High-Efficiency Circulating Fluid Bed Scrubber

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ABSTRACT

The lecture describes the development of dry and semi-dry flue gas scrubbing using circulating fluid beds as well as the applications of this technology in various industrial areas.

It also summarizes the fundamental process features of the system, circulating fluid beds, in flue gas scrubbing, in particular the GRAF / WULFF technology.

Details are presented of design and operating experience with an installation of a circulating fluid bed scrubber of advanced design in large size. This unit, which is operating with coal firing conditions as well as with oil firing conditions, is in Austria, retrofitted to a 300 mWe oil fired power station. The paper also covers the problems encountered, the corrections made and the resulting technical improvements achieved.

From the favorable design and operating reference to date it can be concluded that the GRAF / WULFF technology can be employed beneficially and without risk in medium- and large-size flue gas scrubbing plants of single-train design serving FGD-units with inlet raw gas flow rates from coal-fired power stations up to 400 MW electric power and for gaseous pollutant removal efficiencies up to 99%.
1. INTRODUCTION

A major milestone has been reached in commercial development of dry flue gas desulfurization (FGD) that applies circulating fluid bed (CFB) scrubbing. As of early year 2000, a single module system of unprecedented 300 mWe capacity is in full successful commercial operation in high-sulfur service at an Austrian electric utility plant. With attractively low capital cost this technology now surpasses wet scrubbing in both cost effectiveness and SOx removal efficiency for many electric utility applications.

The basic commercial development work in the application of FGD technology using circulating fluidized beds, was completed in the seventies. Prior to 1980 this method gained acceptance for the separation of HF in flue gas from the aluminum electrolysis in direct competition with the common means of wet and dry flue gas scrubbing.

Based on such early application in the aluminum industry, the use of the CFB technology in flue gas scrubbing began in the early eighties in the municipal waste incineration sector (for removal of HCl, SO2, HF and particulate). In the middle of the eighties, advancement of this technology led to applications for SO2 removal in coal-fired power station boiler service. At the present time many flue gas scrubbing plants using CFB technology and supplied by several firms are in commercial operation in diverse applications:

- power station (and combined heat and power station) boilers
- cement kilns
- glass furnaces
- municipal waste incineration plants.

GRAF / WULFF began in the mid-eighties to develop, test and install the earliest flue gas scrubbing plants with high-efficiency removal of SO2, HCl and particulate.

The flue gas scrubbing system design detailed herein, that has been previously described extensively [REF:1,2,3,4,5,6,7] is based on the functioning of a reflux circulating fluid bed (RCFB), which is an enhancement of the circulating fluidized bed (CFB) technology. [REF:1].

The main technical advancement of the RCFB-absorber as compared to the conventional CFB-absorber is the superimposition of an internal reflux, i.e. within the absorber-proper, of the reacting particulate in conjunction with external particulate (solids) recirculation, i.e. from the particulate collector. This creates a turbulent gas-solids-mixing employing the wall-shaped turbulator design.

With these fundamental improvements, the reaction conditions for noxious gas removal are particularly optimal in this advanced absorber. A highly efficient desulfurization is achieved due to the turbulent shear flow brought about by the solids reflux descending counterflow to the gas flow.

Moreover, an increase in effective gas/solids contact time with improved reagent utilization and enhanced SOx removal efficiency is gained by the intensive internal reflux action brought about by both internal and external particulate recirculation.
The internal particulate reflux is equivalent to approximately 30-50% external solids recycle. Thus, the solids loading to the particulate collector is correspondingly reduced by reduction in external recycle that is thereby made possible.

Commercial applications of this technology include the desulfurization of flue gas from power stations and combined heat and power stations with individual installations in the capacity range of 3 to 300 mWe of equivalent boiler capacity, as well as the flue gas scrubbing for simultaneous removal of SO₂, HCl, HF, dioxins, furans, mercury and other heavy metals in plants for incinerating municipal waste, sewage sludge and waste wood.

The GRAF / WULFF technology applies semi-dry flue gas scrubbing using a RCFB as absorber - the heart of the system. For the separation of the solids, a fabric filter or an electrostatic precipitator (ESP) is used, depending on emission limits and cost effectiveness.

The main design features can be explained in conjunction with a sample plant (Figure 1):

Figure 1: Dry Flue Gas Scrubbing with a Reflux Circulating Fluid Bed

(Basic Design and Flow Sequence)
Among the most important features of the GRAF / WULFF technology are the very high pollutant removal efficiencies and - at the same time - a very low reagent consumption rate. This is achieved primarily by the optimal reaction conditions within the RCFB due to:

- intensive contact between gas and solids
- long solids residence time
- sustained activity of the reactive surface of the solids.

In new plants, the absorber is placed directly upstream of the particulate collector, which thus serves as part of the flue gas scrubbing (FGS) process. In existing plants or in the case of scrubbing of flue gases with a high content of solid particulate, a preliminary particulate collector may be used upstream of the installation, if an isolated desulfurization byproduct is to be generated.

The gaseous pollutants are collected in the RCFB by absorption and by reaction with hydrated lime and in contact with reaction products that are separated and recirculated from the particulate collector. The efficiency of removal of SO₂, HCl and HF may be regulated according to site-specific requirements within a range of 50 and 99%. (SO₃⁻ removal efficiency is invariably very high).

The flue gas entering the absorber is conditioned at a controlled temperature by humidification with water. The resulting reduction in temperature and increase in humidity of the flue gas contribute considerably to high pollutant removal efficiency. The flue gas, loaded with reaction products, leaves the RCFB at its top and is dedusted in the downstream particulate collector unit. The bulk of the byproduct is collected in an intermediate hopper and then routed to the solids recirculation system for reuse in the RCFB. The balance of the byproduct is collected in the Byproduct Silo. The dry byproduct may be utilized in the cement industry, in coal mining operations or as a stabilized pozzolan for use in landfill.

According to the requirements of the flue gas scrubbing plant (e.g. boiler capacity, design efficiency of the cleaning unit, costs of the sorbent, etc.) the sorbent may differ from that indicated in the example version. That is to say, the sorbent supply may be charged as a dry powder (generally hydrated lime) or as a slaked lime suspension. In installations for large power stations, high-reactive hydrated lime powder is produced on site (using quicklime supply) by integrating a dry lime hydrating installation with the FGS unit.

Initial information from the WULFF dry-FGS system at Theiss 2000 Power Station was presented at the “Pittsburgh Coal Conference”, September 11-15, 2000, USA [REF: 7].
2. **FLUE GAS SCRUBBING PLANT AT THE THEISS 2000 (EVN) POWER STATION IN AUSTRIA**

In 1996, WULFF was given the order by the EVN (Energieversorgung Niederösterreich / Energy Supply for Lower Austria, Maria Enzersdorf, Vienna) to provide for its Theiss Power station the presently largest single-train FGS-plant based on a semi-dry and dry flue gas scrubbing technology.

Important considerations that led to the choice of this technology using a RCFB scrubber were the proven, extremely high standard of performance of this technology, its high availability (>98%), the low personnel costs, its wastewater-free operating mode, its very high SO$_2$ removal (>98%), and the extremely high SO$_3$-removal efficiency (>99%).

2.1 **Description of the Plant**

The process technology of the plant is illustrated in Figure 2.

![Flue Gas Scrubbing Plant at Theiss, Austria](image-url)

(System Design and Flow Sequence)
2.1.1 Installation upstream the FGS-Plant

In the recently modified utility boiler, heavy fuel oil and natural gas are fired with combustion supported by ambient air or in combination with gas discharged from gas turbines.

Such “hot windbox” operation vastly improves boiler efficiency but, in effect, dilutes fuel-oil derived flue gas with externally generated, natural-gas, derived flue gas and demands FGS performance that achieves unusually low, actual SO2 emission concentration. There are, however, four distinct firing modes that may be in operation at any time:

- Fuel oil fired with ambient air
- Fuel oil fired with a combination of ambient air and gas turbine exhaust
- Natural gas fired with ambient air
- Natural gas fired with a combination of ambient air and gas turbine exhaust.

The nominal capacity of the turbine generator, which is part of the boiler, is 275 mWe. At the boiler outlet there is a catalytic deNox-system (SCR). The flue gas is subsequently cooled in the final economizer (ECO), downstream of the deNox-system. After having passed the final ECO and the flue gas ducts, the raw flue gas is conducted while natural gas operation thru the bypass and the induct draft fan into the stack. During fuel oil operation it is conducted into the desulfurization and particulate collection unit supplied by WULFF.

2.1.2 FGS - Plant Description

The FGS plant described as follows was supplied by WULFF as a turn key plant including concrete and steelwork as well as the building and cladding. The hole process is controlled by means of a process visualization and control system. To supervise the fully automatic operation of the whole plant all measured values and binary signals are fed into the overall control facility which is located in the power plants main control room. The supervision is carried out by one operator.

The flue gas enters the 10 m-diameter RCFB absorber at its bottom, comes into turbulent circulating movement together with the hydrated lime and the solids continuously recirculated from the fabric filter and moves towards the top of the absorber. There, a separation of the solids takes place, with a partial reflux of the solids downward into the fluid bed.

The flue gas is desulfurized within the RCFB, leaving the RCFB at its top as a particulate-gas-mixture, and is conducted into the four-chamber fabric filter for the particulate separation. Within this filter, the particulate-content is reduced to a level less than the regulatory limit. The SO2-content is additionally reduced within the filter.

The treated flue gas flows into the existing stack via a rotor-controlled booster fan and silencer.
Since operation of the boiler may periodically use fueling by natural gas only, a flue gas bypass has been provided to route flue gas from natural gas firing directly to the stack.

The SO$_2$ is removed by a reaction with dry lime produced in-situ. Small-grained quicklime delivered by silo vehicles is unloaded pneumatically to the quicklime silos. Using the dry lime hydrating-technology recently developed by WULFF, the quicklime is hydrated with water. The quicklime is transported pneumatically from the quicklime silo to a hopper of the dry lime hydrating installation. From this hopper, the quicklime is charged into the lime hydrating fluid bed reactor.

To convert the quicklime, fresh water is injected into the fluid bed. The amount of the injected fresh water is proportional to the amount of the charged quicklime and in an amount corresponding to the hydrating process parameters. The required amount of water is about 50% greater than the stoichiometric need.

The reaction product is a highly reactive hydrated lime with particular advantages with regard to the reduced lime consumption, the composition of the final product as well as the increased availability in combination with the WULFF / GRAF FGS-process.

The hydrated lime is transported pneumatically from the dry lime hydrating installation into the hydrated lime silo. A small quantity of the hydrated lime produced in the dry lime hydrating installation, together with the exhaust vapors resulting from the hydrating process, is introduced directly into the RCFB and thus into the desulfurization process.

The exact quantity of hydrated lime required is introduced by means of a speed-adjustable rotary feeding system adaptable to the prescribed amount of SO$_2$ and SO$_3$ to be removed.

To improve the efficiency of the desulfurization reaction, water is injected directly into the RCFB. This water evaporates completely due to the elevated inlet flue gas temperature, the massive surface area of gasborne solids and the high relative velocity of gas and solids. Consequently, the reactive product is dry, and no wastewater is produced.

The evaporation of the water within the absorber leads to a decrease of the flue gas temperature along with an increase of the humidity to a prescribed level. As a consequence, the quantity of hydrated lime needed for the reaction is also minimized. The water is drawn from the Danube river, filtered and then atomized by four WULFF-nozzles of tailored design.

After almost complete reaction of the hydrated lime introduced, which takes place mainly within the absorber, the final reaction product is transported to the byproduct hopper after an average reaction residence time of half an hour.
2.1.2.1 Sequence for Operations equivalent to Coal Firing

The plant is operated to fulfill the requirements for the utilization of the byproduct as a stabilized product, i.e. with addition of fly ash.

These operational conditions for the FGD-unit are akin to FGD operating conditions for a coal fired boiler.

In order to obtain a final byproduct that is cementitious, stable waterproof enough for its storage or utilization, the fly ash, formed at a neighboring coal power station, is continuously introduced to the flue gas at the inlet of the RCFB. The amount of the added solids is about 30-40% of the total byproduct.

The addition of fly ash and its intermixture with the reaction products of the RCFB forms a stabilized product that is humidified in a storage place at the plant in order to obtain the necessary stability and solidity.

Moistened to a nearly flowable form, the byproduct is temporarily stored at grade and becomes transformed to a wet beach sand consistency over a period of several days. Easily handled, placed and compacted in this form, a strong monolithic mass with permeability as low as that of clay can be achieved by final curing in place as with Portland-cement based concrete.

In order to achieve requirements mentioned above, the FGD-plant has been designed to take the following major parameters in to account:- The mixing rate between fly ash and lime product must be variable
- The composition of the FGD-product must be adjustable via flexible operating parameters, e.g. temperature, solids residence time
- Location of temperature reduction by water injection
- Location of the sorbent and fly ash feeding systems
- The fluid dynamics encompasses intense turbulence-creating devices for mixing.

All these optimizations are obtainable without any influence on the boiler operation and the turndown capability by optimizing the FGD efficiency.

The design of the entire WULFF-process for the sequence of coal firing operation includes the capability for optimizing all the parameters during the start-up operation of the plant.

2.1.2.2 Sequence for ordinary Oil Firing Operation

In all operational case, in which the byproduct is not to be utilized as a stabilized material, the FGS-plant is operated without addition of fly ash. During this operation, the oil-firing conditions are normal.

When switching to this sequence the flue gas dynamics and also the kinetical parameters for SO₂ removal are optimized on a different operational basis.
The major requirements for operational optimizations, as contrasted with coal-fired operation, include:

- Modification of the operational temperature and solids residence time
- Modification of the water injection location
- Change of the fluid dynamics including the solids recirculation system
- Variation in the sorbent feed to the FGD-unit.

All these major modifications have to be carried out in order to obtain optimized conditions. These changes are fully automated, so that the operating staff works with only two operational modes within the process control system.

Figure 3 provides a view of the RCFB-scrubbing site, which is part of the power station at Theiss, Austria.

![Figure 3: Flue Gas Scrubbing Plant at Theiss, Austria](image)

### 2.2 Processing of the Order

The time schedule in fulfilling the order, placed in January, 1996, was as follows:

Installation work began in October, 1997, and the operation within the warranty period was successfully completed in March, 2000.
After satisfactory retrofitting that overcame space limitations, etc., and within only a short period of operation, the facility has been fully integrated into the existing operation of the power station at Theiss.

2.3 Construction and Technical Data

The following principal data were the basis for the purchase and the design of this plant:

Table 1: Boiler data at Theiss power plant, Austria

<table>
<thead>
<tr>
<th>Boiler specification</th>
<th>Concentrations based on 3% O₂-reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler combustion supported by ambient air and exhaust gas from gas turbine operation</td>
<td>heavy fuel oil (S-content 1.0-2.0%)</td>
</tr>
<tr>
<td>Turbine-generator capacity nominal (mWe)</td>
<td>275</td>
</tr>
<tr>
<td>Flue gas flowrate, nominal (m³/h, NTP, wet)</td>
<td>856,000</td>
</tr>
<tr>
<td>Load change rate (%)</td>
<td>7</td>
</tr>
<tr>
<td>Capacity range (%)</td>
<td>45 – 110</td>
</tr>
<tr>
<td>Flue gas temperature (°C)</td>
<td>160 – 180</td>
</tr>
<tr>
<td>SO₂-content (mg/m³, NTP, dry)</td>
<td>1,700 - 3,400</td>
</tr>
<tr>
<td>SO₃-content (mg/m³, NTP, dry)</td>
<td>&lt; 250</td>
</tr>
<tr>
<td>HCl-content (mg/m³, NTP, dry)</td>
<td>&lt; 21</td>
</tr>
<tr>
<td>Particulate-content (mg/m³, NTP, dry)</td>
<td>&lt; 300</td>
</tr>
</tbody>
</table>

Based on the input data given above, the flue gas scrubbing plant was designed for the following data:

Table 2: Design data for FGS-plant at Theiss, Austria

<table>
<thead>
<tr>
<th>Flue gas specifications downstream FGS-plant</th>
<th>Concentrations based on 3% O₂-reference value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas flow rate, Nominal</td>
<td>945,000</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>65-80</td>
</tr>
<tr>
<td>SO₂-removal efficiency (%)</td>
<td>&gt; 97</td>
</tr>
<tr>
<td>SO₂-content (mg/m³, NTP, dry)</td>
<td>51 (S-content 1%), 102 (S-content 2%)</td>
</tr>
<tr>
<td>SO₃-content (mg/m³, NTP, dry)</td>
<td>&lt; 14</td>
</tr>
<tr>
<td>HCl-content (mg/m³, NTP, dry)</td>
<td>&lt; 21</td>
</tr>
<tr>
<td>Particulate-content (mg/m³, NTP, dry)</td>
<td>&lt; 30</td>
</tr>
</tbody>
</table>
2.4 Operating Experience

Before commencing test operation of the flue gas scrubbing plant and the dry lime hydrating installation, a modification was necessary at the absorber-inlet, wherein the bottom nozzles were optimized.

These modifications eliminated loss of solids material from the bed bottom during low-load operation. Afterwards, the plant could be operated in the full capacity range in a stable manner and without any restrictions in its availability.

The WULFF dry lime hydration plant was optimized via the pneumatic conveying system for the highly activated hydrated product as well as reactor residence time control.

This hydrating process is capable of operation within the full operating range of the FGS-plant with highly reactive products, the turndown ratio lying between 45 -110%.

The dry lime hydrating unit has been fully integrated into the whole process, without any restrictions in the total availability. Furthermore, it is important to realize, that this dry lime hydrating plant is not producing any liquid waste or other residues.

Based on the input data given in table 1, the flue gas specifications indicated in table 2 were measured and maintained. All emission limits were safely within the guarantees given by WULFF.

2.4.1 Operating Experience with equivalent Coal Firing Conditions

During the commissioning and the test run, the FGS-plant was optimized according to the requirements of the owner, so as to produce a byproduct that can be used as a stabilized product.

The major changes / adjustments for this process sequence were as follows:

- Optimization of the fly ash feeding control
- Variation of the temperature history as well as the setup of new temperature profiles
- Uniform water injection over the full solids volume.

Based on a narrow range of composition as follows all optimizations above had to be carried out in order to obtain a stabilized material:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Composition</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>1 % ± 0.5%</td>
<td>before water addition</td>
</tr>
<tr>
<td>Fly ash content</td>
<td>35 % ± 5 %</td>
<td></td>
</tr>
<tr>
<td>Ca(OH)₂ content</td>
<td>5 % ± 2 %</td>
<td></td>
</tr>
<tr>
<td>CaSO₄ / CaSO₃ ratio</td>
<td>2 ± 0.5</td>
<td></td>
</tr>
</tbody>
</table>

All these major parameters had to be obtained by the complete range of the SO₂ inlet-concentration and the full range of the boiler operational load (between 45 - 110%).
Considering the operational period in the Year 2000, the flue gas scrubbing plant has fulfilled all warranted emission levels as well as the high specified availability (98%) within the full capacity range (45-110%) in all firing modes („Ambient air - fuel oil“, „Combined mode - fuel oil“, „Ambient air - natural gas“, „Combined mode - natural gas“).

The proof of the fully-complying performance of the flue gas scrubbing plant including the dry lime hydrating unit was provided during the test run of six weeks duration. On March 14, 2000, the test run was successfully completed and the flue gas scrubbing plant handed over to the Owner of the plant, thereupon began a warranty period of four years duration.

### 2.4.2 Operating Experience with Oil Firing Conditions

Whereas a stabilized product suitable for the use in landfill was produced during the equivalent coal-firing operation (addition of fly ash), the final product of the oil firing process is utilized in the building material or cement industry.

For its use in the cement industry it is required that this material can be added in conjunction with the ground cement to the cement production process. The requirements in quality in this product must be met during the entire period and should be reproducible for all operational conditions. During this operational condition / sequence, the following parameters were modified/optimized and transferred or integrated into the process control system:

- Position of the water injection
- Size of the water drops and spray characteristics
- Reduction of the gas temperature so that the plant was operated with a temperature approach to the wet-bulb temperature of 10-20°C
- Increase of the solids residence time by 30-50%.

The most important characteristics of the final product are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content</td>
<td>1 % ± 0.5 %</td>
</tr>
<tr>
<td>Ca(OH)₂ content</td>
<td>2 % ± 1 %</td>
</tr>
<tr>
<td>CaSO₄ / CaSO₃ ratio</td>
<td>2 ± 0.5</td>
</tr>
</tbody>
</table>

### 2.5 Operation Data and Measured Values

#### 2.5.1 Typical operation data

The following typical operation data were measured with the continuous pollution measurement instrumentation at site.

The measurement instrumentation for SO₂, O₂ and flue gas flow rate was proofed by the Official Institute for the Calibration of Pollution Control Instrumentation in Austria.
Table 3: Operating Results of FGS-Plant at Theiss, Austria

<table>
<thead>
<tr>
<th>Treated flue gas specification downstream FGS-plant (Concentrations based on 3% O₂-reference value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flue gas flow rate, max.</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>SO₂-removal efficiency</td>
</tr>
<tr>
<td>SO₂-content</td>
</tr>
<tr>
<td>Particulate-content</td>
</tr>
<tr>
<td>Stoichiometric ratio</td>
</tr>
</tbody>
</table>

2.5.2 Measured values for the guarantee evidence, for SO₂, HCl und Particulate-content

The measurements were made by the Official Institutes for the Calibration of Pollution Control in Austria. The measurements were made at the different guarantee operation points. The following table show the operation values at full load. It is calculated that the SO₃ inlet concentration will increase up to 250 mg/m³, NTP, dry, during the SCR total operation period.

Table 4: Measured values for the guarantee evidence

<table>
<thead>
<tr>
<th>Measured values (Concentrations based on 3% O₂-reference value)</th>
<th>Average values upstream FGD</th>
<th>Average values downstream FGD</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO₃-content</td>
<td>(mg/m³, NTP, dry)</td>
<td>20 – 120</td>
</tr>
<tr>
<td>SO₃-removal efficiency</td>
<td>(%)</td>
<td></td>
</tr>
<tr>
<td>HCl-content</td>
<td>(mg/m³, NTP, dry)</td>
<td>0.4</td>
</tr>
<tr>
<td>HCl-removal efficiency * (%)</td>
<td></td>
<td>&gt; 75</td>
</tr>
<tr>
<td>Particulate-content</td>
<td>(mg/m³, NTP, dry)</td>
<td>600.000</td>
</tr>
<tr>
<td>Particulate-removal efficiency</td>
<td>(mg/m³, NTP, dry)</td>
<td></td>
</tr>
</tbody>
</table>

(*) The HCl-measurement for this extreme low rates were limited due to the measuring equipment.
3. FURTHER ADVANTAGES OF THE GRAF / WULFF SCRUBBING TECHNOLOGY

The GRAF / WULFF scrubbing technology is also in use with coal fired boiler plants, waste combustion plants, sewage sludge combustion plants and waste wood combustion plants.

Using these technology for plants govern the “17 BImSchV” (the official German Environmental Legislation) mercury as well as dioxins and furans are captured by an activated lignite coke component in the lime feed and separated in the RCFB reactor and the baghouse. Mercury (II) chloride formed in the presence of chloride in the flue gas is bound via adsorption by an activated lignite coke. Metallic mercury is captured as follows: first, H₂O and SO₂ are adsorbed as sulfuric and sulfurous acid. Metallic mercury then reacts with the adsorbed sulfuric acid, forming mercury sulfate:

\[
2 \text{Hg} + 2\text{H}_2\text{SO}_4,\text{ads} = \text{Hg}_2\text{SO}_4,\text{ads} + 2\text{H}_2\text{O} + \text{SO}_2
\]

The following table shows inlet contamination data from a waste wood combustion plant supplied by WULFF as a turnkey plant (delivery included waste wood feeding, and combustion system, boiler, RCFB flue gas scrubbing system) and characterizes pollutant concentrations for the various kinds of wood waste processed.

The typical pollutant concentration in the used fuels are listed below:

**Table 5:** Fuel contamination data

<table>
<thead>
<tr>
<th>Typical pollutant concentration in waste wood fuels</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash</td>
<td>( % )</td>
</tr>
<tr>
<td>Mercury</td>
<td>(mg/kg)</td>
</tr>
<tr>
<td>Sulphur</td>
<td>(mg/kg)</td>
</tr>
<tr>
<td>Chloride</td>
<td>(mg/kg)</td>
</tr>
<tr>
<td>Fluoride</td>
<td>(mg/kg)</td>
</tr>
</tbody>
</table>

For the combustion of the fuel listed in Table 5, the following flue gas emission at the stack has been measured.

In the following table values are shown for two measurements during commercial operation.
Table 6: Flue gas emission from waste wood combustion

<table>
<thead>
<tr>
<th>Component</th>
<th>30-minute / 24-hours emission limits</th>
<th>Test run A</th>
<th>Test run B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total dust content (mg/m³, NTP, dry)</td>
<td>30 / 10</td>
<td>3 / 3</td>
<td>3 / 3</td>
</tr>
<tr>
<td>Hydrogen chloride (mg/m³, NTP, dry)</td>
<td>60 / 10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hydrogen fluoride (mg/m³, NTP, dry)</td>
<td>4 / 1</td>
<td>1 / &lt;1</td>
<td>1 / &lt;1</td>
</tr>
<tr>
<td>Sulphur dioxide (mg/m³, NTP, dry)</td>
<td>200 / 50</td>
<td>60 / 20</td>
<td>5 / 2</td>
</tr>
<tr>
<td>Mercury &amp; its compounds* (mg/m³, NTP, dry)</td>
<td>0.05</td>
<td>0.013</td>
<td>0.008</td>
</tr>
<tr>
<td>Other heavy metals *(mg/m³, NTP, dry)</td>
<td>0.5</td>
<td>0.094</td>
<td>0.140</td>
</tr>
<tr>
<td>Dioxins &amp; furans *(mg/m³, NTP, dry)</td>
<td>0.1</td>
<td>0.009</td>
<td>0.008</td>
</tr>
</tbody>
</table>

*) measured as a 1-hour average

Results of both official measurements (Test run A and Test run B) are far below the emission limits of the German environmental standard, valid for 30 minutes und 1 day average.

4. SUMMARY

The main features of the GRAF / WULFF technology can be summarized as follows:

The principal component of the flue gas scrubbing plant is the unique absorber - a RCFB. It is operated in combination with a downstream deduster for solids separation. Through intensive mixing of gas and solids streams and a long sorbent residence time in the RCFB optimal sorbent usage is achieved in accomplishing optimal system operation with individual control of exit flue gas temperature (via water supply) and outlet SO₂-concentration (via sorbent supply), an adequately close approach of the exit gas dry bulb temperature to the gas wet bulb temperature is maintained.

The alkaline sorbent used in removing acid gas pollutants is hydrated lime. In large-capacity installations, an in-situ dry lime hydrating technology is used. In this added component, quicklime is converted into hydrated lime, and high SOₓ removal efficiency is achieved in conjunction with a very low consumption and cost of lime. The dry lime hydrating unit makes possible the use of the less costly quicklime supply.
Long-term commercial operating experience has demonstrated a very high availability of the RCFB operation along with minimal maintenance requirements. In addition, the system offers a high operating flexibility with regard to variation in load and raw-gas SO\textsubscript{2}-level.

The capital and operating costs of the GRAF / WULFF-technology are low as a result of simple process design and very low rate of consumption of hydrated lime.

The operating experience gained to date has demonstrated very low annual maintenance cost (less than 1% of the total investment costs) and very high system availabilities (greater than 98%).

Furthermore, it was possible within a single installation to demonstrate two very different ways of utilizing the dry byproduct:

The use for landfill purposes required mainly a stabilized product, obtained during the desulfurization process by addition and intermixing of fly ash supplied from a coal station.

A dry byproduct suitable for use in the building material or cement industry could be obtained during the desulfurization process in oil fired operation, meeting all the strict emission values and the technical requirements via the optimized and modified conditions.

The performance of GRAF / WULFF RCFB technology has demonstrated oil firing operation as well as equivalent coal firing operation for a large size power station as well as the flue gas scrubbing for simultaneous removal of SO\textsubscript{2}, HCl, HF, dioxins, furans, mercury and other heavy metals, particularly in plants for incinerating municipal waste, sewage sludge or waste wood. This extreme high deduction rates has been obtained by a few percentage lignite coke addition into the RCFB scrubber.

In summary, it can be concluded from the favorable design and operating reference to date, that the GRAF / WULFF RCFB technology can be employed beneficially and without risk in medium- and large-size flue gas scrubbing plants of single-train design serving units with inlet raw flue gas flow rates which are equivalent to a electric power of 400 mWe and for gaseous pollutant removal efficiencies up to 99%.
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KEYWORDS: Scrubber, Fluid bed, SO₂, Large modules, Fgd, Cfb, Desulfurization, Efficient, Low cost