LIME-BASED WET FLUE GAS DESULPHURIZATION SYSTEMS (WET SCRUBBER)

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ABSTRACT

Harmful emissions polluting the atmosphere and disrupt the natural balance of the earth, are quite numerous. Examples of these chemical processes released by hydrocarbons, sulfur compounds released by the combustion of fossil fuels (SO_x), nitrogen oxides (NOx), carbon released by the incomplete combustion of carbon monoxide (Co), and especially coal, such as lignite thermal power plants that burn solid fuels such as mercury compounds can be considered a pollutant released. In addition to artificial sources, natural sources such as volcanic events also play a role in the production of these pollutant emissions. Almost all of these pollutants can be removed from the smoke gas body at a certain rate before being released into the atmosphere. Thus, the negative effects of these pollutants on the atmosphere can be reduced or even eliminated. The process of cleaning each pollutant is a separate technology and a separate subject of research. In this study, brief information about the cleaning of sulfur oxides (FGD or Desulphurization) will be given and the lime-based desulphurization process in tower-type wet filters will be examined in more detail.

Keywords: Sulfur Oxides, Desulphurization, Wet Filter

SULPHUR OXIDES (SO_x) AND ITS EFFECTS

Sulphur oxides are polluting compounds consisting of oxygen and sulfur elements, which are common in atmospheric conditions, especially in the form of sulfur dioxide (SO_2). They are normally colorless gases that can be detected by taste and odor at concentrations between 100 - 3,000 μg/m³ and can be felt with a sharp odor at 10,000 μg/m³ levels. SO_2 can react very easily with water under atmospheric conditions to form hydrogen sulfide (H2SO3). Another form, SO_3, is not as common as SO_2, but can be released directly from the source to the atmosphere, or it can be formed by conversion reactions of SO_2. As a result of the reaction of SO_3 gas with water, corrosive sulfuric acid (H2SO4) formation is observed.

Sulfur oxides can be released as a result of the combustion of fossil fuels, and a particularly significant amount (35-65%) is released as a result of natural events (volcanoes). Thermal power plants, industrial boilers, melting furnaces and cement plants are the main artificial sources that produce SO_x by burning sulfur fuels. In addition, domestic fossil fuel use and exhaust gases from motor vehicles are other SO_x sources.

It has been determined that the periodic release of sulfur dioxide (SO_2) into the atmosphere has serious effects on human and plant communities. Depending on temperature, wind, humidity and location, SO_2 gases can be found near ground level. At the end of the measurement made in the city center of London in 1952, it was observed that the concentration reached 3.500 μg/m³ and remained for 5 days.

Health problems such as raising premature death rates, respiratory problems, eyes, nose and throat irritations have been detected as a result of vulnerability to SO_2 gas. These symptoms are felt in case of exposure for at least 10 minutes at a concentration of 1,000 $\mu g/m^3$ SO_2 emissions also cause serious damage to forest and agricultural vegetation. It has been determined that there is a decrease in the early extinction and reproduction of vegetation close to SO_2 sources.

It is known that the vegetation located far from the emission source is also affected by acid rains and sulfur oxides. The effects on the forest ecosystem may vary according to soil type, insect population, atmospheric conditions and many more unknown parameters. Acid dissolutions formed as a result of the reaction of SO_3 and water can destroy many fish species in the lake by lowering the pH value of the lakes in the ecosystem. By affecting concrete and steel, sulfuric acid can also damage building structures, accelerate the corrosion of these materials and cause them to weaken in a short time. In addition, sulfuric acids are capable of damaging leather and paper materials. [1,2]

METHODS TO REDUCE SO_x EMISSIONS

Various approaches applied for the control of sulfur oxides; it can be summarized as the use of low sulfur fuels such as natural gas, the application of appropriate combustion techniques and the desulphurization of the flue gas.
Since the SO_x composition of the flue gas is proportional to the sulfur in the fuel, the use of natural gas or similar low sulfur fuels directly reduces flue gas emissions. However, if we consider that today's clean fossil fuel reserves such as natural gas are limited, we can see that the use of sulphurous solid or liquid fuels is not a choice, but a necessity.

It is one of the methods applied to obtain low sulfur fuel by reducing the sulfur in the coal with enrichment processes. Usually, up to 70% of the sulfur found in coal is dead or in the form of mineral sulphate, so there is no chemical bond. With coal enrichment processes, up to 20-30% of the sulfur in the coal can be removed. Coal beneficiation processes cannot remove sulfur of organic origin, but they can also remove ash-forming materials from the coal. Although enrichment processes can often be cost-effective, they have limitations due to the solid wastes and acidic liquids produced by the process.

In liquid fuels, sulfur can be removed by chemical desulphurization processes, but it is not a common method outside the petroleum industry. Fluidized bed combustion systems are also one of the successful and common methods to reduce SO_x emissions. Lime or dolomite injected into the combustion chamber can reduce sulfur oxide emissions from combustion.

The most common control methods today are the use of sorbent and desulphurization methods. In the use of sorbent, SO_x retention efficiency of 30-60% can be achieved by adding lime products or sodium-based sorbents to the combustion products. [1] Chemicals such as caustic soda and soda ash are less preferred because they are 3-4 times more expensive than lime products. [3]

In desulphurization processes, the flue gas is washed with absorbing liquids in units such as wet filters. Reversible and irreversible methods are available. In recyclable systems, the final product with market value is obtained, while in non-recyclable systems, wastes that need to be disposed of.

90% of the flue gas desulphurization methods used today are applied as non-recycling. While the recycling systems are costly in terms of using expensive sorbents, they also have advantages such as less waste amount and market value of the product (Sulfuric acid, gypsum) formed. In general, both systems are similar to each other and in this study the common parts of both systems will be examined.

DESULPHURIZATION WITH WET FILTER

This method, which can also be named as Wet Scrubbing or De-SO_x in the literature, has been applied for nearly 40 years, especially for the desulphurization of the flue gases of coal-burning systems. In this method, the general principle is to provide a chemical interaction by contacting the flue gases with high SO_x content and the absorption liquid sprayed into the gas, thus keeping the sulfur oxides and rendering them harmless. Absorption agents used in the system can be lime (CaO), limestone ($CaCO_3$), ammonia (NH_3), sodium alkali solutions (Na_2CO_3, $NaOH$, Na_2SO_3) and various chemicals used as additives. The most preferred among these are lime products, especially in large systems, as they are economical. In these systems where lime is preferred, the SO_x retention efficiency is around 95%, but the efficiency can be increased to 99% by adding more reactive additives such as magnesium.
In general, every desulphurization plant has an electrostatic filter, bag filter, cyclone filter or a combination of these in order to reduce the particle load before the wet filter. Thus, both SO_x holding efficiency increased and the circulation pumps or connection lines in the system can be prevented from filling up quickly.

A reversible wet desulphurization system diagram is shown in Figure 1. The polluted gas coming from the emission source is first passed through the other pre-cleaning elements (Cyclone filter, Bag filter etc.) in the system. The polluted gas with reduced particle load is then transferred to the wet filter unit by means of a fan. When the wet filter unit is not in operation or is taken into maintenance, the by-pass flap is opened and the flap going to the filter is closed, thus the flue gas is directly bypassed to the chimney. In cases where it is desired to improve the chimney draft with high temperature, bypassing a part of the gas to the chimney without washing is also one of the methods applied.

In systems with heat recovery, the polluted gas coming to the wet filter unit is first cooled in the primary heat exchanger and then fed to the wet filter. Flue gases entering the heat exchanger at temperatures of 130-150 °C enter the wet filter after cooling at approximately 50 °C. Here, too, the smoke gas, which comes to the saturation point with the water it receives, cools down to 50-60 °C and is reheated at about 50 °C in the secondary heat exchanger, and is released into the atmosphere at around 100-110 °C. Thus, the consumption of the absorption liquid, and especially the water, is significantly reduced. The temperatures indicated are typical values and may vary depending on conditions.

In this study, systems using milk of lime as absorption liquid will be examined. These liquids, also called lime slurry, are typically used with a concentration of 90% water + 10% lime.

The system components of the use of lime (limestone) in desulphurization applications can be grouped under 4 headings. (Figure 1)

1. Washing and absorption: Tower, absorber tank, spray nozzles and circulation pumps,
2. Lime transport and preparation: Lime transport, storage and lime milk preparation equipment,

3. Sludge separation: Sludge separation, pumping and dewatering equipment,
4. Flue gas transport: Ducts, fans, dampers, heaters and chimney.

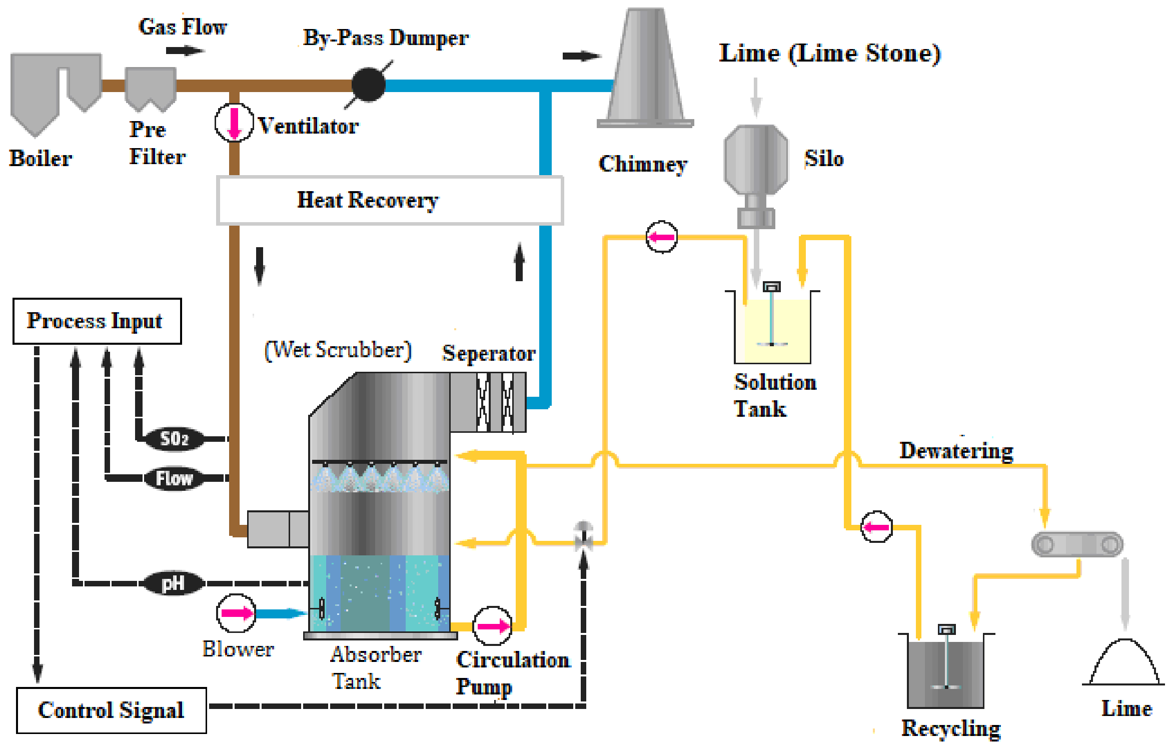

Figure 1. Lime-Based Wet Filter (Wet Scrubber) Application Flow Chart For Industrial Systems [5]

LIME REACTION (CaO)

In lime-based processes, milk of lime, which is created by adding water to lime (CaO) with a purity of approximately 90%, is used. The circulation liquid taken from the absorber tank is sprayed into the flue gas to capture (absorb) SOx molecules. The following reactions take place with the lime fed into the tank in a controlled manner. As a result of the chemical reaction, calcium sulfide ($CaSO_3$) and sulfate ($CaSO_4$) salts are formed and separated as sludge by precipitation. In a chemical reaction, calcium and SO_2 must first dissociate into their own ions. This happens when calcium dissolves in water and SO_2 is dissociated into ions with the liquid sprayed on SO_2.

Sulfur Dioxide Decomposition:

$$SO_{2(gaz)} \rightarrow SO_{2(Sulu)}$$

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$H_2SO_3 \rightarrow H^+ + HSO_3^- \rightarrow 2H^+ + SO_3^=$$

Calcium Dissolution:

$$CaO_{(katı)} + H_2O \rightarrow Ca(OH)_{2(sulu)}$$

$$Ca(OH)_2 \rightarrow Ca^{++} + 2OH^-$$

After dissociating into calcium and SO2 ions, the following reaction occurs.

$$Ca^{++} + SO_3^{=} + 2H^+ + 2OH^- \rightarrow CaSO_{3(katı)} + 2H_2O$$

Thus, calcium sulfide is obtained. If there is too much oxygen in the environment, calcium sulfate (Gypsum) is formed by the following reaction.

$$SO_3^{=} + 1/2O_2 \rightarrow SO_4^{=}$$
$$SO_4^{=} + Ca^{++} \rightarrow CaSO_{4(katı)}$$

This can be accomplished by supplying oxygen (Air) to the reaction tank with a blower (Fan). Considering that the lime is 90% pure according to these reactions, it can be said that 1,1 moles of lime is required for 1 mole of SO_2. [4] If the total flue gas amount and SO_2 content are known, the approximate amount of lime to be fed into the system can be calculated from here.

LIMESTONE REACTION ($CaCO_3$)

The limestone reaction is similar to the lime reaction. Only the preparation stages and the liquid/gas ratios required for washing differ. Since limestone is less active than limestone, a higher liquid/gas ratio is required for washing in limestone reactions. However, for example, a system that works with one can work with another. Most of the chemical reactions are the same, but the only difference is the dissociation reaction.

$$CaCO_{3(katı)} + H_2O \rightarrow Ca^{++} + HCO_3^- + OH^-$$

Other than that, other reactions and processes are pretty much the same. The limestone grinded in the mill is given to the solution tank and mixed with water. The large pieces that cannot pass through the sieve are sent to grinding again. The most important point that makes limestone more common is that its cost is up to ¼ of that of lime.

In general, the efficiency of the reaction in the absorber is related to the pH value of the liquid. Since more alkaline liquid will react at high pH value, the yield increases. Limestone and water feeding adjustment should be controlled and pH should be kept at optimum level.

Another situation encountered in lime and limestone reactions is that calcium sulfide cannot be easily filtered. As a solution to this, with the following reaction developed in EPA laboratories, calcium sulfide is converted to calcium sulfate and its retention is facilitated. Here, the above mentioned oxidation air is supplied to the system.

$$CaSO_3 + H_2O + 1/2O_2 \rightarrow CaSO_4 + H_2O$$

The summary of the reaction with limestone is as follows.

$$SO_2 + 2H_2O + CaCO_3(Kireçtaşi) + 1/2O_2 \rightarrow CaSO_4.2H_2O(Alçı) + CO_2$$

As a result, the calcium sulfate obtained is separated more easily due to its coarse crystal structure and can be used in the production of materials such as gypsum and cement. Since calcium sulfate is easily filtered, accumulation is less in the wet filter inner surfaces and in the installation.

Considering Figure 1, some of the absorption liquid taken from the absorption tank is sent to the tower for gas washing, while some is sent to the recovery unit for cleaning. Thus, the solids concentration in the tower tank is tried to be kept at a certain value. In these systems, in order to cool the flue gas up to the saturation point, very serious amounts of water have to be thrown into the atmosphere. Based on this, water and solution savings are achieved with the clean liquid coming from recycling (treatment). The final product (gypsum) coming to the recovery unit is also dewatered by passing through units such as classifier and thickener.

WORKING PRINCIPLES OF WET FILTERS

Wet scrubbers can be used for desulphurization purposes as well as for desulphurization and dust holding purposes. In wet filters, in general, mechanisms such as diffusion that occurs as a result of contacting the trapping liquid with the dirty gas in small droplets (spraying with nozzles) or retention by impact effect are used. The gas taken from the gas inlet to the tower is first passed through the distribution plates to ensure a homogeneous flow. The plates also contribute to the absorption efficiency by increasing the surface. The polluted gas, which moves towards the top of the tower in a homogeneous state, is washed with the absorption liquid sprayed from above with nozzles. (Spraying) The absorption liquid is taken from the continuously ventilated and stirred absorber tank at the bottom of the tower. The washed gas enters the droplet eliminator section to leave excess water droplets, if any, after the temperature drops, saturated with moisture and cleaned. (It is also called a mist eliminator or separator) Here, after leaving the excess water in its body, it comes out of the tower. (Figure 2)

The parameters affecting the retention efficiency can be listed as particle size, droplet size and relative velocities. In general, large particles are easier to handle. In addition, the reduction in droplet size also increases the holding efficiency. This also increases operating costs because small droplet size means high pumping power. If gaseous pollutants are retained, the pollutant must be soluble in the chosen holding liquid. In addition, in these cases, good mixing and sufficient time must be provided for the gas to dissolve well in the liquid. Another important point in the holding efficiency is the well-adjustment of the amount of liquid required for a unit volume of polluted gas. (L/G ratio)

In order for the excess liquid entrained with the gas not to be discharged to the atmosphere through the wet filter body, it must be kept in the droplet eliminator and fed back again. Otherwise, besides excessive water consumption, it is inevitable that acidic water will scatter into the environment and have negative effects.

Pollutant particle retention and pollutant gas retention (Absorption), two functions that wet filters basically perform, will be detailed below.

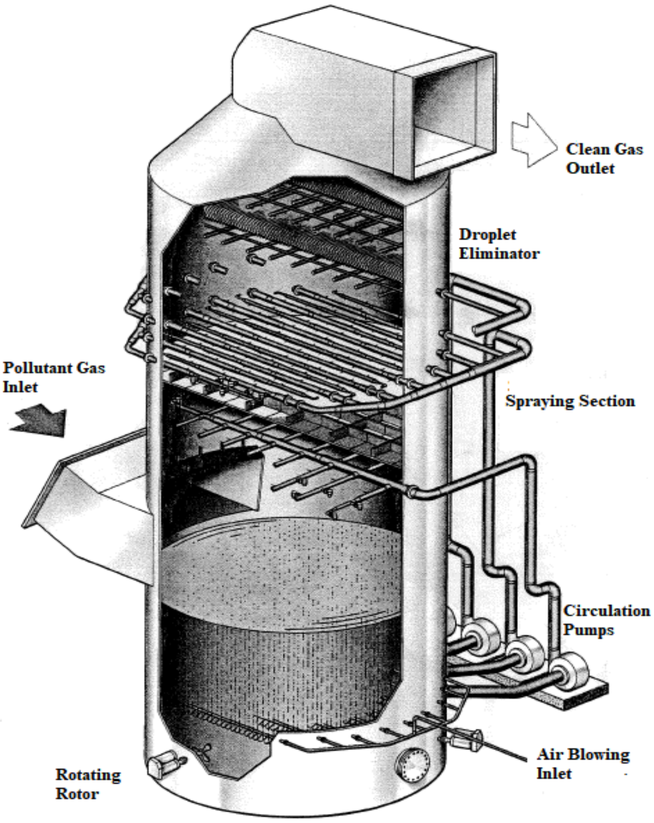

Figure 2. Schematic View of Tower Type Wet Filter [6]

Particle Retention:

Wet filters can hold relatively large liquid droplets and very small particles. In most applications, the droplet diameter is over 50 µm (150-500 µm). For example, the thickness of a human hair varies between 50 and 100 µm. The diameter of the particles to be retained depends on the source from which they are produced. For example, particles formed as a result of mechanical processes such as crushing and grinding show a distribution above 10 µm, while particles resulting from combustion or chemical processes show a distribution below 5 µm. For scrubber applications, the hardest particle size to handle is between 0.1-0.5 µm.

The droplets required for retention can be created by several methods, these are;

a. By spraying the liquid with pressure from special nozzles (the most preferred method)
b. By passing particulate gas through the liquid,
c. With the use of a rotating rotor in the liquid.

The droplets produced by such methods hold the particles by one or more different retention mechanisms. These mechanisms can be listed as collision effect, diffusion, stopping, electrostatic effect, condensation, centrifugal effect and gravity effect. The most important mechanisms among these are diffusion and collision.

Collision:

In a scrubbing system, dust particles will want to travel along gas streamlines. (Figure 3) At this moment, due to the droplets sent into the stream, the particles will hit the droplets and will mix with the liquid body with this effect. The impact of impact increases with increasing particle diameter and relative velocity. Since the particles always move faster than the droplets, the probability of collision is always high. For this reason, the impact mechanism has always been dominant in scrubbers where the velocity is greater than 0.3 m/s. (Perry 1973) Therefore, at speeds above 0.3 m/s, particles above 1 μm are retained by impact. [4]

Diffusion:

Very small particles under 0.1 μm in the gas make very fast and sudden movements. As these molecules move through the gas, they make sudden and rapid movements towards other large gas molecules and droplets. As a result of these rapidly changing movements, some of these particles diffuse into the droplet. Particles below 0.1 μm can be captured quite successfully by this mechanism. [4] Diffusion rate depends on parameters such as relative velocity, particle diameter and droplet diameter.

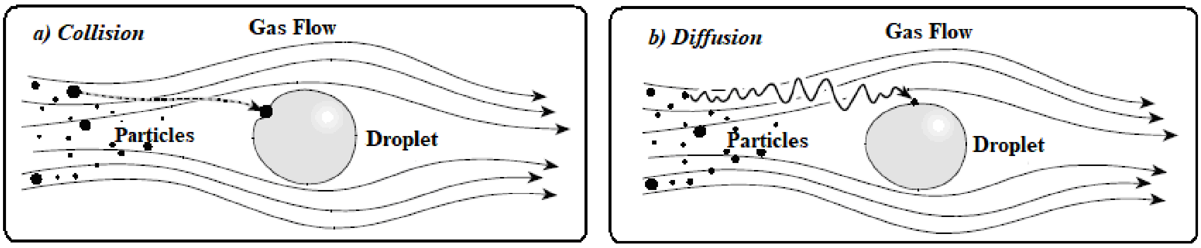

Figure 3. Droplet and Particle Interaction; Collision and Diffusion. [4]

Increasing the relative velocity increases the efficiency in both diffusion and multiplication. For sizes between 0.1-1 μm, neither diffusion nor multiplication is dominant, that is, there is a co-effect.

In addition to particle retention mechanisms, condensing and electrostatic effective methods that require less energy consumption have been developed in recent years. In the electrostatic effective method, electrons are charged to the particles and then they adhere to each other with this effect. Thus, larger particles are obtained and retention is facilitated. By condensing water vapor on the particles, extra mass can be added to the particles, making retention easier.

Gas Collection:

The dissolution of a gas in a liquid is called absorption. Absorption is basically a mass transfer phenomenon. In other words, it is the transfer of particles from one phase or current to another phase or current. The mass transfer mechanism can be compared in principle to heat transfer. In heat transfer, heat flow occurs until the equilibrium state due to the temperature gradient, while in mass transfer, particle transfer occurs until the concentration difference disappears. To collect polluting particles from a polluted gas, the gas stream must be brought into contact with the absorption liquid at the maximum surface area.

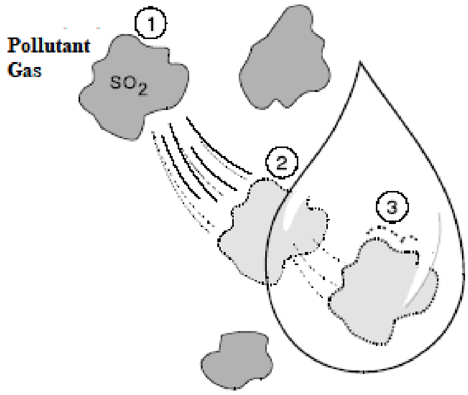

Figure 4. Gas Absorption Stages [4]

As it can be seen in Figure 4, in case of SO_2 absorption, the gas stream rushes to the liquid-gas interface in the first step. In the second step, the pollutant particles in the gas stream diffuse into the liquid. This event happens pretty quickly. In the last step, gas molecules accumulate in the liquid. The absorption efficiency in this event mainly depends on the diffusion rates in the gas phase (1) and the liquid phase (2). The points to be considered in order to increase the absorption efficiency can be listed as follows.

1. To provide a large contact surface (Lots of liquid droplets),
2. To provide a good mix,
3. To provide sufficient contact time between the liquid and gas phases.

The first two of these are also necessary parameters for particle retention mechanisms. The third factor has the opposite effect on particle retention. That is, providing a long contact time means reducing the relative velocity between the liquid droplet and the particle which reduces the particle retention efficiency. For this reason, if the gas to be absorbed does not dissolve very well in the liquid, it is very difficult to perform absorption and particle retention in the same process.

Solubility is a very important parameter in terms of directly determining the absorption efficiency. While determining the liquid/gas ratio directly, the contact time also depends on the solubility of the gas in the liquid. Good soluble gases require less liquid consumption and contribute to faster absorption. Solubility also depends on temperature and a small amount of pressure. As the temperature increases, the solubility decreases, while the increase in pressure increases the solubility slightly. In addition, the increase in temperature will increase the volume of the gas, resulting in more liquid consumption. For this reason, pre-cooling (Quenching) of the flue gas mentioned before is applied in most systems.

WET DESULPHURIZATION SYSTEM COMPONENTS

Induced Draft Fan

The main task of the ID fan used in desulphurization units is to compensate the pressure that the flue gas will lose in the wet filter unit. At this point, it should be ensured that the pressure loss of the wet filter units is as low as possible. Thus, energy consumption and thus process operating cost will be reduced. The fans to be placed in the system can be before or after the filter. Fans to be placed before the filter are generally subject to high particle density, so they must be made of wear-resistant materials or the wear effect can be reduced by keeping the gas velocity low by using large fans. Fans to be placed after the filter, on the other hand, should be made of corrosion-resistant materials, taking into account the effect of sulfuric acid corrosion.

Heat Exchanger Unit

As a general principle, if the flue gas inlet temperature is high, it means that the water required for saturation during washing - and therefore the solution - is high. Because, in order to saturate the flue gas with water at a certain pressure, it must evaporate a large amount of water in proportion to the inlet temperature. At this point, the presence of the heat exchanger in the system is related to the necessity of the flue gas entering the filtering unit at a temperature as low as possible. For this purpose, the gas coming out of the filter is heated with the heat taken from the gas entering the filter. Thus, extra water and solution consumption during washing is reduced, and operating costs are reduced. However, the flue gas that comes out of the filter at a constant temperature (50-60°C) is thrown into the atmosphere at a high temperature (100-110°C), thus reducing the possibility of re-condensation. Thus, the effect of the gas on the equipment and the environment as a result of condensation is reduced and the chimney draft can be improved. The process flow chart of the system is given in Figure 5.

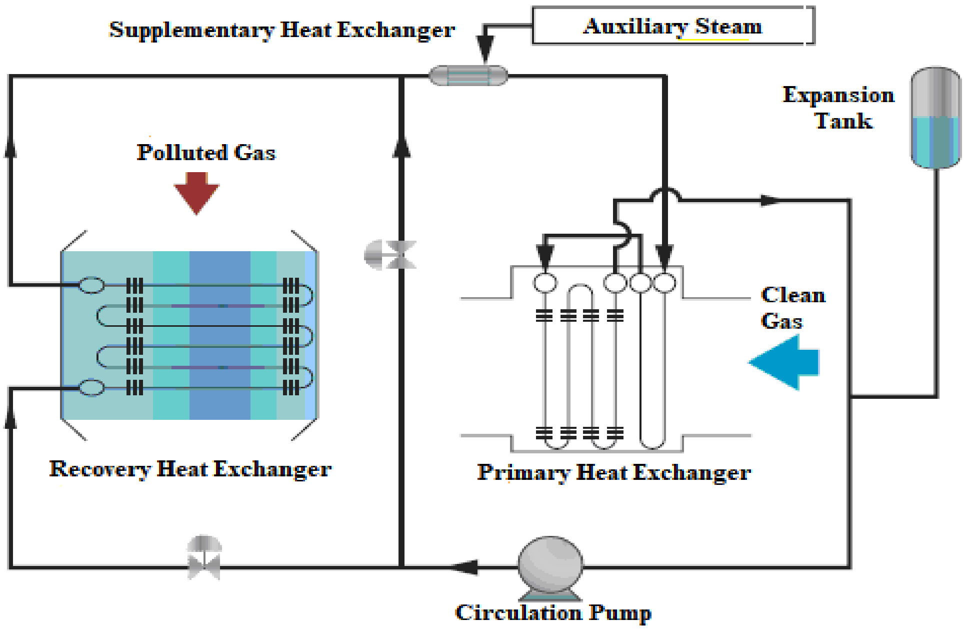

Figure 5. Flow Chart of the Heat Recovery System [5]

Water is generally used as the heat carrier fluid, and thermal oils can also be used. In the diagram in Figure 5, the system is designed compactly. When the bypass valve in the system is closed, the clean gas is heated by using the heat of the polluted gas entering the filtering unit. However, if for some reason the temperature of the entering gas becomes too low and the heat carrier fluid cannot be heated, supplementary heating can be done with auxiliary steam by opening the bypass valve and closing the valve going to the primary heat exchanger. In case the heat carrier fluid decreases for any reason, there may be a reserve tank in the system to supplement, and an expansion tank to compensate for the expansion of the fluid, especially if the system is operating under pressure.

There are various alternatives for the placement of heat recovery units in the waste gas system, and the two most common are shown below.

In the first system in Figure 6, known as the classical method, the primary heat exchanger is placed after the electrostatic filter and the fan. In the second system designed as an alternative, the heat exchanger is placed before the electrostatic filter. This system is newer and has many advantages. The advantages of the system can be listed as follows.

- Reduced flue gas volume, low pre-filter (Electro Static Filter-ESP, Bag filter, etc.) capacity.
- Low fan (ventilator) energy consumption due to reduced flue gas volume.
- Low flue gas emissions.
- Increase in the quality of the final product gypsum (if any).

Heat recovery units are expensive equipment to increase savings for desulphurization plants and their use is not very common yet.

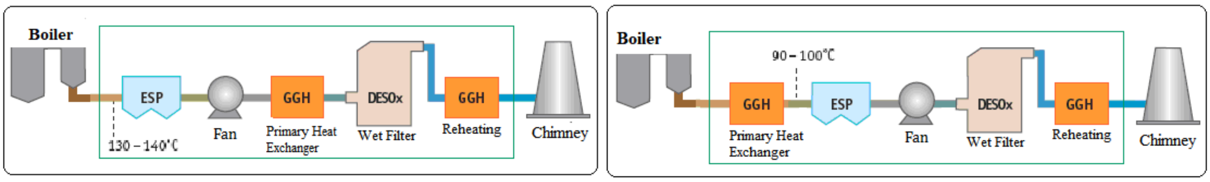

Figure 6. Heat Recovery Unit Layout Alternatives [5]

Smoke Ducts and Chimney

Smoke ducts are one of the most important components of the system in terms of transporting and directing the flue gas. They need to be carefully designed, especially in terms of reducing pressure losses and thus operating costs. For example, while sizing, certain gas velocities should not be exceeded in terms of pressure drop, certain velocities should not be exceeded in terms of reducing dust accumulation, and constructions such as elbows, contraction-expansion elements that will create local losses should be avoided as much as possible.

As with ventilators, wear is a big problem, especially in the channels before the filter, and wear can be prevented by using materials or coatings that are resistant to wear. As an option, partial protection can be applied by covering only the parts that will be most subject to wear, such as the elbow. Channels after the filter should be made of corrosion resistant materials or coated as they will be exposed to sulfuric acid.

To be able to release cleaned gas to the atmosphere at a sufficient height, the chimneys must be designed correctly. The height and diameter of the chimney change according to the emission after the cleaning process. As the emission from the chimney increases, the height of the chimney also increases. Relevant calculations and tables are available in standards and regulations.

Chimneys to be used after the wet filter must be protected against high sulfuric acid corrosion. In our country, the inner walls of such chimneys are generally covered with austenitic stainless materials. In larger systems, materials such as glass and plastic can also be used. In order to prevent cooling and condensation, especially in the ducts and chimneys on the outlet side, external heat insulation (Cold casing) should be made.

Pumps

In wet filter processes, there are circulation and sludge pumps to transport fluids released. Circulation pumps pressurize the solution taken from the absorption tank and give it to the spray nozzles. Here, the liquid coming out of the nozzles at high pressure is pulverized and meets the flue gas in the form of small droplets. The head of circulation pumps can generally be selected between 30 and 70 mSS depending on the design. Sludge removal pumps are used to remove the sludge consisting of sulfide and sulfate, which is about to settle in the absorption tank, from the system. One of the common problems in sludge removal pumps is clogging due to high solid density. In order to prevent this, it is recommended that the solid concentration of the discharged sludge should not be more than 15%. In addition, the pumps must be highly corrosion resistant as the corrosion potential is high in both cases.

Piping

The transfer and distribution of liquids and solutions in the system is carried out with piping lines manufactured to be resistant to corrosion. It is suggested that optimum water velocities should be between 1.2 and 2.1 m/s in piping systems, considering both pressure drops and parameters such as clogging and wear. Pipe materials recommended for piping installations to be used in wet filters can be listed as stainless steel, PVC, FRP, rubber and glass. While choosing the material, parameters such as corrosion severity and temperature should be evaluated together.

Saturators

They are used to saturate the high temperature flue gas with water before it enters the tower. The flue gas entering the saturator at high temperature is supplied with water in pulverized form here and is saturated with moisture and its temperature is brought to the level of saturation. If this pre-saturation is not applied, the high-temperature flue gas will be saturated in the scrubber. In this case, more solution will be consumed than necessary for the desulphurization process, thus increasing the operating cost. For this reason, it is a more rational approach to give the flue gas to the tower after saturating it with water. In addition, pre-saturation with absorber liquid reduces the overall filtration efficiency. Because there are particles and undissolved substances in this liquid. These substances, on the other hand, can reduce the filtration efficiency as they will enter the scrubber unit again with the flue gas. (EPA 1982) As saturators reduce the inlet temperature of the gas into the tower, they also reduce the filter size.

In addition, since the gases entering the tower at high temperature completely evaporate the sprayed liquid, the droplets in the spray liquid are prevented from contacting the sulfur oxides, which significantly reduces the retention and reaction efficiency.

The feeder system can be a separate unit outside the tower, or it can be within the tower. A certain amount of time must pass for the complete evaporation of the saturator. For flue gases below 540 °C, it is recommended that this time be between 0.2 and 0.3 seconds. (Shifftner 1979) Therefore, the sizing should be done accordingly.

Spray Nozzles

Basically produced in 3 types, the spray nozzles allow the liquid to come into contact with the flue gas in the form of small droplets by spraying with pressure. (Figure 7) The smaller droplets make the contact area the larger and this increases the filtration efficiency. If Figure 7 is examined, in the first type, *the impingement* nozzle, high pressure liquid is impinged on a plate to obtain uniform sized droplets. The droplet diameters that can be obtained with this nozzle range from 25 to 400 µm. Since, it does not have any internal mechanism negativities such as clogging are minimal. These types of nozzles are generally made of stainless steel and brass.

In the *conical* nozzle, the liquid is passed through the conical structure and separated into small droplets. These nozzles can be made of stainless steel, brass, Teflon and plastic. Spraying angles between 15-140° can be achieved.

In the *helical* nozzle, the pressurized liquid is passed through the helical structure. Since there is no internal structure in such nozzles, the risk of clogging is very low. Helical nozzles can also be made of stainless steel, brass, Teflon and plastic materials. Spraying angles between 50-180° can be achieved.

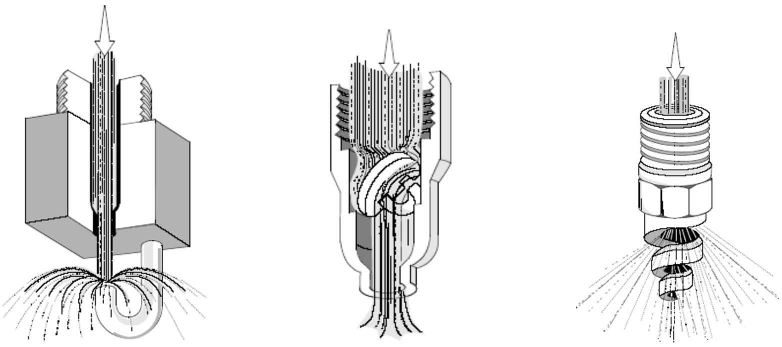

Figure 7. Spray Nozzle Types; Impinged, Conical, Helical [4]

Some parameters to be considered in nozzle selection and arrangement are as follows;

- Created Droplet Diameter: Decreasing the droplet diameter increases the efficiency while increasing the energy consumption,
- Spraying Geometry: Nozzles can spray in various geometries such as square and conical. Especially in full conical spraying, a very effective washing can be done,
- Risk of Clogging: Nozzles that will pose the least risk of clogging and are easy to clean should be preferred,
- Energy Consumption: Nozzle selection, arrangement and piping should be done in such a way that the pumping power is kept as low as possible,
- Nozzle Arrangement: As can be seen in Figure 8, it is important for filtration efficiency to arrange the nozzles in such a way that there is no blind spot and spraying can be done on all sides.

For nozzles, capacity tables are given by the manufacturers according to the operating pressures. Therefore, after determining the amount of liquid required for filtration, it can be determined at what pressure, which type and how many nozzles should be used.

The most common problem that can be encountered during the operation of nozzles is clogging. In order to understand the clogging, either the spray geometry can be observed through the sight glasses or it can be checked whether there is a blockage by looking at the fluid consumption and the flue outlet temperature.

To avoid clogging, frequent cleaning of the nozzles, adequate filtering of the washer fluid, or diluting the solution may be the solution.

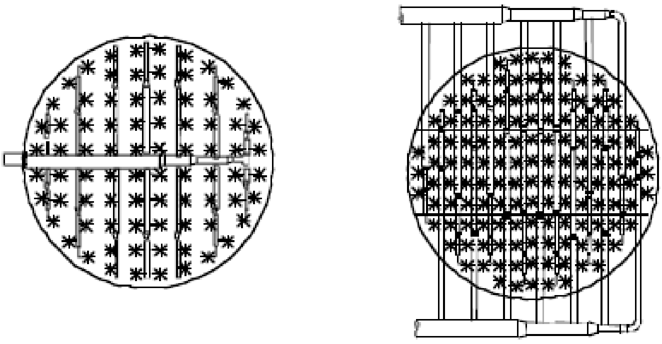

Figure 8. Nozzle Array Alternatives for Effective Spraying [7]

Droplet Eliminators (Separators)

Droplets carrying sulfuric acid are one of the most important parts of the wet filter, which ensures that the droplets carrying sulfuric acid are retained before they go to the chimney channels and the atmosphere. Another benefit of the droplet eliminators is that the washing liquid is retained and reused.

The diameters of the drops to be retained vary according to the form of formation. For example, while the diameters of the droplets obtained from a liquid mass are between 10-100 µm , the diameters of the droplets formed by chemical reaction and condensation are below 5 µm . Various holder constructions are available to hold these varying droplets. The ones used in pollution control applications are cyclonic, vane and mesh-pad type holders.

The *cyclonic* separator, which is especially used in venturi type filters, works by taking advantage of the centrifugal force of the droplets and its internal structure is quite simple. (Fig. 9) It can perform a good holding operation in diameters between 10-25 µm. In this type, a pressure drop of 100-150 mmSS occurs for 20-25 µm droplets and 98% retention efficiency.

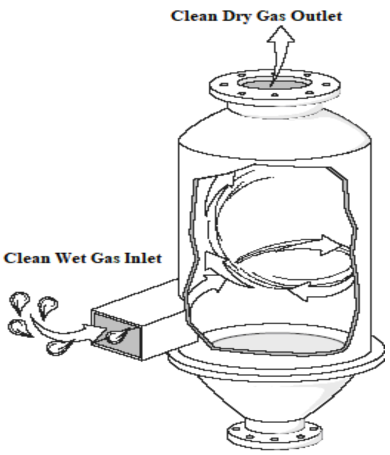

Figure 9. Cyclonic Droplet Eliminator [4]

In mesh-pad type separators, a fibrous structure made of 10-15 cm thick plastic is used. 10-150 mmSS pressure loss may occur in these separators, which are adapted to the inner diameter of the scrubber. The biggest disadvantage of these separators is that the small passage holes get clogged quickly. To prevent this, the separator should be washed frequently by spraying it with washing water from the top and bottom. (Fig. 10)

Vane type separators can be divided into 2 groups. One of them is the *Chevron* type. In this type, the gas flow is forced to pass between the vanes by making a zig-zag. Meanwhile, the droplets, which are heavy due to the law of inertia, hit the vanes and fall back by collecting. Here, the performance can be increased by increasing the number of oriented vanes. Typical pressure loss in these separators with holding performance up to 5 μm diameter can reach up to 60 mmSS. It is the most preferred separator type in tower type filters.

In the second type, impingement separators, the droplets in the flue gas passing between the plates resembling fan blades are kept by the effect of being thrown to the walls. Typical pressure loss is in the range of 50-150 mmSS.

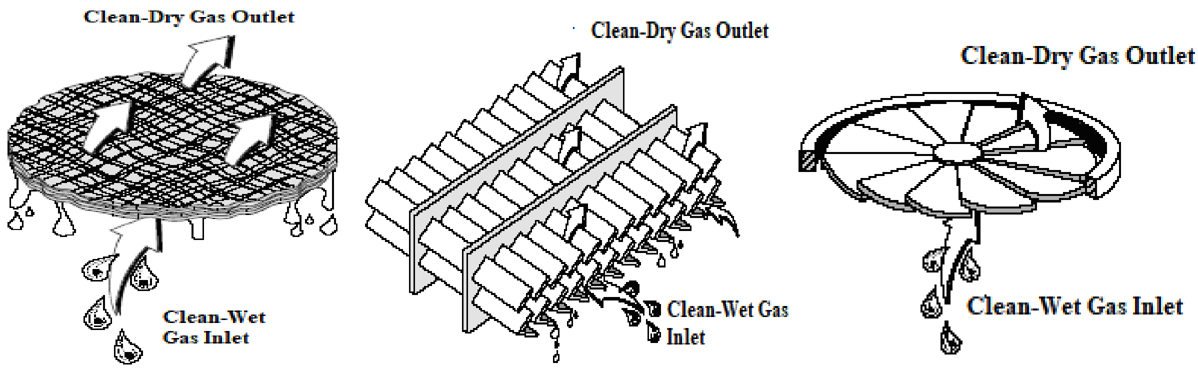

Figure 10. Mesh Pad, Chevron and Impingement Type Separator Applications [4]

The most important parameter that can be observed in the performance of the separator is the pressure drop. For example, a decrease in pressure drop at constant load is probably an indication of damage or partial breakage of the blades. A sudden increase in pressure drop, even by 5 mmSS, is a sign of sludge build-up or clogging. Scrubber units have washing nozzles to periodically clean the separators.

If the gas velocity is selected too high in the drop catchers, droplet transport may occur. In this respect, velocities below 3 m/s in the Chevron type, below 5 m/s in the mesh-pad type, and below 8 m/s in the impingement type should be preferred.

MATERIAL SELECTIONS IN WET FILTER APPLICATIONS

Due to the high sulfuric acid corrosion potential in wet filter applications, material selection should be made carefully. In the manufacture of towers or internal components, carbon steel or similar materials corrode in a very short time and become unusable. Although the use of austenitic stainless steel material instead of these will increase the initial investment cost significantly, it will extend the life of the equipment. Although martensitic and ferritic stainless steels also find application, Ni-alloyed austenitic stainless steels have the best corrosion resistance. Another important point in material selection is temperature. For example, in areas where very high temperatures are not expected inside the tower, it is common practice to coat surfaces exposed to corrosion with glass or rubber-based materials. Glass-based coatings are particularly resistant to sulfuric acid and hydrochloric acid corrosion, although cracking may occur with thermal shock at high temperatures. If coating will not be made, the 316 series from the austenitic stainless steel class gives very good results.

Coating the inside of the tower with bricks is also a common practice and gives good results against wear and corrosion up to 540 °C. In addition, since it has thermal insulation feature, it insulates the surface on which it is coated against the external environment.
Nozzles and inner piping used in the system must be made of high Ni alloy stainless material.
In external lines such as solution or waste sludge transport, rubber-rubber-based materials such as PVC, FPR can be used as temperature is not a problem. It should not be forgotten that the usage temperature limit of these is 105 °C.

All welding or assembly consumables should be similarly selected while manufacturing and assembly is being performed.

DESULPHURIZATION PROCESS CONTROL PARAMETERS

Pressure Measurement

One of the most important parameters is the gas pressure loss in the filter. Pressure losses measured inside the tower or, for example, in the separators can provide information about clogging-like events in that area. The easiest way to measure pressure is to insert pitot tube-like equipment into the stream. In this case, the static pressure can be measured realistically. The lines taken from these arms can be connected directly to a manometer and the pressure can be measured, or it can be transferred to a digital device by means of a pressure transmitter. The biggest problem in such pressure measuring methods is that the measurement accuracy can be reduced due to clogging and condensation in the measuring arms.

The overall pressure drop of the system is also important in terms of fan electricity consumption. In tower type wet filters, a pressure drop typically occurs in the range of 150 – 250 mmSS on the gas side. [8] In general, as the efficiency increases in wet filters, the gas side pressure loss also increases.

Temperature Measurement

Temperature is also an important parameter that must be measured both at the inlet and at the outlet. While very high inlet temperature increases fluid loss, it can also destroy materials that are not resistant to high temperature inside the unit. For example, if the tower has a glass-based interior coating, their operating temperature limits are in the range of 200 °C. In this respect, temperature control is also important for safety. A high temperature at the outlet can damage the components at the outlet, as well as an indication that the process is incomplete. Because the temperature of the saturated gas at the exit conditions should not exceed 50-60

°C. If temperatures higher than these values are obtained, incomplete fluid supply, pump failure-clogging, blockages in nozzles or supply lines can be predicted.

Liquid Flow Measurement

In particular, solution liquid flow measurement can give information about the course of the process by comparing it with the design conditions. Since the orifice or venturimeters used for flow measurement are in direct contact with the liquid, they are prone to hazards such as clogging and wear. Ultrasonic and magnetic flow meters, on the other hand, work more healthily because they do not make any contact, but they are expensive.

pH Measurement

The pH levels of the liquids used are often monitored manually. A low pH level (pH<5) brings a high risk of corrosion on metals, and also causes precipitation of components such as calcium and magnesium. The most important points where pH measurement should be made are the lines where the spray liquid is fed and the recycling lines. The pH control in the absorber tank is usually carried out to adjust the dosing amount. pH control units are equipment that requires frequent maintenance and must be calibrated continuously.

PHYSICAL AND CHEMICAL PARAMETERS AFFECTING WET FILTER PERFORMANCE

Liquid-Gas Ratio (L/G): It is the amount of liquid used per unit gas volume during desulphurization. In the literature, the unit is usually given as gpm/acfm or lt/m3. The minimum L/G ratio required to meet certain holding conditions must be carefully determined, due to reasons such as plumbing, pump size enlargement, and increased energy consumption. Tolerances of 25% to 100% can be added to the calculated theoretical value. [9] Depending on parameters such as sulfur composition and temperature, values between 4 and 18 lt/m3 are used. [8]

pH Level: In addition to the purpose of neutralizing the liquid, the pH value must be kept within certain limits in order to ensure the high solubility of the SO_x components and to prevent the formation of sediment. As a general approach, the liquid pH value in the absorber should not be lowered below 5.

Gas Speed: In order to minimize the initial investment costs, the gas speed should generally be selected high. However, the speed should not exceed certain limits due to the increase in operating costs and the decrease in the holding efficiency in the desiccant. Although it varies according to the scrubber type, typical gas velocities that can be selected for the tower type are around 2-3 m/s.

Residence Time: In order to use the alkaline liquid in maximum amount, especially in absorption, the liquid-gas contact time must be at certain values.

Gas Distribution: Before the washing zone in the scrubber tower, distribution plates (Trays) must be arranged to homogenize the gas distribution. In this way, the liquid-gas contact surface is also increased and a more efficient filtration is realized.

Fuel Calorific Value: It affects the amount of smoke gas, in general, as the fuel calorific value decreases for a given heat capacity, the amount of smoke and the amount of solution required increase.

Moisture Ratio in Fuel: As the amount of moisture increases, the heating value of the fuel decreases and the amount of smoke gas produced increases.
Amount of Sulfur: The amount of sulfur in the fuel directly affects the capacity and complexity of the system. As the amount of sulfur increases, the lime consumption increases, and problems such as clogging in the system are more common.
Ash Amount: It has an adverse effect on SO_x holding efficiency, keeping the ash before the wet filter increases the efficiency,
Chlorine Composition: Requires the use of high alloy metals or corrosion resistant coatings. It may also affect the process chemistry, necessitating pre-washing.

ADVANTAGES AND DISADVANTAGES OF WET FILTERS

Equipment such as electrostatic, cyclone or bag filters can also perform the pollutant particle retention work performed by wet filters. Besides, the main advantages and disadvantages of the system are as follows;

Advantages;

- It can hold both particulate and polluting gases.
- Dimensions are smaller as it works at low gas temperatures, the tower part can also form a part of the chimney height that should be.
- It is out of question that the retained particles are returned to the environment as dust during transportation.
- Since it is water-based, there is no possibility of ignition of unburned carbon, for example in a bag filter.

Disadvantages;

- They produce wastes that have a high risk of corrosion and need to be disposed of, expensive materials are needed.
- Electricity consumption is high due to high pressure drops.
- It is costly to obtain by-products such as gypsum, which can be obtained as a result of the process.

CONCLUSION AND RECOMMENDATIONS

In our country, the use of solid fuels is increasing day by day in parallel with the foreign dependency of around 90% in liquid and gaseous fuels. For example, the share of natural gas in electricity generation, which is around 45% as installed power today, is planned to be below 30% according to the 2023 scenario [10]. A significant part of the gap will be covered by coal power plants as well as nuclear power plants.

According to the same scenario, besides electricity generation, the use of coal for industrial facilities will be encouraged and natural gas dependency will be reduced. As can be seen from these scenarios, we will have to release more emissions to the environment in the coming years.

It is vital for environmental sustainability that solid fuels such as coal and biomass, which are obligatory to be used in electricity generation as well as for process and heating needs, are cleaned and released into the atmosphere. Although the sulfur treatment systems mentioned in the article are only one of many treatment systems required in solid fuel combustion systems, they are one of the processes that find the most application area today. One of the main reasons for this is the fact of serious damage to people, nature and the structures around us, especially with acid rains. However, although desulphurization plants are more common than other emission reduction plants, they are not sufficient. For example, most desulphurization systems installed in old power plants do not work properly or operate inefficiently. Making these systems efficient and especially adding the heat recovery units mentioned in the article to old and new facilities will provide serious benefits to the environment as well as the economy.

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