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Researches of Aggressive Gas Flow Cleaning from Wood Ash Particulate Matter in the Multi-Channel Cyclone

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Abstract. The studies examined the gas flow aerodynamic parameters and treatment efficiency from the wood ash particulate matter, also an adhesion dependencies in multi-channel cyclone using aggressive gas flow – temperature up to 75 °C and relative humidity more than 95%. Researches of gas flow velocity and cyclone aerodynamic resistance in case of different average gas flow velocity in the cyclone and particle adhesion analysis inside the cyclone. Cyclones work is based on centrifugal forces and additionally resulting filtration process operation. Due to the interaction between inlet flow from the (peripheral) channel coming next and the flow following the direction towards the axis of the cyclone along the channel (transit), additional filtration takes place. Studies was carried out the prototype of multi-channel cyclone, which is used with curvilinear quarter-rings with opening slot folded at an angle, so that the peripheral and transit flows are equal to each other. The aim – to determine the multi-channel cyclone aerodynamic parameters, and their dependencies, to make aggressive gas flow and to analyse the wood ash particles adhesion and its impact to multi-channel cyclone operation by occluding device's internal design. The average velocity of gas flow was equal to 8, 12 and 16 m/s, the highest aerodynamic resistance was equal to 410 Pa, which was determined in the case at 16 m/s. Based on experimental tests, PM which the diameter up to 20 microns, the gas cleaning efficiency is above 85% when inlet concentration was 5 g/m^3.

Keywords: multi-channel cyclone, aggressive gas flow, particulate matter, adhesion.

Conference topic: Environmental protection.

Introduction

A possible solution to cleaning gas flows contaminated with particulate matter (PM) produced in industry remains one of the most important issues of atmosphere protection. Due to pollution, air quality decreases and working conditions become unfavourable for employees and equipment performance. When particulate matter enters the human body, it can cause eye, skin and breathing injuries, blood vessel and heart diseases and have a carcinogenic effect (Li, Zhou 2015; Xu *et al.* 2016).

Gas flow treatment for removing fine particles is the process that employs the application of gas treatment devices. Particle traps are used for separating particles emitted from the exhausted air in the flow ventilation systems during technological processes. Electrostatic and bag filters most commonly applied in world practice are highly effective equipment employed for purifying gas flow from particulate matter. However, they are expensive and their exploitation is rather difficult, especially, to separate sticky and moist PM. These devices are not suitable (dangerous) for cleaning dusted flow of aggressive gas (Kauppinen, Pakkanen 1990; Shi *et al.* 2013). Multi-channel cyclones widely applied to separate from 1 µm and higher in diameter PM from dusted non-aggressive gas flow.

The work of channel cyclone-separator is based on centrifugal forces and additionally occurring filtration process. Due to the interaction between inlet flow from the (peripheral) channel coming next and the flow following the direction towards the axis of the cyclone along the channel (transit), additional filtration takes place (Baltrėnas *et al.* 2012; Burov *et al.* 2005; Vaitiekūnas, Jakštonienė 2010).

Multi-channel cyclones have a curvilinear channels, thereby forming the closed-end contours, as usual hollow construction cyclones, a simple design, the manufacturing process is not complicated, easy-to-installed and operated (Senior *et al.* 2000).

Due to these advantages, multi-channel cyclone is reliable, versatile and economical. The closed contour with the half-ring spaces inside the cyclone enables the gas flow to the inflow and outflow to/from the channels. The gas flow many times filtered through that spaces where the feedback and partially purified gas (contained therein-fine PM) flows circulate together. These interactions result fine PM is further separated, directed into the external continuous or annular sectional slit, and precipitated in cyclone hopper. Gas purification as a complex operation using filtration and centrifugal separation is gas treatment innovation (Jasevičius *et al.* 2014).

The wet dusted gas flow movement into the cyclone channels causes the fine PM sediment layers forming.

Solids sediment layer formation is analysed as a PM elastic rebound and adhesion to the surface, these two factors force and their comparison (Montazeri *et al.* 2015; Schaik *et al.* 2010). The relative strengths of the particles is directly proportional to the diameter of the third degree. In this way, fine particles exposed to the surface of the material and significant are the adhesion and cohesion forces (Portet-Koltalo *et al.* 2011). Studies have found that even rectangular shaped channel is intense particle deposition on the surface. Small particles are treated as such, which is swept along with the flow on the turbulent pulsations (Hyunhee *et al.* 2011; Sobolev *et al.* 2011).

The first stage of the fine PM deposits is monolayers formation, which composed of fine particles (Zhou *et al.* 2013). These fine PM smooth the surface on which is formed a laminar flow, which has a small effect of dispersing the precipitate. Accumulation of sediments in this layer may intrude coarser particles, which consolidates these derivatives (Sobolev *et al.* 2011; Yan *et al.* 2013; Zhu *et al.* 2010).

The aim is experimentally research of aerodynamic parameters of a multi-channel cyclone to determine gas-cleaning efficiency from wood ash PM and to estimate the particle adhesion on internal cyclone surfaces under the aggressive gas flow which temperature was up to 75 °C and relative humidity above 95%.

Methods

Experimental studies were carried out using a gas purification equipment – multi channel cylindrical cyclone. Cyclone dimensions: a cylindrical separation chamber diameter – 0.53 m, total cyclone height (with a double conical hopper) – 1.10 m, the flow inlet and outlet diameter – 0.16 m, the inlet into the cyclone to the first channel – 0.055×0.29 (m).

Curvilinear elements in the form of a quarter of a ring are situated in the inner construction of the separation chamber, whose angle turns are $\varphi = 0– 0.5\pi, 0.5\pi–\pi, \pi–1.5\pi, 1.5\pi–2\pi$. In case of a cyclone, where there are more than four channels, the arrangement of the elements in a form of a quarter of a ring is created following the same angle turn step. The construction of a multichannel cyclone consists of air ducts for gas inflow into the cyclone and outflow from the cyclone, opening for gas inflow, separation chamber, where elements in the form of a quarter of a ring are installed, external continuous crack as well as a two-part conical bunker to collect fine dispersion solid particles. The submitted data with the results was gained under conditions of laboratory – non-aggressive and aggressive gas–vapour–fog flow. By installing cylindrical curvilinear elements in the form of a quarter of a ring in the cyclone of the cylindrical housing, they are situated in the descending order of rays as well as retracted, considering the width of the inflow. Because of such arrangement and the distinctive design of the cyclone, the back of the channels is of the decreasing cross-sectional area.

When analysing the multichannel cyclone, following the previous research (Baltrėnas, Chlebnikovas 2015, 2016), an optimum case of 50:50 flow distribution ratio was chosen in the flow division zones, which was established by adjusting the position of the elements in the form of a quarter of a ring. In such a manner, a flow, coming from the channel in the cracks of these elements is divided into peripheral (return) and transit (moving to the next channel) flow, while the peripheral and transit flow constitute 50% of the total incoming flow, i.e. the flow distribution ratios are equal to each other. Cylindrical cyclone was used for the research, taking the elements in the form of a quarter of a ring with the unfolded plates of the openings, installed on the bottom of the separation chamber, in such a manner, obtaining a four-channel cyclone.

When performing the velocity of gas flow research in air ducts, the cross-sections are relatively divided into several concentric rings, the amount of which depends on the peculiarities of the gas velocity distribution in the cross-section of an air duct. When the symmetry and distribution of uniformity in velocity are reducing as well as when the diameter of the air duct is increasing, the amount of rings should be increasing. The measuring point distances from the inner air duct wall are calculated in every ring.

In a general case, internal geometry of a multichannel cyclone may be formed, by adjusting the flow distribution ratios in the flow separation zones, where the flow, coming from the channel, is divided into the peripheral – returning to the previous channel ant transit – flowing to the next channel towards the axis of the device.

The arrangement of the velocity measuring points (v.m.p.) in the experimental stand of a special cyclone is provided in Figure 1.

Gas flow research was performed by establishing various average velocities in the channels of a cyclone. The rpm regulator, situated in the control unit of a ventilator, changed the entering gas flow. The cases were examined, by establishing 8 m/s, 12 m/s and 16 m/s gas flow velocity in the channels of a cyclone. These velocities were chosen after considering the results of a previous research, when the efficiency of the cleaning, performed by the cyclone was the highest, i.e. at 12 m/s as well as by choosing additional borderline cases at 8 and 16 m/s.

Pitot tube is inserted into the holes, drilled in the selected areas on the lid of a multichannel cyclone (Fig. 2). *Testo–350* multifunctional meter performs a recalculation to a gas flow velocity, by directly measuring the dynamic pressure.

Pitot dynamic tube was used for the experimental research, which is connected with the dynamic probe and multifunctional meter *Testo–350* through hoses (temperature measurement range: 20–700 °C, margin of error ±0.2 °C, velocity measurement range: 1–30 m/s, margin of error – ±0.05 m/s).

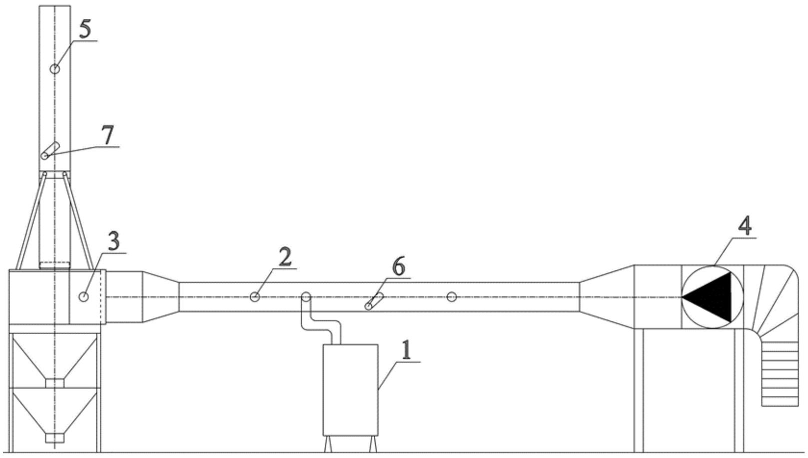
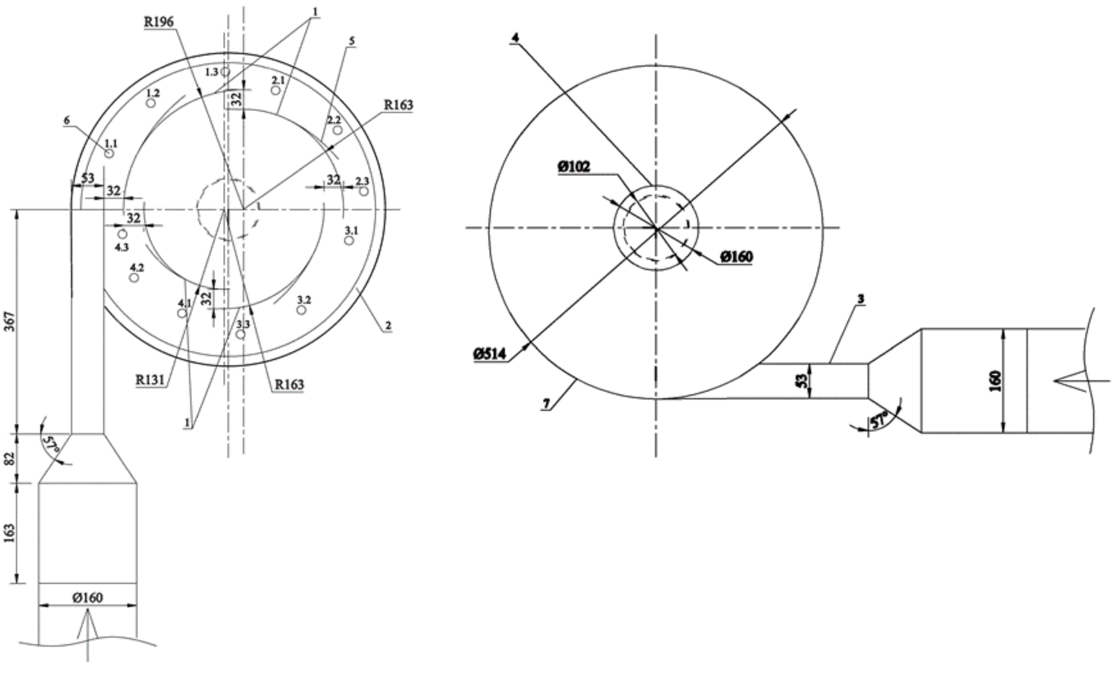


Fig. 1. Multi-channel cyclone experimental stand: 1 – autoclave, 2 – velocity measuring point (v.m.p.) in the duct before the cyclone, 3 – v.m.p. in the separation chamber of special cyclone, in the channels, 4 – fan, 5 – v.m.p. in the duct after the cyclone, 6 – pressure measuring point (p.m.p.) before the cyclone, 7 – p.m.p. after the cyclone



a

b

Fig. 2. Scheme of measuring points arrangement in the cyclone channel (a) and top view (b): 1 – curved quarter-rings; 2 – external continuous slit; 3 – gas inlet duct into the cyclone; 4 – gas outlet duct; 5 – opening slots with 5° angle folded plate in the quarter-rings; 6 – measuring point; 7 – separation chamber

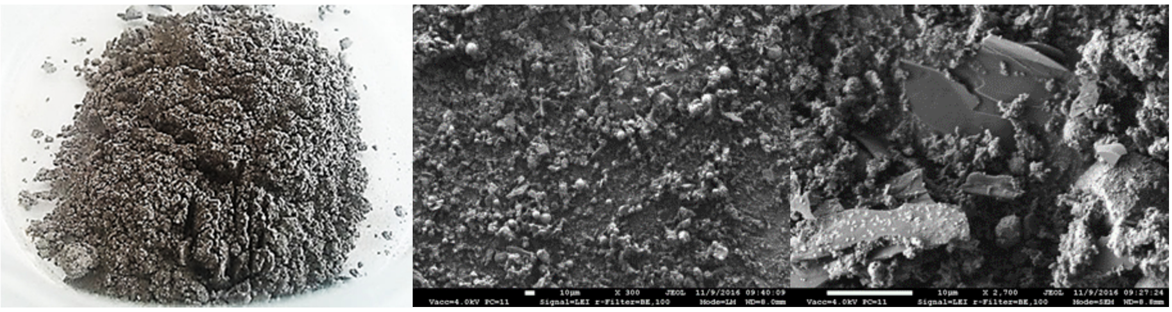
Atmospheric pressure was measured by a barometer in the laboratory of environmental and working conditions, while the temperature and humidity in the laboratory are measured with moisture meter *Extech M0290* (relative humidity measurement range – 0–100%, resolution – 0.1%; temperature measurement range – –29–77 °C, resolution – 0.1%). For the aerodynamic resistance tests and to measure the pressure before and after the cyclone, holes were drilled in the selected areas on the air duct as well as metal branch pipes in the length of 50 mm were installed (Fig. 1, No. 7 and No. 8). Aerodynamic resistance was measured based on the difference of the static pressure in the incoming and outgoing air ducts.

Cohesion and adhesion especially increase under the action of aggressive gas flow, which is characterized by high humidity and increased temperature, as a result gets a strong interaction of fine PM and cyclone inner surface (Crowe *et al.* 2012). It is therefore important to assess the multi-channel cyclone operation, at such environment. Research of experimental stand of cyclone was established by maintaining the humidity up to 95% and the temperature up to 145 °C.

Wood ash fine PM were used for the experimental research in order to establish the efficiency of a multi-channel cyclone, which is meant for cleaning the polluted gas flow. Before performing the tests, PM were sieved through sieves, using the sample shaker *Rotoshake RS 12*. *MORIS* 900, 200, 50 and 20 µm mesh size sieves were used for the tests. Fine PM, with the diameter, which was smaller than 20 µm were used in the experimental tests.

Particles structure and surface were analysed by using the scanning electron microscope *JEOL JSM-7600F* (range of probe currents – 1 pA – 200 nA; magnification 10^6X; resolution – 1 nm).

Wood ash fine PM: density of a dry sample – 624, density of a saturated sample – 2238 kg/m^3, total porosity – 0.0016, overall density – 800–900 kg/m^3, apparent density – 710 kg/m^3. Wood ash fine PM composition were determined by using laser particle size analyser CILAS 1090 (error ≤1%; accuracy – ≤3%; resolution – 0.04 – 500 µm). Wood ash PM sample: ≤1 µm – 1.0%; 1 – 2.5 µm – 3.8%; 2.5 – 10 µm – 34.4%; 10 – 20 µm – 60.8%.



a b c

Fig. 3. Fine particulate matter used form experimental researches: a) wood ash PM (x1), b) wood ash PM (x300), c) wood ash PM (x2700)

As presented in Figure 3, wood ash PM were bonded to each other, as a result was making the larger agglomerates, the other part – it is single, regular round-shaped PM. Furthermore, an analysis of macro structure (Fig. 3c) was shown that the coarse PM were flat and plastered with other less than 1 µm further smaller particles. This is evidenced by the fact that cohesion forces act the wood ash PM even at the dry conditions (Goodarzi 2006). This phenomenon encourages the formation of larger particles, while at the same time; it is possible to create congestion inside the cyclone and to make the disturbances to normal efficient operation.

The cleaning efficiency under the action of aggressive gas flow was carried out by maintaining the humidity of >95% and the temperature of the gas-vapour flow: at 8 m/s – 75 °C, 12 m/s – 70 °C and 16 m/s – 60 °C.

Results and Discussion

Researches of aerodynamic parameters

It was examined a change of gas flow velocity into the cyclone channels. The gas inflow was regulated so that the average velocity was equal 8, 12 and 16 m/s. Distribution of velocity values was made at 8 m/s average velocity at the beginning (point 1), middle (2 points) and at the end of each channel (point 3) (Fig. 4). According to the results, it can be seen that the velocity of channels varies slightly – from 7.5 to 8.9 m/s. The highest velocity was set at the end of the first channel – 10.1 m/s. This trend continues in other channels. The lowest velocity was established at the beginning of the fourth channel – 5.2 m/s. At the end of the fourth channel, the velocity was equal to 9.7 m/s. In this way, the change between the highest and lowest values was 1.94 times. Therefore, it can be stated that all velocities into the cyclone channels varies smoothly, without sudden changes, which leads to an even centrifugal forces. This distribution allow avoiding additional eddy (turbulent) flow, which impedes the efficient cyclone operation (Kim *et al.* 2014).

Briefly summarizing the research that carried out by the speed setting at 12 and 16 m/s that can be said that the trend remains similar. In the case at 12 m/s, the highest velocity was 14.9 m/s and at 16 m/s – 19.9 m/s. The gas flow velocity was from 11.3 to 13.2 m/s and 10.5 to 19.9 m/s at 12 m/s and 16 m/s respectively. The velocities in the beginning of fourth channel in all cases was lowest (1 point).

To analyse of the gas flow velocity distribution it can be concluded that the gas flow in the third and fourth cyclone channel may be insufficient in the case at 8 m/s. The centrifugal force will not be able to remove particles near to the peripheral wall, and the particles will not come through external continuous slit in the cyclone hopper. The flow filtration will not be effective at the low dusted gas flow velocity, because of the clean flows from the previous channel will not have enough energy to filter the contaminated flow, the velocity was not sufficient to overcome the resistance forces. In this way the wood ash fine PM, accumulate on the bottom of the separation chamber by creating an additional system blockage.

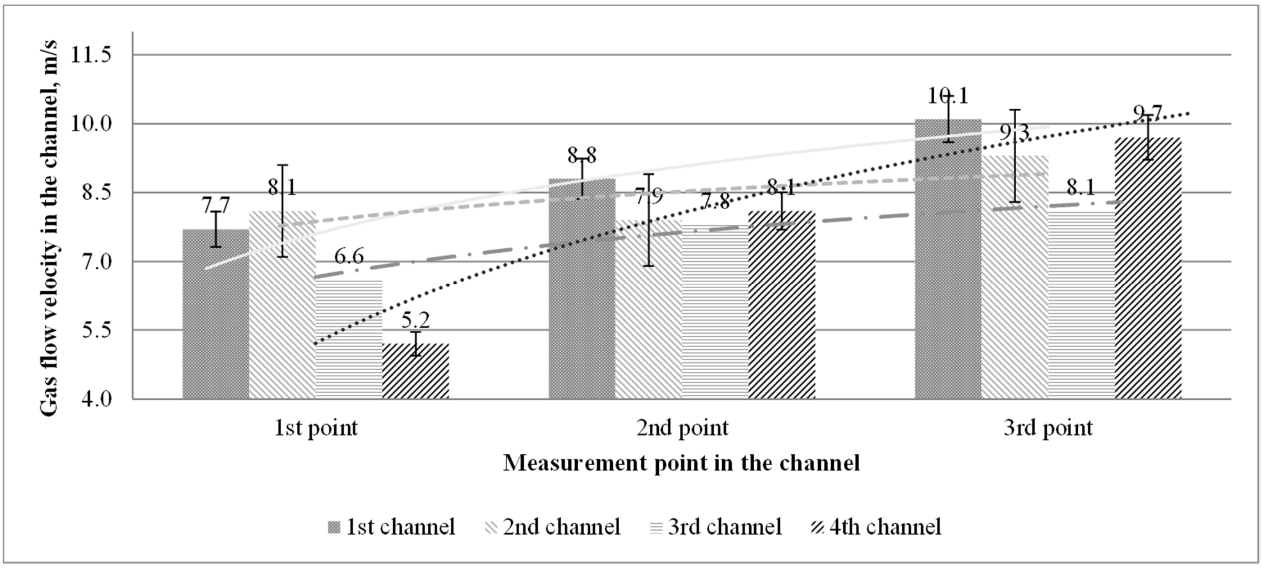


Fig. 4. Gas flow velocity distribution in the channels of the four-channel cyclone using the quarter-rings with opening slots folded at an angle of 5° under flow distribution ratio 50/50 and an average velocity of 8 m/s in the cyclone

Research of aerodynamic resistance was carried out analysing the fourth channel cyclone, by using the elements in the form of a quarter of a ring with a 5° angle plate unfolds of the openings. The studies analysed the variation at the velocity of average gas flow of 8–16 m/s. The curved elements in the form of a quarter of a ring has been positioned when the ratio of peripheral and transitional flows was equal to 50/50 (Fig. 5).

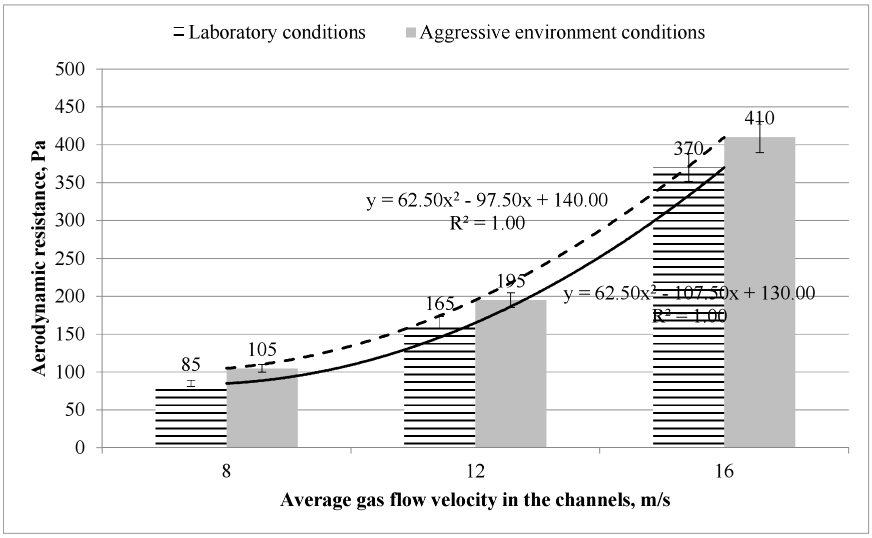


Fig. 5. The dependence of aerodynamic resistance under laboratory and under the action of aggressive gas flow when flow distribution ratio 50/50 and an average velocity of 8–16 m/s in the cyclone‘s channel

Aerodynamic resistance values varies the velocity squared, it is obvious that the minimum value set in the case at 8 m/s velocity – 105 Pa under the action of aggressive gas flow. In this case, the difference between the different condition was not significant, because of the value varies within proximity of error limits intervals, so the resistance at laboratory conditions was equal to 85 Pa. Multi-channel cyclone have a low enough aerodynamic resistance as compared to another (Venckus *et al.* 2014), which is important economically for reducing the energy demand.

The comparison between the case of 8 and 12 m/s, the aerodynamic resistance increased by approximately 1.9 times under the action of aggressive gas flow and at laboratory conditions respectively. The highest aerodynamic resistance was created at the velocity of 16 m/s, thus the resistance at laboratory conditions was equal to 370 Pa and under the action of aggressive gas flow – 410 Pa, and i.e. an increase was 9.8%.

It is estimated that an increase of the pressure creates a friction force, the gas flow passing through the steam input that forming of steam cloud (Shanthanu *et al.* 2013). The difference between the values in different conditions consisted of 15.4%, that is. y. 30 Pa. In all cases, this tendency remains the same – cyclone aerodynamic resistance at laboratory conditions approximately 15% lower than under the action of aggressive gas flow.

Research of cleaning efficiency

The cleaning process in the multi-channel cyclone from the PM under the action of aggressive gas flow were considered the treatment efficiency in several periods of operation. The initial starting point – the cyclone working zero time under the action of aggressive gas flow, i.e. gas dispersed flow at normal (laboratory) conditions. The operation time which was equal to 30 thousand. m^3 cleaned gas-vapour-mist flow was equivalent to 30 hours of operation time, 50 thousand. m^3 – 50 working hours etc. As shown in Figure 5, the highest efficiency from wood ash fine PM was reached at 12 m/s velocity into the cyclone channels and it was equal to 86.9%. In cases where the velocity was reduced to 8 m/s, the efficiency decreased by 2.4%. It was also observed that some slight PM accumulates on the bottom of the cyclone separation chamber. It can be argued that the lower centrifugal forces were unable to take out part of the particle when flow velocity was decreased. In addition, the ongoing new incoming flow did not take place effectively by filtrating in the gaps between the quarters of the ring elements. As the velocity was greater, e.g. 16 m/s, the cleaning efficiency from the wood ash fine PM was evenly decreasing. Dispersed gas flow Reynolds number at 16 m/s was equal to more than $1.1 \cdot 10^5$, so the particles in that case were taken away from the channel through the exhaust duct faster than they were precipitated in the hopper (Fig. 6).

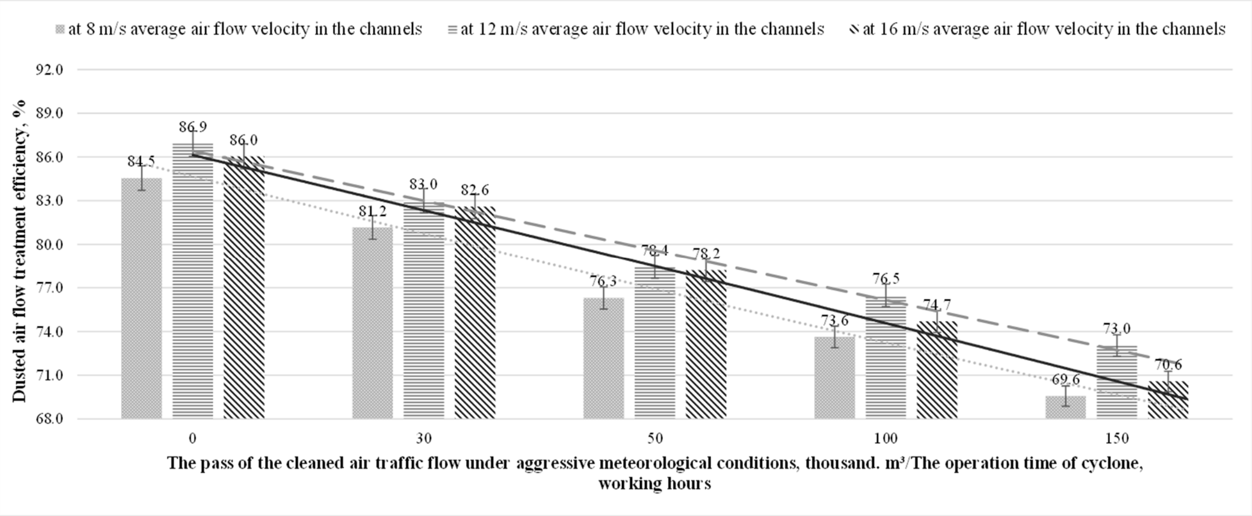


Fig. 6. The dependence of gas-fog flow cleaning efficiency in the four-channel cyclone under different average flow velocity in the channels using the quarter-rings with opening slots folded at an angle of 5°, flow distribution ratio 50/50 at >95% relative humidity and at temperature of 60–75 °C trapping the wood ash fine PM of 20 μm in diameter

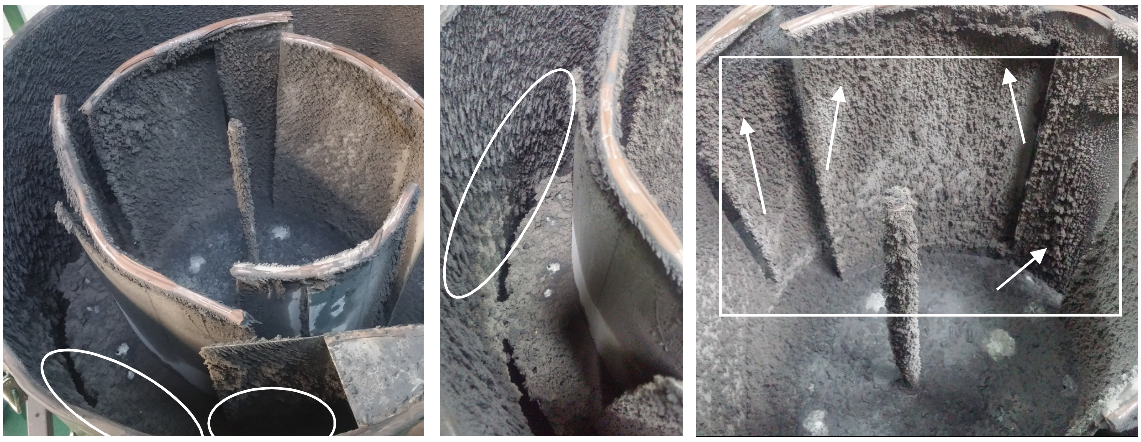
The past gas flow was equal to 30 thousand. m^3 then the cleaning efficiency was decreased proportionally, this decrease as higher as the velocity was lower. The cleaning efficiency was 83% in the case at 12 m/s average gas flow.

The examination of adhesion into the multi-channel cyclone, it is important to mention that the majority of particles clogs the holes in a quarter of the ring-shaped elements, as well as cracks in the bottom of the separation chamber through which the particles fall into the hopper. For this reason, it is recommended to apply a higher dispersed gas flow velocity in cyclone channels, so more so the level of the aggressive gas flow is higher. Importantly, the highest velocity may be limited in that the particles cannot be pump from the hopper and cannot be returned to the cyclone or cannot to be flow out to the outlet.

The operation time of cyclone was equal to 50 hours (50-thousand. m^3), the cleaning efficiency was decreased 8–9%. Therefore, it can be state that the separation of constant dusted flow leads to a greater accumulation of PM under the action of aggressive gas flow into the cyclone, which interferes with the efficient work of the device.

The cases after operation time of 100–150 hours (Fig. 6) shows that the cleaning efficiency was maintained sufficiently high, approximately 70%. The cleaning efficiency in case at 12 and 16 m/s velocity was similar trend, but the cleaning efficiency had a greater impact under the action of aggressive gas flow in the case at 8 m/s. Therefore, an increase of dispersed gas flow velocity is possible not only to maintain the cleaning efficiency under the action of aggressive gas flow, but also to prevent clogging of the cyclone and to avoid of emergency system braking.

The accumulation of wood ash fine PM was observed under the action of aggressive gas flow (increased humidity and temperature) (Fig. 7a) at the inlet to the first cyclone channel, on the separation chamber peripheral wall (the middle and upper parts) (Fig. 7b), in the first and second channel, and on the surface of curved elements of quarter-ring (Fig. 7c). Wood ash fine PM made a roughened surface of a pending adhesion, then the all surfaces inside the cyclone were covered with a thin continuous layer of particles (Bemer *et al.* 2013). The process was intensified on cohesion when the particles were stocked to the formed layer easier (Crowe *et al.* 2012; Kim *et al.* 2014).



a b c

Fig. 7. Wood ash particulate matter and adhesion phenomena in multi-channel cyclone under the action of aggressive gas flow: a – in the inlet of cyclone, b – on the peripheral wall, c – on the surface of quarter-ring formed element

The wood ash PM were covered the bottom of separation chamber and the surface of the peripheral wall, were accumulated on the edges of quarter ring-shaped plate openings. In addition, the external continuous slit in several places was constricted or blocked completely. In that case precipitated particles cannot enter in the cyclone hopper and the flow cannot be removed them from the system, so in this case the cleaning was stopped almost completely, in additional, that phenomenon was increased cyclone aerodynamic resistance (Calle *et al.* 2002). To conclude that the application of multi-channel cyclone can be used under the action of aggressive gas flow is necessary to make a constructive improvement of the facilities in order to reduce the particles adhesion and cohesion.

Conclusions

Based on the research results, it can be said that the optimal gas flow velocity into the cyclone channel was equal to 12 m/s, when dispersed gas flow was distributed evenly. Aerodynamic resistance under the action of aggressive gas flow at optimal velocity was set less than 200 Pa. The cleaning efficiency analysis showed that the highest value achieved at 12 m/s, and was equal to 73–87%. Although, the values were differed slightly set at 12 and 16 m/s. Analysing the adhesion and cohesion processes, it concludes that it is appropriate to apply special device for the effective functioning of the cyclone for continuous non–stop operation to avoid of emergency system braking. As it was observed the multi-channel cyclone inner construction covered by 2–3 mm particle layer after 150 thousand. m^3 dispersed gas flow at aggressive gas conditions. At that case was significantly reduces the cleaning efficiency and the fine PM made the obstructions by clogging internal elements. It is therefore recommended to apply special constructive improvement of the facilities to avoid clogging the system. For example, the application of inlet using secondary flows. By this method, the aggressive dispersed gas flow will be broken down into the components and will flow parallel to the several different channels of cyclone. In this way, the total flow will be diluted at aggressive gas flow conditions due to reduced concentrations of particulate matter in the secondary streams, and, as well, and the ongoing decrease adhesion and cohesion. It also may be used to additional regenerated operations, such as high-pressure purging using air-impact device or vibrating device that is mounted on the casing.

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