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Process Evaluation for Current Ceramic Filters and Granular Bed Filters for High Temperature High Pressure Applications

Jin Do Chung
Korea Electric Power Research Institute, KEPCO

Abstract — The particulate collection at high temperature and high pressure (HTHP) is important on the 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 Coal Gasification Combined Cycle (IGCC) and Pressurized Fluidized Bed Combustion (PFBC) require the absolutely high collection efficiency and reliability. Advanced cyclone, granular bed filter, electrostatic precipitator, and ceramic filter have been developed for particulate collection on the advanced coal power generation system. However, rigid ceramic filters and granular bed filter among them show the best potential. The current technology of these collectors was evaluated in this paper. The experienced problems of these systems on performance, materials, and mechanical design were investigated. Ceramic candle filters has the best potential for IGCC at this moment because it has nearly the highest efficiency comparing with other filtering systems and has accumulated many reliable design data resulted from many field experiences.

1. Introduction

IGCC and PFBC are attractive systems for advanced coal power generation, which are able to achieve high thermal efficiencies more than 41 percent. The high level particulate removal at high temperature high pressure (HTHP) in these system is essential to improve the thermal efficiency. High temperature operation of collector has an another advantage in saving the investment cost with reduction of auxiliary equipments. Temperature ranged between 450 and 500°C is recommended as an optimum operation for IGCC particulate collection¹⁾. This mild temperature is required because of the temperature limitation of deSOx catalyst before a gas turbine. High temperature material cost was also considered for the setting of this economic conditions of operation. On the other hand the operation temperature of PFBC particulate removal system is rather higher temperature range from 700 to 850°C. This is because the combustion gas in PFBC dose not have an opportunity to be refired prior to being introduced into the gas turbine.

The primary reason for particle collection in the advanced power generation system is to protect the gas turbine from abrasion, deposition, and corrosion. According to Burard et al, particles smaller than 4 micrometer in diameter are not so harmful to the turbine blades²⁾. So particle load of less than 20 ppm in weight 5 micrometer in diameter is currently said to be allowable. However, there are several reasons why the fine particles have to be controlled stringently. Particle deposition on the turbine blades has a tendency to form slags at high temperature, which inhibites gas flow and plug its cooling circuit. This causes some serious material problems on the maintenance of the full power system. Fine particles smaller than 5 micrometer is also harmful to human health because it may lodge in the human respiratory tract.

Several particulate collectors have been developed for advanced power generation systems. But none of them has reached to commercialization stage yet. Most prominent ones are ceramic rigid filters and granular bed filters.

2. Principles of the Filters

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.

Temporary layer of dust cake on the filter element is removed periodically by the applying high pressure pulse air. And the characteristics of dust formation is 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, μ is gas viscosity, V is superficial velocity at r, and ρ is the density of gas. Equation (1) is modified by Forchheiner to equation (2) for the cylindrical filter element taking account of the continuity of gas flow.

$$\begin{gathered} rV = r_0 V_0 \\ \Delta P = \mu k_1 r_o \ln(r_o/r_i) V_o/k + k2 \rho r_0^2 \ln(1/r_i - 1/r_o) V_0^2 \end{gathered} \tag{2}$$

Where ΔP is pressure drop across the filter, k is absolute permeability, β is turbulent factor, ro and ri 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 law assuming the thickness of the filter element is thin

$$\Delta P = \eta V_o z/k \tag{3}$$

where η is a dynamic viscosity.

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

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

where V_o is superficial velocity.

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

$$K = K_0 N^{-r} \tag{5}$$

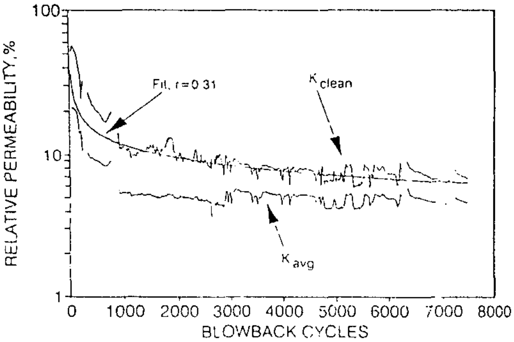


Fig. 1. Permeability history of LayCer ceramic candles and calculated fit using model in equation 5. K-clean uses of DP if all candles had been cleaned simultaneously (equation 2) and K-avg uses one-hour average data for DP.

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 life time. Value of r ranges 0.1 and 0.3 for most of commercial candle filters with this surface membrane. Fig. 1 shows the best fit for experimental results[1].

Pressure drop through the granular bed filter is predicted approximately by Darcy's law.

3. Performance

3-1. Ceramic Filters

Fabric bags, candles, and cross flow filters are common types of barriers. Their typical materials and properties are summarized in Table 1. Honeycomb and monolith type of cross flow filter are compact of which surface area are much larger than that of other type. Vacuum formed aluminosilicate candle is also attractive owing to its very light density. However small tensile strength is the barrier for the commercialization.

Performance of rigid filter depends on the cleaning mechanisms employed and characteristics of particulates. For the case of cohesive dust, single shot of pulse jet may not be sufficient to remove it from the filter surface and frequent shots of high pressure, and large volume of pulse gas is required in that case. These severe cleaning conditions cause the wear and the tear of the filter element. This is critical for fabric

Table 1. Typical properties of fiter elements.

Type	Candle/Tube			Cross flow		
Element	Granulars	Fibers		Lamination	Honeycomb/ Monolith	Fabric Bag
		Fabric	Vacuum formed			
Typical Material	SiC/Aluminosilicate[4]	Alumina/ silicate[5]	Alumino-silicate[6]	Alumina/ mullite[7]	Mullite	Polycrystalline metal oxide
Dimension(mm)	$60^{\phi} \times 1500$	$60^{\phi} \times 1000$	$60^{\phi} \times 1000$	300sq × 100	150sq × 500	$150^{\phi} \times 2400$
Specific area	19			25	155	8
Density	2.5-2.6		0.3			
Temp. limit(°C)	1000	650	1000	1000	650	820
MOR(bar) at RT	120-180		3.5-3.8	217[b]		
at 1000(°C)	140-200		1.2-1.4	188[b]		

[a] Area/volume ratio[8], [b] The 4-point bend, 1/4-point flexural data.

Table 2. Performances of rigid ceramic filters.

Filer type	SiC Candle				Cross flow filter	
	IGCC		PEBC		IGCC	
Process	KRW	SCGP – 1	Tidd	Grimethorpe	Texaco	DOE/METC
(site)	(Waltz Mill)	(Deer Park)	(Brilliant)	(Grimethorpe)	(Montebello)	(Morgantown)
Temp. (°C)	430 – 570	230 – 280	840	850	480-530	538 – 871
Pressure (bar)	12 – 17	24	11	10	23	10 – 17
Eelement size	L 1 m	L 1.5 m	L 1.5 m	L 1.5 m	0.3X 0.3X	0.15X 0.15X
(Number used)	(33)	(44)	(384)	(130)	0.1 m	0.05 m
Space Velocity (Cm/sec)	2 – 25	2 – 3.5	2.2 – 3.3	3.7	2 – 3	1.5 – 4.2
P drop (mbar)	–	90	175 – 337	60-230	–	25-75
Effeciency (%)	99.3^{+}	99.5	–	99.3^{+}	99.8	99
(Outlet load, ppm)	(1.2 – 4.7)	(< 5)	(< 15)	(< 15)		
Duration (Hrs)	1,300	5,000	463	790	48	50

bag, which develops the reduction of collection efficiency and filter life. PFBC dust containing alkaline sorbents gas has relatively high cohesive properties at operation conditions of PFBC. So it tend to develope the ash bridge during operation at high temperature above 800°C. IGCC dust is less cohesive because it contains unburned carbon at high percentage of between 20 and 60%.

Fabric bag's efficiency in IGCC is limited to 92-98 percent due to both the unstable dust cake and the particle bleed through. The low density of IGCC dust is also a reason for the increase of the reentrainment, which needs more intensive pulse conditions.

Rigid candles and cross flow filters meet the high efficiency of more than 99.5 percent and the limited outlet loading below 10 ppmw as shown in Table 2. Face velocity applied in rigid ceramic filters is normally 2-3 cm/sec, develope the pressure drop of 50-200 mbar and collection efficiency more than 99.9 percent.

3-2. Granular Bed Filter (GBF)

Shallow static and moving bed are typical GBFs which have been developed for HTHP. Ducon Co. developed a shallow static bed GBF which captures particulates during the dirty gas passes downward through the fixed shallow bed. This system was tested by Westinghouse in their PFBC simulator[9]. Short term experience showed that initial high efficiency decreased gradually by the duration at 840°C as shown in the second column of Table 3. It needs a large filtering volume and suffered difficulties on the cleaning of the filter media.

Combustion power company (CPC) has developed moving GBF in which dirty gas is cleaned through granular media bed circulating continuously after in-situ cleaning as shown in Fig. 2(b). There are many types of GBF according to the methods of their cleaning and circulating the media as shown in Fig. 2.

In conventional GBF, the media was cleaned through a screen. Otherwise dirty media in screenless GBF moved by gravity continuously to collection vessel and pneumatically conveyed upward to a disengagement chamber where the dirty air are separated from media as shown in Fig. 3.

There are many successful test results[15] at ambient conditions for filter media cleaning. But it is not fully realized under HTHP yet.

One of the problems in GBF operation is reentrainment of dust bound on the filter media, which is the main reason of the low collection efficiency of GBF. Table 3 shows the test results during the short term experiences carried out by CPC/WH[9] and NYU[10].

Table 3 shows low efficiency below 97 percent. Kawasaki heavy industry (KHI) reported[11] that a good performance was in their Yubari PFBG (Pressurized Fluidized Bed Gasifier) as shown in the fifth column in Table 4.2. Westinghouse reported recently that standleg moving GBF with one-through pelletized media showed a good performance[12]. But it has been pointed out that many real problems lies on the fabrication the media by pelletizing at HTHP. Operation temperature of GBF is limited in the circulation of the filter media.

Table 3. Performances of granular bed filters.

Process (site)	WH/DUN-CON	CPC Screenless	NYU	KHI (Yubari)
Temp. (°C)	840	826	850	360
Pressure(bar)	10	1.2	6 - 8	18
Space Vel. (Cm/sec)	22.8	54	15 - 30	-
P drop (mbar)	75	60	-	-
Efficiency (%)	99-77	98.8	97	99.9
Duration (Hrs)	50	400	164	246

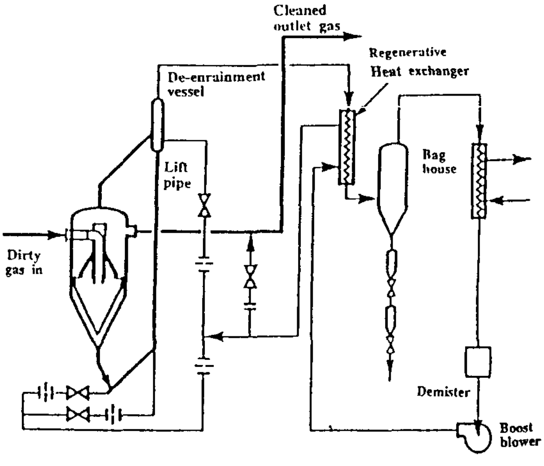
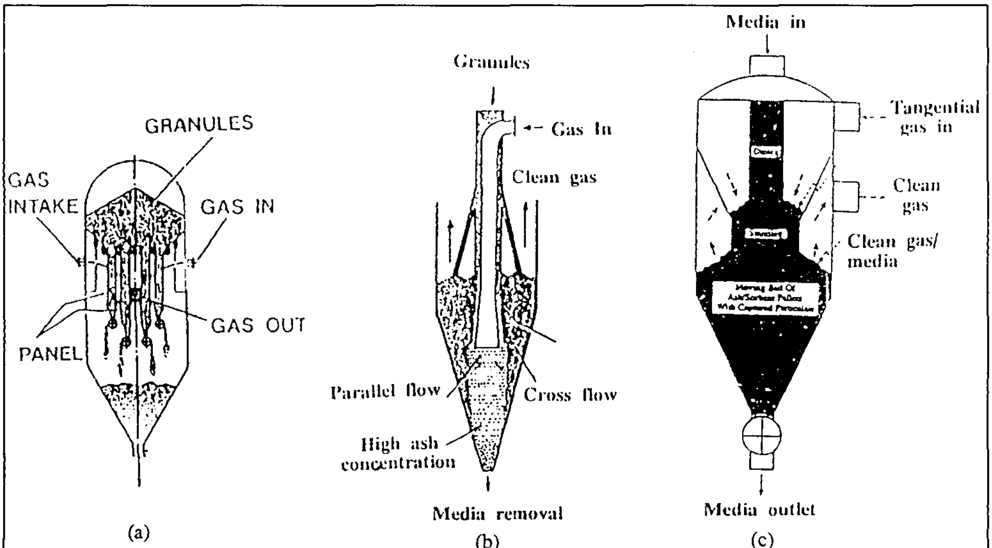


Fig. 3. The process flow diagram of GBF desiged by Southern Company Services Inc.



(a) GBF element in Nakoso pilot plant

(b) GBF element designed by Combustion Power Co.

(c) Westinghouse Standleg GBF concept

Fig. 2. The design concepts of GBF element.

4. Materials Problems

4-1. Rigid Ceramic Filters

Element failure during the operation is the one of major problems in the barrier filter. During conduct of HTHP filtration, ceramic filter elements experience to not only contact with fine particles, but aggressive gases which lead filter element degradation by chemical reactions. In addition to them, the filter elements are subjected to thermal and mechanical stress from pulse jet cleaning by cold gas or abnormal operations. Alvin reported that chemical degradation of filter element at high temperature was serious[13]. She investigated the phase transfer, chemical reaction and oxidation of element materials with the aggressive gases. Alumina/mullite was strengthened initially by thermal treating effect or alkali exposure which crystallized its amorphous phase. But it experienced a loss of strength due to the formation of tridymite in the long term operation at high temperature. Glasses in cordierite was also transferred to crystallite like a tridymite. Tridymite has a different thermal expansionivity from the main filter elements, which causes the formation of fine crack during thermal cycles and develops the breakage of the filter element during continuous pulse cycles.

Silicon carbide showed a rapid degradation at alkali containing stream at 870°C due to the formation of sodium silicate and the oxidation. Predominant cracks was observed during the short term test at PFBC. SiC candle filter has been well worked in Rheinbraun's KRW IGCC at 350°C during 14,000 hours. Long term experience of SiC candle in PFBC was carried out at Grimethorpe establishment[2] During 2,300 hours duration between 1987 and 1992, total 17 elements among 130 were broken. It was reported that the failure was caused from the plant excursion not from the definitive filter element degradation. From the result of analysis on TiDD pilot plant ash bridge was pointed out the one of the reason why the filter elements were broken out.

In case of fabric filter, mechanical degradation of ceramic threads was major reason for the failure[14]. Frictional abrasion and reaction with aggressive gas have also been suspected of the loss of element strength. Experiments at mild conditions was carrier out at North Dakota university's coal fired steam plant using Nextel™ bag filter[15]. This test showed no considerable bag degradation during the test duration of 16,800 hours at 427~538°C. Its strength was reduced to 85% of as-fabricated one after the test[15].

Failures of cross flow filter element caused by the delamination of the filter body have been reported. Improvement of bind and fabrication technologies of the element have solved this problem. The short term phenomena on the cross flow filter materials showed a good strength as summarized in Table 1.

However, the prediction for long term is not good at this moment.

The most critical material problems in GBF lie on the valve suitable for the media circulating at HTHP. There is no reliable one withstanding at above 800°C. GBF is the most reliable system if the media cleaning and circulation are operated at low temperature.

5. Mechanical Design Problems

5-1. Candle Filters

Two main inspections of SiC candle filter failures were carried out in British coal's Grimethorpe PFBC facility[17] and Tidd PFBC unit[18]. After continuous operation of 800 hours, internal inspection of pressure vessel revealed many failures[2]. The header sheet which supports candles was distorted due to thermal expansion and material creep, which caused the misalignment of candles. Pulse jet cleaning nozzles were displaced. 17 candles among 130 were broken. It was reported[2] that the failure caused from the malfunctions of the system; pulse valve failed open during the run, trip during turbine start-up, and dislodging a counterweight.

Ash bridging between the elements was also pointed out to make the filter element be broken. This problem may occur from a combination effects involving ineffective cleaning, ineffective dust shedding, and insufficient element separation during tubesheet mounting. There is also suspection of cake sintering on the filter element at high temperature. Abnormally local high temperature may be produced from the burning heat of accumulated dust by any cause.

Alvin[18] analysed the cause of filter element failures in Westinghouse's Advanced Particulate Filtration system [Tidd PFBC in Ohio Power co., Brilliant, Ohio] under PFBC conditions. He reported that 21 bottom plenum candles were broken from the result of ash bridging. Ash bridged between adjacent candles provides a sustained bending load, which causes the bow of the candle filter elements along the filter body at high temperature. The sustained load ultimately caused a delayed fracture. Photograph of ash bridge was shown at Fig. 4.

Typical failures during cross flow filter test have occurred at the sealing part between filter elements and metal holder. But advanced technologies improved the mounting skills using creep resistant bolting materials and flexible clamp design to distribute the stress uniformly. And the reinforced alumina fiber blanket gasket has a successful role to seal the system workable at high temperature during 1300 hours[19]. However there is no definitive experience showing a reliability at long term operation. Another problem lies on the array of huge number of candles in commercial plant. Fig. 5 shows the conceptional design of filter array by Westinghouse, which is compact. This tier type was not demonstrated yet.

The abrasion of the pipe in GBF by circulating granular media occurs critically at high temperature. The granular wear also reduces the size of filter media, which make a problem on the stable circulation of them. So the development of ceramic lined-piping and the skill of stable operation are important. Technologies to effectively clean the filter media at HTHP have still many unsolved problems.

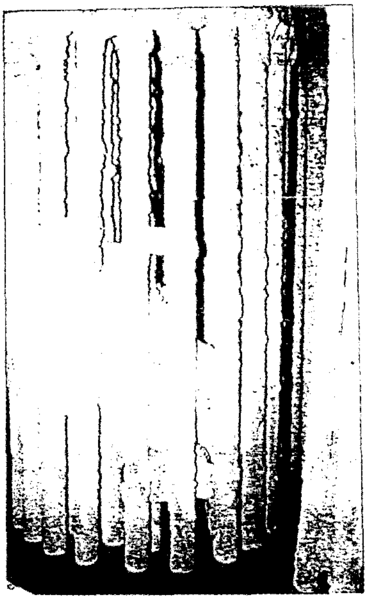


Fig. 4. Photograph of filter candles showing ash bridge in Tidd PFBC.

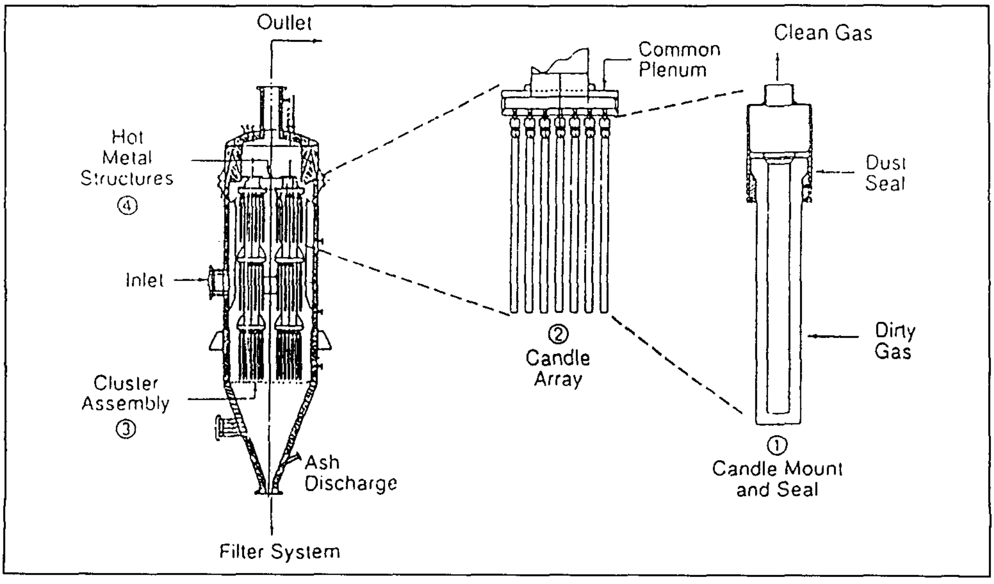


Fig. 5. Westinghouse candle filter system.

6. Summary

Development status of HTHP particulate collectors were summarized in Table 4. Candle filters have its wide experiences from bench test to commercial size. There are more than 9 plants which are going to adopt this system. Demkolec IGCC plant now in operation will give us practical answers on SiC candle filter for IGCC.
This system was already demonstrated well at Shell's SCGP-1. SiC candle system has the best potential for IGCC particulate collector as shown in Table 5 because its efficiency is the best and has the most technical design data resulted from many field tests.

The development status of cross flow filter stays in the rig scaled-facilities with short term experiences. And there is no reliability on long term operation yet. GBF has a systematic development experiences. The largest operation experience is being carried out at Nakoso IGCC plant by IGC of Japan. But it is in the course of demonstration state. Though there were many efforts to develop the proper dust removal system for HTHP, there is no demonstrated system which has shown an absolute reliability.

7. Conclusions

Several particulate collectors have been developed for advanced power generation systems. But none of them has reached to commercialization stage yet. Most prominent ones are ceramic rigid filters and granular bed filters. The development status and problems of these systems were discussed here. HTHP particulate collectors for IGCC were evaluated and

Table 4. The status of the development of the HTHP particulate collectors.

Collector	Operating				Plan (95~96)
	Bench (< 1 tpd)	Rig (1~10 tpd)	Pilot (10~250 tpd)	Commercial (> 250 tpd)	
Candle filters	RWTH PFBC, Shumacher, Karlssrube *et al.*	CRIEPI IGCC	IGCC Texaco, Prenflo, Nakoso, SCGP-1, PFBC KRW, Ahlstrom, Tidd, Grimethorpe, Rheinbraun, HTW, British Coal, LLB	Demkolec IGCC (250MWe, '93~)	IGCC (MWe) Elcogas (300), Puertollano (330), Kobra Pine ('95), PiNon Pine (95), Destec (265), Sierra Pacific (80MWe), Tampella (55) Springfield (65), PFBC Foster Wheeler 2nd (250)
Cross flow filters	WH Tester, EPA Tester, ANL PFBC	WH Simul., Foster-Wheeler			Foester Wheeler 2nd PFBC (250MWe)
GBF	EXXON, WH, KHI	CMRC	IGCC Nakoso, PFBC KHI, KRW, KRW, JEPD, CM, RC, NYU, CPC, Tidd, WH/DUCON		

Table 5. Summary of particulate collector's performace at HTHP.

Collector	Efficiency (dp_{100}, μm)	Capacity	P drop (mbar)	Space Vel. (Cm/sec)	Development Status	Potential problems
Candle filter	99.9 (5)	385	200-300	2-3	Commercial	Heavy, Element failure
Cross flow filter	99.9 (5)	620	20-70	2-3	Subpilot	Delamination, Path plug, Less exper.
Moving GBF	99 (10)	217	50-100	20-30	Pilot	Media cleaning & Circulation, Less exper.

[a] Normal gas flow rate/collector size(N m^3/m^3 hr)

summarized in the ground of literatures reported.

Ceramic candle filters has the best potential for IGCC at this moment because it has nearly the highest efficiency comparing with other filtering systems and has accumulated many reliable design data resulted from many field experiences. Ceramic cross flow filters need further long term experiences so as to be applied for the commercial size of IGCC plant. Granular bed filter had less reliability in the granular media circulation than the ceramic candle filter at HTHP and had a poor collection efficiency due to reentrainment of dust sticked on the media.

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