PULSE-CYCLIC COMBUSTION OF GASES IN A LIQUID FOR NEW ENERGY SYSTEMS

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The results of experimental investigations of hydrodynamic processes in cylindrical and conical combustion chambers submerged into water are presented. It is shown that after the combustion of one portion of stoichiometric propane–oxygen mixture on a thrust wall, a cyclic generation of force impulses occurs: the first impulse is formed during the gas combustion and the subsequent ones are formed due to hydrodynamic pulsations of gas cavity in the tube.

It is shown experimentally that in order to obtain the efficient thrust generation, it is necessary to use all bubble pulsations after the combustion of one portion of gas charge in the tube. In the presented experiments, the specific force impulses on the thrust wall were in the range 10^4–10^5 s (10^5–10^6 m/s) with taking into account positive and negative components.

Introduction

In modern propulsion systems of waterborne vehicles, internal combustion engines (ICEs) or turbines, in which different transmissions drive the propeller screws, are used.

The main disadvantage of such propulsion systems is a great amount of friction mechanical details in the chain of transfer of mechanical energy from the combustion chamber to the propeller screw. These systems are complicated in construction and have high manufacturing and maintenance costs. The use of all systems of mechanical pulse transfer leads to great energy losses [1]. The systems with direct transfer of mechanical energy of combustion products to the thrust impulses,

e. g., hydrojet movers [2], are promising. However, existing hydrojet movers working on the basis of combustion of special fuels, for which the oxidizer is water, are not acceptable for a wide use for the reasons of ecology safety standards. Therefore, for waterborne vehicles, the systems using widely available fuels such as natural gas can be of special interest.

The important vector in developing the methods of gas combustion in a liquid is the method of separate supply of combustible gas and oxidizer directly into a liquid. The methods of separate supply of combustible gas and oxidizer directly into a liquid in impulse-cyclic regimes provide for operation safety of the developed systems and devices. This method is tested experimentally and presented in [3].

In the present work, the possibilities to apply the methods of impulse combustion of combustible gases directly in water are considered in order to make a scientific base for development of pulsating hydrojet movers and heat generators. The investigation results of combustion of propane–oxygen mixture on the open rigid wall in cylindrical and conical chambers submerged into water are presented.

Experimental Setup

Figure 1 shows a principal diagram of the experiments. Plastic cylindrical chamber (*2*) of inner diameter d, outer diameter D, and height H was placed vertically in plexiglas cuvette (*1*) 0.5 m high and filled with water. The chamber was filled with a combustible mixture (*3*) to a required level. The combustible mixture was ignited by a spark of high-voltage power supply (*5*) of energy of 2 J. The combustion of predetermined portions of the gas mixture (*3*) provided generation of force impulses acting on the thrust wall (*4*) and transferring force to a dynamometer (*6*). The dynamometer was mounted on a horizontal rigid beam (*7*). The registration of force impulses acting on the wall was performed by dynamometer (*6*) 40 mm in diameter and 15 mm high, made of lead zirconate–titanate (PZT) piezoceramics and having acoustic isolation along the axis. Electrical signal from the dynamometer was sent to an emitter-follower amplifier with a time constant of $\theta \approx 10$ s and it was recorded using a TDS-210 digital oscilloscope (*8*). Simultaneously with the measurements of force impulses, the pressure

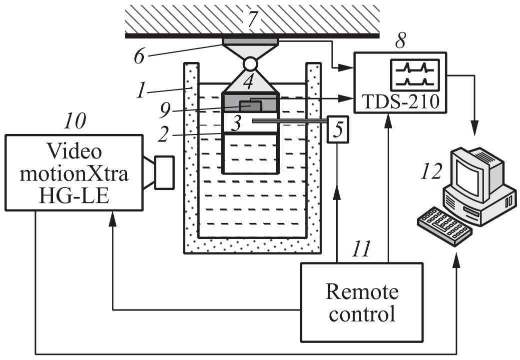

Figure 1 Schematic diagram of the experimental setup

impulses in the combustion chamber (*3*) were measured by using tourmaline transducers (*9*) with characteristic resolution time of 0.3 μs and time constant of registration not less than 1 s. The pressure transducer was built in the end of the tube on the thrust wall. The errors of the measured parameters were within 5%–15%. The experiments were performed with gaseous charges of stoichiometric propane–oxygen mixture ($C_3H_8 + 5O_2$) of volumes V_g = 0.5–20 ml. Shadowgraphs of hydrodynamic processes were taken with a MotionXtra HG-LE digital camera (*10*). The control of system was carried out by using a remote control (*11*). The results were recorded by using a computer (*12*). Additionally, the experiments considering free moving of cylindrical tubes out of water were carried out recording the dynamics of moving of cylindrical tubes in a vertical direction.

Experimental Results

Figure 2 presents the example of shadowgraphs of hydrodynamic processes occurring during the gas combustion in a cylindrical chamber (V_g = 3 ml and H = 83 mm). It is seen that almost over the whole cross-sectional area of the chamber except for a small part near the wall, the bubble boundary has a plane shape during the whole period of bubble growth.

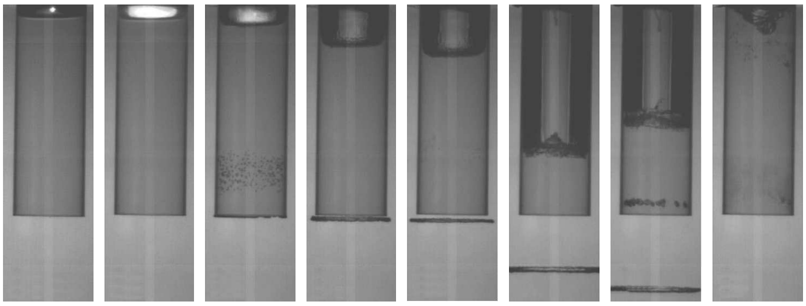

Figure 2 Shadowgraphs of the dynamics of the processes inside and outside the chamber for a gaseous charge with $V_g = 3$ ml, $d = 29$ mm, $D = 31$ mm, and $H = 83$ mm

These shadowgraphs show the main moments of hydrodynamic processes occurring during the combustion of gaseous charge in a cylindrical tube: 0.1 ms — the combustion of gaseous charge and the start of gas bubble expansion; and 1.4 ms — the initial stage of liquid flowing out of the tube and formation of a cavitation vortex ring (CVR) [4] correlating in time with cavitation zone inside the chamber. At time period from 0.1 to 10 ms, the bubble expands up to the maximal size and the time interval from 10 to 20 ms corresponds to the process of bubble collapse occurring in the direction of the cylinder end and formation of a return liquid flow directed into the combustion chamber. During the bubble collapse, the secondary cavitation field near the tube edge ($t = 14$ ms) is formed but it disappears during the generation of the second pressure impulse formed during the bubble collapse ($t = 20$ ms). For this record, the first period of bubble pulsation is $T_1 \approx 20$ ms.

From the results of records and measurements of force and pressure impulses in the combustion chamber, it follows that the combustion of one portion of gas mixture on the thrust wall leads to the generation of several force impulses (Fig. 3). The first impulse is generated due to gas combustion and subsequent impulses are generated due to the collapse of cavity containing combustion products and water vapor. Here one can observe several cavity pulsations with periods T_1, T_2, T_3.

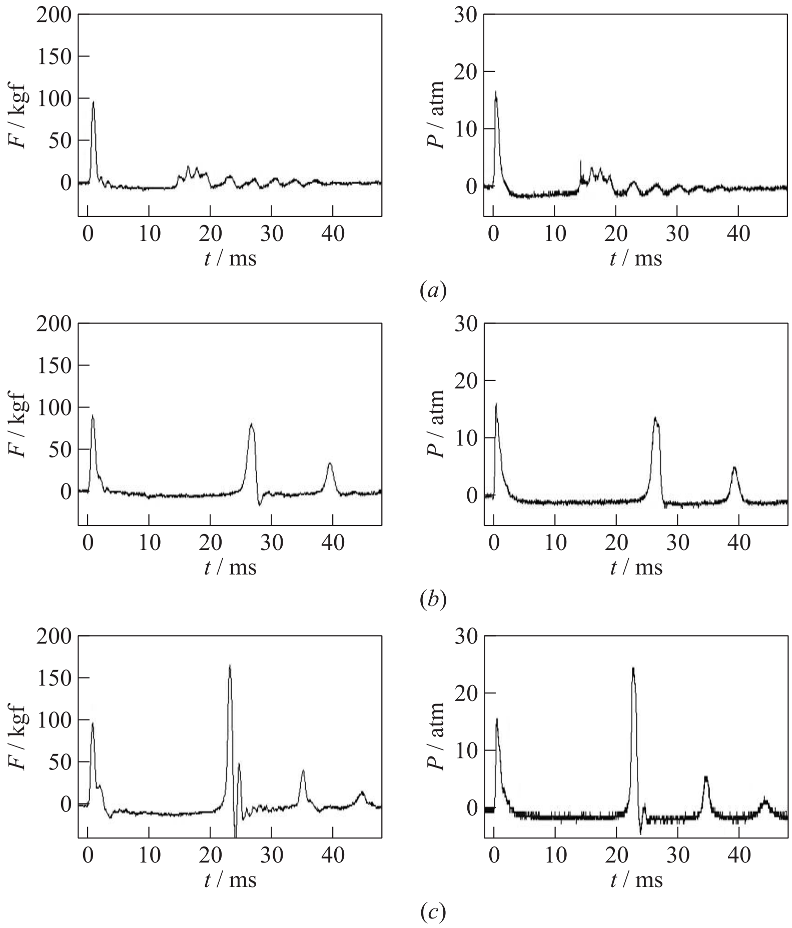

Figure 3 Oscillograms of force $F(t)$ and pressure impulses $P(t)$ in the combustion chamber obtained simultaneously during the combustion of stoichiometric propane–oxygen mixture for cylindrical combustion chambers

Figure 3 demonstrates the oscillograms of recording of force $F(t)$ and pressure impulses $P(t)$ in the combustion chamber obtained simultaneously during the combustion of stoichiometric propane–oxygen mixture for cylindrical combustion chambers.

The oscillograms in Fig. 3a correspond to the experimental studies of combustion of 3 ml of stoichiometric propane–oxygen mixture in the tube of inner diameter $d = 29$ mm, outer diameter $D = 31$ mm, and length $H = 80$ mm. For this oscillogram, the maximal bubble size reached the tube cut. As a result, for these and similar conditions of the experimental setup, the second and subsequent force and pressure impulses disappear that decreased the specific impulse for a given gas charge.

Provided that the volume of the combustion chamber V is more than that of the forming bubble V_b, subsequent force and pressure impulses are generated. Figures 3b and 3c show the oscillograms of force and pressure impulses for $V/V_b > 1$. In Fig. 3b, the oscillograms correspond to the experimental studies of combustion of 3 ml of stoichiometric propane–oxygen mixture in the tube of diameter $d = 29$ mm and length $H = 129$ mm. In Fig. 3c, the oscillograms correspond to the experimental studies of combustion of 3 ml of stoichiometric propane–oxygen mixture in the tube of diameter $d = 29$ mm and length $H = 90$ mm with a conical nozzle with apex angle $\sim 10°$ and cone basis diameter $d = 37$–40 mm. The total tube length is $H = 116$ mm.

Specific Impulse Calculations

According to the data of experimental measurements of force impulses, the integration of all force impulses ($I_n = \int F(t)\,dt$) and the calculation of specific impulses ($I_m = \sum I_n/m$) in the range up to 50 ms were performed. However, when testing different combustion chambers and using different conditions of experiments, not in all experiments the generation of subsequent force impulses was observed. Therefore, for correct comparison of force impulses and specific impulses, the calculations of force impulses and specific thrust impulses were performed by the scheme presented in Fig. 4. The oscillograms were divided into four intervals: (i) interval (t_0–t_1) corresponded to the generation of the first positive impulse I_1 due to the expansion of combustion products of gas mixture; (ii) interval (t_1–t_2) corresponded to negative phase $I_{(-1)}$; (iii) interval (t_2–t_3) corresponded to positive phase I_2 due to the return liquid flow directed to the tube end that corresponds to collapse and subsequent bubble expansion at the chamber end; and ($i\nu$) interval

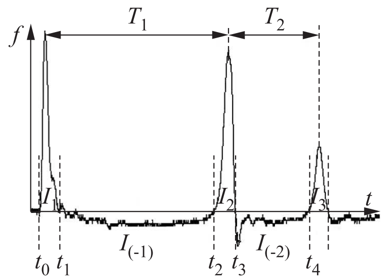

Figure 4 Scheme for calculations of force and specific thrust impulses

(t_3–t_4) corresponded to the second negative phase $I_{(-2)}$.

Figure 5 shows some experimental values of specific impulses for different geometries of combustion chambers resulting from integration of measured force impulses according to the scheme in Fig. 4 for time intervals (t_0–t_4) (*1*) and for the case of complete integration of all impulses in the range up to 50 ms (*2*). On the horizontal axis, the numbers of experiments with assigned geometrical variants of combustion chambers are indicated: in experiments 5–9, the cylinder

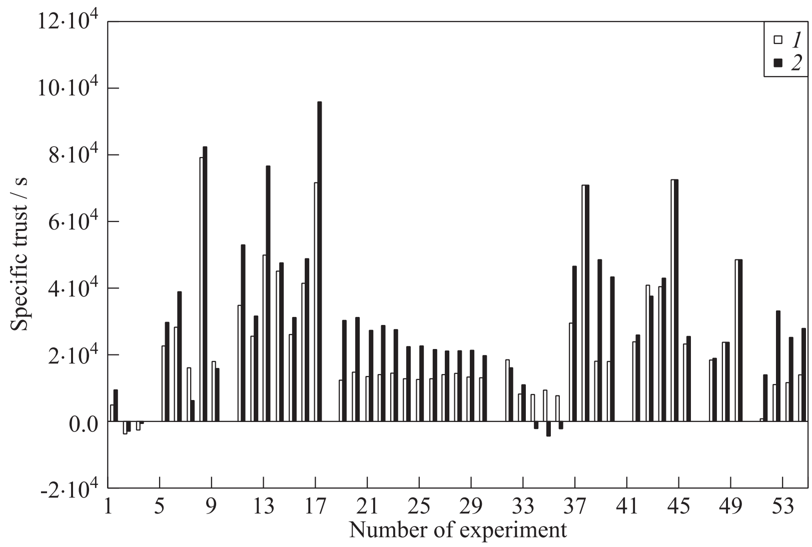

Figure 5 Experimental values of specific impulses for different geometries of combustion chambers resulting from integration of measured force impulses according to the scheme in Fig. 4 for time intervals (t_0–t_4) (*1*) and for the case of complete integration of all impulses in the range up to 50 ms (*2*)

of $d = 29$ mm and $H = 47$ mm is used; in experiments 10–17, the cylinder of $d = 29$ mm and $H = 93$ mm is used; in experiments 19–31, the ringed cone in the cylinder of $D = 86$ mm and $H = 22$ mm is used; in experiments 32–36, the truncated cone with open outer surface of $D = 60$ mm and $H = 40$ mm is used; in experiments 37–41, the truncated cone in a cylindrical body of $D = 60$ mm and $H = 30$ mm is used; in experiments 42–50, the hemisphere of $D = 52$ mm and $H = 9$ mm is used; and in experiments 52–55, a flat disk of $D = 99$ mm is used. In these calculations, the total charge mass of propane–oxygen mixture ($C_3H_8 + 5O_2$) was taken as mass (m).

The presented results clearly demonstrate the essential spread of the measured parameters in the experiments. It is caused by poor repeatability of processes of gas charge combustion for the reasons of small volumes of charges. Despite the great spread of the measured parameters, the value of total specific impulses mostly ranged within 10^4–10^5 s (10^5–10^6 m/s). In some experiments, the values exceeded the value of 10^5 s. It is assumed that in such experiments, the conditions of transition of combustion to the regime of gas detonation were provided.

Bubble Pulsations

In order to give a cyclicity of gas supply to the combustion chamber, it is necessary to know the periods of bubble pulsations in the chamber. In [5], the theoretical formula for the calculation of the first period of bubble pulsation T_1 in the cylindrical tube depending on the tube length H for charges $V_g = 1 - 3$ ml was obtained. Figure 6 shows the dependence of experimental and calculated values of the first period of bubble pulsations on the length of the cylindrical tube

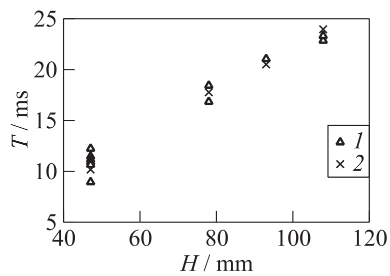

Figure 6 Dependence of experimental (*1*) and calculated (*2*) values of the first period of bubble pulsations on the length of the cylindrical tube according to data from [5]

according to data from [5]. The experimental points were found by averaging of at least four experimental values. The experimental error of measurement of periods did not exceed 1%.

Dynamic Tests

The comparison of diagrams in Fig. 5, clearly demonstrates the fact that for the thrust generation, it is necessary to use not only two first periods of pulsation but also the subsequent periods as they provide the increase of specific impulse for one cycle of gas combustion. In order to elicit the roles of subsequent force impulses on thrust characteristics of the mover clearly and thoroughly, the operation of such a mover was dynamically tested in the following way: a vertical model in the form of cylinder 220 mm long, 45 mm in diameter, and weighing 168 g freely moves from the water during the combustion of 1.5–3 ml of stoichiometric propane–oxygen mixture in the combustion chamber of diameter $d = 29$ mm and height $H = 47$ mm. Figure 7 shows the experimental results with the recorded dynamics of model moving up.

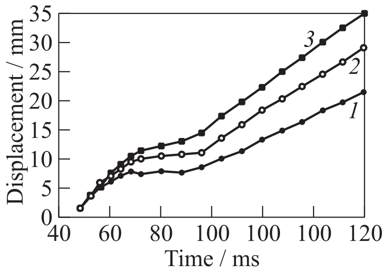

Figure 7 Experimental results at combustion of stoichiometric propane–oxygen mixture: *1* — $V = 1.5$ cm^3; *2* — 2.5; and *3* — $V = 3$ cm^3

For the used combustion chamber of the given model, the period of the first bubble pulsation T_1 was within 12 ms. Figure 7 demonstrates that the first force impulse provides the initial moving of the model during first 7–8 ms, then braking occurs (owing to impulse $I_{(-1)}$) and starting from 13–14 ms, the moving of the model takes place due to the energy of subsequent force impulses. The given graphs clearly demonstrate that the model velocity increases with the gas charge V_g.

Brief Analysis of the Results

Taking into account the fact that using a cylindrical chamber, the thrust wall area $S = const$, the thrust $F(t)$ can be calculated by multiplying the cross-sectional area of the chamber by the gas pressure measured by the pressure transducer in the combustion chamber. The experiments showed that the thrust force values calculated by the results of pressure measurement $F_p(t) = P(t)S$ exceeded the force values measured directly by the dynamometer F_d. On average, the values $(F_p - F_d)/F_p$ ranged within 0.15–0.3. This indicates the presence of losses in the system which may occur due to hydrodynamic processes which were not taken into account.

The important peculiarities of the generated force impulses are the facts of presence of the consequent impulses. For cylindrical combustion chambers, the registered force impulses allow one to estimate the values of pressure inside the bubble both for the first and for the subsequent impulses (see Fig. 3). The subsequent impulses are observed only if the maximal size of the formed bubble (V_b) does not exceed the volume of the used tube (V). If $V_b > V$, the bubble is "ejected" from the tube and only the first impulse is registered; the amplitudes of subsequent impulses with stochastic structure are small (see Fig. 3*a*). If conditions $V_b/V < 1$ are satisfied, the subsequent force impulses are generated (see Figs. 3*b* and 3*c*). These impulses are connected with pulsations of the formed bubble in the chamber with T_1, T_2, T_3, ... Moreover, the second positive impulse is comparable with the first one. But in the case of conical chambers, the processes of the second impulse increase were observed. This effect may occur for two reasons: (*i*) due to vapor condensation during the bubble collapse which was considered in [6], and (*ii*) due to increasing the liquid velocity in the return flow directed into the cone. Here, the correlation of force impulses and the measured values in the chamber has been observed (see Figs. 3*b* and 3*c*). The experiments and calculations showed that initial pressures in the bubble ranged from 15 to 20 atm that is close to the regimes of deflagration combustion at constant volume.

As it follows from the presented results, for giving the cycles of gas injections into the system, it is reasonable to supply a subsequent gas portion after all force impulses. The use of the subsequent periods of pulsations provides the increase of specific thrust for one cycle of fuel combustion in comparison with one or two periods (as in Fig. 3*a*). These peculiarities predetermine the parameters of giving the cyclicity (T) of supply of subsequent combustible gas portions into the chamber. Here, the period of the first pulsation T_1 is given by the parameters of the combustion chamber, i. e., longitudinal dimensions, e. g., as for the cylindrical tube (see Fig. 6). The process of cyclic supply of gas portion into the chamber can be also realized during the subsequent period of bubble pulsations that will provide a higher efficiency of the mover. At present, it is reasonable to consider the later moments of fuel supply into the system either with allowance for generation of the subsequent force impulses, which are different for each geometry.

Concluding Remarks

Based on the performed experimental and theoretical investigations of the processes of thrust generation during the pulse gas combustion in water in submerged combustion chambers, the following main results have been obtained.

1. The performed complex investigations of the processes of thrust generation during the pulse gas combustion in model chambers with simultaneous measurements of thrust force, pressure, and hydrodynamic processes showed that obtaining the specific impulses up to 10^5 s (10^6 m/s) is provided due to the use of the subsequent impulses formed owing to the bubble pulsations in the combustion chambers.

2. It is shown that for the considered type of movers provided that the maximal volume of the formed bubble (V_b) does not exceed the volume of combustion chamber (V_c), i. e., at $V_b/V_c < 1$, two or three force impulses are generated, the total specific impulse is $P_{\mathrm{sp}} = 10^5$ s, and at $V_b/V_c > 1$, the subsequent impulses disappear that leads to decrease of the specific impulse for one cycle of gas combustion.

3. The results of this work may be taken as a preliminary basis of development of relatively simple pulsating hydrojet movers, heat generators, and devices using the energy of high-speed hydrodynamic flows.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (grants Nos. 13-08-00838 and 14-08-00226).

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