

## OPTIMIZATION OF DESULPHURIZATION PROCESS IN A FLUE GAS ABSORBER BY ADJUSTING FLOW PATTERNS AND ROTARY ATOMIZER

Katolicky J. \* and Jicha M.

\*Author for correspondence

Faculty of Mechanical Engineering,  
 Brno University of Technology,  
 Brno, Technicka 2, 61669,  
 Czech Republic,  
 E-mail: katolicky@fme.vutbr.cz

### ABSTRACT

Efficiency of desulphurization process in a flue gas absorber depends strongly on flow patterns of the continuous gas phase and interaction with water slurry phase that is injected into the absorber. The main task is to ensure that undesulphurized flue gas moves optimally to where a high concentration of water slurry in the form of droplets “flies”.

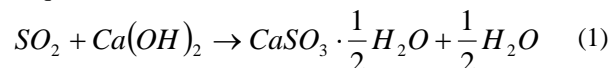
In the paper, a model for desulphurization process is presented. The problem was solved using commercial CFD code StarCD into which a model for desulphurization was integrated. The model distinguishes between two phases of heat and mass transfer. One called “constant rate period” where the water droplet formed by an aggregate of calcium hydroxide particles encapsulated in water evaporates by convection mechanism and sulphur dioxide is transferred by the same mechanism. In this phase the spherical reaction front recedes as calcium hydroxide is converted. In the second phase called “falling rate period” water is contained only in the free space between solid particles of calcium hydroxide and sulphur dioxide is transferred by diffusion that is modified by tortuosity reflecting torturous paths inside the structure of particles. By the same mechanism water evaporates from the aggregate of particles.

A model for age of flue gas was developed that shows residing time of flue gas in individual parts of the absorber. Together with values of water content and void fraction of water phase one can suggest different design modifications of the absorber (for example different inclination of inlet vanes that guide the flue gas into the absorber).

### INTRODUCTION

Many different methods are available for a reduction of the emissions of SO<sub>2</sub> from the flue gases. The main flue gas desulphurization technology is based on absorption of SO<sub>2</sub> in

lime slurry. Several different types of flue gas absorber are available for desulphurization process. In this case, optimization was done for the absorber with the semi-dry desulphurization process. The semi-dry desulphurization process is generally represented by the following overall reaction equation (1).



The absorbed SO<sub>2</sub> reacts in the alkaline aqueous phase with the dissolved lime. Although the overall reaction equations are simple, the chemistry is quite complex. Detailed information about the most relevant chemical reactions involved in the total desulphurization process can also be found in the literature. For instance, the SO<sub>2</sub> absorption is analysed in detail by Pasiuk-Bronikowska and Rudzinski [1]

Experimental and theoretical studies have shown that numerous species in the slurry are of importance to the absorption [2]. And also the experimental studies generally confirm the importance of the flow pattern in the desulphurization process [3,4]. Aspects such as residence times of fluid, flow field disposition in a place of flue gas and slurry contact have significant influence on desulphurization process. No less important are the implications of quality of lime slurry splashing as droplet size spectrum. Droplets trajectories and momentum are significantly determined by just the droplet size and that determines which droplets impacts and sticks on a wall. All the above factors affect on the desulphurization effectiveness.

The deficiency of some above factors can be remedied by the use of detailed Computational Fluid Dynamics simulations that account for both the local flow conditions and the mass transfer of SO<sub>2</sub> between flue gases and lime slurry.

## NOMENCLATURE

$A$	[m <sup>2</sup> ]	surface area
$C$	[-]	concentration
$d$	[m]	droplet diameter
$k$	[m/s]	mass-transfer coefficients
$\dot{N}$	[kmol/s]	mole flux
$N$	[-]	frequency
$Re$	[-]	Reynolds number
$S$	[-]	geometrical factor
$Sh$	[-]	Sherwood number
$Sc$	[-]	Schmidt number
$t$	[s]	time

### Special characters

$\beta$	[m/s]	mass-transfer coefficients
$\delta$	[m <sup>2</sup> /s]	diffusivity
$\mu$	[-]	tortuosity factor
$\rho$	[kg/m <sup>3</sup> ]	density

### Subscripts

$ag$	agglomerate
$g$	gas
$I$	interface
$S$	species

## MODEL OF DESULPHURIZATION PROCESS DESCRIPTION

The model for SO<sub>2</sub> absorption is based on the combination of a model for the heat and mass transfer processes for a single droplet with a simple model for the two phase flow of gas and droplets inside a flue gas absorber.

In the flue gas desulphurization process the hot flue gas gets in contact with a fine spray of lime slurry suspension in a reaction chamber where a droplet residence time of 10–15 s is provided. During this time the sprayed droplets simultaneously evaporate and absorb SO<sub>2</sub>. The absorbed SO<sub>2</sub> reacts in the alkaline aqueous phase with the dissolved lime. The desulphurization efficiency in a flue gas absorber is the result of the reciprocal impact between the SO<sub>2</sub> absorption rate in the slurry droplets and the water evaporation rate from the droplets [5,7,8].

Both processes are intensive near the atomizer where high relative velocities between flue gas and droplets result in increased mass and heat transfer rates. Lower transfer rates can be expected further in the absorber chamber, decreasing significantly after the formation of a solids porous coherent crust around the droplets. The whole process can be divided into two steps. First one labelled as a 'constant rate' phase, where a droplet consist of a cluster of particles enclosed in water film. This phase accounts for most of the sulfur removal, until the solid crust starts to form on the surface of the droplets. Second phase labelled as 'falling rate', where a water film on surface was evaporated and water is only inside of the droplets. [5,6,8].

The model solves simultaneous evaporation of aqueous phase from a surface of single droplets and mass transfer SO<sub>2</sub> between flue gas and single droplet. Mole flux of SO<sub>2</sub> between flue gas and droplet is described by following equation.

$$\dot{N}_{SO_2} = \rho_g k_{g,SO_2} A_I (C_{SO_2,g} - C_{SO_2,I}) \quad (2)$$

As fundamental parameter, the overall mass-transfer coefficients  $k_{g,SO_2}$  for SO<sub>2</sub> in the gas phase is calculated according to following equation.

$$k_{g,SO_2} = \left[ (\beta_{SO_2})^{-1} + \left( \frac{\delta_{SO_2/gas} S_{d_i,d_{ag}}}{\mu A_{ag}} \right)^{-1} \right]^{-1} \quad (3)$$

The first term in the equation (3)  $\beta_{SO_2}$  is mass-transfer coefficient in the gas phase based on the Sherwood number Sh. This is done, for any gas species S as

$$Sh = \frac{\beta_S d}{\delta_S} \quad (4)$$

where, d is the droplet diameter and  $\delta_S$  is the diffusivity of species S in the gas phase. The Sherwood number is calculated with the often used correlation for spherical droplets.

$$Sh = 2 + 0.6 Re^{1/2} . Sc^{1/3} \quad (5)$$

The second term in equation (3) is used only in falling rate phase, where  $S_{di,dag}$  is a geometrical factor, which takes into account difference between diameter of dry agglomerate and diameter of reaction zone.  $A_{ag}$  is surface of droplet consist of only dry agglomerate and  $\mu$  is tortuosity factor.

## AGE OF FLUE GAS MODEL DESCRIPTION

Age of flue gas model was used for assessment of the residential time of flue gas and its contact with lime slurry in a local part of absorber. The age of flue gas is time  $t_p$  required to get to common location p from the inlet. For consideration of age of flue gas in any location is necessary to take into account overall population of gas particles, whereas each one is characterized by cumulative distribution function  $F(t)$  and frequency distribution function  $f(t)$ .

$$F(t) = \int_0^t f(t) dt \quad (6)$$

$$t_p = \int_0^\infty t f(t) dt \quad (7)$$

In case, that time is expressed as dimensionless concentration C, then time  $t_p$  can be express as follows.

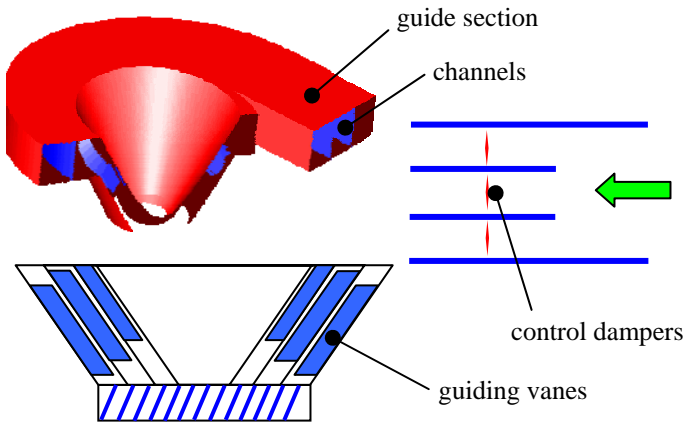
$$t_p = \int_0^{\infty} \left[ 1 - \frac{C_p(t)}{C_p(\infty)} \right] dt \quad (8)$$

The basic equation that solves the age of flue gas in form of concentration C has the following form.

$$\frac{\partial C_p}{\partial t} + \frac{\partial(u_j C_p)}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \Gamma \frac{\partial C_p}{\partial x_j} \right) + S_c \quad (9)$$

## MODEL OF ABSORBER DESCRIPTION

Modelled domain of desulphurization absorber consists of two parts. The guiding section is located in the upper part of the absorber. This part is formed by nine channels leading into three concentric cones. **Figure 1** shows one of the three concentric cones, where guiding vanes are located around circumference. The flow rate control through individual channels is carried out by control dampers at the inlet of the channels.



**Figure 1** Guide section of the desulphurization absorber

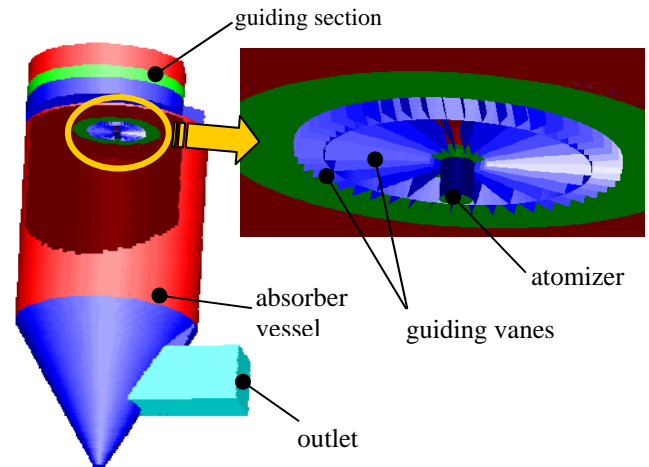
Second part of desulphurization absorber is the vessel of the absorber into which flue gas flows from the guiding section at the top of the absorber. Flue gas is supplied into vessel through the two rows of guiding vanes (**Figure 2**). Under the top of the vessel a rotary atomizer is placed in centre of the flue gas supply. The rotary atomizer sprinkles lime slurry droplets into hot flue gas in the vessel. An outlet of the absorber is located at the lower part of the vessel. The basic dimensions of the vessel are: diameter 12.6 m, height 18.5 m. The total height of the absorber is 22.5 m.

Optimization of flow pattern was carried out for following operational condition: flue gas flow rate of 512 000 m<sup>3</sup>/h, flue gas temperature at the inlet 152 °C, lime slurry flow rate of 18.25 m<sup>3</sup>/h and lime slurry temperature 30 °C.

The radial and tangential velocity and droplet size distribution, characterized by SMD (Sauter mean diameter),

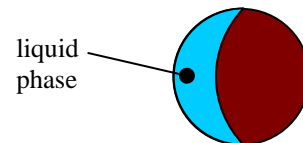
where used as input data for the solution of discrete phase (lime slurry droplets).

$$SMD = \frac{\sum N_i \cdot d_i^3}{\sum N_i \cdot d_i^2} \quad (10)$$



**Figure 2** The desulphurization absorber

Due to the high speed of the rotary atomizer that causes high centrifugal forces, the liquid phase flows out only through a part of the nozzles opening as shown in **Figure 3**. This effect had to be taken into account in calculation of radial velocity. The actual radial velocity is greater than the velocity corresponding to the area of the nozzle opening.



**Figure 3** Schema of liquid phase outflow from nozzles opening

These quantities were obtained from literature empirical relation [9,10]. Input data were determined for the following conditions:

revolutions of rotary atomizer	5000, 7800, 10000 min <sup>-1</sup>
number of nozzles around the atomizer	16, 32
diameter of nozzles	6, 8 mm.

Droplet size distribution was divided to 5 size fractions and number of injection positions around the atomizer was 240, this mean 1200 computational droplet parcels.

Optimization of the flow pattern in relation to desulphurization efficiency was carried out via control flow rate through individual channels in guiding section using control dampers. The second parameter was the setting of two rows of guiding vanes in the upper part of the vessel, which was combination of 15 ° and 30 ° for each of row. The last sets of parameters were conditions of injecting lime slurry which depend on condition of atomizer described above.

## RESULTS AND CONCLUSIONS

By solving the equation for the flue gas age we tried to investigate the relation between the time that flue gas spent in a certain zone of the reactor and the concentration of SO<sub>2</sub>. Obviously, longer time is needed in the zones with a low content of dispersed suspension and a shorter time is sufficient in the zone with high content of dispersed suspension.

The results of the solved variants show that the flow pattern in the absorber plays a crucial role in the effectiveness of desulphurization. The setting of two rows of the guiding vanes (**Figure 2**) at the upper part of the vessel has the biggest impact on the flow pattern. The results of the parametric study aimed at the characteristics of the rotational atomizer indicate relatively small impact on the process of desulphurization when the parameters of the rotary atomizer are within the range of the recommended values (circumferential speed lower than 150 m/s). The results can be seen in **Figure 4**.

The high rotation speed leads to generation of smaller droplets with higher speed at the outlets of the atomizer channels. The smaller droplets have a lower range, travel at a smaller radius and fill up smaller part of the volume of the absorber. The liquid phase (volumetric ratio) spreads to the lower part of the absorber. A higher number of the radial channels (32 compared to 16) on one side decreases the radial speed of the droplets, but only in case of small droplets. The overall characteristic of the absorber performance does not change.

The character of evaporation slightly changes at the low speeds of the rotary atomizer (5000 min<sup>-1</sup>) due to the lower speed at which the suspense leaves the rotary atomizer. This reduces recirculation in the core of the absorber, but the total amount of evaporated substance does not change much. The evaporation take place mostly in the lower part of the absorber in this case.

It can be generally stated that the rotational speed, number of channels, diameter of the atomizer and the area of the channels do not have a significant impact on the results.

The biggest impact on the flow pattern was the angle of the guiding vanes of the inner and outer ring of the flue gas inlet in the cylindrical part just above the rotary atomizer. This is obvious from the results of the flue gas age that indicate the period of time the flue gas spends in different zones of the absorber **Figure 4**. The closing of the dampers in the channels makes the evaporation more asymmetrical.

The following conclusions can be drawn from the comparison of different flow regimes and guiding vanes settings:

Concentrations of SO<sub>2</sub> show a good correlation with the age of the flue gas. In the areas with the high values of the gas flue age are low concentrations of SO<sub>2</sub>. This is given by the fact that in such areas is a high concentration of discrete liquid phase (void fraction). In other words most of the spray from the atomizer ends up in this area

The highest concentrations of SO<sub>2</sub> occur in the variant I30\_E30. The pitch angle of the guiding vanes is maximal and the flue gas is lead to the circumference of the reactor. It was assumed in the calculations that the droplets containing more than 50% of water would end up on the wall where they would evaporate. The small droplets would ricochet off the wall and continue in their way.

## ACKNOWLEDGMENTS

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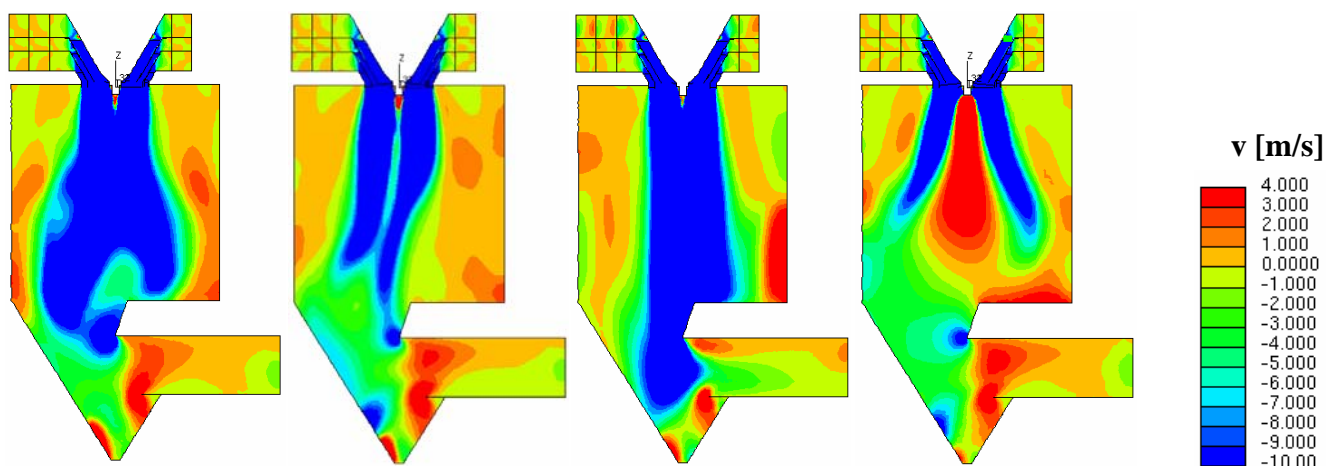
I15\_E30

I30\_E15

I15\_E15

I30\_E30

Vertical velocity component



Age of flue gas



Concentration SO<sub>2</sub>

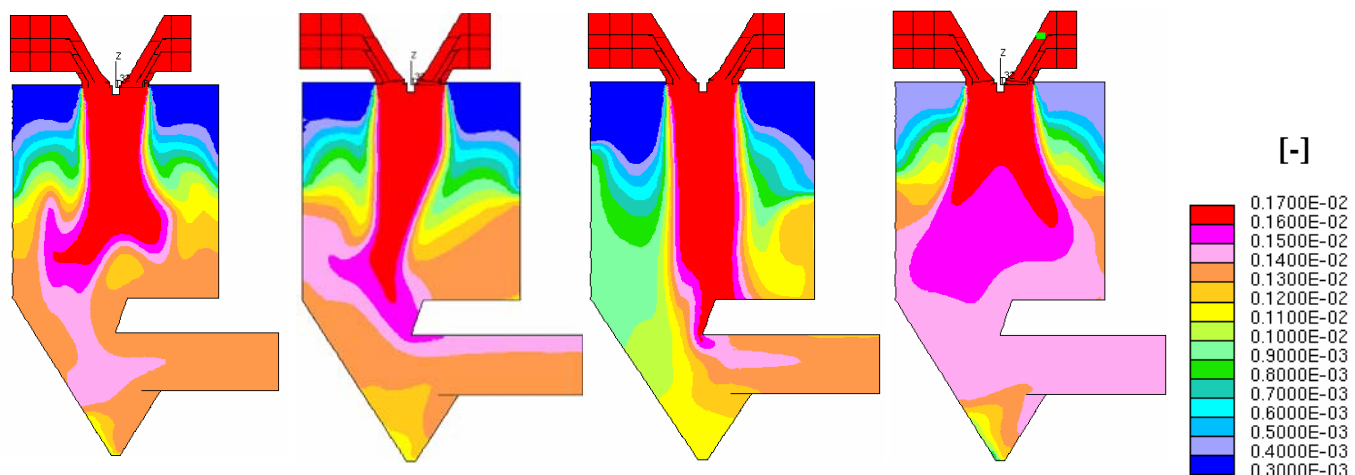


Figure 4 Results for variants of different combination of orientation of guide vanes (15° and 30°), I – inner row, E – external row