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REFINING THE HYDROCAVITATION TECHNOLOGY FOR RECYCLING HYDRAULIC FRACTURING FLOWBACK WATER BY USING NUMERICAL SIMULATION AND PHYSICAL MODELLING METHODS*

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Abstract

A methodology was developed for determining the impact of hydrocavitation activation on the consumer properties and energy ecological characteristics of combustion of new kinds of composite fuels. This methodology, jointly with numerical simulation and physical modelling methods enables refining the design of process equipment for the production, spraying and combustion of composite fuels comprising organo-mineral wastewater of different origin. An energy-technological complex was developed to conduct physical modelling and comprehensive research in the fluid dynamics and heat-and-mass transfer during the hydrocavitation activation of fuel mixtures, and to hold industrial tests of the developed technologies. The application of the developed methodology and of the energy-technological complex improved the hydrocavitation technology of recycling hydraulic fracturing flowback water as a part of composite boiler fuels. In particular, the following was achieved: the stability parameters of the produced fuel mixture were improved; the efficiency parameters of the processes of combustion of the investigated composite fuel were improved; the amount of hazardous substances in atmospheric flue gas emission was reduced.

Keywords: composite fuel, energy-ecological indicators of combustion processes, hydrocavitation activation, hydrocavitation device, simulation

1. Introduction

A challenge for the majority of countries is the need to recycle a huge amount of industrial and domestic wastewater containing organo-mineral pollutants. Presently, a significant amount of effluents from the agricultural, oil-and-gas production, metallurgical,

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power, public utilities and other industry sectors is either accumulated or discharged to water reservoirs, with a devastating environmental effect.

An example of such an effluent is the hydraulic fracturing (HF) flowback water. Hydraulic fracturing is the most widespread technology for intensifying the production of hydrocarbons and, virtually, it is the sole one for extracting unconventional oil and gas (Armstrong et al., 1995). This technology is based on injecting a special hydraulic fracturing fluid under pressure into the well pay horizon, which is sufficient for creating an elongated fracture in the rock. The HF fluid is a suspension, in which specially prepared sand is used most often as the solid dispersion phase. The flowback water is consequently pumped to the surface and stored in special open waterproof containment pits. As a rule, this water is very mineralised and contains a big amount of organic substances. The main hazardous pollutants contained in the HF flowback water are boron compounds and organic amines formed by decomposition of initial chemical compounds, including breakers.

Damage to the waterproofing coating of the containment pit can lead to ingress of these chemical elements to the soil, pollution of ground waters, and evaporation from open containment pits, and to pollution of the air basin with toxic chemical substances. Recycling of flowback water to prepare a new HF suspension is impossible because a decomposing agent residue is found therein. Hence, certain environmental problems occur, the foremost one being the need to treat a huge amount of flowback water, making the development of a close cycle technology for treatment of HF effluents a critical task.

The authors (Homan and Kravchenko, 2016a) have suggested and developed a technology for closed cycle treatment of HF flowback water. It is based on applying certain physico-chemical purification methods that yield purified water and related substances (mineral salts and chemical components) suitable for recycling, and a concentrate of HF flowback water. The isolated concentrate, with application of the hydrocavitation activation (HCA) methodology (Kravchenko et al., 2017), is introduced to the composition of the artificial composite liquid fuel (ACLF) and combusted to produce thermal and electric power.

The process of producing composite fuels has a substantial effect not only on the thermophysical properties of the fuel composition being produced (Pinchuk et al., 2016), but also on the energy-ecological characteristics of their combustion. In addition, an important consumer characteristic of liquid composite fuels is their stability (resistance to settling with time) and viscosity. These indicators define the requirements to fuel storage and transportation conditions, and the technologies and methods of their spraying and combustion. The quality of fuel emulsion spraying affects substantially the composite fuel combustion efficiency (Zhuravskii, 2019), and the additional dispersion and homogenisation of hazardous wastewater components in the burner flame ensures their combustion. The HCA methodology enables producing and combusting high-quality composite liquid boiler fuels containing organo-mineral wastewater of different origin. Hence, optimisation of parameters of HCA processes is a topical problem.

The purpose of this research is the refining of the hydrocavitation technology for recycling hydraulic fracturing flowback water. The following objectives need to be achieved to realise the purpose:

1) Develop a methodology for determining the effectiveness of HCA for the production and combustion of ACLF based on hydrocarbons and organo-mineral wastewater of different origin;

2) Use numerical simulation and physical modelling of the fluid dynamics of flows of a viscous incompressible medium to improve hydrocavitation equipment for producing and combusting composite fuel;

3) Conduct experimental research in the impact of HCA on the effectiveness of producing and combusting composite fuels, and modifying their thermophysical and energy-ecological properties.

2. Materials and methods

To determine HCA effectiveness for producing and combusting ACLF based on hydrocarbons and organo-mineral wastewater of different origin, a methodology was developed based on two basic interrelated algorithms:

- determining HCA effectiveness producing a composite fuel;
- identifying the hardware and the process parameters of the effectiveness of composite fuel combustion processes.

Fig. 1 shows the algorithm for determining HCA effectiveness when producing a composite fuel.

To produce a composite fuel with preset energy-ecological indicators, the first stage is to determine the mass ratio of the source fuel components. Their physico-chemical properties are considered, especially those that substantially affect the rheological properties and the stability of the fuel mixture produced. When developing fuel suspensions, an important point is accounting for the properties of the solid phase.

Next, the design features and the effective operating conditions of the hydrocavitation device for producing an ACLF are determined. Numerical simulation of fluid dynamic processes in the hydrocavitation device is performed using software packages for solving problems in the fluid dynamics of viscous fluids, such as ANSYS, Open FOAM, and FloweR (Rusanov et al., 2015). The R-functions method (Kravchenko et al., 2017) is used for numerical simulation of the fluid dynamics of cavitational flows in axisymmetrical and plane complex-shape channels.

Because the expected result depends on a big number of variable parameters, achieving a correspondence between numerical simulation results and the specified objectives requires the solution of optimisation problems that enable the following:

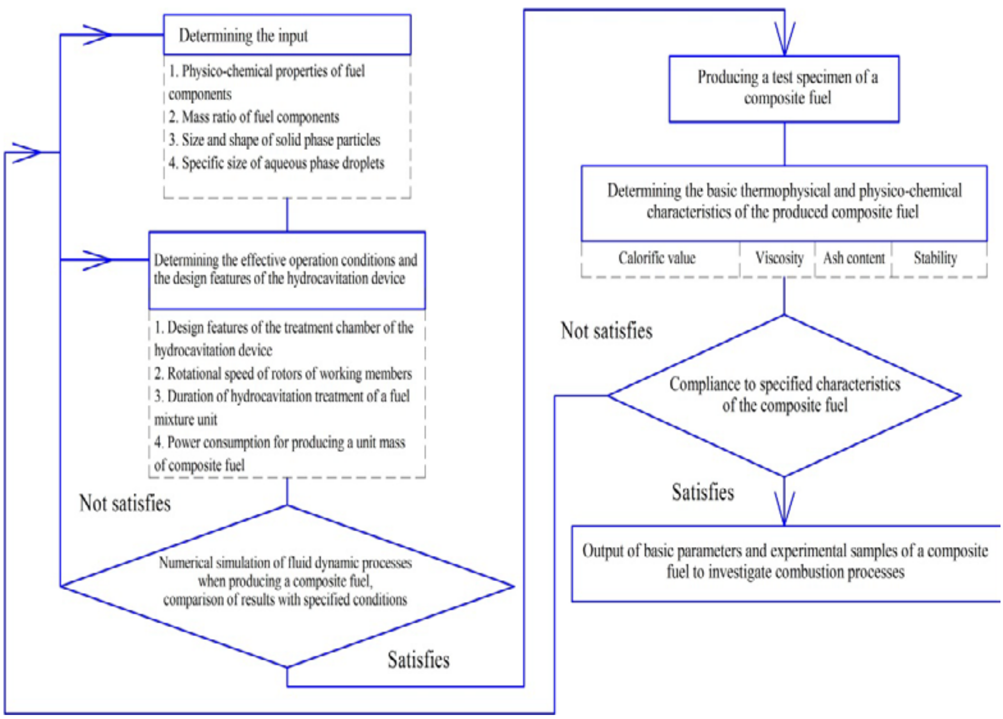


Fig.1. Algorithm for determining HCA effectiveness when producing a composite fuel

- determine the optimal components composition of the fuel mixture;
- determine the effective geometric form of the flow part of the hydrocavitation treatment chamber, and the optimal operating conditions of the device as a whole, including those with account for specific energy consumption;
- increase the capacity and the operating effectiveness of the hydrocavitation device, and other components.

In particular, the optimisation method (Shupikov et al., 2012) can be used for successfully completing these tasks. It is based on the hybrid search method with adaptive control of the extremum search process. Having received numerical simulation results that satisfy the specified requirements to process effectiveness, a round of experimental research is conducted in preparing a simulative composite fuel. Its thermophysical and consumer properties are determined, including the calorific value. An effective process is considered as being that, during which an ACLF with improved properties was produced.

If the specified properties of the produced composite fuel were not confirmed, a new round of numerical simulation is performed with adjusted input; hydrocavitation devices are refined or new ones are built, and their operating conditions are revised.

This approach allows not only to verify the computer model of the process by comparison with obtained experimental results, but also to refine it. In so doing, the experimentally obtained adjustment coefficients or functions of dependence of parameters that change during the process are input to the mathematical model.

The next research stage, the algorithm of which is shown in Fig. 2, consists in choosing the hydrocavitation equipment design and defining its specific operating conditions that would ensure effective spraying and combustion of the produced composite fuel. Effectiveness is evaluated primarily with account of the energy-ecological indicators of the combustion process.

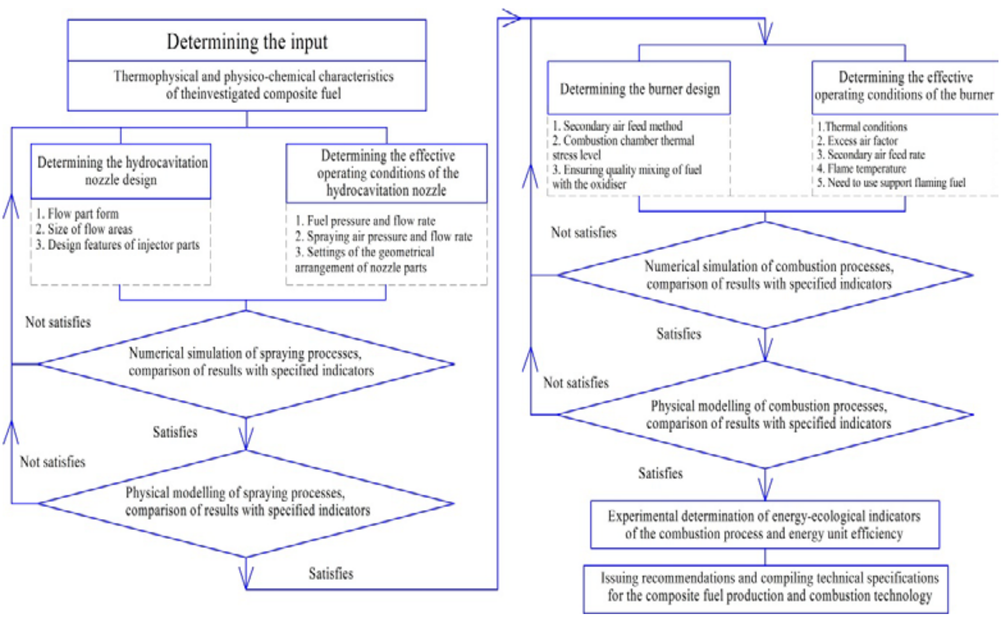


Fig.2. Algorithm for choosing (developing) HCA devices and their operating conditions for effective combustion of composite fuel

The input for conducting such research comprises the thermophysical and physico-chemical characteristics of the fuel mixtures being investigated. According to these indicators, the hydrocavitation nozzle design and its effective operating conditions are determined, followed by numerical simulation of the processes of fuel spraying during combustion. Since a huge number of factors (viscosity and adhesion properties of the fuel mixture, presence and size of the solid phase, and other factors) can affect the effectiveness of operation of injectors, simulation of the fluid dynamic process of spraying a composite fuel also involves solving optimisation problems.

Having received numerical simulation results that satisfy the target tasks, physical modelling of the fuel mixture spraying is performed with determination of injector operation effectiveness. At this stage, the design mathematical model is verified experimentally, and adjustment coefficients for its refinement are found.

The results of numerical simulation with the application of the refined model are used for determining the burner design and choosing its effective operating conditions. Having received numerical simulation results that satisfy the specified indicators, the combustion processes in the investigated composite fuel are modelled physically. Following this, the energy-ecological indicators of the combustion process and the energy unit efficiency are determined experimentally. Experimental research data is used for issuing recommendations on the commercial implementation of the suggested technology, and for compiling the technical specifications for production and combustion of composite fuel.

2.1. Experimental

The described methodology is applicable for improving the effectiveness of the processes of producing a composite fuel with addition of concentrated HF flowback water. The research used samples of source and treated HF flowback water. Sampling was done from the containment pit at the Beliavskaya-400 exploratory well (Ukraine, Kharkiv Region). The chemical compositions of the source and flowback process liquids were found to differ dramatically. The flowback water is characterised by greater mineralisation and presence therein of newly formed chemical compounds. The most hazardous substances in the HF flowback water are organic amines.

At the first stage, the available, previously developed hydrocavitation equipment was used to conduct research (Homan and Kravchenko, 2016b). Its results confirmed the possibility, in principle, to use the hydrocavitation technology for recycling of such wastewater. It was also shown that the maximum permissible concentrations of hazardous atmospheric emissions during combustion of a composite fuel with addition of concentrated HF flowback water meets the environmental regulations in force in Ukraine. However, the application of this technology in countries with more stringent environmental standards required a substantial reduction of the content of hazardous emissions in flue gases. The hydrocavitation technology of producing and combusting composite fuel was refined by applying the developed methodology presented in the previous section of the paper.

The effectiveness of hydrocavitation activation of composite fuels was increased by numerical simulation of fluid dynamic processes in a two-rotor hydrocavitation device with account of the properties of the source fuel components (Fig. 3.).

The intensity of cavitation treatment of liquid was increased. In particular, when treating a fuel mixture in its zones of contact with the impact elements, pressure fluctuations reached 15 kgs/cm^2. Fig. 4 shows the micro photographs of ACLF samples based on resid and a 20% concentrate of HF water, which were obtained using a basic (Fig. 4a) and upgraded hydrocavitation device (Fig. 4b). Evidently, the refined device demonstrated a substantial increase in the dispersion and homogenisation level. This serves as a basis for quality firing neutralisation of environmentally hazardous chemical substances contained in a concentrate of HF flowback water. Thereat, the energy consumption for the production of one ton of

ACLF dropped by 6 %, and hydrocavitation equipment capacity increased due to reducing the time of treatment of a unit volume of the fuel mixture. The ACLF produced has improved thermophysical properties – viscosity was reduced by about four-fold and stability was increased by 10-15 %.

The next research stage involved activities in improving spraying and combustion systems.

When solving boundary problems, the complex shape domains were described using the proven structural method of R-functions (Kravchenko et al., 2017). It was used during numerical simulation of the processes of fuel mixture spraying. The simulation results are shown in Fig. 5.

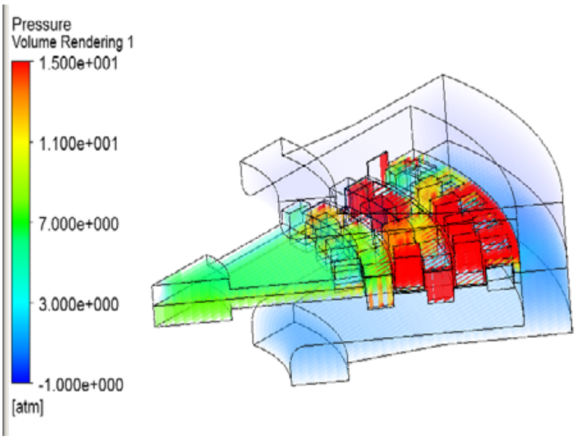
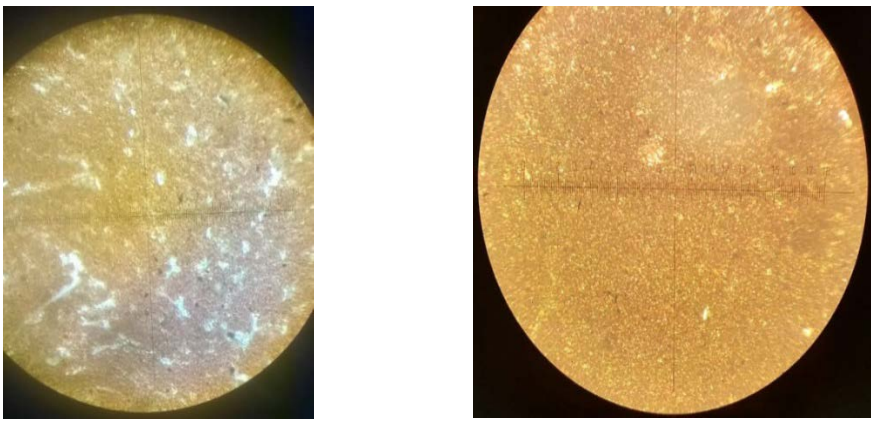


Fig. 3. Results of numerical simulation of fluid dynamic liquid treatment processes



a b

Fig.4. Micro photographs of ACLF samples containing a 20 % concentrate of HF flowback water: a) – ACLF obtained on basic equipment; b) – ACLF obtained following the upgrading of the hydrocavitation device and choosing optimal operating conditions

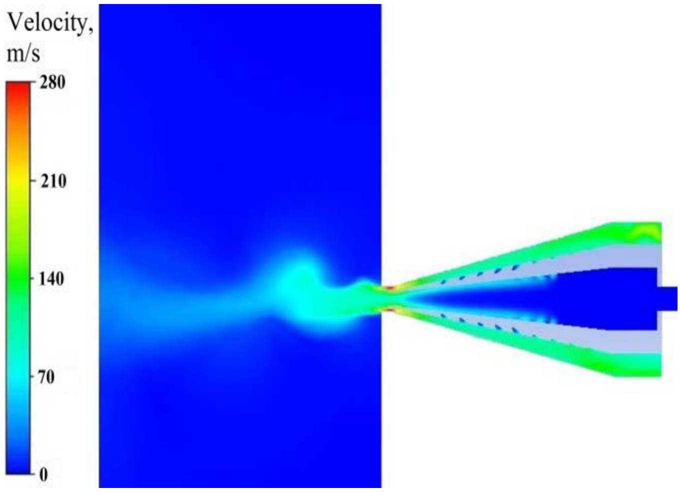


Fig. 5. Distribution of two-phase flow rates during composite fuel spraying

According to the results shown, the temperature level in the developed cyclone-type combustion chamber (Fig. 6a) is within 540-1200 ºC. This is sufficient not only for quality combustion of water-fuel emulsions, but also for effective firing neutralisation of the basic environmentally hazardous chemical compounds contained in the concentrate of the HF flowback water. The results are also indicative of the high quality mixing of the fuel-air flow (Fig. 6b). They allow assuming a high combustion efficiency of the energy resource being used.

The developed burner differs from the previously used one (Homan and Kravchenko, 2016b) by the presence of a fire tube for stabilising the flame and improving fuel mixing with the oxidiser. Implemented also was a multistage feed of secondary air and an additional swirl of hot gases to increase the time of residence of fuel droplets in the zone of high temperatures.

Using the developed burner during ACLF combustion increased the degree of burn off of the fuel mixture. It also increased the thermal stress of the combustion chamber, this being one of the core conditions for recycling of environmentally hazardous waste by using the firing method.

2.2. Practical application

It is shown that one of the most effective methods of recycling wastewater, in particular, the hydraulic fracturing flowback water is the firing technique used in combination with composite fuels produced by applying the hydrocavitation activation technology. An energy technological complex shown in Fig. 7 was developed and built to conduct a complete series of experimental research in the processes of producing and combusting composite fuel with the use of HCA.

The key components of the complex are the hydrocavitation device, the hydrovortex nozzle and the burner, which were developed using the aforesaid methodology (Figs. 3, 5, 6). The complex enables conducting research in the processes of production and combustion of ACLF based on hydrocarbons with addition of liquid moisture-containing industrial waste of different origin to determine the key indicators of energy effectiveness and environmental compatibility of the developed technology.

Fig.7. Experimental energy-technological complex for research in the processes of producing and combusting composite fuel

According to the basic premises of the developed methodology, the energy-technological complex (Fig. 7) was used for experimental research in the processes of producing composite fuel based on oil refining resid and a 20-fold concentrate of HF flowback water as the aqueous phase. Table 1 shows the physico-chemical properties of the obtained samples of the composite fuel.

According to the data in Table 1, the stability of the obtained composite fuel samples decreases with an increasing concentration of HF flowback water. This is because the composition of this kind of waste includes unreacted destructing agent components that reduce the stability of the fuel emulsion obtained. Owing to this, concentrations of HF flowback water in the fuel mixture in excess of 20 % degrade the storage and transportation indicators, and reduce the effectiveness of composite fuel combustion processes.

Physical modelling was performed to investigate combustion of composite fuel based on oil refining resid with addition of HF flowback water (FW) as the aqueous phase. These investigations used steam boiler E–1.0–0.9G–Z(E) with a capacity of one ton of steam per hour. Gas analyser OKSI 5M-5ND CO_2 was used for determining the composition of flue gases during the combustion of the fuel being investigated. Since organic amines are one of the main environmentally hazardous chemical substances in the HF flowback water, when the investigated fuel was combusted the combustion products were sampled to conduct chromatographic analysis to establish the presence of these pollutants in the flue gases. Table 2 shows the results of analysing the composition of flue gases during composite fuel combustion.

Table 1. Physico-chemical properties of investigated composite fuel samples

Type of fuel	*Viscosity, mPa*s*	*Stability, days*	*Calorific value, MJ/kg*
Resid	26	-	44.0
Composite fuel (5 % FW)	2,400	10	42.1
Composite fuel (10 % FW)	2,100	5	40.4
Composite fuel (15 % FW)	1,800	4	38.3
Composite fuel (20 % FW)	1,600	2	36.9

Table 2. Results of analysing the composition of flue gases during combustion

Type of fuel	*Temperature °C*	*α*	*O_2, %*	*CO_2, %*	*CO, mg/m³*	*SO_2, mg/m³*	*NO_x, mg/m³*	*Amine, mg/m³*
Resid	986	1.19	4.3	11.8	12	34	48	-
Composite fuel (5 % FW)	947	1.22	4.4	11.9	19	31	51	-
Composite fuel (10 % FW)	934	1.22	4.4	12.0	16	29	54	-
Composite fuel (15 % FW)	912	1.25	4.6	12.1	14	28	61	-
Composite fuel (20 % FW)	898	1.26	4.7	12.2	21	24	69	-

These results demonstrate not only the complete destruction of organic amines, but also the compliance of key combustion process indicators with the most stringent environmental standards.

The commercial tests confirm the effectiveness of the methodology of refinement of hydrocavitation technologies of HCA and open broad prospects of their application for recycling organo-mineral wastewater of different origin.

3. Resutls and discussion

An effective method of recycling organo-mineral wastewater is firing neutralisation of waste included in the combusted composite fuels produced with the HCA technology. The results obtained on available, previously developed hydrocavitation equipment (Homan and Kravchenko, 2016b) have confirmed the possibility in principle of using the hydrocavitation technology for recycling this kind of waste. A methodology was developed to increase HCA effectiveness during the production and combustion of ACLF based on hydrocarbons and organo-mineral wastewater of different origin. Its application reduced energy consumption for producing a fuel mixture; helped obtain a composite fuel with improved thermophysical and consumer properties, and reduced the amount of toxic atmospheric emissions in flue gases during composite fuel combustion.

Numerical simulation enabled refining the design of the hydrocavitation equipment for producing, spraying and combusting composite fuel. Solving the optimisation problems helped define the most effective operating conditions of this equipment during the production of ACLF of the given type. Owing to this, the thermophysical and the consumer properties of the produced fuel mixtures, as well as the energy-ecological indicators of their combustion were improved substantially.

The developed methodology, by comparison with earlier experimental data, helped reduce the energy consumption for producing ACLF by 6 % and the viscosity of the produced fuel mixture by four-fold, and increase the stability by 10-15 % depending on the concentration of the added waste. It also helped increase the thermal stress in the combustion chamber of the burner. This reduced significantly the amount of hazardous emissions in the flue gases during the combustion of this kind of energy resources.

These results open the prospects of using composite fuels, with addition of HF flowback water as the aqueous phase, as energy resources during the generation of heat and electric power in full compliance with global environmental standards.

4. Conclusions

With a view to improve the hydrocavitation technology of using recycled hydraulic fracturing flowback water in composite boiler fuels, a methodology was developed that is based on numerical simulation and physical modelling methods. The methodology was applied to determine the key parameters of the HCA effectiveness during the production and combustion of composite fuel, to refine hydrocavitation equipment, and to optimise its operating conditions.

Experimental research has shown that the best energy-ecological indicators were achieved during the production of a composite fuel based on oil refining resid and a 20-fold concentrate of HF flowback water. The refined hydrocavitation technology solves two interrelated tasks at the same time – producing a cheaper energy resource and recycling hazardous organo-mineral wastewater in the oil extraction industry in full compliance with the most stringent global environmental standards.

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