*J. of the Korean Radioactive Waste Society*
*Vol.2(3), P. 201-209, Sept. 2004.*

# Performance of High Temperature Filter System for Radioactive Waste Vitrification Plant

# 방사성폐기물 유리화 플랜트 고온여과시스템의 성능 특성

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(Received March 16, 2004 / Approved March 30, 2004)

Abstract

Important operation parameters and performance of a high temperature ceramic candle filter system were evaluated through a series of demonstration tests at a pilot-scale vitrification plant. At the initial period of each test, due to the growth of dust cake on the surface of ceramic candles, the pressure drop across the filter media increased sharply. After that it became stable to a certain range and varied continuously proportion to the face velocity of off-gas. On the contrary, at the initial period of each test, the permeability of filter element decreased rapidly and then it became stable. Back flushing of the filter system was effective under the back flushing air pressure range of 3 ~5 bar. Based on the dust concentrations measured by iso-kinetic dust sampling at the inlet and outlet point of HTF, the dust collection efficiency of HTF evaluated. The result met the designed performance value of 99.9%. During the demonstration tests including a hundred hour long test, no specific failure or problem affecting the performance of HTF system were observed.

**Key Words** : Radioactive Waste Vitrification, High Temperature Filter, Ceramic Candle, Face Velocity, Permeability, Pressure Drop

요약

파일럿 규모의 유리화 플랜트에서 일련의 시험을 통해 고온 세라믹 캔들 필터 시스템의 주요 운전

변수 및 성능을 평가하였다. 실증 시험결과 매 시험초기에는 필터 표면 먼지층(Dust cake)의 생성으로 인해 필터 매질에 걸리는 차압이 급격히 상승하였다. 그런 다음 차압은 곧 일정한 범위에서 안정되었고, 표면유속(Face velocity)에 비례하여 계속적으로 변화하였다. 이와 반대로, 필터 투과율(Permeability)은 매시험 초기에 급격히 감소하였다. 필터표면 먼지의 역세정은 공기압 3~5 bar 범위일때 효율적이었다. 필터 입구 및 출구에서 동시에 등속으로 채취한 먼지농도를 바탕으로 필터의 먼지 포집율(Dust collection efficiency)을 평가한 결과 필터 성능은 설계값인 99.9%과 같은 것으로 나타났다. 100시간의 장기시험을 포함한 일련의 실증시험을 수행하는 동안 고온 필터 시스템의 성능에 영향을 주는 특별한 문제점은 발견되지 않았다.

**중심단어** : 방사성폐기물 유리화, 고온여과기, 세라믹 캔들, 표면속도, 투과율, 압력 강하

## I. Introduction

Low- and intermediate-level radioactive waste vitrification plant was developed by Korea Hydro & Nuclear Power Co., Ltd.Process diagram of the plant is shown in Figure 1. Properties of off-gas from the vitrification plant are much corrosive than the other traditional thermal processes.Among off-gas treatment processes(OGTS), the HTF system is the most important process in removing the radioactive isotopes from such harsh off-gas stream. The ceramic candle elements inside HTF endures the atmosphere of high temperature, high corrosive, and high dust concentration well.

In this paper, the operation parameters of HTF, such as, pressure drop across the filter media, permeability, face velocity, and back flushing pressure were identified and tested respectively. And depend on a series of demonstration test results including one hundred hour feeding test , the dust collection efficiency and durability of the HTF system were evaluated as well. Simulated organic wastes including ion exchange resin(IER) and dry active wastes (DAW) were vitrified at the

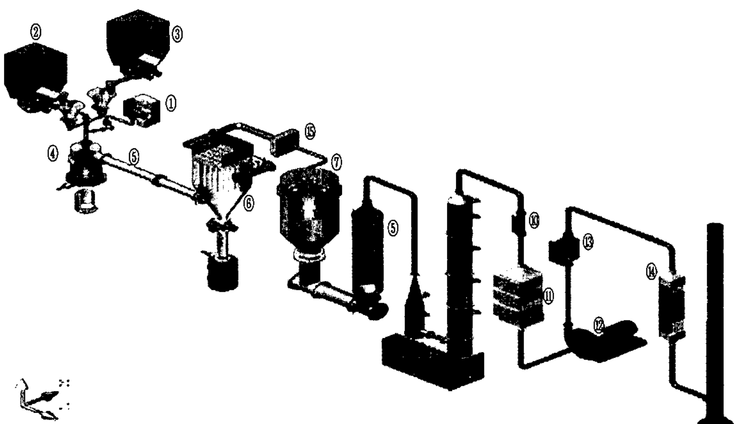


**Fig. 1. Process diagram of the pilot scale vitrification plant in Korea.**

demonstration tests.

## II. High Temprature Filter(HTF) System and Candle type Ceramic Filter Element [1~4]

### 1. HTF System

HTF system consists of a filter hosing, a tube sheet, a back flushing system, and a heating system inside housing jacket. Maximum 64 of one meter long candles can be mounted inside filter housing. To prevent internal leakage of off-gas stream between candle and tube sheet , ceramic wool gaskets were used as sealing material. The off-gas stream containing particles is introduced from the bottom side of filter housing and passes upward through the filter media. The particles remained at the surface of each candle and formed a layer named dust cake. Generally,the dust cake roles positively in filtering fine particles. Especially the sub-micron sized particles are removed by the help of dust cake layer. But it causes the increase of the total operation pressure drop of filtering system simultaneously. Thus thickness of the dust layer should be maintained appropriately by periodical back flushing. The conical ash hopper of filter housing is helpful for the discharging of the ash to the ash can. To maintain the off-gas temperature above dew point, the electrical heating coil is equipped inside the peripheral jacket of filter housing. Designed dust removal efficiency of the HTF system is 99.9% for the 0.3㎛ particles. Figure 2 shows schematic view of the HTF system.

### 2. Candle Type Ceramic Filter Element

The particles larger than 1㎛ can be collected easily by any of traditional filter media. But for the removal of sub-micron sized particles, the more sophisticate filtering system is required. In this regard, the candle type ceramic filter element had been tested for the sub-micron particles removing from the high temperature off-gas stream of the plant. The ceramic candle has not only the high resistance but also the high dust removal efficiency even under hash atmosphere. Mechanisms of particles removing at a filter media are well known as ; the inertial impaction, the Brownian displacement, and the electrostatic attraction at the filter.Thus the candle is made by sintering the

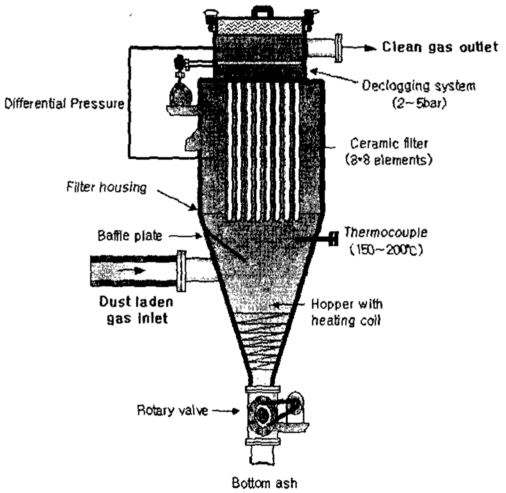


**Fig. 2. Schematic view of HTF system in the vitrification plant**

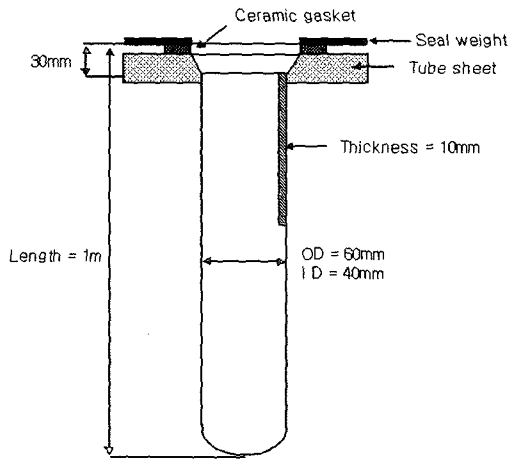


**Fig. 3. Conceptual view of a ceramic candle filter element**

mixture of alumina($Al_2O_3$) and silica($SiO_2$), it can be sustained itself without support material. The ceramic filter endures temperature up to 900°C. The filter media has 86% of porosity and 0.4g/㎤ of density. The lifetime of the filter is expected longer than other filter materials. Dimension of a candle, as shown in Figure 3, is 1 m(L) × 60 mm(OD) × 10 mm(thickness).

## III. Evaluation of Operation Parameters[5-7]

### 1. Pressure Drop Across Filter Media

Figure 4. is showing the cross sectional view of a ceramic candle filter element. In the figure, there are several distinctive layers at the outside of a ceramic filter element. They are the support layer, the coated layer, the residual layer of dust cake, and the temporary layer of dust cake respectively[2]. Accordingly, the total pressure drop( $\Delta P$) is the summation of pressure drops of each layer ; the filter itself( $\Delta P_F$) including the porous support layer and the permanent coating layer, the residual dust cake( $\Delta P_R$), and the temporary dust cake( $\Delta P_T$). Among the pressure drops, baseline pressure drop ( $\Delta P_B$) is the most important information in monitoring the behavior of the filter system.

Conceptual trend of the total pressure drop

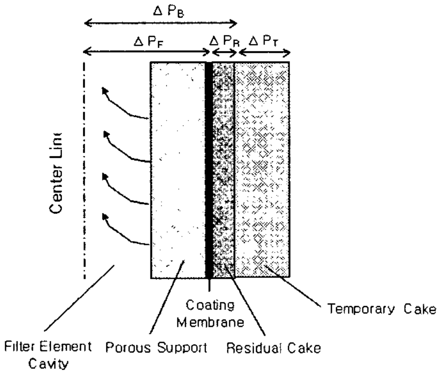


**Fig. 4. Cross section view of a ceramic candle filter element and pressure drops.**

( $\Delta P$)is shown in Fig. 5 In the figure, the line connecting the lowest points of each pitch is the baseline pressure drop( $\Delta P_B$). The figure of $\Delta P_B$ curve is reflecting the accumulated operational history ofa filter system. For example, continuous increase of $\Delta P_B$ nevertheless under normal operation of back flushing, the life time of filter elements might expired already. The total pressure drop( $\Delta P$) of HTF system can be expressed as the CARMAN-KOZENY's equation like below.

$$\Delta P = \bar{V} \cdot \mu \cdot R \quad \cdots\cdots\cdots\cdots(1)$$

where $\bar{V}$. : face velocity, m/sec

$\mu$ : fluid viscpsotu. kg/m·sec

$R$ : the filtration resistance, 1/m

From Eq.(1), the pressure drop( $\Delta P$)of the filter is proportion to the face velocity, the viscosity, and the resistance respectively. The face velocity and viscosity of off-gas will be varied depend on the temperature and the composition of off-gas every moment. And the filtration resistance will be influenced strongly based on the operation time and the operation of skills of filter system as well

Upon the theoretical review of HTF above, the observation of pressure drop of the HTF system had been conducted at a demonstration test. At the test, 32 candle filter elements were mounted inside

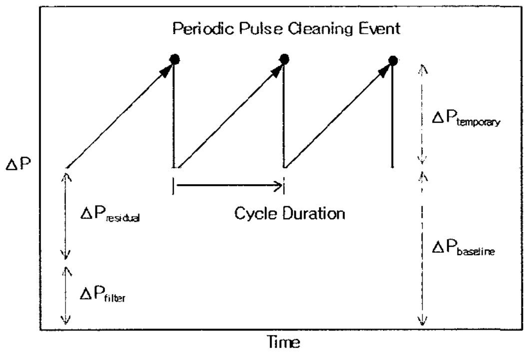


**Fig. 5. Trend of total pressure drops( $\Delta P$) and baseline pressure drop( $\Delta P_B$).**

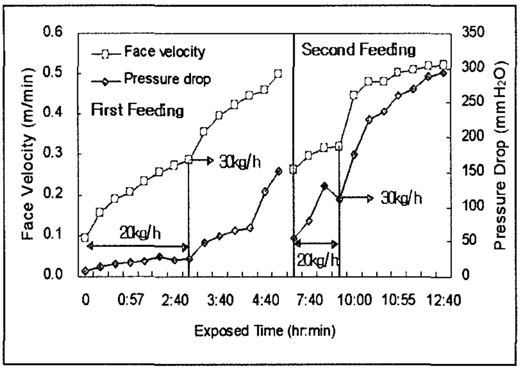


**Fig. 6. Effect of waste feed rate on baseline pressure drop and face velocity.**

the HTF system. And simulated IER waste was vitrified. The test had been continued for 10 hours. But it was separated to two test periods, feeding 5 hours each, internally. And each test period was separated to 20 and 30kg/h of waste feed rates again. In regard to the back flushing, the pressure of air pulse was controlled in between the range of 3 ~5 bar and the pulse cycle and pulse duration was fixed to 3 minutes and 200 msec respectively. For the result, as shown in Figure 6, the pressure drop(see diamond symbol) and face velocity(see square symbol) were increased similar trend at the test. At the first period of the test, the baseline pressure drop of the filter increased steadily following to the filter exposure time and the increase of waste feed rate were reflected together. The behaviors of the two parameters were observed as similar pattern. The total pressure drop was strongly influenced by the face velocity than the concentration of dust in off-gas. The dust concentrations measured by iso-kinetic sampling method were about 2.4 g/Nm$^3$ and they were not much difference between the two feed rates. But even under the similar filtering condition between the test periods, due to the residual dust cake on the surface of the filter media, the total pressure drop became higher at the second period. Nevertheless two hours of feeding stop before the second period, the initial pressure drop was twice of first period. This can be explained that the residual pressure drop( $\Delta P_R$) could not be removed by back flushing for such long time. In due to the residual pressure at the second period feeding, the increase of the two parameters were steeper than the first period as well. Meanwhile, the gap of the two became narrow gradually following to the filter exposure time. Though the face velocity was high enough at the end of the period, no additional increase of pressure drop was observed. The stabilization of pressure drop was relatively clear at the end of the second period feeding. This could be explained that the dust cake was very helpful in collecting the fine particle. Consequently, even under the high face velocity, it prevented the penetration of fine particles into the filter media hence it had been maintained the baseline pressure stable. After all, the stable dust cake on the filter had been improved the efficiency and extends the lifetime of the candle filter.

## 2. Face Velocity

Normally, filtration velocity is calculated base on the actual flow rate of off-gas and the total effective filtration area(EFA) of the filter. In other words, the number of filter element is decided by subdividing the total EFA by the area of a filter element. But because the gradual increase of pressure drop across filter media, the additional filters should be added for the safe operation of HTF. Since the higher face velocity of off-gas gives the higher kinetic energy. Thus too high face velocity makes not only the efficiency low but also shorten the lifetime of it. Therefore, under the high temperature and high dust concentration condition, slow face velocity is recommended. In the industry, it is common that the face velocities of HTF are about 1.8 to 2.4m/min for the oxygen furnaces, 0.9 to 1.5

m/min for the coal fired boilers, 0.7 to1.2 m/min for the municipal incinerators respectively. Base on the theoretical review, the face velocity of the filter was designed as about 0.52m/min. Such slow face velocity was intended to minimize the penetration fo fine particles through filter media.

### 3. Permeability

The penetration and deposition of fine particles inside the filter pores increases the resistivity of the filter. The deposit of ash on the surface of filter element can not be removed by the back flushing. But, as discussed before, the high temperature and the high face velocity causes the penetration and deposition inside the filter and finally reduce the permeability of the filter. The characteristics of the particles such as size distribution, adhesiveness, and density affects to the permeability also[2-3]. The penetration of fine particles could be reduced a little by coating the filter or by using the surface coated filter. Normally corundum powder is used for the coating material. Unfortunately the surface coated filters have both the advantage and the disadvantage points simultaneously. Figure 7. shows the particle size distribution measured from the tests based on three different types of wastes. At the tests, the particle size distribution was analyzed by the cascade impactor under the iso-kinetic sampling method. The summation of below 1.3㎛ size particles captured separately was more than 50 wt% at all three analysis.The fine particles of micron size or under penetrated the filter media cause the resistivity of the filter finally. In this regard, the resistivity of a filter element could be explained by Eq.(2). In the equation, the resitivity, R is expressed the terms of the porosity ε, the specific surface area A, and the media thickness T. The resistance R is the total of filter media resistance $R_F$ and the attached dust cake resistance $R_C$, then

$$R = R_F + R_C \cong \frac{(1-\varepsilon)^2 \cdot A^2 \cdot T}{\varepsilon^3} \quad \cdots\cdots\cdots\cdots(2)$$

Considering the thermodynamic properties of off-gas, the permeability can also be defined as

$$K = \frac{1}{R} = \frac{\overline{V} \cdot \mu}{\Delta P} \quad \cdots\cdots\cdots\cdots(3)$$

The relative permeability expressed by Eq.(4) is convenient to define the filtration performance. The subscript zero in the equation means the initial values.

$$K_d = \frac{K}{K_0} = \frac{\overline{V} / \Delta P}{\overline{V}_0 / \Delta P_0} \cdot \frac{\mu}{\mu_0} \quad \cdots\cdots\cdots\cdots(4)$$

where $K_d$ : Dimensionless permeability
$K_0$ : Permeability of virgin filter element

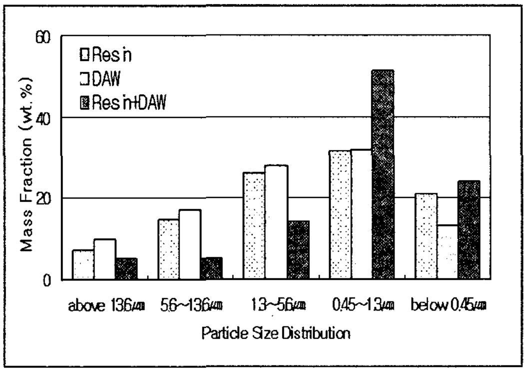


**Fig. 7. Size distribution of particles in off-gas.**

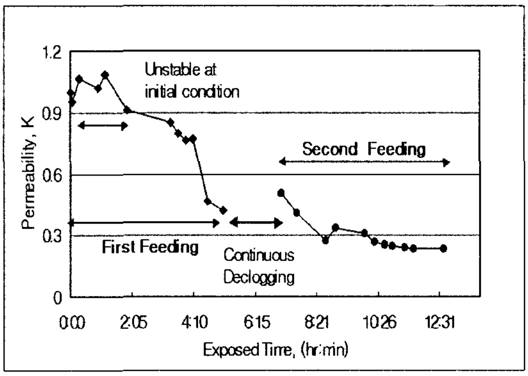


**Fig. 8. Effect of exposed time on the permeability.**

Both the growth of dust cake and the penetration of particles and the exposed time of filter element decrease the permeability of the filter. Figure 8 shows that the permeability of the ceramic candle filter observed in a IER test. Due to the uneven formation of dust cake on the fresh filter surface, the permeability was showingunstable at the first period of time and decreased soon to a certain level. The stabilized permeability of the filter element of the process was evaluated as about 3.5 $\times 10^{-9}$m and this value was similar to the other test results reported by others [2].

## 4. Dust Collection Efficiency

Concentration of dust in off-gas is varied depend on the waste type, the feed rate of waste, and the operation condition of CCM.The dust collection efficiency of the system was calculated based on the measurement of dust concentrations at the inlet and the outlet of HTF system. Iso-kinetic sampling method was utilized for the analysis of dust concentration. Dust concentrations at the inlet of HTF was measured in the range of 1.0 to 5.0 g/Nm$^3$. At the outlet of HTF, it was measured as nearly zero. The collection efficiency of HTF system was calculated by Eq.(5) below.

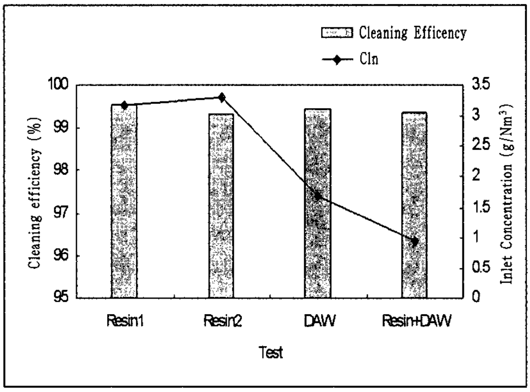


**Fig. 9. Dust concentration at the inlet of HTF and dust collection efficiency of HTF system.**

$$\text{Collection Efficiency}(\%) = \frac{C_{in} - C_{out}}{C_{in}} \times 100 \quad \cdots\cdots(5)$$

where $C_{in}$ = inlet dust concentration (g/Nm$^3$)
$C_{out}$ = outlet dust concentration (g/Nm$^3$)

Figure 9. shows the dust collection efficiency evaluated at the demonstation tests. In the figure, the bars and the line are showing the collection efficiency and the concentration of dust respectively. In case of IER test, in spite of high concentration of dust at the upstream of HTF, the dustcollection efficiency was measured as 99.9%. However, in the other DAW related tests, the dust removal efficiency was slightly lower than resin tests. Because of the higher calorie contest in DAW than IER, the dust collection efficiency was lower at the DAW tests. As discussed, higher portion of sub-micron size particles are generated well under high temperature condition and hence much of sub-micron particles pass the filer media at the DAW tests.

## 5. Back Flushing

Most of the dust in the off-gas was removed at the dust cake on the surface of filter media[4]. In regard to the initial dust cake formation, it is understood that when the back flushing pulse is given, the fine particle detached from the filter surface remained near and make up the dust cake quickly again. Because of this phenomena, the

**Table 1. Parameters of back flushing in the HTF system.**

| Item | Operation range | Operation condition |
|---|---|---|
| Compressed Air Temperature | 5～150 ℉ | Room Temperature |
| Pulse Intensity | 1～5 bar | 3～5 bar |
| Pulse Duration | 0.05～5 sec | 0.2 sec |
| Pulse Interval | 0～180 sec | 22 sec |

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efficiency of the filter ensures high efficiency even under the back flushing period. Meanwhile the candle filter elements are cleaned row by row, the adjacent rows are exposed to the off-gas. Thus, the back flushing condition such as, pulse intensity, pulse interval, pulse duration are most important parameters. The parameters of back flushing applied in the demonstration tests are listed in Table 1.

### 6. Durability

From the view point of safety and economics, the durability of filter is most important. The durability of filter is influenced directly by the material and structure of filter. The skills of operation also give much influence to the durability of a filter system. A sudden exposure to the hot off-gas might shorten the lifetime of the filter. The filter pores are blocked easily with the vapor of alkali metals and calcium. The exposure time makes the filter brittle. Nevertheless these known informations described above, the durability of a filter should be obtained through practical test. Separate out of one effect from the several parameters is not easy as well. Though such the evaluation limitations, a long-term test on the mixture of DAW & IER was successfully completed in the plant at the plant recently. The test continued about 100 hours based on the waste feeding time. 32 filter elements configured inside HTF at the test. The test results have not been evaluated yet. But the performance of the filter system had been proved as very sound. The pressure drop across the filter was started from $8mmH_2O$ and finished at $80mmH_2O$ under the periodic back flushing. The trend of the total and baseline pressure drops was stable through the test time. Collection efficiency measured by the iso-kinetic dust sampling method and the result met the designed value of 99.9%. During the test period, no specific phenomena affectingthe durability or performance of the ceramic candle filter elements was observed at all.

## IV. Conclusions

The characteristic of HTF system utilizing the ceramic candle filter elements had been evaluated through a series of demonstration tests. And based on the observation of the tests, below results were derived.

- To prevent penetration of the sub-micron sized particles into the filter media, the face velocityof the HTF system and temperature of off-gas should be controlled as low as possible.
- The pressure drop across the filter media was affected strongly by the face velocity and weakly by the dust load in the off-gas.
- Initial permeability of the HTF system was evaluated as $3.5 \times 10^{-9}$m.
- The pressure drop across filter elements increased quickly for the first time of a test, but stabilized soon following to the growth of dust cake.
- In normal test conditions, collection efficiency of the HTF system met the designed value of 99.9%.
- Based on the long-term test result, the durability of the ceramic candle filter was proved very sound.

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