Ignition of combustible gases in water

Vyacheslav Teslenko
Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia
E-mail: teslenko@hydro.nsc.ru

Alexey Drozhzhin
Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia
E-mail: drozh@hydro.nsc.ru

Ruslan Medvedev
Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia
E-mail: ruslan@hydro.nsc.ru

Igor Batraev
Lavrentyev Institute of Hydrodynamics SB RAS, Novosibirsk, Russia

Abstract The possibilities of reducing the energy consumption in transformation of chemical energy into heat and mechanical ones due to fundamental change of technologies of fuel combustion are considered by using the methods of combustion of gases being under development.

Key words: Combustion in bubbles; Underwater mover; Heat generator.

1. INTRODUCTION

The method of gas combustion directly in water with separate supply of combustible gas and oxidizer by using linear slot injectors for direct heating of heat carrier was realized in [1, 2]. A separate method of injection is necessary primarily for safety. The mixture of combustible gases in water was formed by injection of two bubbles (combustible gas and oxygen) in a dynamical regime in the form of quasi-cylindrical bubble. Cyclic regimes of combustion of acetylene, hydrogen, and propane are performed with frequency up to 2.5 Hz.

This work deals with the possibilities to apply the methods of pulse combustion of hydrocarbons and hydrogen in water to develop technologies of direct transformation of chemical energy of hydrocarbons into kinetic energy of the body immersed into a liquid (open system). This will make it possible to avoid losses during the momentum transfer from engine to the mover. Moreover, the development of pulsing movers based on the combustion of hydrocarbons on the thrust wall directly in water is in the planning stage.

2. EXPERIMENTAL SET-UP

The scheme of device is presented in Fig. 1. In cylinders 1 and 2 the slots 3 were cut. Each slot is 70 mm long and 0.2 mm wide. Oxygen was injected from one slot and combustible gas was injected from another one. Gases were supplied to the slots through inlet tubes 5. The flow rate of gases was controlled by changing the cross-sectional area of nozzles and time of opening the valves (gas injection time) mounted in gas-supply system. During the process of injection of gases from slots, two quasi-cylindrical bubbles were formed. Then coalescence with mixing of supplied gases and forming of one bubble 4 took place (in Fig. 1, it is shown in grey color). Near the slots of cylinders 1 and 2, isolated conductors were mounted. Between the ends of conductors, a spark discharge was generated. A spark discharge initiated combustion inside the bubble 4. The combustion of mixture in a bubble was performed with specified time intervals from the moment of gas supply commencement.

The investigations of hydrodynamic processes in separate supply of two gases through the slot injectors were performed in Plexiglas cuvette with dimensions of 280x280x500 mm. Calorimetric investigations were carried out in five-liter polycarbonate bottle. The time of gas supply through tubes 5 varied in the intervals 3, 5, and 8 ms. The initiation of combustible mixture in bubbles was performed by a spark discharge with energy up to 4 J. The delay time of mixture combustion after gas supply commencement was 10, 15, 18, 20, 25, 30, 35, 40 ms. The moment of opening the gas valves was taken as the origin of time.

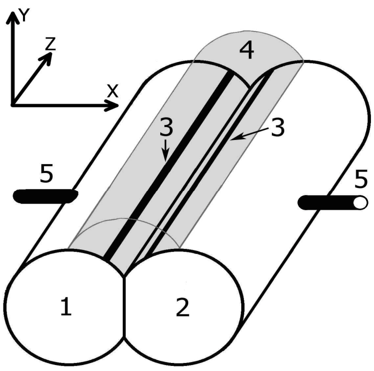


Figure 1. The scheme of linear-slot injector for gas combustion in water in separate supply of gases into water. 1, 2 - copper cylinders; 3 – slots; 4 – quasi-cylindrical bubble with combustible mixture (it is shown in grey color); 5-tubes for separate gas supply.

This work presents the results for lean hydrogen-oxygen ratio and rich ratios of acetylene and propane with oxygen. In all cases the deviation of stoichiometric compositions was so that it had no influence on the stability of combustion.

All necessary parameters, including flow rate, cyclicity of supply of gas and spark discharges and time between them were specified by using the automated system of multifunctional pulse detonation system CCDS-2000 developed in Lavrentyev Institute of Hydrodynamics SB RAS. Figure 2 demonstrates a principal scheme of the set-up with functions of automated gas supply through a slot injector.

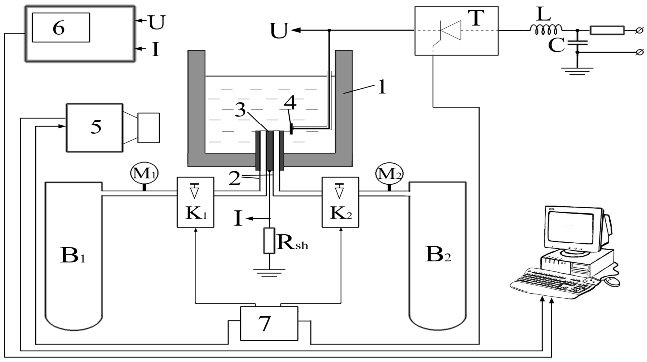


Figure 2. Principal scheme of the experimental set-up: 1 – Plexiglas or polycarbonate cuvette; 2 – inlet gas tubes; 3 – injection device for combustion of gas fuels in water (Fig.1); 4 – electrode for initiation of combustion; 5 – high-speed video camera; 6 – oscilloscope; 7 – control panel; B_1, B_2 – gas bottles; M_1, M_2 – manometers; K_1, K_2 – valves of speed gas supply into water; T – electronic switchboard.

For more detailed investigations of hydrodynamic processes in combustion of gases in water, the experiments were performed with gases mixed beforehand. The bubble was placed in horizontal plane into cylindrical (30-70 mm long) or circular (30-60 mm in diameter) groove on the metal wall that correspond to the scheme shown in Fig. 1 if the set-up is turned through 180 degrees. Initiation of combustible mixture in bubbles was performed by a spark discharge of energy up to 4 J.

A high-speed record of gas combustion in bubbles and dynamics of expansion of bubbles after gas mixture combustion was taken. The record was taken in both front and sidewise projections. Measurements of force pulses F(t) acting on the wall were made synchronously. Registration of force pulses on the wall was carried out with digital oscilloscope TDS-210 by using lead-zirconate-titanate piezometers (with diameter of 40 mm and height 15 mm) and emitter follower with constant time component $\theta \approx 10$ s.

3. EXPERIMENTAL RESULTS

Figure 3 presents the example of shadow recording of the processes of injection and dynamic mixing of gases in water, initiation and expansion of quasi-cylindrical bubble. The record is taken along Z-axis (Fig.1).

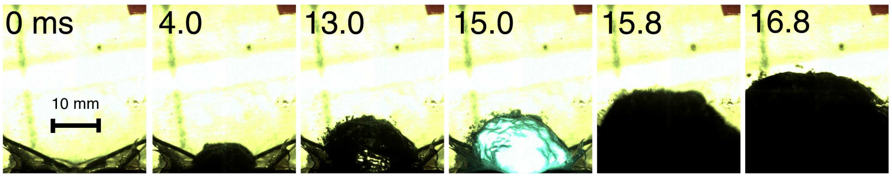


Figure 3. The example of shadow record of injection, initiation and expansion of quasi-cylindrical bubble. The speed of recording is 5000 frames per second.

Fig. 3 clearly demonstrates that it is necessary to divide formally the process of cyclic gas combustion in water into 3 main stages:

1) injecting gases into water until the bubble becomes of required size with specified gas proportion;
2) initiation of gas combustion in a bubble with specified delay;
3) expansion of the bubble after gas combustion with subsequent pulsations and disintegration.

According to results of high-speed recordings of hydrodynamic processes, the velocity of propagation of light fronts was estimated. During the injection of acetylene and oxygen into water (injection time is 3 ms, initiation time is in 15 ms), visible velocity of light fronts was within the interval of 200-400 m/s. For propane, visible velocity of light fronts was 60-100 m/s.

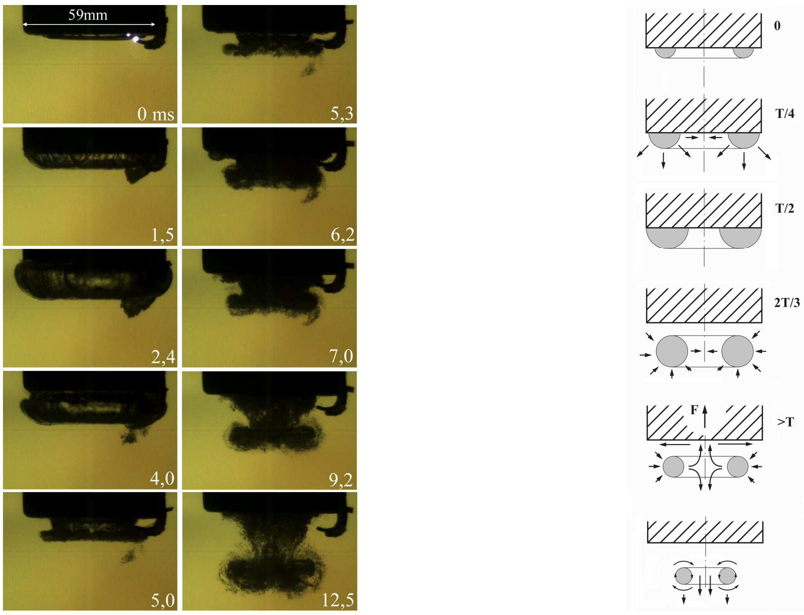
Table 1 presents the results of calorimetric measurements of burnt-gas heat transfer in three-liter volume of water for experiments with gas injection time of 8 ms and ignition time in 15 ms. The error of experimental measurements was 8-22%. The error of gas flow rate was 15 %. The cyclic regime was provided with frequency 2.5 Hz (http://www.swsl.newmail.ru/video/MVI_1779.flv.html). Experiments were carried out in series from 400 up to 1990 combustion cycles.

Table 1

Gas	Heat value of combustible gases [J/cm^3], reference data	Volume of injected combustible gas for one cycle [cm^3]	Volume of injected oxygen for one cycle [cm^3]	Burnt-gas heat transfer in three - liter volume of water [J/cm^3]
Acetylene	56.9	5.1	8	17-25
Hydrogen	10.8	12.6	8	9.3
Propane	93.4	3.55	10.44	21

Figure 4a presents separate frames of shadow recording of hydrodynamic processes in combustion of stoichiometric propane-oxygen mixture in a circular bubble with diameter of 40 mm and volume 3 cm^3 located on the end of the cylinder 59 mm in diameter. Figure 4b presents a corresponding schematic pattern of hydrodynamic processes near the end of the cylinder, where T is the period of bubble pulsation.

It is seen from the experiment that the bubble collapses in the direction to the cylinder axis and forms opposite jet flow along the axis. On the record, at stages t > T, the liquid flow directed from the cylinder is seen in the form of jet flow forming a circular vortex consisting of small bubbles. The jet that is directed to the cylinder can be found in the form of lateral flowing of bubble sheet over the cylinder end and the motion of cylinder if it is not fixed (Fig. 4a).



a b

Figure4. Frames of shadow recording (a) and corresponding schematic pattern (b) of hydrodynamic processes during the gas combustion in a circular bubble with diameter of 40 mm on the end of the cylinder 59 mm in diameter.

Figure 5 shows the oscillogram of pulses of force F acting on the fixed cylinder in combustion of stoichiometric propane-oxygen mixture 2 cm^3 by volume. On this oscillogram, two main pulses are shown. The first pulse (F_1) corresponds to the process of bubble expansion caused by gas combustion and the second pulse (F_2) corresponds to the moment of collapse of the formed bubble. It is seen that the second pulse is proportionate to the first one. Here, $P_1 = \int F_1 dt = 0.077$ kg·s, $P_2 = \int F_2 dt = 0.075$ kg·s.

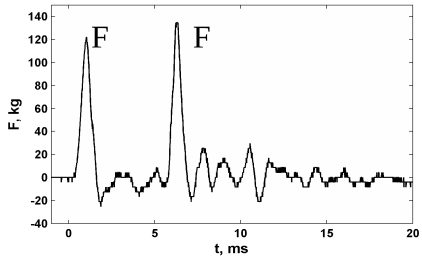


Figure 5. Oscillogram of pulses of force F caused by bubble expansion and collapse.

4. ANALYSIS OF EXPERIMENTAL RESULTS

Both for dynamic mixing of combustible gas and oxygen [1] and for the mixture made beforehand, visible velocity of combustion front in bubbles did not succeed 400 m/sec. Thus, we deal with deflagration mechanism of gas combustion in a bubble.

The observed dynamics of jet flows in a liquid in expanding and pulsing of a bubble near the rigid wall is qualitatively similar to the processes of jet flows described in monograph [3] for cases of bubble pulsations caused by explosions of condensed explosives near the free surface of a liquid. It is necessary to note the following difference taking place in explosions of condensed explosives and those of gases in water: in the second case, the detonation processes of explosion source are absent. Hence, energy redistribution between kinetic energy of liquid caused by gas bubble expansion and shock wave energy will occur in favor of the bubble.

From the results of synchronous registration of hydrodynamic processes and measurements of force acting on the cylinder end it follows that the first pulse corresponds to the process of bubble expansion and the second one corresponds to bubble collapse and forming of two axial flows of liquid bordering to inner boundary of toroidal bubble. Note that in cases of closing of a toroidal bubble on the axis, the tore becomes an oblate ellipsoid and the process pattern remains unchanged except for that the liquid bordering to the outer perimeter of ex-tore is focused to the axis. This process qualitatively corresponds to cumulation processes.

5. CONCLUSIONS

1. It is shown experimentally that combustion of gases in water near the rigid wall makes it possible to transform chemical energy of burnt gas mixture into mechanical energy due to force pulses caused by expansion of gas combustion products in water and bubble collapse. Here, due to forming of axial liquid flows during the bubble collapse near the wall, an additional secondary force pulse proportionate to the first one is provided.
2. By using the considered methods of gas combustion on a rigid wall, it is possible to exclude energy losses in a complex chain of existing technologies of transformation of chemical energy into mechanical one (compression ignition engine, gear reduction, propeller) by changing the methods of combustion of fuels for water movers with direct pulse combustion of gases in water.

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