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The concept of a new aerodynamic multiphase reactor with catalyst injection for a pulverized coal boiler

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Abstract
This paper presents the development of a multiphase aerodynamic reactor designed for multi-component systems, focusing on precise catalyst dosing in the combustion chamber. The study aims to underscore the significance of this work by emphasizing the critical role of optimized operational conditions in enhancing the transportation of the modifier for combustion processes. Through comprehensive numerical simulations and experimental tests, this research explores the impact of parameters such as flow rates of the dosed substance and air, dosing nozzle outlet diameter, and conduit diameter on the flow rate and trajectory of the transported modifier. The findings highlight the importance of a minimum droplet diameter of 30 μm, preferably 50 μm, for proper delivery to the combustion chamber. This study not only identifies key differences between analyzed structures but also emphasizes the crucial role of these operational parameters in achieving optimal conditions for modifier transport.

Keywords
multiphase flows, pulverized coal boiler, aerodynamic multiphase reactor

1. INTRODUCTION

The combustion of pulverized coal is the most commonly used technology in the world for generating energy on an industrial scale (Hurskainen and Vainikka, 2016). In turn, the most widely used coal technology for power generation is the Pulverized Coal boiler (PC). A typical pulverized coal boiler consists of a furnace, which is the lower part of the boiler where the burners and the combustion system are installed, and where combustion takes place. Such a boiler also has a convection part, in which convection heat exchangers are located. The walls of the boiler usually function as the boiler's evaporator (Agraniotis et al., 2017). Within the convective part, the heat exchanger sections are arranged in a specific sequence along the flue gas pathway, and have an arrangement that is typical for lignite-fired boilers.

The used modifiers allow for the improvement of the effectiveness, efficiency and speed of the combustion process by, among others, burning heavier hydrocarbon fractions that are generated during the process. This results in a reduction of the loss of incomplete combustion. Catalysts also influence the level of pollutant emissions into the atmosphere (Guziałowska-Tic and Tic, 2012). The management of coal waste and the reduction of harmful substances generated during coal combustion are some of the main directions of current activities, which result from having to comply with standards related to atmospheric protection (Olszewski et al., 2012). Fuel additives enable the load related to coal combustion to be reduced, and therefore the amount of fuel that is needed to produce a unit amount of energy to also be lowered (Bielecki et al., 2021). The transport of the catalyst through the dust duct to the fuel combustion chamber is a complex issue. It is necessary to take into account many variables that affect the dosing process. The most important factors include: the parameters of the stream that transports the catalyst, the assumed amount and form of the catalyst, the catalyst concentration, or the geometry of the system. In order for the catalyst to perform its function, it is often dosed in the form of a suspension. Solid particles are suspended in a highly viscous liquid solution, and in this form, using a specially adapted nozzle, they are delivered to the duct (Blondeau et al., 2016). The high viscosity of the suspension results in specific requirements for dispensing nozzles. It should be remembered that it is not only the type or form of the catalyst that is important, but also the place of injection and the injection system itself.

Another way to optimize and improve the efficiency of the combustion process in boilers is to analyze the method of supplying the catalyst to the system. The choice of the catalyst delivery method depends on the dust parameters and the characteristics of the combustion process itself (Bielecki 2023). In order for the atomized catalyst system to be properly used, it is necessary to obtain a specific aerosol. To make this possible, proper homogenization of the system must be ensured. Apart from the issue of the size of a droplet and the shape of the atomized stream, the selection of the appropriate gas flow rate is also an obligatory condition. The selection should be correlated with the amount of the supplied catalyst and the obtained atomization effect. If a fluid is sprayed into another fluid or gas, mixing will occur naturally over time. However, the finer the spray, and the more evenly distributed it is, the quicker this mixing will occur. In a moving fluid stream, complete mixing may be required by a certain point further downstream. This effectively places a time limit on how and by when the injected fluid needs to be fully disseminated (SNP, 2022). In recent years, the use of aerodynamic multiphase reactors for generating droplets has become increasingly common (Guo et al., 2021; Naterer, 2002). For example, a so-called swirling vortex flow reactor has been proposed by Guo et al. (2021) as a high-shear mixer used for synthesis of nanoparticles, due to its unique hydrodynamic characteristics of mixing and mass transfer. Conventional reactor-mixer designs are limited by the size of generated droplets, the maximum viscosity of the sprayed substance, and the intensity of stream.

The purpose of this work was to design, manufacture and test an aerodynamic multiphase reactor for feeding the catalyst in a liquid state to the dust duct. The main purpose of the research was to develop a system that would allow for the precise dosing of the catalyst to the combustion chamber. The studies also aimed to analyze the effectiveness of the developed concept by performing numerical calculations and experimental tests. The result of the conducted simulations and tests is a multiphase aerodynamic reactor for multi-component systems. In this reactor, thanks to the kinetic energy of the gas, the spraying of the supplied substrates or substrate, as well as the mixing and production of a suspension, take place. Moreover, a reaction (if possible) occurs, with the finished product then being collected. Such a product can be used in the pharmaceutical, food and construction industries, in chemical engineering and technology, and also for environmental protection. In the authors' research, the reactor was used to atomize a highly viscous solution that had catalyst particles, and then to deliver it – as droplets – to a dust duct, in which air that carries coal dust flows.

2. MATERIALS AND METHODS

2.1. FLOEFD program

The FLOEFD program solves Navier-Stokes equations, which are formulations of mass, momentum and the law of the conservation of energy for fluid flows (Simcenter, 2022). These equations are supplemented with equations of state, which define the nature of the fluid, as well as the empirical relationships of the fluid's density, viscosity and thermal conductivity with regards to temperature. Non-Newtonian inelastic fluids are modelled in the FLOEFD program by introducing the dependence between their dynamic viscosity and shear rate and temperature. In turn, compressible fluids are modeled by introducing the dependence between their density and pressure. A particular problem is specified by defining its geometry, as well as its boundary and initial conditions.

The FLOEFD commercial program by Siemens is able to predict both laminar and turbulent flows (Simcenter, 2022). However, the program was developed primarily for the simulation of turbulent flows. Most fluid flows that are encountered in engineering practice, including those in dust ducts and aerodynamic multiphase reactors, are turbulent in their nature. To calculate turbulent flows, Navier-Stokes equations are used, in which the effects of the turbulence of the flow on its parameters are averaged. FLOEFD uses transport equations for the kinetic energy of turbulence and its rate of dissipation, the so-called k–ε model. It also uses a single set of equations to describe both laminar and turbulent flows. Flows in models that have movable walls (without changing the model's geometry) are calculated according to appropriate boundary conditions. Flows in models with rotating parts are calculated in coordinate systems that are attached to the models of rotating parts, i.e. rotating with them. The stationary parts of models must be axially symmetrical with regards to the axis of rotation. Flows in models with rotating parts are computed in coordinate systems attached to the models rotating parts, i.e. rotating with them, so the models' stationary parts must be axisymmetric with respect to the rotation axis (Simcenter, 2022). Figure 1 shows the mesh that was generated for an aerodynamic multiphase reactor. FLOEFD computational approach is based on locally refined rectangular mesh near geometry boundaries (rectangular polyhedron hybrid). Polyhedrons near the boundary allow to treat the geometry in a highly accurate way.

The boundary conditions for the analyzed gas process were determined based on actual data that occurs in industrial processes (Bielecki 2023). The gas mass flow rate at the inlet was assumed to be 0.0005 kg/s, and its density 1.2 kg/m^3. The gas pressure was set at 3 bar and the gas temperature was 20 °C. The sprayed liquid was isopropyl alcohol, the mass flow rate of which was $3.275\cdot10^{-5}$ kg/s. Using isopropanol as a catalyst for burning coal dust can have several rational reasons. However, it is important to note that the choice of a specific catalyst depends on the particular requirements and conditions of the process. Here are a few reasons why isopropanol might be selected for this purpose: isopropanol is highly flammable, making it an efficient choice for initiating and sustaining combustion (its low ignition temperature ensures rapid ignition, which is essential for efficient burning of coal dust particles); miscibility with water (isopropanol is miscible with water, which can be advantageous in coal dust applications where water is used as a suppressant); compared to some other catalysts, isopropanol has relatively low toxicity and is considered to have a lower environmental impact;

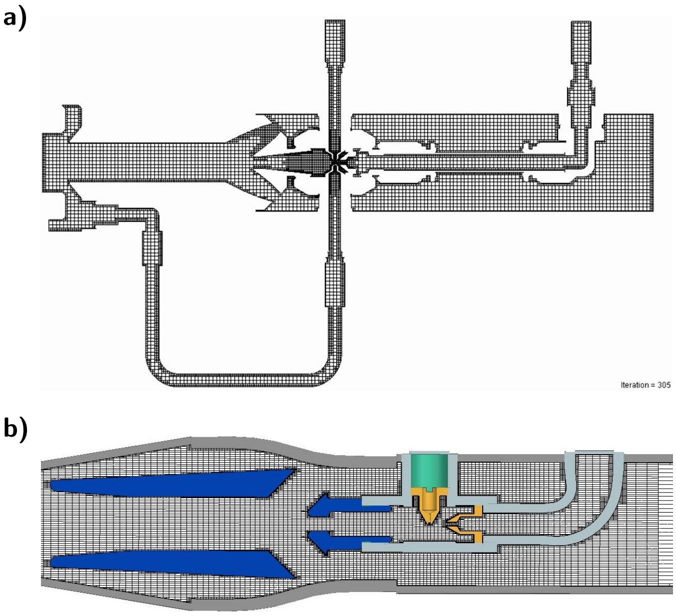

Figure 1. Mesh generated in the FLOEFD program for an aerodynamic multiphase reactor: a) with an element to capture large droplets; b) the modified structure.

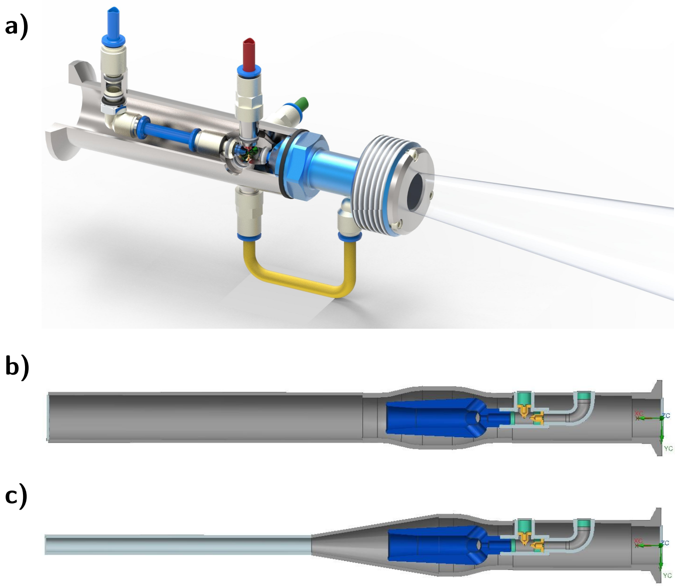

Figure 2. The designed aerodynamic multiphase reactor: a) primary construction, b) modified construction, c) final construction.

isopropanol can be controlled effectively, allowing for precise dosing; isopropanol is widely available and relatively inexpensive, which can be a significant factor in large-scale industrial applications and compatibility with coal dust.

2.2. The results

The reactor design, illustrated in Figure 2a and described by Bielecki et al. (2022b), incorporates pneumatic atomization of substances supplied through internal nozzles. These nozzles are carefully selected to match the specific substance being sprayed, ensuring efficient atomization. Positioned along the axis of the gas nozzle outlet, the diameter of the gas nozzle is chosen based on the desired droplet diameter and the required velocity for effective atomization.

During the experimental phase, a modified version of the reactor was developed, depicted in Figure 2b, eliminating the element designed for capturing large droplets. This modification was necessitated by the ineffective performance of the large droplet-capturing element, prompting its removal from the design.

Subsequent to preliminary experiments conducted on an industrial-scale setup, a further adjustment was made in the final design, as shown in Figure 2c. The outlet conduit diameter was reduced, a decision informed by the results of the industrial-scale trials. This reduction aimed to increase droplet velocity, consequently extending the distance over which the modifier could be delivered into the dust duct.

These modifications were crucial in refining the reactor functionality. The removal of the large droplet capturing element, proven ineffective in practical applications, streamlined the design for improved efficiency. Additionally, the reduction in the cross-sectional area of the reactor outlet not only increased droplet velocity but also enhanced the precision and effectiveness of the modifier delivery system, ensuring optimal performance in transporting the modifying substance into the dust duct.

The inner nozzles (Figure 3) are single hole jet nozzles. The diameter of the nozzle outlet ranges from 0.1 to 2 mm, and depends on the type and size of particles, and the substrate feed rate. In the tested reactor, nozzles with a diameter of 0.5 mm and 1 mm (due to the size of the catalyst particles) were used, and the amount of the substrate was regulated and controlled from 200 mL/h to 2000 mL/h. The length of the reactor is 192 mm and the connection diameter G is 1 and 1/2 inch.

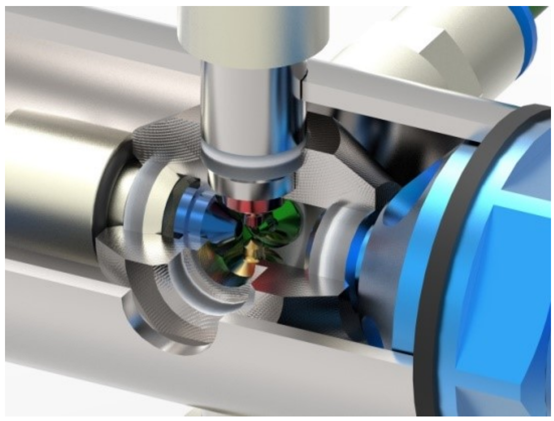

Figure 3. The detailed visualization of the liquid supply nozzles in the aerodynamic multiphase reactor.

The motivation to conduct granulometric tests of the catalyst was the significant difference that was observed between the properties provided by reagent manufacturers. The properties were recorded during homogenization tests of catalyst suspensions in a highly viscous liquid. The preparation of samples for testing required the use of an appropriate dispersant (it was decided to use a wet dispersion; demineralized water was used for this purpose). A very interesting catalyst is Raney Nickel (Maranda et al., 2016). It belongs to sponge catalysts, which enable the hydrogenation reaction to occur. However, one of the main problems associated with its use is its spontaneous ignition when exposed to air. Its auto-ignition temperature is only 87 °C. The volume-surface diameter of catalyst particles most often ranges from 1 to 35 μm (Bielecki, 2023).

The numerical calculations of the aerodynamic multi-phase reactor were made for the real geometry of the apparatus, which was subjected to experimental tests. As a result, such apparatus was implemented on an industrial-scale stand on the OP-430 boiler No. 15 in the Siekierki CHP plant. On an industrial scale, the gas flow rate through the dust duct is 5000 m^3N/h (at a speed of 26.8 m/s), the amount of dust fed is 1.2 t/h, and its grain size is from 20 to 200 μm. Exemplary results of the numerical analysis, which are shown in Figures 4 and 5, present the determined trajectories of the generated droplets, and their velocity, during a given air flow rate.

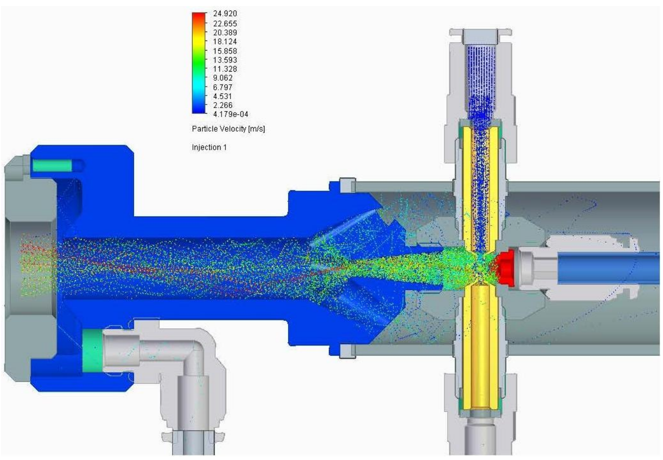

Figure 4. Movement trajectories of the droplets and their velocities for a reactor with an element for capturing large droplets.

On the basis of the obtained data regarding the droplet trajectory, it was found that smaller droplets occurred in the upper part of the dust duct, with larger ones being found in the lower part. In industrial practice, this means that it is required to generate the catalyst-containing liquid droplets with diameters between 30 and 50 μm (> 30 μm). Such droplets will reach the end of the dust duct, and effectively transfer the catalyst. Analysis of the obtained results can provide information regarding the velocities and droplet sizes that guarantee the droplets to reach the end of the dust duct. A very important component of the performed simulations is

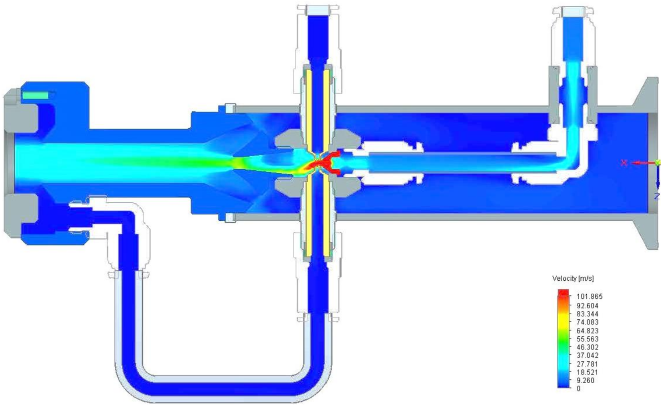

Figure 5. The designed aerodynamic multiphase reactor with an element for capturing large droplets, and also the velocity fields of the fluid flow.

also the droplet evaporation process. Transporting the catalyst through a dust duct to the fuel combustion chamber is a multi-threaded issue. It is necessary to take into account many variables that influence the dosing process (e.g. pressures, flow rates, droplet diameters, geometry of reactor, injection site). The most important factors include: the parameters of the stream that transports the catalyst, the assumed amount and form of the catalyst, its concentration, and the geometry of the system. In order for the catalyst to fulfill its function, it is often dosed in the form of a suspension. Solid particles are suspended in a solution of a highly viscous liquid, and in this form they are delivered to the conduit using a specially adapted nozzle (Blondeau et al., 2016). The high viscosity of the suspension results in specific requirements for the nozzles. It should be remembered that it is not only the type or form of the catalyst that is important. The place of injection and the injection system itself are also crucial parameters. In order for the sprayed system with a catalyst to be properly used, it is necessary to obtain a specific aerosol. To enable this, the proper homogenization of the system must be ensured. If an appropriate droplet size containing isopropanol and catalyst particles is obtained, the droplets of the modifier can be delivered to the pyrolysis zone, i.e. to the central part of the dust duct and the burner (taking into account the evaporation process). The catalyst efficiency significantly depends on the way its particles are delivered to the combustion zone. For optimal performance, the catalyst particles must be coated with isopropanol before reaching the combustion zone. While the catalyst still functions without isopropanol, its efficiency is markedly lower compared to when it is present in liquid form, emphasizing the importance of the isopropanol coating for maximizing its effectiveness.

Droplet evaporation was compared for the same diameters and for two different air inlet velocities, i.e. 30 and 120 m/s. The obtained results show which droplets will not evaporate before reaching the end of the dust duct. The modeling of the phenomena described above allows for the inlet parameters of the applied modifier to be changed, which is extremely important with regards to the adaptation of such a modifier to various types of boilers. It is also significant regarding the selection of the appropriate flow velocities, droplet size range, and inclination angle of the multiphase reactor that injects the modifier.

Figure 6 shows the simulation results of the isopropanol spraying process in two reactors, i.e. in the reactor with a modified structure and in the reactor with the final structure, which was used on an industrial scale on the OP-430 boiler No. 15 in the Siekierki CHP plant. The analysis of the obtained images shows that in the case of the final structure, an axial flow of isopropanol and its more even distribution in the air stream were achieved. The problem appears at the outlet from the nozzle for liquid. In the case of the modified design, the gas is unable to break up the isopropanol stream, and therefore the stream hits the opposite wall of the reactor. Spraying is then ineffective. The analysis of subsequent data concerning the distribution of isopropanol in the stream (Fig. 7) confirms that the final design allows for the undisturbed delivery of isopropanol to the reactor's outlet in order for it to be introduced into the dust duct. In the case of the modified design, the results of the simulations suggest that there are disruptions during the spraying of isopropanol at the outlet from the nozzle for liquid, and also disruptions to the flow inside the reactor. Due to this, some of the isopropanol may remain unsprayed. Such isopropanol does not act as a modifier, because droplets with a diameter of 30–50 μm were not produced, and therefore it was impossible to deliver such a modifier to the interior of the dust duct.

a)

b)

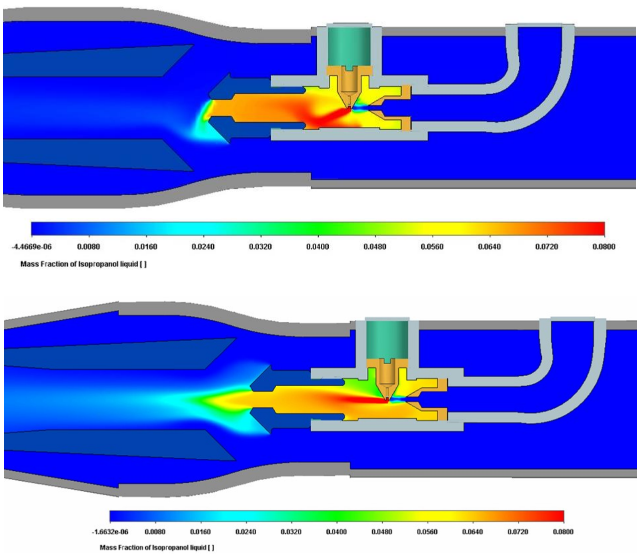

Figure 6. Comparison of the mass fraction of isopropanol in the stream for: a) the modified design, b) the final design.

When developing new designs, it is important to remember that droplets with appropriate diameters and atomization spectrums must be generated when adding a minimal amount of additional air. Moreover, the construction of an atomization device should be simplified. At a gas flow velocity of 20 m/s

a)

b)

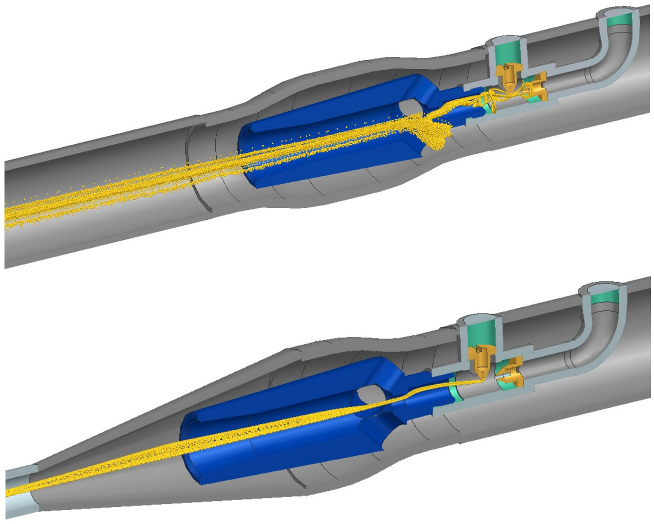

Figure 7. Comparison of the distribution of isopropanol in the stream in the case of: a) the modified design, b) the final design.

(real flow speed of the mixture of air and coal dust in the dust duct into which the modifier is introduced), the minimum droplet lifetime is 0.05 s, and the evaporation time of a 30 μm diameter droplet is approximately 1.4 s at 293 K, 0.1 s at 308 K, 0.087 s at 313 K, and 0.023 s at 373 K. When taking into consideration the temperature changes along the dust duct leading to the boiler, the droplets should be capable of covering the necessary distance in the aerosol (Bielecki et al., 2021; Bielecki et al., 2022a). For practical reasons, it is advisable to generate droplets with a larger diameter, such as 50 μm. This is due to the fact that the flow conditions and dust duct length may affect both the droplet diameter and its lifetime, which is related to smaller droplets evaporating, coalescing or undergoing other transformations (Ochowiak et al., 2022; Bielecki, 2023).

The designed aerodynamic multiphase reactor is a crucial component of the system that feeds the catalyst to the boiler in which coal dust is burned. It utilizes a two-phase atomizing nozzle in order to produce controlled droplets of a catalyst suspension. The schematic diagram of the nozzle is shown in Figure 2, and its operation is described in detail by [5]Bielecki et al. (2022b). The size of the generated droplets is adjustable based on process parameters and the viscosity of the catalyst suspension. The liquid supply nozzle was angled at 90° in relation to the gas nozzle, with the wall on the opposite side of the central conduit being cut at an angle of 30°. It is not only important to generate droplets with appropriate diameters, but also to deliver the aerosol deep into the dust ducts. Moreover, efforts are made to minimize the introduction of additional air into the boiler (pneumatic spraying requires the atomizing and transporting of air, which if supplied in excessive amounts may affect the combustion process of coal dust in a pulverized coal boiler) (Ochowiak et al., 2023), and also to create a simple, cost-effective design.

3. CONCLUSIONS

The combustion processes of solid fuels are extremely complex operations that are difficult to optimize, but they are the main source of energy. In order to meet energy policy guidelines, such as the minimizing of emissions of harmful substances, low energy prices, and the ensuring of the security of supply, the authors focused on the use of flow control and atomization methods of multiphase fluids in order to optimize combustion processes. The modifier is delivered via pneumatic transport and it is a solid catalyst in the form of a suspension. The authors analyzed complex phenomena related to multiphase flows and determined the requirements regarding the form of the catalyst and the method of its delivery. This work aimed to introduce a control system for the process of dosing a modifier to the pyrolysis zone in a large dust boiler. As a result of the simulation of the real model, a very wide spectrum of results was obtained. Their analysis allowed for the formulation of the following conclusions:

- An aerodynamic multiphase reactor for generating droplets of appropriate sizes was designed, constructed and subjected to numerical and experimental studies.
- The desired droplet size was determined, i.e. the minimum droplet diameter (critical) for the given operating parameters of the dust duct. As a result of the conducted laboratory tests, previous CFD simulation predictions regarding the size of droplets were confirmed. It was shown that in order to bring the catalyst to the system, droplets with a diameter of at least 30 µm, and preferably of about 50 µm, should be generated.
- The research also showed that by properly controlling the flow parameters, it is possible to obtain the optimal, i.e. desired, size of droplets. This is of great importance, because the real objects on which the solution is to be ultimately applied have different geometries and operating parameters.

Thanks to the use of the proposed design of the aerodynamic multi-phase reactor, it is possible to improve the dynamics of boiler operation, and thus increase the stability of the flame and the degree of fuel burnout. The designed system, which allows for the precise dosing of the catalyst that improves the combustion parameters of solid fuels in the boiler, was verified on a real object.

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