

NUMERICAL SIMULATION OF WET FLUE GAS DESULPHURIZATION IN WET SPRAY ABSORBER

M. M. Petrovic^{*1}, V.D. Stevanovic¹, S. Milivojevic¹ and M. Ilic²

*University of Belgrade, Faculty of Mechanical Engineering, Kraljice Marije 16, 11120 Belgrade,
Serbia¹*

*University of Belgrade, Innovation Centre of the Faculty of Mechanical Engineering, Kraljice
Marije 16, 11120 Belgrade Serbia²*

Abstract: A concise one-dimensional thermal-hydraulic two-fluid model is presented for the numerical prediction of sulphur dioxide absorption from the flue gas onto drops of the water-limestone slurry in the vertical spray tower absorber. The model is based on mass, momentum and energy balance equations for each phase separately, i.e. downward falling droplets of water-limestone slurry and upward flowing flue gas. The sulphur dioxide content in the flue gas is predicted by a balance equation of the sulphur dioxide mass fraction in the flue gas. Interface transfer processes between the flue gas and the droplets are determined by closure laws. The obtained steady-state balance equations are transformed in a form suitable for a direct application of the numerical integration method for the system of ordinary differential equations. The developed thermal-hydraulic model is validated by comparing numerical results with available measured data at the large utility absorber. The presented results clearly show the dynamics of flue gas and droplets thermal-hydraulic processes and their influence on the absorption process. The influence of liquid-to-gas ratio and droplet diameter on sulphur dioxide removal efficiency has been investigated.

Keywords: Wet flue gas desulphurization, Absorption, Two-phase flow, Liquid-to-gas ratio

1. INTRODUCTION

Due to low operational cost, reliable operation and high absorption efficiency, the wet flue gas desulphurization (FGD) technology is the most common technique for large coal-fired power plants [1,2]. The absorption of sulphur dioxide in wet desulphurization units is performed in spray tower absorbers. The efficiency of sulphur dioxide absorption in the spray tower absorber strongly depends on thermal and hydraulic interactions between droplets and flue gas in counter-current flow [3].

* Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

Previous works in the sulphur dioxide absorption process in spray absorbers are done in several experimental and numerical investigations and only a few representative papers will be presented here. Gomez et al. [2] were the first that derived a full-scale Euler-Euler numerical simulation of the absorption process. Marocco and Inzoli [4] performed simulations of sulphur dioxide absorption in the pilot plant. Later on Marocco [5] applied the same model to an industrial power plant and investigated the effect of injection levels on desulphurization efficiency. Dou et al. [6] investigated how pH value, droplet size, limestone concentration and the gas and liquid flow rate affected the sulphur dioxide removal in an experimental installation. Gao et al. [7] investigated sulphur dioxide absorption in novel PCF device which is used as absorber. Zhu et al. [8] developed a concise algorithm for calculating absorption height in the spray tower. Qu et al. [9] performed a comprehensive three-dimensional CFD simulation of the absorption process in the spray tower and obtained results were validated against measured data from an absorber in 330 MW coal-fired power unit. A CFD simulation of the FGD in the spray tower absorber was also performed by Arif et al. [10] with special attention to water consumption requirements.

In the present paper, a concise one-dimensional thermal-hydraulic two-fluid model is presented for the numerical prediction of sulphur dioxide absorption from the flue gas in drops of the water-limestone slurry in the spray tower absorber. The model is based on mass, momentum and energy balance equations for each phase separately, i.e. downward-falling droplets of water-limestone slurry and upward-flowing flue gas. The sulphur dioxide content in the flue gas is predicted by a balance equation of the sulphur dioxide mass fraction in the flue gas. Interface transfer processes between the flue gas and the droplets are determined by closure laws. The obtained numerical results are compared with available measured data from the large tower absorber in a utility power plant [11]. The influence of liquid-to-gas ratio and droplet diameter on sulphur dioxide removal efficiency has been investigated. The set of applied closure laws for the gas-droplets interface transfer processes and the computational procedure provide a reliable and efficient FGD predictions that require less computational time and lower computer resources than the CFD three-dimensional simulations.

2. GOVERNING EQUATIONS

The fluid dynamics in the spray tower absorber can be described as two-phase flow where one phase is water-limestone slurry and the other is flue gas. A large number of dispersed water-limestone droplets flow downwards and the flue gas flows upwards in the form of continuous phase. Transfer processes at the interfaces of the flue gas and falling droplets, as well as between the fluid streams and the walls are calculated by the closure laws. The prescribed conditions are described with one-

*Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

dimensional flow model, where sulphur dioxide and water contents in the flue gas are predicted with corresponding mass fraction balance equations.

2.1. Balance equations

Mass Balance

$$\frac{\partial(\alpha_k \rho_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \bar{u}_k) = (-1)^{k+1} \Gamma_a + (-1)^k \Gamma_e + (2-k) \dot{m}_k h_k \quad (1)$$

Momentum Balance

$$\begin{aligned} \frac{\partial(\alpha_k \rho_k \bar{u}_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k \bar{u}_k \bar{u}_k) = & -\alpha_k \nabla p + (-1)^{k+1} \alpha_k \rho_k \bar{g} + (-1)^{k+1} \tau_{fg-d} a_{fg-d} + \\ & + (-1)^k \tau_{kw} a_{kw} + (-1)^k \Gamma_e \bar{u}_d + (-1)^{k+1} \Gamma_a \bar{u}_{fg} \end{aligned} \quad (2)$$

Energy Balance

$$\begin{aligned} \frac{\partial(\alpha_k \rho_k h_k)}{\partial t} + \nabla \cdot (\alpha_k \rho_k h_k \bar{u}_k) = & (-1)^k \Gamma_e h_{H_2O}'' + (-1)^{k+1} \Gamma_a h_{SO_2} + \\ & + (-1)^{k+1} \dot{q}_{fg-d} + (2-k) \dot{m}_k h_k \end{aligned} \quad (3)$$

Mass fraction of sulphur dioxide in the flue gas

$$\frac{\partial(\alpha_{fg} \rho_{fg} g_{SO_2})}{\partial t} + \nabla \cdot (\alpha_{fg} \rho_{fg} \bar{u}_{fg} g_{SO_2}) = -\Gamma_a \quad (4)$$

Mass fraction of water vapour in the flue gas

$$\frac{\partial(\alpha_{fg} \rho_{fg} g_{H_2O})}{\partial t} + \nabla \cdot (\alpha_{fg} \rho_{fg} \bar{u}_{fg} g_{H_2O}) = \Gamma_e \quad (5)$$

The right-hand side of Equations (1-3) represents mass, momentum and energy source terms. Index $k=d$ denotes the liquid phase and $k=fg$ denotes the gas phase. The additional equation is the volume fraction balance

$$\sum_{k=1}^2 \alpha_k = 1 \quad (6)$$

Interface transfer processes such as the absorption, the evaporation, the friction between droplets and the flue gas, the friction between the fluid and the wall and the heat transfer from the flue gas to the water-limestone droplets are taken into account in the presented model. Closure laws for the sulphur dioxide absorption, the water-limestone droplets evaporation and the flue gas-droplets heat transfer are presented below.

2.2. Closure laws for sulphur dioxide absorption

The rate of sulphur dioxide absorption is calculated as

*Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

$$\Gamma_a = K_{SO_2, \text{tot}} (p_{SO_2, \infty} - p_{SO_2, i}) M_{SO_2} a_{d-fg} \quad (7)$$

where $K_{SO_2, \text{tot}}$ is the global mass transfer coefficient, $p_{SO_2, \infty}$ is the partial pressure of sulphur dioxide in flue gas, $p_{SO_2, i}$ is the partial pressure of sulphur dioxide at the flue gas droplet interface, M_{SO_2} is the molecular mass of sulphur dioxide and a_{d-fg} is the interfacial area concentration between droplets and flue gas. The overall mass transfer coefficient takes into account both gas-side and liquid-side mass-transfer resistances

$$K_{SO_2, \text{tot}} = \left(\frac{1}{k_{SO_2, g}} + \frac{H_{SO_2}}{E_{SO_2} k_{SO_2, l}} \right)^{-1} \quad (8)$$

where $k_{SO_2, g}$ is the gas-side mass transfer coefficient, H_{SO_2} is the Henry constant for sulphur dioxide, E_{SO_2} is the enhancement factor and $k_{SO_2, l}$ is the liquid-side mass transfer coefficient. The partial pressure of sulphur dioxide in the flue gas in Eq. (7) is calculated using the mass fraction of sulphur dioxide in the flue gas as

$$p_{SO_2, \infty} = \frac{g_{SO_2} p_{fg} R_{SO_2}}{R_{fg}} \quad (9)$$

The partial pressure of sulphur dioxide at the interface depends on the total sulphur dioxide concentration in droplets

$$p_{SO_2, i} = H_{SO_2} C_{SO_2, i} \quad (10)$$

In this model, the total sulphur dioxide concentration value is neglected because its value has less influence on the sulphur dioxide absorption rate than the other pressure term. The interfacial area concentration between the droplets and the flue gas in Eq. (7) is

$$a_{d-fg} = \frac{6\alpha_d}{d} \quad (11)$$

where α_d is the droplets volume fraction and d is the average droplets diameter.

The gas-side mass transfer coefficient in Eq. (8) is evaluated with modified Ranz-Marshall equation [12]

$$k_{SO_2, g} = \frac{D_{SO_2, g}}{dRT_d} \left(2 + 0.69 \text{Re}_r^{0.5} S_c^{0.33} \right) \quad (12)$$

where $D_{SO_2, g}$ is the binary diffusion coefficient of sulphur dioxide in the air, d is the droplet diameter, R is the universal gas constant, T_d is the droplet temperature, Re_r is the relative Reynolds number

and S_c is the Schmidt number. The binary diffusion coefficient of sulphur dioxide in air is calculated with the Fuller-Scherttler-Giddings equation [13] as

$$D_{SO_2,g} = \frac{10^{-4} 10^{-3} T_{fg}^{1.75} \left(\frac{1}{M_{SO_2}} + \frac{1}{M_{air}} \right)^{0.5}}{p [\nu_{SO_2} + \nu_{air}]^2} \quad (13)$$

where T_{fg} is the flue gas temperature, M_{air} is the molar mass of air, p is the static pressure of the fluid, ν_{SO_2} and ν_{air} are the molecule volumes of sulphur dioxide and air.

The Henry constant in Eq. (8) and Eq. (10) is expressed from the Maurer experimental data [14] as

$$\ln(H_{SO_2}) = \frac{A}{T_d} + B \ln(T_d) + CT_d + D \quad (14)$$

The liquid-side mass transfer coefficient is calculated from the surface stretch model developed by Hsu and Shih [15] as

$$k_{SO_2,l} = \alpha \frac{2}{\sqrt{\pi}} \sqrt{D_{SO_2,l} \sqrt{\frac{8\sigma_{d-g}}{3\pi m_d}}} \quad (15)$$

where α is the correction factor equal 0.78, σ_{d-g} is the surface tension of the droplet according to Desch [16]

$$\sigma_{d-g} = 235.8 \cdot 10^{-3} \left(\frac{645 - T_d}{645} \right)^{1.245} \left[1 - 0.625 \left(\frac{645 - T_d}{645} \right) \right] \quad (16)$$

The value of the liquid diffusion coefficient of sulphur dioxide in aqueous solution at 25 °C [17] is extrapolated from the Stokes-Einstein equation for the corresponding droplet's temperature

$$\frac{D_{SO_2,l} \mu_l}{T_d} = const \quad (17)$$

2.3. Closure laws for water-limestone droplets evaporation

The rate of droplets evaporation is calculated as

$$\Gamma_e = K_{H_2O,g} (p_{H_2O,i} - p_{H_2O,\infty}) M_{H_2O} a_{d-fg} \quad (18)$$

where $K_{H_2O,g}$ is the gas-side mass transfer coefficient between water and flue gas, $p_{H_2O,i}$ is the partial pressure of water at the interface and $p_{H_2O,\infty}$ is the partial pressure of water in the flue gas.

The gas-side mass transfer coefficient is obtained with the following expression [12]

$$K_{H_2O,g} = \frac{D_{H_2O,g}}{dRT_{fg}} (2 + 0.69 \text{Re}_r^{0.5} S_c^{0.33}) \quad (19)$$

where $D_{H_2O,g}$ is the diffusion coefficient of sulphur dioxide in the flue gas, and it is considered equal to the diffusion coefficient of sulphur dioxide in air [13]

$$D_{H_2O,g} = \frac{10^{-4} 10^{-3} T_{fg}^{1.75} \left(\frac{1}{M_{H_2O}} + \frac{1}{M_{air}} \right)^{0.5}}{p [\nu_{H_2O} + \nu_{air}]^2} \quad (20)$$

The partial pressure of water at the interface in Eq. (18) is equal to saturation pressure of water at the droplet temperature

$$p_{H_2O,i} = p_{sat}(T_d) \quad (21)$$

The partial pressure of water in the flue gas is calculated using the mass fraction of water vapour in the flue gas

$$p_{H_2O,\infty} = \frac{g_{H_2O} p_{fg} R_{H_2O}}{R_{fg}} \quad (22)$$

2.4. Closure laws for flue gas-droplets heat transfer

The convective heat transfer between the flue gas and the droplets is obtained with expression

$$q_{fg-d} = h_{fg-d} (T_{fg} - T_d) a_{fg-d} \quad (23)$$

where h_{fg-d} is the heat transfer coefficient, T_{fg} is the flue gas temperature, T_d is the droplet temperature. The heat transfer coefficient from the flue gas to the droplet is calculated with Ranz-Marshall correlation [18] where instead original constant of 0.6, the value of 0.4 is used

$$Nu_{fg-d} = \frac{h_{fg-d} d}{k_{fg}} = 2 + 0.4 \text{Re}_r^{0.5} P_{r,fg}^{0.33} \quad (24)$$

3. NUMERICAL SOLUTION

The steady-state condition in the spray tower is assumed so the first terms on the left-hand side of Eqs. (1-5) are equal to zero. Equations (1-5) are transformed in the form with spatial derivatives which enables direct numerical solution by the Runge-Kutta method for the initial spatial conditions prescribed at the top exit section of the absorber. The prescribed initial values of the dependent

*Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

parameters are void fractions, velocities and enthalpies of the slurry droplets and the flue gas, as well as the water vapour and sulphur dioxide concentrations in the flue gas.

4. RESULTS AND DISCUSSION

The developed two-fluid model of counter-current upward flue gas and downward slurry droplets flow with the sulphur dioxide absorption is applied to the prediction of measured conditions in the spray tower absorber at Unit 5 of the Thermal Power Plant Asnæs in Denmark, which has electrical power of 620 MWe [11]. The spray tower layout is presented in Fig. 1. Design data of the spray tower absorber is presented in Table 1. The flue gas enters the absorber laterally from 6.7 m to 8.9 m above the liquid level. The water-limestone slurry is introduced into the spray tower absorber through five different injection levels. The sulphur dioxide concentrations in the flue gas were measured by a gas analyzer in samples of the flue gas that were extracted from the absorber inner volume. The direct measurement of sulphur dioxide concentrations in the flue gas was not possible due to the impact of slurry droplets movement inside spray tower. At each injection level, the flue gas samples for the sulphur dioxide concentration measurements were taken at three different radial positions 0.9 m, 1.87 m and 3 m from the wall.

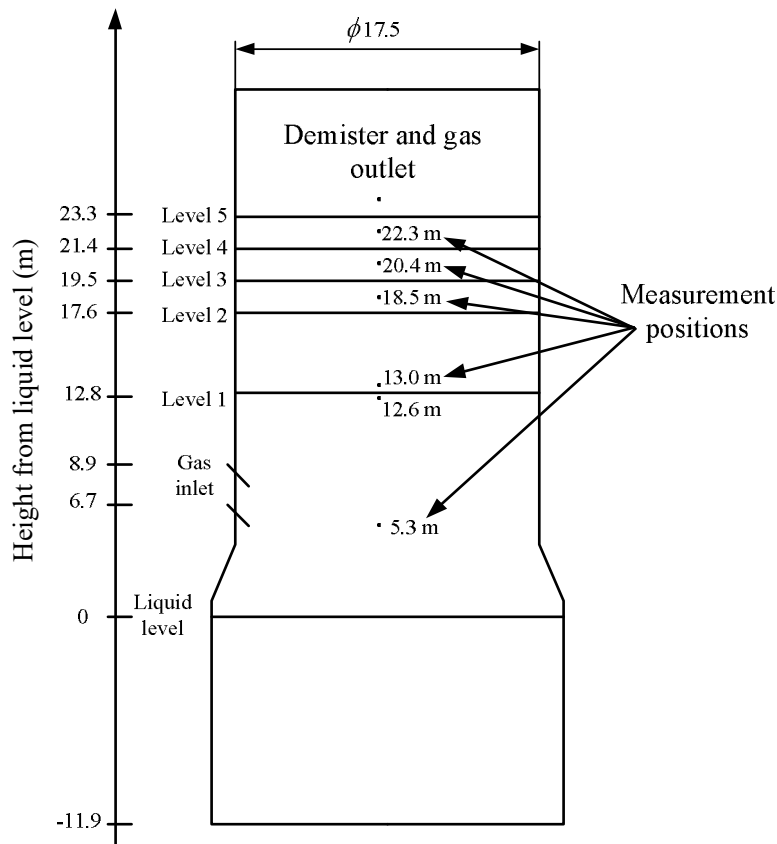


Fig. 1 Layout of the spray tower absorber in 620 MWe Thermal Power Plant Asnæs [11].

* Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

Table 1. Design data of spray tower absorber

FGD installation at Asnaes power plant	
Column diameter	17.5 m
Nozzle levels	5
Number of nozzles per level	184
Absorber height from liquid level	23.3 m
Gas flow rate	$2 \cdot 10^6 \text{ Nm}^3/\text{h}$
Liquid flow rate per nozzle	779 l/min
Liquid flow rate per nozzle level	$8600 \text{ Nm}^3/\text{h}$
Operation pressure	1 atm
Height from the centre of the gas inlet to nozzle level 1	6.1 m
Height from the centre of the gas inlet to nozzle level 2	10.9 m
Height from the centre of the gas inlet to nozzle level 3	12.8 m
Height from the centre of the gas inlet to nozzle level 4	14.7 m
Height from the centre of the gas inlet to nozzle level 5	16.6 m
Approximate slurry volume of holding tank	3925 m^3
Inlet flue gas temperature	125-150 °C
Inlet sulphur dioxide concentration	375-425 ppmv
Droplet diameter	2-3mm

Measured and calculated sulphur dioxide concentrations along the spray tower are presented in Fig. 2. Measured values presented in Fig. 2 correspond to those measured at 1.87 m from the wall. The simulation results show good agreement with experimental results except for the measurement point above injection level 2 at the height of 18.5 m. The reason for this disagreement could be the large sulphur dioxide measurement deviation with the radial position at this point caused by non-uniform slurry droplets distribution, where slurry flow near the wall column is probably lower than the flow in the middle of the column. However, even though this model is one-dimensional, it shows good overall agreement in terms of sulphur dioxide concentration distribution with absorber height. Especially good agreement is achieved for the two points that are close to the flue gas exit from the absorber and which indicates of the desulphurization efficiency.

* Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

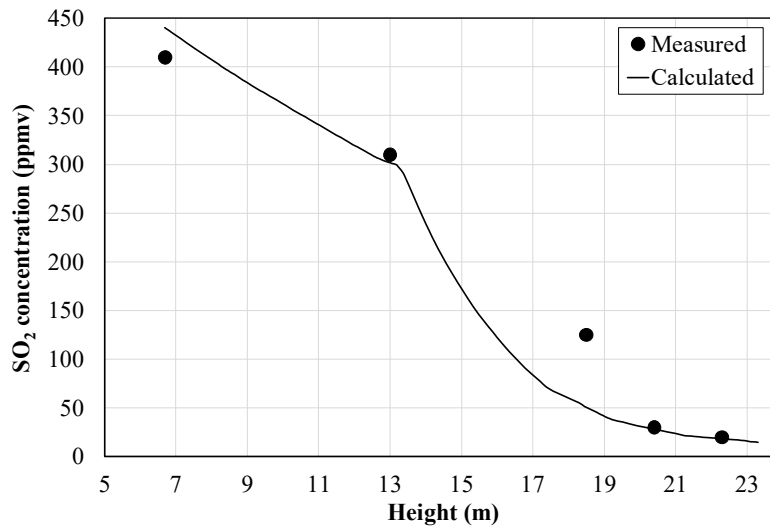


Fig. 2. Comparison of measured and calculated SO₂ concentration.

Once sulphur dioxide concentration distribution with height is solved with the model, the sulphur dioxide removal efficiency can be calculated using obtained concentrations

$$\eta = \left(1 - \frac{C_{SO_2, \text{outlet}}}{C_{SO_2, \text{inlet}}} \right) \cdot 100\% \quad (24)$$

where $C_{SO_2, \text{outlet}}$ is the concentration of sulphur dioxide in the flue gas at the top of the absorber and $C_{SO_2, \text{inlet}}$ is the concentration of sulphur dioxide in the flue gas at the inlet.

In Fig. 3 relationship between sulphur dioxide removal efficiency and the liquid-to-gas ratio is presented. During the measurement campaign, the average droplet diameter was in the range 2-3 mm, so its influence on sulphur dioxide removal efficiency is also analyzed. From the data in Table 1, it could be concluded that the absorber liquid-to-gas ratio at design conditions is 23.65 kgm⁻³ which corresponds to the flue gas flow rate of 2 · 10⁶ Nm³h⁻¹ and the slurry flow rate 5x8600 Nm³h⁻¹. In measurement, the decrease in liquid-to-gas ratio is obtained with decreasing of slurry flow rate with constant flow rate of flue gas. In Fig. 3 decreasing of liquid-to-gas ratio is obtained with turning off one or two injection levels i.e. the liquid-to-gas ratio value of 18.92 kgm⁻³ corresponds to scenario when injection level 1 is turned off and the rest four have full flow rate of 4x8600 Nm³h⁻¹. On the same figure, the liquid-to-gas ratio value of 14.19 kgm⁻³ corresponds to the scenario when injection level 1 and 2 are turned off, and the rest three has full flow rate of 3x8600 Nm³h⁻¹. It can be concluded that sulphur dioxide removal efficiency decreases with decreasing liquid-to-gas ratio. The lower value of the total injected liquid in the spray tower leads to the decrease of water volume fraction and causes the lower interfacial area concentration for the absorption rate. The second important parameter for

*Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs

the sulphur-removal efficiency is the droplet diameter. Figure 3 shows that decrease of the droplet diameter leads to the sulphur dioxide efficiency increase. One reason for this is that both the gas side and liquid side mass-transfer coefficient gradually increase with droplet size increase. Another reason is that smaller diameters of droplets lead to larger interfacial area concentrations.

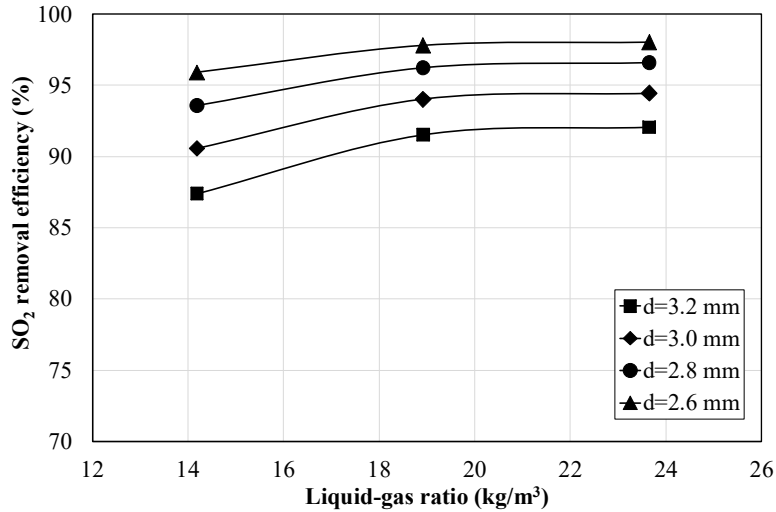


Fig. 3. Relationship between SO₂ removal efficiency and L/G ratio.

In Fig. 4 the liquid-to-gas ratio is decreased with the percentual flow rate decreasing at each injection level. For example, the liquid-to-gas ratio value of 18.92 kgm⁻³ corresponds to the scenario when all injection levels are turned on and have flow rate 5x6880 m³h⁻¹. For the liquid-to-gas ratio value of 14.19 kgm⁻³ all injection levels have are turned on and have flow rate 5x5160 m³h⁻¹.

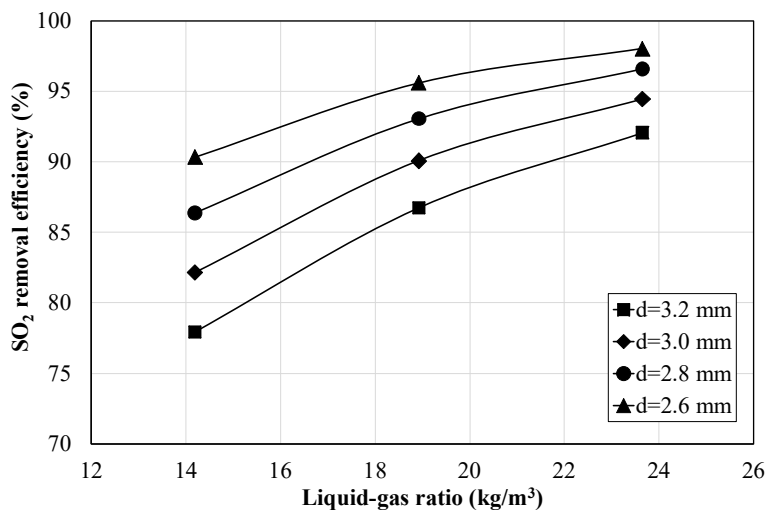


Fig. 4. Relationship between SO₂ removal efficiency and L/G ratio.

Results presented in Fig. 4 show a significant decrease in sulphur-removal efficiency regarding results in Fig. 3. For the same liquid-to-gas ratio of 14.19 kgm^{-3} and droplet diameter of 2.6 mm, sulphur removal efficiency is decreased from 87.5% to 77%. The lower flow rate of slurry at each injection level causes lower interfacial area concentration. This effect is the most pronounced in the middle of the spray tower where the absorption rate has the highest values.

5. CONCLUSIONS

The one-dimensional two-fluid model for the prediction of counter-current flue gas and droplets flow and SO_2 removal from the flue gas in the spray tower absorber is presented in this paper. The model is solved numerically for the conditions of the large utility plant tower absorber. The obtained results are compared with the available measured data and a good agreement is obtained. It is shown that sulphur dioxide removal efficiency strongly depends on the liquid-to-gas ratio and droplets diameter. Also through results, two different ways of decreasing the design liquid-to-gas ratio are analyzed. It is shown that the effect of turning off the injection level presented in Fig. 3 has less impact on removal efficiency than percent decrease of slurry flow rate analysed in Fig. 4. Droplets injections through nozzles at several levels have a strong influence on the thermal-hydraulic conditions in the tower absorber. The developed model is a support to the spray tower design.

REFERENCES

- [1] C. Brogren, H.T. Karlsson. "Modeling the absorption of SO₂ in a spray scrubber using the penetration theory". *Chemical Engineering Science*, vol. 52 (No.18), pp. 3085-3099, 1997.
- [2] A. Gomez, A. Fueyo, A. Tomas. "Detailed modelling of a flue-gas desulfurisation plant". *Computers and Chemical Engineering*, vol. 31, pp. 1419-1431, 2007.
- [3] M.M. Petrovic, V.D. Stevanovic, S. Jankovic, S. Milivojevic. "Dynamics of wet flue gas desulphurization in spray absorber," in *Proc. 29th International Conference on Efficiency, Cost, Optimization and Environmental impact of Energy Systems*, 2016.
- [4] L. Marocco, F. Inzoli. "Multiphase Euler–Lagrange CFD simulation applied to Wet Flue Gas Desulphurisation technology". *International Journal of Multiphase Flow*, vol. 35, pp. 184-194, 2009.
- [5] L. Marocco. "Modeling of the fluid dynamics and SO₂ absorption in a gas-liquid reactor". *Chemical Engineering*, vol. 162, pp. 217-226, 2010.
- [6] B. Dou, W. Pan, Q. Jin, W. Wang, Y. Li. "Prediction of SO₂ removal efficiency for wet flue gas desulfurization". *Energy Conversion and Management*. vol. 50, Issue 10, pp. 2547-2553, 2009.
- [7] H. Gao, C. Li, G. Zeng, W. Zhang, L. Shi, S. Li, Y. Zeng, X. Fan, Q. Wen, X. Shu. "Flue gas desulphurization based on limestone-gypsum with a novel wet-type PCF device". *Separation and Purification Technology*, vol. 76, pp. 253-260, 2011.
- [8] J. Zhu, S. Ye, J. Bai, Z. Wu, Z. Liu, Y. Yang. "A concise algorithm for calculation absorption height in spray tower for wet limestone-gypsum flue gas desulphurization". *Fuel Processing Technology*, vol. 129, pp. 15-23, 2015.
- [9] J. Qu, N. Qi, K. Zhang, L. Li, P. Wang. "Wet flue gas desulfurization performance of 330 MW coal-fired power unit based on computational fluid dynamics region identification of flow pattern and transfer process". *Chinese Journal of Chemical Engineering*, vol. 29, pp. 13-16, 2021.
- [10] A. Arif, C. Stephen, D. Branken, R. Everson, H. Neomagus, S. Piketh. "Modeling Wet Flue Gas Desulfurization," presented at Conference of the National Association for Clean Air (NACA 2015), South Africa, 2015.
- [11] H.G. Nygaard, S. Kiilb, J.E. Johnssonb, J.N. Jensen, J. Hansenb, F. Foghc, K. Dam-Johansenb. "Full-scale measurements of SO₂ gas phase concentrations and slurry compositions in a wet flue gas desulphurisation spray absorber". *Fuel*, vol. 83, pp. 1151–1164, 2004.
- [12] P.N. Rowe, K.T. Claxton, J.B. Lewis. "Heat and mass transfer from a single sphere in an extensive flowing fluid". *Trans. Inst. Chem. Eng.*, vol. 43, 1965.
- [13] E.N. Fuller, P.D. Schettler, J.C. Giddings "A new method for prediction of binary gas-phase diffusion coefficient". *Ind. Eng. Chem. Res.*, vol. 58 (5), pp. 18-27, 1966.
- [14] G. Maurer. "On the solubility of volatile weak electrolytes in aqueous solutions". *ACS Symp. Ser.*, vol. 133, pp. 139-172, 1980.
- [15] C.T. Hsu, S.M. Shih. "Semiempirical equation for liquid-phase mass-transfer coefficient for drops". *AIChJ*, vol. 39 (6), pp. 1090-1092, 1993.
- [16] W. Desch, K. Horn, G. Propst. "Computation of equilibria flows in CFB riser with drag corrections based on particle distribution characterization". *Chem. Eng. J.*, vol. 303, pp. 145-155, 2006.
- [17] R.H. Perry, D. W. Green. *Chemical Engineers Handbook*, 7th edition, McGraw-hill, USA, 1998.
- [18] W.E. Ranz, W.R. Marshall. "Evaporation from drops". *I and II. Chem. Eng. Program 1952*; 48/3-48/4;22,141-146,173-18.

*Corresponding author e-mail: mlpetrovic@mas.bg.ac.rs