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EFFECT OF ATOMIZATION DEGREE OF $CaCO_3$ ABSORPTION SUSPENSION IN SPRAY ABSORBER ON ITS HEIGHT

The paper provides the analysis of the effect of greater atomizing degree of absorption slurry on reducing the height of absorption zone in the absorber, hence the height of the whole absorber, and on reduction of power demand for pumps used to lift the absorption slurry from retention reservoir to atomizers.

1. INTRODUCTION

In boiler flue gas desulphurization plants, where we deal with very large streams of flue gas (reaching or even exceeding 2 mln m^3/h) and due to monolithic construction of absorption suspension reservoir supporting vertical spray absorber, the upper headers with spray nozzles (atomizers) are situated at a height of over 25–30 m. High-elevation head pumps are necessary to feed absorption suspension to such heights and to spray it in the absorber to obtain large interphase contact surface. Volumetric flow rate of the limestone slurry, a geometrical height at which it should be elevated and the spraying pressure required affect the size of pumps and power demand to drive them.

Theoretical pump power rating (excluding its efficiency) is

$$P = \frac{H_c \dot{V}_c \rho_c g}{1000}, \tag{1}$$

where:

P – the theoretical pump power (kW),
H_c – the total elevation head of the pump (m),
$\dot{V}_c$ – the volumetric flow rate of absorption slurry (m^3/s),
g – the gravitational acceleration (m/s^2),

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ρ_c – the density of absorption slurry (kg/m^3).

According to Bernoulli's theorem, the total elevation head of the pump depends on the geometric difference between pump axis and slurry level in the reservoir, geometric lift of slurry being pumped to spray nozzles installed in headers, local and linear pressure drops in pipelines, on pump suction and delivery sides and slurry spraying pressure in the absorber (figure 1).

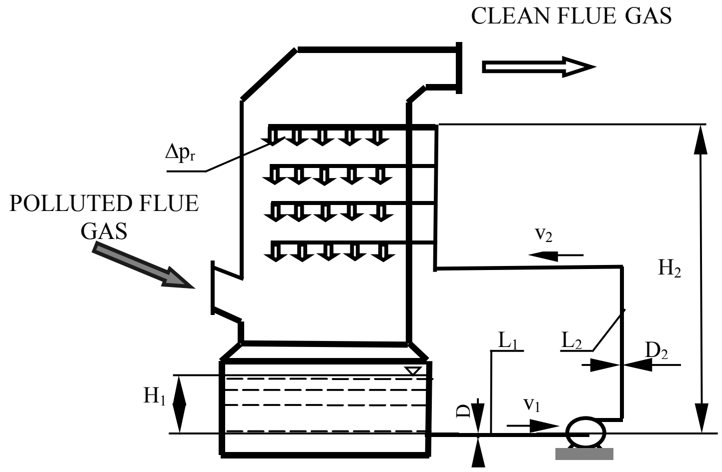

Fig. 1. Circulation of absorption slurry in the system: slurry reservoir – the highest level of slurry spraying in absorber

The equation describing the total elevation head of the pump operating in the absorber for absorption slurry circulation is as follows

$$H_c = -H_1 + \sum\left(\lambda_1 \frac{L_1}{D_1} + \zeta_1\right)\frac{v_1^2}{2g} + H_2 + \sum\left(\lambda_2 \frac{L_2}{D_2} + \zeta_2\right)\frac{v_2^2}{2g} + \Delta p_r\,, \tag{2}$$

where:

H_1 – the liquid column height in absorption slurry reservoir above the pump axis (m),

H_2 – the geometric elevation head for the slurry measured from pump axis to the highest header with spray nozzles in the absorber (m),

D_1, D_2 – the internal diameters of suction and delivery lines, respectively (m),

L_1, L_2 – the length of suction and delivery lines, respectively (m),

v_1, v_2 – the liquid velocity in suction and delivery lines, respectively (m/s),

λ_1, λ_2 – the friction factors in suction and delivery lines, respectively,

ζ_1, ζ_2 – the local loss coefficients in suction and delivery lines, respectively,

Δp_r – the pressure loss in spray nozzle (liquid spraying pressure) (Pa).

2. ANALYSIS OF POTENTIAL REDUCTION OF ABSORBER HEIGHT

The pump power, and thus the energy demand to feed the slurry from reservoir to spray nozzles, may be modified by a change in delivery height to the highest spray nozzles (H_2) and in slurry spraying pressure (Δp_r). The surface level of liquid in the reservoir over the pump axis (H_1) may be changed in a very limited range as it is dependent on many factors affecting pH value of the slurry, its concentration and retention in the reservoir. These factors influence the degree of oxidizing calcium sulfite to calcium sulfate and the gypsum crystallization.

The delivery head (H_2) affects the time of contact between flue gas subjected to desulphurization and the atomized slurry (τ_{kr}) and the interfacial contact surface area ($A_{k.mf}$).

The interfacial contact time is given by the relation:

$$\tau_{kr} = \frac{H_{\text{abs.}}}{w_{w.kr}}, \tag{3}$$

where:

$H_{\text{abs.}}$ – the height of absorption zone in absorber (zone where flue gas comes into contact with droplets) (m),

$w_{w.kr}$ – the relative velocity of droplets in absorption zone of the absorber (m/s).

The relative velocity of droplets is:

$$w_{w.kr} = w_{o.s} - w_g , \tag{4}$$

where:

$w_{o.s}$ – the velocity of free droplet fall in the absorption zone (m/s),

w_g – the average velocity of flue gas in the absorber (m/s).

The velocity of droplet free fall is described by the following equation:

$$w_{o.s} = \sqrt{\frac{4D_S(\rho_{\text{z.abs}} - \rho_g)g}{3\rho_g C_x}} , \tag{5}$$

where:

D_S – the average volumetric/surface diameter of droplets (Sauter's diameter) specifying the atomization spectrum of absorption slurry (m),

C_x – the resistance coefficient of droplet movement (aerodynamic resistance coefficient),

$\rho_{\text{z.abs.}}$ – the density of absorption slurry (kg/m^3),

ρ_g – the flue gas density (kg/m^3).

The interfacial contact surface area is given by the equation:

$$A_{k.mf} = S_{kr}\left(\frac{V_c}{V_{kr}}\right) = \frac{6\dot{V}_c H_{\text{abs.}}}{D_S(w_{o.s} - w_g)} = 6\frac{\dot{V}_{g2}}{D_S}\left(\frac{L}{G}\right)\tau_{kr}\,, \tag{6}$$

where:

G – the flow rate of desulphurized flue gas under conditions created at absorber outlet (m^3/s),

L – the volumetric flow rate of absorption slurry atomized in the absorber (dm^3/s),

S_{kr} – the surface area of a droplet treated as a rigid ball (m^2),

V_c – the volume of absorption slurry suspended in the absorption zone (m^3),

V_{kr} – the volume of individual droplet of absorption slurry (m^3),

$\dot{V}_c$ – the volumetric flow rate of absorption slurry atomized in the absorber (m^3/s).

The slurry spraying pressure (Δp_r) affects the degree of its atomization and hence the diameters of droplets (D_S) in the atomization spectrum. A substantial atomization degree means small diameters of droplets of poly-dispersion system in the form of atomization spectrum. Obviously, a considerable atomization degree affects advantageously the total surface area of droplets suspended in the stream of flue gas subjected to desulphurization (equation (6)), since the increase of interfacial contact area of slurry in the absorber (equation (7)) improves the desulphurization efficiency (equation (8)).

The stream of SO_2 flowing from gaseous phase (flue gas) to liquid phase (absorption slurry) is determined by the equation of the general form:

$$\dot{n}_{SO_2} = k_{SO_2} A_{k.mf} \Delta\pi_{SO_2} = \frac{\dot{V}_g (y_1 - y_2)}{M_{SO_2}}\,, \tag{7}$$

where:

k_{SO_2} – the mass penetration coefficient (kmol/(m^2·s)),

M_{SO_2} – the molar mass of SO_2 (g/kmol),

$\dot{V}_g$ – the volumetric flow rate of flue gas subjected to desulphurization (m^3/s),

y_1 – the SO_2 concentration in flue gas at the inlet to the absorber (g/m^3),

y_2 – the SO_2 concentration in flue gas at the outlet from the absorber (g/m^3),

$\Delta\pi_{SO_2}$ – the average driving module of mass penetration.

Desulphurization efficiency is given by:

$$\eta_{SO_2} = \frac{y_1 - y_2}{y_1}\,. \tag{8}$$

Relation (6) shows that the interfacial contact area in the absorber may be increased by applying higher: (i) volumetric flow rate of atomized slurry, (ii) height of the absorption zone in the absorber, (iii) velocity of flue gas and (iv) by using smaller droplet diameter, i.e. lower velocity of their free fall. It is not advantageous to increase the volumetric flow rate of the slurry and the height of the absorption zone as these parameters in plants have essential impact on the pump power rating. It would be better to search for any efficient means allowing these values to be reduced. It is possible, for example, to increase the atomization degree of absorption slurry by applying higher spraying pressure (Δp_r) which at the same, or even smaller, volumetric flow rate of slurry fed to spray nozzles ($\dot{V}_c$) and a smaller height of the absorption zone in the absorber (H_{abs}) would lead to the larger unit surface area of slurry droplets suspended in flue gas stream. Hence, based on the analysis of equation (6), we arrive at:

$$a_{k.mf} = \frac{A_{k.mf}}{V_{abs}} = \frac{4A_{k.mf}}{\pi D^2_{w.abs} \cdot H_{abs}} . \tag{9}$$

where $a_{k.mf}$ is the unit surface area of interfacial contact (related to the unit of absorber volume being active in mass exchange process) (m^2/m^3).

3. EFFECT OF ABSORPTION SLURRY ATOMIZATION DEGREE ON EFFICIENCY OF FLUE GAS DESULPHURIZATION AND HEIGHT OF ABSORPTION ZONE IN SPRAY ABSORBER

It is worth following the example of slurry atomization with eccentric rotary atomizers with empty spraying cone with a stream of droplets in order to define the relationship between flue gas desulphurization efficiency and atomization degree of absorption slurry and the height of absorption zone in the absorber. Figure 2 shows a characteristic curve that represents the work this atomizer. It also presents a simplified equation for the volumetric flow of ground limestone slurry being sprayed versus the spraying pressure.

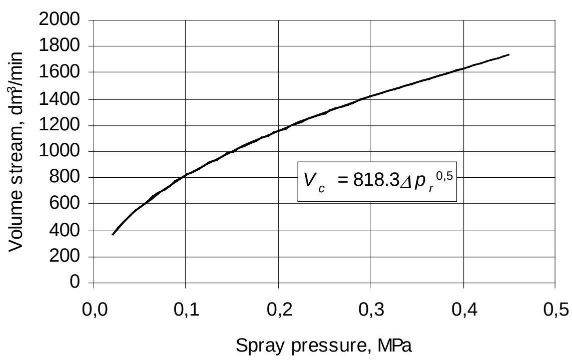

Fig. 2. Characteristic curve of work of eccentric atomizer of $CaCO_3$ slurry

The atomization degree of absorption slurry determined based on average Sauter's diameter of droplets is shown in figure 3. The curve in figure 3 proves that the absorption slurry should not be sprayed when its pressure upstream the atomizer is lower than 0.1 MPa.

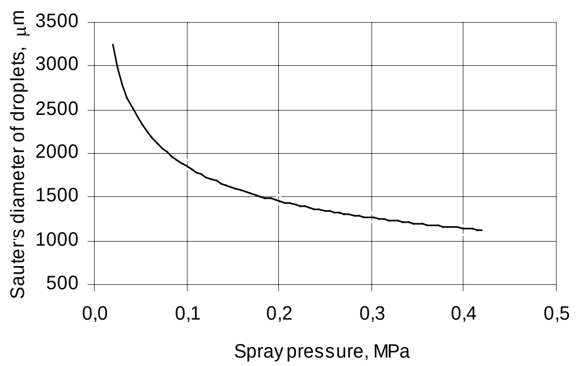

Fig. 3. Average Sauter's diameter of droplets versus absorption slurry spraying pressure

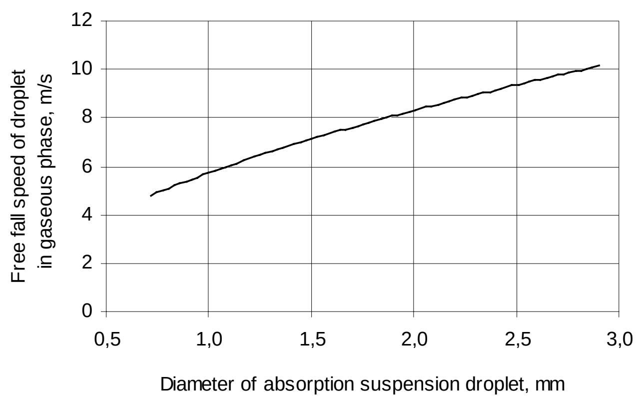

Fig. 4. Free fall velocity of absorption slurry droplets

The relation between the free fall velocity of droplets and their size, calculated according to equation (5), is shown in figure 4. The value of the resistance factor C_x in equation (5) was calculated from the relation [1]:

$$C_x = \pi\left(0.128 + \frac{12.8}{Re}\right), \tag{10}$$

which may be used in a wide range of the Reynolds number, i.e. from 2 to $1 \cdot 10^4$, defined as follows:

$$Re = \frac{w_{o.s} D_S}{\nu_g}, \tag{11}$$

where ν_g is the flue gas kinematic viscosity (m^2/s).

When we insert equation (11) into (10), and then the resultant formula into equation (5), the following quadratic equation is obtained:

$$w_{o.s}^2 0.384\pi\rho_g + w_{o.s}\frac{38.4\pi\rho_g \nu_g}{D_S} = 4D_S g(\rho_{z.\text{abs}} - g_g)\,. \tag{12}$$

It allows us to determine the free fall velocity ($w_{o.s}$) of a droplet in gaseous phase.

If we assume that the flue gas desulphurization efficiency, as guaranteed by the tenderer for specific power unit, is not lower than 95%, then it depends on the absorption slurry atomization degree, as specified by Sauter's diameter of droplets, and if the volumetric flow rate of flue gas subjected to desulphurization and also the flow rate of absorption slurry are kept constant, and when the spray nozzles applied are of the same type and size, the required height of the absorption zone in the absorber would change, depending on the atomization degree as shown in figure 5 and in table 1. The dashed line in figure 5 specifies the conditions necessary to reach the flue gas efficiency of 95%; these conditions are also given in table 1.

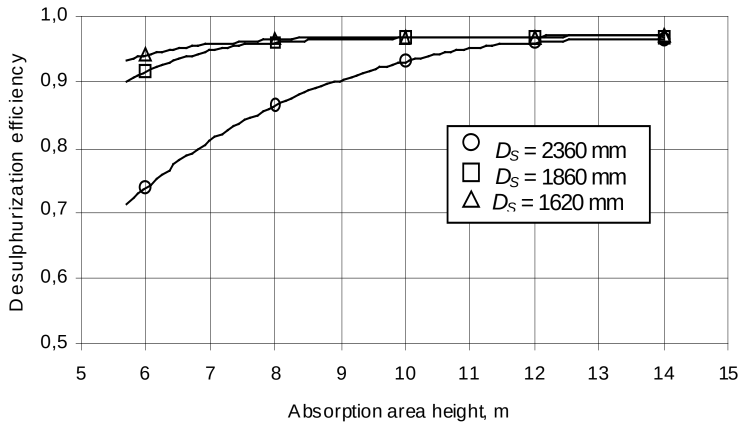

Fig. 5. Desulphurization efficiency versus height of absorption zone in vertical spray absorber and diameter of absorption slurry droplets (L/G = 12 dm^3/m^3)

The efficiency of flue gas desulphurization for variable (preset) parameters of the absorber operation was calculated using my own correlation based on the experiments having been run at fractional technical scale plant, and the results of full-scale examinations are available in bibliography [2]–[4].

The calculations were made for the following conditions:

• the flue gas temperature of the absorber inlet and outlet of 413 K and 323 K, respectively;

• the absorber diameter: 15.0 m;

• $CaCO_3$ slurry at 12% wt/wt. concentration (pH 5.8) is sprayed in the absorber using eccentric atomizers (characteristic curves shown in figures 2 and 3);

• SO_2 concentration in gaseous phase: 2,500 mg/m^3.

The greater the atomizing degree of absorption slurry, the higher the spraying pressure. Hence, the operating conditions of atomizers should be made such that the spraying pressure be definitely higher than that having been used so far in operating plants (0.05–0.07 MPa). At the spraying pressure of 0.1–0.15 MPa, very high efficiency of flue gas desulphurization can be reached. The increase in effective contact surface between flue gas and atomized absorption slurry due to an increased spraying pressure does not have to be a result of applying the pumps of higher elevation head.

It is not necessary to use the pumps with higher elevation head in order to rise the spraying pressure of absorption slurry – such an effect may be a result of reducing the height of absorption zone in the absorber, since according to equation (2) when the elevation head of absorption slurry (H_2) in the system is reduced, the spraying pressure (Δp_r) in the absorber increases.

As it has been proved in the aforementioned analysis, absorbers used for flue gas desulphurization do not have to be so high and so expensive as it has been practiced so far to meet the requirements of the efficiency of flue gas desulphurization (table 1).

Table 1

Height of SO_2 absorption zone in spray absorber versus atomizing degree of absorption slurry

Volume stream of wet flue gas (m_n^3/h)	Flue gas velocity in scrubber (m/s)	Ratio of liquid to flue gas volume streams (L/G) (dm^3/m^3)	Sprayed liquid volume stream (m^3/h)	Liquid spray pressure (MPa)	Absorption liquid pH	Sauter's diameter of droplets (mm)	Absorption area height (m)	Desulphurization efficiency (%)
1,600,000	3.5	12	19,200	0.05	5.4	2.36	11.0	95.0
1,600,000	3.5	12	19,200	0.10	5.4	1.86	7.0	95.0
1,600,000	3.5	12	19,200	0.15	5.4	1.62	6.4	95.0

The zone of reduced absorption in the absorber means that the total height of this piece of equipment is also reduced. Also the power demand to drive the pumps feeding the atomizers is decreased. Power advantages resulting from a higher degree of atomizing the absorption slurry in the absorber are summarized in table 2.

Table 2

Effect of reduced height of absorption zone in the absorber due to increased atomizing degree of $CaCO_3$ absorption slurry on reduced theoretical power demand to drive pumps feeding the slurry to atomizers

Suspension spray pressure (MPa)	Absorption area height (m)	Decrease of absorption area height (m)	Required theoretical pump power for lifting the suspension to the atomizers (kW)	Decrease of required theoretical pump power for lifting the suspension to the atomizers (kW)	Decrease of power (%)
0.05	11.0	0.0	690.6	0.0	0.0
0.10	7.0	4.0	439.5	251.1	36.4
0.15	6.4	4.6	401.8	288.8	41.8

When atomizing degree of $CaCO_3$ slurry is increased by a change in the pressure of its spraying, which allows us to reduce the height of the absorption zone in the absorber, a substantial reduction of power demand necessary to drive the pumps feeding the slurry to atomizers is achieved. When atomizing pressure is risen from 0.05 to 0.1 MPa, the power demand is reduced by 36.4%; when the pressure is 0.15 MPa, the power demand reduction equals 41.8%.

The above analysis takes no account of the power demand for slurry atomizing process. The issue will be discussed in another paper.

4. CONCLUSIONS

According to the aforementioned analysis of the relation between the height of absorption zone in vertical spray absorber and atomization degree of $CaCO_3$ absorption slurry in the process of boiler flue gas desulphurization, one can find that an increase in the absorption slurry atomization degree:

- leads to larger surface of interfacial contact and higher efficiency of flue gas desulphurization in the absorber,
- allows us to reduce the absorption zone in the absorber, hence the total height of the absorber without deteriorating the efficiency of flue gas desulphurization (while the volumetric flow rate of sprayed absorption slurry remains unchanged),
- reduces the power demand for pumps that lift the absorption slurry to specified geometric height (to atomizers).

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WPŁYW STOPNIA ROZPYLENIA ZAWIESINY ABSORPCYJNEJ $CaCO_3$ W ABSORBERZE NATRYSKOWYM NA JEGO WYSOKOŚĆ

Zanalizowano wpływ zwiększenia stopnia rozpylenia zawiesiny absorpcyjnej na zmniejszenie wysokości strefy absorpcji w absorberze, a tym samym całego absorbera, oraz na ograniczenie składowej zapotrzebowania mocy pomp na podnoszenie zawiesiny absorpcyjnej ze zbiornika retencyjnego do rozpylaczy.