Flue Gas Desulfurization Scrubbers in Heavy Diesel Combustion Plants

Tevfik Gemci[1*]

[1]Synergy CFD Consulting LLC, 1250 S Rainbow Blvd, Las Vegas, NV 89146, USA

ABSTRACT

Through the purification technology of flue gas desulfurization, ultralow emissions of SO_2 flue gas in industrial flue gas can be achieved. In this article, wet flue gas desulfurization (FGD) processes using limestone (calcium carbonate $CaCO_3$) and caustic (sodium hydroxide $NaOH$) as absorption solutions are introduced in terms of fluid mechanics and mass transfer phenomena as well as absorption unit processes. Also, initial investment and operation costs are compared for wet flue gas desulfurization processes using limestone and caustic.

Keywords: Flue gas desulfurization; Wet desulfurization process; Fluid mechanics; Mass transfer; Absorption unit processes

Ağır Dizel Yakma Tesislerinde Atık Gaz Kükürt Giderme Üniteleri

ÖZ

Baca gazı kükürt giderme saflaştırma teknolojisi sayesinde, endüstriyel baca gazında son derece düşük SO_2 baca gazı emisyonları elde edilebilir. Bu makalede absorpsiyon çözeltisi olarak kireç taşı (kalsiyum karbonat $CaCO_3$) ve kostik (sodyum hidroksit $NaOH$) kullanan ıslak kükürt giderme prosesleri, absorpsiyon ünitesi proseslerinin yanı sıra akışkanlar mekaniği ve kütle transferi fenomenleri açısından tanıtılmaktadır. Ayrıca kireçtaşı ve kostik kullanılan ıslak baca gazı kükürt giderme proseslerinin ilk yatırım ve işletme maliyetleri karşılaştırılmıştır.

Anahtar Kelimeler: Atık gaz kükürt giderme; Islak kükürt giderme prosesi; Akışkanlar mekaniği, Kütle transferi; Absorpsiyon ünite işlemleri

1. INTRODUCTION

As a result of the combustion of high-sulfur fossil fuels in cogeneration and diesel engines or steam boiler plants, flue (waste) gas containing SO_2 is released. SO_2 emissions are known to have detrimental impacts on human health and the environment [33]. On the other hand, waste gas containing SO_2 must be passed through a flue gas treatment unit before it is released into the atmosphere, thus preventing acid rains that may reach the earth. Separation of sulfur dioxide (SO_2) from the flue gas is possible by dry or wet absorption processes using alkaline absorption solutions [1-4, 6, 20]. It is obligatory to treat other flue gases from combustion processes and heavy metals and ashes in the fuel up to the permissible emission values [7, 17]. Many clinical studies have shown that the correlation between atmospheric air pollutants (including acid aerosols and sulfates) and respiratory diseases is highly complicated [27-29]. The serious health concerns associated with exposure to high SO_2 concentration include breathing difficulty, respiratory illness, and aggravation of existing cardiovascular disease [33]. Strong inorganic acid mists containing sulfuric acid (H_2SO_4) have been reported to correlate with lung and laryngeal cancer in humans [30-32].

As is known, wet, dry, and semi-wet processes are used for SO_2 removal [7]. In this article, wet systems, which are seen as the most suitable solution for Turkish situations, will be examined. The final products resulting from the dry process are rarely or only obtained as usable raw materials at great expense. The end products from dry absorption plants are sometimes only sent to a solid waste warehouse, but often to a hazardous solid waste warehouse, resulting in increased waste disposal costs. On the other hand, the use of excess absorption solution, which adversely affects operating costs, should be reduced as much as possible in providing the sulfur dioxide emission value limited by the emission regulation. The use of excess absorption solution will eventually considerably increase the amount of end product that must be further disposed of. For this reason, dry systems that use a large amount of absorption agent as a process requirement are not very attractive.

This paper analyses the advantages and disadvantages of two wet FGD scrubbers to their environmental and financial aspects. Total costs of FGD systems include both capital and annualized costs. The major capital cost components of an FGD system consist of plant equipment, installation, site development, and indirect costs. In the FGD scrubber market throughout the world, wet FGD limestone scrubbers take the lead, the byproduct of which is a marketable gypsum. Most of the second wet FGD scrubbers cover a similar process but produce a disposal product (waste).

2. WET FLUE GAS DESULFURIZATION PROCESSES

Two groups of absorption solutions for the wet FGD absorption process are widely used [1-4, 6-12, 24-25]:

- Sodium hydroxide (caustic) or sodium carbonate, where a diluted solution or a crystalline sodium sulfate/sulfite mixture is formed as the final substance or

- Calcium oxide (lime), calcium hydroxide (slaked lime), or calcium carbonate (limestone); here, the final product is exposed as gypsum raw material.

In this article, both alternative processes will be examined in detail.

2.1. Wet FGD process with caustic or sodium carbonate

If these absorption solutions are used in the absorption of sulfur dioxide, sodium sulfide (Na_2SO_3) is formed in the first step in the absorption solution. The caustic soda (NaOH) slurry can produce Na_2SO_3 by Eq. (1) which can be further oxidized by Eq. (2) to produce marketable Na_2SO_4 (sodium sulfate) by Eq. (3) [14]:

$$2NaOH + SO_2 \rightarrow NaSO_3 + HO_2 \tag{1}$$
$$NaSO_3 + \tfrac{1}{2}O_2 \rightarrow NaSO_4 \tag{2}$$

$$\overline{2NaOH + SO_2 + \tfrac{1}{2}O_2 \rightarrow NaSO_4 + HO_2} \tag{3}$$

At the same time, heavy metals such as vanadium and nickel and soot particles in the waste gas are retained during washing and pass into the absorption solution. As a result of the excess oxygen present in the flue gas in the absorption zone of the washer, some sodium sulfite is oxidized and turns into soluble sodium sulfate again. To complete the oxidation of the remaining sodium sulfite, air must be blown into the solution at the bottom of the washer with the help of a blower fan. Another alternative is to complete this oxidation process with air in a separate tank. In both systems, it is not possible to obtain sodium sulfate by performing a perfect oxidation. In any case, up to 20% sodium sulfide can be found in the discarded washing solution. It is also not possible to deliver this amount of sodium sulfide, which is toxic and fatal for living creatures in the receiving environment, to a wastewater treatment plant.

The washing solution contains some toxic sodium sulfide, as well as heavy metals and soot/particles retained during washing. For this reason, a precaution must be taken to separate these heavy metals from the washing solution. Likewise, the soot/particles that pass into the solution during washing should be separated and removed by a filtering device. Even if the sulfide is completely converted to sulfate, the resulting sulfate concentration is well above the permissible value. It is forbidden to give sulfate to the receiving environment at this rate, and it cannot be discharged into a sewer system as it will destroy the concrete. A crystallization process is required so that the sodium sulfate formed can be used as a raw

material, for example in glass production. Again, in this case, it is necessary to separate heavy metals and soot/particles. Because soot/particles and heavy metals cause undesirable color changes on the glass. Crystallization is mainly achieved by cooling/evaporation crystallization or by evaporation of the waste washing solution in a spray dryer with hot waste gas. The spray dryer is followed by a bag filter. The crystallization process with these two techniques causes additional investment and operating costs, as well as a very serious increase in operating effort.

Also, caustic or sodium carbonate is much more expensive than calcium-based sorbents. Chemical consumption, on the other hand, significantly affects the operating costs of desulfurization plants. This issue is explained in more detail in the section on operating cost comparison. Due to the disadvantages mentioned here, the wet absorption process with sodium hydroxide (caustic) or sodium carbonate for the removal of sulfur dioxide from the flue gases of combustion plants has little use and can only be used in small power plants. Fig. 1 adapted from [2, 11] shows the simplified process flow diagram of flue gas desulfurization and wastewater treatment with sodium hydroxide/sodium carbonate.

2.2. Wet FGD process with calcium-based alkalis

Because of the many disadvantages of wet absorption of sulfur dioxide with caustic or sodium carbonate, almost all desulfurization plants today use cheaper calcium-based alkalis as absorption solutions. As a first step in this process, either partially soluble calcium hydrogen sulfide or sparingly soluble calcium sulfide is formed. The limestone-forced oxidation (LSFO) of calcium hydrogen sulfide to insoluble calcium sulfate (gypsum) begins with the excess oxygen in the flue gas in the absorption zone of the washer [1-2, 6, 9-10]. LSFO is a newer process based on wet limestone scrubbing which reduces scale. In LSFO, air is added by a blower fan to the reaction tank which oxidizes the spent slurry to gypsum [23]. Since the reaction product gypsum is removed as a continuous solid based on mass balance, a high oxidation rate is still reached in the absorption zone. The remaining oxidation is provided by the introduction of air into the liquid solution at the bottom of the washer using a blower fan. Thus, perfect oxidation is achieved. This process is very important for the released gypsum to be used as raw material [6]. Fig. 2 adapted from [2, 9-10] shows a simplified flow chart of a lime flue gas desulfurization plant with gypsum raw material as the final product.

The reactions that take place in wet absorption with calcium components are briefly represented by Eq. (4-6) in the example of calcium carbonate $CaCO_3$ (limestone) [1-2, 6]:

$$CaCO_3 + SO_2 \rightarrow CaSO_3 + CO_2 \tag{4}$$

$$CaSO_3 + \tfrac{1}{2}O_2 \rightarrow CaSO_4 \tag{5}$$

$$\overline{CaCO_3 + SO_2 + \tfrac{1}{2}O_2 \rightarrow CaSO_4 + CO_2} \tag{6}$$

The gypsum ($CaSO_4$) formed during absorption is present as a solid in the washing solution and is continuously separated and dewatered in a filter press, vacuum band filter, or drum filter. The amount of residual water (moisture) in the dewatered gypsum is around 10% and does not constitute any obstacle to its use as raw material. The only thing to be considered is that heavy metals coming from the fuel, such as nickel and vanadium, in the filter permeate water that does not contain any other toxic and harmful substance (such as sulfate) are precipitated by a simple chemical treatment.
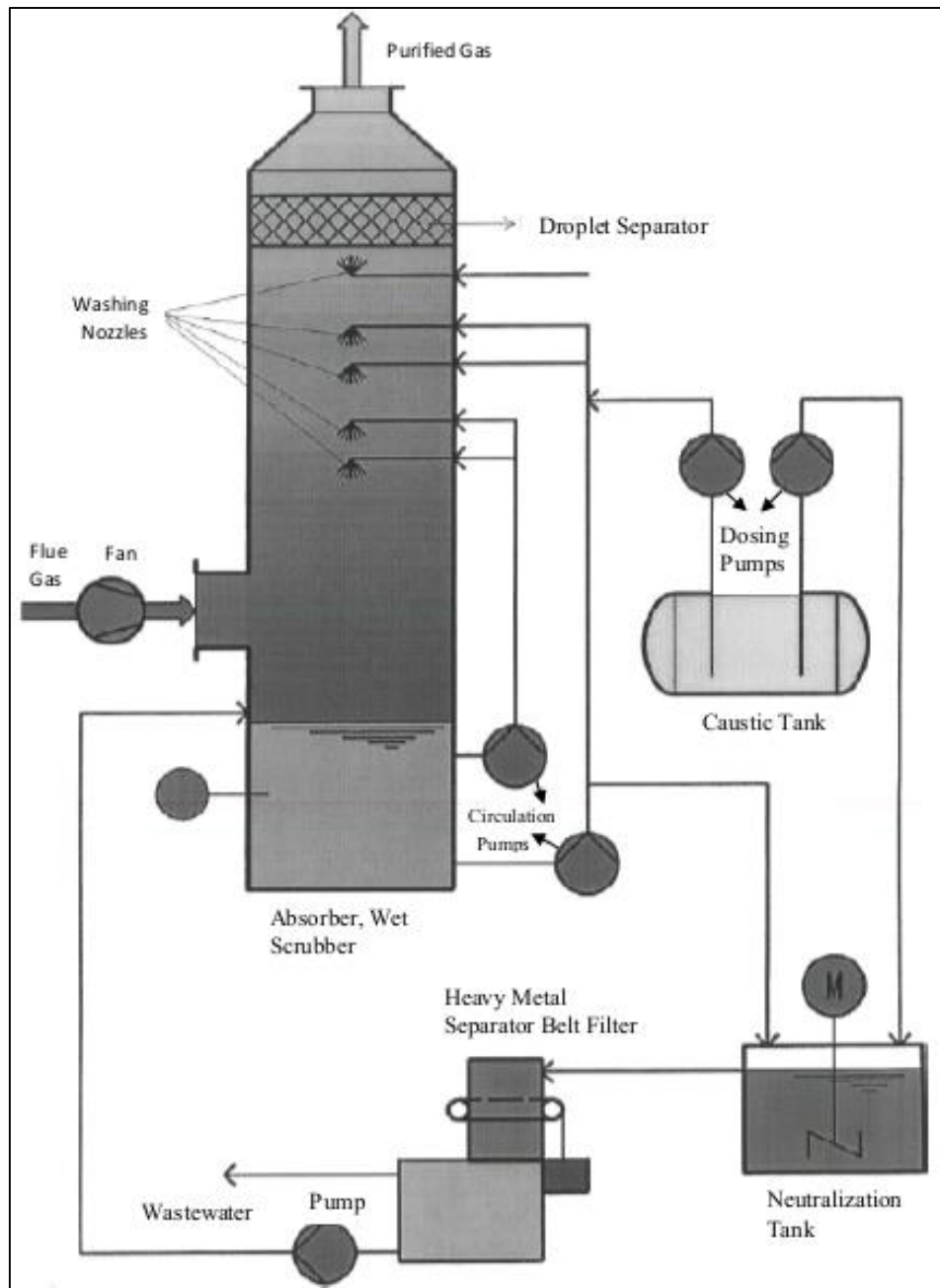

Figure 1: Simplified process flow chart of flue gas desulfurization and wastewater treatment (heavy metal) with sodium hydroxide (caustic) which is adapted from [2, 11].
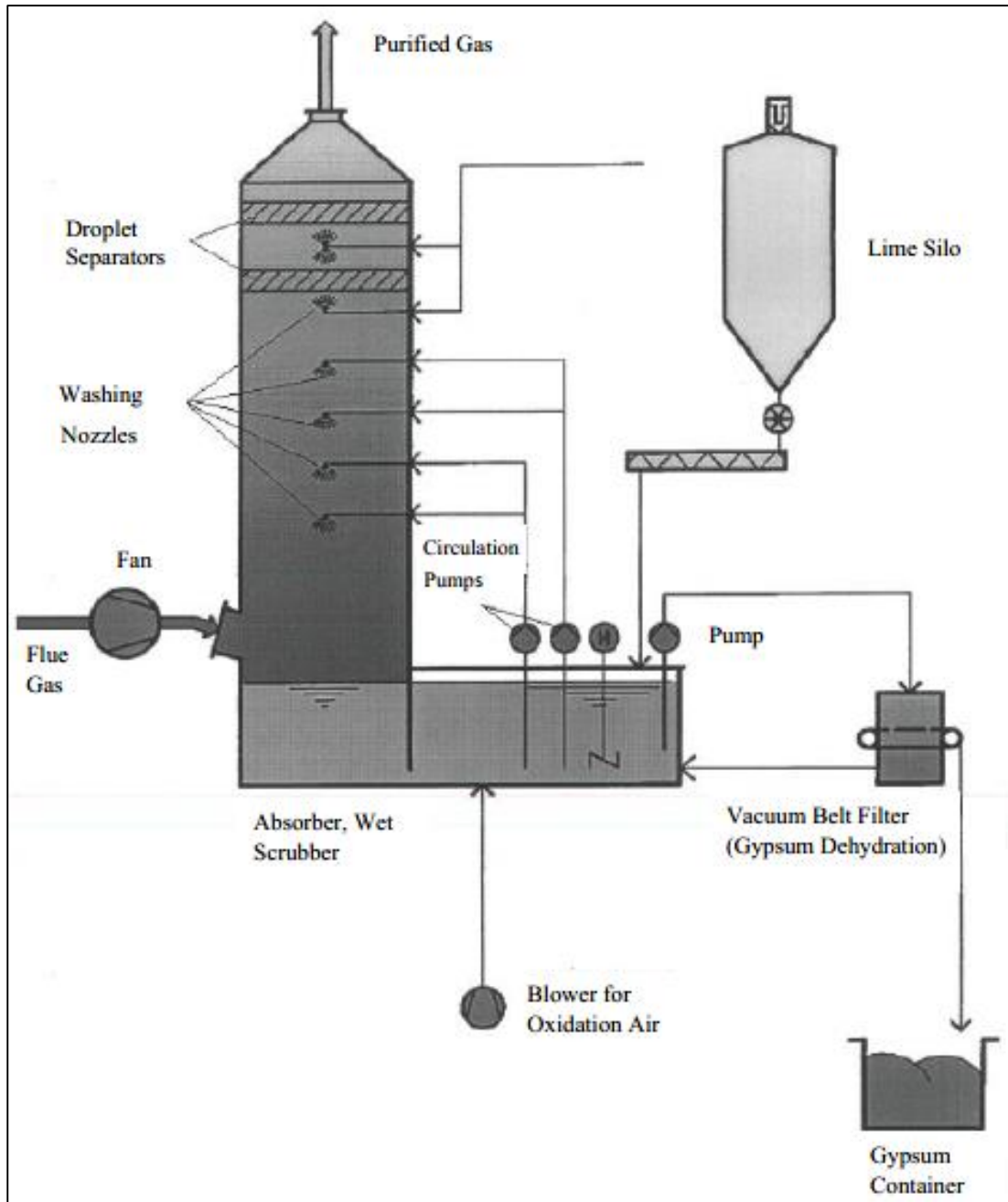
241

Figure 2: Simplified process flow chart of a lime flue gas desulfurization plant with gypsum raw material as the final product which is adapted from [2, 9-10, 20].

The permeate water, which is purified from heavy metals, is fed back to the absorption plant as a rewashing solution and in this way a closed cycle is provided. In this process, there is no wastewater that must be treated and removed. The soot/particles in gypsum do not affect the use of gypsum as a raw material in the cement industry. The flue gas problem in the capture of sulfur dioxide with calcium

compounds does not create a new environmental problem. On the contrary, a raw material (gypsum) that has no wastewater problem and has economic value emerges [6-7].

3. FACILITY FEATURES

3.1. Wet FGD scrubber with sodium hydroxide/carbonate

The flue gas desulfurization plant based on sodium hydroxide or sodium carbonate mainly consists of the following equipment [2, 9-10].

- Washer (with circulation/reaction tank and droplet trap)
- Circulation pumps
- Chemical tank and dosage unit
- Purification of wastewater

The washer system is generally designed in two ways either filled (packed tower) washer/scrubber or unfilled washer/scrubber type. The advantage of the filled washer/scrubber over the unfilled washer/scrubber is that it has a smaller diameter washer due to the filler material and therefore a larger contact surface [9, 15]. However, in the filled type of washer/scrubber, the ash/particles in the flue gas accumulate on the filling material and cause the risk of clogging. Cleaning the filling materials costs a lot of money. This is why the electric power plant, or the motors will have to be out of order frequently.

On the other hand, the initial investment cost of the filled washer/scrubber remains at the same level as the unfilled washer/scrubber due to the cost of the filling material, despite its smaller size [15]. Stainless steel, plastic materials, rubber-coated steel, or plastic-coated concrete washers/scrubbers can be used as washer/scrubber material. If stainless steel material is used, the chloride in the washing solution passing from the feed water to the system causes corrosion and wear. Therefore, the use of stainless steel is limited to some special cases. The initial investment cost of a stainless-steel washer/scrubber may equal the cost of washers/scrubbers made of other materials, depending on the appropriate price of the stainless steel to be used.

Due to the risk of corrosion, plastic scrubbers, rubber-coated steel, or plastic-coated concrete scrubbers are often used in flue gas treatment plants. Their initial investment cost is as high as stainless steel washers. Of these washers, the lowest initial investment cost is plastic-coated concrete washers, followed by plastic washers and rubber-coated steel washers. Concrete type washer has great advantages over other systems due to both operational safety and initial investment cost advantages. Concrete is protected against corrosion by mechanically fixing plastic plates to the concrete. The mounting of the plastic plates to the washer is done at the construction site, thus eliminating huge transportation work. Plastic plates are mounted together with the concrete as an inner wall. Then, each plate is welded on top of each other at the joints. If a possible leaking problem occurs during operation, it can simply be repaired locally. Fig. 3

shows the scheme of covering concrete with a Bekaplast plastic plate [8]. PP, PE, PVC, or PVDF are used as plate material.

A droplet trap is mounted on the upper outlet side of the washer, which allows the holding of small droplets carried by the gas flow. Since the flue gas is carried in solid particles, the particles are kept in the droplet holder. On the other hand, the droplet trap is equipped with a water spray system. Thus, solid particles are removed with the occasional spray water, and clogging is prevented. Chemically resistant pumps are used as circulation pumps and the washing solution is continuously pumped into the absorption zone. The spray nozzles mounted on the pump delivery line ensure that the washing solution is distributed homogeneously to the cross-sectional area in the washer absorption zone and sprayed. Since the spray nozzles do not contain internally connected parts, the danger of clogging is thus eliminated.

The absorption agent is circulated from the chemical storage tank to the washing solution depending on the pH value of the washing solution. In this way, the pH value of the washing solution is kept in the weak acid range and the chemical consumption is reduced as much as possible. The sodium sulfate/sodium sulfite solution formed during SO_2 capture is withdrawn from the system depending on the dosed chemical amount and sent to wastewater treatment. This treatment system requires a high-cost advanced treatment process as described above [1, 9, 20].
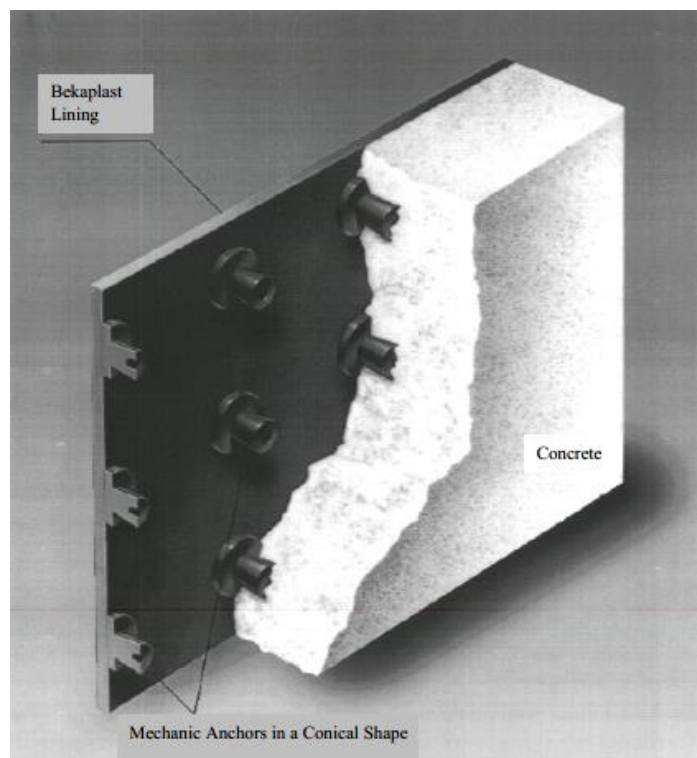

Figure 3: Covering concrete with plastic plate [8].

3.2. Wet FGD scrubber with calcium-based alkalis

By using calcium oxide (lime), calcium hydroxide (slaked lime), or calcium carbonate (limestone) as the absorption solution, gypsum is formed as a solid material in flue gas desulfurization and only unfilled scrubbers are used. The same limitations on the choice of washer material used in wet washers that used sodium-based alkali apply to calcium-based wet washers. The flue gas desulfurization plant with the calcium-based alkali process consists of the following equipment [2, 11]:

- Unfilled washer (with circulation/reaction tank and droplet trap)
- Circulation pumps
- Lime silo and dosing unit
- Gypsum dewatering
- Separation of heavy metals (if necessary)

The structure of the unfilled free-flow washer/scrubber and the circulation pumps is practically the same as the sodium component washer system. The washer size is slightly larger than the sodium component washers, due to the considerably lower reaction rate of the calcium components. The droplet trap system is the same in both processes. The scrubber solution is also kept in the weak acid pH range. Likewise, the administration of calcium components is provided depending on the pH value of the washing solution.

While the sodium components are stored in the system as an aqueous solution, the calcium components are stored dry in silos. The introduction of calcium oxide (lime) into the system is usually accomplished by dosing a pre-prepared suspension. Calcium carbonate (limestone) is fed directly from the storage silo via a screw conveyor to the tank under the washer dry, where it is mixed with water to prepare a solution. If necessary, it is also possible to feed dry in calcium hydroxide and calcium oxide. Circulation pumps and spray nozzles are the same as described in Section 4.1.

The gypsum formed by the absorption of sulfur dioxide in the washing solution is dewatered to 10% humidity in a continuous vacuum band filter. The gypsum obtained in this way is used as a raw material in the construction industry, for example in cement production. The permeate water released from the gypsum dewatering unit is sent back to the process and thus a closed water circulation is provided. The disadvantage of the calcium component process compared to the sodium component is that it has a higher initial investment cost. The initial investment cost of the calcium component desulfurization plant is 60-70% higher due to the required plant/equipment technique, especially the vacuum belt filter and the silo, as well as the slightly larger size of the scrubber. As can be seen from the comparison given below, this high initial investment cost also pays for itself in a short period with considerably lower operating costs. However, if the crystallization unit required for the caustic process is also used, this disadvantage is eliminated.

4. OPERATING COST COMPARISON OF WET FGD SCRUBBERS

To compare the operation costs of wet FGD scrubbers operating with a caustic and limestone process, a 60 MWh electric diesel power plant was investigated. As fuel, approximately 3.5% sulfur heavy fuel (No. 6 Fuel-Oil), which is consumed for this purpose in Türkiye, was used. The operating values and operating expenses unit prices of a diesel power plant with a 60 MWh electric power plant at 8,000 hours annual operation time are given in Table 1 and explained as follows:

- The large diesel engine power plant requires an air intake flow rate in the range of 4-8 Nm3 per kWh [12]. Assuming a wet air intake flow rate of 5.65 Nm^3/kWh, the hourly flue gas flow rate will be $\dot{Q}_{flue\ gas,wet} = 340,000$ Nm^3/h for the wet air and $\dot{Q}_{flue\ gas,dry} = 310,000$ Nm^3/h for dry air for a 60 MWh diesel power plant. The flue gas temperature is assumed to be 200°C.

- The SO_2 inlet concentration in flue gas is $C_{SO2,inlet} = 3,900$ mg/Nm^3,dry based on burning a heavy fuel with 3.5% sulfur content. The SO_2 outlet concentration after scrubber in clean gas is set to less than $C_{SO2,outlet} < 700$ mg/Nm^3. The SO_2 emission limit for liquid fuel-burning power plants between 50-100 MWh is 850 mg/Nm^3 in Türkiye (see page 5 in [17]). The SO_2 removal efficiency (E_{SO_2}) of the wet scrubber can be calculated by Eq. (7):

$$E_{SO_2} = \left(1 - \frac{C_{SO_2,outlet}}{C_{SO_2,inlet}}\right)100\% = \left(1 - \frac{700\frac{mg}{Nm^3}}{3900\frac{mg}{Nm^3}}\right)100\% = 82\% \tag{7}$$

- The SO_2 amount captured per hour ($\dot{m}_{SO_2,captured}$) in a 60 MWh power plant can be calculated by Eq. (8-9) as 992 kg/h:

$$\dot{m}_{SO_2,captured} = \left(C_{SO_2,inlet} - C_{SO_2,outlet}\right)\dot{Q}_{flue\ gas,dry} \tag{8}$$

$$\dot{m}_{SO_2,captured} = \left(3900\ \frac{mg}{Nm^3} - 700\ \frac{mg}{Nm^3}\right)310000\frac{Nm^3}{h} = 992\ \frac{kg}{h} \cong 1000\ \frac{kg}{h} \tag{9}$$

- Average the capital installation cost of the limestone FGD process unit was $108.15 per kWh of a electric power plant (101.66 Euro per kWh with an exchange rate of $1=0.94 Euro) in the year 2022 [13]. The capital cost of the limestone FGD unit of a 60 MWh power plant, including installation, commissioning, and construction works, is approximately based on 2022 prices to be 6.0 million Euros for the limestone FGD process unit (101.66 Euro/kWh x 60,000 kWh = 6.0 million Euro).

- The capital installation costs of the caustic FGD process unit with a filled packed-tower scrubber are ranged from $23,000 to $117,000 per Nm^3/sec flue gas flow rate based on U.S. EPA (Environmental Protection Agency) Air Pollution Control Technology Fact Sheet [15] which was based on 2002 US Dollars. Assuming a capital cost of $26,500 per Nm^3/sec flue gas flow rate is appropriate for the Turkish market, the capital cost of a caustic FGD process unit for a flue gas flow rate of 310,000 Nm^3/h, dry (86.11 Nm^3/sec) will be $2.28 Million in 2002 prices. Based on

the Consumer Price Index (CPI) inflation calculation [16], $1 in 2002 is equivalent in purchasing power to about $1.63 in 2022. So, $2.28 million in 2002 is equivalent to $3.72 million in 2022 (equivalent to 3.5 million Euros in 2022 with an exchange rate of $1=0.94 Euro). So, the capital cost of the caustic FGD unit of a 60 MWh electric power plant, including installation, commissioning, and construction works, is approximately based on 2022 prices to be 3.5 million Euros for the caustic FGD process unit.

Table 2 shows the operating material consumption values for caustic and limestone FGD scrubbers which are explained as follows:

Table 1: Operating values and unit prices of operating expenses of a 60 MWh power plant.

Operating Values	Amount	Unit
Flue gas flow rate	340,000	Nm^3/h, wet
	310,000	Nm^3/h, dry
Flue gas temperature	200	°C
SO_2 Concentration, flue gas	3,900	mg/Nm^3, dry (O_2=%12)
SO_2 Concentration, clean gas	<700	mg/Nm^3, dry
Amount of captured SO_2	992 ≅ 1,000[1]	kg/h
Operation time	8,000	h/year
Operating Expenses Unit Prices		
$CaCO_3$ – 100%	50	Euro/Ton
NaOH – 100%	500	Euro/Ton
Water	2.36[2]	Euro/m^3
Electric	0.15[3]	Euro/kWh
Blower air	0.075[4]	Euro/Nm^3
Gypsum transport	4.5[5]	Euro/Ton
$NaSO_4$ waste disposal	18.8[6]	Euro/Ton

[1] Calculated with Eq. (9).
[2] 2022 average industrial water price in Türkiye was 35 YTL/m^3 x 0.0676 Euro/YTL=2.36 Euro/m^3.
[3] In 2022 the average industrial electric price in Turkey was 0.2174 YTL/kWh x 0.0676 Euro/YTL=0.15 Euro/kWh [18].
[4] Compressed air cost was $0.08 (0.075 Euro) per Nm^3 in Türkiye in 2022 [21].
[5] The cost of gypsum transport by truck was set as $0.19 per ton-mile (see page C-8 in [22]). For a 40 km (25 mile) transportation distance, the gypsum transport cost in Türkiye will be approximately $4.75 (4.5 Euro).
[6] $NaSO_4$ waste product disposal costs vary from $10/ton to $30/ton in 2001 (see page 2 of [23]). The sodium sulfate ($NaSO_4$) waste is a low hazardous waste and its disposal per ton is assumed to be around $20 (18.8 Euro) in 2022 ($12 in 2001) with CPI inflation calculation [16].

Table 2: Consumption of FGD operating materials.

Operating Materials	Unit	NaOH Scrubber	CaCO₃ Scrubber
Captured SO_2	kg/h	1,000	1,000
	Ton/year	(1,000 kg/h) x (8,000 h/year) = 8,000 ton/year	(1,000 kg/h) x (8,000 h/year) = 8,000 ton/year
$CaCO_3$ consumption	kg/h	-	1,600
	Ton/year	-	12,800
NaOH consumption	kg/h	1,250	-
	Ton/year	10,000	-
Water consumption	m³/h	52	25
	m³/year	416,000	200,000
Electric consumption	kW/h	340	600
	kWh/year	2.72 million	4.8 million
LSFO blower air	Nm³/h	-	3150[7]
	Nm³/year	-	25.2 million
Produced gypsum	kg/h	-	2,200
	Ton/year	-	17,600
Produced $NaSO_4$ waste	kg/h	2,220	-
	Ton/year	17,760	-

- Limestone consumption: 1 kmol (64.066 kg) SO2 removal requires 1 kmol (100.087 kg) CaCO3 per Equation 6 which is equal to 1562 kg CaCO3 is needed to capture 1,000 kg SO2 per hour. With a chemical reaction efficiency of 97%, approximately 1,600 kg/h CaCO3 is needed for the required SO2 removal amount.

- Caustic soda consumption: 1 kmol (64.066 kg) SO_2 removal requires 2 kmol (179.994 kg) NaOH per Equation 3 which is equivalent to 1,248.62 kg (approximately 1,250 kg) NaOH is required to capture 1000 kg SO_2 per hour.

- Water consumption for $CaCO_3$ scrubber: Typical makeup water consumption for limestone wet scrubbers is 5.7-6.8 L/min (0.342-0.408 m³/h) per MWh (see Section 3.1 in [19]). By assuming

6.8 L/min water consumption, a 60 MWh power plant needs $24.5 \cong 25$ m^3/h fresh water per hour for its limestone wet scrubber unit.

Table 3: Comparison of wet FGD scrubbers' operating costs.

Operating Expenses	Unit	NaOH Scrubber	CaCO$_3$ Scrubber
CaCO$_3$ consumption	Ton/year	-	12,800
	Euro/year	-	0.64 million
NaOH consumption	Ton/year	10,000	-
	Euro/year	5 million	-
Water consumption	m^3/year	416,000	200,000
	Euro/year	0.982 million	0.472 million
Electric consumption	kWh/year	2.72 million	4.8 million
	Euro/year	0.408 million	0.72 million
Compressed air	Nm^3/h	-	25.2 million
	Euro/year	-	1.89 million
Gypsum transport	Ton/year	-	17,600
	Euro/year	-	0.0792 million
NaSO$_4$ waste removal	Ton/year	17,760	-
	Euro/year	0.3339 million	-
Total Cost	**Euro/year**	**6.724 million**	**3.801 million**

- Water consumption for NaOH scrubber: Packed-bed scrubbers have a recommended liquid-to-gas ratio (L/G) in the range of 1.2 to 1.5 gpm (gallon per minute) per 1000 cfm (cubic feet per minute) of waste gas (0.16 to 0.2 L/Nm^3) per U.S. EPA Air Economics Group (see page 1-69 in [20]. Assuming an L/G ratio of 0.167 L/Nm^3, the NaOH packed-bed scrubber requires approximately 52 m^3/h water for washing out 310,000 Nm^3 dry flue gas flow per hour.

- Electric consumption for CaCO$_3$ scrubber: FGD limestone wet scrubber systems have a relatively low auxiliary power consumption of around 1-2% of the power plant [24]. So CaCO$_3$ scrubber will consume around 600 kWh/h which is around 1% consumption of a 60 MWh electric power plant.

- Electric consumption for NaOH scrubber: Alkaline NaOH scrubber's energy usage lies between 0.2-1.0 kWh per 1000 Nm^3/h flue gas flow [25]. By using a conservative value of 1.0 kWh/1000 Nm^3/h, the NaOH scrubber will consume 340 kWh for 340,000 Nm^3/h wet flue gas flow rate.

- LSFO blower air for $CaCO_3$ reaction tank: An LSFO blower air amount of 7.9 kg/h is used for a flue gas SO_2 inlet amount of 2.38 kg/h in a U.S. EPA test for sludge oxidation in a limestone FGD scrubber (see page 51 in [26]). The SO_2 inlet amount ($C_{SO_2,inlet} \dot{Q}_{flue\ gas,dry}$) for 60 MWh electric diesel power plant is 1210 kg/h which requires an oxidation blower amount of 4,016 kg/h (3,106 Nm^3/h with an air density 1.293 kg/Nm^3). A blower size of 3,150 Nm^3/h is suitable for this limestone FGD reaction tank.

- Produced gypsum ($CaSO_4$): 1 kmol (100.087 kg) $CaCO_3$ can produce 1 kmol (136.14 kg) gypsum per Equation 6. A total of 1,600 kg/h limestone consumption will produce 2,176.35≅2,200 kg/h gypsum.

- Produced $NaSO_4$ waste: 2 kmol (79.994 kg) NaOH can produce 1 kmol (142.04 kg) $NaSO_4$ per Equation 3. A total of 1250 kg/h caustic soda consumption will produce 2,219.54≅2,220 kg/h sodium sulphate waste.

Table 3 compares the two types of wet FGD scrubbers in terms of operation costs which were calculated by multiplying the annual consumption values in Table 2 with the unit prices in Table1.

4. CONCLUSION

As explained in detail before, the flue gas desulfurization process with calcium carbonate as the absorption agent has more fundamental advantages over the caustic (sodium hydroxide) process, due to the final gypsum raw material formation. In addition to the very low operating cost, the process using limestone results in a final product that does not need treatment. In addition, since no wastewater is generated, the very difficult and costly wastewater treatment process is eliminated. Fig. 4 shows a limestone flue gas desulfurization plant.

$NaSO_4$ waste released in caustic desulfurization causes additional wastewater treatment investment and operating costs. As can be seen from the above comparisons, the operating cost of the washer that uses limestone as a chemical solution is 4.36 million Euros less per year than the caustic washer. As a result, the limestone washer, whose initial investment cost is 2.5 million Euros higher than the caustic washer, pays for itself within 10 months. Thus, the system with caustic and limestone reaches the same level within 10 months in terms of initial investment cost. The most important thing is that 2.923 million Euros will be saved every year.

Figure 4: A limestone flue gas desulfurization plant [5].

CONFLICT OF INTEREST STATEMENT

No conflict of interest or common interest has been declared by the author.

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THE DECLARATION OF ETHICS COMMITTEE APPROVAL

This study does not require ethics committee permission or any special permission.

THE DECLARATION OF RESEARCH AND PUBLICATION ETHICS

The author of the paper declares that he complies with the scientific, ethical, and quotation rules of Kırklareli University Journal of Engineering and Science) (KUJES) in all processes of the paper and that they do not make any falsification on the data collected. In addition, he declares that Kırklareli University Journal of Engineering and Science and its editorial board have no responsibility for any ethical violations that may be encountered and that this study has not been evaluated in any academic publication environment other than Kırklareli University Journal of Engineering and Science.

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