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Review

Nozzles for Spraying Coal–Water Fuels

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Abstract: This work presents a review of modern devices for spraying coal–water fuels. The efficiency of their operation was analyzed according to several criteria: the simplicity of their design (A), the fuel channel's predisposition to clogging (B), durability in terms of the erosive wear of the nozzle channel (C), and dispersion of the jet—the average size of droplets in the jet (D). It was established that, from the point of view of operational efficiency, the most preferred devices for spraying coal–water fuels are those with a quasi-internal mixing of fuel and spraying agents. In combination with refractory or ceramic materials and the large diameter of the fuel channel, its rapid erosion wear and the likelihood of clogging with large particles of coal or agglomerates of viscous coal–water fuel are excluded. At the same time, the possibility of forming a fine-dispersed jet remains. The cooling of the nozzle with an external mixing of fuel and spraying agents during its operation also reduces the rate of erosion wear. Narrowing the fuel channel was proven to be an undesirable solution when creating a coal–water fuel nozzle. This review will be useful for both researchers studying the processes of spraying coal–water fuels and designers involved in the creation of coal–water fuel injectors or the transfer of existing boilers to coal–water fuel.

Keywords: nozzle; spraying; coal–water fuel; air; fuel drop

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1. Introduction

Coal–water fuel (CWF) is a mixed liquid fuel consisting of crushed coal, water, and surfactants [1]. Such fuel gained wide popularity in the second half of the 20th century as an alternative to traditional boiler fuel oils [2]. The positive qualities of CWF are considered to be the following: fire and explosion safety—there is no dry coal dust [3]; environmental friendliness—less compounds of harmful substances are emitted into the atmosphere during combustion due to the presence of water vapor [4]; independence from oil supplies—coal deposits are more evenly distributed across continents [5]; logistical indicators—the possibility of being delivered to a thermal power plant by road, rail, and sea transport via pipelines [6]; stability—it can be stored for a sufficiently long time without sedimentation typical for liquids in a composition with suspended solids [7]; low cost—waste from coal-processing plants (filter cake) can be used as a solid component [8]; and versatility—use for fuel oils and pulverized coal boilers [9]. Despite the impressive list of the positive qualities of coal–water fuels, there are also reasons that restrain their widespread introduction into the thermal power industry. One of the main reasons is the combustion process.

1.1. Problems with the Combustion of CWF

The process of burning coal–water fuel in the combustion chambers of boilers is carried out similarly to oil, fuel oil, diesel fuel, and coal dust [10]. At the same time, the characteristics of CWF spraying differ from the characteristics of spraying the above-mentioned fuels. Firstly, after spraying the CWF, regardless of the type of spraying device, as a rule, fairly large droplets are formed [11]. This is primarily explained by the high viscosity of coal–water fuel. For example, it is noted in [12] that the recommended value of the dynamic viscosity of coal–water fuel for spraying is 1000–1200 mPa·s at a viscometer spindle shear rate of 100 s^{-1}. This is a fairly high value, in comparison with the viscosity of heated fuel oil—20–50 mPa·s. As a result of high viscosity values, the diameter of the CWF droplets after spraying is quite large. Secondly, the ignition delay times of the CWF droplets, depending on their size, reach several seconds [13], which is a large amount of time for full-fledged combustion in the combustion chamber of a boiler. This is explained by the fact that water is present in a CWF drop as a component of the fuel in addition to coal and surfactants. Figure 1 shows a typical process of spraying coal–water fuel. The photograph illustrates well the mechanisms of fuel drop formation in the jet.

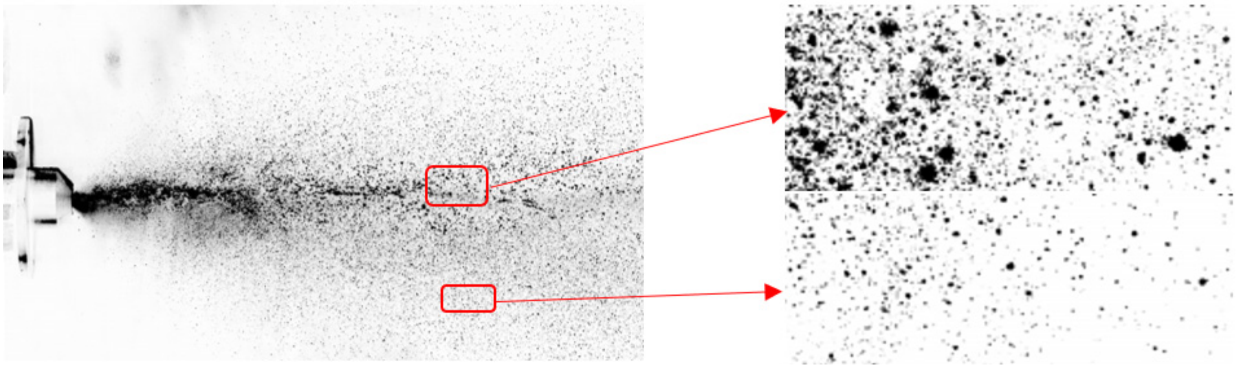


Figure 1. The process of CWF spraying.

It is possible to distinguish droplets and fragments of fuel with a significantly different characteristic size in the CWF jet in Figure 1. At the same time, large drops of CWF are also present at a considerable distance from the nozzle. It can be concluded that these large drops of fuel will not burn completely. A drop of sprayed CWF differs in its structure from drops of sprayed fuel oil or diesel fuel. A drop of CWF is heterogeneous and multiphase. Its heterogeneity is explained by the fact that, even in the presence of surfactants or after mechanical homogenization, a drop of CWF consists of coal particles of various sizes. The spraying process is also different from spraying coal dust. In the latter case, each particle of fine coal moves independently in a pulverized coal jet, as a rule. In some cases, there may be sticking—for example, in the path of a dust pipeline—and a subsequent sintering of several coal particles and the formation of agglomerates due to the excessive humidity of coal or a spray substance—for example, air. The result of this is the underburning of coal and its precipitation into ash. The process of the formation of large agglomerates in the jet can occur more intensively during CWF spraying in comparison with the spraying of coal dust. In general, the mechanism of CWF spraying and burning, taking into account high-speed shooting (for example, Figure 1), is illustrated in Figure 2, which shows the main stages typical for CWF spraying and burning.

After the discharge from the nozzle, the CWF is mixed with the spraying agent (SA) or already represents a mixture of fuel and SA (1), depending on the type of the nozzle. In some cases, almost a single-phase jet of fuel is possible near the nozzle. Large fragments of the slurry are destroyed after the CWF leaves the nozzle, usually due to the environmental resistance forces, centrifugal forces, or as a result of chaotic rotation (2). Small and rather large drops of CWF (3) are formed as a result of these processes. The CWF droplets warm up under the thermal influence of the environment—combustible recirculation gases and radiation from the structural elements of the combustion chamber or reactor. This is accompanied by evaporation of moisture (4). After that, the already drained drops undergo additional destruction during movement (5). Then, the combustion of CWF particles (6), including those that have been baked, begins. At the same time, coagulation of large fuel droplets (7) and their sintering (8) partially occurs. After the complete combustion of small droplets in the air, ash is formed (9). At the same time, large sintered agglomerates of CWF in the composition with unburned coal fall into ash. Thus, it turns out that not all the coal in the fuel burns during CWF combustion.

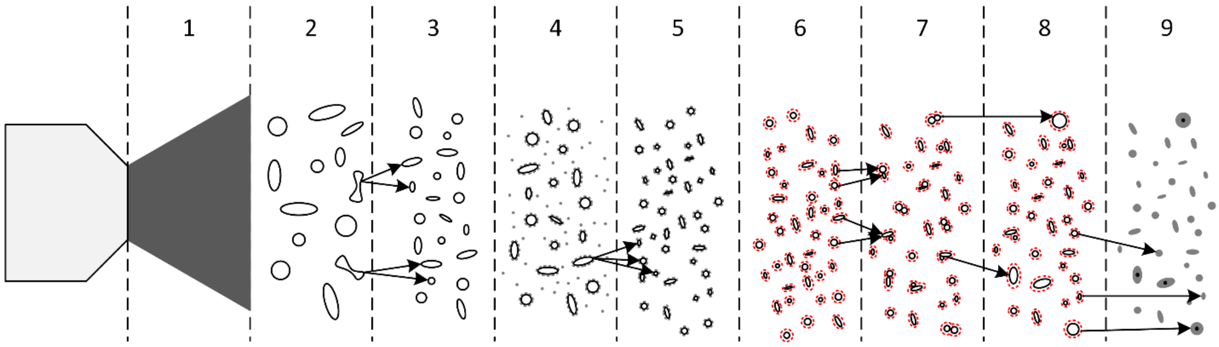


Figure 2. The mechanism of CWF spraying and burning. 1—mixture of fuel and SA; 2—destruction of large fragments; 3—formation of large and small drops; 4—evaporation of moisture; 5—additional destruction; 6—combustion of CWF particles; 7—coagulation of large fuel drops; 8—sintering; 9—formation of the ash.

It should also be taken into account that CWF has an erosive effect on the nozzle channels of the injectors due to the presence of fine coal [14]. As a result, premature wear of the nozzle may occur. As a rule, the area of the nozzle channel is exposed to this [15]. Its destruction occurs, accompanied by an increase in the diameter of the outlet nozzle [16]. The latter factor has a negative impact on the characteristics of the CWF spraying. The fact that the fuel channels of the injectors are clogged with large particles of coal or agglomerates of CWF formed during the preparation of fuel is also important.

There are not many results from studies of the characteristics of CWF spraying and designs of coal–water fuel nozzles in the modern literature. As a rule, known variants of CWF spraying devices were developed and created for specific tasks—coal–water fuel combustion or gasification. The principle of operation of injectors may depend on the design features of combustion chambers or reactors. In general, the known designs of coal–water fuel nozzles can be divided into two types. The first one is with an internal mixing of CWF and SA, for example [17]. The second one is with an external mixing of CWF and SA, for example [7]. At the same time, the main requirements for spraying devices of coal–water fuels remain the formation of a fine jet and the reliable uninterrupted operation of the nozzle.

A number of issues related to the types of injectors, their designs and principles of operation remain unresolved. Therefore, it is relevant to study the existing CWF spraying devices and develop criteria and requirements corresponding to the efficient and trouble-free operation of coal–water fuel nozzles.

1.2. Aim of the Work

The aim of this work is to analyze the known variants of coal–water fuel nozzles presented in the modern literature, to establish the influence of their designs on the principle operation conditions, spraying characteristics, advantages, disadvantages and to establish general factors affecting the process of spraying and combustion of CWF.

The information presented in this article will be useful for researchers involved in the study of CWF spraying processes and the creation of new CWF spraying devices, will provide a prognostic analysis of the injectors' efficiency, and also aid the designers involved in the creation of coal–water fuel injectors or the transfer of existing boilers to CWF.

2. CWF Injectors

Spraying and burning of CWF in the combustion chambers of boilers is carried out similarly to fuel oil or diesel fuel, with the help of injectors. At the same time, unlike the above fuels, the CWF is not subjected to thermal preparation before spraying. In addition, the properties and characteristics of coal–water fuels differ significantly from traditional liquid boiler fuels. The main differences are high viscosity, the presence of solid coal particles and low reactivity. Therefore, it is necessary to provide a number of requirements for CWF sprayers in order to ensure a stable combustion process of such fuel.

The analysis of the known coal–water fuel nozzles was performed considering the results of their tests presented in the literature. The study of the characteristics of coal–water fuels spraying under the conditions and parameters of real combustion chambers is a rather complex process regardless of the type of nozzle.

A nozzle for CWF spraying with internal mixing of fuel and SA is presented in [17]. The nozzle has inner diameter of 5 mm, outer diameter of 12 mm, and a length of 10 mm (Figure 3). The design of the nozzle is quite simple. The main purpose of the research was to study the erosion wear of the nozzle channel. Wear-resistant ceramics, carbide, and metal materials were considered.

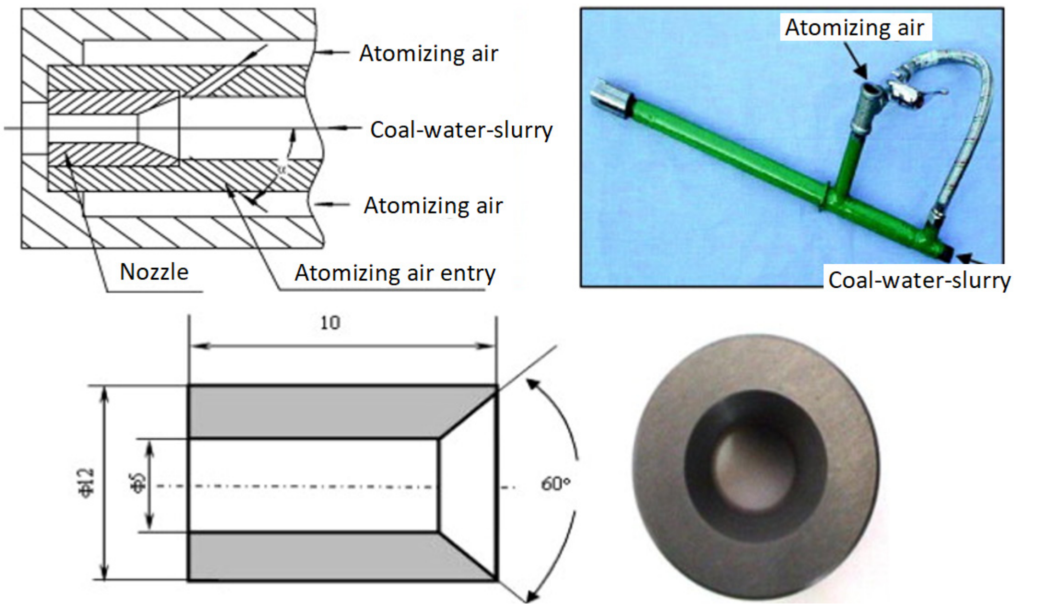


Figure 3. Nozzle for CWF spraying with ceramic orifice [17].

The fuel channel of the injectors of such a design is not protected against clogging with large particles of coal or agglomerates of CWF. The disadvantage is the narrowing of the fuel channel, which is a significant hydraulic resistance for viscous CWF. This may be aggravated by the fact that chipping of the material from which the nozzle is made is possible during the operation of such injectors. The slurry may cause narrowing and a subsequent overlap of the nozzle channel in the case of sticking or sintering on its inner walls. Organization of internal mixing of CWF and SA allows for a finely dispersed jet to be obtained. At the same time, the presence of large droplets in the jet is not excluded. The main reason is that uneven mixing of the CWF and SA is possible in the mixing chamber. The use of ceramic and refractory materials will allow the nozzle to be used for a long time. The expansion of the nozzle orifice will eliminate chipping and subsequent geometry changes.

The results of studies of the spraying characteristics of coal–water fuel with a pneumatic nozzle and its combustion are presented in [7]. The nozzle was made of metal. This device provides for mixing the CWF and SA outside the nozzle (Figure 4). Such an approach allows the CWF to be sprayed with a high-speed air jet (up to 450 m/s and the Mach number about 1.4). The air pressure in the annular chamber was up to 6.0 bar and the liquid flow rate was 180–360 kg/h during the tests, which correspond to the modes in a real boiler.

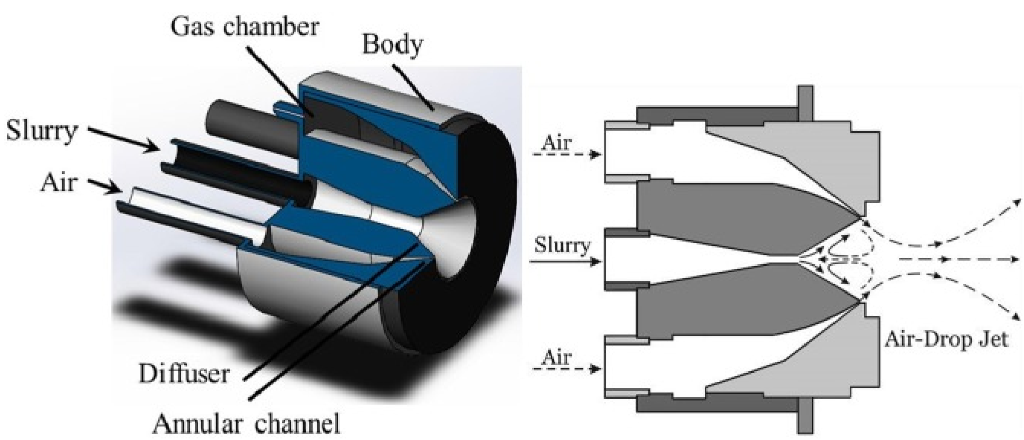


Figure 4. Pneumatic CWF nozzle [7].

The nozzle [7] has a cylindrical body, with a gas chamber inside with an annular conical hole and a channel with a diffuser nozzle for fuel supply. A sufficiently wide (8 mm) diameter of the nozzle channel should ensure an uninterrupted CWF flow even if there are large (for example, up to 3–4 mm) fragments of coal or agglomerates of fuel in it. At the same time, there is a narrowing in the fuel channel in the nozzle design, which is a significant hydraulic resistance for viscous CWF. The slurry may cause narrowing and subsequent overlap of the nozzle channel in the case of sticking or sintering on its inner walls. The issue of the durability of the nozzle remains unresolved. Erosion wear is not excluded. The advantage of this nozzle is the ability to obtain a finely dispersed fuel jet. The average size of the CWF droplets in the jet after spraying is less than 100 microns. This is a very good indicator that will ensure the full combustion of coal. It is worth noting that the ability to change the width of the annular gap of the SA allows the size of the CWF drops to be adjusted.

The variations in the coal–water fuel nozzle in [18], as well as [7], refer to the type of CWF spraying devices with external mixing (Figure 5). The nozzle was made of metal. The size of the CWF droplets after spraying, as well as in the case of [7], can be changed by turning the spraying nozzle. The sprayer consists of three interconnected parts: a housing forming an air flow, a spraying nozzle with a special front section with an internal supply of liquid or pulp, and an air supply fitting perpendicular to the housing.

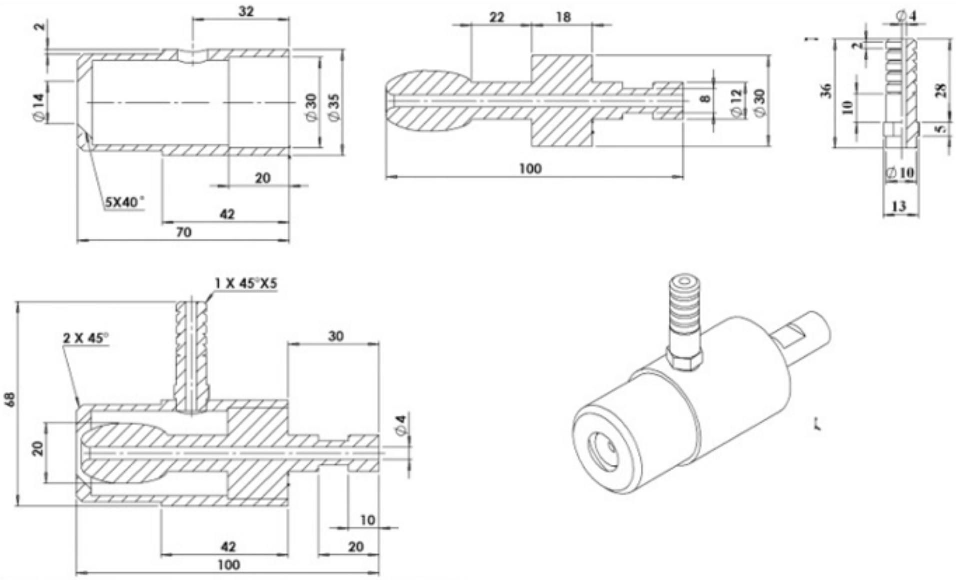


Figure 5. Pneumatic nozzle [18] for spraying slurry fuels.

The authors of [18] noted that the characteristics of the air flow affect the size, speed, and trajectories of the CWF droplets. The disadvantage of this type of CWF sprayer is a very small fuel channel—4 mm—which will contribute to its clogging with large coal particles or fuel agglomerates. The perpendicular feed of the SA can affect the geometry of the jet—displacement and asymmetry. In addition, as in the case of [18], the issue of nozzle durability and erosion wear remains unresolved. The advantage of this nozzle is the ability to obtain a finely dispersed fuel jet.

The characteristics of spraying of subbituminous coal and an aqueous slurry of petroleum coke from a two-liquid vortex sprayer with internal mixing were studied in [19]. The nozzle was made of metal. The proposed nozzle (Figure 6) has three inlet openings for swirling air on the main liquid core located in the mixing chamber inside the nozzle. Then, the two-phase flow collides with the impact plate, which contributes to further mixing. After that, the two-phase mixture exits the nozzle through an annular channel formed by a pin. The ambient pressure in the tank was set at 15 bar during the tests. The flow rates of the slurry and spraying gas were 80 kg/h and 40 kg/h, respectively. The droplet size of petroleum coke and coal slurry was 198 microns at these parameters.

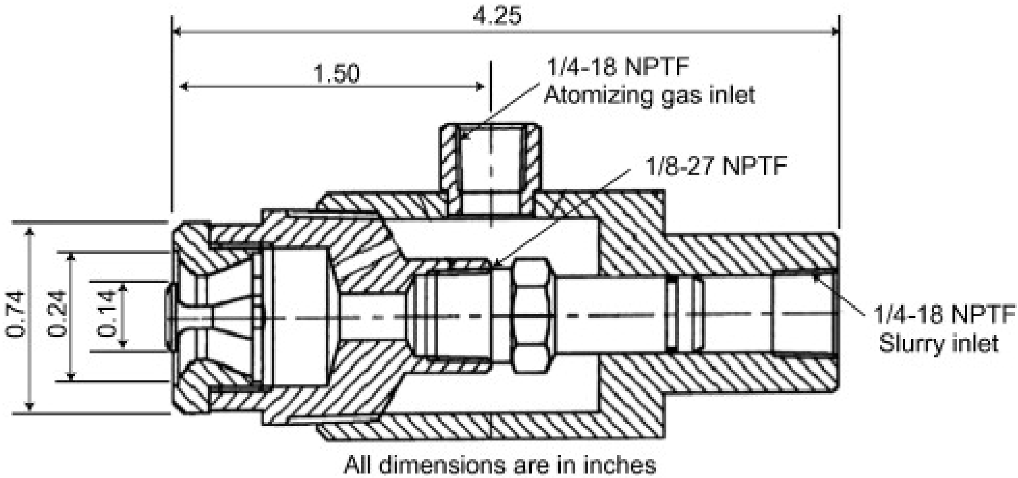


Figure 6. Two-liquid CWF sprayer [19].

This type of CWF spraying device has an internal mixing chamber of fuel and air. The disadvantage of this type of nozzle is the high probability of clogging of the mixing chamber. The issue of the durability of the nozzle remains unresolved. Erosion wear is not excluded. It is necessary to carefully monitor the pressure of the fuel and the spraying agent in order to prevent clogging in this type of injectors.

The effect of the nozzle geometry on the spraying of coal–water slurry was studied in [20]. Three sets of burners with different designs were developed for the study. This device provided mixing of CWF and SA outside the nozzle (Figure 7). The nozzle was made of metal. The CWF flow rate was 10 kg/h, while the oxygen velocity was 120 m/s during the studies. The droplet size was 225–325 microns at different ratios of the burner outlet areas.

Despite the fairly simple design of the injector, its fuel channel was also too small and had a narrowing, which was not protected against clogging with large particles of coal or agglomerates of CWF. The disadvantage is the narrowing of the fuel channel near the orifice, which is a significant hydraulic resistance for viscous CWF. The issue of the nozzle durability and erosion wear remains unresolved. The advantage of this nozzle is the ability to obtain a finely dispersed fuel jet. The average size of fuel droplets after spraying was approximately 200 microns. Large drops of CWF may be present in the jet, but their number is insignificant.

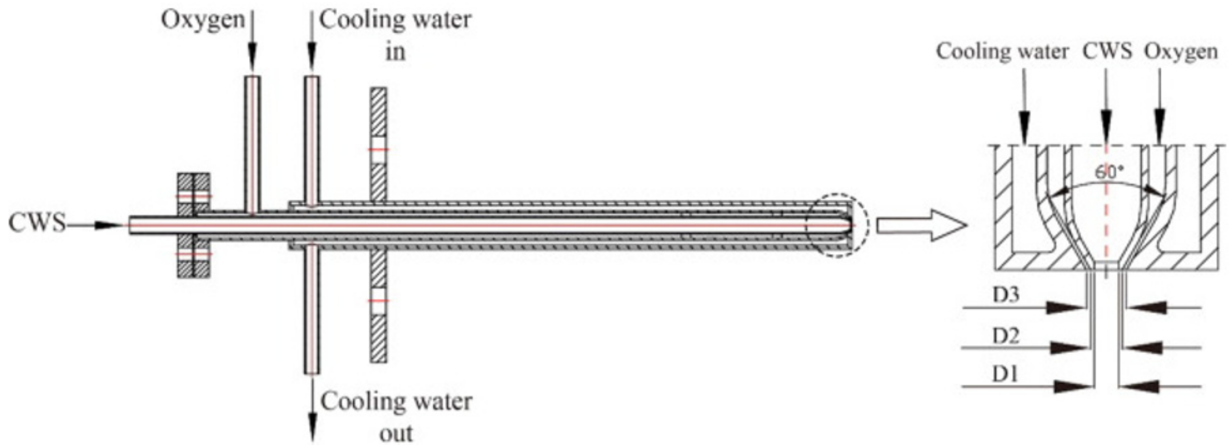


Figure 7. Nozzle for CWF spraying [20].

The characteristics of the granulometric composition and velocity of droplets of coal–water slurry subjected to air-jet electrostatic spraying are presented in [11]. The nozzle was made of metal. A Y-shaped three-level sprayer with a simple design was developed (Figure 8). The authors considered that the nozzle channel could easily be clogged due to its small size (the inner diameter of the hole is 2 mm). The authors pointed out that such design can reduce the loss of resistance of a highly viscous slurry in the fuel path, thereby guaranteeing an unblocked channel in the atomizer, increasing the experimental operation time and reducing unnecessary cleaning in offline mode. In addition, the direct-flow channel can also reduce the wear of the atomizer.

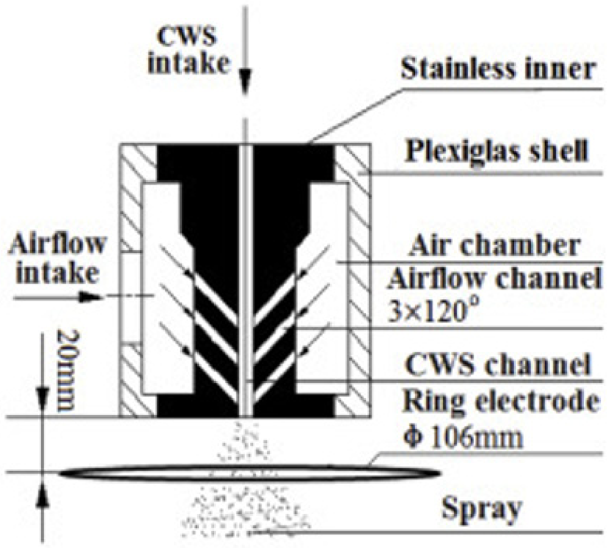


Figure 8. Nozzle for CWF spraying with internal mixing [11].

The slurry in the direct-flow channel was sprayed forming an aerosol after exposure to high-speed air flows from nine holes. Despite the fact that the authors pointed out that such design reduces the likelihood of clogging, this type of sprayer is applicable only in cases of laboratory tests with homogenized slurries based on finely dispersed coal (less than 100 microns). The pressure of the slurry and air was controlled and maintained at 0.3 MPa by a constant pressure valve during the experiment. The slurry flow rate remained at 7.5 kg/h, and the air–slurry ratio was maintained at 0.1.

The results of experimental studies of the characteristics of CWF spraying for a fluidized bed under pressure with a fairly simple spraying device are presented in [21]. The authors took into account that CWF are complex multicomponent liquids, the properties of which significantly depend on the number and type of components. Therefore, two types of two-liquid sealed nozzles were used during the research, direct internal mixing type A (Figure 9a) and internal mixing type B (Figure 9b), with output diameters D 20, 32, and 40 mm. The CWF flow rate was 500 kg/h during the experiments.

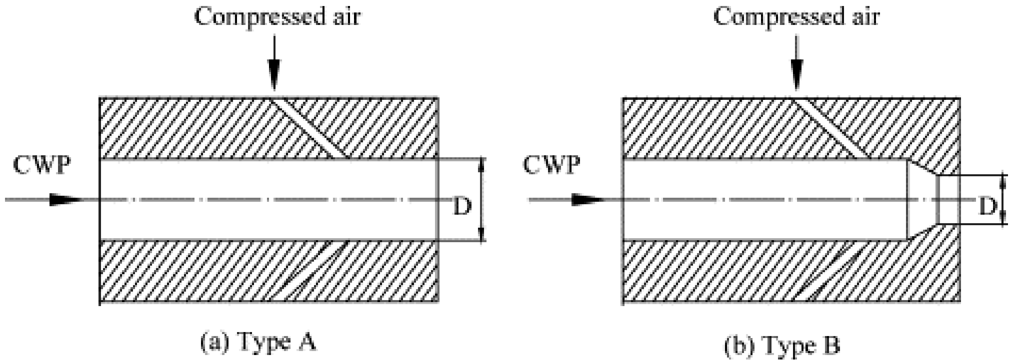


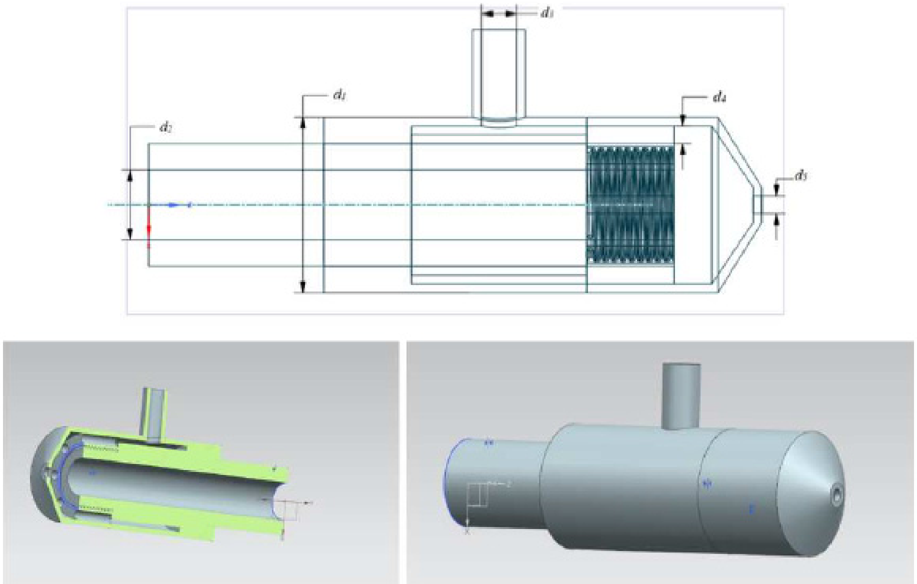
Figure 9. Nozzle for CWF spraying with internal mixing [21]. CWP—Coal–Water Paste.

There are 4–6 symmetrical holes with a diameter of 4 mm along the circumference of each nozzle, through which the spraying air with axial injection angles of 45° is blown in and mixed with the CWF. This type of injector differs significantly in the diameter of the fuel channel. The disadvantage of this type of CWF spraying device can be called "the organization of mixing of the spraying agent and the slurry". In addition, the narrowing of the fuel channel (type B) can also be the disadvantage, which is a significant hydraulic resistance for viscous CWF. This can also adversely affect the spraying process. Clogging of the fuel channel and the mixing chamber at their specified sizes is almost impossible.

The nozzle with internal mixing of liquid and spraying agent in [22] provides formation of a fine jet. The nozzle was made of metal. This type of CWF spraying device (Figure 10) has an internal mixing chamber of fuel and air. The disadvantage of this type of nozzle is the high probability of clogging of the mixing chamber.

The pressure of the fuel and the spraying agent should be carefully monitored in order to prevent clogging in this type of injector [22]. Mixing of the spraying agent and the slurry inside the nozzle may adversely affect the spraying process. Blockages of the mixing chamber are possible. The issue of the durability of the nozzle remains unresolved. Erosion wear is not excluded. It is necessary to carefully monitor the pressure of the fuel and the spraying agent to prevent clogging in this type of injectors. The perpendicular feed of the SA can affect the geometry of the jet—displacement and asymmetry. The disadvantage is the narrowing of the fuel–air channel in the nozzle, which is a significant hydraulic resistance for viscous CWF. The average size of CWF drops in the jet after spraying is 250 microns assuming careful pressure control of the CWF and SA.

A review of the CWF spraying devices presented in the literature showed their certain similarity. In particular, researchers have used a rather small diameter of the fuel channel in the designs of their injectors, for example [7,11,17–20,22], and in some cases, even its narrowing. The practical operation of such injectors with a small diameter of the fuel channel will lead to rapid clogging of the nozzle, for example, with large coal particles (especially in cases of burning the filter cake), mechanical impurities, and fuel agglomerates. Mechanical cleaning of the channel or replacement of the nozzle with a new one will be required as a result. Such actions will certainly have a negative impact on the combustion mode of CWF and the boiler as a whole. A distinctive feature of the nozzle design in [21] is certainly a fairly wide fuel channel (more than 20 mm). In practice, clogging of such a nozzle is unlikely. A similar solution could be found in the nozzle design in [17]. In combination with the wear-resistant material of the nozzle, it could work smoothly and reliably for a long time. The ability to adjust the size of the CWF droplets is presented by the design of the nozzles in [7,18]. This is also very important in cases of using CWF of different viscosities. At the same time, it is worth noting that the spraying characteristics can be changed using the values of the CWF and SA spraying parameters [23,24]. Thus, complicating the design of the nozzle is not entirely effective from the point of view of its operation.



Parameter	Value
Outer diameter of the nozzle d_1, mm	20
Diameter of the fuel inlet channel d_2, mm	8
Diameter of the air inlet channel d_3, mm	4
Height of the air supply channel to the mixing chamber d_4, mm	2
Diameter of the nozzle outlet d_5, mm	3

Figure 10. CWF spraying nozzle [22].

3. Generalization of Information

The review of modern CWF spraying devices allows for an evaluation of their efficiency in terms of several criteria: simplicity of design (A), predisposition to clogging of the fuel channel (B), durability in terms of erosion wear of the nozzle channel (C), dispersion of the jet—the average size of CWF droplets in the jet (D). Table 1 shows the indicators of the analyzed CWF spraying devices according to the above criteria.

The analysis of the considered coal–water fuel nozzles [7,11,17–22] allows the conclusion that they all meet the requirement—the formation of a fine-dispersed CWF jet. Simple design and durability from the point of view of erosive wear of the nozzle channel is typical of the nozzle in [17]. A sufficiently fine-dispersed jet is formed during its operation, but the presence of large CWF drops is not excluded. The pressure of the CWF and SA is approximately equal due to the mixing inside the nozzle which leads to fine atomization of the fuel. However, the instability of the spraying characteristics is typical for injectors with internal mixing. As a result, large drops of fuel are present in the jet during their operation. The fuel channel is possible to be clogged with large coal particles or fuel agglomerates (with characteristic size of more than 1 mm) when spraying viscous CWF. Thus, the CWF nozzle in [17] meets criteria A and C.

Table 1. Indicators of CWF injectors.

No.	Nozzle Type	Design Features	The Possibility of Clogging of the Fuel Channel (Yes "+"/No "−")	Durability in Terms of Erosive Wear of the Nozzle Channel (Yes "+"/No "−")	Size of CWF Droplets after Spraying		Source
					Small (Less Than 200 Microns)	Large (More Than 200 Microns)	
1	With internal mixing of CWF and SA	Simple	Yes	Yes	Yes	Yes	[17]
2	With external mixing of CWF and SA	Complicated	Yes	No	Yes	No	[7]
3	With external mixing of CWF and SA	Complicated	Yes	No	Yes	No	[18]
4	Two-liquid with internal mixing of CWF and SA	Complicated	Yes	No	Yes	Yes	[19]
5	With external mixing of CWF and SA	Simple	Yes	No	Yes	No	[20]
6	With internal mixing of CWF and SA	Simple	Yes	No	Yes	No	[11]
7	With internal mixing of CWF and SA	Simple	No	No	Yes	Yes	[21]
8	With internal mixing of CWF and SA	Complicated	Yes	No	Yes	Yes	[22]

The spraying devices in [7,18] exclude the presence of large fuel droplets in the jet. First of all, this happens due to the high consumption of SA. A large amount of SA at high speed breaks the CWF jet and large drops occur even at a considerable distance from the nozzle. The fuel flow rate for such injectors is insignificant, for example, no more than 1000 kg/h. At the same time, the injectors in [7,18] have a rather complex design and a small diameter of the fuel channel. The latter can cause clogging with large coal particles or fuel agglomerates. The geometric characteristics of the fuel channel may cause the relatively short operation of the nozzle in combination with the erosion wear. Thus, the CWF spraying devices in [7,18] correspond only to criterion D.

The spraying device with the internal mixing of CWF and SA in [19] has a rather complex design, while geometrically the characteristics of the nozzle indicate that it is not protected against clogging of the fuel channel (diameter of the fuel channel is no more than 4 mm) for the same reasons characteristic of the injectors in [7,17,18], and erosion wear. Large fuel droplets are present in the jet despite the presence of small-sized CWF droplets. A well-homogenized coal–water fuel prepared with very fine coal is necessary when using such a nozzle. Thus, the CWF spraying device in [19] does not meet any of the criteria.

Injectors with external [20] and internal [11] mixing of CWF and SA have a fairly simple design (there is no complex geometry of the nozzle channel). At the same time, they also allow for the exclusion of large drops of CWF in the jet. However, the relatively small diameter of the fuel channel may also cause its clogging and erosion wear. The issue of fuel flow rate remains unsolved. Thus, the coal–water fuel nozzles in [11,20] meet criteria A and D.

The positive qualities of the nozzle in [21] certainly include a large diameter of the nozzle channel. The clogging of the fuel channel is possible to be eliminated due to this. The high probability of erosion wear remains. At the same time, this nozzle has a fairly simple design, which is very important for practical application. A sufficiently fine jet is formed due to the internal mixing of CWF and SA. This type of CWF nozzle is characterized by instability of the spraying characteristics, as in the case of [17]. As a result, large drops of fuel are present in the jet during their operation. Considering the above, the nozzle for CWF spraying in [21] meets criteria A and B.

The nozzle for CWF spraying in [22] is of the internal mixing type. The complex design and small diameter of the fuel channel may cause clogging of the fuel channel for reasons typical of the injectors in [7,17,18] and erosion wear. The pressure of fuel and SA should be controlled when using such spraying devices. In the case of even a small excess of SA pressure over CWF pressure, the spraying process will stop, which may become an additional factor in clogging the fuel channel. Large fuel droplets are present in the jet despite the presence of the small-sized ones. Well-homogenized coal–water fuel is necessary to use such a nozzle in practice. Thus, the CWF spraying device in [22] does not meet any of the criteria.

As a result, the characteristics and design solutions of injectors [7,11,17,18,20,21] are possible to be considered out of the eight [7,11,17–22] studied CWF spraying devices from the point of view of operational efficiency. Each of them meets one or two of the criteria:

- simple design [17,20,21];
- no predisposition to clogging of the fuel channel [21];
- durability in terms of erosive wear of the nozzle channel [17];
- fine-dispersed jet [7,11,18,20].

At the same time, the nozzle design of the injectors in [11,17,21] should be separately noted. These are injectors with internal mixing of CWF and SA. They do not have a characteristic chamber inside the nozzle for mixing fuel and SA as in the spraying devices in [19,22]. This greatly simplifies the spraying process, especially with a sufficiently large diameter of the nozzle channel, similar to [21]. This excludes the possibility of their clogging with large coal particles or fuel agglomerates. Thus, the principle of CWF and SA mixing in these injectors [11,17,21] should be considered an intermediate (middle) option between the devices with internal and external mixing. The most uniform mixing of CWF and SA is assumed to be in such spraying devices. As a result, an extremely homogenized jet will be formed at the outlet of the nozzle, the characteristics of which will be stable in comparison with injectors with an internal mixing of CWF and SA. Thus, the designs of injectors [11,17,21] with quasi-internal mixing of fuel and SA can be concluded to be the most attractive from the point of view of the mixing efficiency and design. The rapid erosion wear due to the high velocity of the CWF droplets and individual coal particles is possible to be eliminated in such nozzles by using various refractory alloys or ceramics, as in [17].

Analysis of the injectors with external mixing in [7,18,20] showed that a sufficiently fine jet can be achieved using such a mixture of fuel and SA—the average size of CWF droplets in the jet after spraying is less than 100 microns. But at the same time, the complex design and high predisposition to clogging and wear of the fuel channel make them ineffective in terms of durability. The nozzle in [20] can be distinguished from these three spraying devices. The effect of erosion wear of the fuel channel can be reduced due to the possibility of its cooling during operation. The absence of a narrowing of the nozzle and an increase in its diameter would cause the most efficient use of this spraying device in practice.

Thus, solutions implemented in the injectors in [11,17,21] should be provided in the design in order for the CWF spraying device with an internal mixing of fuel and SA to meet the criteria A, B, C, and D. The nozzle in [20] is the most preferred of the considered spraying devices with external mixing.

The devices for spraying coal–water fuels considered in this article can be widely used both in the energy sector and in the chemical industry. For example, the nozzle in [17] has shown a good efficiency for operation in the CWF gasifier. Increase in the turbulence degree of the jet during the spraying process increases the spraying efficiency. The coal–water fuel nozzle in [7] can be effectively used in industrial power boilers with a capacity of 5 MW. The nozzle in [21] (Type A) is better suited for preventing the formation of agglomerates.

The review of modern CWF spraying devices made it possible to establish the most efficient design solutions for creating coal–water fuel nozzles that meet the most important criteria for their operation. Creation of an efficient device for spraying coal–water fuel is possible, if these criteria are considered. The presented analysis will be useful for researchers involved in the study of CWF spraying processes and the creation of new CWF spraying devices, as well as designers involved in the creation of coal–water fuel injectors or the transfer of existing boilers to CWF. It will allow a prognostic analysis to be given of the efficiency of coal–water fuel injectors.

4. Conclusions

An analysis of the known variants of coal–water fuel nozzles presented in modern literature was performed. The influence of their design on the principle and conditions of operation, characteristics of spraying (the average size of droplets of coal–water fuel), and advantages and disadvantages were shown. The nozzles for spraying coal–water fuel with quasi-internal mixing of fuel and spraying agent were established as the most attractive from the point of view of efficiency. At the same time, the possibility of forming a fine-dispersed jet remains. Their rapid erosion wear and clogging with large coal particles or agglomerates of viscous coal–water fuel are excluded, if refractory or ceramic materials are used and the device has a large diameter of fuel channel. Cooling of the nozzle with external mixing of fuel and spraying agent during its operation will also reduce the rate of erosion wear. The narrowing of the fuel channel is an undesirable solution when creating a coal–water fuel nozzle. This can cause the failure of the nozzle in practice. The presented analysis will be useful for researchers studying the processes of spraying coal–water fuel, including the ones based on waste from coal processing enterprises. In addition, it will be useful to designers engaged in the creation of coal–water fuel injectors or the transfer of existing boilers to coal–water fuel.

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