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GAS FLOW EXPERIMENTAL RESEARCH IN A NEWLY DEVELOPED CENTRIFUGAL-ELECTROSTATIC PRECIPITATOR

Aleksandras CHLEBNIKOVAS*, Artūras KILIKEVIČIUS

Research Institute of Mechanical Science, Faculty of Mechanics, Vilnius Gediminas Technical University, J. Basanavičiaus g. 28, Vilnius, Lithuania

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Abstract. In this paper, one of the most common environmental pollution problems is investigated – air pollution with particulate matter, and the object of study is a newly created device of a hybrid type of centrifugal and electrostatic cleaning principle. These technologies are increasingly being introduced in a sequential order on past lines, but the unified model has not yet been used. The set of cleaning methods in this model allows to clean the gas flow from fine and ultra-fine particulate matter. By adopting an improved section to reduce flow turbulence, the gas flow rate has been equalized to an average of 17% to 4.6% before the inlet. Also, the designed system achieved a theoretically optimal gas flow rate of 2.2 m/s for subsequent particulate matter injection into the system of several cleaning stages. The flow before and after the purification device in the range of 1.2–2.4 m/s was also studied. The results of this work were obtained in an experimental way to analyze the dynamics of the flow in the system of the apparatus for cleaning the flow in the range from 50 to 200 m^3/h, under various operating modes of this technology. The direct current in the electrostatic filter reached no more than 10 kV. The maximum gas yield is equal to 0.03 m^3/s at inlet and outlet gas flow rate of 2.4 m/s and 0.77 m/s respectively, and pressure drop is up to 51 Pa.

Keywords: gas flow, ultra-fine particulate matter, precipitator, centrifugal, electrostatic.

Introduction

Decontamination of industrial gas flow is particularly important in the chain of technological processes, in the production of various products, in raw material processing lines and in other anthropogenic pollution activities. On the one hand, this process creates additional costs, but on the other hand, it is a process aimed at reducing emissions into the environment, which means reducing the pollution taxes paid, as well as controlling emissions, allows to achieve lower consumption of raw materials, and in individual cases to avoid or reduce the formation of waste volumes, and ultimately, this constitutes environmental well-being towards the green course (Araujo et al., 2009; de Araujo et al., 2009; Talaei et al., 2020; Tikadar et al., 2021; J. Zeng et al., 2022). There is a wide variety of air cleaning devices available in the market for industry and research testing, some of which are applied to the selective removal of particulate matter from the gas stream (Agbadede et al., 2015; X. Zeng et al., 2018). The most common are sleeve (cassette of various modifications), electrostatic filters and mechanical separators (Ghasemzadeh et al., 2020; Ji et al., 2021; Rashid, 2021). The operation of the first mentioned is based on pure filtration through fibrous natural or synthetic material. The second – the principle of operation is the deposition of electrostatically charged particles in the flow on the oppositely charged elements-electrodes. Mechanical separators are used as primary precipitators, and their more complex new generation designs are used to settle finely dispersed particulate matter under the action of centrifugal forces and filtration between swirling flows in filter channels. The main disadvantages of the applied technologies are their insufficient cleaning efficiency in the deposition of fine and ultra-fine particulate matter, as well as their rather limited application possibilities considering the operating conditions: concentration of particulate matter, range of optimal air flow rate, physical characteristics of the gas flow, including high temperature, relative humidity/vapor content, static pressure created by the flow; complex operation requiring special training of employees, high operating costs for energy/permanent costs for the replaceable filters used (Chia et al., 2021).

Increasingly, cleaning devices play a secondary role – they are used as an additional device in the process line to protect the apparatus installed in the system from contamination, erosion and / or corrosion after this

* Corresponding author. E-mail: *aleksandras.chlebnikovas@vilniustech.lt*

cleaning by removing harmful ash, soot and other mechanical contaminants (Chakrovorty et al., 2021; Vasiliu et al., 2020). In other cases, treatment devices can be applied as distributors or selectors (Olenius et al., 2021). In this way, the particulate matter of all fractions present in the polluted flow are separated in different stages in the cleaning device, each time the deposited particles are directed to the corresponding hoppers-storage (Z. Li et al., 2021). In this way, it is possible not only to clean the polluted gas flow from the pollutants contained in it, but also to later use the collected particulate matter, which are grouped according to fractions or depending on their density, and continue to purposefully use them as secondary raw materials (W. Sun et al., 2020; Yu et al., 2020).

Applied electrostatic filters differ little in their geometry and application, so their weakness remains – relatively quick contamination of the ionization electrode due to particle adhesion (Chen et al., 2021). At the same time, with a high concentration of particulate matter and a relatively small surface area of the deposition electrode, a sharp drop in efficiency occurs, which continues to decrease until regeneration is performed.

Multi-channel cyclones, which are more and more frequently applied and studied, capable of settling finely dispersed particulate matter, lack a primary cleaning stage, in which the particles of the largest fractions would be removed and they would not disturb the entire cleaning process.

According to all the presented arguments, the current problem is clearly defined – a multi-stage treatment device or system is required, which is able to perform the function of primary rough cleaning, then the flow must be immediately directed to the next stage – the deposition of finely dispersed and finally ultra-fine particulate matter. As a rule, these processes must be coordinated with each other, and also the entire technology must meet the requirements for cleaning industrial gases, i.e., be resistant to mechanical, temperature, aerodynamic and other significant effects, and the efficiency must be sufficient to avoid additional filters for clean cleaning.

Studies of aerodynamic parameters are important from a technological point of view, when studies of changes in gas flow in characteristic sections of the cleaning system are observed, the optimal performance of the cleaned air or the rate of the supplied flow is determined, pressure losses are observed, the characteristic of the electric field is selected according to the design of the device and the physical properties of the deposited particulate matter. and the elements that create it (S. Li et al., 2022; Y. Li et al., 2022; P. Sun et al., 2022; Yan, 2022; Zheng & Ni, 2022). When applying individual devices, theoretical design parameters are adhered to, at which the standard device achieves maximum efficiency. For a conventional hollow cyclone, this rate is 3–5 m/s (Babaoğlu et al., 2022; Liu et al., 2022; Vaziri Naeen Nejad & Kheradmand, 2022; Yohana et al., 2022), for a multi-channel cyclone is 7–12 m/s (Baltrėnas & Chlebnikovas, 2015), and for ESP is 0.5–1.5 m/s (Pu et al., 2022; Yuan et al., 2022). Theoretical parameters of improved or fundamentally changed design cleaning technologies will not necessarily allow to achieve optimal indicators, so they are determined by tests and applied only to that original device. The application of complex cleaning technology imposes even more requirements, as the parameters of successive separately applied devices must be harmonized with each other, and their variation in these stages must not be critical for adjacent connected devices in the technological line.

With this in mind, this work analyzes a newly developed centrifugal-electrostatic precipitator and performs aerodynamic studies of the gas flow of the first stage during system testing of this device.

Methodology

Previous studies were presented in researches (Baltrėnas et al., 2022; Chlebnikovas et al., 2022; Chlebnikovas & Jasevičius, 2022) of multi-channel cyclone-filter and based of few physical prototypes and simulations the newly developed centrifugal-electrostatic precipitator (CEP) was designed. The primary version of the stand was made at laboratory conditions in order to study the aerodynamic parameters of the gas flow. The principal design of the apparatus is shown in Figure 1. Only a short view of the technology is provided, as a European patent application is being prepared for this apparatus, which will be submitted for consideration in the near future.

A stand of CEP consists of a fan of changeable flow rate connected with the gas flow inlet duct. The gas flow goes through the inlet-confuser into the centrifugal part of outer cyclone in the apparatus. The gas flow makes a rotation around the axis of 2π and goes toward to the part of multi-channel cyclone-filter to the first channel made from the first curvilinear element. By this way, the gas flow goes through all four channels, a part of flow is divided into peripheral and transitional flow at the edge of each curvilinear element. The biggest and smaller PM were separated in the first and second parts of cyclone by centrifugal forces and centrifugal-filtration phenomenon accordingly. PM go down through the slits and accumulate in the hopper made below the separation chamber (Figure 1 and Figure 2).

In experimental studies, equipment was used to study gas flow parameters: gas flow rate and static pressure are determined by thermocouples Testo (Testo SE & Co. KGaA, Germany, range of rate measurements: 0.01–30 m/s, deviation ± 0.05 m/s and differential pressure gauge Testo 330-2 LL (Testo SE & Co. KGaA, Germany, range of measurements: 0–30,000 kPa; deviation ± 0.5 Pa (for 0–50 hPa or ±1.5% of measurement value).

Each test was repeated not less than five times until constant measurement value under the same meteorological conditions. The measuring equipment was connected at significant points. An experimental mock-up bench with test points for aerodynamic parameters testing is provided in Figure 1.

In the first stage of the research, studies of the flow rate and gas flow yield were carried out in the full apparatus of three parts in one module. Studies of the air flow rate generated by the installed tubular fan and the tests of different apparatus capacity was tested. An additional section is created in the system to equalize the flow and supply it to the inlet spigot. Of particular importance is the study of rate changes before and after the cleaning apparatus, because it uses different principles of impact for the deposition of solid particles. Therefore, it is important according to the size of the created apparatus and as a consequence of the volume of the flow of purified air to choose the optimal rate of gas supply from the source to the inlet of the device, with the condition of achieving but not exceeding the calculated necessary theoretical speeds of deposition of pollutants. The difficulty lies in the fact that without such a study, all stages of purification, having different optimal intervals of effective operation, will not achieve the maximum result. The hypotheses put forward before the study were based on theoretical confirmation of the operating principle at each stage of cleaning, which have been confirmed in this study. Additional studies will probably be expanded in the framework of cleaning studies under real conditions, or in simulation of dusty gas flow.

The cleaning process is effective with a uniform and isokinetic flow without significant pulsations. To study this process, case studies were carried out afore and after a separate section to equalize the gas flow. Flow rate studies were carried out over the entire cross section at test points (Figure 1).

Each test was repeated (not less than five times) until the values had level of standard deviation not more than 2.5% (twice less that the maximum possible deviation of the equipment) of the average level of the actual test point. The statistical evaluation of results was made to evaluate the reliability of research results by calculating the actual parameters as average, variance, standard deviation and uncertainty of the input data (Anderson et al., 1980). To study the comparative assessment of the correlation of various parameters of gas flow rate at various cases, an analysis was performed using the Pearson index.

The purpose of these tests was to get the primary full potential intervals of aerodynamic characteristic conditions and to detect any discrepancies and optimal case for uniform distribution of the air flow and potential better flow pattern for settling PM in the apparatus.

Figure 1. An experimental centrifugal electrostatic precipitator bench with (1) air flow fan; (2) air flow rate test point afore an equalization section; (3) equalization section; (4) air flow static pressure afore the apparatus; (5) air flow rate test point toward to the apparatus; (6) air flow inlet to the apparatus; (7) centrifugal electrostatic precipitator with hopper; (7.1) centrifugal part of outer cyclone and inner multi-channel cyclone-filter; (7.2) integrated electrostatic filter part; (8) outlet duct of the cleaned air; (9) air flow static pressure toward to the outlet

Results and discussion

In the first stage, rate studies of the gas flow generated by the axial fan were performed before and after the smoothing section to reduce gas flow turbulization, the obtained results are shown in Figure 2.

The determined gas flow rates clearly show the non-uniformity of the flow in the cross-section before smoothing. The difference between the gas flow rate at the test point near the inner wall, where the rate was the largest throughout the cross-section, was from 1.02 times higher at the lowest supplied gas flow (position I) to 1.23 times at the average (position III) and 1.16 times at the maximum (position VI) for the supplied gas flow. The non-uniform flow of the gas stream is also determined by the gas flow rates at the inner and outer walls. In position I-II, the gas flow rate at the inner wall was higher than at the outer wall by an average of 1.1–1.9%, further increasing the gas flow (position III-VI) – the rate at the outer wall was higher than the values at the inner wall by an average of 2.4–2.9 times. Statistical analysis of the data obtained showed high reliability, for example, the results of the flow rate at I-IV positions had no more than 1.4×10^{-3} variance, at V and VI – the variance was from 1.6×10^{-3} to 8.2×10^{-3}. The standard deviation of the values at positions I-II was no more than 8.4×10^{-3}, and at positions III-VI the variance was from 0.8×10^{-3} to 9×10^{-2}. Standard uncertainty at positions I-III was no more than $\pm9.9\times10^{-3}$, and at positions IV-VI the standard uncertainty was from 9.2×10^{-3} to 3.4×10^{-2}. The relationship between the results of the distribution of gas flow across the duct cross section based on the Pearson index showed that the greatest relationship exists between the flow rate at the inner and outer walls, the index is 0.9996, and the lowest – in the center and the outer wall – 0.9896.

In the experimental stand, a smoothing section was connected to the flow duct of the supplied air flow source, where a network consisting of internal elements was installed, reducing the turbulence of the flow. The tests were carried out under the same conditions after the smoothing section. The obtained results proved the effectiveness of this section, when the maximum unevenness between the gas flow rates in the duct cross-section reached only 8.7% at the maximum gas flow (position VI). In other cases, the unevenness was 2.4–4.3%, and the maximum gas flow rate was localized in the center of the duct in all cases.

The pressure drop created by the cleaning device causes additional energy losses during operation. In the second stage, tests were carried out on how the static pressure created by the gas flow changes depending on the rate and performance of the gas flow, passing through the entire cleaning system, the results of the tests are shown in Figure 3.

Static pressure drops at low capacities, i.e., 0.015–0.017 m^3/s, reached approximately 14 Pa and differed slightly among all cases, the average gas flow rate in these cases was 1.27 m/s. After increasing the performance of the air supplied to the system to 0.02 m^3/s, the pressure drop increased to 1.8 times and reached 25 Pa, when the gas flow rate was 1.62 m/s. When the V position of the supply air flow fan was set, the gas flow performance reached 0.0271 m^3/s, and the pressure drop was one of the highest and reached 1.68 times at a rate of 2.21 m/s. Finally, at the highest gas flow rate of 0.0293 m^3/s, the pressure drop increased only 1.2 times, reaching 51 Pa at a gas flow rate of 2.39 m/s. Thus, comparing positions I and VI, the total pressure drop ratio reached 4.25 times, when the gas flow rate changed 1.96 times, and the performance increased from 0.015 m^3/s to 0.0293 m^3/s. By adopting an improved section to reduce flow turbulence, the gas flow rate has been equalized to an average of 17% to 4.6% before the inlet. Also, the designed system achieved a theoretically optimal gas flow rate of 2.2 m/s for subsequent particulate matter injection into the system of several cleaning stages. The flow before and after the purification device in the range of 1.2–2.4 m/s was also studied. The Pearson index between the results of the gas flow yield and pressure drop showed that the correlation level is very strong, the index is 0.9979.

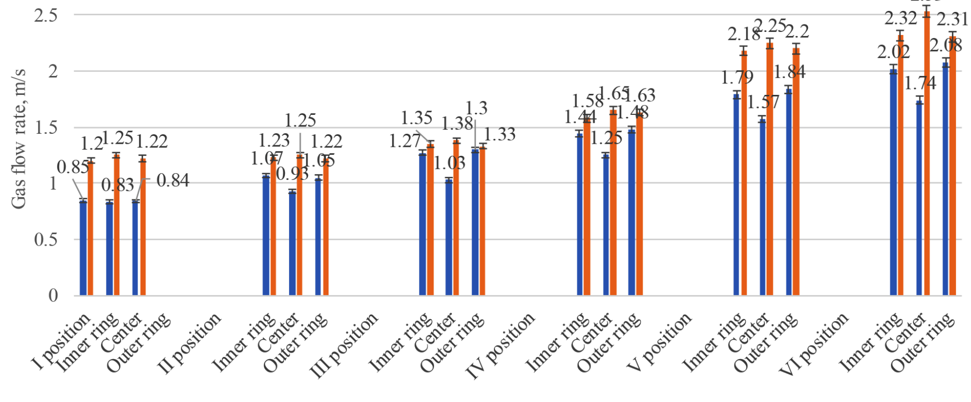

Figure 2. Variation of the gas flow rate before and after the equalization section at different axial fan flow rates (where position I is minimum and position VI is maximum) in the duct cross-sections of the experimental bench

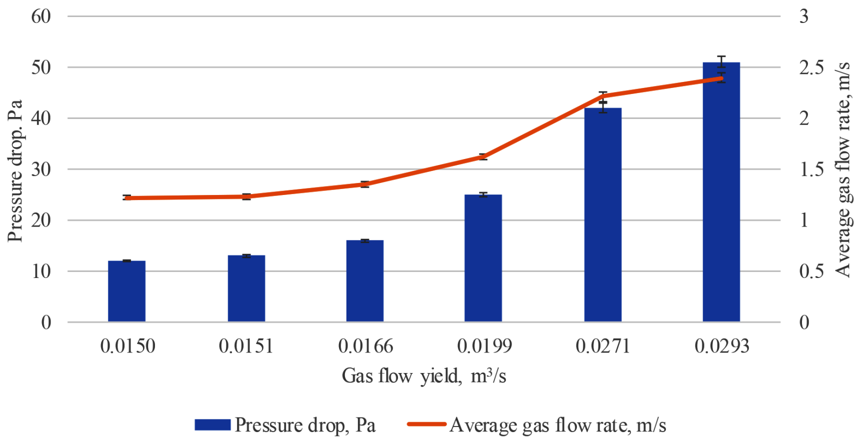

Figure 3. A static pressure drop of the gas flow depending on the rate and performance of the gas flow to be cleaned in the system of the complex treatment device

A variation of the gas flow rate leaving the complex treatment device in the cross-section depending on the supplied gas flow rate of experimental bench was analyzed, as well as the variation of the static pressure before the equalization section, the obtained results are presented in Figure 4.

The gas flow rate in the outlet duct drops due to the sequential three cleaning stages of the complex device. The first two are based on the centrifugal cleaning principle, with the condition that the multi-channel cyclone section is additionally equipped with curvilinear elements that create additional pressure losses when filtering the gas flow. In this way, the flow supplied to the electrostatic precipitation section has a lower rate, which is required by the cleaning principle applied in this part of the device. By itself, the electrostatic filter does not cause significant pressure losses, since the flow leaving the multi-channel cyclone part is already tilted and moves in a vertical direction between the spiral-shaped element. Research has established that at low gas flow rates at the inlet in the range of 1.22–1.35 m/s, the static pressure before the equalization section changes insignificantly and is equal to about 15 Pa. Meanwhile, the gas flow rate at the outlet is about 0.45 m/s, and the difference between the peripheral and central gas flow rates in the cross section is not significant. At an inflow rate of 1.62 m/s, the static pressure increased 1.7 times and equaled 27 Pa. In this case, the gas flow rate in the center of the outlet duct decreases and the average reaches 0.65 m/s, while at the walls the peripheral flow is about 9.8% higher. At the maximum inlet gas flow rates of 2.21 m/s and 2.39 m/s, the static pressure increases to 45 Pa and 52 Pa, respectively.

The statistical results analysis of the average flow rate in outlet peripheral of 1.22–1.35 m/s had $1.1–1.52\times10^{-1}$ variance, of 1.62–2.39 m/s – the variance was from 9.5×10^{-2} to 2.7×10^{-1}. The variance of the average flow rate in outlet central of 1.22–2.39 m/s had no more than 6.5×10^{-4} variance, the maximum was at gas flow rate in outlet peripheral of 1.62 m/s. The standard deviation of the values at gas flow rate in outlet peripheral of 1.22–2.39 m/s was no more than 5.15×10^{-1}, in outlet central this value was no more than 2.55×10^{-2}. Standard uncertainty was at case of minimal gas flow rate in outlet peripheral and was no more than $\pm6.25\times10^{-1}$, and the standard uncertainty in outlet central was from 2.38×10^{-2} to 4.3×10^{-2}. The relationship between the results of gas flow distribution across the duct cross section

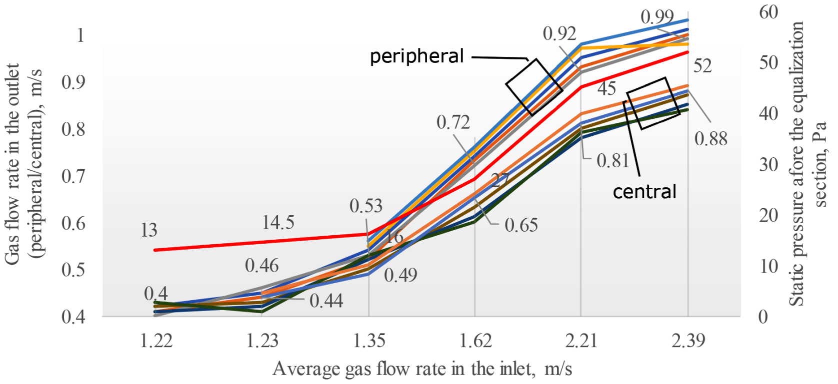

Figure 4. A dependence of the variation of the gas flow rate in the cross-section of the outlet duct and the static pressure before the equalization section on the gas flow rate at the inlet

at the outlet based on the Pearson index showed that the greatest relationship exists at higher flow rate, the maximum value was obtained at an average inlet rate of 2.21 m/s equal to 0.92. At inlet rate less than 1.35 m/s the dependence is inverse, and at 1.62 and more it is direct. The relatively low static pressure of the flow created by the fan as a source was most likely also important for this dependence. The flow at low rates was absorbed by the resistance of the cleaning apparatus, and only at a flow rate above 1.35 m/s reached the prevailing pressure over the resistance. The trend of the gas flow rate at the exit remains similar – in the center of the duct, the rates reach 0.81 m/s and 0.88 m/s, while at the periphery of the exit gas flow duct, the gas flow rate is higher by about 11.5%. Based on the obtained studies, it can be stated that the available gas flow both at the outlet of the electrostatic precipitator testifies that both the minimum gas flow performance and the maximum can be applied when testing the comprehensive cleaning device in fine and ultra-fine particulate matter deposition studies.

Conclusions

The results of the aerodynamic parameters and their variation depending on characteristic indicators such as performance and the rate of the supplied gas flow were obtained in the research of the newly developed complex treatment device. It was found that with the performance of the gas flow to be cleaned from 53.8 m^3/h to 105.5 m^3/h, which corresponds to the average gas flow inflow rate from 1.22 m/s to 2.39 m/s, the pressure drop of the gas flow reaches from 12 Pa to 51 Pa. The equalization section in front of the complex device will reduce the unevenness of the gas flow in the entire cross-section, which is about 4%. The variation of the gas flow rate creates favorable aerodynamic conditions for the application of a complex cleaning device throughout, i.e., from 0.84 m/s to 1.95 m/s before the equalization section, in the gas flow rate range considered. Aerodynamic conditions at the lower gas flow rates under study will have a greater potential to deposit solids of lower density and finer fraction. However, this gas flow rate may not be sufficient for the centrifugal filtration section, especially for higher specific gravity solids, and on the contrary, the highest rates will provide short-term solids charging capability in the electrostatic filter section. The value of this paper lies in the new results obtained on the sequential study of a new apparatus for the purification of deposited solids, especially hard to deposit ultrafine particles. The study of the aerodynamics of the gas flow is an integral part of the scientific investigation of this type of technology, without which the purification process will be initially unsettled, which will entail additional limitations and reduced efficiency of the result.

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