The 7th World Congress on Particle Technology (WCPT7)

Application and operating experience of sintered metal fiber hot gas filters for FCC unit

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Abstract

A long-term test was performed in a Fluid Catalytic Cracking (FCC) hot gas filtration facility using sintered metal candle filters. The operating temperature and pressure were maximum 550°C and 0.28MPa respectively. Specific particles sampling systems were used to measure the particle size and concentration directly at high temperature. The inlet particles concentration ranged from 150 to 165mg/Nm\textsuperscript{3}. The outlet particles concentration was in the range of 0.71 - 2.77mg/Nm\textsuperscript{3} in stable operation. The filtration efficiency ranged from 98.23\% to 99.55\%. The inlet volume median diameters and the outlet volume median diameters of the particles were about 1\,\mu\text{m} and 2.2\,\mu\text{m} respectively. The effects of operating parameters including face velocity, gas cleaning pressure and maximum pressure drop were investigated. Operating experience, optimal operating conditions and cleaning strategies were determined. The results show that sintered metal fiber filters are suitable for industrial applications due to the better performance and higher efficiency observed.

1. Introduction

Hot gas filtration from industrial processes offers various advantages in terms of improvement of process efficiencies, heat recovery and protection of plant installation. Especially, hot gas filtration is an essential technology...
for pressurized fluidized bed combustion (PFBC) and integrated gasification combined cycle (IGCC), promising coal fired generation of electricity with substantially greater thermodynamic efficiencies and reduced particulate pollutant emissions [1-4]. The filtration protects gas turbine blades from the erosion and corrosion and improves the performance of a heat exchanger connected to a steam turbine by decreasing particles deposition.

Initially, the combined cycle power generation mentioned above has driven this development, but the focus now shifts to the chemical and process industries. Fluid catalytic cracking (FCC) is a process for converting higher molecular weight into lighter, more valuable hydrocarbons through contact with a powdered catalyst at appropriate process conditions [5-7]. Basically, the FCC process has one section for the cracking to take place on contact with hot catalyst particles at approximately 520°C, and another section for the regeneration of the catalyst at approximately 720°C, where the carbon deposit is reduced from 1-2wt% to 0.05-0.2wt% by burning in air which is fed to the regenerator at approximately 0.3MPa. In gas-catalytic reactions, the major drive for hot gas filtration is to recover waste heat and reduce particle release, besides the protection of downstream equipment and meeting environmental standards. In gas-solid reactions, the gas must be thoroughly cleaned in order to avoid turbine blade damage, and there is a strong thermal advantage for gas turbine power generation.

New materials and advanced operating strategies for FCC process at higher temperatures are required to be developed. Ceramic filters seem to be the most promising hot gas filtration technology. However, successful long term operation with ceramic filters is still limited mainly by design or materials [8]. There are certain fundamental limitations to be improved due to the intrinsic material properties [9], the unreliability of the ceramic filters in demonstration trials and the high capital cost of these systems have hindered their applications [10]. Sintered metal fiber filters have been successfully used in hot gas systems for many years [11, 12]. They have also been used for hot gas filtration in various plants due to their characteristics of fracture toughness, high thermal shock resistance and long service life.

The aim of this research is to evaluate the performance of high temperature sintered metal fiber filters under a variety of operating conditions in a FCC hot gas filtration facility. The effects of operating parameters were investigated in order to determine the operating experience, optimal operating conditions and cleaning strategies.

2. Experimental facility

A schematic diagram of the hot gas filtration facility is illustrated in Fig. 1. Main screen of the programming control system is shown in Fig. 2. Main operating parameters and composition of the FCC dusty gas are summarized in Table 1. Major parts of the facility are the filtration unit with pulse cleaning, particles sampling systems and data acquisition systems. The facility is designed operated at maximum temperature of 800°C.

The filter vessel is a 360mm diameter, 3300mm height stainless steel cylindrical column. The vessel is designed to accept three candle filters of 60mm outer diameter and 600 mm overall length. An overall view of the filter vessel is given in Fig. 3. Dusty gas from the FCC regenerator goes into the filter vessel through a 50mm diameter pipe with its centre line approximately 0.2m below the tube plate. A diffuser plate is placed in the front of the inlet to avoid direct impact of dusty gas on the filters. Compressed nitrogen in the pressure range 0.3-0.7MPa is used for gas cleaning. The pulse cleaning duration is controlled by three solenoid valves mounted above the filter vessel. Each solenoid valve is connected to a nozzle which is directed vertically downward into a venturi injector mounted on top of the filter. An electrical heater keeps the compressed nitrogen temperature about 250°C to prevent condensation during pulse cleaning. The frequency of pulse cleaning was automatically controlled by pressure in the way that the cleaning system is activated when a pre-determined pressure drop is reached. The facility is instrumented so that the operating parameters of the system can be logged into a computer and continuously monitored during the tests.

The candle filters tested during this study were sintered metal fiber filters manufactured by Bekaert Corporation. The dimensions of the filter are 60mm outer diameter, 50mm internal diameter, 600mm total length with 8mm neck for the fixation to the tube plate. The effective filtration area is 0.113m² for each candle filter. The porosity is about 85% and the pores are between 10 and 60μm. The density of the filters is about 1650kg/m³. The filters that fabricated from metal alloys of AISI 430 can resist high-temperature at 1000°C.

The particles sampling systems has been specifically designed with the aim of determining the particles concentration and particle size distribution (PSD) prior and after the filtration vessel. It can measure under the maximum temperature of 650°C. The main part of the particles sampling system is a sintered metal filter tube with...
high efficiency of 99.9% for 0.3 μm particle removal. The temperature of the particle sampling system is controlled above 180°C by electronic heater to avoid condensation. The weight of the particles remaining in the filter tube is determined by weighing the filter tube before and after sampling. The filtration efficiencies reported below are based on the inlet gas concentrations, gas flow rate duration of sampling and the changes in the weight of the filter tube.

Fig. 1. Schematic diagram of the hot gas filtration facility.

Fig. 2. Main screen of the programming control system.
Table 1. Main operating parameters and composition of the FCC dusty gas.

<table>
<thead>
<tr>
<th>Main operating parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC dusty gas flow rate</td>
<td>10-100Nm³/h</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>200-550°C</td>
</tr>
<tr>
<td>Operating pressure</td>
<td>0.28MPa</td>
</tr>
<tr>
<td>Cleaning gas</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>Gas cleaning temperature</td>
<td>250°C</td>
</tr>
<tr>
<td>Gas cleaning pressure</td>
<td>0.3-0.7MPa</td>
</tr>
<tr>
<td>Pulse duration</td>
<td>120-350ms</td>
</tr>
<tr>
<td>Maximum pressure drop</td>
<td>2-6kPa</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composition of the FCC dusty gas</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ 4.15%</td>
<td>CO₂ 9.55%</td>
</tr>
<tr>
<td>NO 128ppm</td>
<td>NO₂ 0.8ppm</td>
</tr>
<tr>
<td>SO₂ 20ppm</td>
<td>H₂ 3ppm</td>
</tr>
<tr>
<td>Dew point of FCC dusty gas</td>
<td>86.3°C</td>
</tr>
</tbody>
</table>

### 3. Results and discussion

#### 3.1. Initial and residual pressure drop

The initial pressure drop is defined as variation of the pressure drop across filters with the face velocity by considering clean gas through them. The influence of the temperature and face velocity on the pressure drop across the filters can be investigated during these tests.

Fig. 4 shows the evolution of the initial pressure drop with the face velocity at three temperature levels, 305 °C, 425 °C and 550 °C, respectively. It was observed that the pressure drop linearly increased with the face velocity, as Darcy’s Law indicates. When the operating temperature increased from 305 °C to 550 °C, the initial pressure drop increased for the same face velocity values, this phenomenon was mainly due to the rise of the gas viscosity with temperature.
Fig. 4. Evolution of the initial pressure drop with the face velocity at three temperature levels.

One of the parameters to measure the influence of the number of hours of operation is the residual pressure drop evolution. A lower temperature and a lower face velocity were selected for this test in order to be operated under stable operation. Fig. 5 shows the variations of pressure drop along the operating time of filtration. The initial pressure drop is about 0.85kPa. When the pressure drop approaches to 2kPa, the filters are cleaned by pulse cleaning and the pressure drop is reduced nearly to the initial. However, the particles collected on the filters are not removed completely and some are remained on the filters, so that the pressure drop is not recovered to the initial. This is because fine particles collected deeply into filter pores are not easily detached. The residual pressure drop increases as the pulse cleaning is repeated and becomes over 1.1kPa after the 120h. The residual pressure drop keeps about 1.35kPa stably after 720h.

Fig. 5. The variations of residual pressure drop during operation.
3.2. Catalyst particle properties

Scanning Electron Microscopy (SEM) is used to observe the microstructure of catalyst particles. The results are shown in Fig. 6. The particle size distribution (PSD) of the off-line particles system is determined by a Coulter counter analyzer (Coulter Multisizer 3). The results are shown in Fig. 7.

It can be observed from Fig. 6 that the inlet particles have good sphericity. The inlet volume median diameters and the outlet volume median diameters of the particles measured by the particles sampling system were about 1.14μm and 2.37μm, respectively. The results measured by particles sampling system agree well with those of SEM.

![Fig. 6. SEM of the catalyst particles (left is the outlet particles and right is the inlet particles).](image)

![Fig. 7. PSD measured by the Coulter counter analyzer.](image)

3.3. Filtration efficiency

A peak emission is found after each pulse cleaning during unstable operation and a typical emission profile is illustrated in Fig. 8. However, the emission phenomenon disappeared after the 100th cycles. During pulse cleaning, it is found that the outlet particles concentration measured increases rapidly. The outlet particles concentration measured ranges from 16.25mg/Nm³ to 37.55mg/Nm³ during pulse cleaning. The phenomenon is caused by several mechanisms such as decreasing filtration efficiency because of dust cake detachment, particles through the filter media due to the pulse cleaning shock or direct particles penetration straight through the filters [13-15]. One of the reasons for this problem may be the serious gas reflux from outside to inside of filters during pulse cleaning. The reflux causes fine particles to redeposit on outer surface of the filters or even penetrate into the filters. However, due
to the formation of a constant and dense residual dust cake layer on the filters surface, the emission peaks progressively decrease. This residual dust cake layer dominates the subsequent filtration and stable operation.

When the filters are in stable operation, the filtration efficiencies were measured at three face velocities (1.15 m/min, 1.5 m/min and 2.2 m/min) and three temperature ranges (305 °C, 425 °C and 550 °C). Test results of particles concentration and filtration efficiency are listed in Table 2. Maximum pressure drop is 2 kPa, gas cleaning pressure is 0.6 MPa and the test results based on the average five measurements. Significant effect of temperature on the filtration efficiency was not observed during these tests. The inlet particles average concentration ranges from 150-165 mg/Nm³. The outlet particles average concentration was in the range 0.71-2.77 mg/Nm³. Slower pressure drop building up during the filtration, which results in longer pulse cleaning intervals, was one of the reasons for the higher filtration efficiencies. The filtration efficiency decreased from 99.55% to 98.23% when the face velocity was increased from 1.15 m/min to 2.2 m/min. The decrease in the filtration efficiency was associated with an increase in the pulse cleaning frequency, which eventually resulted in a thinner dust cake and poorer filtration.

Table 2. Test results of particles concentration and filtration efficiency.

<table>
<thead>
<tr>
<th>Face velocity/m/min</th>
<th>Temperature/°C</th>
<th>Inlet particles concentration/mg/Nm³</th>
<th>Outlet particles concentration/mg/Nm³</th>
<th>Filtration efficiency %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.15</td>
<td>305</td>
<td>162.65</td>
<td>1.24</td>
<td>99.23</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>155.76</td>
<td>1.02</td>
<td>99.34</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>159.43</td>
<td>0.71</td>
<td>99.55</td>
</tr>
<tr>
<td>1.5</td>
<td>305</td>
<td>158.32</td>
<td>1.23</td>
<td>99.22</td>
</tr>
<tr>
<td></td>
<td>425</td>
<td>152.45</td>
<td>1.13</td>
<td>99.26</td>
</tr>
<tr>
<td></td>
<td>550</td>
<td>161.23</td>
<td>1.37</td>
<td>99.15</td>
</tr>
<tr>
<td>2.2</td>
<td>305</td>
<td>156.54</td>
<td>2.77</td>
<td>98.23</td>
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<tr>
<td></td>
<td>425</td>
<td>163.42</td>
<td>2.35</td>
<td>98.56</td>
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<tr>
<td></td>
<td>550</td>
<td>153.25</td>
<td>2.02</td>
<td>98.68</td>
</tr>
</tbody>
</table>

3.4. Effect of the operational parameters

3.4.1. Face velocity

The pressure drop across the filters was primarily affected by the face velocity. Fig. 9 and Fig. 10 show the pressure drop variations as a function of time for face velocities of 1.15, 1.5, 2.2 and 2.55 m/min. The maximum pressure drop was set at 5 kPa during these tests. At a face velocity of 1.15 m/min, it took about 28 h for the pressure drop to build from the initial to the maximum pressure drop. The reasons for the extremely slow increase in the
pressure drop were the high bulk density of the catalyst particles, low inlet particles concentration and the relatively smooth and slippery surfaces of the filters leading to weak adhesion of the dust cake to the filters. Similar behavior was observed for the face velocity of 1.5m/min and 2.2m/min, and it can be observed that operation is stable when filtration velocity is from 1.15m/min to 2.2m/min. However, unstable operation was occurred at higher face velocity of 2.55m/min. During the unstable operation illustrated in Fig. 10, a rapid increase in the pressure drop across the filters is found and the slope of initial pressure drop increases continuously, leading to an unstable operation and more frequent pulse cleaning, and determining a maximum value for the face velocity that should not be overcome.

![Fig. 9. Pressure drop variations for face velocities of 1.15m/min and 1.5m/min.](image)

3.4.2. Gas cleaning pressure

Four different gas cleaning pressures are tested under the same operating conditions. Fig. 11 presents the effect of the gas cleaning pressure on the pressure drop evolution. However, it must be pointed out that an upper limit of pressure cleaning was determined, from which the frequency of the pulse remains constant despite of an increase in the cleaning pressure, the improvement of using higher pressure over 0.6MPa was not very significant, therefore this latter interval was selected for the tests so as to minimize the consumption of nitrogen. A lower limit of gas cleaning pressure was also determined, below which the operation was not feasible. It can be observed that the operation is
not stable when gas cleaning pressure is lower than 0.45MPa. The efficient gas cleaning pressure value depends on the operating conditions but it is normally about twice the pressure value inside the filter vessel.

![Fig. 11. Pressure drop variations for gas cleaning pressure of 0.68MPa, 0.6MPa, 0.53MPa and 0.45MPa.](image)

### 3.4.3. Maximum pressure drop

Fig. 12 shows the results of pressure drop variations as a function of time for three different maximum pressure drops at a face velocity of 1.5m/min. In Fig. 15, it can be seen that stable operation is possible at three values of maximum pressure drop. For maximum pressure drop value of 3.5kPa and 4.2kPa, both initial pressure drop remained constant and the same to each other. But for the maximum pressure drop of 2.8kPa, the initial pressure drop was higher than those of the other two values. The reason for this phenomenon may be the lower maximum pressure drop results in a thin dust cake thickness which decreases the pulse cleaning efficiency.

The frequency of the pulse cleaning decreases with the higher level of maximum pressure drop. The pulse interval increased from 3h to 5h when the maximum pressure drop was increased from 3.5kPa to 4.2kPa. Thus, a 40% reduction of pulse cleaning interval can be achieved by the higher value of maximum pressure drop. However, major deterioration of the filters may be expected since the operation becomes more severe at higher levels of maximum pressure drop.

![Fig. 12. Pressure drop variations for maximum pressure drop of 2.8kPa, 3.5kPa and 4.2kPa.](image)
4. Conclusions

A long-term test was performed in a Fluid Catalytic Cracking (FCC) hot gas filtration facility using three sintered metal candle filters under a variety of operating conditions. The effects of operating parameters including face velocity, gas cleaning pressure and maximum pressure drop were investigated.

Due to the rise of the gas viscosity with temperature, pressure drop increases when operating temperature increases in the same face velocity values. The inlet particles concentration ranged from 150-165mg/Nm³. The outlet particles concentration was in the range 0.71-2.77mg/Nm³ during stable operation. The inlet volume median diameters and the outlet volume median diameters of the particles were about 1μm and 2.2μm, respectively. The filtration efficiency was more than 99% when the face velocity was kept in the range of 1.15-1.5m/min. At a face velocity of 2.2m/min, however, the filtration efficiency was reduced to less than 99%.

The pressure drop across the filters was primarily affected by the face velocity. The appropriate face velocity should not exceed 2.2m/min in this research. Excessive filtration velocity leads to an unfeasible operation. The improvement of using gas cleaning pressure higher than 0.6MPa was not very significant, and the operation was not feasible below 0.45MPa. The frequency of the pulse cleaning decreases with the higher level of maximum pressure drop. However, major deterioration of the filters may be expected since the operation becomes more severe when maximum pressure drop is higher. In general, the results show that sintered metal fiber filters are suitable for industrial applications due to the better performance and higher efficiency observed in this research.

Acknowledgements

The authors thank Xu Qiaoqi for his great help in control programming system. The authors acknowledge the filters provided by Bekaert Corporation Belgium and experiment assistance by PetroChina Changqing Petrochemical Company.

References