Запропонована гідрокавітаційна технологія створення композиційних палив на основі вуглеводів та різних відходів. Показано, що застосування даної технології комплексно вирішує не тільки енергетичну задачу одержання більш дешевої теплової енергії, а й екологічну проблему зниження шкідливих викидів в атмосферу при спалюванні. Одночасно вирішується задача з утилізації і знезараження відходів, що додаються в якості компонентів до складу композиційних палив

Ключові слова: гідрокавітаційна технологія, композиційні палива, форсунки, роторно-кавітаційний пристрій, відходи виробництв

Предложена гидрокавитационная технология создания композиционных топлив на основе углеводородов и различных отходов. Показано, что применение данной технологии комплексно решает не только энергетическую задачу получения более дешевой тепловой энергии, но и экологическую проблему снижения вредных выбросов в атмосферу при сжигании. Одновременно решается задача по утилизации и обеззараживанию отходов, добавляемых в качестве компонентов в состав композиционных топлив

Ключевые слова: гидрокавитационная технология, композиционные топлива, форсунки, роторно-кавитационное устройство, отходы производств

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HYDROCAVITATIONAL ACTIVATION IN THE TECHNOLOGIES OF PRODUCTION AND COMBUSTION OF COMPOSITE FUELS

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1. Introduction

Rational use of non-renewable energy sources is an urgent problem. Disposal of waste from various industries is no less important. Hydrocavitational technology for production of composite fuels based on “classic” hydrocarbons (mazut, diesel fuel) and various types of waste makes it possible to cope with a complex problem. Composite fuels include substandard hydrocarbons: old mazut, tank wash-outs, vat residues, waste of coal preparation plants. As additives, biomass, industrial effluents, in particular, phenolic water and spent technological liquids of oil production are used. Products of recycling solid household waste, polymers, rubber and other wastes can also be used.

Application of hydrocavitation technology solves the problem of obtaining cheaper thermal and electric energy. The ecological problem of reducing harmful emissions into atmosphere during combustion is also being addressed. Recycling and disinfection of wastes added as components to composite fuels take place.

Intensification of physical and chemical processes contributes to the improvement of existing and development of new efficient technologies and equipment for processing and consumption of hydrocarbon energy carriers. Enhancement of functionality and cutting costs of the introduction of new technologies is a relevant scientific and applied problem.

2. Literature review and problem statement

Analysis of papers connected with the development of new types of fuels is mainly aimed at solving environmental problems. The emphasis is laid on the production of biodiesel and alternative fuel types. It is assumed that biodiesel fuel can become an alternative to diesel fuel. Biodiesel fuel is produced from vegetable oils and animal fats. Such technologies will not work for industrial production and introduction into the energy complex since they will be unable to satisfy the required energy consumption. A process of production of biodiesel fuel from free fatty acids, such as processed restaurant fat, animal fat and soap stock is proposed in article [1]. The results of paper [2] are aimed at producing engine fuel from plastic wastes. It was shown that a plastic pyrolysis oil is a promising alternative fuel for engines but under certain operating conditions. Studies have been conducted on the use of low-value hydrocarbons obtained in processing of crude oil as additives to diesel fuel [3]. There are no recommendations on the use of such fuel at power plants. After making analysis of the use of oil, gas and coal reserves, transition to renewable and alternative energy sources was proposed in [4] but no economic studies of such transition were conducted. Paper [5] emphasized expansion of use of alternative and renewable energy sources, too, but no economic substantiation was proposed.

The main fuel components at the current stage of the development of the energy complex are hydrocarbons. To reduce the share of hydrocarbons in fuel compositions, a process for production of composite fuel was proposed. Various additives were offered as fuel components. Agricultural wastes were considered as additives in [6]. Consideration was also given to the production of liquid fuels using rapid pyrolysis of pine wood [7]. Microalgae can be used in the production of biodiesel fuel, bioethanol, methane or hydrogen [8]. None of the papers provides a calculation of production volumes of such composite fuels, no economic calculations were made.

The process of production of composite fuels is a multistage physicochemical process consisting of several parallel and (or) successive stages [9]. As a rule, the rate of these processes is determined in whole by the stages that are limited. Articles [10, 11] suggested using cavitation in the processes of energy transformation. These papers do not contain a comprehensive approach to solving the problem of production and reprocessing of composite fuels.

The basis for production of composite fuels is the method of hydrocavitational activation [12], which consists in processing initial components in devices, which generate hydrodynamic cavitation. A certain amount of water is present in composite fuels. Under the influence of high-speed cumulative jets and collapse of cavitation bubbles, water molecules become excited, split into H^+ and hydroxyl group OH^- and ionized with formation of hydrated ions. Temperature and pressure in the zones of collapse of cavitation bubbles and action of cumulative jets exceed the values necessary for realization of hydrocracking processes. This makes it possible to achieve not only formation of time-stable emulsions and suspensions but also a change in the fractional composition, which enables reduction of the flash point and improvement of fuels reactivity. Due to such transformations, consumer properties of composite fuels are improved: chemical and mechanical incomplete combustion is reduced and the energy and environmental characteristics of the combustion processes get better [13]. Hydrocavitational treatment of composite fuels is carried out in a hydrocavitation unit (HCU) [14] (Fig. 1). The liquid being treated undergoes an intensive action of impact elements of the HCU which leads to significant pressure pulsations and the flow integrity is violated with formation of vapor cavities, that is cavitation bubbles. With a subsequent sharp increase in pressure, bubbles collapse creating shock waves. Processes of molecular destruction, cracking and hydrocracking of hydrocarbons take place in the zones of collapse of cavitation vapor bubbles.

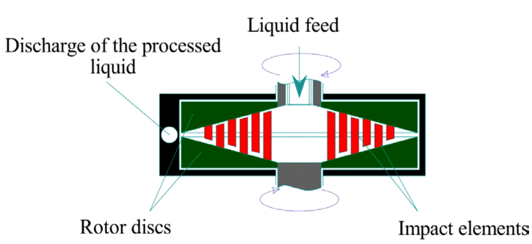


Fig. 1. Schematic diagram of the hydrocavitation device

Organization of composite fuel combustion should be considered separately. The standard types of injectors for such fuels are generally inapplicable due to the presence of a solid phase in their composition, increased viscosity and often lower reactivity. To ensure ultradisperse spraying of composite fuels in order to increase contact area of fuel droplets and oxidizer during combustion, hydrocavitation units (HCU) have been developed [15].

Organization of effective activation processes in the technological cycle of production and combustion of composite fuels depends on a multitude of parameters. Not only physicochemical properties of the raw material and consumer properties of the final product, that is, the composite fuels, but also design features of the devices for hydrocavitational activation and their operating modes are of importance.

Improvement of existing and creation of new equipment for implementation of the method of hydrocavitational activation requires further improvement of methods for computer simulation of the liquid medium flow in channels of a complex shape and experimental studies of production and combustion of new types of composite fuels.

3. The study objectives and tasks

This work objective was to improve quality and efficiency of physicochemical processes of production and burning of composite fuels, which can be achieved by the use of activation and owing to the methods of mathematical and physical modeling. The following tasks were set:

– improve mathematical model of flow hydrodynamics in hydrocavitational devices to enhance efficiency of production and combustion of composite fuels;

– develop and produce samples of experimental equipment for studying efficiency of production and combustion of composite fuels using hydrocavitational activation;

– investigate energy and environmental indicators of production and combustion of composite fuels with various types of waste in their composition;

– prove the possibility of introducing various waste products into composition of composite fuels.

4. Mathematical methods of calculating hydrocavitational equipment

4. 1. Mathematical modeling of hydrodynamics problems

Calculations of HCU and hydrovortex nozzles are based on mathematical modeling of hydrodynamic processes in such devices. In turn, mathematical modeling of hydrodynamic problems is based on a numerical solution of a system of Navier-Stokes equations. Various methods for solving such problems were considered in [16–18]. To solve boundary-value problems of hydrodynamics in plane and axisymmetric channels, a variational method is used in conjunction with the structural one [19, 20]. Mathematical models are constructed on the basis of a system of Navier-Stokes equations, which reduce in two-dimensional and axisymmetric cases to fourth-order nonlinear partial differential equations with respect to the stream function ψ and the Poisson equations with respect to static pressure.

A plane stationary flow of a viscous incompressible fluid is described by a system of Navier-Stokes equations [21, 22]:

$$V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y} + \frac{\partial P}{\partial x} - \frac{1}{\mathrm{Re}} \Delta V_x = 0, \qquad (1)$$

$$V_x \frac{\partial V_y}{\partial x} + V_y \frac{\partial V_y}{\partial y} + \frac{\partial P}{\partial y} - \frac{1}{\mathrm{Re}} \Delta V_y = 0, \qquad (2)$$

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} = 0, \qquad (3)$$

where (1), (2) are the equations of motion, (3) is the equation of motion continuity, Re is the Reynolds number, (V_x, V_y) is the velocity vector, P is the static pressure.

Using the stream function ψ determined from relationships $V_x = \frac{\partial \psi}{\partial y}$, $V_y = -\frac{\partial \psi}{\partial x}$, the system (1)–(3) reduces to a fourth-order nonlinear partial differential equation with respect to the stream function ψ [21]:

$$\frac{1}{\mathrm{Re}} \Delta\Delta\psi - \frac{\partial \psi}{\partial y} \cdot \frac{\partial \Delta\psi}{\partial x} + \frac{\partial \psi}{\partial x} \cdot \frac{\partial \Delta\psi}{\partial y} = 0. \qquad (4)$$

To describe motion of a viscous incompressible fluid in a channel, it is necessary to set boundary conditions in addition to the differential equation. Let the problem be solved in a region Ω for which $\partial\Omega$ is its boundary. Sections of the region boundaries can correspond to solid channel walls, the channel inlet, and the channel outlet. Boundary conditions for equation (4) follow from the condition of sticking to a solid wall and a given velocity at the inlet (outlet). Velocity distribution according to which the stream function is determined is set at the channel inlet. If velocity distribution at the outlet is known (for example, steady laminar flow of Poiseuille [22]), then it can also be specified.

From the system of Navier-Stokes equations, the following is obtained by differentiating (1) with respect to x, and (2) with respect to y and adding these two equations:

$$\Delta P = 2\left(\frac{\partial V_x}{\partial x} \frac{\partial V_y}{\partial y} - \frac{\partial V_y}{\partial x} \frac{\partial V_x}{\partial y} \right).$$

This equation can be rewritten in respect to the stream function ψ as follows:

$$\Delta P = 2\left(\frac{\partial^2 \psi}{\partial x^2} \frac{\partial^2 \psi}{\partial y^2} - \left(\frac{\partial^2 \psi}{\partial x \partial y} \right)^2 \right). \qquad (5)$$

Consider boundary conditions for this equation. The following is obtained from Navier-Stokes equations:

$$\frac{\partial P}{\partial x} = \left(\frac{1}{\mathrm{Re}} \Delta V_x - V_x \frac{\partial V_x}{\partial x} - V_y \frac{\partial V_x}{\partial y} \right),$$

$$\frac{\partial P}{\partial y} = \left(\frac{1}{\mathrm{Re}} \Delta V_y - V_x \frac{\partial V_y}{\partial x} - V_y \frac{\partial V_y}{\partial y} \right).$$

Since $\frac{\partial P}{\partial n} = (\nabla P, \vec{n})$, then the following is obtained on a solid wall taking into account sticking conditions ($V_x = 0$, $V_y = 0$):

$$\frac{\partial P}{\partial n} = \left(\left(\frac{1}{\mathrm{Re}} \Delta V_x, \frac{1}{\mathrm{Re}} \Delta V_y \right), \vec{n} \right) = \frac{1}{\mathrm{Re}} \Delta((V_x, V_y), \vec{n}) = \frac{1}{\mathrm{Re}} \Delta V_n,$$

where V_n is the projection of the velocity vector on the vector of normal $\vec{n}$ to the boundary.

Consider boundary conditions at the channel inlet and outlet.

$$\frac{\partial P}{\partial n} = \left(\left(\left(\frac{1}{\mathrm{Re}} \Delta V_x - V_x \frac{\partial V_x}{\partial x} - V_y \frac{\partial V_x}{\partial y} \right), \left(\frac{1}{\mathrm{Re}} \Delta V_y - V_x \frac{\partial V_y}{\partial x} - V_y \frac{\partial V_y}{\partial y} \right) \right), \vec{n} \right) =$$

$$= \left(\frac{1}{\mathrm{Re}} (\Delta V_x, \Delta V_y) - V_x \left(\frac{\partial V_x}{\partial x}, \frac{\partial V_y}{\partial x} \right) - V_y \left(\frac{\partial V_x}{\partial y}, \frac{\partial V_y}{\partial y} \right), \vec{n} \right) =$$

$$= \frac{1}{\mathrm{Re}} \Delta V_n - V_x \frac{\partial V_n}{\partial x} - V_y \frac{\partial V_n}{\partial y},$$

Using structural methods, solution of the boundary value problem for equation (4) with the corresponding boundary conditions will be sought in the form of $\psi = \psi_1 + \psi_0$, where ψ_0 is a function that satisfies the inhomogeneous boundary conditions of the problem, ψ_1 is a function with zero Dirichlet and Neumann boundary conditions. The structure of solution for function ψ_1 appears as $\psi_1 = \omega^2 P_k$ where P_k is the undefined component of the structure, ω:

$$\omega(x,y) > 0, \quad (x,y) \in \Omega, \quad \omega(x,y)\big|_{\partial\Omega} = 0,$$

$$P_k(x,y) = \sum_{i=1}^{k} c_i \phi_i(x,y), \quad k = 121,$$

$\{\phi_i(x,y)\}$ are basic splines of the 5th order.

With respect to functions ψ_1 and ψ_0, equation (4) takes the form:

$$\frac{1}{\mathrm{Re}} \Delta\Delta\psi_1 - \left\{ \frac{\partial \psi_1}{\partial y} \cdot \frac{\partial \Delta\psi_1}{\partial x} - \frac{\partial \psi_1}{\partial x} \cdot \frac{\partial \Delta\psi_1}{\partial y} \right\} -$$
$$- \frac{\partial \psi_1}{\partial y} \cdot \frac{\partial \Delta\psi_0}{\partial x} - \frac{\partial \psi_0}{\partial y} \cdot \frac{\partial \Delta\psi_1}{\partial x} +$$
$$+ \frac{\partial \psi_1}{\partial x} \cdot \frac{\partial \Delta\psi_0}{\partial y} + \frac{\partial \psi_0}{\partial x} \cdot \frac{\partial \Delta\psi_1}{\partial y} =$$
$$= -\frac{1}{\mathrm{Re}} \Delta\Delta\psi_0 + \frac{\partial \psi_0}{\partial y} \cdot \frac{\partial \Delta\psi_0}{\partial x} - \frac{\partial \psi_0}{\partial x} \cdot \frac{\partial \Delta\psi_0}{\partial y}. \qquad (6)$$

Applying linearization process to equation (6), a sequence of linear equations is obtained [23]:

$$\frac{1}{\mathrm{Re}} \Delta\Delta\psi_{n+1} -$$
$$- \left\{ \frac{\partial \psi_n}{\partial y} \frac{\partial \Delta\psi_{n+1}}{\partial x} + \frac{\partial \psi_{n+1}}{\partial y} \frac{\partial \Delta\psi_n}{\partial x} - \frac{\partial \psi_n}{\partial x} \frac{\partial \Delta\psi_{n+1}}{\partial y} - \frac{\partial \psi_{n+1}}{\partial x} \frac{\partial \Delta\psi_n}{\partial y} \right\} -$$
$$- \frac{\partial \psi_{n+1}}{\partial y} \frac{\partial \Delta\psi_0}{\partial x} - \frac{\partial \psi_0}{\partial y} \frac{\partial \Delta\psi_{n+1}}{\partial x} +$$
$$+ \frac{\partial \psi_{n+1}}{\partial x} \frac{\partial \Delta\psi_0}{\partial y} + \frac{\partial \psi_0}{\partial x} \frac{\partial \Delta\psi_{n+1}}{\partial y} =$$
$$= -\frac{1}{\mathrm{Re}} \Delta\Delta\psi_0 + \frac{\partial \psi_0}{\partial y} \frac{\partial \Delta\psi_0}{\partial x} - \frac{\partial \psi_0}{\partial x} \frac{\partial \Delta\psi_0}{\partial y} -$$
$$- \frac{\partial \psi_n}{\partial y} \frac{\partial \Delta\psi_n}{\partial x} + \frac{\partial \psi_n}{\partial x} \frac{\partial \Delta\psi_n}{\partial y}. \qquad (7)$$

This problem can be solved by the method of least squares or by the Bubnov-Galerkin method [24].

Next, solve equation (5) with respect to function P in the region Ω.

The structure of solution for equation (5) with the Neumann boundary condition at all boundary sections except for the channel outlet and the Dirichlet condition on the remaining boundary section takes the form:

$$P = P_{2,k}\omega_2 - \omega\left(\frac{\partial\omega_1}{\partial x}\frac{\partial(P_{2,k}\omega_2)}{\partial x} + \frac{\partial\omega_1}{\partial y}\frac{\partial(P_{2,k}\omega_2)}{\partial y}\right) -$$
$$-\omega\phi + \omega_1{}^2\omega_2 P_{3,k} + C,$$

where ω, ω_1, ω_2 are the normalized functions describing the entire region boundary, the boundary of the region without "outlet" and "outlet", respectively; ϕ is the function satisfying inhomogeneous Neumann condition; $P_{1,k}(x,y)$, $P_{2,k}(x,y)$ are the undefined components of the structure; C is the value of the static pressure at the outlet. Undefined components are represented as

$$P_{l,k}(x,y) = \sum_{i=1}^{k} c_{l,i}\phi_i(x,y),$$

where $l = 1,2,$ $\{\phi_i(x,y)\}$ are the basic splines of fifth order, $\{c_{l,i}\},$ $i = 1,\dots,k,$ $l = 1,2,$ are the constants, which must be determined.

Function φ can be constructed using the gluing formula [19].

4. 2. Mathematical modeling of the motion of a viscous incompressible fluid along axisymmetric channels

Motion of a viscous incompressible fluid is described by a system of Navier-Stokes equations, which takes the following form in cylindrical coordinates [21]:

$$\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_r}{\partial \phi} + v_z\frac{\partial v_r}{\partial z} - \frac{v_\phi^2}{r} =$$
$$= -\frac{1}{\rho}\frac{\partial p}{\partial r} + \nu\left(\Delta v_r - \frac{v_r}{r^2} - \frac{2}{r^2}\frac{\partial v_\phi}{\partial \phi}\right), \quad (8)$$

$$\frac{\partial v_\phi}{\partial t} + v_r\frac{\partial v_\phi}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_\phi}{\partial \phi} + v_z\frac{\partial v_\phi}{\partial z} + \frac{v_r v_\phi}{r} =$$
$$= -\frac{1}{\rho r}\frac{\partial p}{\partial \phi} + \nu\left(\Delta v_\phi - \frac{v_\phi}{r^2} + \frac{2}{r^2}\frac{\partial v_r}{\partial \phi}\right), \quad (9)$$

$$\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + \frac{v_\phi}{r}\frac{\partial v_z}{\partial \phi} + v_z\frac{\partial v_z}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\Delta v_z, \quad (10)$$

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r} + \frac{1}{r}\frac{\partial v_\phi}{\partial \phi} + \frac{\partial v_z}{\partial z} = 0, \quad (11)$$

where (8)–(10) are the Navier-Stokes equations; (11) is the equation of motion continuity; operator Δ is defined by formula:

$$\Delta = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2}{\partial \phi^2} + \frac{\partial^2}{\partial z^2}.$$

For stationary and axisymmetric cases, this system of equations in a dimensionless form is transformed into the following:

$$v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z} = -\frac{\partial p}{\partial r} + \frac{1}{\mathrm{Re}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) + \frac{\partial^2 v_r}{\partial z^2} - \frac{v_r}{r^2}\right), \quad (12)$$

$$v_r\frac{\partial v_z}{\partial r} + v_z\frac{\partial v_z}{\partial z} =$$
$$= -\frac{\partial p}{\partial z} + \frac{1}{\mathrm{Re}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{\partial^2 v_z}{\partial z^2}\right), \quad (13)$$

$$\frac{1}{r}\frac{\partial(rv_r)}{\partial r} + \frac{\partial v_z}{\partial z} = 0, \quad (14)$$

where Re is the Reynolds number, (v_r, v_z) is the velocity vector, p is the static pressure.

Differentiate equation (12) with respect to z, and equation (13) with respect to r and subtract from the first obtained equation the second one while eliminating the terms with pressure p and introduce the stream function by means of relationships

$$v_z = \frac{1}{r}\frac{\partial\psi}{\partial r}, \quad v_r = -\frac{1}{r}\frac{\partial\psi}{\partial z}.$$

As a result of these transformations, the following nonlinear equation of the fourth order is obtained with respect to the stream function ψ [20]:

$$-\frac{3}{r^4}\frac{\partial\psi}{\partial z}\frac{\partial\psi}{\partial r} + \frac{3}{r^3}\frac{\partial\psi}{\partial z}\frac{\partial^2\psi}{\partial r^2} + \frac{2}{r^3}\frac{\partial\psi}{\partial z}\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r^3}\frac{\partial\psi}{\partial r}\frac{\partial^2\psi}{\partial r\partial z} -$$
$$-\frac{1}{r^2}\frac{\partial\psi}{\partial z}\frac{\partial^3\psi}{\partial r^3} - \frac{1}{r^2}\frac{\partial\psi}{\partial z}\frac{\partial^3\psi}{\partial r\partial z^2} + \frac{1}{r^2}\frac{\partial\psi}{\partial r}\frac{\partial^3\psi}{\partial r^2\partial z} + \frac{1}{r^2}\frac{\partial\psi}{\partial r}\frac{\partial^3\psi}{\partial z^3} +$$
$$+\frac{1}{\mathrm{Re}}\left(-\frac{1}{r}\frac{\partial^4\psi}{\partial r^4} - \frac{2}{r}\frac{\partial^4\psi}{\partial r^2\partial z^2} - \frac{1}{r}\frac{\partial^4\psi}{\partial z^4} + \frac{2}{r^2}\frac{\partial^3\psi}{\partial r^3} + \right.$$
$$\left. + \frac{2}{r^2}\frac{\partial^3\psi}{\partial r\partial z^2} - \frac{3}{r^3}\frac{\partial^2\psi}{\partial r^2} + \frac{3}{r^4}\frac{\partial\psi}{\partial r}\right) = 0. \quad (15)$$

To describe motion of a viscous incompressible fluid in an axisymmetric channel, it is necessary to set boundary conditions. Let the problem be solved in a region Ω with boundary ∂Ω. Sections of the region boundaries can correspond to the solid channel walls, the channel inlet, the channel outlet and the axis of symmetry. Boundary conditions for equation (15) follow from the condition of sticking to a solid wall, velocity at the inlet (outlet) and the condition of impermeability at the axis of symmetry.

At the channel inlet, speed distribution is determined from which the stream function is determined. If velocity distribution at the outlet is known (for example, the steady laminar flow of Poiseuille [22]), then it can also be specified.

Following constructing solution for the stream function, pressure can be determined from the Poisson equation [20] where the right-hand part is expressed in terms of the stream function derivatives.

$$\frac{\partial^2 p}{\partial z^2} + \frac{\partial^2 p}{\partial r^2} + \frac{1}{r}\frac{\partial p}{\partial r} =$$
$$= \frac{2}{r^2}\left[\frac{\partial^2\psi}{\partial z^2}\left(\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r}\right) - \frac{1}{r^2}\left(\frac{\partial\psi}{\partial z}\right)^2 + \frac{\partial^2\psi}{\partial z\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial z} - \frac{\partial^2\psi}{\partial z\partial r}\right)\right]. \quad (16)$$

Consider boundary conditions for this equation. The following is obtained from the Navier-Stokes equations (12), (13):

$$\frac{\partial p}{\partial r} = -v_r \frac{\partial v_r}{\partial r} - v_z \frac{\partial v_r}{\partial z} + \frac{1}{\mathrm{Re}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_r}{\partial r}\right) + \frac{\partial^2 v_r}{\partial z^2} - \frac{v_r}{r^2}\right),$$

$$\frac{\partial p}{\partial z} = -v_r \frac{\partial v_z}{\partial r} - v_z \frac{\partial v_z}{\partial z} + \frac{1}{\mathrm{Re}}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{\partial^2 v_z}{\partial z^2}\right).$$

At the axis of symmetry,

$$\frac{\partial p}{\partial n} = 0. \qquad (17)$$

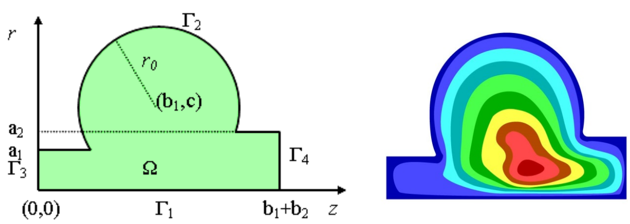
Since $\frac{\partial p}{\partial n} = (\nabla p, \vec{n})$, the following is obtained for a solid wall taking into account the sticking condition ($v_r = 0, v_z = 0$):

$$\frac{\partial P}{\partial n} = \left(\left(\frac{1}{\mathrm{Re}}\Delta v_r, \frac{1}{\mathrm{Re}}\Delta v_z\right), \vec{n}\right) = \frac{1}{\mathrm{Re}}\Delta((v_r, v_z), \vec{n}) = \frac{1}{\mathrm{Re}}\Delta v_n,$$

where v_n is the velocity vector projection on the vector of $\vec{n}$ normal to the region boundary.

4. 3. Calculation of hydrodynamic characteristics in the hydrovortex nozzle

The considered problem is determining velocity and pressure fields in a stream of liquid moving through a hydrovortex nozzle. Such nozzles are designed for ultrafine dispersion of various composite fuels. To solve the problem, it is necessary to solve the boundary value problem for equation (15) and then the boundary value problem for equation (16) with respect to function p in the region Ω, which is shown in Fig. 2, *a* for the model of the hydrovortex nozzle channel. The function $\omega(r, z)$, which describes region Ω, is shown in Fig. 2, *b*.



a *b*

Fig. 2. The problem solution region: region Ω (*a*); graph of the function ω(*r, z*) describing the region Ω in the form of lines of a constant level in the *rOz* plane (*b*)

Specify the following boundary conditions for the region Ω: $\psi = 0, \frac{\partial \psi}{\partial n} = 0$; on Γ_1 $\psi = \frac{a_1^2}{4}$, on Γ_2; $\psi = \frac{r^2}{2} - \frac{r^4}{4a_1^2}$ on Γ_3 (Poiseuille's parabolic velocity profile), $\frac{\partial \psi}{\partial n} = 0$. Solution of the boundary value problem for equation (15) with corresponding boundary conditions will be sought as $\psi = \psi_1 + \psi_0$ [20] where ψ_1 is a function with zero Dirichlet and Neumann boundary conditions, ψ_0 is a function that satisfies all inhomogeneous boundary conditions of the problem. The structure of solution for the function ψ_1 has the form $\psi_1 = \omega_1^2 P_1$, where P_1 is the undefined component of the structure, ω_1 is the function describing a part of the region $(\Gamma_1 \cup \Gamma_2 \cup \Gamma_3)$ boundary.

Represent the undefined component of the solution structure as

$$P_1(x, y) = \sum_{i=1}^{k} c_i \phi_i(r, z),$$

where $\{\phi_i(r, z)\}$ are the basic splines of fifth order; $\{c_i\}, i = 1, \ldots, k$ are the constants to be determined.

For the problem under consideration, construct function ω_1 as

$$\omega_1 = \left(f_1 \overset{\alpha}{\wedge_0} f_2\right) \overset{\alpha}{\vee_0} \left(f_3 \overset{\alpha}{\wedge_0} f_4\right) \overset{\alpha}{\vee_0} (f_5),$$

where

$$x \overset{\alpha}{\wedge_0} y = x + y - \sqrt{x^2 + y^2 + \alpha},$$

$$x \overset{\alpha}{\vee_0} y = x + y + \sqrt{x^2 + y^2 + \alpha},$$

$$f_1 = z(b_1 + b_2 - z)/(b_1 + b_2),$$

$$f_2 = r(a_1 - r)/a_1, \quad f_3 = (z - b_1),$$

$$f_4 = r(a_2 - r)/a_2,$$

$$f_5 = \left(r_0^2 - (z - b_1)^2 - (r - c)^2\right)/(2r_0),$$

where a_1 is the nozzle inlet radius, a_2 is the nozzle outlet radius, $b_1 + b_2$ is the nozzle length, b_1 is the value by which the torus center is spaced from the inlet along the Oz axis, c is the amount by which the torus center is spaced from the symmetry axis of the inlet along the Or axis, r_0 is the circle radius.

Construct function ψ_0

$$\psi_0\big|_{\Gamma_i} = \Psi_i, \quad \frac{\partial \psi_0}{\partial n}\Big|_{\Gamma_i} = 0, \quad i = 1, 2, 3$$

using the gluing formula

$$\psi_0 = \sum_{i=1}^{3} \frac{\Psi_i}{w_i^2} \Big/ \sum_{i=1}^{3} \frac{1}{w_i^2},$$

where

$$\Psi_1 = 0, \quad \Psi_2 = \frac{a_1^2}{4},$$

$$\Psi_3 = \frac{r^2}{2} - \frac{r^4}{4a_1^2}, \quad w_1 = r, \quad w_3 = z,$$

$$w_2 = \left((z - b_1) \overset{\alpha}{\wedge_0} (a_2 - r) \overset{\alpha}{\vee_0} (a_1 - r) \overset{\alpha}{\vee_0} \left(r_0^2 - (z - b_1)^2 - (r - c)^2\right)\right).$$

Respecting functions ψ_1 and ψ_0, equation (15) takes the form of a sequence of linear equations [20] after applying the Newton-Kantorovich linearization process, similarly to the plane case:

$$
\begin{aligned}
&\frac{1}{\mathrm{Re}}\left(-\frac{1}{r}\frac{\partial^4\psi_{n+1}}{\partial r^4}-\frac{2}{r}\frac{\partial^4\psi_{n+1}}{\partial z^2\partial r^2}-\frac{1}{r}\frac{\partial^4\psi_{n+1}}{\partial z^4}+\frac{2}{r^2}\frac{\partial^3\psi_{n+1}}{\partial r^3}+\right.\\
&\left.+\frac{2}{r^2}\frac{\partial^3\psi_{n+1}}{\partial z^2\partial r}-\frac{3}{r^3}\frac{\partial^2\psi_{n+1}}{\partial r^2}+\frac{3}{r^4}\frac{\partial\psi_{n+1}}{\partial r}\right)-\\
&-\frac{1}{r^2}\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^3\psi_n}{\partial z^2\partial r}-\frac{1}{r^2}\frac{\partial\psi_n}{\partial z}\frac{\partial^3\psi_{n+1}}{\partial z^2\partial r}-\frac{1}{r^2}\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^3\psi_n}{\partial r^3}-\frac{1}{r^2}\frac{\partial\psi_n}{\partial z}\frac{\partial^3\psi_{n+1}}{\partial r^3}+\\
&+\frac{2}{r^3}\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^2\psi_n}{\partial z^2}+\frac{2}{r^3}\frac{\partial\psi_n}{\partial z}\frac{\partial^2\psi_{n+1}}{\partial z^2}+\frac{3}{r^3}\frac{\partial\psi_n}{\partial z}\frac{\partial^2\psi_{n+1}}{\partial r^2}+\frac{3}{r^3}\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^2\psi_n}{\partial r^2}-\\
&-\frac{3}{r^4}\frac{\partial\psi_n}{\partial z}\frac{\partial\psi_{n+1}}{\partial r}-\frac{3}{r^4}\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial\psi_n}{\partial r}+\frac{1}{r^2}\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^3\psi_n}{\partial z^3}+\frac{1}{r^2}\frac{\partial\psi_n}{\partial r}\frac{\partial^3\psi_{n+1}}{\partial z^3}+\\
&+\frac{1}{r^2}\frac{\partial\psi_n}{\partial r}\frac{\partial^3\psi_{n+1}}{\partial r^2\partial z}+\frac{1}{r^2}\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^3\psi_n}{\partial r^2\partial z}-\frac{1}{r^3}\frac{\partial\psi_n}{\partial r}\frac{\partial^2\psi_{n+1}}{\partial r\partial z}-\frac{1}{r^3}\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^2\psi_n}{\partial r\partial z}-\\
&-\frac{1}{r^2}\left(\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^3\psi_0}{\partial z^2\partial r}+\frac{\partial\psi_0}{\partial z}\frac{\partial^3\psi_{n+1}}{\partial z^2\partial r}\right)-\frac{1}{r^2}\left(\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^3\psi_0}{\partial r^3}+\frac{\partial\psi_0}{\partial z}\frac{\partial^3\psi_{n+1}}{\partial r^3}\right)+\\
&+\frac{2}{r^3}\left(\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^2\psi_0}{\partial z^2}+\frac{\partial\psi_0}{\partial z}\frac{\partial^2\psi_{n+1}}{\partial z^2}\right)+\frac{3}{r^3}\left(\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial^2\psi_0}{\partial r^2}+\frac{\partial\psi_0}{\partial z}\frac{\partial^2\psi_{n+1}}{\partial r^2}\right)-\\
&-\frac{3}{r^4}\left(\frac{\partial\psi_{n+1}}{\partial z}\frac{\partial\psi_0}{\partial r}+\frac{\partial\psi_0}{\partial z}\frac{\partial\psi_{n+1}}{\partial r}\right)+\frac{1}{r^2}\left(\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^3\psi_0}{\partial z^3}+\frac{\partial\psi_0}{\partial r}\frac{\partial^3\psi_{n+1}}{\partial z^3}\right)+\\
&+\frac{1}{r^2}\left(\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^3\psi_0}{\partial r^2\partial z}+\frac{\partial\psi_0}{\partial r}\frac{\partial^3\psi_{n+1}}{\partial r^2\partial z}\right)-\frac{1}{r^3}\left(\frac{\partial\psi_{n+1}}{\partial r}\frac{\partial^2\psi_0}{\partial r\partial z}+\frac{\partial\psi_0}{\partial r}\frac{\partial^2\psi_{n+1}}{\partial r\partial z}\right)=\\
&=-\frac{1}{\mathrm{Re}}\left(-\frac{1}{r}\frac{\partial^4\psi_0}{\partial r^4}-\frac{2}{r}\frac{\partial^4\psi_0}{\partial z^2\partial r^2}-\frac{1}{r}\frac{\partial^4\psi_0}{\partial z^4}+\right.\\
&\left.+\frac{2}{r^2}\frac{\partial^3\psi_0}{\partial r^3}+\frac{2}{r^2}\frac{\partial^3\psi_0}{\partial z^2\partial r}-\frac{3}{r^3}\frac{\partial^2\psi_0}{\partial r^2}+\frac{3}{r^4}\frac{\partial\psi_0}{\partial r}\right)+\\
&+\frac{1}{r^2}\frac{\partial\psi_0}{\partial z}\frac{\partial^3\psi_0}{\partial z^2\partial r}+\frac{1}{r^2}\frac{\partial\psi_0}{\partial z}\frac{\partial^3\psi_0}{\partial r^3}-\frac{2}{r^3}\frac{\partial\psi_0}{\partial z}\frac{\partial^2\psi_0}{\partial z^2}-\frac{3}{r^3}\frac{\partial\psi_0}{\partial z}\frac{\partial^2\psi_0}{\partial r^2}+\\
&+\frac{3}{r^4}\frac{\partial\psi_0}{\partial z}\frac{\partial\psi_0}{\partial r}-\frac{1}{r^2}\frac{\partial\psi_0}{\partial r}\frac{\partial^3\psi_0}{\partial z^3}-\frac{1}{r^2}\frac{\partial\psi_0}{\partial r}\frac{\partial^3\psi_0}{\partial r^2\partial z}+\frac{1}{r^3}\frac{\partial\psi_0}{\partial r}\frac{\partial^2\psi_0}{\partial r\partial z}-\\
&-\frac{1}{r^2}\frac{\partial\psi_n}{\partial z}\frac{\partial^3\psi_n}{\partial z^2\partial r}-\frac{1}{r^2}\frac{\partial\psi_n}{\partial z}\frac{\partial^3\psi_n}{\partial r^3}+\frac{2}{r^3}\frac{\partial\psi_n}{\partial z}\frac{\partial^2\psi_n}{\partial z^2}+\frac{3}{r^3}\frac{\partial\psi_n}{\partial z}\frac{\partial^2\psi_n}{\partial r^2}-\\
&-\frac{3}{r^4}\frac{\partial\psi_n}{\partial z}\frac{\partial\psi_n}{\partial r}+\frac{1}{r^2}\frac{\partial\psi_n}{\partial r}\frac{\partial^3\psi_n}{\partial z^3}+\frac{1}{r^2}\frac{\partial\psi_n}{\partial r}\frac{\partial^3\psi_n}{\partial r^2\partial z}-\frac{1}{r^3}\frac{\partial\psi_n}{\partial r}\frac{\partial^2\psi_n}{\partial r\partial z}.
\end{aligned}
$$

The problem is solved by the method of least squares.

Next, equation (16) is solved with respect to the function p in the region Ω.

Consider boundary conditions for the boundary-value problem for equation (15).

On (Γ_2) and the symmetry axis (Γ_1), make use of the boundary condition $\frac{\partial p}{\partial n}=0.$

At the channel inlet (Γ_4), make use of the boundary condition $\frac{\partial p}{\partial n}=\mathrm{const}.$

At the channel outlet (F_5), make use of the boundary condition $P=\mathrm{const}.$

The structure of solution for equation (15) with the corresponding conditions has the form

$$
\begin{aligned}
&p=P_{2,k}\omega_2-\omega\left(\frac{\partial\omega_1}{\partial x}\frac{\partial(P_{2,k}\omega_2)}{\partial x}+\frac{\partial\omega_1}{\partial y}\frac{\partial(P_{2,k}\omega_2)}{\partial y}\right)-\\
&-\omega\phi+\omega_1{}^2\omega_2P_{3,k}+C,
\end{aligned}
$$

where ω, ω_1, ω_2 are the normalized functions describing the entire region boundary, the region boundary without section Γ_4 and the boundary section Γ_4, respectively; function ϕ: $\phi\big|_{\Gamma_i}=\frac{\partial P}{\partial n}\Big|_{\Gamma_i}$, i=1, 2, 3; $P_{1,k}(x, y)$, $P_{2,k}(x, y)$ are the undefined components of the structure; C is the value of static pressure at the outlet.

For the problem under consideration, construct functions ω, ω_1, ω_2 according to [19] in the following form:

$$\omega_1=\left(f_1\overset{\alpha}{\wedge}_0 f_2\right)\overset{\alpha}{\vee}_0\left(f_3\overset{\alpha}{\wedge}_0 f_4\right)\overset{\alpha}{\vee}_0\left(f_5\right),$$

$$\omega=\left(f_1\overset{\alpha}{\wedge}_0 f_2\right)\overset{\alpha}{\vee}_0\left(f_7\overset{\alpha}{\wedge}_0 f_4\right)\overset{\alpha}{\vee}_0\left(f_5\right),$$

$$\omega_2=(b_1+b_2-z),$$

where

$$f_7=(z-b_1)(b_1+b_2-z)/b_2.$$

Introduce the undefined components as

$$P_{l,k}(r,z)=\sum_{i=1}^{k}c_{l,i}\phi_i(r,z),$$

where $l=1,2,$ $\{\phi_i(r,z)\}$ are basic splines of the 5th order, $\{c_{l,i}\}$ are unknown constants.

Construct function ϕ:

$$\phi\big|_{\Gamma_i}=\frac{\partial P}{\partial n}\Big|_{\Gamma_i},\quad i=1,\,2,\,3$$

using the gluing formula [19]

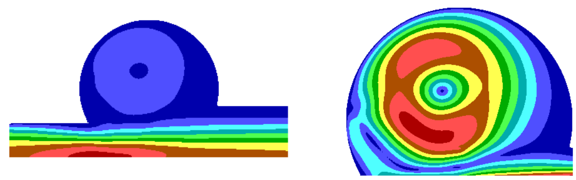
$$\phi=\sum_{i=1}^{3}\frac{\phi_i}{w_i}\Bigg/\sum_{i=1}^{3}\frac{1}{w_i},$$

where

$$\phi_1=0,\quad \phi_2=0,\quad \phi_3=\frac{4}{\mathrm{Re}\,a_1{}^2}.$$

Next, apply the method of least squares.

Fig. 3, 4 show graphs of functions in the form of lines of constant level in the rOz plane constructed from the results of computational experiments. The results of computational experiments were mapped on a grid of 40×40 splines of fifth order, the number of iterations was 9. Calculations were carried out in the POLE system [20].

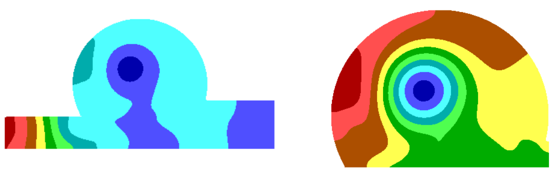


a *b*

Fig. 3. Graph of the velocity modulus function (Re=200): *a* – the whole area; *b* – toroidal chamber

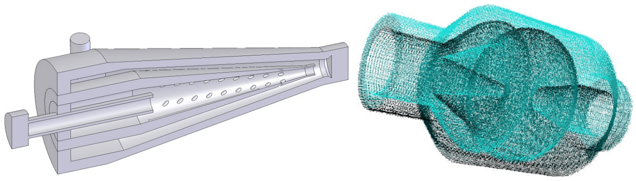
Based on the above mathematical modeling, high-efficiency devices for spraying (hydrovortex nozzles) have been developed. A unique feature of this type of nozzles is the ability to supply fuel suspensions and high-viscosity emulsions to combustion chambers of the heat generating units. The main problem for maintaining sustainable combustion of such fuels is formation of filler conglomerates, both along the fuel supply path and directly in the combustion chamber. Cavitation is the most effective way to combat the conglomerates. Therefore, when designing hydrovortex nozzles, it is necessary to ensure formation of intensive cavitation zones in the flow. Application of the proposed approach in modeling spraying devices for composite fuels can significantly improve technical, economic, and environmental performance indicators of power generating units.

Fig. 5 shows models of hydrovortex nozzles, Fig. 6 exhibits results of computer simulation of the processes occurring in spraying composite fuels using hydrovortex nozzles and real hydrovortex nozzles are shown in Fig. 7.



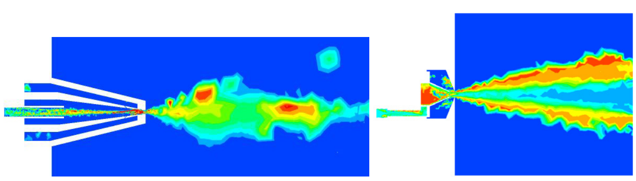
a *b*

Fig. 4. Graph of the static pressure function (Re=200): *a* — the whole area; *b* — toroidal chambe



a *b*

Fig. 5. Models of hydrovortex nozzles: *a* — for suspension fuel; *b* — for emulsion fuels



a *b*

Fig. 6. Results of computer modeling of the torch at the nozzle outlet: *a* — for suspension fuels; *b* — for emulsion fuels

a *b*

Fig. 7. Hydrovortex nozzles: *a* — for emulsion fuels; *b* — for suspension fuels

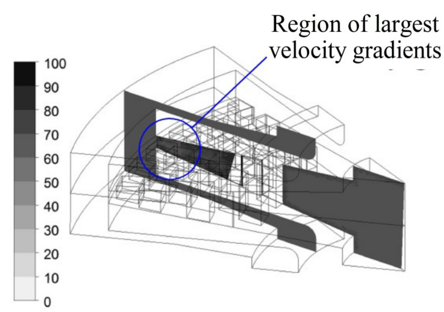
Thus, based on the results of mathematical modeling and computer simulation, unique hydrovortex nozzles have been developed and manufactured. They ensure high-quality ultradisperse spraying of highly viscous composite fuels and an improved mixing of the fuel droplets with oxidizer. The use of such nozzles for burning composite fuels makes it possible to improve technical, economic and environmental performance indicators of power units [12, 13, 25].

4. 4. Computer simulation of the processes of hydrocavitation activation in a rotary cavitation device

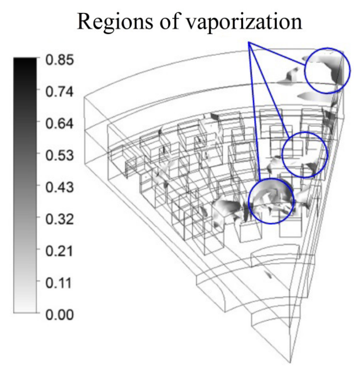
Based on the presented methodology of mathematical modeling, calculations can be made for a rotary cavitation device, the schematic of which is presented in Fig. 1.

To intensify the cavitation processes taking place in hydrocavitational processing (HCP), it is necessary to provide a significant increase in intensity and amplitude of pressure pulsations in the processed liquids.

Mathematical modeling was carried out to describe the processes occurring in the HCP of the produced composite fuels. Mathematical modeling of the processes of composite fuel preparation in a rotary cavitation device is considered in a three-dimensional nonstationary formulation in cylindrical coordinates. The results of the calculations are shown in Fig. 8.



a



b

Fig. 8. Distribution of flow rates and the region of vaporization in the fuel-flow section of the rotary cavitation device: *a* — distribution of flow velocities in the fuel-flow section; *b* — regions of vaporization in the fuel-flow section

The calculations which were made have allowed us to draw the following conclusions.

The maximum values of the instantaneous velocity (up to 100 m/s) of the processed flow are observed in the gap between the impact elements of the counter-rotating rotors. In the same regions, significant pressure pulsations take place resulting in steam cavitation. Thus, the process of cavitation in these regions develops most intensively.

5. Experimental studies of composite fuel production processes with addition of waste of various origins

When developing new types of energy resources in a form of composite fuels, much attention is paid to qualitative characteristics of the resulting fuel mixtures for ensuring their use in existing power generating units without significant structural changes in the latter. Stability (resistance to stratification over time) and viscosity are important consumer properties of the composite fuels. Namely, these properties determine the possibility and duration of storage of fuels, their transportation conditions, technologies and methods of their spraying and burning. To ensure specified consumer properties, hydrodynamic cavitational activation of the fuel components is carried out using a rotary cavitation device schematic view of which is shown in Fig. 9.

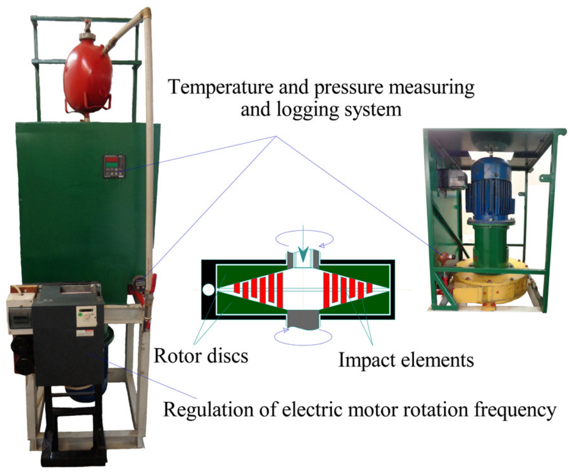


Fig. 9. Schematic view of a rotary cavitation device

Studies were carried out into the processes of production of composite fuels with the addition of waste of various origin (spent fracturing fluid, phenolic wastewater, biomud, products of processing solid domestic waste, etc. [25–27]) as the source fuel components. Such fuels were produced under various operating conditions of the rotary cavitation device, since the properties of the produced fuel can vary considerably depending on the added components.

In the production of composite fuel with the addition of spent fracturing fluid (FF) as an aqueous phase, the most important task was to ensure stability of the fuel emulsion. The waste contains chemical gel breaking agents, which are able to destroy emulsion structure and significantly reduce fuel stability. It is difficult to ensure fuel stability to layering in the case of liquid low-viscosity hydrocarbons as a basis. Composite fuels were produced on the basis of diesel fuel (DF) with the addition of waste FF in various concentrations. The experiments confirmed possibility of obtaining stable fuel emulsion with the addition of this type of waste [27]. The characteristics of the resulting composite fuels are given in Table 1.

According to the results given in Table 1, an increase in the amount and concentration of the added spent FF results in a lower fuel stability due to the increase in the quantity of chemical gel breaking agents, which destroy the emulsion structure. The decrease in viscosity of the fuel emulsion in the case of increase in the quantity and concentration of these wastes is explained by the increase in the quantity of organic amines in the spent FF composition. These amines can be used as plasticizers in the preparation of emulsions and suspensions.

Table 1

Characteristics of the tested composite fuel samples

Fuel characteristic	10-fold FF concentrate			20-fold FF concentrate		
	90 % DF+ +10 % aq. phase	85 % DF+ +15 % aq. phase	80 % DF+ +20 % aq. phase	90 % DF+ +10 % aq. phase	85 % DF+ +15 % aq. phase	80 % DF+ +20 % aq. phase
Viscosity, mPa·s	2.9	2.8	2.7	2.7	2.6	2.4
Stability, days	4	3	2	3	2	1
Calorific power, mJ/kg	38.6	36.7	34.5	38.8	36.8	34.7

6. Experimental studies of combustion of composite fuels and analysis of flue gases

Combustion of the produced composite fuels was studied by means of a burner [27] with a tangential supply of secondary air. Fuel combustion processes were studied both for direct-flow and vortex methods of combustion to determine optimum characteristics of these process. If necessary, it is possible to use high-reaction fuel for illumination. Because environmentally hazardous wastes of different origins are introduced in composition of these fuels as starting components, it is necessary to check composition of the flue gases arising from combustion for its compliance with ecostandards and requirements. Measurement of the volumetric concentration of harmful substances in flue gases evolving during combustion of the produced fuel was carried out with the help of OKSI 5M-5ND CO_2 gas analyzer (Ukraine). The gas analyzer detects presence and determines concentration of common contaminants, such as nitrogen oxides, carbon, sulphur, and does not detect presence of various types of carcinogenic contaminants. For this purpose, an additional sampling system was designed and manufactured. This system enables additional analysis of the flue gas composition to check compliance of the tested fuel with ecostandards and requirements.

Schematic view of the burner and the flue gas sampling system is shown in Fig. 10.

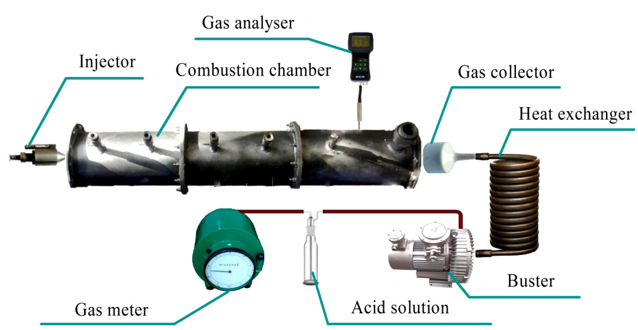


Fig. 10. Schematic view of the burner unit and the flue gas sampling system

When studying combustion of composite fuels based on a diesel fuel with addition of spent FF, the main task was to detect the presence of organic amines in the flue gas composition, which are the main pollutant of this type of waste. They cannot be separated by other physical-chemical methods of purification. The fuel combustion process is shown in Fig. 11.

Fig. 11. The process of combustion of a composite fuel with the addition of spent FF

According to data of experimental studies, the combustion temperature was 1050–1150 °C in the flare zone and 450–550 °C in the fuel injection zone. In the studies of composite fuel combustion processes, composition of flue gases was analyzed for the presence of harmful emissions. The analysis results are given in Table 2.

According to the data given in Table 2, the studied composite fuel with the addition of spent FF is fully in line with environmental standards and requirements for power-generating boilers. Analysis for the presence of amines showed their complete fire neutralization in all samples of the investigated composite fuel.

In studying combustion of water-mazut emulsions with the addition of phenolic wastewater, samples were taken and analyzed for the combustion products. The samples showed a 99.6 % neutralization of phenols.

Studies of combustion of composite fuels with the addition of biomud, products of recycling solid domestic and other types of wastes have shown compliance with environmental regulations. This gives grounds to believe that ecologically hazardous wastes of various origins can be used in fuel combustion. Such wastes must be introduced into the composition of composite fuels and burnt at power generating facilities using methods of hydrocavitational activation.

Table 2

Results of analysis of composition of flue gases

Fuel under study	O_2, %	CO, mg/m³	SO_2, mg/m³	CO_2, %	α	NOx, mg/m³	T, °C	Amine mg/m³
80 % DF+ +20 % aq. ph. (spent FF)	5.1	45	68	12.2	1.21	160	883	–
80 % DF+ +20 % aq. ph. (2-fold concentrate)	4.2	70	76	12.1	1.27	168	903	–
80 % DF+ +20 % aq. ph. (10-fold concentrate)	4.1	55	85	11.9	1.24	171	887	–
80 % DF+ +20 % aq. ph. (20-fold concentrate)	4.4	60	100	12.4	1.26	177	898	–
MAC	–	250	500	–	–	500	–	–

7. Discussion of the results obtained when studying production and combustion of composite fuels

To produce new types of liquid composite fuels with addition of industrial wastes of various origins, application of special technological methods is necessary.

The most important consumer properties of composite fuels include the possibility of their long-term storage (resistance to stratification) and viscosity. To achieve such properties, hydrocavitational activation of fuel components was carried out using a rotary cavitation device (Fig. 9) for which a rotor and a stator of a special type were designed and manufactured. Design solutions for the equipment intended for hydrocavitational activation have made it possible to broaden the nomenclature of composite fuels with addition of waste of various origins as fuel components, for example, spent fracturing fluid, phenolic wastewater, biomud, solid waste products (for example, rubber), etc. [25–27]. Depending on the components being added, respective operating conditions for the rotary cavitation device were selected to improve the fuel properties. An example of obtaining a composite fuel with the addition of spent FF to a diesel fuel at various concentrations showed the possibility of rational use of harmful wastes (Table 1).

For the combustion of composite fuels in which environmentally hazardous wastes of various origins have been introduced, a special burner has been designed (Fig. 10). Analysis of the composition of flue gases evolved in the combustion of composite fuels (Table 2) fully complies with environmental standards and requirements.

The technology developed for burning composite fuels solves the ecological problem of recycling industrial waste and the task of obtaining cheaper thermal energy. The proposed technological approach is universal and can be used for the disposal and neutralization of organic and mineral wastes of various origins using methods of hydrocavitational activation at the stages of production and combustion of composite fuels.

8. Conclusions

1. We devised methods of mathematical and computer simulation of hydrodynamics of viscous incompressible fluid flows in channels of a complex shape using the structural method of R-functions enabling detection of turbulence and cavitation zones in which intensification of physicochemical and heat exchange processes in heterogeneous media takes place. Application of these methods makes it possible to shorten time and improve quality of designing devices for hydrocavitational treatment for liquids.

2. Comprehensive studies into production and burning of composite fuels with the application of methods of activation of physical and chemical processes were carried out. The obtained composite liquid fuels based on "classic" hydrocarbons (mazut, diesel fuel) with the addition of various types of waste ensure compliance with current energy, ecology and consumer related requirements. Solutions were proposed concerning reduction of atmosphere pollution with harmful emissions resulting from burning of composite fuels.

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