The effect of buoyancy on flame acceleration in hydrogen-air mixtures: experiments in horizontal and vertical tubes

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1 Introduction

Accidents at large-scale production facilities or hydrogen storages can result in the release of large amounts of pure hydrogen. When mixing with air, hydrogen generates explosive mixtures, which can lead to significant damage to infrastructure or injure the staff of the facility. The main problems and uncertainties when estimating safety [1] have been identified in the framework of studying hydrogen safety at NPPs, also relevant for hydrogen power facilities. In particular, the emphasis should be put on refining the limit of self-propagating deflagration combustion, capable of transition to fast flames.

Flame acceleration at deflagration is due to the formation of jet reagent flows before the flame front, forced out through the obstacles (such as equipment, tubes, connections, bridges, doors, windows, etc.) by the pressure created by the flame front (the front is moving at s subsonic velocity). The flame front flows immediately after the mixture flows, which are turbulized due to the development of instabilities and then turbulize the flame. This contributes to the growth of combustion surface area, and, correspondingly, to the fast pressure growth. Regularity of obstacles increases the probability of combustion transition from slow deflagration regime to fast flames, and then to detonation.

When the velocities in the reaction products approach the sound velocity, as it was noted in [2-5], a significant increase in pressure occurs at the front that can result in damage of real hydrogen power facilities. Two lower limits in terms of flame acceleration in hydrogen-air mixture can be identified; at 10 vol.% of hydrogen in air, the flame front velocity can increase from several dozens of meters per second up to 600 m/s and over (fast flames), and at 16-18 vol.% - up to 1200 m/s and over (quasidetonation). Horizontal tubes of various diameters and obstacles of different sizes were used in the experiments. However, similar experiments were not conducted for vertically oriented tubes.

A BM-T facility (Big Model – Tube) was developed at FSUE "RFNC-VNIITF named after Academ. E.I. Zababakhin" to study flames acceleration process in homogeneous combustion mixtures of hydrogen–methane–carbon monoxide–steam–air. The main feature of the facility is that it allows

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conducting experiments both in horizontal and vertical orientations. In 2019, a series of test experiments was conducted; and in 2021, the works were initiated to assess the influence of tube orientation on acceleration limit of flames from slow to fast flames in homogenous hydrogen-air mixtures. The given work presents the results of our first experiments.

2 Experimental setup

The BM-T facility consists of a steel tube 6 m long with the inner diameter of 325 mm designed for mixture ignition, and of a mixer with the volume of 1 m^3 to prepare the mixture. The facility with the mixer is depicted in Figure 1. The facility is made with thermal insulation (thermal insulation envelope is not shown in Figure 1), and there are heating spreads to heat the tube and to reach the required initial temperature conditions. The tube has a swivel joint to ensure horizontal or vertical tube orientation.

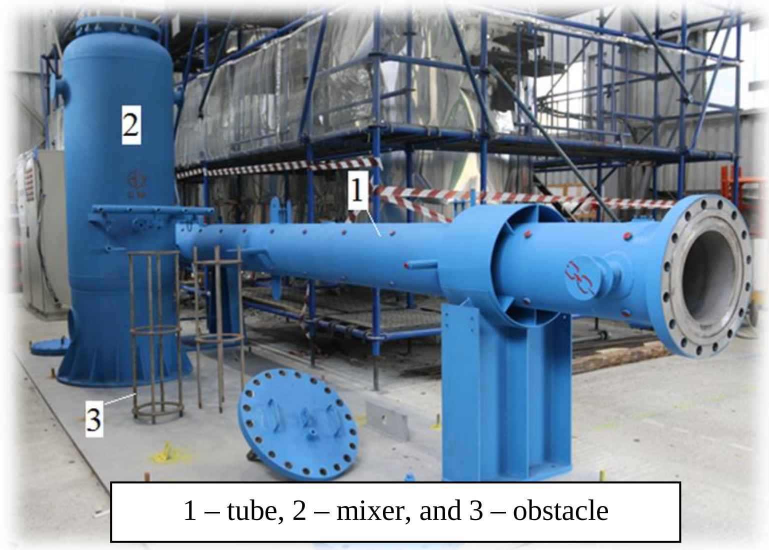

Figure 1: Picture of BM-T facility.

Obstacles with holes in rings were inserted into the tube, corresponding to the following blockage ratio:

$$BR = 1 - \left(\frac{d}{D}\right)^2$$

where d is the hole diameter, and D is the tube diameter. The rings divide the tube space into compartments. The equidistant holes are made in the centerы of these compartments to fix the instrumentation such as pressure gauges, thermocouples, and time-of-arrival sensors marking the flame front.

The static pressure was measured using ELEMER AIR-30M to prepare the required composition of the flammable mixture through partial pressure method. The measurement range was up to 250 kPa, the error not exceeding ±0.15 kPa. Sampling to vacuumized tanks was performed before the ignition to analyze the composition. The absolute error of hydrogen concentration measured did not exceed ±0.3 vol.%. The final error when determining the composition and taking into account the manometer technique did not exceed ±0.2 vol.%.

Hydrogen-containing mixture was ignited from the tube flange through the spark plug with the spark energy of 20 mJ and the spark gap of 1 mm.

The time during which the combustion front of hydrogen-containing mixture passed along the BM-T facility was estimated through the data obtained by time-of-arrival sensors, the hydrogen-containing gas mixture emitting ultra violet radiation within the range of 300-320 nm. Silicon photomultipliers were used as time-of-arrival sensors. Sensing elements were located in narrow channels acting as collimators and directed normally to the direction of flame front motion.

Dynamic pressure of hydrogen-containing gas mixture in the facility was measured using MIDA-DI-12P-082-Ex-V tensor pressure gauges (measuring range of up to 2.5 MPa) with relative measurement error of ± 6 % and PS01-02 piezo electric gauges (upper pressure limit of 25 MPa) with relative measurement error of ± 11 %.

The experimental procedure was similar in all the experiments. The gases are fed in required proportions into the mixer (through partial pressure method). Then the fan is turned on to ensure the mixture homogeneity. After that, the tube is vacuumized, and the mixture is pumped from the mixer into the tube up to the required pressure. Sampling is performed before the ignition. After the ignition, the tube is purged to remove the reaction products.

3 Experimental results

The schedule of the experiments is given in Table 1. In T1 and T3 series for horizontal tube orientation, the BR parameter was sought such as to ensure flame acceleration at 10 vol.% hydrogen concentration corresponding to the results presented in [2]. According to the above work, flames acceleration limit is assumed to be hydrogen concentration quantity at which the flame front velocity surpasses half the sound velocity in reaction products.

Then, the tube was turned to vertical orientation, and in T4 series of experiments, possible shifts of flames acceleration limit were investigated. The results of T2 series devoted to the study of hydrogen-air mixtures in the tube without obstacles are not cited here, since they present no interest for the purpose of the given article.

Figure 2 gives the comparison between the data obtained by Lee [2] and the results from our experiments in terms of maximum velocity of the flame front. Evidently, the obstacles with BR=0.45 did not contribute to the significant flame acceleration in horizontal tube while the obstacles with BR=0.6 allowed approaching the results obtained by our foregoers. At that, a front velocity peak is clearly seen at 10.6 vol.% exceeding the sound velocity in combustion reaction products. The similar peak is observed in the pressure function under the mixture combustion (Figure 3) that confirms the presence of explosive instable process at the given concentration.

Table 1: Parameters of BM-T facility experiments.

Series No.	Mixture pressure, kPa	Mixture temperature, °C	Hydrogen content in air, vol.%	BR	Tube orientation
T1	100	20	9.3 – 11.3	0.45	Horizontal
T3	100	20	9.9 – 11.7	0.6	Horizontal
T4	100	20	9.0 – 13.8	0.6	Vertical

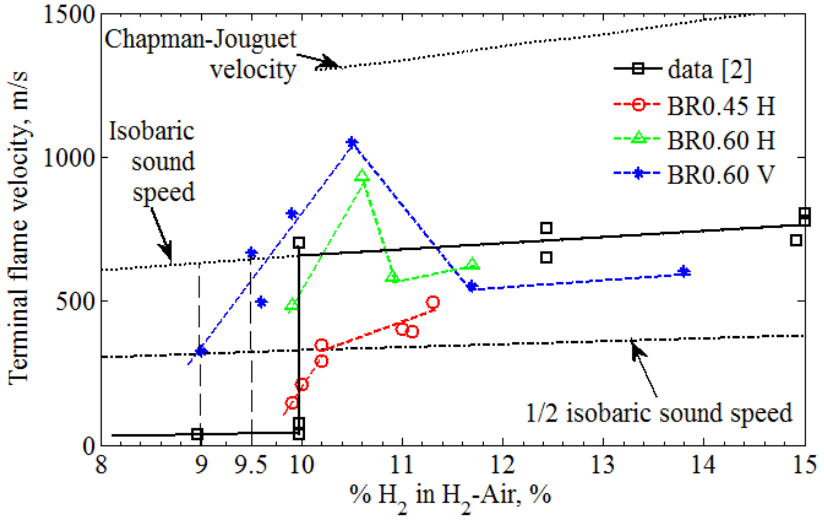

Figure 2: Comparison between the experimental results (T1 series – BR0.45 H, T3 series – BR0.60 H, and T4 series – BR0.60 V) and the data obtained by Lee [2] in terms of maximal velocities of the flame front versus hydrogen concentration in air.

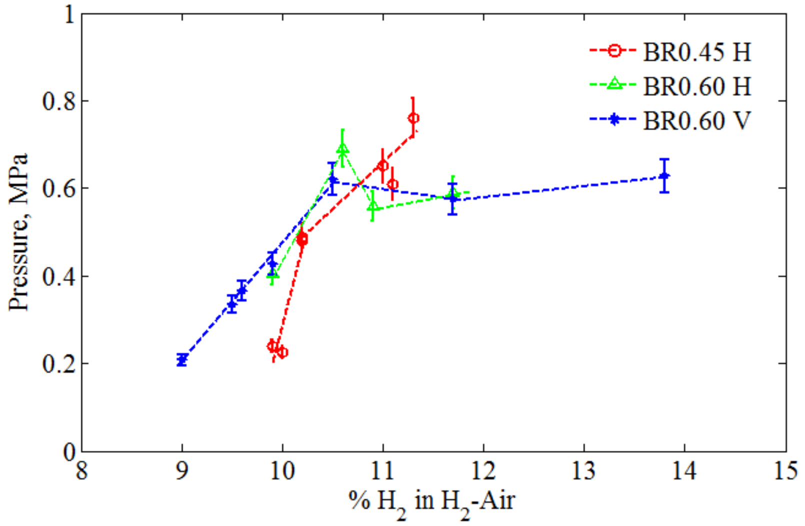

Figure 3: Comparison between the experimental results (T1 series – BR0.45 H, T3 series – BR0.60 H, and T4 series – BR0.60 V) in terms of maximal pressures versus hydrogen concentration in air.

For vertically oriented tube, there is a shift to the left by 0.5 vol.% of hydrogen in average. At that, a flame velocity peak is distinguished at 10.5 vol.%, as for horizontal tube, which is also seen in the pressure function. If reaching half the sound velocity in products is assumed to be the criterion of flames acceleration limit, then this limit was reached at 9.0 vol.% of hydrogen in air that is 1 vol.% lower than the one admitted in [2-3]. Note, that the BM-T facility is characterized by a more fluent transition from slow to fast flames depending on hydrogen concentration if compare to [2,3].

The main difference for horizontal and vertical tube is associated with the effect of gravitation force on the shape of initial flame propagation. It is known [2] that laminar flame velocity decreases with the decrease in hydrogen concentration, and the influence of combustion products buoyancy becomes more pronounced, i.e. the flame propagates asymmetrically from the ignition source with the shift towards the upper tube point. Since turbulization of reagent flows before the flame front is the key factor of flame acceleration acting as a kind of a piston, the asymmetry of the flame front for the case of horizontal tube leads to losses in flows acceleration that could cause the observed shift of flames acceleration limit. The additional cause is the heat dissipation from the flame front towards the upper wall of the tube.

The results presented in this article are initial and preliminary. It is planned to continue the works on refining the acceleration limit.

4 Conclusion

The work gives the results of the first experiments on the BM-T facility designed to determine the acceleration limits of flames from slow to fast flames in homogeneous hydrogen-air mixtures for horizontal and vertical tube orientations. A decrease in acceleration limit was revealed for the obstacles with BR=0.6 in the vertical tube. This indicates the influence of gravitation force on flame acceleration process, which is likely to be considered when adjusting the existing criteria and flame acceleration limits.

References

[1] Bentaib, A., Meynet, N., Bleyer, A., 2015. Overview on hydrogen risk research and development activities: Methodology and open issues. Nucl. Eng. Technol. 47, 26–32. https://doi.org/10.1016/J.NET.2014.12.001

[2] Lee, J.H.S., Berman, M., 1997. Hydrogen Combustion and Its Application to Nuclear Reactor Safety, in: Greene, G.A., Hartnett, J.P., Irvine, T.F., Cho, Y.I.B.T.-A. in H.T. (Eds.), Heat Transfer in Nuclear Reacter Safety. Elsevier, pp. 59–127. https://doi.org/10.1016/S0065-2717(08)70184-9

[3] Ciccarelli, G., SB, D., 2008. Flame acceleration and transition to detonation in ducts. Prog. Energy Combust. Sci. - PROG ENERG COMBUST SCI 34, 499–550. https://doi.org/10.1016/j.pecs.2007.11.002

[4] Boeck, L., 2015. Deflagration-to-Detonation Transition and Detonation Propagation in H2-Air Mixtures with Transverse Concentration Gradients.

[5] Scarpa, R., Studer, E., Cariteau, B., Kudriakov, S., Chaumeix, N., 2019. Infrared Absorption Measurements of the Velocity of a Premixed Hydrogen/Air Flame Propagating in an Obstacle-Laden Tube. Combust. Sci. Technol. 191, 696–710. https://doi.org/10.1080/00102202.2018.1502754