Dynamics of force impulses and bubble oscillations during gas burning on a thrust wall in water

V S Teslenko, A P Drozhzhin and R N Medvedev

Lavrentyev Institute of Hydrodynamics SB RAS, Lavrentyev Prosp. 15, 630090, Novosibirsk, Russia

E-mail: teslenko@hydro.nsc.ru

Abstract. Comparative experiments are formed for measuring the force impulses during combustion of a stoichiometric propane-oxygen mixture on a thrust wall in cylindrical combustors and on an open wall shaped as a flat disk. For identical gas charges, the mean specific impulse generated by pulsed burning of the gas on an open thrust wall is found to be higher than that in the case of gas charge burning in cylindrical barrels.

1. Introduction
A series of experiments with measurements of force impulses and shadowgraphy of bubble oscillations in various submerged combustion chambers was performed for the purpose of developing effective methods of pulsed burning of gases in water for thrust generation [1, 2]. Previous experiments and model calculations with cylindrical combustors showed that the amplitude of the first force impulse depends weakly on the volume of the gas burned in the cylindrical combustor. The amplitudes of the subsequent force impulses arising at the bubble collapse instants depend on the combustor geometry. For cylindrical combustors, the time between the first and second impulses (period of the first oscillation of the bubble in the barrel) depends on the barrel length [3]. As the barrel length increases, the bubble oscillation period also increases. The accompanying edge effects in the form of cavitation vortex rings at the exit of the cylindrical barrel and cavitation inside the barrel [4] lead to dissipative losses of the impulses; therefore, these phenomena should be avoided.

2. Experimental
The arrangement of experiments is illustrated in figure 1. A plastic cylindrical chamber (2) with an inner diameter \(d\), outer diameter \(D\), and height \(H\) was placed vertically in a plexiglas cuvette (1) 0.5 m high, which was filled with water. The chamber was filled with a combustible mixture (3) up to a needed level. The mixture was ignited by a spark generated by a high-voltage source (5) with the energy up to 2 J. Burning of predetermined portions of the gas mixture (3) ensured generation of force impulses on a thrust wall (4) with force transfer to a dynamometer (6). The dynamometer was fixed on a horizontal rigid beam (7). The force impulses on the thrust wall were measured by the dynamometer (6), 40 mm in diameter and 15 mm high, which was made of lead zirconate-titanate and was acoustically uncoupled along the axis. The electric signal from the dynamometer passed to an emitter-follower with a time constant \(\theta \approx 10\) s and was recorded by a TDS-210 digital oscilloscope (8). Simultaneously with force impulse measurements, the pressure in the combustion chamber (3) was measured by tourmaline sensors (9) with the characteristic resolution of 0.3 \(\mu\)s and the time constant of more than 1 s. The pressure sensor was mounted in the upper end of the chamber on the thrust wall.
All parameters were measured within the error from 5 to 15%. The experiments were performed with gas charges of a stoichiometric propane-oxygen mixture \((\text{C}_3\text{H}_8 + 5\cdot \text{O}_2)\) with the volume \(V_g\) from 1 to 3 ml. Shadowgraphs of the hydrodynamic processes were taken by a MotionXtra HG-LE digital camera (10). The system was controlled by a remote control panel (11), and the measured results were fed to a computer (12).

Figure 1. Arrangement of experiments.

3. Experimental results

Figure 2 shows several shadowgraphs, which illustrate the dynamics of the processes in a cylindrical chamber with a diameter \(d = 29\) mm and length \(H = 91\) mm in the course of burning a stoichiometric propane-oxygen mixture with a volume \(V_g = 3\) ml.

Figure 2. Shadowgraphs illustrating the processes in a cylindrical chamber \((d = 29\) mm and \(H = 91\) mm) for a gas mixture with \(V_g = 3\) ml.

For numerical comparisons of the force impulses (figures 4 and 6), the thrust oscillograms were divided into four intervals (figure 3): 1) the interval \((t_0 - t_1)\) corresponds to generation of the first positive impulse \(I_1\) (first phase) owing to pressure generated by combustion of the gas mixture; 2) the interval \((t_1 - t_2)\) corresponds to the negative phase \(I_{-1}\) in the course of cavity expansion; 3) the interval \((t_2 - t_3)\) corresponds to the positive impulse \(I_2\) (second positive phase) due to a collapse of the cavity at the end face of the thrust wall; 4) the interval \((t_3 - t_4)\) corresponds to the second negative phase \(I_{-2}\) due to secondary expansion of the cavity.

Figure 4 shows the force impulse oscillograms (figure 4a) and the relationships of the first four phases (figure 4b) calculated in accordance with the scheme in figure 3 for the case of burning the gas mixture presented in the shadowgraphs (see figure 2).
Figure 3. The scheme of dividing the thrust force into time intervals.

Figure 4. a) the oscillogram of thrust for gas mixture ($V_g = 3$ ml) combustion in cylindrical chamber ($d = 29$ mm, $H = 91$ mm), b) thrust integrals with time for initial 4th phases (1-4), their sum (5) and the full integral (6) over the oscillogram.

The frames illustrating the hydrodynamic processes that occur during combustion of a propane-oxygen mixture with a volume $V_g = 2$ ml on the open thrust wall shaped as a disk of the diameter $D = 98$ mm are presented in figure 5. Figure 6 shows the force impulse oscillograms (figure 6a) and relationships of the numerical values of the force impulses (figure 6b) for the case of combustion of a gas charge with a volume $V_g = 3$ ml.

Figure 5. Frames illustrating bubble oscillations on a disk-shaped thrust wall for a gas charge with $V_g = 2$ ml.
Figure 6. a) the oscillogram of thrust for gas mixture ($V_g = 3$ ml) combustion at open wall shaped as a disk ($D = 98$ mm), b) thrust integrals with time for initial 4th phases (1-4), their sum (5) and the full integral (6) over the oscillogram.

Figure 7 shows the experimental dependence of the period of the first oscillation of the bubble ($T_1$) as a function of the initial volume of the gas charge $V_g$ for the case of gas mixture combustion at flat wall.

Figure 7. The dependence of the first period of bubble pulsation at flat wall on the volume of initial gas mixture $V_g$.

4. Analysis of results
It is clearly seen from the presented results that the amplitude values of the thrust (kgf) and force impulses (kg·s) for identical volumes of the gas charge ($V_g = 3$ ml) are higher in the case of an open thrust wall than in the case of burning the gas charge in a cylindrical barrel.

As the quantitative comparisons of the thrust characteristics were performed for identical gas charges, the results can be compared in terms of the following parameters: specific impulse and averaged specific thrust.

The specific impulse per one cycle of gas combustion was determined as

$$I_m = \frac{1}{m} \int_0^{T_N} F(t) dt,$$

where $F(t)$ is the force acting on the thrust wall, $m$ is the mass of the charge of the combustible gas mixture, and $T_N$ is the total duration of all phases during one cycle of gas combustion.
As it follows from the oscillograms (see figures 4a and 6a), the amplitudes and duration of the phases depend on the geometry of the gas charge and of the device used for gas charge burning. In our experiments, the calculations were performed for all phases (positive and negative) with summation of the first four values (5 in figures 4b and 6b) and with integration with respect to time of the entire thrust oscillogram during one cycle of gas charge combustion (values 6 in figures 4b and 6b).

As the amplitude values of subsequent force impulses (after the second one) drastically decrease, the thrust parameters were compared by two methods to ensure meaningful comparisons: a) based on the sum of the first four intervals (values 5 in figures 4b and 6b); b) based on complete integration of the entire oscillogram (up to 45 ms, values 6 in figures 4b and 6b). The experiments allowed one the following results to be obtained.

1a) In the case of gas charge combustion in a cylindrical chamber \((H = 91\text{ mm})\), the specific impulse \(I_m\) after summation of the first four intervals was from \(7.7 \times 10^3\) to \(1.1 \times 10^4\) s.

1b) In the case of gas charge combustion in a cylindrical chamber \((H = 91\text{ mm})\), the specific impulse \(I_m\) after complete integration was from \(1.4 \times 10^4\) to \(1.9 \times 10^4\) s.

2a) In the case of gas charge combustion on a disk, the specific impulse \(I_m\) after summation of the first four intervals was from \(1.1 \times 10^4\) to \(1.4 \times 10^4\) s.

2b) In the case of gas charge combustion on a disk, the specific impulse \(I_m\) after complete integration was from \(2.5 \times 10^4\) to \(5.7 \times 10^4\) s.

The averaged specific thrust was determined as

\[
\langle I_N \rangle = \frac{1}{mT_N} \int_0^{T_N} F(t)dt,
\]

where \(F(t)\) is the total force acting on the thrust wall in the motion axis direction and \(T_N\) is the duration of all positive and negative phases within one cycle of gas charge combustion.

Based on this definition, we find the averaged values of the specific thrust for the first four intervals.

1) In the case of combustion of the gas charge with \(V_g = 3\text{ ml}\) in a cylindrical barrel, the duration of the first four intervals was \(T_N = 33\text{ ms}\); therefore, the averaged specific thrust \(I_N = I_m/T_N\) was from \(0.23 \times 10^6\) to \(0.33 \times 10^6\).

2) In the case of combustion of the gas discharge with \(V_g = 3\text{ ml}\) on a disk, the duration of the first four intervals was \(T_N = 10\text{ ms}\); therefore, the averaged specific thrust \(I_N = I_m/T_N\) was from \(1.1 \times 10^6\) to \(1.4 \times 10^6\).

The results obtained in this study show that gas combustion on an open thrust wall is more effective than in cylindrical chambers in terms of both the specific impulse and the averaged specific thrust. The parameter of the averaged specific thrust shows the maximum possible frequency of fuel burning without the loss of the specific impulse. It is seen that this parameter is higher in the case of gas charge combustion on a disk owing to significant reduction of the period of bubble oscillations. This is similar to an increase in the averaged power of the internal combustion engine due to an increase in the number of revolutions of the crank shaft.

5. Conclusions

The experimental results show that the specific impulse in the case of gas combustion on a disk is at least not lower and sometimes is even higher than the specific impulse of gas combustion in a cylindrical chamber. Possible reasons are the absence of friction-induced losses and the edge effects at the barrel edges [2, 3].

The present results suggest that it is possible to burn gases in water on a flat wall with frequencies higher than the frequency of gas charge combustion in cylindrical chambers, other conditions being identical. The maximum possible frequency of gas combustion on a flat wall \(v_{\text{max}}\) is determined as \(v_{\text{max}} = 1/T\), where \(T\) is the sum of the period of hemispherical bubble oscillations and the time necessary for the next gas charge to form.

An increase in the combustion frequency with retaining the specific impulse value, which is provided by gas combustion on a flat wall as compared to a cylindrical chamber, makes it possible to
increase the averaged thrust of underwater propulsion and to decrease losses due to cavitation and friction.

**References**

[1] Teslenko V S, Drozhzhin A P, Medvedev R N and Batraev I S 2014 In-water gas combustion in linear and annular gas bubbles *Thermophysics and Aeromechanics* **21**(4) 479–88

[2] Teslenko V S, Drozhzhin A P and Medvedev R N 2017 In-water gas combustion for thrust production *Thermophysics and Aeromechanics* **24**(4) (In press)

[3] Medvedev R N, Drozhzhin A P and Teslenko V S 2015 Threshold of cavitation vortex ring formation during liquid outflow from a submerged tube *Modern Science: Researches, Ideas, Results, Technologies* **16**(1) 86–9

[4] Medvedev R N, Drozhzhin A P and Teslenko V S 2016 Thrust generation by pulse combustion of gas in a submerged chamber *International Journal of Multiphase Flow* **83** 232–8