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Filtration and Dust Cake Experiment by Ceramic Candle Filter in High Temperature Conditions

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Abstract−Particulate collection at high temperature and high pressure (HTHP) is important in an advanced coal power generation system not only to improve the thermal efficiency of the system, but also to prevent the gas turbine from erosion and to meet the emission limits of the effluent gas. The specifications for particulate collection in those systems such as Integrated Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) require absolutely high collection efficiency and reliability. Advanced cyclone, granular bed filter, electrostatic precipitator, and ceramic filter have been developed for particulate collection in the advanced coal power generation system. However, rigid ceramic filters and granular bed filters among them show the best potential. The problems experienced of these systems on performance, materials, and mechanical design were investigated. Ceramic candle filters have the best potential for IGCC at this moment because they have nearly the highest efficiency compared with other filtering systems and have accumulated many reliable design data from many field experiences. The purpose of this study was to investigate the efficiency of ceramic filters and stability of material against high temperature and long-term operation condition by applying fly ash on the surface of the filter and relation of pressure drop and dust cake thickness. Experimental conditions were 50 hours at 450 °C, 650 °C and 850 °C.

Key words: Coal Power Generation, Ceramic Filter, Pressure Drop, Dust Cake Thickness, Long Term Operation in High Temperature

INTRODUCTION

A number of gasification systems are approaching commercial readiness for use in integrated gasification combined cycle (IGCC) power plants. The primary advantages of IGCC systems are higher energy conversion efficiency and superior environmental compliance when compared with all other coal-based power generation options. In an IGCC system, particulates must be removed before the raw gas is burned in the gas turbine to protect the turbine blade and to control particulate emissions. It is also important to note that incorporating high temperature gas cleanup for optimization of the IGCC system must carry out particulate removed process.

In an IGCC system, hot gas is introduced to the combustor at about 430 °C and a typical pressure of 25 bar. The gas temperature is much lower than the PFBC system, which is operated at about 800-900 °C and 25 bar. The current status of technical development in IGCC filter systems depends on the system thermal efficiency, material availability, and the economic factor [Choi et al., 1999; Laux et al., 1991]. To raise the filtration temperature and to obtain higher system efficiency, new filtration technologies and materials must be developed. In order to remove particulates from the hot gas at the 10,000 ppmw level to below the 10 ppmw level, a number of filters have been developed. The filtration systems being developed include ceramic filter, granular bed filter, ESP, dry or wet scrubbers, and various types of barrier filters. The major ceramic filters being developed are ceramic candles and tube and cross-flow filters [Alvin, 1993; Alvin et al., 1989; Choi et al., 2001].

Based on engineering studies of 10 different filter systems developed by 1983, in terms of efficiency and economics the cross-flow filter offers the best system for IGCC compared with other filter technologies. Several companies including Coors, 3M, Westinghouse, and EPRI have been major contributors to the development of the cross-flow filter in recent years. The cross-flow filter, however, is still in the pilot-scale testing stages [Gilliberti and Lippert, 1986; John, 1992].

On the other hand, recent efforts have focused on the development of the ceramic candle filter system for successful commercialization. The SiC-type candle filter was developed 25 years ago by the Schumacher Company in Germany and has been tested worldwide for various particulate removal processes. This filter is currently being demonstrated on a commercial scale in a 250 Mw Buggenum IGCC power system [Dust et al., 1994; Laux et al., 1990].

More recently, the Refractron Company, the EPRI and PALL (USA), the NGK Company and MHI (Japan) and LLB (German) have also been developing an advanced candle filter for IGCC systems. Besides the development of the filter system, it is also important to develop the installation technologies of several thousand filter elements for IGCC commercial scale tests. Granular bed filter (GBF) systems are also being developed by Westinghouse and KHI in Japan. One of the major drawbacks for the development of GBF systems is lower efficiency due to circulating dust particles in high temperature conditions [Choi and Chung, 1995; Seville et al., 1996].

The electrostatic precipitator (ESP) has been widely used in the conventional coal-based power generation systems because of the electrode development and operation problems in conditions of high

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temperature and pressure. The Korea Institute of Energy Research (KIER) has been actively involved in the development of the IGCC systems in the last 3-4 years and is currently implementing a program to test a 0.5T/D bench scale unit. In addition, a 3T/D BSU for IGCC gasified gas been successfully installed at the Institute for Advanced Engineering in March of this year.

The lack of technical data on the high temperature filtration processes will mean that a wide variety of technical approaches to the advanced filter systems will be addressed. The SiC candle filter (length 1 m, ID 40 mm and OD 60 mm) obtained from the Schumacher Company in Germany has been tested for its efficiency and operation characteristics. In IGCC systems, the particulate removal system is important to protect the gas turbine from erosion, to meet the emission limits of the effluent gas, and to increase the thermal efficiency in the advanced coal power system. Based on the status of worldwide technical development, system capability, reliability, and safety, the candle filter and tube type filter have been selected for the IGCC power system. In addition, the 1T/D filter system was designed and installed for bench scale tests [Kanaoka et al., 1996; Laux et al., 1993; Yang et al., 2002].

The purpose of this study was to investigate the efficiency of ceramic filter and stability of material against high temperature and long-term operation condition by applying fly ash on the surface of the filter and relation of pressure drop and dust cake thickness. Experimental conditions were 50 hours at 450 °C, 650 °C and 850 °C.

PRINCIPLES OF THE FILTER

The main mechanisms of filter are impaction, interception, and diffusion during the flow of particles through fine pores. Impaction for the particle larger than 1 μm and diffusion for smaller than 0.5 μm in diameter are predominant mechanism, respectively.

Applying high pressure pulse air removes temporary layer of dust cake on the filter element periodically. And the characteristics of dust formation are very important for the cleaning the element. Adhesion property of the dust cake depends on the composition and size distribution of particles and operation conditions.

Pressure drop through the filter media is expressed by Ergun as:

$$dP/dr = k_1\mu V + k_2\rho V^2 \tag{1}$$

where r is radius, k_1 and k_2 is constant, μ is gas viscosity, V is face velocity at r and ρ is the density of gas. Eq. (1) is modified by Forchheiner to Eq. (2) for the cylindrical filter element taking account of the continuity of gas flow.

$$rV = r_oV_o$$
$$\Delta P = \mu k_1 r_o \ln(r_o/r_i)V_o/K + \beta k_2 r_o \ln(1/r_i - 1/r_o)V_o^2 \tag{2}$$

where ΔP is pressure drop across the filter, K is absolute permeability of the filter, β is turbulent factor, r_o and r_i are outer and inner diameters, respectively. The second term of the right hand is negligible in the general filtration because of small filtration velocity. So pressure drop through the filter element is described by Darcy's law assuming the thickness of the filter element is thin.

$$\Delta P = \mu V_o/K \tag{3}$$

Permeability, K, defined by Eq. (4) is used to express the filter performance, i.e., the larger is K, the better is the filter.

$$K = \mu V_o/\Delta P \tag{4}$$

However, it decreases with time because of the accumulation of fine particles inside the element and hence it can be approximated by the following equation

$$K = K_o N^r \tag{5}$$

where K_o is the original permeability of a new filter, N is the number of cleaning. The exponent r is an empirical parameter used to best fit to the experimental data. The smaller is r, the less is the clogging and the longer lifetime. Value of r ranges 0.1 to 0.3 for most of commercial candle filters with this surface membrane.

Pressure drop through the granular bed filter is predicted approximately by Darcy's law [Dust et al., 1994; Pulkrabek and Ibele, 1987].

EXPERIMENTAL

Major research topics on the ceramic filter surface performance tests and optimization of the on-line filter cleanup features were performed on an experimental basis using the bench scale unit under low temperature conditions. The experimental system, shown in Fig. 1, consists of the following three major components: a pressure vessel, filter element, and a pulse-jet cleaning unit.

An array of the three filter elements was mounted on the tube sheet. The filter medium is manufactured by the Schumacher Gmbh and is marketed under the name of Dia-Schumalith. A coarse porous

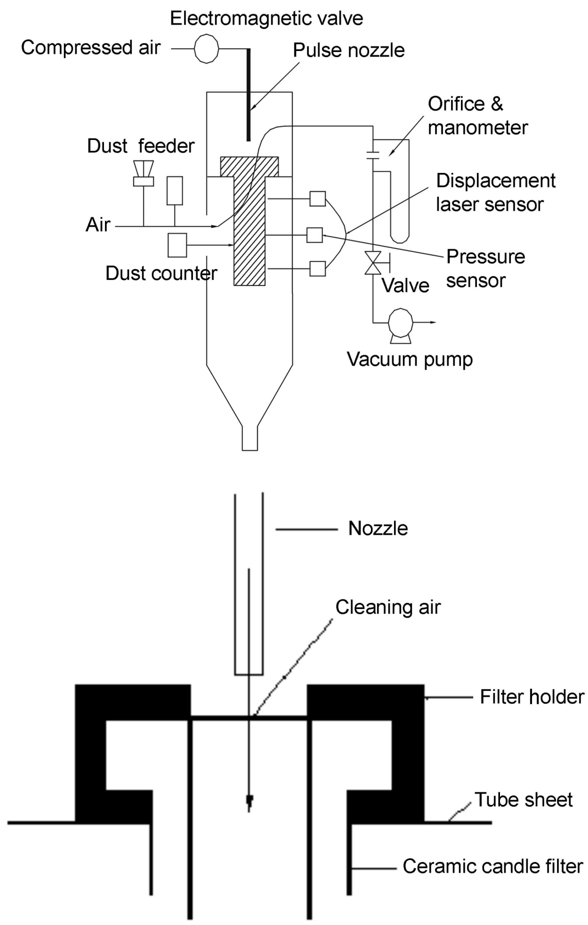

Fig. 1. Schematic diagram of experimental apparatus.

support body made of sintered silicon-carbide coated with a micro porous ceramic diaphragm in the upper outer surface. The vessel is flexible to accept other filter elements for further tests. The filter elements were 1.0 m long, 60 mm in outer diameter, and 40 mm in inner diameter.

The filtration area of each filter element is approximately 0.16 m^2. The dust-laden combustion gases flow upward inside an internal duct and distributed filter cake settled into the lock-hopper system to aid the co-current gases. The dusted filter element should be cleaned not only by a short pulse-jet but also by a counter flow of clean air or gases.

Generally, the pulse-jet cleaning unit mounted on top of the filter module performed periodic on-line cleaning of the ceramic filter elements. The compressed air is homogeneously distributed from the 20 kg/cm^2 reservoir tank to a 3 pulse-jet valve.

The pulse time and pressure can be adjusted by the data acquisition system at any time. The on-line filter cleanup features, such as pulse-jet duration cleaning sequence, pulse pressure, and either initiating time period or initiating pressure drop can be adjusted according to the flue gas conditions. In the ceramic candle filter system, the dust is collected by a silicon carbide ceramic candle filter, while the gas passes through from the outside to the inside of the filter elements. Then, the dust is filtered and accumulated on a layer of thin film of a finer pore size on the filter surface by using another lab-scaled experimental facility is shown in Fig. 2.

Detailed design conditions of dust cake formation apparatus are shown in Table 1. The experimental condition of dust cake formation apparatus is shown in Table 2. The composition of the SEM micrographs of the ceramic candle filter sampled from the bench scale unit was measured after 20 hours of testing and hot conditions (450 °C, 650 °C, 850 °C) and was analyzed after 50 hours for a reliability test.

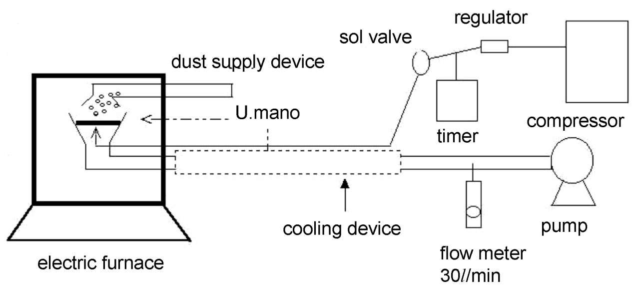

Fig. 2. Schematic of the experimental set up.

Table 1. Design condition of dust cake

Pressure drop (kg/cm^2)	0.347
Temperature (°C)	450, 650, 850
Dust loading (g/Nm^3)	0.38
Face velocity (cm/sec)	3
Filtration area (cm^2)	12.71

Table 2. Experimental condition of dust cake formation apparatus

Filter	
Material	SiC
Size	3.1 cm×4.1 cm
Mean pore diameter	10 μm
Porosity	0.35
Particle	
Material	Fly ash
Geometric mean diameter	3.44 μm
Geometric standard deviation	1.931

RESULTS AND DISCUSSION

1. Size Distribution Test

In the experiment, fly ash produced from coal combustion was used, and the range of ash size was from 1 to 25 μm, which is equivalent to ash size from the IGCC real test ash size. Fig. 3 shows the dust size and the size distribution, and they were measured by using an aerodynamic particle size Analyzer (Sympatec Co. Ltd.), HELOS-RODOS, in the dust supply device. Sauter Mean Diameter (S.M.D) was 3.44 μm and geometric standard deviation was 1.931. This result was good gaussian distribution.

2. Heavy Metal Test

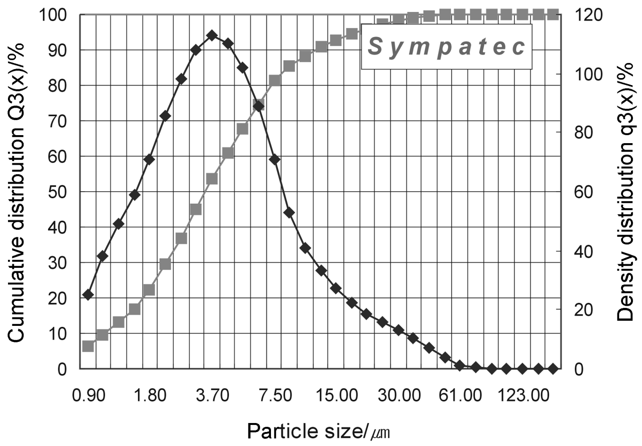

Fig. 3. Distribution of fly ash size.

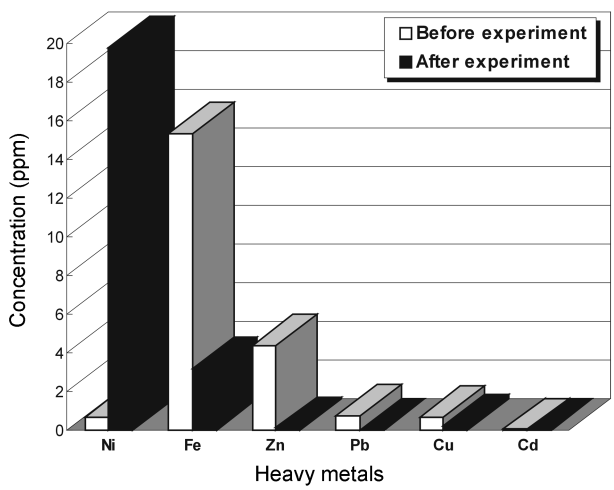

Fig. 4. Concentrations of the heavy metal constituents in fly ash prior to and after the experiment.

In a long-term dust collecting test, melting phenomena of dust were observed on the filter support part while micro-dust was deposited in micro porosity part on the filter. Also, comparisons before and after experiment in heavy metal composition test were analyzed.

The heavy metals (Fe, Zn, Pb, Cu, and Cd) contents were considerable decreased in the residue shown in Fig. 4. This confirms that ceramic filter was efficient in removing dust at high temperature conditions.

3. Surface Analysis Prior to and After Tests with Ceramic Filter

The component analysis of a fresh filter and a used filter is given in Figs. 5 and 6, respectively. As a result of photo-analysis, the porous media layer of the ceramic candle filter is supported by silicon-carbide, and out fine porous media is coated with a diaphragm. During the dust removal process, the particles below 5 μm pass through the membrane, and a few particles remain on the micro porous media. The white area of Fig. 6 appears to be ash.

According to the analysis of the filter components, the peak values of the used filter components, such as C, SiO_2, and Al_2O_3, are much higher than those of the fresh filter.

Figs. 6, 7 and 8 show that pore size is decreased gradually by

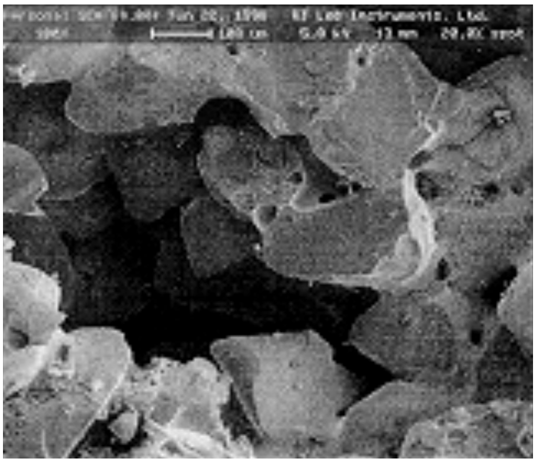

Fig. 5. Unused filter (Original filter).

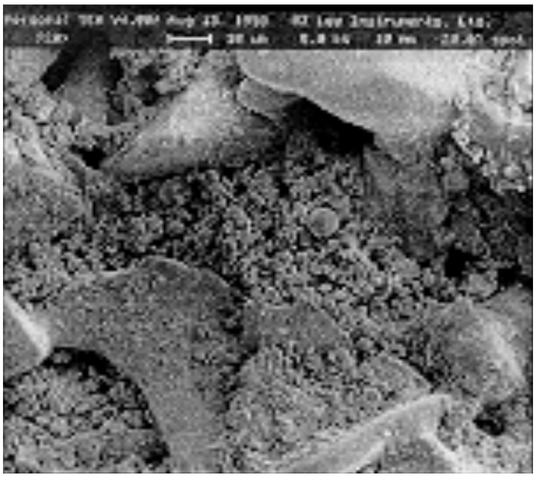

Fig. 6. Used filter after experiment at 450 °C and 50 hours.

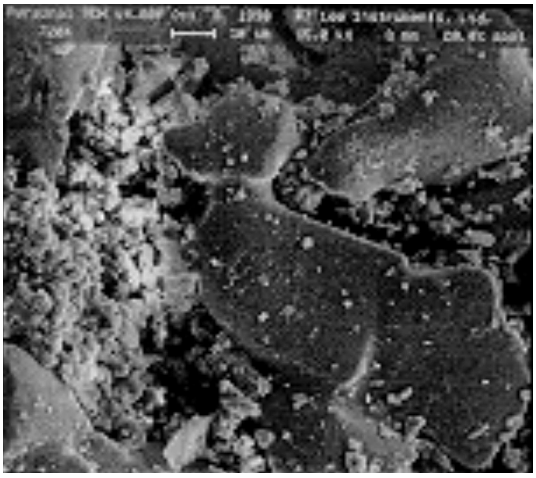

Fig. 7. Used filter after experiment at 650 °C and 50 hours.

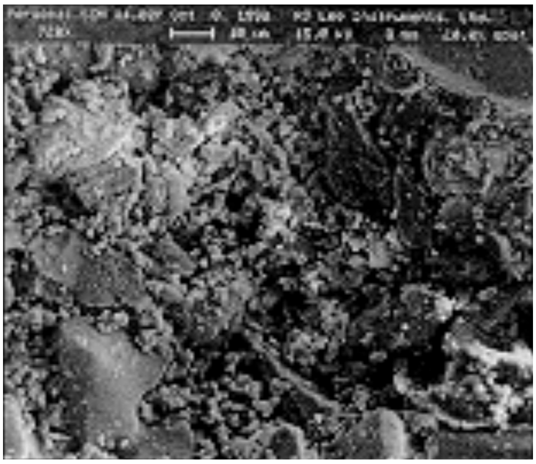

Fig. 8. Used filter after experiment at 850 °C and 50 hours.

deposited particles in the higher temperature condition, and it is caused by particles cohesion. The material of the used filter is monotonous at high temperature conditions. Silicon carbide showed a rapid degradation at alkali containing stream at 850 °C degree due to the formation of sodium silicate and oxidation. Predominant cracks were observed during the short term test at 850 °C. Silicon carbide filter has worked well in KRW IGCC at 350 °C during 14,000 hours [Alvin, 1993]. This fact fits very well fit with the 350 °C test result. Also, we investigated the phase transfer, chemical reaction and oxidation of element materials with aggressive gases caused the failure of the ceramic element. We show that it was affected by a loss of strength due to the formation of tridymite in the long term operation at high temperature.

Figs. 5, 6, 7, and 8 present the results obtained with the Schumalith-20 ceramic candle filter for 50 hours of tests under the experimental conditions as shown in Table 2.

By observing the pulse cleaning event, we observed dislodgement of the dust layer from the ceramic filter element surface with a commercially available video camera, at different pulse pressure of 300 KPa and 100 KPa.

The phenomena show that the dust layer is dislodged from the filter element surface as large longitudinal flakes. All flakes move

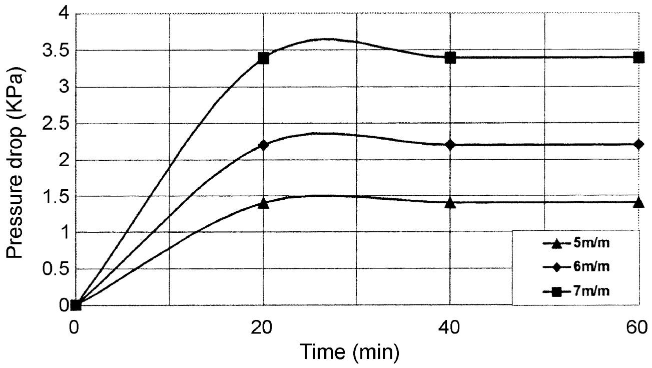

Fig. 9. Relation of pressure drop and dust cake thickness.

immediately and fall down along the filter element surface, and finally settle in the ash hopper.

Fig. 9 shows that pressure drop as a function of time for measuring dust cake thickness to find the dust cake formation process in ceramic filter surroundings in a dust removal laboratory scaled facility. It is clear that the constant pressure drop is 40 minute in the filter element at different dust cake thickness; also, as the increase of dust cake thickness, the pressure drop increases linearly.

CONCLUSIONS

In the present study, a bench-scale filtration system was designed and manufactured by using a ceramic candle filter to evaluate the dust cake characteristics of the dust removal process for the IGCC and PFBC systems. As a result of the preliminary tests, it is now possible to analyze all of the parameters required to design the optimum filtration system. In addition, the dust size and size distribution before and after filtration tests were obtained to analyze the filter surface reaction mechanism.

The major findings of the present study may be summarized as follows:

1. Ceramic candle filters had the best potential for the IGCC, because they had nearly absolute efficiency and had much reliable design data from the many field experiences.

2. The range of ash size used in the present study is 0.25 μm, and the average particle size is 3.44 μm and heavy metals contents were considerably decreased in the residue.

3. It is confirmed that fine ash particles are distributed in the surface of the micro porous media layer in the ceramic filter after 50 hours of filtration tests at high temperature conditions.

4. As the increase of dust cake thickness, the pressure drop increases at different conditions, linearly.

NOMENCLATURE

K : absolute permeability [m^2]
K_o : original permeability [m^2]
N : number of cleaning
ΔP : pressure drop [Pa]
r : experimental exponent
V : face velocity [m/s]

Greek Letters

β : turbulent factor
μ : gas viscosity [Pa·s]
ρ : density of gas [kg/m^3]

Subscripts

i : inner value
o : outer value

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