# GAS COMBUSTION IN WATER

**V. S. Teslenko, A. P. Drozhzhin, and R. N. Medvedev**

M. A. Lavrentyev Institute of Hydrodynamics
Siberian Branch of the Russian Academy of Sciences
e-mail: ruslan@hydro.nsc.ru

The combustion dynamics of stoichiometric propane mixture on rigid wall in water for different geometries is investigated. Pulsing regime of longitudinal velocity of propane combustion in a cylindrical bubble is found. The qualitative model of velocity pulsations is considered.

**Keywords:** combustion; combustion in water; velocity pulsations; gas bubble

## 1 Introduction

At present, the transformation of chemical energy into heat and mechanical energy is performed in different combustion chambers with fixed volumes. With increasing specific capacities, well-known principals of combustion of fuels are limited by several reasons, for example, losses caused by heat transfer at liquid–wall–liquid boundary. In [1, 2], a radically new method of pulse-cyclic combustion of fuel gases directly in water with separate supply of combustible gas and oxidant for direct heating of heat carrier was considered and realized. In modern movers, for above- and underwater means of transport, explosion engines, or turbines, in which propellers and water jets are driven by different transmissions, are used. Energy losses in all systems of mechanical pulse transfer are considerable [3]. The systems with direct transfer of mechanical energy from combustion products to propulsive burns, for example, jet movers, are promising for water devices. However, existing jet movers based on combustion of special fuels are unacceptable for wide use. Therefore, pulsing hydrojet movers, in which hydrocarbons and hydrogen are burned, are of special interest in water transport. It is possible for a pulsing mover to throw outside water by combustion products in the form of added mass during the expansion of bubbles [4].

This work deals with the possibility to apply the methods of pulse combustion of hydrocarbons and hydrogen directly in water for developing radically new heat generators and direct transformation of chemical energy of hydrocarbons into kinetic energy of the body immerged into a liquid. To develop such systems, it is necessary to investigate fundamentally physicochemical and hydrodynamic processes caused by direct combustion of hydrocarbon fuel in water. This work presents the first experimental results concerning this subject.

## 2 Experimental Setup

To investigate the processes of combustion of gas mixtures and hydrodynamic processes in water in details, the experiments concerning initiation and combustion of fuel gases in bubbles are performed. To this end, bubbles filled with stoichiometric mixture of propane and oxygen of volume 1–4 cm$^3$ were injected into water and fixed at the boundary of water and rigid wall. The bubble was hung on in horizontal plane in grooves in the metal wall of length 30–70 mm that corresponds to the scheme in Fig. 1. The initiation of combustible mixture in bubbles was performed by a spark discharge with energy of up to 4 J. High-speed recording of gas combustion in bubbles and dynamics of expansion of bubbles after gas mixture combustion was performed. It was made in two projections: full-face and half-face. Analogous experimental setups were performed for ring grooves in plastic of diameter 30–60 mm. The measurements

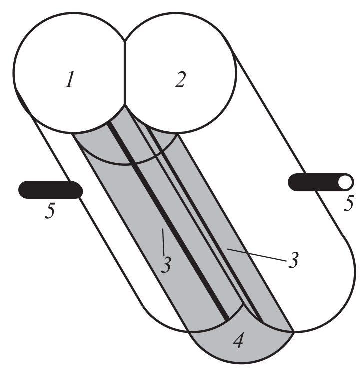


**Figure 1** The scheme of linear-slot injector for gas combustion in water in separate supply of gases into water: *1* and *2* — copper cylinders; *3* — slots; *4* — quasi-cylindrical bubble with combustible mixture (shown in grey color); and *5* — tubes for separate gas supply

of force pulses $F(t)$ acting on the wall keeping the bubble were made synchronously. The force pulses acting on the wall were recorded by using digital oscillograph TDS-210, dynamometer on the lead–zirconate–titanate basis of diameter 40 mm and height 15 mm, and emitter follower with constant time constituent $\theta \approx 10$ s.

## 3 Results of Experiments

Figure 2 shows the frames of shadow recording of hydrodynamic processes occurring during the combustion of stoichiometric mixture of propane and oxygen in a quasi-cylindrical bubble of volume 2 cm$^3$.

Figure 3 demonstrates the plot of velocity of luminescence front $u_f$ for stoichiometric mixture $C_3H_8 + 5O_2$ prepared beforehand in a quasi-cylindrical bubble. Experimental data imply that other factors being equal, the combustion velocity pulses along the bubble. From experiment to experiment for the mixture under investigation, the average velocity value of luminescence front was 160 m/s. In whole, this

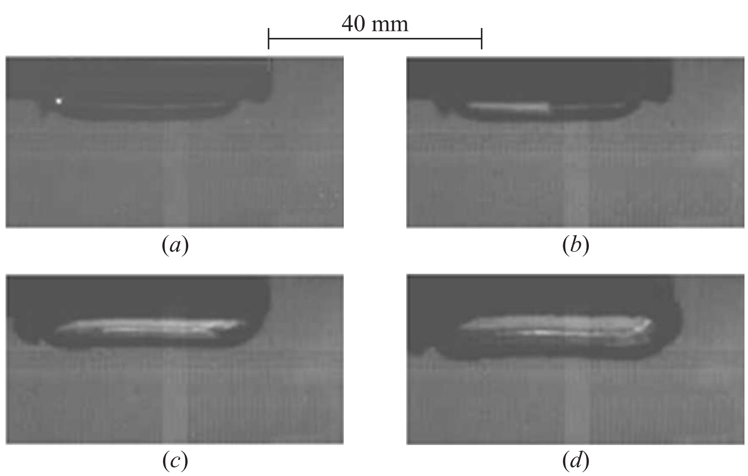


**Figure 2** Speed-recording frames of the process of combustion and beginning of quasi-cylindrical bubble expansion: ($a$) 98 $\mu$s; ($b$) 456; ($c$) 965; and ($d$) 1298 $\mu$s

spread has a statistically slight effect on the dynamics of expansion and pulsations of formed bubbles.

Figure 4 shows the process of combustion of mixture $C_3H_8 + 5O_2$ in the ring bubble of axial diameter 40 mm and volume 3 $cm^3$ located at lower end of the cylinder 59 mm in diameter. At the opposite end of the cylinder, the dynamometer was fixed for measurement of force pulses generated by gas combustion in the bubble.

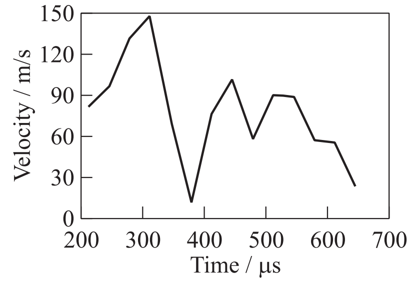


**Figure 3** Diagram of combustion front velocity for mixture $C_3H_8 + 5O_2$ in a quasi-cylindrical bubble

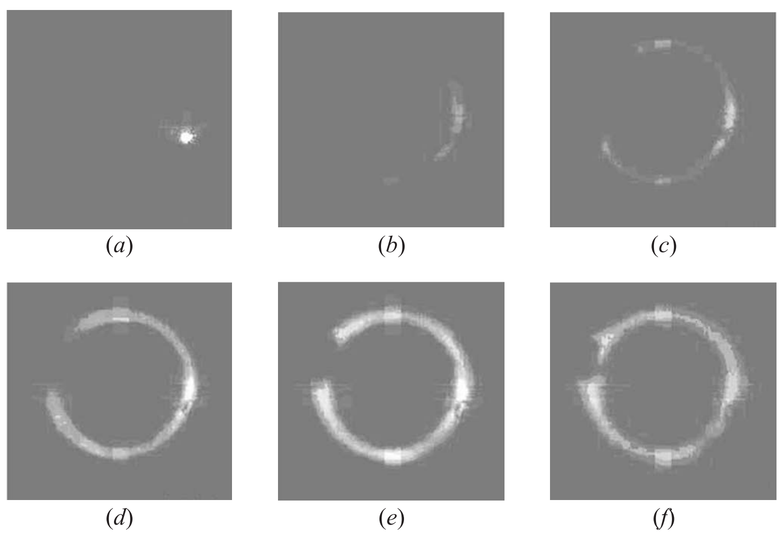


**Figure 4** Speed-recording frames of the process of combustion of propane–oxygen mixture in a circular bubble with ring 4 cm in axis diameter and gas volume is 3 $cm^3$: (*a*) 0 $\mu$s; (*b*) 300; (*c*) 400; (*d*) 500; (*e*) 600; and (*f*) 700 $\mu$s. (Refer color plate, p. XXX.)

It is necessary to emphasize that both for a quasi-cylindrical bubble and for a ring bubble, at stages of decreasing of combustion front velocity, swallowtail structures of luminescence front are observed. Thus, in Fig. 2, it is seen at time moment $t = 965$ $\mu$s. In Fig. 4, it is seen at $t = 700$ $\mu$s. Here, the luminescence front at specified stages of the process is always blue.

## 4 Analysis of Results, Gas Combustion in a Bubble

Both for dynamic mixing of combustible gas and oxygen and for the prepared mixture in bubbles, stochasticity effects of the processes of gas combustion are observed from experiment to experiment. In all experiments (with acetylene, hydrogen, and propane), when dynamic mixing of gases took place, visible velocity of combustion front did not exceed 400 m/s. Thus, we deal with deflagration mechanism of combustion of gases in a bubble. It is possible to assume that a rough surface of the bubble provides the development of turbulent combustion. The observed pulsations of longitudinal velocity of combustion front (see Fig. 3) are connected with instability of the combustion front itself. These pulsations are monitored in recordings. A characteristic peculiarity of the observed processes is the intensification of blue colour in the combustion front at periods of forming of the "swallowtail." It is evident that temperature increases in the zones behind the combustion front.

Consider the fact of decrease of longitudinal combustion velocity along the bubble correlating with observations of fronts of swallowtail luminescence (see Figs. 2 and 4). The fronts of swallowtail luminescence appear at the moments of decreasing the longitudinal velocity of combustion front. Here, as for the combustion of gases in metal tubes, combustion processes along the bubble axis may slow down due to increase of combustion front surface with appearance of quadrature component of front velocity. It is possible to assume that the vapor-drop phase at the boundary of combustion front acting as inhibitor increases with combustion velocity. This causes the delay of combustion front. Then, in regions where the vapor-drop phase is shorter, breaking combustion zones, which are observed in recordings as swallowtail luminescence that is characteristic for quadrature components of combustion front, develop. Thus, the process of combustion is accelerated until the next cycle of slowing. This process may be repeated for definite conditions of the system.

If the hypothesis under consideration is valid, this means that in such systems, it will be possible to limit the processes of development of detonation combustion regimes. Also, it will be possible to specify the necessary combustion regimes. Thus, it is possible to create conditions for self-regulation of the processes of gas combustion avoiding transition to detonation regime.

## 5 Concluding Remarks

The possibility of initiation of propane–oxygen mixture in water is experimentally shown. It is demonstrated that combustion has deflagration character avoiding transition to detonation. Pulsations of combustion propagation velocity, which can be explained by the influence of vapors of surrounding liquid, are found.

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## References

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