Stratified Hydrogen Combustion and Water Spray Mitigation Tests in a Containment of 220 m^3

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ABSTRACT

A series of 11 large scale experiments was performed at the HYKA test site in order to experimentally simulate different flame propagation regimes in a stratified hydrogen-air atmosphere. The total volume of the facility is equal to 220 m^3 with an aspect ratio H/D=1.5. Hydrogen concentration was kept constant (7% vol. in air) for all the experiments. Combustion of a stratified hydrogen-air mixture with different steepness of hydrogen concentration gradient (I: 10=>7=>4% H_2; II: 12=>7=>2% H_2; III: 14=>7=>0% H_2) was investigated and then compared to uniform (7% H_2) mixture combustion using Background Oriented Schlieren (BOS) method combined with high speed camera, pressure and temperature measurements. The mixture was ignited in the center. Ambient initial conditions were 293 K and 1 bar in the tests. Two tests with water spray suppression system demonstrated not a mitigation efficiency but even promote the combustion process due to the generation of highly turbulent flow. The experimental results demonstrate that the highest hydrogen concentration at the top of the containment plays a governing role in combustion process leading to much higher combustion pressure and temperature compared to the combustion of uniform mixture of the same amount of hydrogen in the volume (equal to 7% H_2).

KEYWORDS: Hydrogen, combustion, stratified mixture, water spray mitigation.

INTRODUCTION

Hydrogen release due to the Loss of Cooling Accident (LOCA) and then Molten Corium-Concrete Interaction (MCCI) accidents may lead to formation of a stratified layer of hydrogen-air mixture at the top of the reactor building. Its immediate ignition due to operating ignitors or catalytic recombiners results in fame propagation through a gradient of reactivity and establishing of high pressure and temperature in a containment or reactor building. Such a scenario can be the cause of loss of integrity or damage of the structure. Thus, hydrogen explosion following an accidental hydrogen release in a containment is one of the important safety issues in the case of LOCA and MCCI accident as discovered due to the post-accident analysis of Fukushima-Daiichi accident in Unit 1 and Unit 3 [1-3].

A number of CFD modelling have considered different scenarios of hydrogen distribution in a containment of nuclear reactor [4-7]. Depending on hydrogen inventory, geometry of the containment and exposure time for hydrogen distribution, it might initially be a vertical column (t = 300 s) or, later on, a stratified layer of hydrogen-air mixture (t = 1200 s) (Fig. 1). Similar hydrogen distribution profiles were obtained in [5] for t = 9290 s and t = 9358 s (Fig. 2).

There is no possibility to experimentally reproduce such calculations in real scale in order to validate the CFD codes. The only LACOMECO project proposed to European organizations an

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access to large scale experimental facilities at Karlsruhe Institute of Technology (KIT) to study severe accident safety issues, including the coolability of a degraded core, corium coolability in Reactor Pressure Vessel (RPV), melt dispersion to the reactor cavity, and hydrogen mixing and combustion in the containment [8-9]. Among all facilities the HYKA test site with a number of large and medium scale experimental vessels from 9 to 220 m^3 was chosen to investigate hydrogen behavior in a containment geometry under well controlled conditions. Several experiments have been performed using HYKA facilities to investigate the hydrogen-related phenomena in severe accidents, including hydrogen distribution, hydrogen combustion and hydrogen mitigation measures.

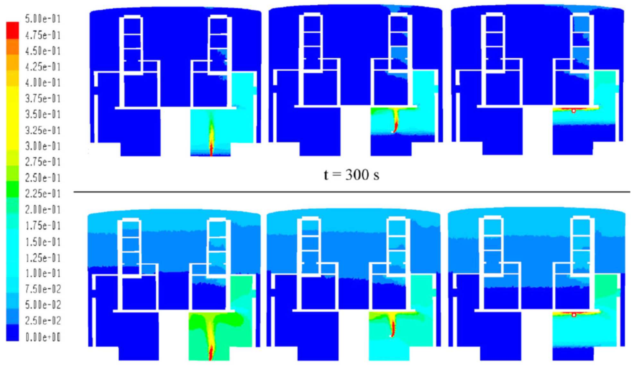

Fig. 1. Distribution of hydrogen for different injection time [4].

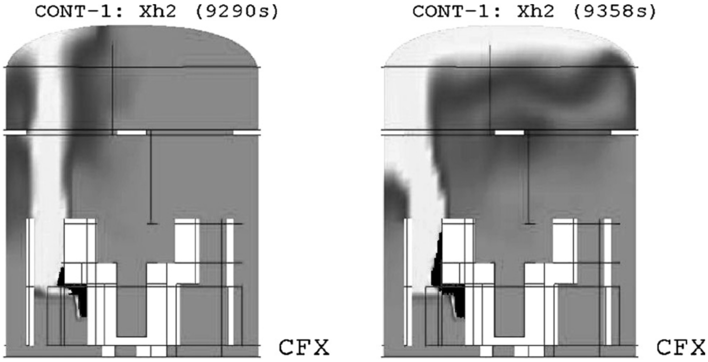

Fig. 2. Hydrogen distribution at a vertical plane through the break room of the PWR Westinghouse case [5].

A set of experiments performed in the framework of LACOMECO project is devoted to flame propagation in an obstructed large scale facility A3 (V = 33 m^3) with initially vertical hydrogen concentration gradients. Positive and negative concentration gradients with respect to gravity are created prior to ignition in the range from 4% to 13%, and the process of flame acceleration is investigated depending on hydrogen concentration gradient and ignition positions [10-11]. Especially, a combustion model was implemented in Europlexus code. This model was successfully applied and validated for some of the tests, and the numerical data for overpressure and flame times of arrival are compared with experimental results.

Very specific problem of local or global flame extinction during the flame propagation through the longitudinal concentration gradient should also be investigated for the complex 3D geometry. For instance, the global flame quenching occurred at the distance of 8 m from ignition point (Fig. 3) in the case of flame propagation in a non-uniform mixture with a gradient of hydrogen concentration from 14% to 6% H_2 in a DRIVER shock tube of ID=174 mm and L = 12 m [12]. It happens independent of reaching the speed of sound for the flame. It was found that the quenching issue in a tube geometry was reached at relatively high local hydrogen concentration of 8% H_2 (two times higher than the lower flammability limit) due to the turbulent flow produced by the obstructions with high blockage ratio in presence of descending mixture reactivity.

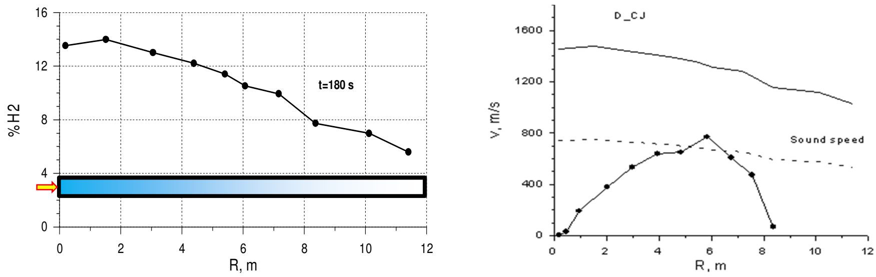

Fig. 3. Hydrogen concentration profile (left) and dynamics of flame propagation velocity with a concentration gradient 14→6% H_2 (right) [12]. A sub-image of DRIVER shock tube with ignition position is shown (left).

During a hypothetical severe accident in a nuclear reactor and reactor core degradation hydrogen can be produced and then accumulated as a stratified layer of hydrogen-air mixture at the top of reactor building [4-5]. Different flame propagation regimes of such a mixture may occur. Water spay as a combustion suppression system can be used.

In the present ALISA project, we choose the HYKA-A2 facility and analyze the experimental data obtained during the project. The HYKA-A2 facility was chosen as the most representative for the scaling analysis. The advantage is that the real objects as EPR or APWR reactor containments and HYKA-A2 facility are related as 8.3:1.5 in terms of the scale. They also have almost the same aspect ratios (H/D ratio): 1.3(EPR):1.5(A2). This might be a very important issue for the experimental scaling of combustion processes in a containment of nuclear reactor.

OBJECTIVES

The main purpose of the experiment is to investigate the influence of hydrogen stratification and water spray mitigation system on combustion characteristics in a large scale of the combustion vessel HYKA A2. The experimental data are also required to be used as benchmark experiments for CFD codes and lamped-parameter models validation of large scale hydrogen deflagrations.

To do that a series of experiments on flame propagation in a stratified hydrogen-air mixture in a large scale facility HYKA-A2 (220 m^3) has been performed. Three different vertical linear hydrogen concentration gradients of 14→0, 12→2 and 10→4% H_2 with the same amount of hydrogen equal to 7% of the average concentration are investigated. Experiments with central ignition point with uniform and non-uniform hydrogen concentration are performed. A mitigation test with water spray on flame suppression is also conducted.

Dynamics of the combustion process is registered by measuring of temperature, pressure, acoustic effects and use of optical observation by Background Oriented Schlieren Method (BOS).

EXPERIMENTAL DETAILS

Experimental facility

The largest safety vessel A2 of the KIT HYKA test site with main dimensions of 6 m id and 9 m height provides an empty test volume of about 220 m^3 (Fig. 4). It is designed for fire and explosion tests with an operating overpressure from -1 to 10 bar. Depending on the purpose, large samples or structures can be tested inside, or the whole vessel can be used as a test volume. The vessel can be evacuated or filled with inert atmosphere of nitrogen or steam and be heated up to 150 ^{o}C. The vessel is equipped with many vents and ports for experiment and measurement set-ups as well as with windows for visual observations. It has 3 vents of 2000 mm id, 4 vents of 700 mm id, 5 vents of 400 mm id and about 40 vents of smaller inner diameters (50-250 mm). The measuring system consists of thermocouples array (gas temperature, flame arrival time); piezoelectric and piezoresistive gauges (initial pressure, explosion pressure); gas analyzer and mass spectrometer (to control mixture composition); sonic hydrogen sensors, photodiodes and ion probes (flame arrival time, flame speed), strain gauges (deformations). The data acquisition system is based on multi-channel (64) ADC with a sampling rate of 1 MHz. The vessel was successfully tested within LACOMECO Project using 2 large scale combustion experiments of hydrogen-steam-air mixture (10:25:75 = H_2:H_2O:air) at 1.5 bar of initial pressure and 90 ^{o}C temperature [8-9].

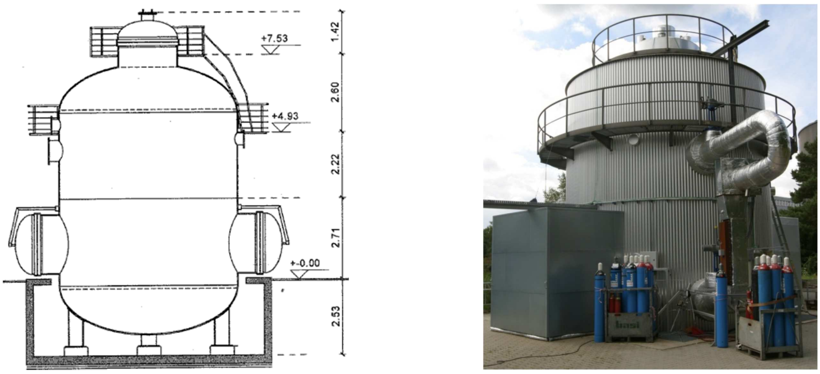

Fig. 4. HYKA-A2 facility: main dimensions and a side view.

Test matrix and experimental technique. Measurements

Full arrangement of the measuring system is schematically shown in Fig. 5. The measurement system consists of 7 pressure sensors, 24 thermoelements, 7 H_2-sampling probes, 3 Stemmer high speed cameras (70 fps), 2 Canon cameras (30 fps), 2 finger cameras (25 fps) and 2 microphones. The facility is also equipped with a gas filling system, sampling probes and concentration measurements and ignition device. Two ventilators and a system of pneumatic valves also belong to the gas filling system. Safety alarm sensors were installed inside the A2-vessel to control a flammable hydrogen concentration and minimum oxygen concentration for personal in between the experiments to be able to work for test preparation inside the vessel A2. A detailed scheme of gauges location inside the test vessel is shown in Fig. 5.

Three different types of pressure sensors were used in order to test their availability for such combustion processes. The location of all three types at the same position H = 3.27 m allows to compare the pressure signals with respect to thermal sensitivity of pressure sensors. All the sensors were mounted flush to the internal wall surface to measure the level of combustion pressure and dynamics of combustion. Initial part of the pressure records was used to evaluate an initial quasi-laminar flame speed using so called pressure method in an assumption of spherical flame shape.

To eliminate the effect of mechanical vibrations all the gauges were sitting inside the massive led brick mounted directly to the side wall. It was four layers of pressure measurements at the altitude H = 1.77, 3.27, 6.07 and 9.80 m above the floor. The temperature compensation is operating in the range 27–232 °C, with a thermal drift of ±5% of full scale output for the Kulite transducers, for instance. The compensated operating high temperature range for Kistler type was 70–140 °C. The

PCB pressure transducers had no thermal compensation. The total record time was about 10 and 20 seconds with a time response of 1 microsecond.

An array of 24 thermoelements type K was installed to cover 4 radial positions and 8 positions at the centerline (R = 0). The positioning of thermoelements is also shown in Fig. 5. Thermocouples (Type K [NiCr/Ni] 0.36 mm, open tip) allow to measure local temperature and also flame arrival time in order to measure flame shape and flame propagation velocity. The data processing is based on the data of arrival time against thermocouple co-ordinate (x, H). The procedure allows to interpolate all positioned arrival time points to build isochrones, the lines of equal flame arrival time which correspond to flame shape at different moments.

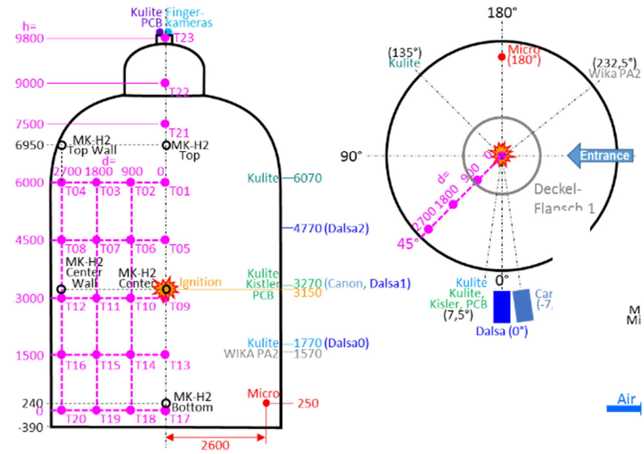

Fig. 5. Positions and orientation of sensors: thermocouples (T); gas analyzer (MK-H2); microphone (Micro). A center ignition position (CI) is shown.

Gas filling system

Three different vertical linear hydrogen concentration gradients of 14→0, 12→2 and 10→4%H_2 with the same amount of hydrogen equal to 7% of the average hydrogen concentration have been created using a gas filling system. Required amount of hydrogen equal to 7% H_2 in average was injected with or without mixing by fans. Mixing option was only used for uniform compositions. To create a gradient of concentration, hydrogen-air mixtures of required concentrations (14, 12, 10, 7, 4, 2% H_2) were injected at different altitude and then equilibrated due to a turbulent diffusion. Local hydrogen concentration was measured by 5 to 7 sampling probes. Then, a thermo-conductivity gas-analyzer Fisher-Rosemount was used to measure hydrogen concentration in air. The accuracy of measured concentrations was within the limit ±0.15%. 5 measuring points were located at the centerline and two at the side wall. The level of 7% H_2 was always kept at the ignition point in the center. Required hydrogen concentrations at the top (14, 12, 10% H_2) and bottom (4, 2, 0% H_2) have also been well established and controlled.

Experimental conditions and main experimental results are shown in Table 1. It includes a series of experiments with stratified compositions of 3 different gradients, two tests with uniform mixture of 6.5 and 7% H_2, one test with upper ignition position (UI) and two experiments with water spray (SPRAY). Table 1 mentions maximum combustion over-pressure and temperature and characteristic combustion time, $t_{1/2}$, as integral characteristics of combustion process. Characteristic combustion velocity can roughly be evaluated as a ratio $U_f = R/\ t_{1/2}$.

Since the mixtures to be tested have so called Lewis number Le = 0.33 (Le < 1), the flame for such compositions might be characterized as unstable due to thermal diffusion instability, with a trend to produce highly wrinkled cellular flames. Such an unstable flame will be very sensitive to acoustic instability as well [4, 5]. The expansion ratio σ is not only a factor of visible flame speed amplification but also a criterion for the capability of the flame to accelerate to speed of sound. According to paper [6], the threshold between subsonic and sonic flames for hydrogen-air at ambient pressure and temperature is $\sigma^* = 3.75$. This means that in presence of obstructions in a proper geometry the test mixtures with local hydrogen concentration above 11% have a potential to efficiently accelerate to speed of sound and then even to detonate.

Table 1. HYKA-A2 test conditions and main results (T_0 = 300 K, P_0 =1 bar)

Test#	Mixture % [H_2]	Spray	Ignition	Time $t_{1/2}$ [s]	Over-pressure [bar]			Temperature
					KU*	KI*	PCB*	T_{max} [°C]
Test1	**6.5**	**DRY**	**CI***	**12.66**	**0.096**	**0.095**	**0.023**	**261**
Test2	**7**	**DRY**	**CI**	**4.67**	**0.161**	**0.162**	**0.048**	**371**
Test3	10-7-1	DRY	CI	4.46	1.456	1.441	0.864	823
Test4	10-7-4	DRY	CI	4.59	1.393	1.378	0.504	809
Test5	12-7-2	DRY	CI	2.53	1.701	1.693	0.807	1338
Test6	12-7-2	DRY	CI	3.34	1.594	1.579	1.443	991
Test7	14-7-0	DRY	CI	3.05	(-)	1.632	1.809	1025
Test8	14-7-0	DRY	CI	3.24	1.559	1.544	1.766	1680
Test9	**14-7-0**	**SPRAY**	**CI**	**2.72**	**1.689**	**1.66**	**1.829**	**1138**
Test10	**14-7-0**	**SPRAY**	**CI**	**2.72**	**1.793**	**1.711**	**1.403**	**1419**
Test11	14-7-0	DRY	UI*	0.71	1.712	1.708	1.554	988

Note: CI – center ignition; UI – upper ignition; KU – Kulite pressure sensors; KI – Kistler pressure sensors; PCB – PCB pressure sensors

Ignition

A hot wire provided an ignition of the test mixtures in 2-3 minutes after the mixing procedure to suppress a turbulence generated by mixing fans. A center ignition (CI) position at the centerline H = 3.15 m from floor level was used in the tests where the concentration kept constant 7% H_2. The only one test with upper ignition (UI) position (H = 6.95 m) at highest hydrogen concentration was used (Table 1). Pressure, temperature records simultaneously with video observations of combustion process were performed in the tests. Total record time was about 10.5-21.0 seconds for fast controllers and about 1400 seconds for slow controllers. All the pressure and temperature records and video cameras were synchronized with an ignition moment with a pre-record time of about 0.5 s.

Mitigation system. Water spray

A water dispersion system has built on top of the A2 vessel at H = 8.14m. It was based on the WhirlJet Spray Nozzles type 1CX-SS15, full cone spray, with a capacity of 100 liter/min. The water spray provides a 120° of opening angle (Fig. 6).

The spray is initiated by overpressure up to 8 bar. In order to investigate the efficiency of water spray mitigation, the spray was actuated with 100 and 60 ms of time delay after an ignition moment. The time delay has provided to allow a well-developed flame kernel. The flame dimension with such a delay was about 1 m radius.

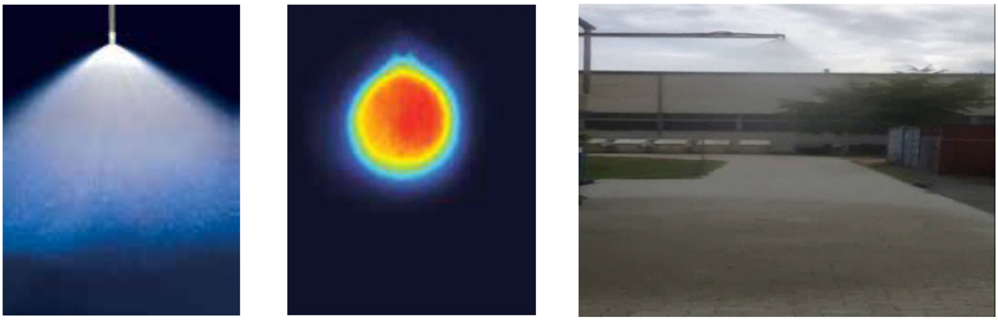

Fig. 6. Structure of water spray: declared by manufacturer (left); actual (right).

EXPERIMENTAL RESULTS AND DISCUSSION

Strong influence of hydrogen stratification and ignition position was found in the tests (Fig. 7). The most representative and reliable pressure sensor KU3 (Kulite) at the middle position H = 3.27 m was chosen for the analysis. The maximum combustion pressure of 1.7 bar increases 10 times for stratified hydrogen mixtures as compared with uniform mixture of the same amount of hydrogen equal to 7% H_2 (0.16 bar). The time for maximum pressure roughly corresponds to complete combustion time equal to ~$2 \cdot t_{1/2}$, which is inversely proportional to the average flame speed (Table 1). Assuming a spherical shape of combustion zone after ignition, a visible flame speed can be calculated according to papers [13-14]. Figure 7 (right) shows that combustion velocity for a stratified mixture (1.5-3.5 m/s) is about 2.5-6 times higher than that (0.6 m/s) for uniform mixture of the same amount of hydrogen (7% H_2). An additional confirmation of the importance of maximum hydrogen concentration on combustion process is done by upper ignition position (UI). The ignition at highest hydrogen concentration of 14% H_2 leads to maximum combustion pressure increase up to 1.7 bar and two times higher average combustion velocity (~6 m/s) compared to center ignition at 7% H_2 for the same stratified mixture 14→7→0% H_2. Upper ignition position at 14% H_2 also leads to tenfold velocity increase compared to that for uniform composition of the same amount of hydrogen (7% in average).

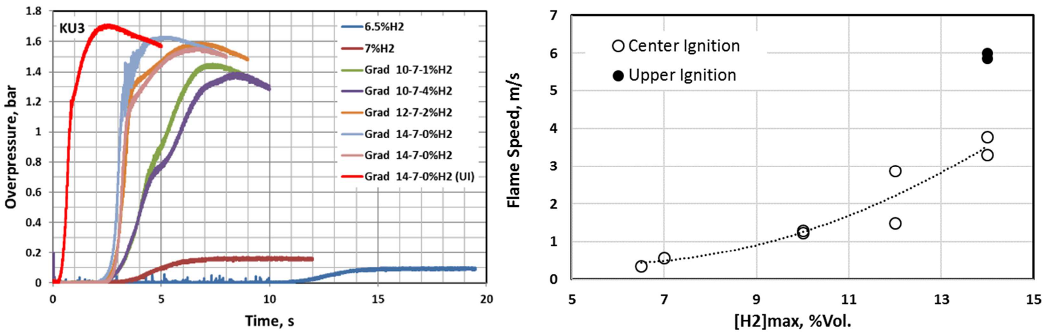

Fig. 7. Combustion pressure records (left) and visible flame velocity as function of maximum hydrogen concentration (right) for stratified and uniform hydrogen-air mixtures.

Maximum combustion temperature behaves almost the same way as the pressure. Namely, the maximum combustion temperature of 1300-1600 °C for stratified combustion is much higher than for uniform combustion (260 °C for 6.5% H_2 and 380 °C for 7% H_2). Figures 7-8 confirm that for stratified compositions the combustion rate governs by highest hydrogen concentration at the sealing rather than an average hydrogen concentration of the mixture. The changing of highest hydrogen concentration from 10 to 14% H_2 leads to maximum combustion pressure increase from 1.4 bar to 1.7 bar and combustion temperature increase from 800 ^oC to 1300 ^oC.

The temperature grows very quick until the mixture completely or partially burns. At least until the flame reaches the top of the volume. Since the downward flame propagation limit for hydrogen-air mixtures is 8% H_2, the flame at 6.5 and 7% H_2 is able to propagate only upward after center ignition. This means that only a part of the mixture burns completely. Bottom part of the volume up to H = 3.0 m remains unburned. The maximum temperature within unburned part does not exceed 30-35 ^oC. The difference between stratified and uniform compositions is that for uniform compositions 6.5% and 7% H_2 more than half of the mixture remains unburned in comparison with stratified mixture with much higher completeness of combustion.

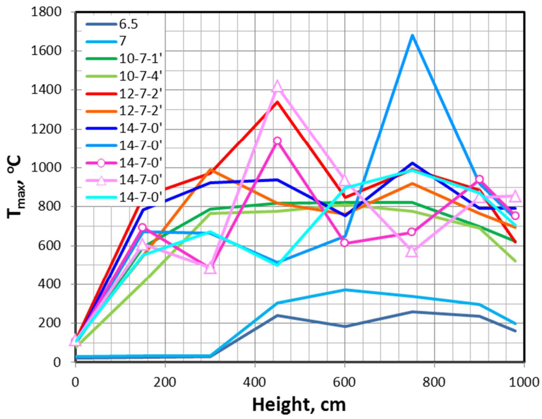

Fig. 8. Distribution of maximum combustion temperature for stratified and uniform hydrogen-air mixtures.

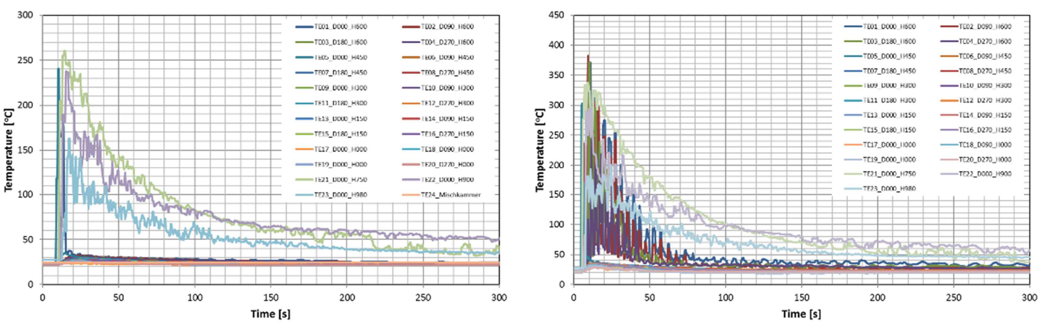

Fig. 9. Maximum combustion temperature for uniform compositions of hydrogen – air mixtures with 6.5% (left) and 7% H_2 (right).

Figure 9 shows temperature records for uniform compositions with 6.5% and 7% H_2. Thermoelements at the centerline positions H = 4.5 m and H = 6 m showed very short heating time corresponding to passing a fireball through the thermocouple. It takes only 3 sec for 4.5 m and 4 sec for 6 m positions. Then, the combustible zone is localized at upper center part of the volume (H > 7.5 m), without horizontal expansion of the flame. The maximum combustion temperature (260 ^oC for 6.5% H_2 and 380 ^oC for 7% H_2) is reached in 6 sec (6.5% H_2) or 3.5 sec (7% H_2) after ignition then the temperature of combustion products slowly decays to 30-50 ^oC within 150 sec. The difference of flame arrival time for gauges positions 4.5 m and 6 m takes about 2 sec for 6.5% H_2 in air. It corresponds to flame propagation velocity of about 0.75 m/s. The same procedure for 7% H_2

gave the local flame propagation velocity of about 2 m/s. Such slow flame propagation velocity is almost equal to characteristic velocity of hot buoyant gas lifting up due to the convection.

An influence of hydrogen concentration gradient on maximum temperature was found in the tests for stratified compositions. Stronger hydrogen concentration gradient from 10=>7=>4 to 12=>7=>2% H_2 leads to the increase of maximum combustion temperature from 810 °C to 1330 °C (Fig. 10). The completeness of combustion for stratified compositions is much higher than for uniform compositions. The highest combustion temperature >700 °C is kept at H = 3 m, even below the ignition point. The temperature of about 400 °C occurs at H = 1.5 m probably due to turbulent mixing of combustion products and reactants. At ground level the temperature does not exceed 80 °C. As follows from Fig. 8, the maximum combustion temperature for stratified compositions is localized at the upper part of the system H = 7.5 m with highest hydrogen concentration.

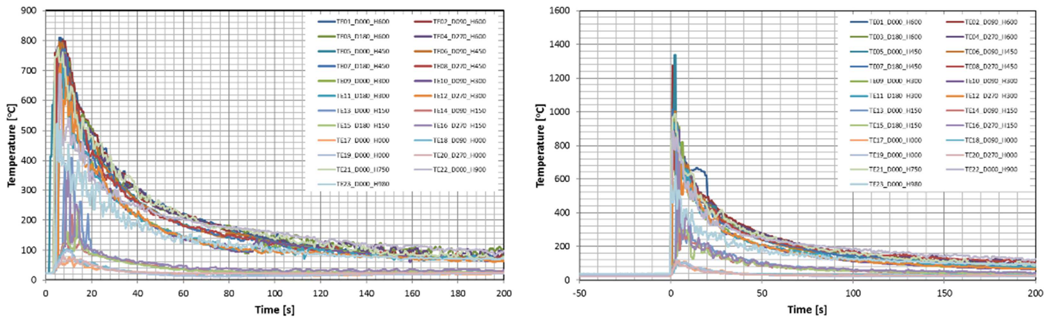

Fig. 10. Maximum combustion temperature for stratified compositions of hydrogen-air mixtures with two gradients from 10=>7=>4% H_2 (left) to 12=>7=>2% H_2 (right).

A weak influence or even promoting effect of water spray on combustion process has been found. The spray was initiated 60 ms after ignition of the mixture when the flame develops quite well (about 1 m radius). Higher combustion pressure (1.6-1.7 bar) and faster combustion time ($t_{1/2}$ = 2.72 s) were registered due to an additional turbulence in the presence of water spray (Fig. 11, left). It corresponds to 1.5-2 times of the flame velocity increase according to Fig. 11, right. The velocities also were calculated from pressure measurements using a procedure described in papers [13-14]. Combustion temperature has also increased by 100-200 °C compared to dry mixtures of the same concentration profile (Fig. 8). The highest combustion temperature is localized at H = 4.5 m, exactly at the interacting interface of water spray and combustion zone. The reason could be a turbulent transport of hydrogen enriched mixture to the combustion zone by water spray injection from the upper position.

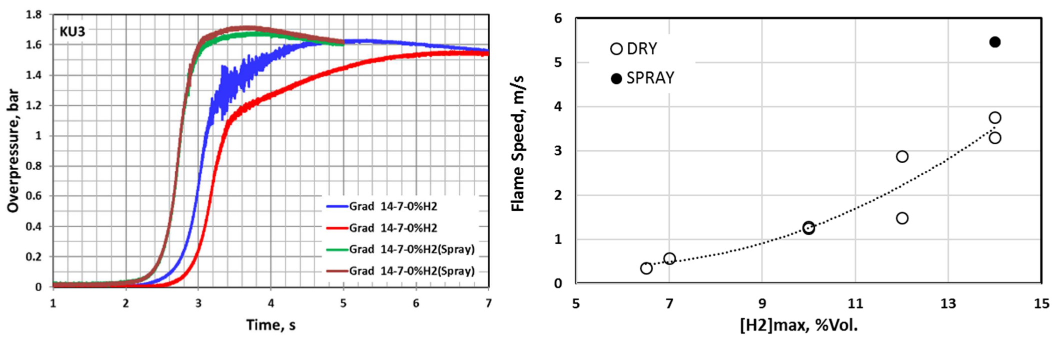

Fig. 11. Maximum combustion pressure (left) and visible flame velocity as function of maximum hydrogen concentration (right) for dry mixture and wet composition in presence of water spray.

Acoustic oscillations due to the flame instability have also been measured by microphone in the tests. For instance, two resonance frequencies 86 and 366 Hz in the test with a gradient 12-7-2% H_2 were distinguished (Fig. 12). It might be an evidence of acoustic and parametric flame instabilities. Characteristic frequencies of acoustic oscillations in presence of water spray can be shifted to 150 Hz and 450 Hz for two first resonant bands.

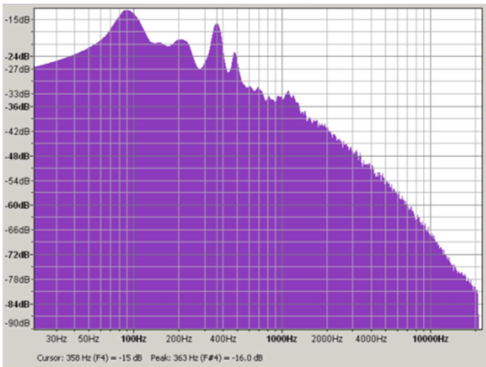

Fig. 12. Spectrum of sound record for stratified combustion of the mixture with a gradient 12-7-2% H_2.

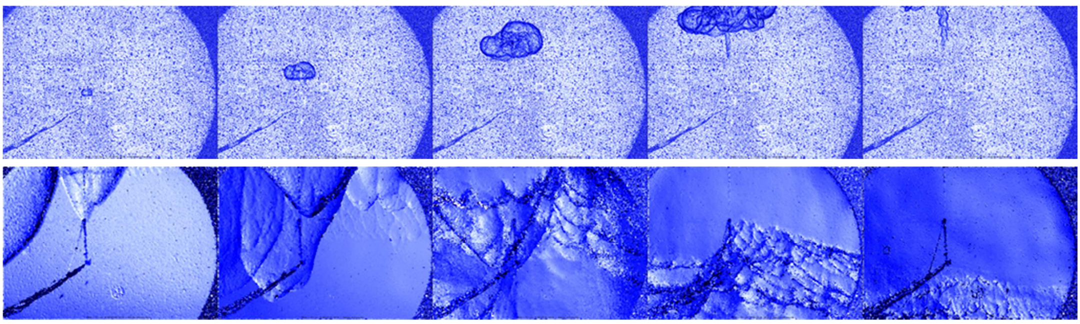

Fig. 13. A sequence of BOS images for non-uniform combustion with a gradient 10-7-4% H_2.

An example of BOS images for non-uniform combustion with a gradient 10-7-4% H_2 and a center ignition is shown in Fig. 13. Initially, the flame ball develops with a velocity 0.16-0.52 m/s. It lifts up due to the buoyancy in the direction of more reactive mixture. Then, the turbulent wrinkled flame propagates downward with a velocity 1.11-2.83 m/s. This is very close to calculations by pressure.

CONCLUSIONS

(1) Hydrogen distribution experiments in HYKA-A2 vessel were performed in order to create a relatively stable vertical hydrogen concentration gradients.

(2) Flame propagation experiments with uniform hydrogen concentration of 6.5% and 7% H_2 for center ignition (CI) point have been carried out as reference tests.

(3) Flame propagation tests with center ignition point for three different hydrogen concentration gradients 14→0, 12→2 and 10→4% H_2 with the same amount of hydrogen equal to 7% of average concentration in the whole vessel volume have been performed. Strong influence of hydrogen stratification was found. The combustion maximum pressure (1.7 bar) was increased by 10 times for stratified mixture compared to uniform mixture with the same amount of hydrogen equal to 7% H_2

(0.16 bar). The same factor of 10 was found to be applicable to the flame velocity increase (from 0.6 to 6 m/s). The temperature is increased from 370 ^oC (7%) to 1300-1700 ^oC (14→7→0% H_2).

(4) The governing role of highest hydrogen concentration on combustion process for stratified mixture was experimentally shown. There is no effect of average hydrogen concentration.

(5) One test with upper ignition (UI) position and vertical hydrogen concentration gradient of 14→7→0% H_2 was performed. It leads to the highest combustion over-pressure (1.7 bar) due to two times higher combustion velocity as compared to stratified composition with a center ignition (CI) point. It confirms a dominating role of highest hydrogen concentration on combustion process.

(6) An effect of water spray on flame propagation was studied in two tests with center ignition and vertical hydrogen concentration gradient of 14→7→0% H_2. No suppression effect of water spray (100 l/min) was found on combustion. Maximum combustion temperature increases from 1020 ^oC to 1400 ^oC due to an additional turbulence in the presence of water spray.

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