Using Pneumo-Hydrovortex Nozzles for Effective Combustion of Liquid Boiler Fuels

Oleg Kravchenko(✉), Vitalii Homan, Iryna Suvorova, and Igor Baranov

A. Pidhornyi Institute of Mechanical Engineering Problems of NAS of Ukraine, Kharkiv, Ukraine
krav@ipmach.kharkov.ua

Abstract. The research aim is to manage an effective and ecological combustion of liquid fuels, including composite ones, in power plant boilers by using refined pneumo-mechanical nozzles, in which air is the atomizing medium. The main distinction of the developed pneumo-hydrovortex nozzles from existing pneumo-mechanical ones is that the dispersed liquid is fed using the film technique with a flow swirl. Numerical simulation and physical modeling methods were used to refine the standard design of the pneumo-hydrovortex nozzle. Without degrading dispersion quality, this enabled to reduce the flow velocity of the atomized fuel and increase significantly the flame cone angle. Preliminary tests of the quality of atomizing a model liquid were performed using plastic pneumo-hydrovortex nozzles obtained with 3D printers. Industrial tests of the new type pneumo-hydrovortex nozzle demonstrated that its application for hydrocarbon fuel combustion could reduce toxic emissions into the atmosphere with flue gases and offer a saving of energy resources during heat and electric power production.

Keywords: Reducing toxic emissions · Combustion process intensification · Atomization devices · Liquid stream dispersion

1 Introduction

The energy and environmental indicators of the power-plant boilers operation depend directly on the fuel combustion quality. During liquid fuel combustion even a minor loss of atomization quality can lead to an increased consumption of energy resources; an increased amount of toxic atmospheric emissions in flue gases; contamination of boiler heat exchange surfaces, and so forth [1]. Improving the performance of power installations with simultaneous improvement of their environmental performance calls for developing the new types of burners. The emergence in the energy market of new kinds of liquid composite boiler fuels in the form of emulsions and suspensions, differing in their physical-chemical and rheological properties from conventional hydrocarbons, including greater viscosity and the presence of a solid dispersion phase also implies the need to upgrade burners. Hence, the development of new atomization devices for effective flame combustion of liquid fuels is a topical problem [2].

Mechanical, steam-mechanical and pneumatic nozzles are used most often to atomize liquid boiler fuel.

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The dispersion of combusted fuel with mechanical nozzles requires substantial pressures at the nozzle inlet. These nozzles have a small adjustment range and are sensitive to fuel quality. A significant increase in the adjustment range can be achieved by using steam-mechanical nozzles. However, at certain operating conditions steam consumption can be up to 0.3 kg per kilogram of fuel. This involves substantial energy expenditures to manage effective combustion. In addition, the problem of nozzle contamination is not fully eliminated [3].

The research aim is to manage an effective and ecological combustion of liquid fuels, including composite ones, in power-plant boilers without an extensive upgrading of burners by using refined pneumo-mechanical nozzles, in which air is the atomizing medium. Pneumo-mechanical nozzles ensure high dispersion and atomization quality. In spite of that partial mixing of combustion mixture components (air oxygen and combustible matter) occurs prior to the initiation of the combustion reaction (inside the nozzles), the combustion process per se in this case is that of the diffusion type [4]. This is because the amount of air fed to the nozzle is insufficient for complete fuel combustion. Therefore, the bulk of secondary air is fed directly into the combustion zone.

Since during diffusion combustion the rate of oxidation of the burnt fuel depends on the intensity of the process of mixing with the secondary air, managing an effective formation of a fuel-air mixture is pivotal. Thus, managing effective combustion of liquid fuel requires not only its quality atomization but also a thorough mixing of its fine droplets with air. With quality atomization, the specific surface of contact of hydrocarbon fuel droplets with secondary air can increase to over 2,500 times to accelerate substantially the heating and evaporation of the combusted energy resource.

2 Literature Reviews

Numerical simulation techniques are used commonly to develop new devices [5]. A computational research was conducted in different approaches to simulating laminar diffusion combustion. Paper [6] considers the classical Burke-Schurmann problem in application to building a mathematical model of a diffusion flame above a fuel film. However, to ensure complete fuel combustion in a small volume and better mixing with the oxidiser (secondary air), it is required to provide turbulence of the injected flow of combusted liquid in the furnace volume. Hence, the fuel is dispersed most often with a swirl of the atomized flow, and burners use special flame tubes whose design features enable to increase a fuel-air mixture formation effectiveness [7].

Paper [8] presents the results of research in the processes of liquid fuels dispersion with account of the Ohnesorge number (Oh) of the Sauter mean droplet diameter. It is shown that the majority of combustible liquids are burnt in the gas phase because the heating of these substances above the surface of the droplets forms a steam space, from which the combusted fuel particles flow into the zone for mixing with air oxygen [9].

Papers [1, 10–14] describe in details the results of experimental research in the dispersion of liquid droplets in the atomized nozzle flame using compressed air. Fuel dispersion with compressed air significantly increases the combustible liquid evaporation rate. This is because the oxidizer is fed directly into the atomized flame core and a partially prepared fuel-air mixture flows into the furnace volume.

Atomization with pneumo-mechanical nozzles using compressed air as an atomizing medium intensifies the processes of fuel droplets ignition and evaporation. Due to this, the fuel is ignited at earlier stages, the heating and evaporation rate of fuel droplets increases, and the flame length shortens.

The above advantages of pneumo-mechanical nozzles during the atomization of liquid fuels, including composite ones (emulsions and suspensions), allows drawing a conclusion that one of the ways of increasing the efficiency of existing power-plant boilers with minimal upgrading is to replace in-service nozzles with devices using compressed air as an atomizing medium.

3 Research Methodologies

IPMash NAS of Ukraine has developed and built a number of pneumo-hydrovortex nozzles for atomizing liquids by using compressed air as an atomizing medium [15]. They were developed using numerical simulation and physical modelling methods. Computer simulation of fluid dynamics for nozzles was performed using the structural *R*-functions method. The mathematical models were built based on the Navier-Stokes system of equations reduced to a nonlinear fourth-order partial differential equation for the stream function and Poisson's equation for static pressure [15].

The main distinction of the developed pneumo-hydrovortex nozzles from existing pneumo-mechanical ones is that the dispersed liquid feeding uses the film technique with a flow swirl. When the atomizing medium (air) is fed tangentially with a high speed into the nozzle, intense vortex formation takes place in its mixing chamber with occurrence of local zones with reduced pressure. This ensures an effective dispersion of the liquid and better quality mixing of the high-viscosity fuel with the oxidizer. Also, note that due to the film tangential compressed air feed to the atomizing path, the abrasive wear of its inner surfaces, including the orifice part is reduced. The latter is especially significant for atomizing suspension fuels. Preliminary tests of the quality of atomizing a model liquid were performed using plastic pneumo-hydrovortex nozzles manufactured by 3D printers. Figures 1 and 2 are clearly displaying the vortex character of the nozzle stream. 3D printing significantly reduces the cost of developed devices and speeds up the process of their experimental research. It also shortens the process of refining and making production prototypes.

The results of commercial pneumo-hydrovortex nozzles performance quality pilot-scale tests demonstrated their high effectiveness for combustion of a wide range of non-standard low-reactivity fuels. The substantial energy and environmental indicators improvement was achieved as compared to those of commonly used nozzles.

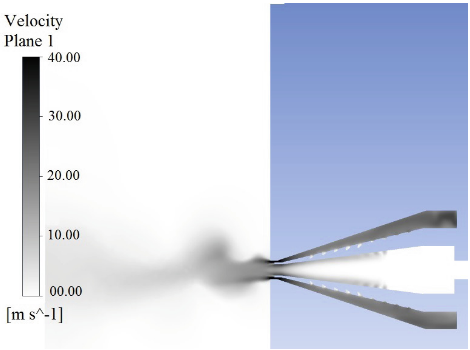

Fig. 1. Simulating the dispersed liquid flow by means of a pneumo-hydrovortex nozzle

Fig. 2. Model liquid atomization with a pneumo-hydrovortex nozzle made by 3D printing

The developed nozzles passed the tests successfully. They are used for combustion of high-viscosity composite fuels based on oil tanker crude oil slops, high ash content waste of coal preparation plants, highly watered sewage from municipal water treatment plants and other kinds of waste of various origins.

Table 1 shows the results of comparative experimental research in the environmental indicators of combustion of hydrocarbon fuel (fuel oil) for different atomization devices—the developed pneumo-hydrovortex nozzle and a mechanical rotatory one.

Table 1. Environmental indicators of the processes of fuel oil combustion for different types of nozzles

Nozzle type	CO, ppm	CO_2, %	NO_x, ppm	SO_x, ppm
Pneumo-hydrovortex	12	11.1	91	132
Rotatory	33	8.4	97	136

According to the results (Table 1), using pneumo-hydrovortex nozzles reduces the amount of toxic emissions into the atmosphere in flue gases during the combustion of hydrocarbon energy carriers. The result of higher quality fuel dispersion and mixing in the developed devices is the combustion with a lower excess air factor to consequently reduce NO_x emissions.

Experimental research in the combustion of non-standard alternative low-reactivity fuel mixtures containing a significant amount of moisture and solid impurities has confirmed not only the possibility of using the developed nozzles but also the high efficiency of combustion processes.

In particular, experimental research in the processes of combustion of composite fuels based on fuel oil with addition of alcoholic beverage production waste as the aqueous phase (AP) was conducted. The composite fuel of the given type was produced using the energy-technological research complex shown in [15]. Tests demonstrated the inadaptability of standard commercial nozzles and burners due to the unsatisfactory dispersion of high-viscosity fuel mixtures and the loss of flame caused by their clogging. Hence, the results of combustion of a composite fuel are given only for the pneumo-hydrovortex nozzle.

The basic physico-chemical and rheological properties of the combusted composite fuel are shown in Table 2.

Table 2. Physico-chemical and rheological properties of researched composite fuels

Fuel	Moisture content, %	Ash content, %	Specific combustion heat, MJ/kg	Viscosity, mPa·s
Fuel oil + 20% AP	19.7	0.18	33.4	264
Fuel oil + 25% AP	24.4	0.22	32.5	276
Fuel oil + 30% AP	29.1	0.26	31.7	329
Fuel oil + 35% AP	33.9	0.32	31.1	436
Fuel oil + 40% AP	38.8	0.38	29.2	524

During the research of the composite fuel combustion processes (Table 2), the focus was on the combustion environmental indicators because the task was to assess the possibility of using waste of given origin in the composition of fuel emulsions during their flame utilisation. The results of analysing the composition of flue gases during composite fuel combustion are given in Table 3.

Table 3. Results of analysing the composition of flue gases during composite fuel combustion

Fuel	Excess air factor, α	CO,ppm	CO_2, %	NO_x, ppm	SO_x, ppm
Fuel oil + 20% AP	1.22	19	11.8	69	94
Fuel oil + 25% AP	1.24	20	11.6	76	95
Fuel oil + 30% AP	1.27	24	11.5	75	96
Fuel oil + 35% AP	1.29	27	11.4	78	96
Fuel oil + 40% AP	1.31	32	11.2	84	98

An analysis of the results of experimental research allows making a conclusion that using pneumo-hydrovortex nozzles can ensure high-quality and environmentally safe combustion of low-reactivity high-viscosity composite fuels. Their use can significantly increase the efficiency of power-plant boilers during combustion of both conventional fuel oil and fuel-water emulsions without a substantial upgrading of power equipment.

4 Results and Discussion

According to IEA data [16], currently about 38% of electric power in the world is produced by coal-fired thermal power plants. The boiler units at these plants are started up and brought to predesigned thermal operating conditions by combustion of natural gas or fuel oil. When fuel oil is used as the start-up fuel, mechanical or steam-mechanical nozzles are used in the majority of cases. The drawbacks of these nozzles were described earlier in this paper.

The developed pneumo-hydrovortex nozzles are considered as an alternative to these nozzles. As demonstrated above, pneumo-hydrovortex nozzles ensure not only high-quality dispersion of the burnt fuel but also a resistance to clogging, including the case when suspension fuels are used.

Depending on the purpose and design of the power-plant boiler, a number of requirements are imposed on the fuel flame: the flame length and pattern, its temperature, radiation capability, the atomized fuel stream discharge velocity (largely affects combustion stability), heat transfer to heated surfaces, and other parameters. Proceeding from these requirements, the design of a nozzle for atomizing the combusted liquid fuel should ensure not only the specified dispersion of the droplets but also the required flame pattern with the specified atomized stream discharge velocity.

The developed designs of pneumo-hydrovortex nozzle ensure ultradispersion atomizing with a flame cone angle within 20–90° and the atomized fuel stream discharge velocity of 20–30 m/s.

Nozzles that provide a small cone angle and a long flame are most often used in very long furnace units. For instance, cyclone primary furnaces with a length of 8–10 m are provided for burning water-coal suspensions in industrial power-plant boilers. The combustion chambers of these primary furnaces are lined with refractory materials to create the required thermal stress level. The big length of the primary furnaces is due to the low moisture evaporation rate from the surface of coal particles and their complete combustion. Such primary furnaces cannot use nozzles with big flame cone angles because the contact of fuel droplets with the refractory lining of the walls leads to the formation of solid deposits of unburnt fuel.

For power-plant boilers with a big furnace volume, when the fuel flow rate reaches 500–2,000 kg/h and more, secondary air is supplied by force-flow fans with low heads. In this case, the atomized flame cone angle should be 75–90°. At smaller angles, the quality of atomized fuel mixing with the secondary air degrades, combustion efficiency drops, toxic atmosphere emissions (incl. CO) grow, and the unburnt fuel contacts the heat exchange and other boiler surfaces to form solid deposits that degrade heat transfer and the operation of the boiler unit as a whole.

Industrial pilot-scale tests were conducted for pneumo-hydrovortex nozzles developed by IPMash NAS of Ukraine. These pneumo-hydrovortex nozzles are intended for burning fuel oil during starting up and bringing to design thermal operating conditions of a 200 MW pulverised coal-fired power-plant boiler. The need to replace standard mechanical nozzles was due to the low quality of fuel oil combustion, and big chemical and mechanical underburns.

The first stage of this research used a hydraulic test bench to conduct preliminary tests of the quality of atomization of a model liquid (water) and determine the cone angle. Nozzles with a design fuel flow rate of 1,500 kg/h and various flame cone angles were tested. Air with a pressure of 5 bar was fed to the nozzle for atomization. The fuel feed pressure was 7 bar.

Figures 3 and 4 show photographs of water atomization with cone angles of 20° and 90°.

Fig. 3. Water atomization with a cone angle of 20°

Visual monitoring of the operation of the nozzles suggested that the atomization process was steady in the hydro-gas-dynamic sense and that the dispersion quality was high (no films, and compact and homogeneous filling of the flame).

Both nozzles were tested in a power-plant boiler during its start up. The developed nozzles were installed in place of standard mechanical ones. Nozzles with the flame cone angle of 20° failed to ensure steady fuel oil combustion and their operation was characterised by short-time fuel ignition with subsequent flame loss. This is attributed to high discharge velocities of the atomized stream and a small flame cone angle, failing to ensure quality fuel mixing with the secondary air. Thereat, the amount of primary air

Fig. 4. Water atomization with a cone angle of 90°

fed for atomizing (less than 8% of the required volume) is insufficient for stabilising combustion, thus resulting in flame loss and extinction.

Using nozzles with a flame cone angle of 90° resulted in a substantial decrease in the discharge velocity of the atomized flame with the same flow rate parameters.

From the moment of firing and further during boiler operation, we observed steady fuel combustion with a bright-yellow flame. There was no evidence of the formation of "black" smoke – one of the principal indicators of fuel underburning. Figure 5 illustrates the process of fuel oil combustion in the furnace of a power-plant boiler using a pneumo-hydrovortex nozzle with a cone angle of 90°.

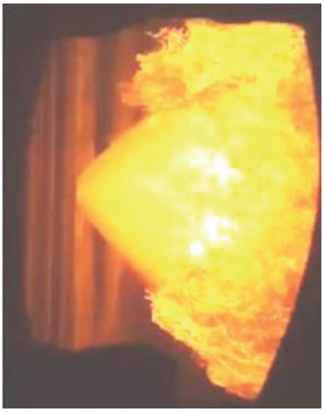

Fig. 5. Fuel oil combustion in the furnace of a power-plant boiler using a pneumo-hydrovortex nozzle

At the same time, we monitored the operation of standard mechanical nozzles. As distinct to fuel combustion in a boiler with a pneumo-hydrovortex nozzle, the flame colour has a pink hue when mechanical nozzles are used (indicative of low combustion temperatures), and a big amount of black smoke was seen.

To determine the basic energy and environmental indicators of using pneumo-hydrovortex nozzles when fuel oil is combusted, it is planned to conduct industrial pilot-scale tests on a power-plant boiler with replacement of all mechanical atomizing devices.

Such tests will allow determining the amount of toxic atmospheric emissions in the flue gases, as well as the amount of fuel consumed for bringing the boiler unit to design thermal operating conditions. According to tentative estimates, using pneumo-hydrovortex nozzles instead of mechanical ones for fuel oil combustion, when a pulverised-coal boiler will be brought to steady-state operating conditions, will provide fuel oil savings of 3–4%. This will also result in a substantial reduction of CO and NO_x in the flue gases. Further, this will open the prospects of expanding the fuel base due to using composite fuels.

5 Results and Discussion

The operating efficiency and environmental indicators of power installations when liquid fuels are combusted depend on both fuel atomization quality and the quality of their mixing with the oxidiser.

Since there are several types of nozzles as per the criterion of dispersion, a multi-faceted approach is needed to install them in power-plant boilers. It must account for the following: the basic characteristics of the combusted fuels; the equipment design and the technical prospects of its revamping (managing the use of an atomizing agent, and the possibility of providing auxiliary systems for preparing and feeding compressed air, and so forth); and the energy, environmental and economic requirements to the thermal energy process.

By the example of fuel oil combustion, the paper has shown the environmental advantages of using pneumo-hydrovortex nozzles over rotary ones. Pneumo-hydrovortex nozzles ensure high-quality fuel dispersion and intensify the processes of evaporation and ignition of fuel droplets. Subsequent comparative tests in composite fuel combustion showed that the suggested type of nozzles is optimal. They ensure quality dispersion of viscous watered composite fuel based on fuel oil and alcoholic beverage production waste. In this case, the environmental combustion indicators confirmed process efficiency.

Industrial pilot-stage tests conducted on a 200 MW fuel oil-fired boiler also confirmed the possibility of increasing the efficiency of combustion of hydrocarbon fuels in power plant equipment without its extensive upgrading by using pneumo-hydrovortex nozzles.

The pneumo-hydrovortex nozzles developed by IPMash NAS of Ukraine are a unique type of devices for atomizing liquids and fuels of different origin including high-viscosity highly watered ones, as well as those with solid impurities. Apart from the fuel-and-energy complex, these types of atomizing devices can be used in the food industry, fire-fighting systems, for dust suppression, in the production of nano powders and in many other industries.

6 Conclusions

Experiments have proved the possibility of essentially increasing the efficiency of the processes of combustion of hydrocarbon liquid fuel in power-plant boilers by using new types of pneumo-hydrovortex nozzles. It was shown that the developed devices ensure quality atomization of composite fuels and substantially reduce the amount of hazardous emissions with flue gases. A comparison of the environmental indicators of the processes of combustion of fuel based on fuel oil and alcoholic beverage production waste has shown that using pneumo-hydrovortex nozzles is an optimal solution enabling a quality dispersion of viscous watered composite fuel.

During the research, the design of pneumo-hydrovortex nozzles was refined. This helped achieve the specified (required) flame cone angles and velocity of discharge of the atomized liquid. This makes it possible to use nozzles of such type in industrial power-plant high-capacity boiler units without a substantial upgrading of the equipment in place to improve the energy and environmental indicators of producing thermal and electric power.

According to the results of preliminary theoretical research, using pneumo-hydrovortex nozzles instead of mechanical ones for burning fuel oil, when bringing the pulverised-coal firing boiler to its specified operating conditions, fuel oil savings can be 3–4%, and the amount of CO and NO_x in the flue gases can be significantly reduced. Further, this opens the prospects of extending the fuel base by using composite fuels.

The developed pneumo-hydrovortex nozzle can be used with success not only in the power industry, but also in other industries requiring quality atomization of liquids, including suspensions.

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