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In-water gas combustion in linear and annular gas bubbles*

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A new pulsed-cyclic method of in-water gas combustion was developed with separate feed of fuel gas and oxygen with the focus on development of new technologies for heat generators and submerged propellers. The results of calorimetric and hydrodynamic measurements are presented. In-water combustion of acetylene, hydrogen, and propane was tested with the operation frequency of 2–2.5 Hz and with a linear injector. The combustion dynamics of combustion of stoichiometric mixture with propane (C_3H_8+$5O_2$) was studied for a bubble near a solid wall; the produced gas bubble continues expansion and oscillations (for the case of linear and annular bubbles). It was demonstrated that gas combustion in annular bubbles produces two same-magnitude pulses of force acting on the wall. The first pulse is produced due to expansion of combustion products, and the second pulse is produced due to axial cumulative processes after bubble collapse. This process shapes an annular vortex which facilitates high-speed convective processes between combustion products and liquid; and this convection produces small-size bubbles.

Keywords: heat generator, underwater mover, gas combustion in water, combustion, annular bubble, pulse of force.

Introduction

In modern industry, the conversion of chemical energy into heat occurs in boiler systems of different types. The boiler principle of fuel combustion for higher specific power meets limitations. These limitations are related to film boiling at the boiler walls, and this fact forced the engineers to enlarge the sizes of power systems. The papers [1, 2] tested the method of impulse-cyclic combustion of fuel directly in water; gas and oxidant are fed separately through slot nozzles with the aim of direct heat-up of heat carrier. The combustible gaseous mixture in water was produced in dynamic mode: this was a quasicylindrical bubble made from two converging bubbles (fuel gas and oxygen). The cyclic operation modes of fuel combustion were carried out for acetylene, hydrogen, and propane (with the frequency of 2.5 Hz).

The modern propellers for on-water and submerged boats are based on internal combustion engines or turbines: these engines drive a propeller screw or water-jet via various kinds of motion transmission. All those systems demonstrate high energy loss in transfer of mechanical power [3]. The water transport engineers consider other perspective methods with direct generation of mechanical energy from combustion products (e.g., jet propulsion

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systems). However, existing jet propulsion systems use special kinds of fuels with water taken as oxidizer. Obviously, these systems cannot be used in wide practice: the environmental issues are serious. The pulsing water-jet propellers might be of interest for development of water transport. The pulsing propeller would eject the overboard water using the combustion products through the principle of attached mass driven by expanding gas bubbles [4]. This principle makes redundant any kinds of metallic combustion chambers.

The present paper considers the possibilities of application of pulsed combustion of hydrocarbons and hydrogen directly in water with the focus on two different tasks:

– development of absolutely new types of heat generators (closed systems);

– development of direct conversion of chemical energy of hydrocarbons into energy of body submerged into water (open systems).

For the first direction, the research is focused on development of small-size heat generators with direct heat transfer from the working body to the heat carrier (no boiler walls for heat transfer are required). The second direction of research is focused on pulsing propellers using direct combustion of hydrocarbons in water near the thrust wall, i.e., a combustion chamber is redundant for this design.

1. Arrangement of experiment for dynamic mixing of gases in water

Separate injection of fuel and oxidant into water is required by safety reasons formulated for that kind of devices. Previously, a study was carried out on the bubble coalescence problem aimed at optimization of gas ignition inside bubbles whilst separate injection of fuel and oxidant into water; the authors made a conclusion that gas injection via round nozzles does not work properly for this task. We developed a method of slot injection for two sorts of gases with coalescence of "cylindrical" bubbles at the initial stage of fuel and oxygen supply. Reliable regimes of fuel-oxygen mixing were demonstrated for a single quasicylindrical bubble.

The result of this study was development and testing of a device for gas injection into water through straight slot-like nozzles [2]. The device diagram is presented in Fig. 1. The hollow copper cylinders *1* and *2* have slots *3*. The length of linear slots is 70 mm, and the slot width is 0.2 mm. One slot is used for injection of oxygen, and the other slot is for supply of a fuel gas. Both gases are fed through the feed tubes *5*. The gas flow rate was controlled through variation in the nozzle cross section and the time of valve opening (duration of gas feed) installed in the gas supply system. The injected gases undergo coalescence of gas bubbles and mixing with blowing of a single bubble *4* (shown in grey color in Fig. 1). A couple of insulated wires were installed near the middle part of two cylinders *1* and *2*: a spark was triggered between the wires. The discharge is initiated inside the bubble *4* and this spark launched gas mixture combustion. The moment of mixture ignition in the bubble was controlled by a program with a known interval from the gas feed startup.

The study of hydrodynamic processes for the case of separate feeding of two gases through slot injectors was carried out in a plexiglass box with dimensions 280×280×500 mm. The calorimetric measurements were carried out in a 5-liter polycarbonate

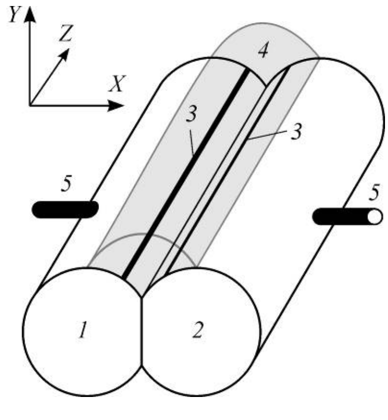

Рис. 1. The scheme of linear-slot injector for gas combustion with separate feed of gases into water.

1, *2* — copper cylinders, *3* — slots, *4* — quasicylindrical bubble (shaded in gray color), *5* — tubes for separate feed of gases.

bottle. The high-speed recording of gas combustion and hydrodynamic process was performed with MotionXtra HG-LE camera. The time of gas feed through tubes *5* was chosen equal to 3, 5, and 8 ms. The delay time for gas ignition (t_{ign}) after gas feed was selected from several values: 10, 15, 18, 20, 25, 30, 35, and 40 ms (stability of cyclic operation was the main criterion). The zero time was the moment of valve opening. Different ratios of fuel gas and oxygen were tested after timed opening of the valves. In our experiments, lean mixtures of hydrogen and oxygen were tested as well as rich mixtures of acetylene/propane with oxygen. In all cases tested, the deviation from the stoichiometric ratio was moderate and did not spoil the ignition efficiency and cyclic operation of the system. All key parameters, including flow rates of gases, time intervals for gas feed and spark ignition, and time between them were assigned using the automation system of a multifunctional pulse detonation apparatus CCDS-2000 designed in the Institute of Hydrodynamics SB RAS [5].

Figure 2 shows a general diagram of the setup with options of automated gas feed through a slot injector.

This arrangement of test procedures and setup was different from our previous experiments or those described in literature. This test model was used for performing hydrodynamic and calorimetric measurements on ignition and combustion of acetylene, hydrogen, and propane. The cyclic operation of the setup was adjusted with the frequencies up to 2.5 Hz. The video of operation of this prototype is available at the website:
http://www.swsl.newmail.ru/video/hydrogen_121101_1717.flv.html.

2. Arrangement of experiments with premixed gases

Since the dynamic modes of gas combustion in water have been tested previously [2], we performed a series of bubble combustion with premixed gas-oxygen mixtures (for more detailed study of hydrodynamics for in-water gas combustion). The gases with stoichiometric percentage of propane and oxygen produced single bubbles in water (with volume about 1–4 cm^3), and the bubble was fixed at the boundary between water and solid wall. The bubble

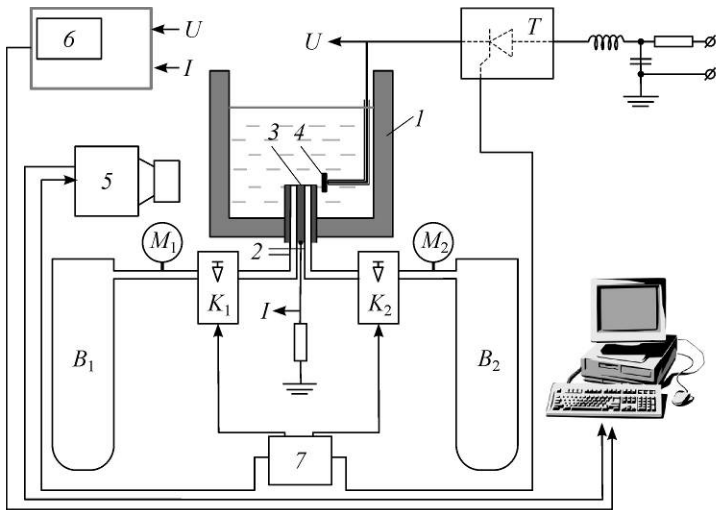

Fig.2. Principal scheme of the experimental set-up.

1 — plexiglass or polycarbonate cuvette, *2* — gas feed tubes, *3* — injection device on combustion of fuel gases in water (see Fig. 1), *4* — electrode for ignition of gases, *5* — high-speed video camera, *6* — oscilloscope, *7* — control board, *B* — gas cylinders, *M* — manometers, *K* — high-speed valves for gas feed into water, *T* — electronic commutator, *U* — voltage, *I* — current.

holds in the horizontal plane within the slots machined in the metal wall (the slot length was 30–70 mm, which corresponds to the sizes in Fig. 1, if the apparatus was switched by 180°). Similar statements of experiments were carried out for two annular slots with the diameter of 30–60 mm at the end of a metallic cylinder. The combustible mixture was ignited by a spark discharge with the energy of 4 J and voltage of 1 kV. High-speed video was taken for gas combustion in bubbles and for dynamics of bubble expansion after burning of the gaseous mixture. The video was recorded in two projections.

We performed synchronous measurement of pulsed force $F(t)$ on a wall holding the bubble. The force on the wall recorded by a digital oscillograph TDS-210 connected to a dynamometer on the base of a piezoceramic sensor made of $PbTiO_3$ with the diameter of 40 mm and height of 15 mm, which was equipped with an emitter repeater with a time constant $\theta \approx 10$ sec.

3. Experimental results

3.1. Results on dynamic mixing of gases in water

The video for hydrodynamic processes was taken in two projections, along the slots (by Z axis, see Fig. 1) and by normal to the slot ejector (Y axis). Figure 3 demonstrates an example of shadow picturing along Z axis for processes of dynamic mixing of gases in water, gas bubbling, ignition and expansion of a quasicylindrical bubble.

One can see from Fig. 3 that the process of cyclic combustion of gases in water can be divided into three main stages:

– gas injection into water;

– ignition and combustion of gas in the bubble;

– dynamics of expansion and pulsation of bubble after combustion of gas.

Note. All listed stages have own features that require systematic study for choosing the proper combustion regimes dictated by requirements of different technologies.

Figure 4 presents video frames (5000 fps) for the second stage of the first cycle of pulsed-cyclic mode of propane combustion; the video was taken by normal to the slot injectors (by Y axis, Fig. 1). The spark ignition of the mixture was performed in the middle part of the slot injector. The frame sequence shows that the produced quasicylindrical bubble exhibits instabilities depicted as “rough” boundaries of bubble (size $\delta \sim 1$ mm).

The high-speed pictures of fluid dynamics gave estimates for speed of the fronts of luminescence. For example, the time of acetylene-oxygen injection into water was 3 ms, the moment of delayed ignition was $t_{\text{ign}} \approx 15$ ms after the start of the combustion cycle. The visible velocity of luminescence fronts was in the range $u_f = 60–400$ m/s. The recorded speed of luminescence front for propane combustion was in the range $u_f = 60–160$ m/s. The results

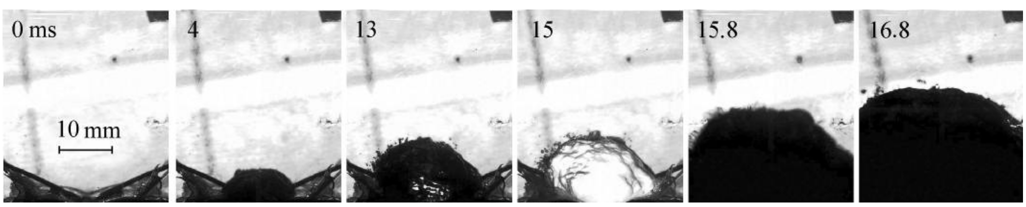

Fig. 3. The example of shadow record of injection, ignition, and expansion of quasi-cylindrical bubble. The bubble length is of 70 mm. Recording along slots. The recoding speed is 5000 fps.

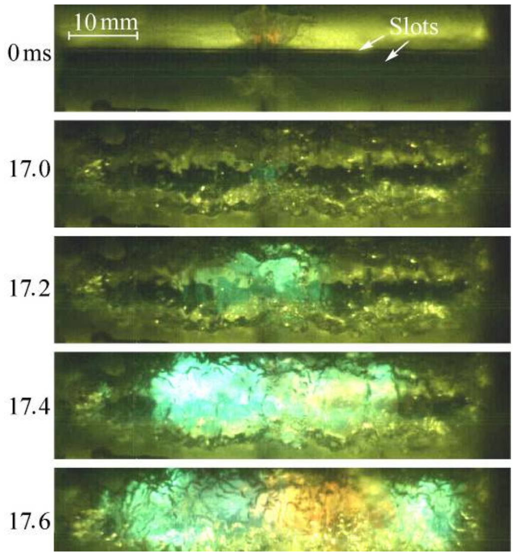

Fig. 4. Frames of recording of the second stage of combustion: propane combustion in a quasi-cylindrical bubble.
Record speed is 5000 fps.

demonstrate no detonation modes of acetylene or propane combustion; only unsteady deflagration combustion processes took place. Note that combustion rate has a pulsating feature. This was confirmed in experiments with premixed gases combustion.

3.2. Cyclic combustion of gas in enclosed vessel. Calorimetric study

Calorimetric study of heat transfer efficiency of in-water gas combustion in the tested setup operating under cyclic mode of 2.5 Hz frequency was carried out in a polycarbonate polymer bottle with the water volume of three liters (http://www.swsl.newmail.ru/video/MVI_1779.flv.html). The stable combustion regimes were accomplished for the duration of gas injection 5–8 ms with the delayed ignition at t_{ign} = 15 – 18 ms. The volumes of injected fuel and oxidant for a single cycle were under control. The energy loss due to heat transfer between the bottle and ambient air was neglected in our estimates. Every experimental run had from 500 up to 1990 cycles of bubble combustion. In calculation of specific heat energy q_n transferred to water, we took into account the design of the slot gas injector, mass and heat capacity of details. The total error in estimating the released heat was about 20–37 % . The accuracy in gas flow rate was 15 %.

Table

Calorimetric measurements

Gas	Heat value (upper) of fuel gas [6], J/cm^3	Volume of fuel gas injected per cycle, cm^3	Volume of oxygen injected per cycle, cm^3	Specific heat energy transferred from fuel gas to water (q_n), J/cm^3
Acetylene	54.08	5.1	8	21
Hydrogen	11.89	12.6	8	9.3
Propane	92.29	3.55	10.44	21

The Table summarizes the results of calorimetric measurements for specific heat energy received by water media from combustible gas in cyclic combustion mode (q_n), the duration of gas injection was 8 ms and the ignition delay was t_{ign} = 15 ms. These experimental parameters provided stable cyclic operation in the prototype with a slot injector. The experiments with hydrogen demonstrated only small amount of floating bubbles, but in acetylene-propane combustion experiments, the water “boiled” intensively due to floating big bubbles.

3.3 Experimental results on combustion of premixed gases

Figure 5 shows the frames of the shadow recording for fluid dynamics during combustion of a stoichiometric mixture of propane with oxygen in a quasicylindrical bubble with the volume of 2 cm^3. The special resolution in recording of fluid dynamics was about 0.2 mm.

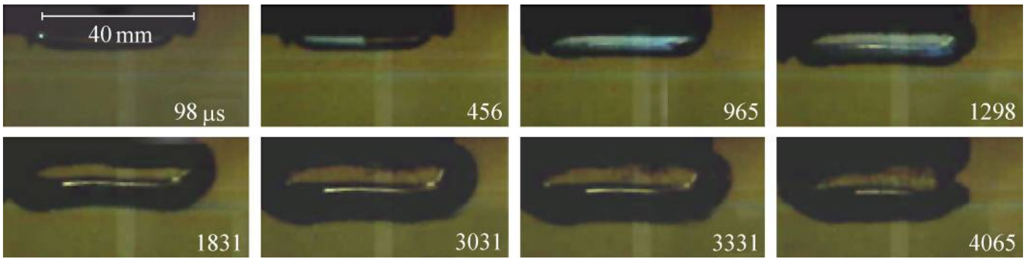

Fig. 5. Frames of high-speed video recording of gas combustion and initial stage of bubble expansion.

Figure 6 presents a diagram on measuring of the luminescence front speed u_f for a premixed stoichiometric mixture C_3H_8 + $5O_2$ in a quasi-cylindrical bubble. Experiments have shown that under other conditions equal, the rate of combustion pulses along the bubble. For different numbers of experiments with the same mixture, the discrepancy in the measured speed of front propagation was about 160 m/s. However, the observed instability in combustion speed has low influence on the dynamics of bubble expansion.

Figure 7 presents the frames of video of combustion C_3H_8 + $5O_2$ mixture in the annular bubble with the annular diameter of 40 mm and the volume of 3 cm^3; the bubble was placed at the bottom of the cylinder with the diameter of 59 mm. The opposite end of the cylinder has a dynamometer for registration of pulsed force (generated due to gas combustion in the bubble).

We should note that in-bubble combustion on the intervals of decline in combustion speed the structure of the luminescence front shaped as a dovetail is observed. This structure is shown in Fig. 5 for the current time t = 965 ms, and Figure 7 shows a similar structure at t = 700 ms. For the mentioned stages of combustion, the luminescence front has blue color.

Figure 8*a* presents selected frames of the shadow pictures for fluid dynamics during combustion of C_3H_8 + $5O_2$ mixture occurring in the annular bubble with the diameter of 40 mm and the volume of 3 cm^3; the bubble grows at the end of a cylinder with the diameter of 59 mm. Figure 8*b* shows also the matched schemes of hydrodynamic processes at the lower end of the cylinder (here T is the pulsation period of generated bubble).

The key parameter in the studied processes is the initial volume of combustible mixture: this determines the bubble pulsation period and the entire fluid flow features. For example, the injected gas

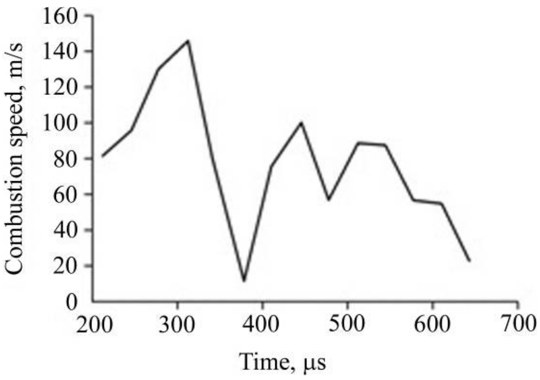

Fig. 6. Example of diagram showing pulsation of combustion velocity for the mixture C_3H_8 + $5O_2$ in a quasicylindrical bubble.

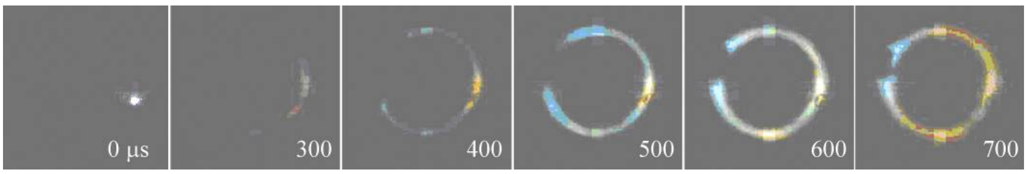

Fig. 7. High-speed video frames for propane-oxygen mixture in an annular bubble with the ring diameter of 4 cm. Gas volume is 3 cm^3.

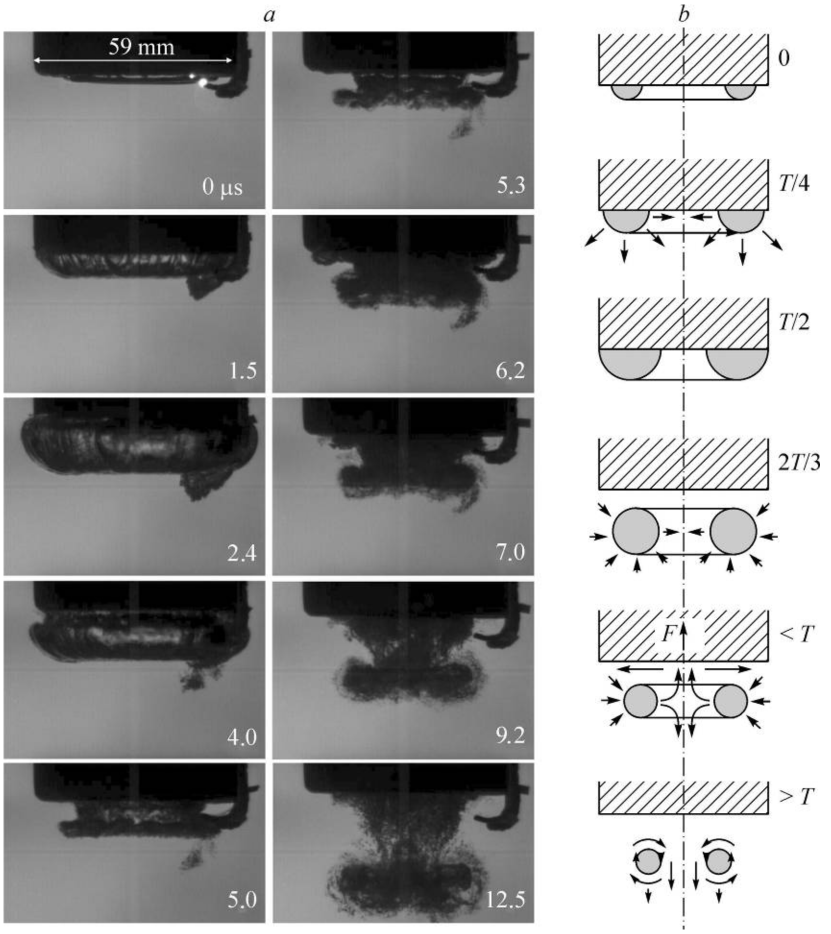

Fig. 8. Frames of shadow video (*a*) and matched schematic picture (*b*) of hydrodynamic processes for combustion of gas mixture in an annular bubble with the main diameter $d = 40$ at the face of a cylinder with $D = 59$ mm.

T is the period of pulsation for a torus-shaped bubble, F is the direction of pulsed force.

with volume 1–2 cm^3 produces a torus-shaped bubble. This bubble collapses in radial direction and symmetrically to the ring axis; that process produces symmetrical and opposite flows of liquid along the main axis. If the gas mixture volume exceeds 2 cm^3, the torus-shaped bubble transforms into ellipsoid which is flattened in the direction of cylinder axis. This shape of bubble collapses in radial direction towards the ring axis and generates axial flows of liquid. But for the dynamics with times $t > T$, the pictures show the liquid jet flow from the wall (with generation of an annular vortex comprising small bubbles). The jet directed towards the wall can be detected indirectly: this is a curtain of bubbles spreading in radial direction along the cylinder end. The additional indication of pulses from expansion and collapse of bubble is the observed process of motion of free cylinder upward (Fig. 8).

Figure 9 presents oscillogram of the pulsed force F produced by combustion of 2 cm^3 of premixed propane-oxygen mixture. This plotting demonstrates two main pulses. The first pulse (F_1) is attributed to the bubble expansion due to gas combustion, and the second pulse in force (F_2) corresponds to the moment of collapse of generated bubble and generation of liquid flow toward the thrust wall, which ensures upward movement of the cylinder. It is shown from Fig. 9 that the second pulse is comparable with the first one, whilst: $P_1 = \int F_1 dt = 0.077$ kgf·s,

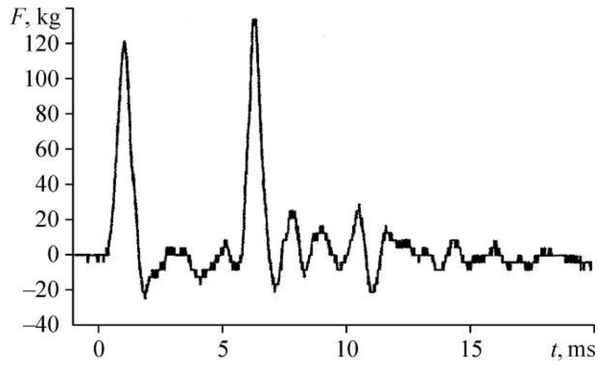

Fig. 9. Oscillogram for pulses of force F generated by expanding and collapsing torus-shaped bubble.

$P_2 = \int F_2\,dt = 0.075$ kgf·s. The total pulse for the duration of 13 ms: $P = \int_0^{13\text{ ms}} f dt = 0.13$ kgf·s. In this experiment the mass of propane was $m = 2.7 \cdot 10^{-6}$ kg, so the specific impulse for one cycle of combustion $P_{sp} = P/m = 4.8 \cdot 10^4$ s.

After the collapse of the first torus-shaped (or ellipsoid) bubble ($t > T$), the disintegration of this bubble into small bubbles and formation of a bubbly vortex was observed. This annular bubbly vortex travels along the cylinder axis and pulsates with the period of 2 ms. These pulsations are found in video pictures and oscillograms as weak pulses which developed due to in-phase cooperative processes of small bubbles in vortical cluster.

4. Analysis of experimental results

Here we present result analysis with account for process division into three stages.

1. Gas injection into water.
2. Ignition and combustion of gas in the bubble.
3. Hydrodynamic processes accompanying bubble pulsation.

4.1. Gas injection into water

It was found that the most serious problem of the in-liquid gas combustion was the problem of coalescence of a bubble of fuel gas and a bubble of oxidant. Since the coalescence of bubbles blown out through round holes was problematic, we declined this approach and started testing gas bubbling through linear slots. This approach assumes that the boundaries of quasicylindrical bubbles would be unstable, and this instability helps in reliable coalescence of two bubbles and gas mixing with a united bubble. Coalescence of two gas bubbles in contact (for cases of adverse or tangential gas blow into water) may occur due to breaking of a water film by parallel or normal gas flow or due to disruption of moving bubbles [2]. Our experiments confirmed these hypotheses. Reliable ignition and combustion of fuel mixtures in water was obtained with gas blowing frequency up to 2.5 Hz. The video frames demonstrate bubble boundary instability as "rough" surface; this is observed in all stages: before ignition, during gas combustion or during gas bubble expansion (Figs. 3 and 4). The initial bubble boundary instability (roughly surface) is related to the turbulent mode of gas combustion within the bubble.

4.2. Gas combustion in bubble

Stochastic phenomena for gas combustion in repeated experiments were observed both for variants of dynamic gases mixing or for blowing of premixed gases. For all experiments (acetylene, hydrogen, propane as fuel gas) with dynamic mixing fuel+oxidant the visible velocity of the burning front was less than 400 m/s. This means that we deal with deflagration regime of gas combustion inside the bubble. We assume also that the roughly surface of bubble facilitates turbulent mode of gas combustion [7]. The observed pulsations in the longitudinal velocity of combustion front (Fig. 6) are explained by instability of the combustion front (visible in video pictures). One of features in observed processes was the gain in the blue color intensity in the near zone of combustion front when the front takes a dovetail shape. This is a manifestation of a higher temperature in the zones behind the combustion front.

Let us consider the fact of decline in combustion velocity along the bubble in correlation with the phenomena of observed dovetail-shaped luminescence front (Figs. 5, 7). The dovetail-shaped fronts develop when we observe a decline in the longitudinal velocity of combustion front. During this process, as it was observed for gas combustion in metal pipes [7], the combustion along the bubble axis can be decelerated because of larger combustion front (when the across component of front velocity appears). We assume that the increase in combustion velocity induces the vapor-droplet phase at the combustion front (this phase works as inhibitor). The inhibitor makes the combustion front slower. However, in the regions with low vapor-droplet phase content, the break-through of combustion zones develops: this is manifested as dovetail-shaped structure (typical of the transversal development of combustion front). This speeds up combustion until the next cycle of deceleration. Under certain conditions, this process tends to repeat.

If the considered hypothesis is correct, this means that this kind of system offers opportunity of restrictions for combustion to go into detonation direction; hence, we can arrange the required combustion mode. In turn, this creates conditions for self-regulation of combustion process (keeping the process away from detonation mode).

We should emphasize that results of calorimetric study are novel and far from optimum. It was observed that combustion experiments with hydrogen fuel (a lean mixture) produce a small amount of floating bubbles. The tests with acetylene or propane (rich mixtures) demonstrated that the liquid in the bottle "boiled" intensively through big floating bubbles. This indicates about energy loss: besides incomplete burning of those gaseous mixtures, some heat was lost with gas bubbles. This was a shortcoming of the first prototype with a slot injector. Experiments with annular bubbles (Fig. 8) demonstrated more efficient decay of hot bubbles via convective processes in vortex flow. These tests have given directions for further improvements. The proportion between fuel gas and oxidant is an important parameter in optimization of combustion process. Optimization of pulsed-cyclic in-water gas combustion can be achieved through analysis of results in publications [8, 9], where the authors studied regimes of stationary combustion of hydrogen in water as a function of oxygen balance. For example, those publications shed light on high efficiency of hydrogen combustion: at optimum in oxygen concentration, the most part of combustion products condensates into water (as was observed in experiments). However, it is difficult to compare results of the presented paper and previous research [8, 9], since the problem statement and procedures were different.

4.3. Hydrodynamic processes. Pulses of force

The observed fluid dynamics and jet flows in liquid during bubble expansion and pulsations near a solid wall is similar to the flows described in [10] (for situation of pulsating bubbles produced by explosions of solid explosives near the free liquid interface). However, the following difference exists between explosion of solid explosives and explosion of gas in water [11, 12]: in the latter case, we have no detonation of explosive source. Therefore, energy redistribution between the kinetic energy of liquid from expanding gas bubble and the energy of shock wave will be in favor of the kinetic energy from the bubble.

Synchronization of fluid dynamics and measured force applied to the cylinder end demonstrated that the first pulse (Fig. 9) corresponds to bubble expansion, but the second pulse occurs due to the development of axial focusing of liquid flow attached to the internal boundary of the toroid bubble. Here the maximum of axial jet velocity toward the cylinder end corresponds to the moment of time of the first pulsation of the toroid bubble. The moment of collapse of a toroid bubble ($t = T$) corresponds to the maximum of the pulsed force applied to the cylinder end. These results demonstrate the general possibility for application of the tested methods for designing of pulsed submerged propellers. We should note also that after merging of a toroid bubble on its axis, this bubble transforms into a flatten ellipsoid; the process pattern remains the same except the feature of axial focusing of liquid placed at the external perimeter of the ex-torus.

Conclusions

1. The pulsed-cyclic method of in-water combustion of gaseous hydrocarbons or hydrogen was accomplished with separate feed of fuel gas and oxygen into water medium; this novel method can be used in developing of new technologies for fuel combustion in heat generators or for submerged propellers.

2. Experiments demonstrated that in-water gas combustion near a solid wall opens the ways for transformation of chemical energy of combustible mixture into the translation motion on the thrust wall driven by pulses of force (originated due to expansion of combustion products in water and after bubble collapse). The bubble collapse near the wall creates axial liquid flow, and this provides additional (second) pulse of force which is comparable with the first pulse in magnitude.

3. The tested method of in-water gas combustion near a solid wall allows one to reduce the energy loss in a complicated chain of energy transformation into mechanical energy inherent in conventional technologies (this includes an internal combustion engine, transmission, screw). The method offers new approach for fuel combustion adapted for water propulsion unit: direct in-water pulsed combustion of gases offers several advantages.

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