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"Gheorghe Asachi" Technical University of Iasi, Romania

FLUE GAS DEDUSTING IN VENTURI SCRUBBERS AT THERMAL POWER PLANTS

Igor Volchyn*, Vladyslav Raschepkin, Andrey Iasynetskyi

Laboratory of the Environmental Problems in Power Industry, Coal Energy Technology Institute of the National Academy of Sciences of Ukraine 19, Andriyivska Str., Kiev, Ukraine, 04070

Abstract

In this paper, an improved engineering model and analysis techniques are presented of the fly ash particles coagulation with droplets in Venturi tubes of industrial scale, based on spatial variation of the collection efficiency of particles on individual droplets, accounting for spray water flow polydispersity and particle size distribution, which allows to define optimal droplets size and spray water flow rate at different modes of thermal power units operation. The model is validated with the published experimental data on the wet Venturi scrubbers operations at the thermal power plants (TPP) in Ukraine, Russia and Kazakhstan. The results of calculations demonstrate good coincidence with experimental data. The influence of the boiler load and spray water consumption on an efficiency of the TPP Venturi wet scrubbers was studied. The simulation results have shown that moderate increment of spray water consumption up to 0.24 L/m^3 allows increasing of the Venturi wet scrubber's efficiency without threat of reaching the dew point in flue gas flow, thus preventing potential corrosion of the power plant equipment downstream. The calculations confirmed that without retrofit of wet scrubbers installed at Ukrainian power plants it will not be possible by these stations to meet European requirements on the allowable levels of emissions from the coal firing power plants.

Keywords: dedusting, flue gas, fly ash particles, Venturi scrubber

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1. Introduction

Regulations on harmful pollutions to the atmosphere from combustion plants, including regulations regarding emissions of solid particles stated in EC Directive (2001) and EC Directive (2010), force generating companies to seek ways to enhance efficiency of the existing flue gas cleaning systems. Ukrainian thermal power plants (TPP) are on 63 per cent equipped with the electrostatic precipitators, and about 46 per cent of the boilers, with productivity ranging from 160 to 640 tons of steam per hour, are equipped with the Venturi-type wet scrubbing systems. Efficiency of these systems in average is no higher than 92-96%. Such levels of efficiency of the existing flue gas cleaning equipment cannot satisfy the norms of the legally allowable emissions. One way to resolve the problem of increasing efficiency of flue gas cleaning systems at Ukrainian thermal power plants is to replace existing flue gas cleaning installation with efficient, though costly, equipment. Another way is to implement alternative solutions that may include low-cost options of changing and tuning operational parameters of flue gas cleaning equipment, or to retrofit or top existing equipment with less costly installation with the final (polishing) cleaning equipment (wet electrostatic precipitators (ESP), or fabric filters).

Analysis of the possible solutions for flue gas flows cleaning from particulates in wet scrubbers requires modeling of the processes of particles capturing. Operations and parameters of Venturi scrubbers were extensively investigated and modeled by many researchers (Boll, 1973; Cooper and Leith,

* Author to whom all correspondence should be addressed: e-mail: volchyn@gmail.com; Phone: +38044 4253511; Fax: +38044 5372241

1984; Costa et al., 2005; Goniva and Pirker, 2009; Kropp and Akrbut, 1977; Yung et al., 1984; Ravi et al., 2002).

However, most of the experimental works were performed at a small scale installation, and the obtained results not obviously could be replicated at industrial scale. In this paper, we provide results of our modeling of industrial-scale Venturi wet scrubbers with constructions specific to existing equipment installed at Ukrainian TPPs.

2. Material and methods

2.1. Model description

In Fig. 1, typical arrangement is shown of the wet scrubber with Venturi tube usually installed at the thermal power plants to remove solid particles from the dusted flue gas flow downstream the TPP boiler. A nozzle 6, installed in the converging section 2 of Venturi tube, generates a spray of water droplets to capture solid ash particles moving with the flow of flue gas. After being captured with the droplets, solid particles suspended in the liquid film formed on the walls of mist eliminator 7, as a result of tangential feeding of the flue gas flow from the outlet section 5 of Venturi tube, are further discharged to pulp ash removal system in the bottom of the mist eliminator.

The modeling of the wet Venturi scrubbers has passed a long history, from Calvert et al. (1972), through Boll (1973) and Yung et al. (1984) models, to Goniva and Pirker (2009) and works of Christian Doppler Laboratory on Particulate Flow Modelling (2009), and other researchers. However, the most frequently used and proved model for the calculation of the efficiency of particle coagulation with droplets in Venturi tubes could be obtained from the following consideration (Belousov, 1988; Boll, 1973; CDLPFM, 2009; Flagan and Seinfeld, 1988; Kropp and Akrbut, 1977).

Assume that number of particles at the inlet to Venturi tube is ***N***, and the amount of particles captured by droplets per unit length ***dx*** is ***dN***. Then the particles capturing rate equals Eq. (1):

$$\eta = \frac{N - dN}{N} \tag{1}$$

It is presumed that particles and droplets are moving along Venturi tube in parallel and collide with each other, as a result of the difference in velocities they acquire in the gas flow with the speed that alters along the tube. It is presumed also that number and size of the droplets remain unaltered along Venturi tube. Decrease of the number of solid particles captured by the droplets upon their pass of distance ***dx*** along Venturi tube shall depend on the concentration of the particles, total surface of the droplets, probability of particles capturing by the droplets, and relative velocity of particles toward the droplets speed which yields simple differential equation that allows to calculate decrease of the number of particles in the dusted flow in Venturi tube, as follows (Eqs. 2-3):

$$\begin{aligned} dN &= -\eta_\Sigma \cdot S_d \cdot N_d \cdot \frac{v_r}{v} dx \cdot N = \\ &-\eta_\Sigma \cdot \left(\frac{\pi D_d^2}{4}\right) \cdot \frac{v_r}{v} dx \cdot \frac{q_0}{\rho_l \left(\frac{\pi D_d^3}{6}\right)} \cdot N \end{aligned} \tag{2}$$

$$\frac{dN}{dx} = -\left[\frac{3}{2}\frac{q_0}{\rho_l D_{d0}} \cdot \eta_\Sigma \cdot \left|\frac{v_p - v_d}{v_d}\right|\right] N \tag{3}$$

where:

q_0 – a volume of water sprayed to the dusted gas (kg/m^3);

η_Σ – the collection efficiency of dust particles d_p at the spherical droplets with diameter D_{d0};

ρ_l – the density of a spray water (kg/m^3);

v_p – is the velocity of the dust particles d_p (m/s);

v_d – the velocity of the droplets D_d, (m/s).

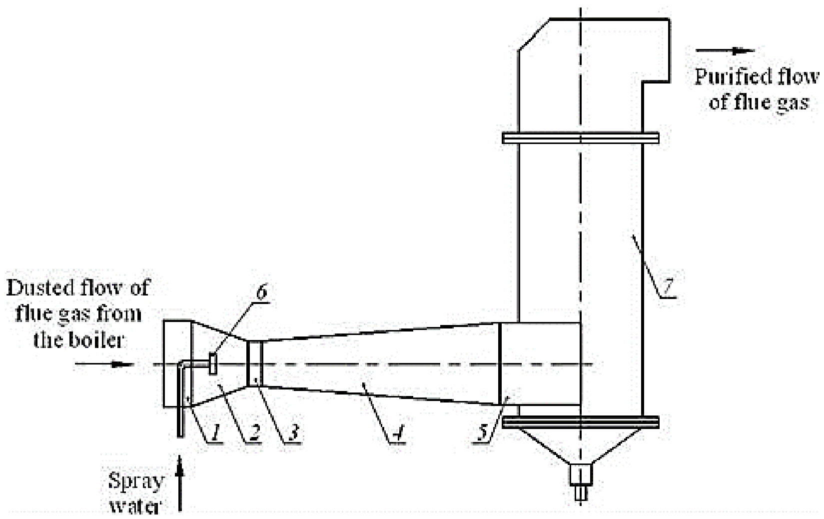


Fig. 1. Typical scheme of the Venturi scrubber installed at the thermal power plants (1 - inlet section, 2 - converging section, 3 - throat, 4 - diffuser, 5 - outlet section, 6 - spray nozzle, 7 - mist eliminator)

Solution of the above differential equation of the efficiency of fly ash particles by droplets in the Venturi tube leads to the following relation (Eq. 4):

$$\eta = 1 - \exp\left(-\frac{3}{2}\int_0^L \frac{q_0}{D_{d0}\cdot\rho_l}\cdot\eta_\Sigma\cdot\left|\frac{v_p - v_d}{v_d}\right| dx \right) \qquad (4)$$

where q_0 is the spray water consumption; η_Σ is the coefficient of dust particles capturing with diameter d_p by the droplets with diameter D_{d0}; D_{d0} is average droplets diameter; ρ_l is water density; v_p is dust particles velocity, v_d is droplet velocity; L is the length of Venturi tube from the edge of the nozzle to the inlet to mist eliminator; x is coordinate along Venturi tube axis.

We believe this approach of determining the efficiency of dust particles capturing with droplets in the industrial scale Venturi scrubbers quite productive, as it is confirmed by many researchers (Boll, 1973; Belousov, 1988; CDLPFM, 2009; Flagan and Seinfeld, 1988; Goniva and Pirker, 2009 and by other researchers), by the results of our calculation presented below, and the experimental data obtained in a process of metering efficiency of Venturi scrubbers installed at large thermal power plants (Kropp and Akrbut, 1977).

Coefficient of dust capturing $\boldsymbol{\eta_\Sigma}$ and $\boldsymbol{|(v_p\text{-}v_d)/v_d|}$ complex are the values which alter along the Venturi tube and depend on the flue gas flow velocity. Also velocities of dust particles and droplets, relative to the flue gas flow velocity, are the functions of particles and droplets diameters. Coefficient of capturing $\boldsymbol{\eta_\Sigma}$ is the probabilistic characteristic that accounts for a Brownian diffusion, interception and inertial mechanism of capturing of dust particles by droplets (Flagan and Seinfeld, 1988; Volchyn and Raschepkin, 2012).

The conclusion from Eq. (4) is that the extent of dust capturing in Venturi tube is the higher the higher are the values $\boldsymbol{q_0 / D_{d0}}$, $\boldsymbol{\eta_\Sigma}$ and $\boldsymbol{|(v_p\text{-}v_d)/v_d|}$. Therefore, maximization of these parameters provides that the total capturing capability of particulates in Venturi tube and in the wet scrubber in general shall increase. Thus, it is important to define which parameters and operational conditions may in the better way help to enhance the efficiency of the fly ash capturing in the wet Venturi scrubber. In the accepted model, Euler-Lagrange approach was applied, where firstly the profile of gas flow in the Venturi tube was calculated. Then, the velocities of fly ash particles and droplets were calculated, accounting the drag force acting on particles and droplets in gas flow with the calculated profile.

The profile of the gas velocity along the Venturi tube (Loytsianskii, 1987) was calculated on the assumption that the vector of velocity in the given cross-section of the tube is directed along the x axis, and the velocity v, pressure p, density ρ and the temperature T are constant across the given section and are considered the values that varies from section to section, following a given law of variation of cross-sectional area of the Venturi tube along x axis. In such an approach, the gas flow is considered to be adiabatic; gas is considered perfect and ideal, and its movement isentropic.

Fig. 2 below shows results of calculation of the gas velocity profile along Venturi tube L= 7.2 m with a gas speed at inlet $\boldsymbol{v_g}$= 22 m/s and gas speed in the throat $\boldsymbol{w_g}$= 70 m/s.

In this model, the relative velocity of the droplets and gas $\boldsymbol{v_r = v_d - v_g}$ is determined by viscous drag forces of the medium (gas), and the movement of the droplet with diameter $\boldsymbol{D_d}$ is determined by the following equation (Eq. 5):

$$\rho_l \frac{\pi D_d^3}{6}\cdot\frac{dv_d}{dt} = \xi\frac{\pi D_d^2}{8}\rho_g v_r^2 \qquad (5)$$

where ρ_g is the density of gas (kg/m^3); ξ – aerodynamic drag coefficient.

For the drag coefficient, various approximation dependencies are used. In this model, for coefficient of resistance to the movement of droplets in gas the following formula was used (Flagan and Seinfeld, 1988) (Eq. 6):

$$\left.\begin{aligned} \xi &= \frac{24}{\mathrm{Re}} + \frac{4}{\sqrt{\mathrm{Re}}} + 0{,}4 \\ \mathrm{Re} &= \frac{D_d \rho_g v_r}{\eta_g} \end{aligned}\right\} \qquad (6)$$

where: Re is Reynolds number; η_g – dynamic viscosity of gas (Pa·s).

After substitution of Eq. (6) into Eq. (5), one obtains the equation which has not analytical solution, and should be solved using numerical methods. Fig. 3 shows the results of calculation of gas velocity profile along Venturi tube and velocities of the droplets in a range of sizes $\boldsymbol{D_{d0}}$ = 25,50,...500 µm, with initial speed 12 m/s at the edge of spray nozzle, typical for spray nozzles used for wet cleaning of the dusted gas flow at the thermal power plants. In the same way, velocity profiles were calculated for fly ash particles, where equations were used, similar to Eq. (5) and Eq. (6), however, drag coefficient $\boldsymbol{\xi' = \xi / C_c}$ in Eq. (6) in this case was adjusted to Cunningham correction factor $\boldsymbol{C_c}$ (Kilpinen and Zevenhoven, 2004).

The finest ash particles with low induction time in their movement practically follow the gas streamlines in the Venturi tube. More massive droplets firstly move in gas slower, but gradually acquire the velocity of gas and in a certain point of the diffuser exceed the velocity of gas. For ash particles, aerodynamic diameter of which is generally smaller than aerodynamic diameter of the droplets, the pattern of movement is similar: ash particles initially move ahead of the more massive droplets, but then lag behind them.

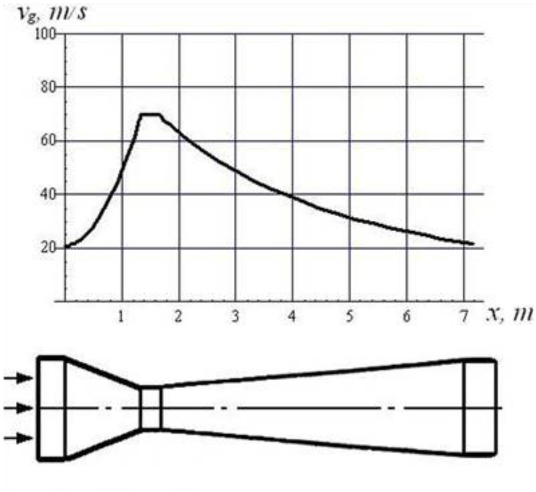


Fig. 2. Distribution of the flue gas v_g velocity along Venturi tube

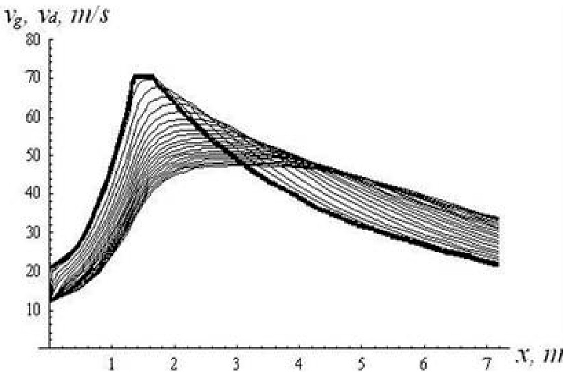


Fig. 3. Distribution along Venturi tube of the flue gas v_g velocity and velocity of droplets $\boldsymbol{v_d}$ with diameters $\boldsymbol{D_{d0}}$=25,50…500 μm

The difference in the speeds of the ash particles and droplets leads to a directed motion of the particles toward droplets, and vice versa. At a time, when the speed of ash particles and droplets become equal, inertial mechanism ceases to act, at some point behind the Venturi throat, and then resumes its action, as shown in Fig. 4.

Collection efficiency $\boldsymbol{\eta_\Sigma}$ of the particles on spherical droplets in Eq. (4) is the probabilistic characteristic, and conditions of coagulation of ash particles on the droplets in the Venturi tube has at least three components, which take into account the Brownian diffusion of particles to the droplets, $\boldsymbol{\eta_d}$, effect of particles interception, $\boldsymbol{\eta_t}$, and the actual inertial impaction of particles with droplets $\boldsymbol{\eta_i}$ (Eq. 7):

$$\eta_\Sigma = \eta_d + \eta_t + \eta_i \le 1 \qquad (7)$$

There a vast information exists, on theoretical and experimental studies on the integrated collection efficiency rate of particles on spheres, $\boldsymbol{\eta_\Sigma}$ (for example, Cooper et al., 1984; Flagan and Seinfeld, 1988; Rudnick et al., 1986). For purpose of this paper, the Brownian component of collection efficiency, $\boldsymbol{\eta_d}$, was used defined by the following approximation given by Flagan and Seinfeld (1988) (Eq. 8):

$$\eta_d = \frac{8}{\mathrm{Re}\cdot Sc}\left[1+\frac{0.4}{\sqrt{2}}\mathrm{Re}^{1/2}Sc^{1/3}+\frac{0.16}{\sqrt{2}}\mathrm{Re}^{1/2}Sc^{1/2}\right] \qquad (8)$$

where $Sc=\eta_g/\rho_g D_B$ is Schmidt number for dust particles with diameter d_p; in which η_g is the dynamic viscosity of gas (Pa·s); ρ_g – gas density (kg/m^3); $D_B= kT_gC_c/3\pi\mu d_p$ is the coefficient of Brownian diffusion, corrected to the Cunningham factor C_c; k – Boltzmann constant, (J/kg); T_g – gas temperature (K).

It is often accepted that for calculations the interception component, $\boldsymbol{\eta_t}$, of the collection efficiency coefficient $\boldsymbol{\eta_\Sigma}$ is combined with coefficient of inertial deposition $\boldsymbol{\eta_i}$ (Kropp and Akrbut, 1977; Belousov, 1988). In our calculations, for the collection efficiency via inertial deposition mechanism the following widely used approximation was adopted (Costa et al., 2005; Rudnick et al., 1986) (Eq. 9):

$$\eta_i = \left(\frac{St}{St+0.35}\right)^2 \qquad (9)$$

in which coefficient of inertial deposition of the dust particles on the droplets is the function of Stokes criterion (Belousov, 1988; Calvert et al., 1972) (Eq. 10):

$$St = \frac{\rho_p d_p^2 (v_p - v_d) C_c}{18\cdot\mu\, D_d} \qquad (10)$$

where ρ_p is the density of dust particles (kg/m^3).

As an example, Fig. 5 shows the calculated distribution of the total collection efficiency $\boldsymbol{\eta_\Sigma}$ along Venturi tube for particles with diameter $\boldsymbol{d_p}$ = 2.5 μm at the droplets with diameters $\boldsymbol{D_{d0}}$ = 25, 50 ... 500 microns. It is seen that to assume collection efficiency being constant along the Venturi tube and equal to unity (contrary to some existing adopted approach of calculating efficiency in the models of Venturi scrubbers (Kropp and Akrbut, 1977), at least for particles with a diameter less than 10 microns, is not correct.

As an example, Fig. 5 shows the calculated distribution of the total collection efficiency $\boldsymbol{\eta_\Sigma}$ along Venturi tube for particles with diameter $\boldsymbol{d_p}$ = 2.5 μm at the droplets with diameters $\boldsymbol{D_{d0}}$ = 25, 50 ... 500 microns. It is seen that to assume collection efficiency being constant along the Venturi tube and equal to unity (contrary to some existing adopted approach of calculating efficiency in the models of Venturi scrubbers (Kropp and Akrbut, 1977), at least for particles with a diameter less than 10 microns, is not correct. Finally, based on Eq. (4), two-dimensional function $\boldsymbol{\eta(d_p,D_d)}$ was calculated, of the efficiency of fly ash particles capturing by droplets in Venturi tube, presented in Fig. 6 for Venturi tube $\boldsymbol{L}$=7.18 m. The obtained function for each pair of values $\boldsymbol{d_p}$, $\boldsymbol{D_d}$ allows to derive efficiency of particles capturing $\boldsymbol{\eta}$ in Venturi tube.

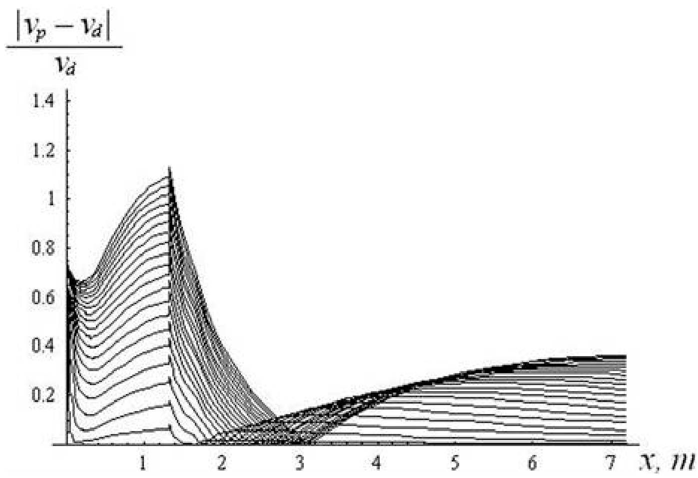


Fig. 4. Variation along Venturi tube of the relative velocity $\left|\frac{v_p - v_d}{v_d}\right|$ of the particle with diameter $\boldsymbol{d_p}$ = 2.5 μm and the droplets in the range of diameters $\boldsymbol{D_{d0}}$ = 25.50 ... 500 μm

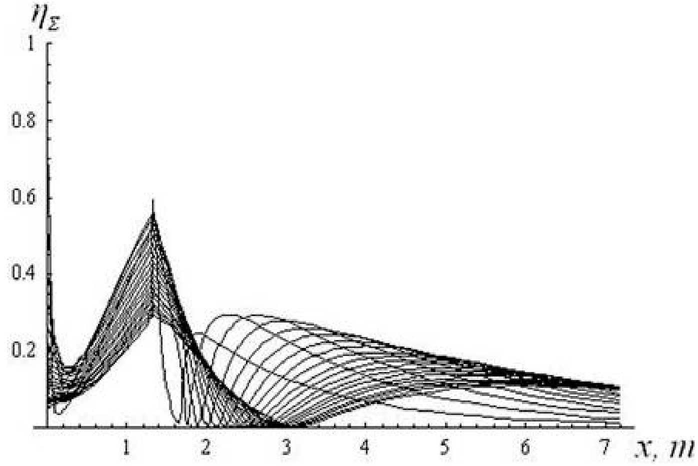


Fig. 5. Variation of the collection efficiency along Venturi tube of the particle with diameter $\boldsymbol{d_p}$ = 2.5 μm at the droplets with diameters in the range $\boldsymbol{D_{d0}}$ = 25.50 ... 500 μm

There is a distinct area of maximum efficiency of solid particles capturing by droplets. Drop behind the hump of maximum efficiency is explained by the fact that in this range of particles and drops sizes their velocities in gas flow are practically equal and inertial impaction cease to act (Fig. 6). Steep elevation of the curve in case of small droplets diameters at fixed spray water consumption $\boldsymbol{q_0}$ only constitute the fact that with such plentitude of droplets they, with high probability, will deposit on coarse solid particles, which is actually is not a capturing.

3. Results and discussion

For various design of Venturi tubes, we assessed how droplet size in the spray water affects overall efficiency of dust capturing in wet scrubbers. The conclusion from this assessment is that upon high gas velocities and moderate spray water consumption the droplets polydispersity scarcely affects overall scrubber efficiency (See also Shyan and Viswanathan, 2000). Similar conclusion was made by Ravi et al. (2002). As it comes from our modeling, this is true for the long Venturi tubes with high gas velocities in the throat. Although efficiency of some shorter Venturi tubes, with lower gas velocity in the throat, may stronger depend on the choice of spray nozzle characteristics, and on the range of the size of generated water droplets, which may affect overall efficiency of dust particles capturing, as it comes from the diagrams presented at Fig. 7, where $\boldsymbol{w_g}$ is the gas velocity in the throat of Venturi tube. In this figure, the dark innermost area presents maximum particles capturing in the Venturi tube, at the level of about 0.9. Rest isolines are set at the decrementing order with a step of 0.1. The resulting effect of flue gas cleaning depends both on the inlet size distribution of the fly ash particles and the droplets size distribution in the spray.

Of practical interest, is the study on how the load of the boiler, and, consequently, flue gas velocity in the throat of Venturi tube, shall affect the extent of the fly ash particles capturing, likewise also, how the amount of spray water may influence effectiveness of dust precipitation by the droplets. To study these issues, the assessment was performed of efficiency of dust capturing in the Venturi tube and mist eliminators of the TPP wet scrubbers for different geometries of Venturi tubes, and upon changing operational conditions. Using the design data presented by Kropp and Akrbut (1977), we modeled dust particles penetration through the mist eliminator versus flue gas velocity at the Venturi tube outlet. Then, for several loads of the boiler we calculated overall efficiency of dust capturing in the wet scrubber. The results of our calculation are presented in Fig. 8. It is seen that decrease of the boiler load to 70 per cent from the nominal, which corresponds to the flue gas flow velocity in Venturi tube throat of w_g=50 m/s, leads to drop of maximum rated efficiency of wet scrubber from 97% to 93%.

The results of calculations show that decrease of boiler load and corresponding decrease of the flue gas velocity w_g in the throat of Venturi tube cause lowering of the overall fly ash capturing in the scrubber. It should be admitted that, contrary to other flue gas cleaning technologies, like electrostatic precipitators (ESP), where decrease of the boiler load leads to increase of the efficiency of flue gas cleaning due to increase of the residence time of particles in the reaction zone, the decrease of boiler load in case of Venturi wet scrubbers causes decrease in dust capturing efficiency, because the principle of this technology lies in an impaction mechanism of capturing solid particles by the droplets, and capturing ability grows with the growth of the flue gas velocity.

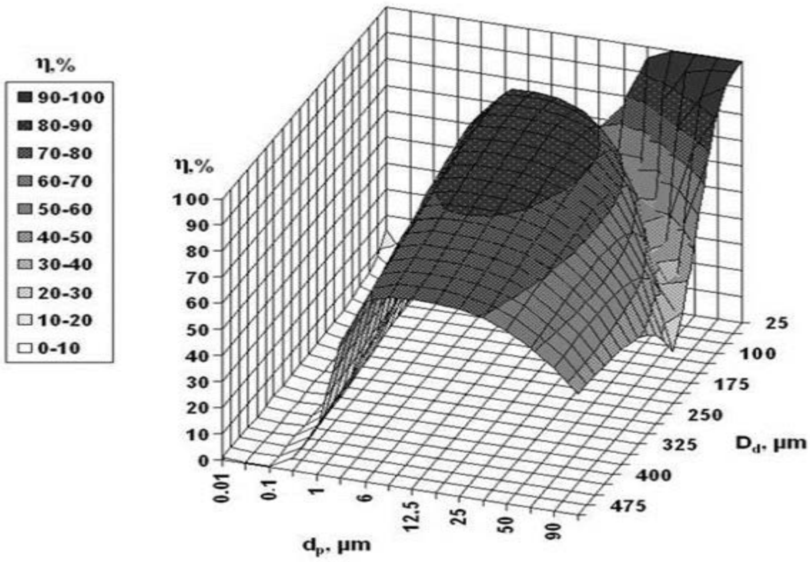
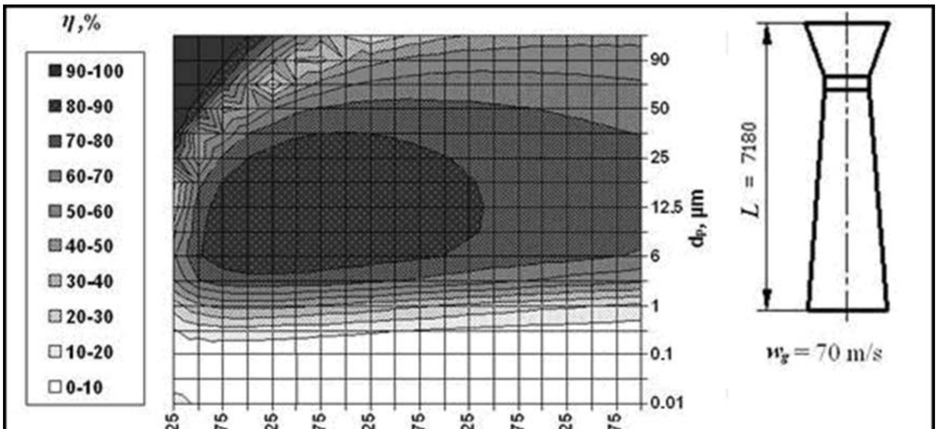
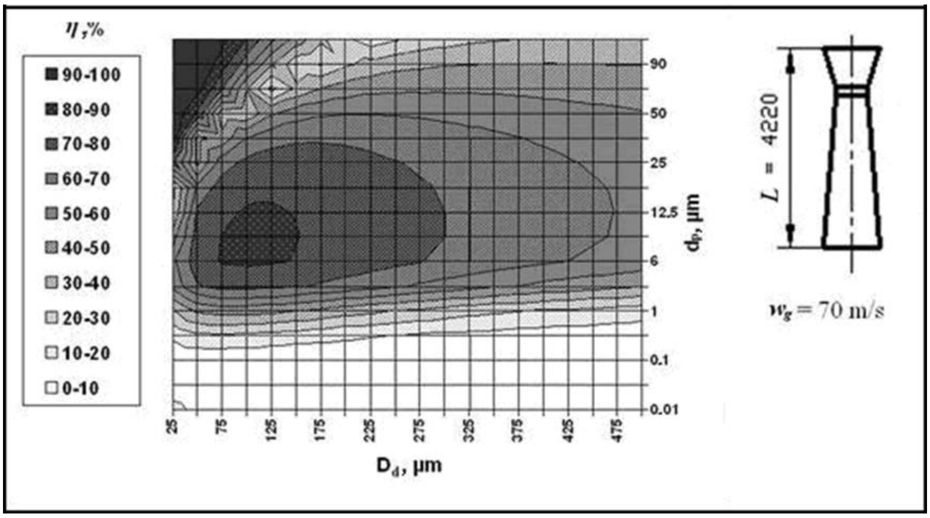


Fig. 6. 3D representation of the efficiency $\eta(d_p,D_d)$ of solid particles capturing with droplets



(a)



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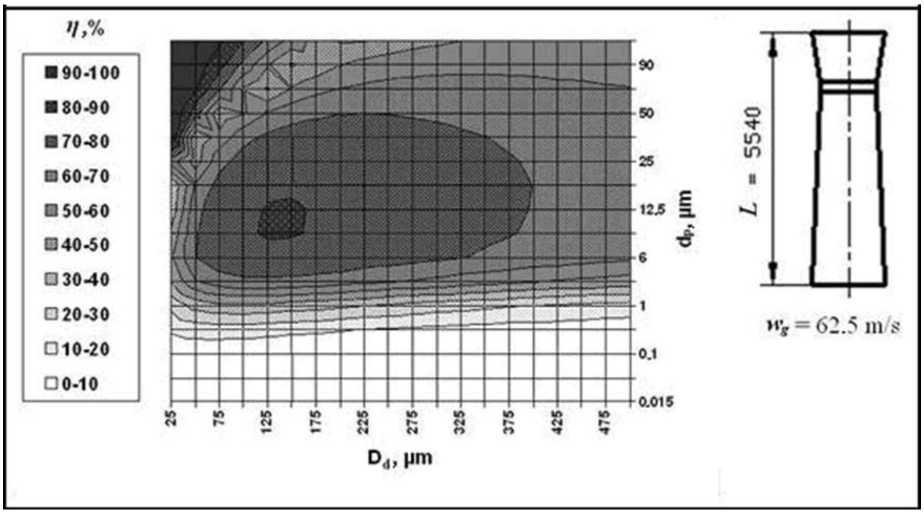

(c)

Fig. 7. Isoline projections of the characteristics ***η(d$_p$,D$_d$)*** for Venturi tubes of various design: (a) – L = 7180 mm, w_g = 70 m/s; (b) – L = 4220 mm, w_g = 70 m/s; (c) – L = 5540 mm, w_g = 62.5 m/s

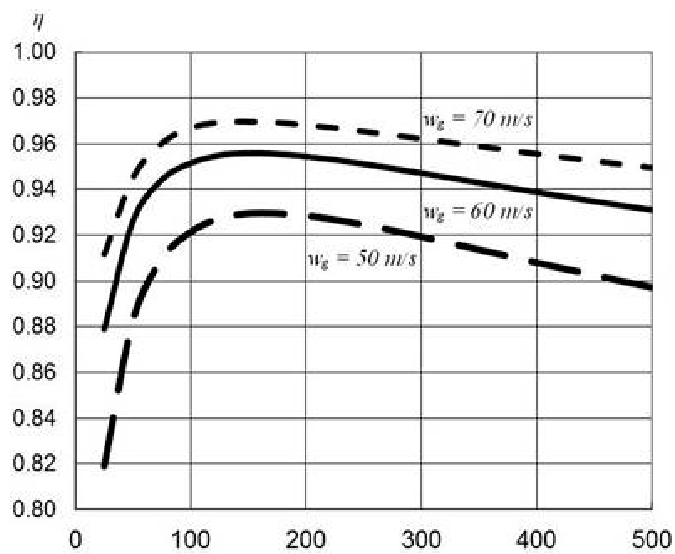

Fig. 8. Dependence of the overall efficiency of dust capturing in the wet Venturi scrubber versus droplet diameter, at different flue gas flow velocities in the throat of Venturi tube

The results of calculations show that decrease of boiler load and corresponding decrease of the flue gas velocity w_g in the throat of Venturi tube cause lowering of the overall fly ash capturing in the scrubber. It should be admitted that, contrary to other flue gas cleaning technologies, like electrostatic precipitators (ESP), where decrease of the boiler load leads to increase of the efficiency of flue gas cleaning due to increase of the residence time of particles in the reaction zone, the decrease of boiler load in case of Venturi wet scrubbers causes decrease in dust capturing efficiency, because the principle of this technology lies in an impaction mechanism of capturing solid particles by the droplets, and capturing ability grows with the growth of the flue gas velocity.

4. Dependence of the fly ash particles capturing efficiency on the droplets diameter

Influence of the size of droplets on an efficiency of dust capturing could be demonstrated by the following example. Suppose that inlet distribution $F_1(d_p)$ of fly ash particles is given by superposition of mass distributions of particles with densities $f_1, f_2, \dots f_n$ so that Eq. (11):

$$F_1(d_p) = f_1 + f_2 + ... + f_n \quad (11)$$

This distribution is presented at Fig. 9 with curve No.1. This is a typical polymodal distribution of fly ash at the outlet of coal firing boilers, burning anthracite and lean coals (Kropp and Akrbut, 1977; Tiwary et al., 2010). Applying the calculated characteristic of the efficiency of fly ash particles capturing in Venturi tube for the fixed droplets diameter D_{d0}, it is easy to obtain the outlet mass distribution of the particles after Venturi tube (Eq. 12):

$$F_2(d_p) = \left[1 - \eta(d_p, D_{d0})\right] \cdot F_1(d_p) \quad (12)$$

Then, the extent of flue gas cleaning from the particulates in Venturi tube with the monofraction of droplets with diameter D_{d0} shall be defined from Eq. (13):

$$\eta(D_{d0}) = \frac{\int_0^\infty \left[1 - \eta(d_p, D_{d0})\right] \cdot F_1(d_p)(dd_p)}{\int_0^\infty F_1(d_p)(dd_p)} \quad (13)$$

Let, in the first case, consider that nozzles at the inlet of Venturi tube disperse volume q_0 of liquid into the droplets of single diameter D_{d0}=125 μm. Then, as shown in Fig. 9, after applying formula (Eq. 2), initial mass distribution of dust particles $F_1(d_p)$ transforms into distribution $F''_2(d_p)$ at the outlet of Venturi tube, presented at the Fig. 9 with curve 2. Let in the second case consider that the same amount of liquid q_0 is dispersed into droplets of single diameter D_{d0}=200 μm. Then, using the correspondent cross-section of characteristic $\eta(d_p, D_{d0})$, outlet dust particles distribution $F'_2(d_p)$ for this case is obtained, presented at Fig. 9 with curve 3.

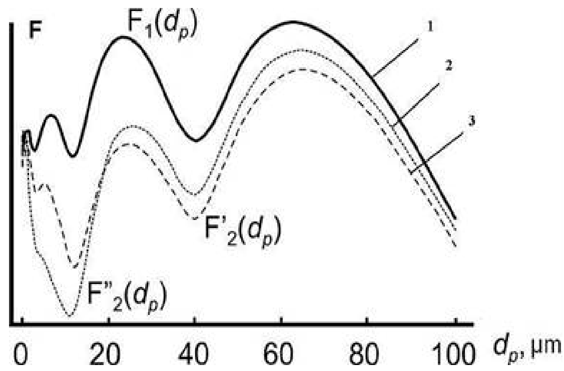

Fig. 9. Input mass polymodal distribution of the fly ash particles $F_1(d_p)$ (Curve 1) and transformation of the function after Venturi tube: Curve 2 is the outlet distribution after spaying flue gas flow with droplets D_{d0}=125 μm; Curve 3 is the same for D_{d0}=200 μm

It is seen from comparison of curves 2 and 3 that upon dispersion of the spray water into finer droplets the share of finer dust particles in the outlet dust distribution is noticeably lower than in case of dispersion of liquid into coarser droplets. Although, from comparison of these curves it also comes that the finer spraying cause decrease in capturing of bigger dust particles by finer droplets. As bigger dust particles have greater mass, the resulting cleaning efficiency of the dusted flow by mass in the Venturi tube in case of a finer water spray is somewhat lower. Thus, it could be concluded that the finer water spray helps to enhance capturing of PM_{10} particles. This qualitative effect leads to the higher quantitative effect, when mass share of fine dust particles in the inlet distribution is higher, like, for example, in case of burning lean coals. Therefore, when designing Venturi scrubbers and choosing the characteristics of the spray water dispersion, the inlet dust particles distribution should be thoroughly considered.

The role of finer droplets should not be overestimated. From our analysis, it could be concluded that droplets with diameter lesser than 50μm during the time of their pass through Venturi tube noticeably lose their mass and size due to intense evaporation. So the diameter of such relatively small particles could not be considered constant. Moreover, while evaporating, these particles are losing their capturing capability, and intense and quick evaporation, in case of excess of spray water, may lead to situation where temperature of flue gases could reach a dew point, causing condensation and potential corrosion of the equipment downstream. Loss in size of the droplets bigger than 100 μm due to evaporation is nearly compensated by their swelling in result of deposition at them of dust particles, and their size in the model could be considered constant.

Until this point, we considered monodisperse droplets sprays. But for real aerosols it is reasonable to account for polydispersity of the water spray. It could be shown that earlier obtained characteristic $\eta(d_p,D_d)$ could be recalculated for a given polydisperse water spay with the known or assumed droplet size distribution function.

Characteristics $\eta(d_p,D_d)$ were obtained upon assumption that the volume of the spray water consumption to Venturi tube nozzles q_0 equals 160 gram per m^3, which provides that the temperature of the resulting flue gas flow shall not reach a dew point. Evident conclusion from formula (Eq. 1) is that for any given value of the spray water consumption q_1 the following relation takes place (Eq. 14):

$$(1-\eta_1)=(1-\eta_0)^{\frac{q_1}{q_0}}, \qquad (14)$$

where η_1 is the efficiency of dust particles capturing in Venturi tube calculated for spray water consumption q_1. Therefore, characteristic $\eta_0(d_p,D_d)$ obtained for the fixed value q_0 could be easily recalculated for any given value q_1, not only for the monodisperse, but also for any arbitrary distribution $f(D_d)$, produced by nozzles of definite design and operation parameters.

Applying the calculated characteristic $\eta(d_p,D_d)$ to the function of the inlet dust particles size distribution, it is possible to calculate the outlet distribution function of dust particles after Venturi tube. Then, integration of the obtained function yields efficiency of the flue gas flow cleaning.

Unlike in case of laboratory scale wet scrubbers, or scrubbers used for outlet gas cleaning in, for example, colour metallurgy, the Venturi wet scrubbers installed at the thermal power plants cannot substantially increment the volume of spray water to enhance the scrubber efficiency. The reason for this is high sulfur content in coal burnt in the TPP boilers (in Ukraine, sulphur content in coal is in the range from 2.5 to 3 percent). Increase of the spray water feeding to a wet scrubber means correspondent decrease of the flue gas temperature, caused by water evaporation, thus creating the medium of potential formation of sulphuric acid in the mist, which could gradually damage the equipment downstream.

Therefore, we overall Venturi scrubber efficiency for different values of the spray water consumption q_0 = 0.16, 0.24 and 0.4 liter/m^3 for Venturi tube with length L = 7.18 m. The results have shown that in case of dispersing water droplets into diameters in the range of 100-150 μm, the assessed total efficiency of Venturi scrubber increases from 97% at q_0 = 0.16 liter/m^3 to 99% at q_0 =0.4 liter/m^3. Experimental tests on Venturi scrubbers efficiency upon increase of spray water consumption were performed by the specialists from All-Union Thermal Engineering Institute (VTI) at Tolyatti CHP (Anichkov et al., 2009). They reported that increase of the volume of spay water in Venturi tube from 0.15 liter/m^3 to 0.45 liter/m^3 caused the raise of the efficiency of flue gas cleaning from 94.55% to 98.85%. The results of our modeling completely coincide with these experimental data. We performed calculations on how the increment of spray water consumption may affect droplets evaporation and correspondent moisture content d_v in flue gas after Venturi tube. The results of calculations are presented at Fig. 10. The fractures in curves presented in Fig. 10 correspond to the moment of time when droplets leave Venturi tube and enter the mist eliminator. Steep growth and dropping of the presented curves are explained by the intensive process of heat and mass exchange between droplets and hot flue gases in Venturi tube (Annamalai and Ryan, 1993; Fernandez et al., 2001), and high values of Nusselt numbers observed in the tube. Normally, the residence time of droplets in Venturi tube is t=0-0.2 seconds. It is seen from Fig. 10 that upon dispersion of spray water q_0 = 0.4 liter/m^3 into single fraction of droplets D_{d0}=100 μm, already in 2 seconds after start of evaporation the moisture content in flue gas reaches saturation point, and further evaporation of the droplets stops, which means that in this case there is a threat of a possible low-temperature corrosion of the equipment downstream the scrubber. Time of evaporation of 100 μm droplets, which capture the fly ash particles most effectively, is about 4 seconds.

Typical residence time of the droplets in the wet scrubber (including mist eliminator) is about 5 seconds. Therefore, saturation and reaching of the dew point by flue gas temperature at spray water volumes q_0 = 0.4 liters/m^3 happens before the flue gas quits the cleaning equipment to the stack.

For spray water consumption at the level q_0 = 0.24 liters/m^3, dispersed into droplets with diameter 150 μm, saturation of the flue gas is reached somewhat later, and therefore the spray water consumption could be increased to 0.24 liters/m^3, on condition that droplets are not entrained from the scrubber. Although even in that case, as simulations reveal, the efficiency of the wet Venturi scrubbers does not exceed 98%, and thus cannot provide the possibility to meet European requirements on the allowable levels of emissions from the coal firing power plants. Therefore, there is a need to seek the ways of increasing fly ash capturing ability, through the retrofit of gas cleaning equipment using, for example, wet ESP and/or fabric filters, installed after the wet scrubbers.

5. Conclusions

The developed improved mathematic model has shown the ways of improving efficiency of particulates capturing in the wet Venturi scrubbers with different design and operating parameters. It is shown that in the long Venturi tubes with high gas velocity in the throat the maximum particles capturing is observed in a wide range of droplet sizes, unlike in case of the shorter Venturi tubes.

Increase of the spray water consumption leads to substantial increment of the efficiency of Venturi scrubbers, theoretically, up to 99 %. Although, volume of the water spray in the industrial wet Venturi scrubbers should provide that no condensation of the wet flue gas and potential corrosion of the equipment downstream occurs.

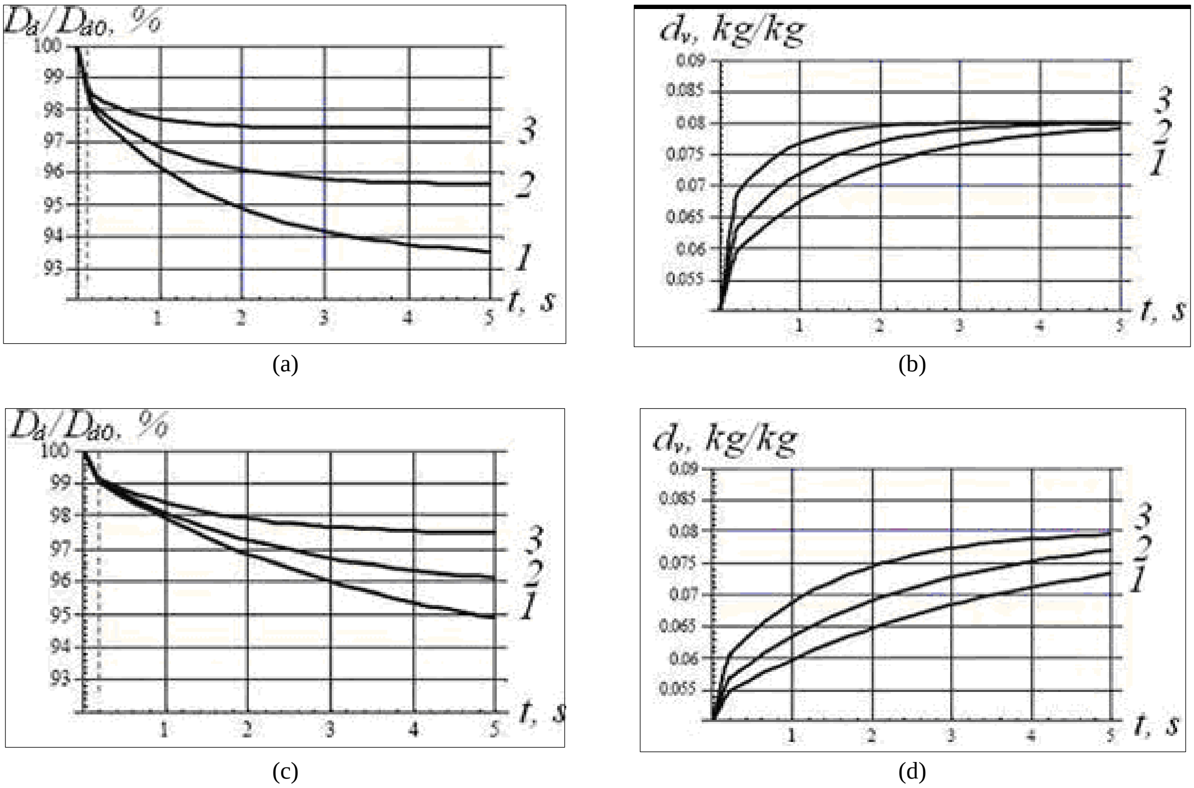

Fig. 10. Dynamics of the change of diameter of droplets 100 μm (a, b) and 150 μm (c, d), and of moisture content in flue gas, as a result of droplets evaporation at different levels of spray water consumption in Venturi tube q_0: 1 – 0.16 L/m^3; 2 – 0.24 L/m^3; 3 – 0.4 L/m^3

Increase of the spray water consumption to 0.24 kg/m^3 allows to noticeably increase Venturi scrubbers efficiency, providing also that the temperature of flue gas does not reach a dew point. Optimal mode of the wet scrubbers operation is the base full-load regime of the boiler, with the maximum flue gas velocity. Decrease of the TPP boiler load to 70 per cent level causes noticeable drop in efficiency of the wet scrubbers.

The results of calculations confirm that the existing, installed at TPPs, Venturi scrubbers cannot provide possibility to meet European requirements on the allowable levels of emissions from the coal firing power plants without additional final flue gas cleaning equipment like, for example, wet electric precipitators, to be installed after the wet scrubbers.

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