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## DESIGNING REACTOR FOR FLUE GAS DESULPHURIZATION

In this paper, the concept of desulphurization technology is proposed. Basic design principles of a reactor for dry flue gas desulphurization are presented. On the basis of literature and real operational data from the Electric Power Station in Opole a full-scale reactor was designed to clean flue gases from steam boiler BP-1150 according to WAWO technology. Brief outline of calculation of material balance was performed. Annual revenue requirements and investment cost were estimated for the designed construction with whole installation. According to these values the costs of removal of 1 kg of SO<sub>2</sub> and 1 kg of ash were determined.

### 1. INTRODUCTION

Flue gas desulphurization (FGD) can be generally divided into two major categories: wet and dry methods. WAWO technology belongs to the latter ones. A dry calcium-based sorbent is injected into the boiler at the temperature of 800–1200 °C. Then flue gas is humidified in reactor with alkaline liquid that increases sorption capacity of the solution and thus improves the SO<sub>2</sub> removal performance. The temperature of inlet gas ranges from 135 to 165 °C, and that of the outlet from 20 to 40 °C over adiabatic saturation temperature.

### 2. DESCRIPTION OF WAWO TECHNOLOGY

Desulphurization installation consists of transport and feed unit for sorbent, activation unit, preparation and feed unit for spray water. Sorbent from a feed tank (5) is conveyed to the retention tank (7), then four rotary feeders (8) and blow-out

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apparatuses (9) supply lime to the boiler (1). Rotary feeders are automatically steered according to  $\text{SO}_2$  concentration in flue gas after ESP (8). Thereafter the flue gas is directed from the boiler to rotary air heaters (10), and finally reaches the reactor (2) where activation and absorption take place. Reactor inlet gases at 407 K (134 °C), contain unreacted sorbent and ash. Liquid-air spray is injected by AIRO No. 30616-27 nozzle system (16). Liquid reacts with ash, lime and saline solution and in consequence the solution of these components is formed. Humidification and cooling of flue gases as well as  $\text{SO}_2$  absorption take place in the reactor. Ash is partly collected in the reactor chute (14), then it is transported to the tank (12). In the upper part of reactor, flue gases are mixed with hot air to increase their temperature to 363 K, then they flow to ESP and the stack (4). ESP reject is transported to the tank (12).

On the basis of these principles and operational data from the "Opole" Electric Power Station the concept of full-scale installation for dry flue gas desulphurization is presented.

Scheme of desulphurization process is shown in figure 1.

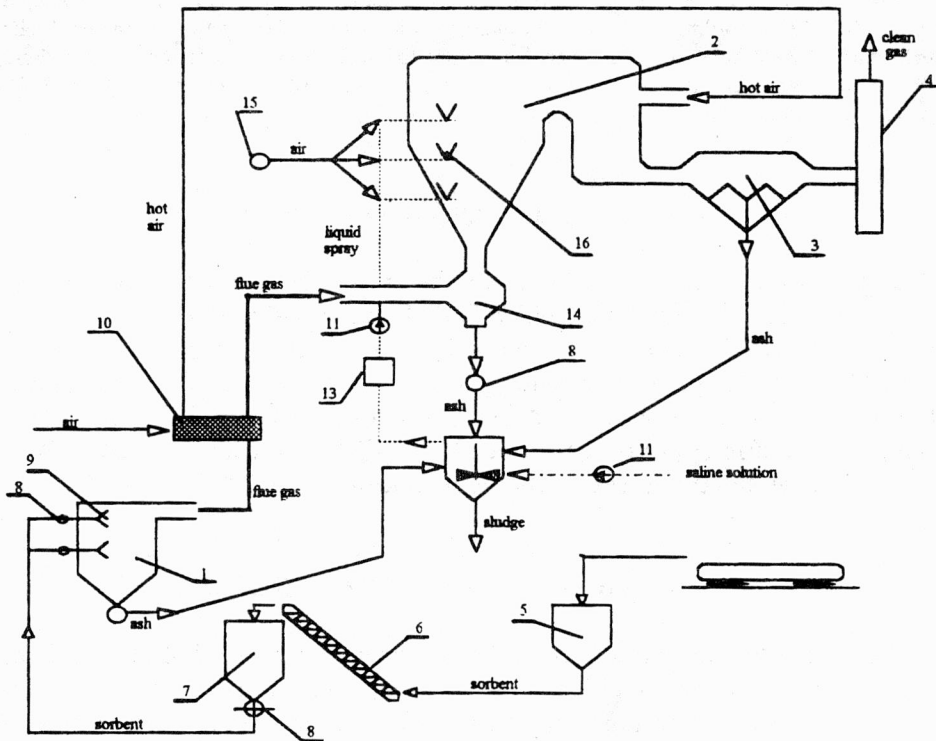


Fig. 1. Scheme of desulphurization process for BP-1150 steam boiler

1 - boiler, 2 - reactor, 3 - ESP, 4 - stack, 5 - sorbent feed tank, 6 - feeding screw, 7 - retention tank, 8 - rotary feeder, 9 - blow-out apparatuses, 10 - rotary air heater, 11 - pump, 12 - tank with mixer, 13 - spray water tank, 14 - reactor chute, 15 - compressor, 16 - AIRO nozzles

### 3. MAJOR STEPS FOR REACTOR DESIGNING

#### 3.1. BASIC OPERATIONAL DATA [1]

The values below are necessary for determining the material balance of the process which allows us to design the reactor with facilities.

steam boiler	BP-1150
max fuel consumption	$B' = 150 \text{ Mg/h}$
average fuel consumption	$B = 120 \text{ Mg/h}$
fuel calorific value	$w_d = 24317 \text{ kJ/kg}$
ash content in fuel	$p = 13.1\%$
sulphur content in fuel	$S = 0.65\%$
flow rate of flue gas	$1.5 \text{ mln Nm}^3/\text{h}$
inlet temperature of reactor gas	$T_l = T_{in} = 407 \text{ K (134 } ^\circ\text{C)}$
time of boiler operation	$6500 \text{ h/yr}$
ash emission	$U = 83 \text{ kg/h}$
thermal power	$360 \text{ MW}$
annual electricity output	$14 \text{ mld kWh}$
annual heat energy output	$4700 \text{ TJ}$
theoretical standard fuel consumption	$273.8 \text{ g/kWh}$
ESP efficiency	$99.5\%$
boiler heat efficiency	$91.7\%$

#### 3.2. MATERIAL BALANCE OF PROCESS

The balance was established according to the operational data and guarantees that the emission of  $\text{SO}_2$  does not exceed its admissible concentration defined in *Dziennik Ustaw* No. 15/90 and City Council.

#### 3.3. $\text{SO}_2$ BALANCE

Theoretical  $\text{SO}_2$  emission is calculated on the basis of percentage sulphur content in coal, average fuel consumption and ash emission (equations (1) and (2)):

$$E_{\text{SO}_2} = BuS = 1950 \text{ [kg/h]}, \quad (1)$$

$$E_{\text{SO}_2(x)} = \frac{E_{\text{SO}_2}}{Bw_d} = 534.6 \text{ [g/GJ]} \quad (2)$$

where:

- $E_{\text{SO}_2}$  –  $\text{SO}_2$  emission when no installation is applied,
- $C_{\text{SO}_2}$  –  $\text{SO}_2$  concentration in flue gas when no installation is applied,
- $u = 2$  – constant factor for the steam boiler BP-1150.

The next step is to estimate the SO<sub>2</sub> concentration in raw flue gas:

$$C_{\text{SO}_2} = \frac{E_{\text{SO}_2}}{V_{\text{sp}}} = 1.3 \text{ [kg/Nm}^3\text{]}. \quad (3)$$

#### 3.4. ASH BALANCE

Theoretical ash emission and concentration are calculated similarly:

$$E_{\text{ash}} = BU_p = 16309.5 \text{ [kg/h]}, \quad (4)$$

$$C_{\text{ash}} = \frac{E_{\text{ash}}}{V_{\text{sp}}} = 10.87 \text{ [g/Nm}^3\text{]} \quad (5)$$

where:

$E_{\text{ash}}$  – ash emission when no installation is applied,

$C_{\text{ash}}$  – ash concentration in flue gas when no installation is applied.

#### 3.5. THEORETICAL EFFICIENCY OF SO<sub>2</sub> REMOVAL

It was assumed 70% efficiency of SO<sub>2</sub> removal. On the basis of the values of raw gas emission, the mass stream of removed SO<sub>2</sub> can be estimated. Equations (7) and (8) give the emission of SO<sub>2</sub> after its passage through the installation:

$$M_{\text{SO}_2} = E_{\text{SO}_2} n = 1365 \text{ [kg/h]}, \quad (6)$$

$$E'_{\text{SO}_2} = E_{\text{SO}_2} - M_{\text{SO}_2} = 585 \text{ [kg/h]}, \quad (7)$$

$$E'_{\text{SO}_2(x)} = \frac{E'_{\text{SO}_2}}{Bw_d} = 160.38 \text{ [g/GJ]} \quad (8)$$

where:

$M_{\text{SO}_2}$  – SO<sub>2</sub> stream removed from flue gas,

$E'_{\text{SO}_2}$  – SO<sub>2</sub> emission after installation.

Based on eq. (7), the concentration of SO<sub>2</sub> in clean gas can be calculated as follows:

$$C'_{\text{SO}_2} = \frac{E'_{\text{SO}_2}}{V_{\text{sp}}} = 0.39 \text{ [g/Nm}^3\text{]} \quad (9)$$

where  $C'_{\text{SO}_2}$  – SO<sub>2</sub> concentration after installation.

The next step is to determine that sorbent quantity which reacts with SO<sub>2</sub>:

$$M'_{\text{CaO}} = M_{\text{SO}_2} \frac{90}{64} = 1194.38 \text{ [kg/h]} \quad (10)$$

where  $M'_{\text{CaO}}$  – CaO quantity reacted with SO<sub>2</sub>.

## 3.6. CALCIUM BALANCE

In WAWO technology, calcium to sulphur molar ratio is generally established as two to one:

$$\frac{\text{Ca}}{\text{S}} = \frac{2}{1} \quad (11)$$

According to eqs. (1) and (11) the demanded sorbent quantity is assessed:

$$M_{\text{CaO}} = 3412.5 \text{ [kg/h]}. \quad (12)$$

## 3.7. REJECT BALANCE

There are three types of reject in this technology. These are: unreacted sorbent, calcium sulphate and ash. The difference between the mass of injected sorbent (eq. (12)) and the mass of sorbent that reacts with  $\text{SO}_2$  (eq. (10)) makes the mass of unreacted sorbent:

$$M_{\text{CaO}_{\text{unreact}}} = M_{\text{CaO}} - M'_{\text{CaO}} = 2218.12 \text{ [kg/h]}. \quad (13)$$

The mass of  $\text{CaSO}_4$  is obtained as the result of multiplication of the mass of the sorbent used (eq. (10)) by the ratio of the molar masses of  $\text{CaSO}_4$  and  $\text{CaO}$ :

$$M_{\text{CaSO}_4} = M'_{\text{CaO}} \cdot \frac{136}{56} = 1194.38 \cdot 2.43 = 2902.34 \text{ [kg/h]}. \quad (14)$$

The mass of ash collected in the whole installation is equal to ash emission because of an almost 100% ESP efficiency:

$$M_{\text{ash}} = E_{\text{ash}} = 16309.5 \text{ [kg/h]}. \quad (15)$$

The total reject mass is a sum of three rejects:

$$M_{\text{rej}} = M_{\text{ash}} + M_{\text{CaO}_{\text{unreact}}} + M_{\text{CaSO}_4} = 21385.6 \text{ [kg/h]}. \quad (16)$$

The reject can be divided into two mass streams. The first one is collected in reactor with 35% efficiency, the other in ESP with 99.5% efficiency.

## 3.8. SPRAY-WATER BALANCE

Two major assumptions were made:

all injected water evaporates,

gas temperature is decreased from 134 °C (407 K) to 70 °C (343 K).

On the basis of simple thermal water-gas balance the quantity of spray water is estimated:

$$m_w = 9.66 \text{ [kg/s]}, \quad (17)$$

$$V_W = 38.52 \text{ [m}^3\text{/h]}. \quad (18)$$

Addition of NaCl enhances the increase in sorption capacity of spray water. It was established that

$$\text{Na}^+/\text{Ca}^{++} = 0.1. \quad (19)$$

The values obtained from eqs. (12) and (19) allow determination of the mass of NaCl:

$$m_{\text{NaCl}} = 620.0 \text{ [kg/h]}. \quad (20)$$

### 3.9. HOT AIR BALANCE

Clean gases are mixed with a stream of hot air to increase the outlet gas temperature to 90 °C (363 K) and decrease its moisture content. Thermal balance of air-gas enables us to estimate the mass of hot air:

$$m_{\text{air}} = 294.69 \text{ [kg/s]}, \quad (21)$$

$$V_{\text{air}} = 313.5 \text{ [m}^3\text{/s]}. \quad (22)$$

### 3.10. PHYSICAL PROCESSES THAT WATER DROPLET UNDERGOES

The water droplet should be of an optimal size and should be in reactor long enough to activate the unreacted sorbent and not fall down because of its weight. Water droplet will not fall down into the chute if its diameter is smaller than  $4.3 \cdot 10^{-3}$  m. According to the mathematical model [2], the drying time for 40  $\mu\text{m}$  droplet is 0.1 s. Such a droplet covers a distance of 6.7 m.

### 3.11. NOZZLES

The reactor must be equipped with nozzles. Total spray water flow rate is 38.52 m<sup>3</sup>/h and single nozzle capacity has to guarantee the flow of 0.5 m<sup>3</sup>/h.

78 AIRO No. 30616-27 nozzles should be fitted. They are located on three levels with three rows, each on both opposite sides of the reactor. Each level has 26 nozzles, 13 on one side.

### 3.12. REACTOR CONSTRUCTION

In the reactor, the major part of installation, the processes of SO<sub>2</sub> absorption and gas humidification take place. Reactor construction should provide optimal process conditions, and the height of apparatus should guarantee 3 second contact time. During this time an unreacted sorbent is activated, and a flue gas is conditioned which enhances the desulphurization efficiency. The reactor is a cone construction

with an increasing cross-section surface, acting as some kind of "fluidized zone". In this zone, an unreacted and sulphated sorbent undergoes particulate fluidization, which makes the real contact time longer. Scheme of the reactor is shown in figure 2, and its basic parameters can be itemized as follows:

Height (contact time: 3 seconds)  $H = 28$  m.

Sections are designed to provide a desired gas velocity.

1-1 section:  $6.0 \times 6.0$  m,  $V = 18$  m/s,

2-2 section:  $13.0 \times 6.0$  m,  $V = 8$  m/s,

3-3 section:  $16.3 \times 6.0$  m,  $V = 6$  m/s,

4-4 section:  $23.2 \times 22.5$  m,  $V = 1$  m/s (ESP inlet).

There is a reject chute at the bottom of the reactor where particulates are collected with 35% efficiency. The volume of chute,  $62.4$  m<sup>3</sup>, is established in such a way as to guarantee the filling time over two shifts.

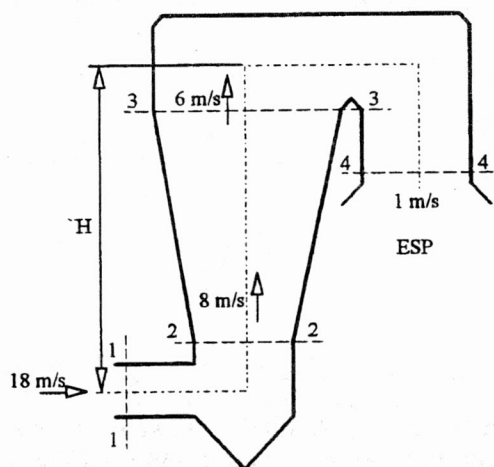


Fig. 2. Reactor construction

The reactor construction should be made of reinforcing steel St3S, 5 mm sheet gauge, without non-corrodible protection, with outer double layer of glass wool insulation ( $2 \times 10$  cm) covered with 1 mm aluminium sheet.

### 3.13. INVESTMENT COSTS

Investment costs of the reactor described and all facilities in the FGD installation are based on prices from March 1994. List of the items of installation is presented in table 1. The investment cost does not comprise the cost of flow gas fan because every boiler is equipped with such an apparatus. Total cost of the whole enterprise came to 1.65 million of U.S. dollars.

Table 1

Investment cost		USD × 1000
List of items		
Reactor with support construction + insulation and protective painting		711.10
Nozzles	(78)	30.93
Compressor	(1)	6.67
Pumps	(3)	7.33
Tank with mixer	500 m <sup>3</sup>	48.89
Compensation tank	200 m <sup>3</sup>	26.81
Sorbent feed tank	40 m <sup>3</sup>	5.38
Sorbent retention tank	40 m <sup>3</sup>	5.38
Feeding screw	(2)	4.44
Rotary feeders	(2)	4.44
Blow-out apparatuses	(4)	1.78
Electric installation		3.55
Automatics		3.55
Starting		6.67
Documentation		11.11
Pipes		0.72
Valves	(102)	0.97
Flue-gas ducts		166.67
Duct insulation		208.98
Ash transport system		133.33
Assembly		266.67
Summary		1655.28

### 3.14. ANNUAL REVENUE REQUIREMENTS

They are presented in table 2. Annual requirements are estimated for 6500 hours per year. Sorbent cost is the highest share followed by waste disposal cost and amortization. Electricity, process water and labour outlay do not really contribute to the costs.

Table 2

Annual revenue requirements			
List of items	Annual quantity	Unit cost USD	Total annual cost USD · 1000
Raw material	22181.2 t	35.55/t	788.54
Ca(OH) <sub>2</sub>			
Labour	6500 m-h	1.33/m-h	8.65
Process water	226044 m <sup>3</sup>	0.089/m <sup>3</sup>	20.12
Electricity	1300000 kWh	0.053/kWh	68.90
Waste disposal	139006.4 t	1.33/t	184.88
Amortization	—	—	165.53
Summary			1236.62



The costs of removal of 1 kg of  $\text{SO}_2$  ( $C_{\text{SO}_2}$ ) and ash ( $C_{\text{ash}}$ ) were determined on the basis of the following estimation:

$$C_{\text{SO}_2} = 185.0 \text{ mills/kg SO}_2.$$

$$C_{\text{ash}} = 16.1 \text{ mills/kg ash.}$$

#### 4. CONCLUSIONS

There are some main criteria which should be taken into consideration when the decision about choice of a proper desulphurization technology is made. They may be itemized as follows:

investment cost and annual requirements of the installation,  
efficiency of the removal of contaminants that guarantees the maintenance of emission limits,

place requirement for a new design in existing arrangement.

WAWO technology has many advantages over other desulphurization methods. Of a great importance are both investment cost, 30–300% lower in comparison with semi-dry or wet methods of cleaning of flue gas, and annual requirements, which are up to 50% lower. There is no need to equip the installation with expensive heat exchangers. Construction of the reactor is easy to fit even in installation built very closely. Exploitation is fully automatic and easy to maintain. WAWO technology is characterized by an average water consumption and low energy consumption. There is no sewage. The reject is stable because of the addition of unreacted calcium. The installation is not complex and is said to be free of damages. Its exploitation time is longer in comparison with the installation for wet methods because of slower corrosion.

The first WAWO installation was built in December 1990 in the Heat Generating Plant in Wrocław for WP-120 boiler. In 1994, next WAWO installation was built for WP-70 boiler in the same plant.

#### REFERENCES

- [1] Commercial leaflet of Electric Power Station in Opole.
- [2] HARRIOTT P., RUETHER J., SUDHOFF F., *Prediction of  $\text{SO}_2$  Removal for Power Plants Using Duct Injection of Lime Slurry*, Energy & Fuels, 1991, Vol. 5, No. 2.

#### PROJEKT REAKTORA DO ODSIARCZANIA GAZÓW ODLOTOWYCH

Przedstawiono technologię odsiarczania oraz główne zasady projektowe reaktora do odsiarczania gazów odlotowych. Opierając się na danych z literatury i danych z elektrowni w Opolu, zaprojektowano reaktor przemysłowy do oczyszczania, zgodnie z technologią WAWO, gazów odlotowych z kotłów

parowych BP-1150. Zrobiono krótki szkic obliczeń bilansu materiałowego. Oszacowano spodziewany roczny przychód i koszty inwestycyjne projektowanej instalacji. Na tej podstawie określono koszt usunięcia 1 kg SO<sub>2</sub> i 1 kg popiołu.

#### ПРОЕКТ РЕАКТОРА ДЛЯ ОБЕССЕРЕНИЯ ОТХОДЯЩИХ ГАЗОВ

Представлена технология обессерения, а также главные проектные принципы реактора для обессерения отходящих газов. Базируя на литературных данных и данных из электростанции в Ополе, запроектировали промышленный реактор для очистки, согласно технологии WAWO, отходящих газов из паровых котлов БП-1150. Сделано краткое обсуждение расчетов баланса материалов. Оценены желаемый годичный приход и инвестиционные затраты на проектируемую установку. На этой основе определены затраты на удаление 1 кг SO<sub>2</sub> и 1 кг золы.