OPEN WATER TESTS OF A TOWED BOAT WITH PULSED COMBUSTION OF FUEL IN A BOTTOM GAS CAVITY

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Preliminary experiments with an air-cavity towed boat have been conducted on open water to confirm the effect discovered in earlier laboratory-scale experiments that is the possibility of creating the positive propulsive force acting on the boat by organizing the pulsed combustion of fuel–air mixture in the cavity. In the experiments, the hydrogen–air mixture was supplied to the bottom gas cavity where it was ignited and burned in a pulsed mode. The experiments confirmed that pulsed combustion of fuel–air mixture in a gas cavity under the boat bottom creates the positive propulsive force acting on the boat. Moreover, in some experiments, a considerable increase in the propulsive force was registered due to flame acceleration causing a higher overpressure in the cavity. The elevated values of the propulsive force in these conditions can be treated in favor of a pulsed detonation mode which will be studied later.

1 Introduction

Conventional propulsion systems for water vehicles indirectly convert the chemical energy of fuel into the energy of water motion using the various mechanical devices like screw propellers, pumps, impellers, etc., which is accompanied with losses. Moreover, such mechanical devices have a limitation on the maximum vehicle speed associated with cavitation. The losses and limitations caused by the

DOI: 10.30826/NEPCAP9B-29

indirect energy transformation can be eliminated by using hydrojet propulsion systems which utilize the direct conversion of fuel energy to water acceleration. There exist several known ways to produce a propulsive force by (*i*) depositing heat to a water flow with the formation of bubbly water with steam bubbles [1]; (*ii*) feeding bubbles of inert gas or combustion products to a water flow [1–3]; and (*iii*) burning a hydroreactive fuel in the water flow [4]. The jet thrust is created by the acceleration of the outboard water under the action of expanding gas bubbles. An alternative approach for creating a jet thrust has been recently suggested in [5, 6]. The jet thrust can be created due to water acceleration in periodic shock waves exiting from a pulsed detonation tube immersed in a submerged water guide. The medium in the water guide is made compressible by saturation with bubbles of gaseous detonation products. The corresponding device was named a pulsed detonation hydroramjet [7]. In [8, 9], we proposed to replace the submerged water guide of a hydroramjet by a profiled gas cavity under the boat bottom. Gas cavities are usually made under boat/ship bottom for reducing the hydrodynamic drag [10–13]. Such cavities partially isolate the bottom from contact with water and provide gas lubrication due to forced supply of air or exhaust gases from the main propulsion system. Such gas cavities can significantly (by 20% to 30%) reduce the hydrodynamic drag of the boat. We proposed to add fuel to the air supplied to the cavity and to arrange stationary or pulsed combustion, pulsed deflagration-to-detonation transition (DDT), or pulsed detonation of the fuel–air mixture in it (Fig. 1). Such a cavity can be referred to as the **active gas cavity** to distinguish it from the conventional (passive) gas cavity. With the proper organization of the combustion process in the active gas cavity, thermal expansion of combustion products can provide an additional lifting force and reduce the area of contact of the boat bottom with water as well as a propulsive force caused by the overpressure of combustion products on redans.

In [14, 15], the processes in the passive and active gas cavities were studied computationally using three-dimensional (3D) numerical simulations and exper-

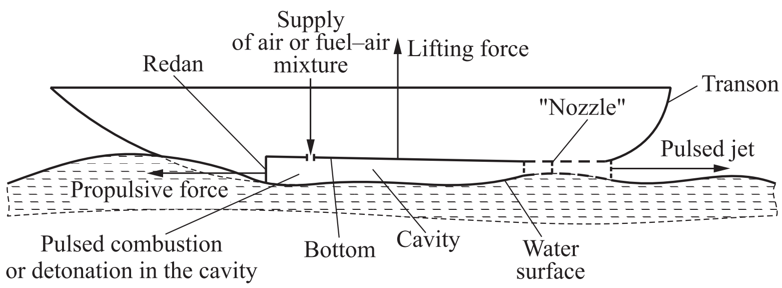


Figure 1 Schematic of a ship with a bottom gas cavity with stationary / pulsed combustion / detonation of the fuel–air mixture in it

imentally on a laboratory test rig at still water conditions. The studies included purging the cavity with pure air and purging it with the stoichiometric homogeneous propane–air mixture. In the latter case, the mixture was ignited and burned in the cavity in the mode of continuous stabilized combustion or pulsed combustion. Both calculations and measurements revealed the generation of the lifting and propulsive forces acting on the cavity and correlated satisfactorily with each other.

For further understanding the processes arising in the active gas cavities, another laboratory test rig was designed and manufactured in [16]. The test rig included a transparent cylindrical tube with one closed end, a pool with an optically transparent window, as well as power, ignition, control, and measurement systems. The tube was vertically immersed with its open end in water and filled with a gaseous explosive mixture. The idea of this test rig was borrowed from [17, 18] where the lifting force acting on the walls of the semi-closed combustion chambers of simple shape (cylindrical, conical, hemispherical, and annular) was measured in experiments with combustion of a stoichiometric propane–oxygen mixture above the free surface of water. Contrary to [17, 18], a stoichiometric propane–air mixture was used in [16]. A series of experiments on combustion of the mixture in the volume above the free surface of water was performed at the test rig. Reported in [16] are the results of measurements of the lifting force acting on the tube, time histories of pressure above the free surface of water, and the results of imaging of the dynamics of flame and gas–water interface motion during combustion. Despite the spatial scale of experiments in [16] was by a factor of 16 smaller than in [15], the physical and mathematical model of [14, 15] was shown to predict satisfactorily the obtained results. To the best of our knowledge, no multidimensional computational studies of the complex two-phase reactive flow dynamics in **active** gas cavities are present in the literature except for [14, 15].

The objective of this work is to provide experimental data for further validation of model [14, 15] in terms of its scaling capability. To follow this objective, we conduct open water experiments with a larger-scale boat with the active gas cavity.

2 Boat with Active Gas Cavity

For performing the larger-scale test fires on open water, we have designed and manufactured a towed boat with active gas cavity (Fig. 2). It is designed for continuous or pulsed combustion of gaseous or liquid fuel. The provision is also made for arranging pulsed detonations of gaseous mixtures in the cavity.

The dimensions of the towed boat correspond to the dimensions (on a scale of 1 : 8.5) of the vessel provided by the Alexeev's Hydrofoil Design Bureau [8]: 2616 mm in length and 524 mm in width. The material of the boat hull is sheet

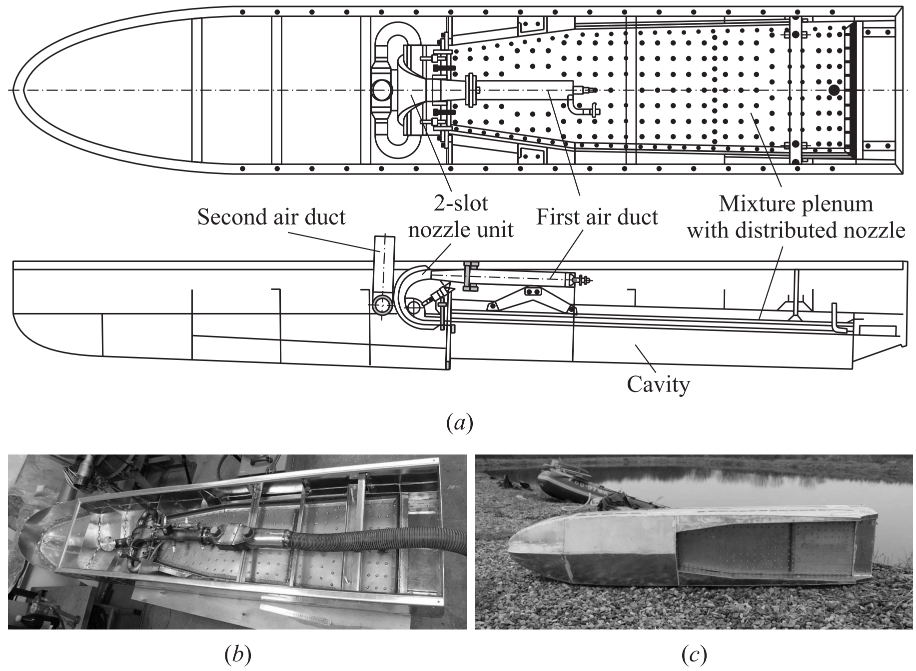


Figure 2 Schematic (*a*) and general view (*b*) of the towed boat and a view of the active gas cavity (*c*)

aluminum of the AMG-5 brand with a thickness of 2 mm. The volume of the active cavity is 20 l; the material is stainless steel.

The bottom gas cavity is equipped with two independent systems for air and fuel supply. In the first, the cavity communicates with the air supply duct via a prechamber, containing a fuel supply port and a spark plug as well as a slot-like opening in the 2-slot nozzle unit (the lower slot with prechamber flame jet in Fig. 3). The prechamber volume is 1.5 l. In the second, the cavity is filled with the reactive mixture through the distributed nozzles in the upper wall separating the cavity and mixture plenum. The mixture is prepared in a separate mixing chamber communicating with an air duct and fuel supply ports and enters the plenum through another slot-like opening in the 2-slot nozzle unit (the upper slot in Fig. 3). The air ducts, fuel supply ports, mixing chamber, prechamber, and plenum are made of stainless steel.

When organizing combustion or detonation in the cavity, both systems of air and fuel supply can be simultaneously activated. In the case of continuous or pulsed combustion, the prechamber is used for creating a continuous or pulsed flame jet to ignite the mixture in the cavity (see Fig. 3).

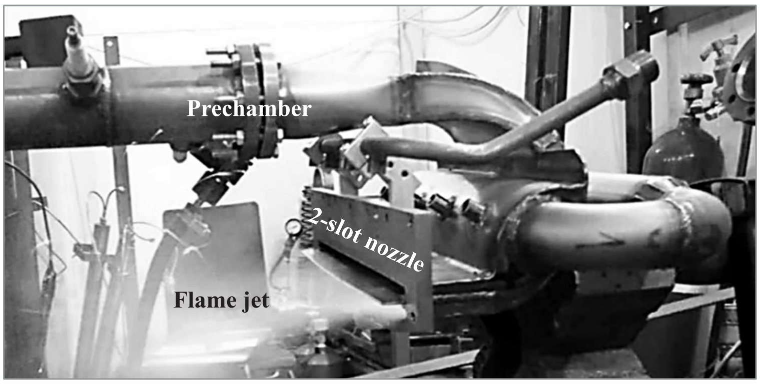


Figure 3 Imaging of the prechamber flame jet emanating from the lower slot-like opening of the 2-slot nozzle

When organizing pulsed detonations in the cavity, the prechamber plays the role of a predetonator. For reliable detonation initiation via DDT in the prechamber, a Shchelkin spiral is installed in it. The arising detonation wave enters the cavity through the lower slot-like opening. As an example, Fig. 4 shows the records of two ionization probes IP1 and IP2 in the prechamber operating in the pulsed combustion mode (Fig. 4*a*) and pulsed detonation mode (Fig. 4*b*). The probes are installed along the prechamber 388 mm from each other. Clearly, in a pulsed combustion mode, the probe signals are smeared and possess a low amplitude. In a pulsed detonation mode, the probe signals are sharp and possess a high amplitude.

In addition, the records in Figs. 4*a* and 4*b* exhibit different time intervals between the signals which are not shown to better resolve signal shapes. A shorter time interval between the signals corresponds to a higher propagation velocity of the reaction front. Thus, the records in Fig. 4*a* and 4*b* correspond to the apparent reaction front velocities of 400 and 1600 m/s, respectively, i. e., a sharper signal of a higher amplitude in Fig. 4*b* corresponds to a shock-induced energy release in a propagating detonation wave.

For test fires on open water, a mobile test rig is developed and manufactured (Fig. 5). The test rig includes a tugboat, a towed boat with active gas cavity, supply systems of air and fuel, ignition system, data acquisition system, control system, and the system for measuring the propulsive force. In addition, video recording is provided: from the coastline and from the tugboat. The air supply system includes a gasoline blower and a corrugated hose. The fuel supply system contains a fuel cylinder with a pressure reducer and a fuel manifold with a solenoid valve. The ignition system contains an ignition unit, a high-voltage wire, and a spark plug mounted in the prechamber. The data acquisition system

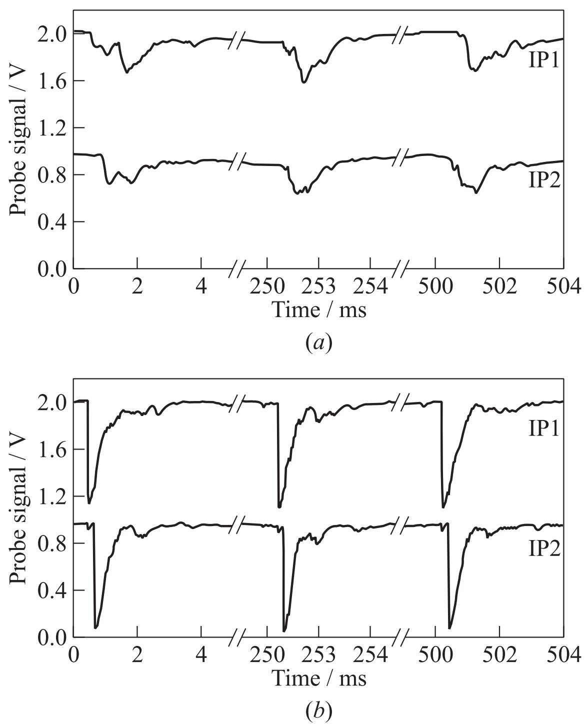
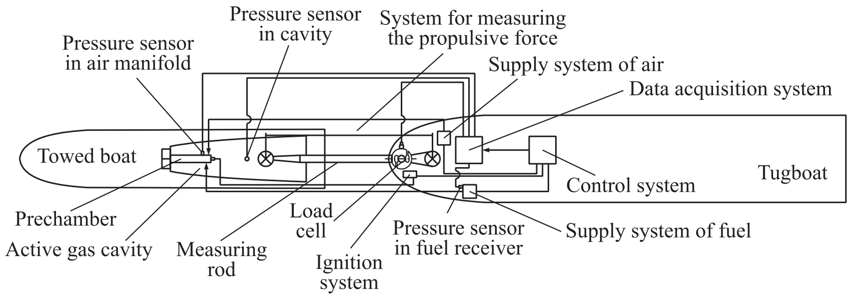


Figure 4 Records of two ionization probes (IPs) in the prechamber operating in pulsed combustion mode (*a*) and in pulsed detonation mode (*b*)

includes pressure sensors in the cavity, in the air manifold, and in the fuel receiver, a load cell, signal amplifiers-converters, analog-to-digital converters, and personal computer (PC). The control system controls solenoid valves and ignition. The system for measuring the propulsive force consists of the measuring rod and load cell which are rigidly fixed on the bow of the tugboat. Another end of the measuring rod is attached to the towed boat. The supply lines of air, fuel, and high voltage for the ignition system, control lines (for activating/deactivating valves), and measurement lines (pressure sensors) are laid along the measuring rod.

The air and fuel are supplied to the towed boat separately. In the preliminary experiments reported herein, atmospheric air was used as an oxidizer and hydrogen was used as a fuel. Air was supplied to the prechamber through a corrugated hose using a gasoline blower Oleo-Mac BV 300. The air supply was continuous. The flow rate of air was controlled by changing the position of the lever in the built-in flow control system. Hydrogen was supplied from a 10-liter receiver to the prechamber through a tube of inner diameter 4 mm



(*a*)

(*b*)

Figure 5 Schematic (*a*) and general view (*b*) of a mobile test rig

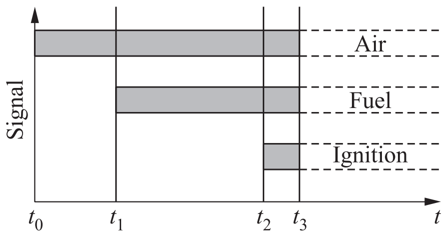


Figure 6 Cyclogram of the operation process in the active gas cavity with pulsed combustion of hydrogen–air mixture

with 10 holes 0.6 mm in diameter located across the airflow. The fuel supply was controlled by the pressure in the fuel manifold and the opening time of the solenoid valve.

When the bottom cavity of the towed boat is purged by pure air (i. e., during idling), the load cell is loaded by the force of hydrodynamic resistance of water (negative force). The readings of the load cell before ignition are taken as a zero-level propulsive force. After ignition, a pulsed combustion or pulsed detonation mode (working stroke) is established in the bottom cavity with the development of a positive propulsive force recorded by the load cell. The cyclogram of the operation process in the active gas cavity with pulsed combustion of gaseous explosive mixture (Fig. 6) includes several stages: purging the prechamber and cavity with pure air during time interval t_0–t_1; filling the prechamber and cavity with gaseous reactive mixture during time interval t_1–t_3; and ignition of the mixture in the prechamber during time interval t_2–t_3.

3 Preliminary Test Fires of the Towed Boat on Open Water

For safety reasons, the preliminary test fires of the towed boat with active gas cavity were performed with a pulsed combustion mode in the cavity. In all test fires, a stable operation process of pulsed combustion was obtained. The stern immersion of the boat was 100 mm with zero trim in all test fires.

Before the start of the experiment, a tugboat with an attached towed boat was positioned along the coastline (see Fig. 5*b*). The sequence of further operations was as follows:

(1) the governing parameters of pulsed combustion, namely, the fuel supply pressure (200 to 1000 kPa), the filling time of the prechamber and the cavity with the gaseous reactive mixture (0.06 to 0.11 s), the cycle frequency (4 to 10 Hz), and the air mass flow rate (35–140 g/s), were set;

(2) the air supply, data acquisition, and video recording systems were activated;

(3) the tugboat accelerated and reached (in 5–8 s) a constant speed of 10–12 km/h along the coastline;

(4) the control system for the preset mode of pulsed combustion in active gas cavity was activated; and

(5) after the preset operation time (normally 10 s), the test fire was terminated by the control system.

The cycle frequency f was controlled by changing time interval t_0–t_1 (see Fig. 6). The instantaneous mass flow rate of the gaseous reactive mixture was controlled by changing the pressure in the fuel manifold using a pressure reducer installed at the outlet of fuel receiver and by changing the air flow rate which is preset before the experiment by setting the lever of the built-in flow control system to one of three positions: minimum, medium, or maximum.

During test fires, the following parameters were recorded: propulsive force acting on the towed boat, pressure in the active gas cavity, pressure in the air manifold, and pressure in the fuel receiver. The propulsive force was measured by the Tenzo-M 200-kilogram load cell with an error of ± 0.05 kg. The pressure in the cavity was measured with a KURANT-DA 1.6-megapascal pressure sensor with an error of 2.4 kPa. The air pressure in the air manifold was measured with a KURANT-DA 250-kilopascal pressure sensor located in front of the check valve. The error of air pressure measurement is 0.4 kPa. The pressure in the fuel receiver was measured with a KURANT-DA 10-megapascal pressure sensor with an error of 15 kPa. The signals from the sensors were fed to the ADC and recorded using the PowerGraph software installed on a PC.

(*a*) (*b*)

Figure 7 Video frames of a test fire with pulsed combustion of hydrogen–air mixture in a gas cavity under the bottom of towed boat: (*a*) filming from the tugboat; and (*b*) filming from the coast

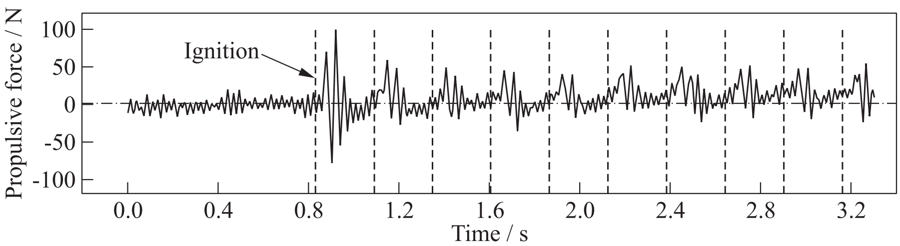


Figure 8 Primary record of the load cell in the test fire with operation frequency of 3.8 Hz

Figure 7 shows the videoframes of one of the test fires with pulsed combustion of hydrogen–air mixture in a gas cavity under the bottom of towed boat. Video filming was made from the tugboat (Fig. 7*a*) and from the coast (Fig. 7*b*). When ignition was turned on, the towed boat started making regular oscillatory movements, accompanied by emissions of a two-phase jet plume and characteristic sound pops from under the stern. After ejection of the jet plume, the stern of the towed boat was submerged back into the water just below the waterline. The vibration amplitude of the stern reached 50–70 mm with its normal immersion of 100 mm. When the boat moved, no deviations from the course were observed, i. e., there were no lateral forces.

Figure 8 shows an example of the primary record of the load cell during pulsed combustion of hydrogen–air mixture in the bottom cavity of the towed boat in the experiment with an operation frequency of 3.8 Hz. The horizontal dash-and-dot line in the plot corresponds to the zero-level propulsive force set at starting the operation process with pulsed combustion in the cavity. The mean propulsive force was determined as the mean integral value of the instantaneous propulsive force measured over some time interval t_1–t_3 in Fig. 6:

$$\overline{F} = \frac{1}{t_3 - t_1} \int\limits_{t_1}^{t_2} F(t)\, dt\,.$$

In preliminary experiments, the maximum values of the force (the amplitude of force pulsations) attained 125 ± 5 N, although the mean thrust (averaging over 10–20 cycles) was only 3 ± 1 N. However, in some test fires, the measured mean value of the propulsive force turned out to be considerably higher, at a level of 12 ± 1 N. These test fires were accompanied with stronger acoustic effects. These effects were caused by higher flame velocities and overpressures in the cavity. The elevated values of the propulsive force in these conditions could be treated in favor of a pulsed detonation mode which will be studied later.

4 Concluding Remarks

In this paper, a set of preliminary experiments with a towed boat with a bottom gas cavity of at least 5 l in volume were conducted on open water. In the experiments, hydrogen–air mixture was ignited and burned in the cavity in a pulsed mode. These experiments confirmed that pulsed combustion of fuel–air mixture in a gas cavity under the boat bottom creates the positive propulsive force acting on the boat. Moreover, in some experiments, a considerable increase in the propulsive force was registered presumably due to flame acceleration causing a higher overpressure in the cavity. The elevated values of the propulsive force in these conditions can be treated in favor of a pulsed detonation mode which will be studied later.

Based on the results of laboratory tests with the cavities of smaller scales (60 ml and 1 l) and open water tests with the larger cavity (~ 5 l), it can be argued that there are solid grounds for creating ships and boats with propulsion ensured solely by combustion/detonation of fuel–air mixture in the active cavities under their bottom, thus avoiding the use of conventional propellers. In the future, we plan to extend the experimental and computational studies to a towed boat with pulsed detonations of fuel–air mixture in a gas cavity under its bottom.

Acknowledgments

This research work was performed at the expense of a subsidy allocated by the Semenov Federal Research Center for Chemical Physics of the Russian Academy of Sciences to implement the State Task on the topic No. 0082-2019-0006 (Registration No. AAAA-A21-121011990037-8) and by the Federal State Institution "Scientific Research Institute for System Analysis of the Russian Academy of Sciences" to implement the State Task on the topic No. 0065-2019-0005 (Registration No. AAAA-A19-119011590092-6).

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НАТУРНЫЕ ИСПЫТАНИЯ БУКСИРУЕМОЙ МОДЕЛИ СУДНА С ГОРЕНИЕМ ТОПЛИВНОЙ СМЕСИ В ДНИЩЕВОЙ КАВЕРНЕ

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Для снижения гидродинамического сопротивления судов под их днищем формируют газовые каверны. Такие каверны частично изолируют днище судна от контакта с водой, обеспечивая «газовую смазку» за счет подачи в них атмосферного воздуха или отработавших газов силовой установки. За счет специального профилирования дна и обводов судна удается снизить его гидродинамическое сопротивление на 20%–30% при относительно низких затратах мощности силовой установки (менее 3%). Нами предложено к подаваемому в каверну воздуху добавлять горючее и организовать в ней стационарное или пульсирующее горение или детонацию топливно-воздушной смеси. При правильной организации процесса горения в каверне тепловое расширение продуктов горения может обеспечить дополнительную подъемную силу, снижающую площадь контакта днища судна с водой, а также движущую силу благодаря воздействию давления продуктов горения на плоские вертикальные участки днища судна — реданы, причем создаваемая движущая сила может быть достаточной для движения судна без использования гребных винтов.

Для проверки идеи нами проведены газодинамические расчеты, на основе которых спроектирована и изготовлена буксируемая модель судна с газовой каверной, в которой предусмотрена возможность организации пульсирующего горения водорода или пропана с воздухом. Для проведения экспериментальных исследований разработана мобильная лабораторная установка, состоящая из катера-буксировщика с тягоизмерительной штангой, буксируемой модели с газовой днищевой каверной и форкамерой, а также систем подачи топлива и воздуха, зажигания, измерения толкающего усилия и датчиков давления. Эксперименты, проведенные на открытой воде при постоянной скорости движения связки «катер-буксировщик – буксируемая модель» не менее 5 м/с и частоте рабочего процесса в каверне от 4 до 10 Гц, подтвердили, что пульсирующее горение топлива в каверне создает положительные подъемную и движущую силы, действующие на буксируемую модель. Результаты работы могут стать основой для проектирования судов нового типа, движение которых полностью обеспечивается горением топлива в газовых кавернах под днищем.

Работа выполнена за счет субсидии, выделенной ФИЦ ХФ РАН на выполнение государственного задания по теме 0082-2019-0006 (номер государственной регистрации АААА-А21-121011990037-8), и субсидии, выделенной ФГУ ФНЦ НИИСИ РАН по теме 0065-2019-0005 (номер государственной регистрации АААА-А19-119011590092-6).