deflagration, turbulent flame acceleration and flame obstacle interaction. Since full scale experiments are not available and affordable to investigate all effects of hydrogen combustion and the corresponding loads, it is inevitable to simulate the whole sequence of combustion using different models. Therefore models describing the thermohydraulical processes during the combustion processes have to be developed and validated by small and medium scale experiments, taking advantage of new, highly sophisticated laser optical measurement techniques, like laser-Doppler-velocimetry (LDV) or laser-induced predissociation fluorescence (LIPF).

Two cost-shared projects will help to improve computer programs describing the thermohydraulical processes during a hypothetical severe accident:

1. "Improved Modelling of Turbulent Hydrogen Combustion and Catalytical Recombination for Hydrogen Risk Mitigation" N° FI4S-CT96-0017 (short "**HYMI**"), which has started 01.05.1996 with a duration of 36 months and
2. "Validation of a Simulation Methodology for Hydrogen Mixing, Catalytic Recombination and Deliberate Combustion" N° FI4S-CT96-0022 (short "**VOASM**"), which has started 01.01.1997 with a duration of 30 months.

2. WORK PROGRAMME

The two projects HYMI and VOASM are divided into several workpackages dealing either with experiments at different facilities or numerical simulation. In workpackage 1 of the HYMI-project flame propagation and the interaction of the expansion flow induced turbulence parameters on the burning velocity are measured at the medium scale facility L.VIEW (1490 litre) in Pisa. With a videocamera, the global flame behaviour is recorded, the two dimensional flow velocities and turbulence parameters are measured with a laser-Doppler-velocimeter.

A second series of tests will be performed to investigate the influence of an inert gas as a heat sink on the combustion process. For these tests steam is substituted by CO_2 to avoid condensation at the observation windows. Some of these tests will also be recalculated with the existing computer code NEVE.

As the flow and the turbulence in front of the flame are produced by the expansion of the exhausted gas and therefore by the combustion process itself, it is quite difficult to vary the turbulence parameters in a wide range, as this could only be done by changing the geometry. But the precise variation of the turbulence parameters in front of the flame is needed to investigate the influence of turbulence on the combustion process.

Therefore a new facility, called PuFlaG (∅ = 80 mm, l = 8 m), was built for this project in workpackage 2, where a single flamefront propagates against a steady counterflow. As this counterflow is produced by a fan, the rotation velocity of the fan and therefore the counterflow velocity can be controlled continuously. Highly sophisticated laser-optical measurement techniques allow an investigation of the flame with a very high spatial and time resolution. The results will deliver a relationship between the turbulence parameters and the flame acceleration in the regime of slow combustion as expected from deliberate ignition.

The increase of turbulence and flame acceleration due to containment typical obstacles is investigated in a third test-facility, called MuSCET (370 x 370 x 3000 mm), which is included in the program in the third workpackage. Inside several obstacles with low blockage ratios (BR << 50%) as well as high blockage ratios (greater than 50%) can be mounted. Parallel to the conventional instrumentation, a couple of laser-optical techniques are applied, allowing to measure the flow and burning behaviour with a very high accuracy.

The experimental results of the workpackages 1 to 3 will be used in workpackage 4 to improve the recently developed lumped parameter model for turbulent flame propagation DECOR, which is implemented in the RALOC code. As medium and small scale facilities can be instrumentated with newest optical measurement devices, the DECOR code will be verified, by calculating selected tests performed at the L.VIEW and MuSCET facilities.

The results of all workpackages will be used to calculate hypothetical real plant accident scenarios of two dry PWR containments. The comparison of two lumped parameter codes (RALOC and MELCOR) at two different PWRs (an actual Spanish-PWR and a KWU-PWR) will deliver important information about the capability of the two models.

In workpackage 4 of the VOASM project it is intended to model the interaction between fluid dynamics and the chemical reaction during the hydrogen combustion. Therefore the big amount of experimental data, delivered by mainly three hydrogen test facilities (L.VIEW, MuSCET and PuFlaG) not only lead to detailed information about the local flow parameters during flame propagation, but also provide data about the flame shape, flame curvature and local quenching zones.

3. PROGRESS OF WORK

3.A The DECOR combustion model (GRS-Köln)

The combustion model DECOR implemented into the lumped parameter code RALOC covers the field of deflagration near ignition limits and moderate flame acceleration, as expected from deliberate ignition in the course of severe accidents [10]. In this zone model, the flame separates two districts – burned and unburned gas – inside a control volume. Both districts are linked by the chemical reaction of hydrogen combustion as shown in figure 1, so that mass and energy are transferred from the unburned part to the burned part. The total displacement of the flame front inside the volume can be split into a burning term and the gas expansion of the burned gas due to the higher temperature of the exhaust gas:

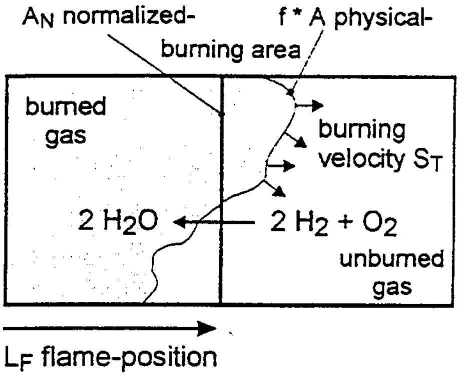

Figure 1: The zone model of DECOR

$$\underset{\text{combustion}}{S_T * f * A_N} + \underset{\text{expansion}}{\frac{dV_{EXP.}}{dt}} = \underset{\text{total displacement of the flame}}{\left(\frac{dL_F}{dt}\right) * A_N} \tag{1}$$

In this equation, the real physical burning surface is simulated by multiplying the normalised area A_N by a " flame bending factor" f.

In the case of a severe accident, due to the complex geometric structure of the containment, turbulent flame acceleration must be expected. An approach for the turbulent burning velocity S_T in relation to the laminar burning velocity S_L, which can be found in literature [13, 14], is given for example by Koroll [13]:

$$S_T / S_L = \left[1+B*(u'/S_L)^2\right]^{0.5} + u''/S_L \tag{2}$$

where B is an experimental factor, which according to Koroll can be assumed to be 16, and u'' is the flame induced turbulence:

$$u'' = S_L\left[1-\exp(-u'/S_L)\right](\rho_u/\rho_b - 1)/\sqrt{3}. \tag{3}$$

Similar equations were developed by other authors, e.g. Beauvais [3].

One can see, that the acceleration of the combustion process is mainly driven by the turbulent fluctuation velocity u' in front of the flame, which enhances the molecular heat- and mass transfer in front of the flame. Equation (2) is the result of experiments with hydrogen concentrations in the range 12%-60% by volume. Hence, this equation is to be verified by experiments in the regime of very lean hydrogen air mixtures, as expected at deliberate ignition.

Nevertheless, nearly no investigations are presently available for two very important dimensions needed for equations (1) and (2): The flame stretching factor f and the r.m.s. velocity fluctuation in front of the flame of the deflagration induced expansion flow inside buildings. In the following, three different experimental set-ups are described to measure these dimensions especially for containment typical configurations.

3.B The L.VIEW test facility (UNI-Pisa, TU-München)

The L.VIEW test facility offers the opportunity to perform medium scaled deflagration tests with full optical access from two directions. The inner dimensions of 677 x 677 x 3200 mm lead to a total volume of 1490 litre, which is divided into two rooms. The first room has a volume of 485.5 litre and is separated from the second room by a wall with a central round orifice of 10 cm diameter. Two axial fans inside the dividing wall ensure an homogeneous hydrogen-air mixture before ignition, which is checked by 3 hydrogen concentration sensors in each room. The conventional instrumentation consists of 7 high-speed piezo-capazitive pressure transducers and 7 thermocouples which are analysed by a high speed analog to digital converter card, installed into a personal computer. The moment of spark ignition is also recorded by the computer. To visualise the flame propagation, a videocamera with a frame rate of 25 Hz is used, recording the whole combustion process inside the facility simultanously through the front windows and, reflected by a 45° mirror, also through the top windows. As the wavelength of the naturally emitted light of the hydrogen flame is in the invisible ultra violet region (around 308 nm), aerosols of a NaCl solution are added, which are stimulated by the high combustion temperature and therefore emit visible light at the flame front. As the flame speed especially in the first room is quite slow, the relaxation time of the NaCl chemiluminescence can be considered being very short compared to the flame velocity.

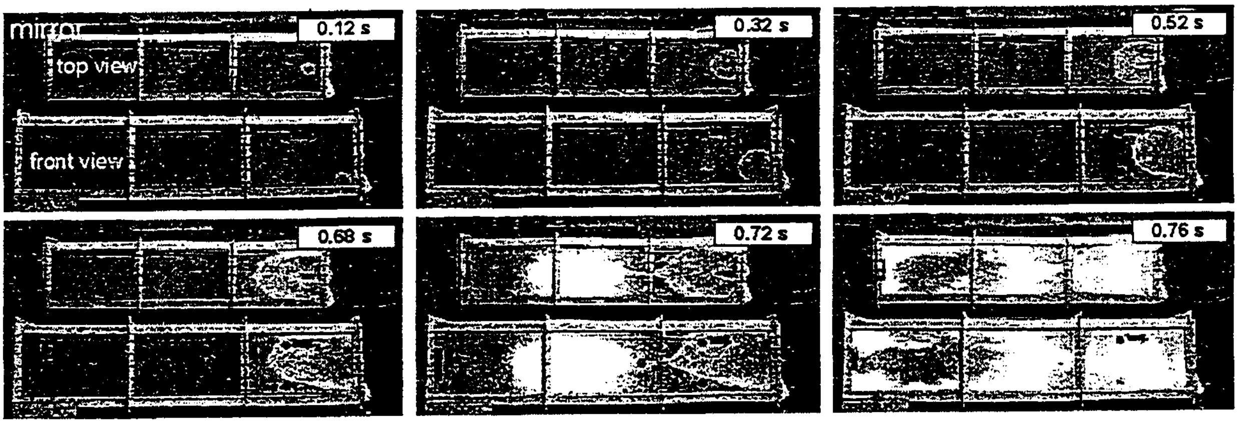

Figure 2: Selected frames of the combustion process in the L.VIEW facility with 9.5 vol.-% hydrogen in hydrogen-air. A mirror above the chamber enables to observe the flame from the front and from the top side simultaneously (time relative to first image with a flame).

In figure 2 selected frames of an 9.5 vol.-% hydrogen in hydrogen-air flame are shown. After ignition, which takes place at the right bottom of the first room, a spherical flame can be observed at the very beginning of the combustion process. Due to the buoyancy of the hot exhaust gas the flame moves preferably upwards before the influence of the wall opening becomes evident. As the expansion flow has to follow the equation of continuity, a high acceleration of the gas takes place, caused by the sudden reduction of the free cross section area. As soon as the flame reaches the second room, hot jet ignition takes place, which leads to a high flame acceleration. Due to the sudden energy and pressure release in the second room a backflow to the first room takes place, which leads to a fast burn-out of the first room. This burn-out can also be seen on the pressure-plots (example figure 3), where, caused by the combustion process, a slight increase of the pressure in the first room is followed by a higher pressure release in the second room, before the maximum pressure is measured in the first room again.

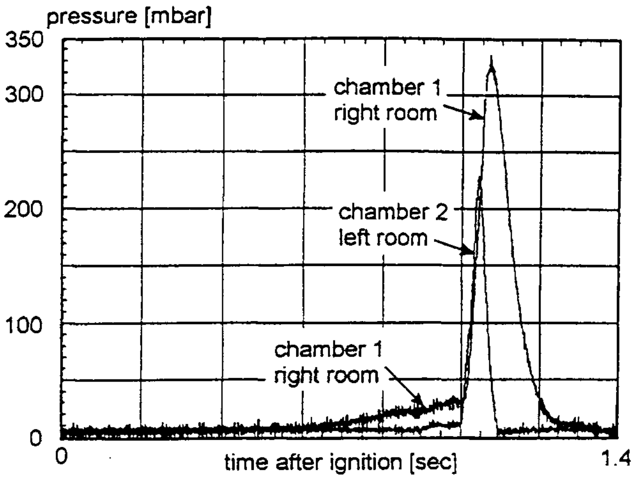

Figure 3: Pressure trace of an 9.5-vol.% H_2 in H_2-air flame in the L.VIEW facility.

As the hot jet ignition takes place very fast, it cannot be analysed with an ordinary videocamera. Therefore the Schlieren technique combined with a high speed video device was used to visualise the flame propagation. As the dimension of the lenses is limited, small scale tests were performed in Munich in a combustion chamber with an inner diameter of 80 mm, also divided into two rooms by a wall with a round opening of 16 mm. The high speed videocamera was driven at a framerate of 9000 frames/s, producing a total of 1000 frames. Figure 4 shows an example of a series of images taken at this facility with 12%-vol. hydrogen in hydrogen-air. The images give a good impression of the dynamics of the process, but one has to keep in mind, that with Schlieren the density gradient of the gas and not the flame itself is visualised. So it is not possible to distinguish between the flame and the exhaust gas. Only the very leading contour can be identified as the flamefront. However, due to the limits of spatial resolution in depth, Schlieren photographs cannot resolve the structure of strongly convoluted flames.

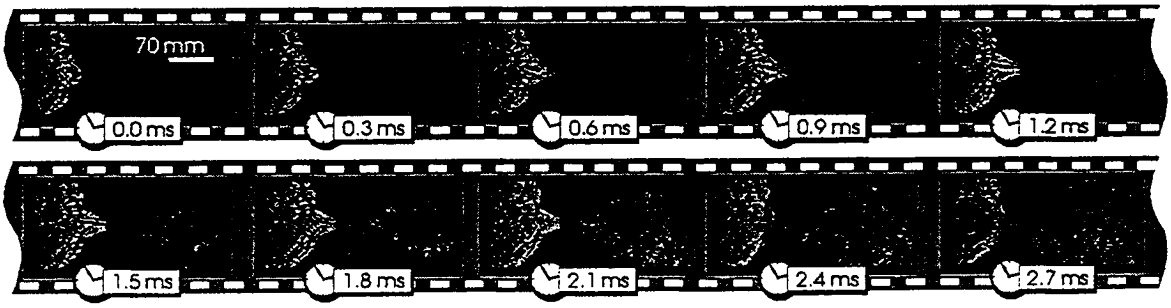

Figure 4: Jet ignition in an 80 mm diameter tube with a wall opening of 16 mm; 12 vol-% H_2 in H_2-air

The experimental results of the tests shown in figure 2 and 3 so far, give an information over the total flame displacement (equ. 1) by analysing the three-dimensional flamecontour and the burned volume. The flame bending factor *f* of equation (1) can also be determined in the same way, as done with earlier tests [6, 7].

A way has now to be found to measure the flow velocities and turbulence parameters just in front of the flame. Since for the simultaneous measurement of turbulence and flame speed conventional hot-wire anemometer cannot operate satisfactorily in a combustion environment, sophisticated laser anemometry must be applied. With this method it is possible to measure the two-dimensional velocity of small particles inertialess and non-intrusive with a datarate of up to 10 kHz. The used Laser and optical system leads to a measuring volume diameter of 199 µm and a measuring volume length of 1.51 mm, which is horizontal and perpendicular to the main flow direction. As tracer particles TiO_2 with a size of 1 µm were used, which ensure

a high tracking ability to the mixture flow. As TiO_2 is not combustible, LDV signals also in the flame and in the exhaust gas are recorded. Additional velocity signals arrive from the approximately 7 µm big NaCl aerosols used for the flame visualisation as described above. Figure 5 shows a typical two dimensional LDV velocity plot as a function of time at the right room in figure 1. As expected, an increase of the flow velocity takes place after ignition, due to the expansion flow, described in equation (1). After 857 ms, the NaCl aerosols dissociate, which can be seen clearly by a sudden decreasing of the datarate. As a small change of both velocity components can be observed exactly at the same time, this can be considered as the arrival time of the flamefront (compare figure 5). The increasing of both velocity components right after the flamefront indicates the expansion flow of the hot burned gas.
The velocity fluctuation in front of the flame can be used to determine the turbulence intensity. As the mean velocity as well as the r.m.s. velocity are defined for stationary flow only, some assumptions regarding these dimensions have to be made. For this measurement position in the first room the mean velocity was calculated for each point as the mean value of the last and following 50 measurement values. After that, the r.m.s. velocity was determined for a certain timespan in front of the flame. As, contrary to a stationary flow, u' changes by time, the better statistics achieved by evaluating a bigger timespan must be paid by evaluating data longer before the flame, which have no influence on the combustion process. Evaluating a timespan of 5 ms leads to an amount of about 250 particles, which can be considered as a good compromise.

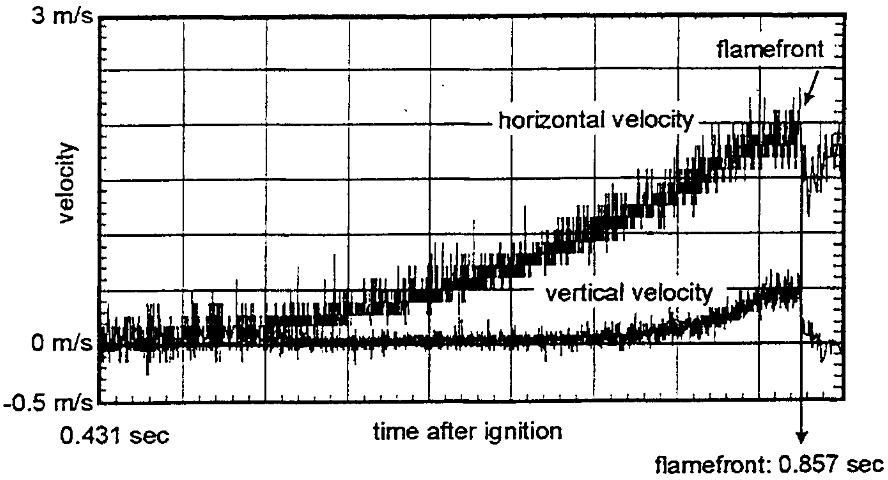

Figure 5: Typical LDV-plot of a 9.5 vol.-% H_2-air flame in the LIEW facility

The second main information, which is evaluated from the LDV plots, is the horizontal mean flow velocity just in front of the flame. This value corresponds directly to the expansion term in equation (1). As the total flame displacement and the stretching factor can easily be determined from the video, as described earlier, the only unknown parameter in equation (1) is the turbulent burning rate S_T. We now not only have the possibility to calculate the turbulent burning rate by the equation of Koroll or Beauvais but also to verify the result for the geometrical configuration at the L.VIEW facility as we know all other terms in equation (1). The experiments at the L.VIEW facility, described above, were performed in April and May 1997, the evaluation of the data is still in process and will be finished this year.

3.C The “Pulsed Flame Generator (PuFlaG)“ test facility (TU-München)

The L.VIEW combustion chamber offers the opportunity to investigate the interaction of the combustion induced expansion flow and the turbulent burning rate at a certain geometry. Hence, the turbulence parameters in front of the flame can only be varied by changing the geometry of the L.VIEW facility. To enhance an combustion model, a systematic investigation of the relationship between flow parameters and chemical reaction is needed. Therefore a continuous variation of the turbulent flowfield would be required. This cannot be done at the L.VIEW facility, as the turbulent flowfield is created by the gas expansion of the combustion process itself.

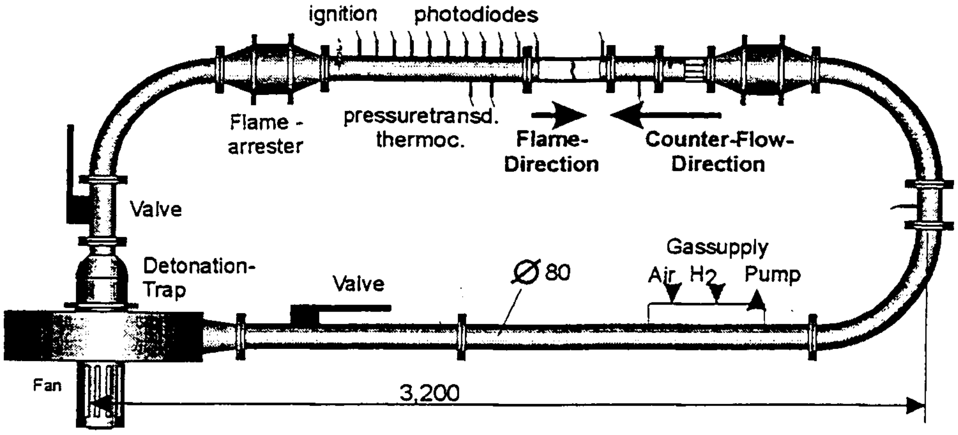

Figure 6: The PuFlaG test facility

Therefore a new combustion chamber was built at TU-Munich, which makes it possible to generate a steady turbulent flow field of a hydrogen-air mixture with a fan, before the combustion process itself is started. By changing the rotational speed of the fan and by applying different turbulence enhancing grids, the mean velocity as well as the turbulence parameters can be varied continuously and the fundamental influence of these dimensions on the burning rate can be investigated under clean circumstances. The facility, as shown in figure 6, has an inner diameter of 80 mm and a total volume of 95 litre, the optical test section has a length of 200 mm with full optical access from four sides. Hence, the above described problem at the L.VIEW facility, of the very short time span in front of the flame to measure the flow velocity and turbulence intensity, can now be solved by measuring the steady flow before the combustion process with a laser-Doppler-velocimeter. Like at the L.VIEW facility, the influence of the flame to this steady counterflow can also be determined with the same technique.

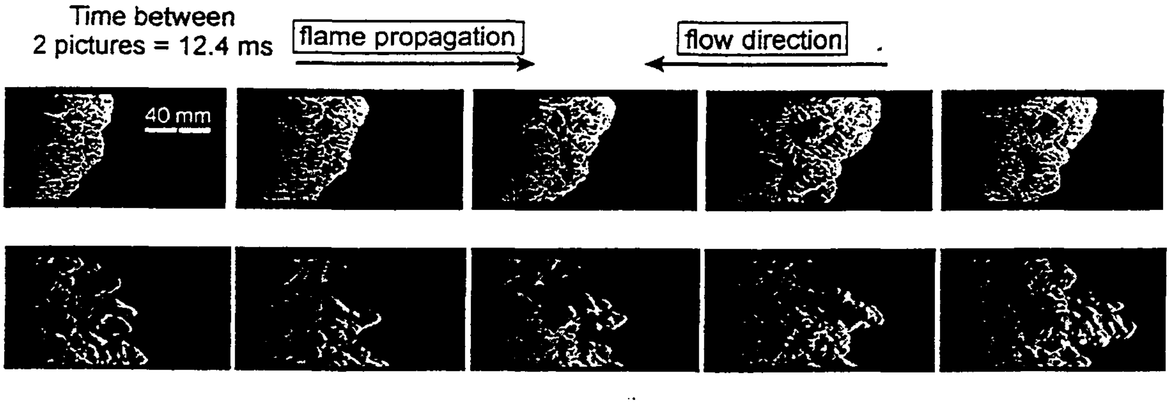

Figure 7: Examples of series of Schlieren images of 10 vol.-% H_2 in H_2-air flames in the PuFlaG facility; upper row: 1 m/s counterflow velocity; lower row: 4 m/s counterflow velocity

After ignition, the flame front burning against the steady turbulent flowfield is studied with various, mainly optical measurement methods, which will deliver a database of the combustion process in the regime of slow deflagration. Classical Schlieren technique in combination with newest high-speed video devices allow to visualise the propagation of the leading flame contour. Similar to the L.VIEW experiments, counting the frames leads to the absolute flame velocity.

Several tests in the regime of slow deflagration between 8 to 12 vol.-% of H_2 in H_2-air at various counterflow velocities were carried out, using three different types of turbulence enhancing grids. Two examples of Schlieren series of 10 vol.-% of H_2 in H_2-air are shown in figure 7. At the upper row flame propagation with a very low counterflow velocity (1 m/s) and correspondingly a low r.m.s. velocity leads to an integral flamestructure, which can be compared to the flames observed at the L.VIEW facility during the beginning of the combustion process in the first chamber. By applying a higher r.m.s. velocity, a complex flamestructure appears, together with a change of the integral burning velocity.

As Schlieren photographs give an integral picture of the density gradient in depth, structures on convoluted flames cannot be resolved. To solve this problem, laser-light sheet methods have been developed, taking advantage of the fluorescence properties of OH radicals, which are a intermediate product of the complex hydrogen combustion process and therefore can be used to determine the reaction zone. Within a thin lightsheet (about 0.3 mm), the OH-radicals are electronically excited by a laser with a pulse duration of 17 ns. Returning to their original quantum state, the OH-radicals emit fluorescence light, which can be observed with an intensified CCD-camera [9, 11]. Figure 8 shows a comparison between 9 vol.-% H_2 Schlieren and LIPF images at several concentrations, recorded at the MuSCET facility in Munich, which is described later.

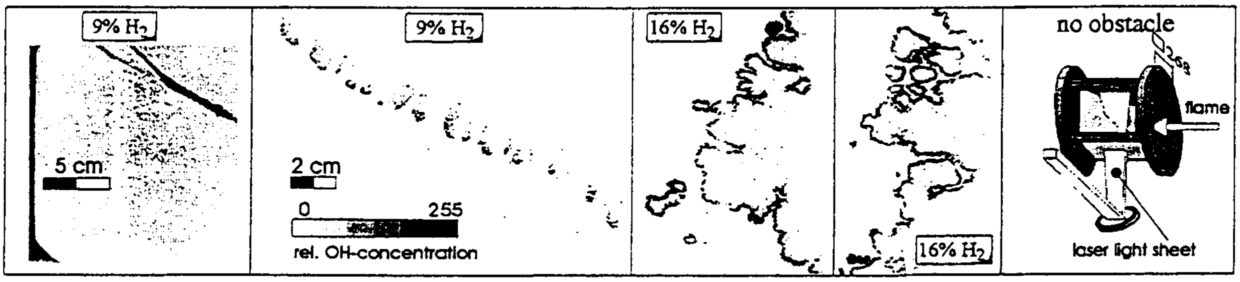

Figure 8: Ultra short exposure LIPF images of a 0.3 mm thin slices, cut out of flames in a smooth tube, compared to a Schlieren image (very left).

The Schlieren image shows a very smooth flamefront, which also can be observed at the L.VIEW facility with the videocamera. By applying the laser-induced predissociation fluorescence (LIPF), which has a very high local resolution in depth, highly reactive areas can be distinguished from locally quenched zones, where nearly no reaction takes place. This effect at lean concentrations is caused by the high diffusivity of H_2 in air, which dominates the stabilising effect of positive curved flame sections. The corresponding negative curved cusps with a diminished preheating zone, contain accordingly less molecules of the deficient reactant. So the effective laminar burning velocity appears to be higher at the crest of the cusp and lower at the corresponding trough in comparison to the average laminar burning velocity [2].

The number of interruptions of the flame front provide evidence for the quenching of flame shreds, which are driven upwards by buoyancy. With increasing H_2 concentration, the effect of buoyancy becomes less dominant. At 16 vol.-% H_2, the flamefront does not show any preferential angle or orientation anymore. The LIPF-images of the unobstructed flames at 16 vol.-% H_2 represent the typical structure of wrinkled and corrugated flamelets. By a closer look to the flame images, a fine scale sub-structure of the flame pockets becomes visible.

3.D The Munich Square Cross Section Explosion Tube MuSCET (TU-München)

Within the scope of this workpackage, selected tests of the MuSCET experiments to investigate the influence of containment-specific flow obstacles on the propagation of hydrogen-air flames, are to be recalculated with the RALOC code.
For that purpose, obstacles with a low blockage ratio (BR << 50%, tube bundles, gridiron) as well as obstacles with a high blockage ratio (BR > 50%, plate with rectangular opening) are applied to a combustion chamber [8]. Passing that kind of obstacles, turbulent hydrogen-air flames can be strongly accelerated. The increase of pressure involved represents an immediate danger potential for the containment safety tank. The mechanisms of flame acceleration at high blockage ratios (jet ignition) basically differ from those at low blockage ratios (turbulence promotion) and they have not yet been sufficiently investigated. The present project contains a classification of several typical obstacle configurations concerning their flame accelerating effect. The fundamental physical phenomena are identified and quantified as far as possible. The results are used for designing a detailed burning law, that makes it possible to evaluate the flame front propagation under the influence of flow obstacles, based on an already existing flow code. The experiments were finished successfully beginning of this year, selected tests are now prepared for a detailed study with the RALOC code.

3.E Real Plant Application (GRS-Köln, UNI-Madrid)

All work done by now deals with detail problems in the field of combustion, without delivering summarised information of the whole scenario during a severe accident in a nuclear power plant. The influence of hydrogen release and the combustion on the thermohydraulic behaviour of the whole system at an actual Spanish PWR containment and a KWU-PWR containment will be compared using two different numerical codes. With the applied lumped parameter codes it is possible to simulate the accident scenarios inside the complex geometry of the hole power plants over a period of several days.
The application of the RALOC code from GRS Cologne and the MELCOR code from Sandia National Laboratories USA at real plant geometries will show the capability of the used combustion models.

4. CONCLUSIONS

In the course of a hypothetical severe accident, a big amount of hydrogen is considered to be released inside the reactor containment. In combination with air and steam, a very explosive mixture endangers the containment integrity. In order to judge the different risk mitigation concepts like deliberate igniters, catalytical recombiners and additional mixing as well as to apply them correctly, a precise knowledge of the combustion process is needed. The present work shows, that not only detonation but also deflagration at the beginning of the combustion process can be a serious risk for the compartment integrity. With three different types of small and medium scale experiments, the influence of turbulence, obstacles and containment geometry on the integral combustion process, the flame structure, burning rate, pressure- and temperature strain is investigated. The results, which are implemented into the recently developed DECOR model, used for the calculation of the combustion inside the RALOC code, lead to a tool for the compartment design, as far as the temperature and pressure strain is concerned.
The work shows, that the interaction of the flame with obstacles can lead to a high flame acceleration and pressure release. Therefore the correct positions of deliberate igniters and catalytical recombiners cannot only be guided by any λ criteria to avoid detonation. It must also

be taken into account, that other violent combustion modes like hot jet ignition promoted by the containment geometry can be a serious danger for the infrastructure inside the compartment.

Due to the alternating pressure stress, as noticed at the experiments, big effort must be given to the design of the subcompartment walls, as a failure of the structure would highly endanger the reactor pressure tank.

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