Large-scale dynamics of ultra-lean hydrogen-air flame kernels in terrestrial gravity conditions

Volodin V.V., Golub V.V., Kiverin A.D., Melnikova K.S., Mikushkin A.Yu., Yakovenko I.S.
Joint Institute for High Temperatures of RAS
Moscow, Russia

1 Introduction

Hydrogen is a perspective renewable energy source. Hydrogen-based fuels possess a number of benefits compared with traditional hydrocarbon fuels. Hydrogen is widely used in industry in such processes as hydration, recovery and hydrotreating. Given high chemical activity of hydrogen the design and operation of facilities where hydrogen emission is possible requires careful analysis of potential emergency scenarios and the development of effective explosion suppression technologies. One of the possible scenarios of accident during hydrogen usage is related to the fuel tanks depressurization while transportation or storage. In this case, hydrogen can be gradually accumulated in closed volume and forms a combustible mixture with air. However, if the volume in which hydrogen accumulation proceeds is large enough then the composition of the formed mixture could be far from stoichiometric. Moreover, hydrogen concentration distribution may be non-uniform due to natural convection. In this case hydrogen concentration near the top of the volume is expected to be highest while near the bottom combustible mixture could have the leanest composition. A similar scenario can be observed during the accident development at a nuclear plant, during which the hydrogen generated in the damaged reactor zone can be accumulated under the containment dome [1]. Locally hydrogen concentration in the atmosphere can correspond to an ultra-lean composition near the lower flammability limit. The development of combustion in such an environment proceeds without significant dynamic effects. Nevertheless, the unsteady evolution of the combustion kernel and its convective transport in the terrestrial gravity condition may cause the ignition in the upper part of the volume filled with a richer and more chemically active mixture.

Combustion of the ultra-lean mixtures has a number of crucial features, mainly related to the deficient specie diffusion to the reaction zone mechanism of the combustion. The change of the deflagrative mechanism of the flame propagation due to thermal conductivity process towards diffusive mechanism is observed at $\sim$10% of the hydrogen content in mixture with air. Theoretically the possibility of the spherical flame kernels existence (so-called flameballs) was predicted by Ya. B. Zel'dovich [2]. In later studies it was shown that such kind of structure can be formed in ultra-lean mixtures. This flame structure is intrinsically unstable, however it can be stabilized due to radiative losses [3], heat losses to the cold walls [4] or due to convective flows developed as a result of buoyancy forces [5]. For the first time stable flameballs were experimentally observed by P.D. Ronney in microgravity conditions [6].

Structure of the ultra-lean combustion kernels in tubes has been discussed in a number of experimental researches aimed at the determination of the flammability limits [7–9]. Analysis of the experimental data allowed to reveal several important patterns of flame propagation in ultra-lean flames in the presence of convective transport. Thus, the convective rise of the ultra-lean flame in a gravitational field proceeds with acceleration until the flame reaches the terminal rising velocity that can be accurately assessed using the relation for the terminal velocity of the gas bubble rising in a liquid [10, 11] and exceeds by several orders of magnitude the burning velocity value for such a mixture. In addition, the experiment shows that the concentration limits depend on the flammability tube width [9, 12]. Flame structure of the ultra-lean flame in terrestrial gravity conditions is determined by the structure of the convective flows formed during the ascent of a hot combustion kernel. The characteristic cap-shaped form of the combustion front is presented in experimental papers [9, 13, 14]. In recent papers [15, 16] the authors experimentally and numerically demonstrated the possibility of formation of the flame balls stabilized in counterflow in terrestrial gravity conditions.

For today the existence and stability of ultra-lean combustion kernels under terrestrial gravity conditions is well documented. Nevertheless to solve practically important problems of fire and explosion safety a detailed analysis of the structure and dynamics of such flames on a large scale, characteristic for real industrial facilities, is required. In a recent paper [17], the authors by means of detailed numerical modeling have studied ultra-lean flame evolution in hydrogen-air mixture with 6% hydrogen content in an unconfined space. The development of a complex multi-kernel flame structure, formed as a result of convective flame transfer and its interaction with shear flows, was demonstrated. The present paper is devoted to the experimental study of the large-scale structure of the ultra-lean flame and, thus, deepening knowledge of ultra-lean flames large-scale dynamics.

2 Experimental setup

Experiments were carried out in cylindrical steel combustion chamber VBK-2 with 4.5 m inner diameter and 7 m height, designed to endure the explosion intensity up to 20 kg TNT. Combustible mixture with 6% hydrogen content was prepared in a gas tank beforehand and kept for 24 hours. After filling the shell, the mixture was held for 3 minutes until internal flows decayed and was ignited by a spark with an energy of 1 mJ. The flame front propagation was visualized using IAB-451 device equipped with high-speed camera ”Videosprint” G/2 with frame rate 200 fps and infra-red camera InfratecTec ImageIR 8320 with frame rate 200 fps. Visualizations were automatically post-processed to obtain time dependencies of the lowest and highest flame points, flame width and flame front curvature radius near the highest point of the flame.

3 Results and discussion

Let us consider the dynamics of the ultra-lean flame during its convective rise. Spherical structure of the flame kernel, formed directly after ignition of the mixture, becomes subject to the buoyancy force [14]. Under the action of buoyancy force, flame kernel starts its vertical movement that results in toroidal vortex formation in a kernel wake. Vortical flow bends and stretches the flame surface that leads to the formation of an axisymmetric ”cap” structure of the flame front (see. Fig. 1).

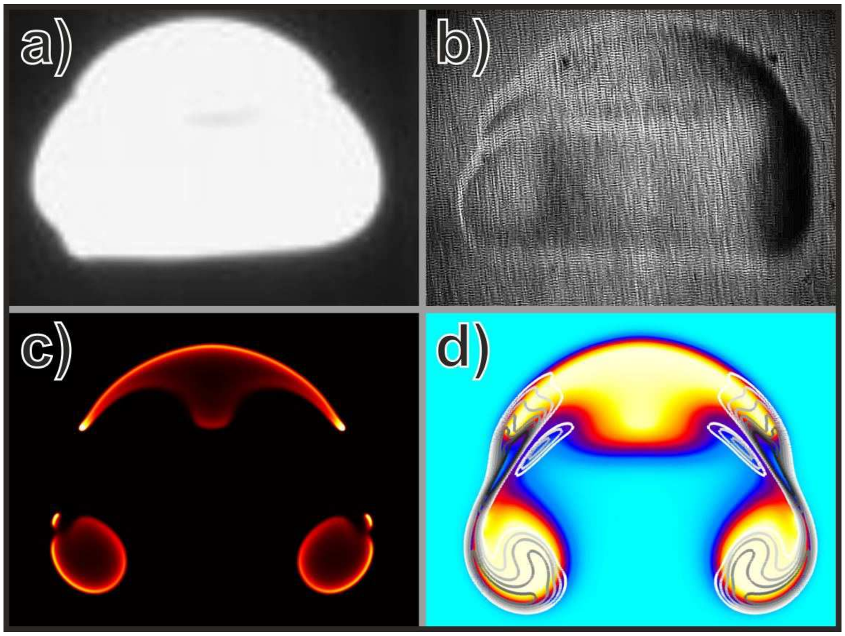

Figure 1: Formation of the "cap-shaped" structure of the flame front on the early stage of the convective motion of the flame kernel. a) infrared camera photo b) shadowgraphy photo c) numerically obtained OH radical distribution d) numerically obtained temperature distribution with vorticity isolines [17], spatial scaling is preserved for all the frames.

Further rising of the kernel is accompanied by its lateral extension and stretching. As a result, flame stretching by the vortical gas motion leads to the separation of the secondary kernel from the main one (see Fig. 2). The secondary toroidal kernel continues its propagation in the wake of the main kernel after its separation. Further, an accelerated rising of the secondary kernel is observed that results in a visible reunion of two kernels. One of the possible explanations for the mechanism of this coupling of kernels is that the movement of the secondary kernel proceeds in the mixture preheated by the main kernel. Subsequently, this process repeats several times.

Comparison between the present results and the results of the computational experiment [17] (see Fig. 2 and Fig. 3) shows the qualitative agreement of the characteristic features of the evolution of the combustion kernel in ultra-lean hydrogen-air mixture. However, there are some quantitative differences in kernel rising dynamics. Thus, the rising velocity of the flame kernel obtained numerically appears to be 1.5 times lower than in real experiment (see Fig. 3). This can be related to the fact that in the calculation two-dimensional planar coordinate system was used. Here it should be noted that the leading role in ultra-lean flame kernel dynamics belongs to the buoyancy force. As the force exerted on the rising kernel is proportional to the ratio of the flame surface and its volume it is straightforward to obtain that in two-dimensional case this ratio appears to be exactly 1.5 times lower than in three-dimensional case. Thus, the difference in the value of the buoyancy force dictates the discrepancies between the flame rising velocities obtained numerically and experimentally.

It is important to note that quantitative differences in flameball structure are much smaller than in the velocity value. The time dependence of the curvature radius of the flame surface near the highest point is presented

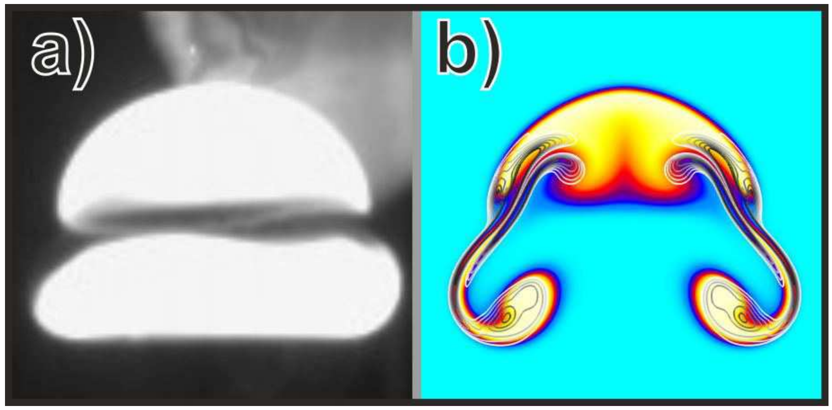

Figure 2: Two-kernel structure of the flame, observed after the secondary kernel breakup. a) infrared camera photo (625 ms, curvature radius near the highest point is 75.3 mm) b) numerically obtained temperature field and vorticity isolines (760 ms, curvature radius near the highest point is 76.7 mm) [17]. Spatial scaling is the same for both pictures.

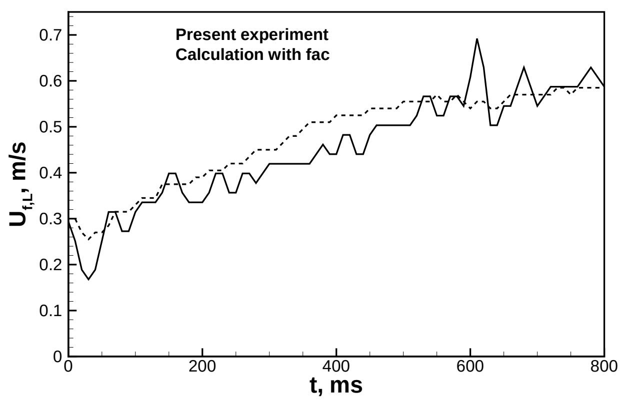

Figure 3: Time dependence of the highest point of the flame front measured in the experiment (solid line) and obtained by means of numerical modeling with factor 1.5 (dashed line).

on fig. 4. Non-monotonic behaviour of the flame curvature radius is related to the secondary kernels breakup events that result in a temporary slowdown of the curvature radius increase. The initial stage of the flame kernel evolution is defined by the fairly close values of the curvature radius obtained in experiment and calculation. Over time, the discrepancy between the experiment and calculation increases. Herewith, one can see a good correspondence between kernel structures characterized by the same value of the curvature radius that were observed in the experiment and obtained numerically.

The analogies between the motion of a bubble in a liquid and ultra-lean flame kernel are not limited only by the common relation for terminal rising velocity. The evolution of the flame kernel also corresponds well to the shape of bubbles that rise in a liquid [18, 19]. At certain values of dimensionless parameters characterizing gaseous bubble in a liquid, its rising motion is also accompanied by the events of satellite bubbles separation from the main bubble. The main difference is that in the case of bubbles there are no mechanisms for the reunion of the satellite bubbles with the main bubble. However, due to the high

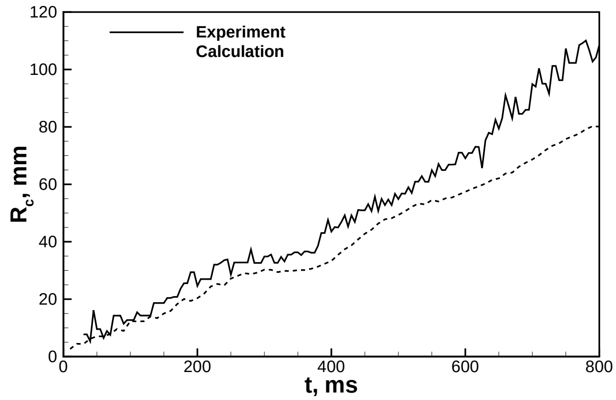

Figure 4: Time dependence of the curvature radius of the flame front near the highest point.

similarity of the processes of ultra-lean flame kernels propagation and movement of gaseous bubbles in a liquid, it seems to be possible to classify various regimes of rising and deformation of the flame kernels on the basis of dimensionless parameters characterizing combustible mixture.

4 Conclusions

In the present paper, an experimental study of the large-scale evolution of the ultra-lean flame kernel in terrestrial gravity conditions is carried out. The results allowed us to determine the main stages of the flame development after ignition. The initial stage is characterized by the isotropic expansion of the flame kernel immediately after ignition. As flame kernel grows it becomes subjected to the buoyancy force that determines its further vertical movement. Convective flows formed as a result of flame rising stretch the flame surface that results in local extinction of the flame on the periphery of the flame kernel and separation of the secondary kernels. Secondary flame kernels move in the thermal wake of the main flame kernel so they can accelerate and catch up with the main flame kernel. Throughout the process, a clear analogy can be traced between the propagation of the hot ultra-lean flame kernel and the gas bubble rising in a liquid.

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