

Simultaneous Extraction of Yttrium and Neodymium from Fly Ash by Two-Step Leaching Process with Aid of Ultrasonic Wave

2단계 침출 과정에서 발생하는 비산회로부터 초음파 활용하여 이트륨과 네오디뮴의 동시 추출

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Abstract

A two-step process for increasing the leaching efficiency of yttrium and neodymium from coal fly ash were investigated at solid loadings of 5.0 g ash ~1,000 g ash/l of 1.0 N~10.0 N H₂SO₄, temperature ranging from 30°C to 90°C, ultrasonic leaching time of 1~10 hours, and ultrasonic power of 25~200 W. The yttrium and neodymium from coal fly ash were effectively leached into ion phases by step change of the first conventional dissolution at room temperature and then the second heating process with the aid of ultrasonic wave, and maximum leaching efficiency of yttrium and neodymium obtained were 66 % and 63 %, respectively. The activation energies for the leaching reaction of yttrium and neodymium at second heating process dependent on leaching time and temperature were derived to be 41.540 kJmol⁻¹ and 507.92 kJmol⁻¹, respectively. The optimum conditions for the maximum leaching of yttrium and neodymium were found to be the solid loading of 250 g ash/l of H₂SO₄, solvent concentration of 2.0 N H₂SO₄, and second step process of temperatures of 30°C for 3 hours and then 90°C for 4 hours with ultrasonic intensity of 100 W.

Keywords: Fly Ash, Leaching, Yttrium, Neodymium, Sulfuric Acid, Ultrasonic Wave

I. Introduction

The output of ashes produced from all coal-fired power plants owned by KEPCO's subsidiary was about 9.35 million tons in 2019, among them 7.01 million tons was being recycled as a concrete mixture additives and the rest was landfilled in the ash pond. In addition, the ash ponds at all coal-fired power plants owned by the KEPCO subsidiary are filled with 59.39 million tons of fly ash and bottom ash containing more than 5.0% unburned carbon, which does not meet the Korean standard carbon content [1]. Meanwhile, coal ashes were found to contain important yttrium in the range of 26 mg/kg - 75 mg/kg, and neodymium with 18 mg/kg - 86 mg/kg. However, it still requires the optimal leaching and recovery technology in order to utilize yttrium and neodymium in coal ash. Recovery of strategic valuable yttrium and neodymium elements from unused ash and ponded ash sources can provide the solution of environmental problems and can significantly improve economic advantage of existing coal power plants [1][2]. Among the rare earth metals in ashes, yttrium and neodymium were high than the concentration of other rare earth elements, and has a wide range utilization fields of high tech industry that require phosphors of fluorescent lamp, liquid crystal display, light emitting diode, and the magnetic material of gas turbine, air craft, engine of advanced industry [3][4]. To replace the imports of strategic rare earth

minerals such as yttrium and neodymium, Korean government is pushing forward an energy technology development policy for recovering a strategic rare earth mineral from 30 % coal ashes [5]. KEPCO Research Institute carried out research for the extraction and recovering of yttrium and neodymium in unused fly ash. This study discussed the leaching condition of yttrium and neodymium, which exhibit the highest concentration in coal fly ash.

II. Experimental

A. Coal Fly Ash Sample

Raw fly ash was sampled from the Tean coal-fired power plant; Tean-gun, Chungnam-do, Korea, owned by the KWEPC (Korea Western Electric Power Corporation) in KEPCO's subsidiary. TABLE 1 shows the chemical and rare earth element components of raw fly ash. The concentration of metal was analyzed by X-ray fluorescence analyzer (EMAX-3770, Horiba) and the chemical components was calculated as a form of stable oxide. Most sample components have the major SiO₂ and Al₂O₃ whereas minor minerals were CaO, Fe₂O₃, MgO, Na₂O, SO₂ and K₂O. The average concentration of yttrium metal containing in coal fly ash samples was about 70.6 mg/kg ($n=5$,

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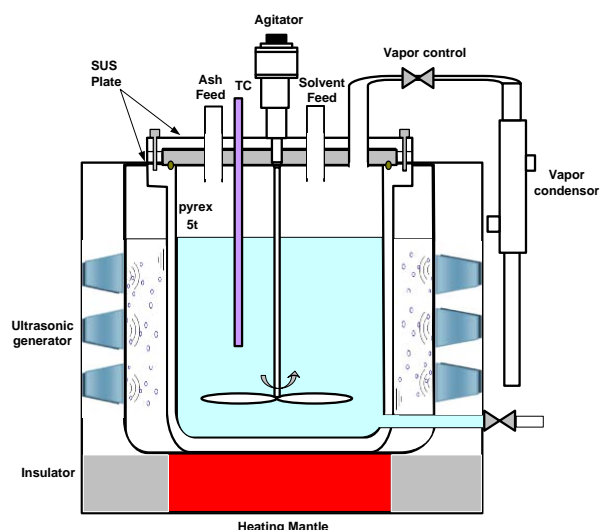


Fig. 1. The apparatus of ultrasonic reactor for leaching process.

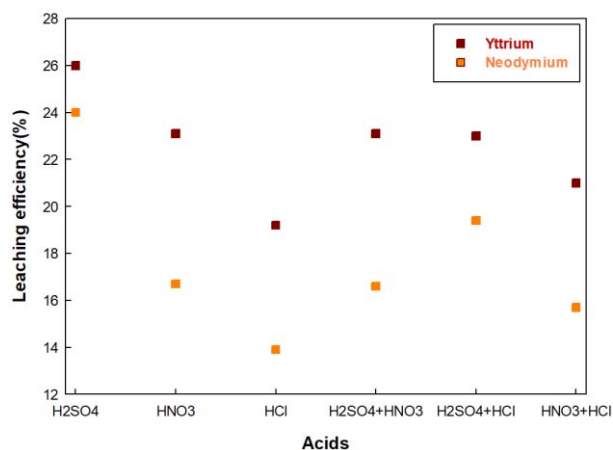


Fig. 2. Leaching efficiency of yttrium and neodymium from coal fly ash at various acids.

$\sigma=1.53$ mg/kg), and concentration of neodymium metal was 56.3 mg/kg ($n=5$, $\sigma=1.28$ mg/kg) with other minor rare earth metals such as Dy, Eu and Tb.

B. Experimental Apparatus

Ultrasonic wave equipment supplied for this study are composed of industrial transducer with a working frequency of 60 kHz (Korea Jeio-Tech Inc. UCS-20) and an ultrasonic output that can vary from 0 to 820 W. The ultrasonic wave leaching apparatus was made by the injection of a thermocouple inside the reactor in order to measure reaction temperature, and the water circulation condenser to enable experiments under stable atmospheric pressure in Fig. 1. Atmospheric pressure has been chosen because it was the common method for leaching at temperature with less than 100°C of water boiling point and allows a security of acid treatment process [6][7]. The effects of temperature on the leaching efficiency of yttrium and neodymium from coal fly ash were performed at temperature interval of 20°C from 30°C to 90°C. The rotation shaft was composed of a SUS 316 blade with Teflon lining and agitation

TABLE 1
Chemical Components and Rare Earth Elements Concentration of Raw Ash Sample

Chemical components [%]								Rare earth metals [mg/kg]				
SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	SO ₃	Y	Nd	Eu	Tb	Dy
51.9	31.6	3.8	5.5	3.2	2.0	0.8	1.1	70.6	56.3	2.5	2.1	1.2

rate was adjusted from 0 to 400 rpm. The leaching reactor was also composed to reflect the high acid resistant materials through Pyrex reactor which has the volume of 1,000 ml.

C. Experimental Procedures and Analysis

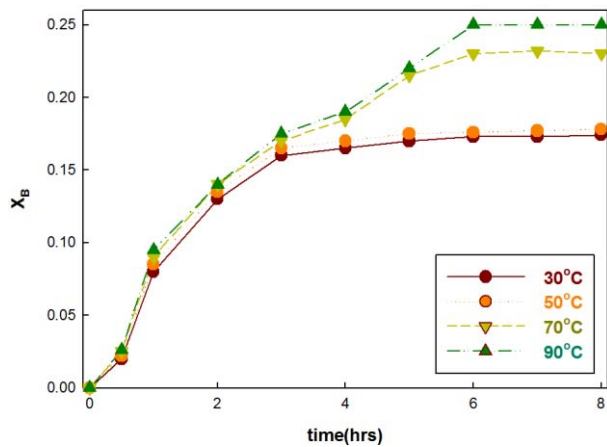
Sulfuric acid of concentration ranging from 1.0 N to 10.0 N was used as solvent reagents for leaching experiments. The raw fly ash according to the variables was injected into a 1.0 liter Pyrex reactor containing each acid solution. The reaction temperature of leaching solvent was adjusted by heating mantle attached at the bottom of the reactor, and the mixing of ash and sulfuric acid solvent was carried by agitator of 250 rpm. The specimen for measuring leaching efficiency of yttrium and neodymium was taken from the lower outlet of reactor when the experiments was completed, and then it filtered by 0.45 μ m cellulose acetate filter. The filtrate after removed the residues was diluted 10 times, and then analyzed by ICP-MS (X-series X5, Thermo Elemental, UK) analysis. Also, Tests of leaching efficiency of yttrium and neodymium was performed by sulfuric acids as well as hydrochloric, nitric and those mixing acids to investigate the optimum solvent for the simultaneous leaching of yttrium and neodymium [8]. The conventional leaching to select the optimal solvent was carried out only by the heating mantle without the ultrasonic wave at agitation of 250 rpm. The conventional leaching tests at various solvents were conducted out under the solid loading of 50 g coal fly ash/l of 1.0 N H₂SO₄, HNO₃, HCl, blending solvent of 1.0 N H₂SO₄ and 1.0 N HNO₃, blending solvent of 1.0 N H₂SO₄ and 1.0 N HCl, or blending solvent of 1.0 N HNO₃ and 1.0 N HCl at temperature ranges from 30°C to 90°C.

Two-step leaching tests were carried out under the solid loadings of 5.0 g ash~1,000 g ash/l of 1.0 N ~10.0 N H₂SO₄ at temperature ranges from 30°C to 90°C to determine effects of the solid loading, sulfuric acid concentration, reaction times, and ultrasonic wave output on leaching. This method carried out both first leaching process of the room temperature without heating and second leaching process with the aid of ultrasonic wave combined to heating mantle at various reaction times, and ultrasonic wave outputs. The crystal phases of raw fly ash and residues of after the leaching were analyzed by XRD (PhilipsPW 1830 diffractometer). Particle morphology of raw ashes and its residues was scanned by SEM (JEOL 5200-2AE). The surface area, pore size and volume of raw ashes and residues has been measured by BET (ASAP2010, Micromeritics) analyzer of N₂ adsorption and desorption method. Its mean particle size (d_{50}) was measured by wet particle size analyzer (Cilas 1064).

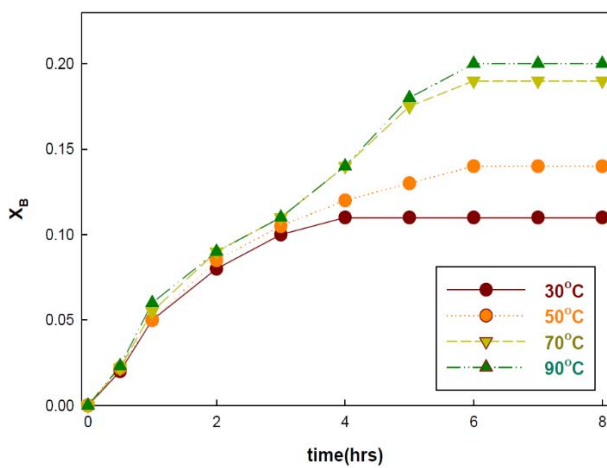
III. Results and Discussion

A. First Step Leaching of Yttrium and Neodymium from Fly Ash

Fig. 2 shows leaching conversion of yttrium and neodymium in fly ash as a function of solvent species under a solid loading of 50 g ash/l of various acids of 1.0N with heating mantle at temperature of 90°C for 6 hours, and agitation speed of 250 rpm. The simultaneous



(a)

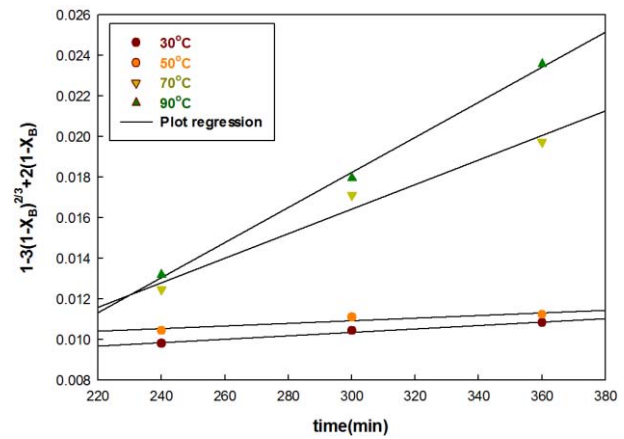
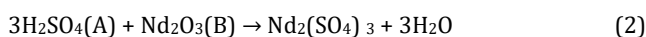
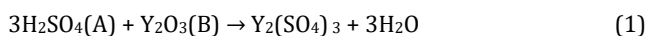


(b)

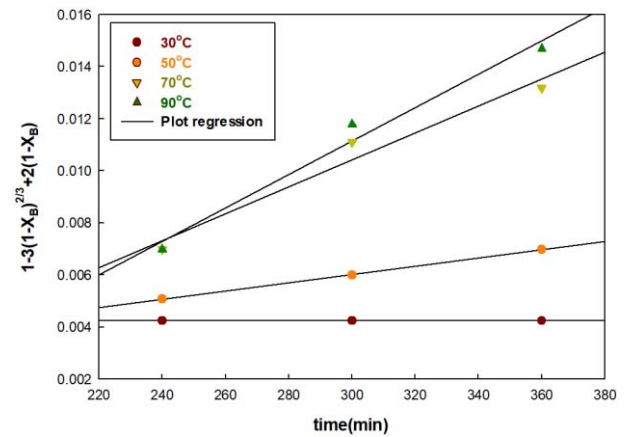
Fig. 3. Leaching conversion of yttrium and neodymium from coal fly ash at various temperature and times in a solid loading of 50 g ash / L of 1.0 N H₂SO₄. (a) Yttrium. (b) Neodymium.

leaching efficiency of yttrium and neodymium from fly ash at sulfuric acid solvent was the highest than other single acid and mixing acids. This means that the selective reactivity of sulfuric acids on yttrium and neodymium leaching was the highest than other acids, the blending acid of H₂SO₄ and HNO₃ in case of yttrium leaching was the second highest, and the blending acid of H₂SO₄ and HCl in case of neodymium leaching was the second highest. Organic acids were not considered in this experiment because of the complexity of organic acids hindering the separation and purification in the recovering process after the leaching reaction. Therefore, the sulfuric acid has been identified as the most suitable solvents for simultaneous leaching of yttrium and neodymium from this fly ash. The reason for selecting the optimal concentration of H₂SO₄ was discussed in following leaching evaluation of yttrium and neodymium from fly ashes at various sulfuric acid concentrations (Fig. 7).

The Y₂O₃ and Nd₂O₃ existing in the fly ash are converted into Y₂(SO₄)₃ and Nd₂(SO₄)₃ phases under H₂SO₄ solution as in the following Eq. (1) and (2).



(a)



(b)

Fig. 4. Relation between conversion and time during the ash inner layer leaching at temperature ranges from 30°C and 90°C.

The simultaneous leaching of yttrium and neodymium from spherical fly ash as a function of reaction time (1~8 hours) and temperatures (30~90°C) were carried out a solid loading of 50 g ash/l of 1.0 N H₂SO₄, with rotation speed of 250 rpm as in Fig. 3.

Leaching efficiency of yttrium and neodymium at the different reaction times and heating temperatures, constantly increased initially (3 hours) independent on temperature, and later remained constant at temperature of less than 50°C whereas increased continually with time of 6 h at temperature of more than 70°C. Y₂O₃ and Nd₂O₃ of 26% and 24%, respectively, existing in the fly ash were leached out to Y₂(SO₄)₃ and Nd₂(SO₄)₃ solution after the leaching of 6 hours at the temperature of 90°C and 1.0 N H₂SO₄. This result was ascertained to two-step leaching mechanism because the conversion rate of rare earth metals in fly ash was divided into two stages, the first stage of ash surface leaching dependent on only time irrelevant to temperature, and the second stage of ash inner layer leaching dependent on both time and temperature. The ash inner layer leaching at reaction time ranges from 3 hours to 6 hours because the leaching conversion was dependent on time and temperature can be considered as a diffusion rate model [9]-[13]. In the ash inner layer diffusion model dependent on time and temperature, there are many kinetic equations [10]-[14], but the leaching rate is expressed as a diffusion controlled rate of H₂SO₄ inside spherical fly ash to the following shrinking core model.

TABLE 2

Kinetic Parameters Calculated from the Regression for the Yttrium and Neodymium Leaching

Leaching Components	Parameters	Reaction temperatures			
		30°C	50°C	70°C	90°C
Yttrium	a(slope)	8.49e-6	6.54e-6	6.05e-5	8.65e-5
	b (y-intercept)	7.82e-3	8.96e-3	-1.72e-3	-7.71e-3
	R2	0.98	0.87	0.98	0.99
	Activation Energy Results	-E/R = -4996 E = 41.54 kJ/mol R2 = 0.79			
	a(slope)	2.88e-20	1.58e-5	5.17e-5	6.42e-5
Neodymium	b (y-intercept)	4.24e-3	1.26e-3	-5.09e-3	-8.11e-3
	R2	0.99	0.99	0.97	0.98
	Activation Energy Results	-E/R = -61,092 E = 507.92 kJ/mol R2 = 0.69			
	a(slope)	2.88e-20	1.58e-5	5.17e-5	6.42e-5
	b (y-intercept)	4.24e-3	1.26e-3	-5.09e-3	-8.11e-3

$$1 - (1 - X_B)^{\frac{2}{3}} + 2(1 - X_B) = k_{c-ash} t \quad (3)$$

k_c is the leaching rate constant for the diffusion in ash inner layer and reciprocal of the time required to complete leaching conversion of a particle, $r_c=0$.

$$k_{c-ash} = \frac{2D_e C_{AO}}{\rho_B R^2} \quad (4)$$

D_e is the diffusion coefficient of H_2SO_4 to the inside of the ash layer.

These ash layers will act as a resistance for H_2SO_4 to go into ash inner layers for the leaching. According to Eq. (4), the leaching rate constant (k_{c-ash}) at leaching time ranges of 3~6 hours dependent on reaction temperature is derived from the least square method with different leaching time and temperatures as shown in Fig. 4. To examine the effect of leaching temperatures, the activation energy and rate constants for leaching yttrium and neodymium in ash inner layer at temperature ranges from 30°C to 90°C were calculated as shown in TABLE 2. In the ash inner layer diffusion stage, the slopes on the leaching of yttrium and neodymium were -4.996×10^3 and -61.092×10^3 , respectively. As shown in Fig. 5 and TABLE 2, finally, the activation energies for leaching of yttrium and neodymium from fly ash were derived to be 41.54 kJmol⁻¹ and 507.92 kJmol⁻¹, respectively, in the temperature range of 30°C to 90°C.

This activation energies were higher than that for leaching rare earth metals from the other industrial slag and ores with 1.0 kJmol⁻¹ ~ 9.98 kJmol⁻¹ [12][13]. The difference in activation energies for leaching yttrium and neodymium between fly ash and other byproducts sources was probably due to the existence of yttrium and neodymium combined with complex crystals such as a α -, β -quartz (SiO₂), and mullite (3Al₂O₃2SiO₂) inside the raw fly ash. In coal burning process at temperature ranges from 1,200°C to 1,400°C, most minerals such as silica and alumina etc. were melting, vaporizing, reacting with other minor minerals and then condensed as a α -, β -quartz (SiO₂), and mullite (3Al₂O₃2SiO₂) etc. As a result, leaching conversion of the rare earth yttrium and neodymium combined with α -, β -quartz (SiO₂), and mullite (3Al₂O₃2SiO₂) crystals as a complex metal oxide becomes more difficult than other industrial by-products sources of existing the glass phases. These compound crystals serve as a resistance role on the leaching of yttrium and neodymium during the leaching behaviors. Therefore, it

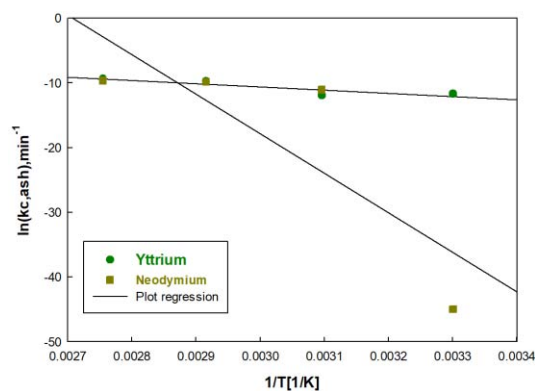


Fig. 5. Arrhenius plot of conversion and temperature at ash layer leaching.

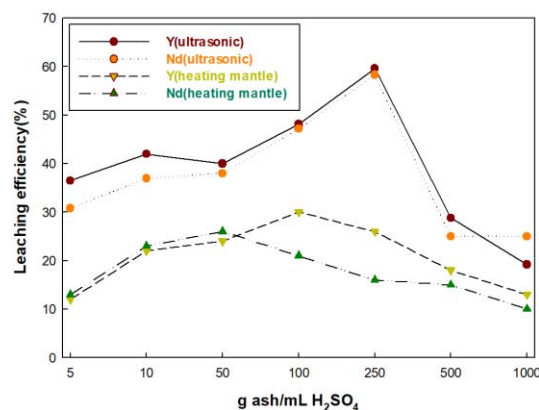


Fig. 6. Leaching efficiency of yttrium and neodymium from coal fly ash at various solid loading after first leaching at temperatures of 30°C for 3 hours.

is necessary to introduce a new process of the two-step leaching because the leaching efficiency of more than 50% of yttrium and neodymium from coal fly ash using conventional heating was found to be limited.

B. Second Step Leaching of Yttrium and Neodymium from Fly Ash

Many researchers [14]-[16] reported that ultrasonic waves significantly improve the leaching efficiency of metals from waste minerals and shale. The leaching efficiency of the combined process of ultrasonic and conventional stirring methods for leaching valuable metals from hydroprocessing wastes is known to have improved significantly.

Other results [17][18] demonstrated that ultrasonic wave could increase the leaching rate of metals from black shale in nitric acid. However, the application of ultrasonic wave in the leaching of the yttrium and neodymium from coal fly ashes has not been studied in detail yet. Ultrasonic wave to increase maximum leaching conversion of yttrium and neodymium in the fly ash was applied at the second heating process compared to only heating process without ultrasonic after the first step leaching at room temperature for 3 hours. The effects of solid loading, solvent concentration, time, and ultrasonic wave power on leaching efficiency based on optimal conditions at above leaching were determined.

To maximum the leaching of yttrium and neodymium in the fly ash, a suitable solid loading must be considered. At low solid loading,

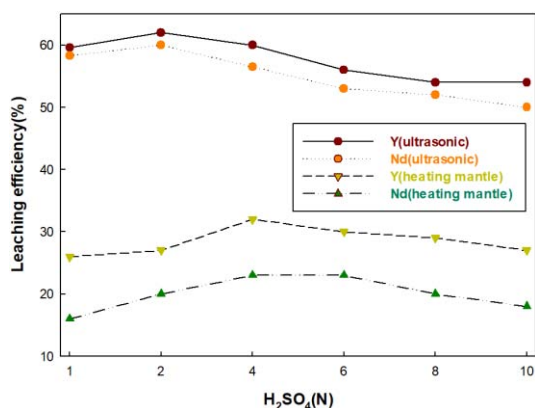


Fig. 7. Leaching efficiency of yttrium and neodymium from fly ash at various sulfuric acid concentrations after the first leaching at temperatures of 30°C for 3 hours.

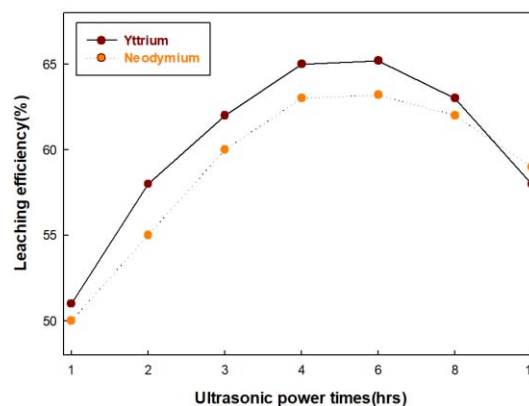


Fig. 9. Leaching efficiency of yttrium and neodymium from coal fly ash at different leaching times at two-step leaching with aid of ultrasonic wave.

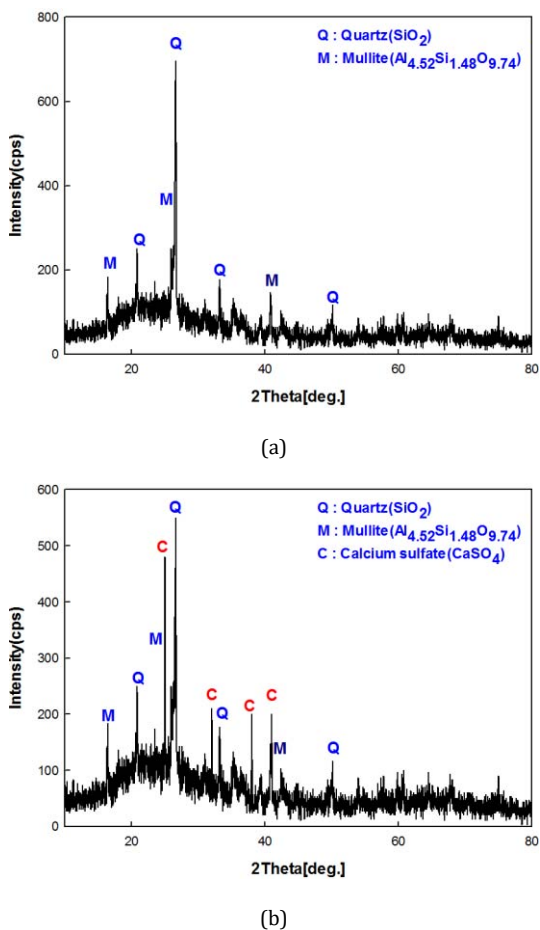


Fig. 8. Crystals of (a) raw ash samples and (b) residues after the yttrium and neodymium leaching.

yttrium and neodymium in fly ash cannot be leached enough. On the contrary, various impurities such as silicon, aluminium, iron, calcium and magnesium ions can simultaneously be leachable with the desired materials of yttrium and neodymium at high solid loading, which can cause undesired effects. Leaching experiments were performed at various solid loadings to find optimum conditions for

leaching of yttrium and neodymium in the ash. Fig. 6 shows the leaching efficiency by two-step process with the aid of ultrasonic wave of 75 W at second heating step compared to the only second heating at temperature of 90°C for 3 hours, after first leaching at room temperature of 30°C for 3 hours with various solid loadings of 5.0 g ash ~1,000 g ash/l of 1.0 N H₂SO₄. Actually, the ultrasonic wave significantly enhanced the leaching rate of yttrium and neodymium at all the solid loading ranges compared to the only heating process, and leaching efficiency was rapidly increased into solid loading of 250 g ash/l of 1.0 N H₂SO₄, but from solid loading in excess of 250 g ash/l of 1.0 N H₂SO₄, it significantly decreased with increasing solid loading. This result ascertained that ultrasonic wave was providing energy to activate the leaching of yttrium and neodymium from coal fly ashes. The ultrasonic waves that assist the existing heating process not only promote the convective motion, but also which increases the contact surface area and frequency of fly ash and solvent to speed up sharply the leaching efficiency. However, the effect of ultrasonic wave with the high solid loading of more than 500 g ash/l H₂SO₄ was not significant on the leaching of yttrium and neodymium from fly ash. This may be expected to result from a reduction of contact surface area and frequency of fly ash to react the sulfuric acid.

Therefore, solid loading has been identified that 250 g ash/l of 1.0 N H₂SO₄ may be the most suitable for simultaneous leaching of yttrium and neodymium from fly ash. Fig. 7 shows the leaching efficiency by two-step process with the aid of ultrasonic wave of 75 W at second heating step compared to the only second heating at temperature of 90°C for 3 hours, after first leaching at room temperature of 30°C for 3 hours with solid loading of 250 g ash/l of various sulfuric acid. When the sulfuric acid concentration was about less than 2.0 N, the maximum leaching efficiencies of yttrium and neodymium from fly ash were about 62% and 60%, respectively. It was increased with increased the sulfuric acid concentration at less than 2.0 N H₂SO₄ whereas it was decreased with increased sulfuric acid concentration at more than 3.0 N H₂SO₄. This is probably due to the precipitation of SO₄²⁻ as calcium sulfate as shown in Fig. 8. As previously study [19], this may be that the consume rate of SO₄²⁻ to form the calcium sulfate during the leaching of high H₂SO₄ concentration was faster than the selective reaction rate with yttrium and neodymium in fly ash. The XRD analysis of the residue after the two-step leaching of yttrium and neodymium shows the peaks of CaSO₄ crystals [Fig. 8(b)] precipitated by reacted Ca²⁺ ion from ash and SO₄²⁻ ion from H₂SO₄. As shown in TABLE 1, the concentration of CaO and SO₃ in raw fly ash were found to be 5.5% and 1.1%, respectively, while the concentration of CaO and SO₃ in

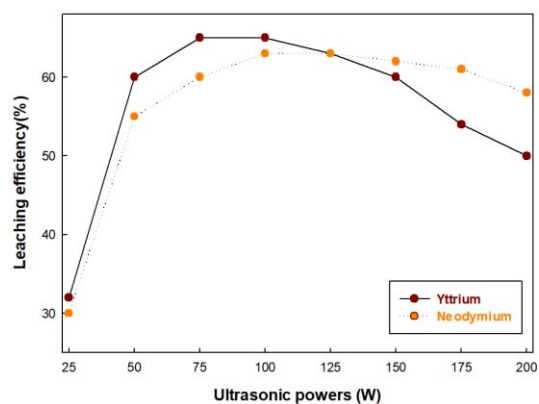


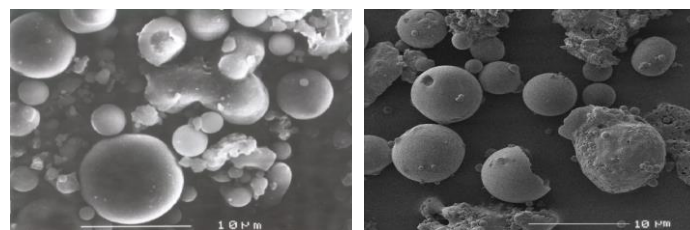
Fig. 10. Leaching efficiency of yttrium and neodymium from coal fly ash at different ultrasonic powers at two-step leaching with aid of ultrasonic wave.

precipitation residue were identified 5.4% and 7.72%, respectively (Data was not shown). The increase in concentration of SO_3 in precipitation residue than raw fly ashes is assumed to have been crystallized by the reaction of Ca^{2+} ion from ash and SO_4^{2-} ion from H_2SO_4 . Therefore, sulfuric acid in excess of 2.0 N may not be suitable for the yttrium and neodymium leaching from fly ash due to formation of precipitates such as calcium sulfates.

Fig. 9 shows the simultaneous leaching efficiency by two-step leaching process with the aid of various ultrasonic outputs from 25 W to 200 W at temperature of 90°C for various times of 1~10 hours, after first leaching at room temperature of 30°C for 3 hours with solid loading of 250 g ash/l of 2.0 N H_2SO_4 . As shown in Fig. 9, the leaching efficiencies of yttrium and neodymium in sulfuric acid are significantly increased to time of 4 hours whereas it was slightly decreased from leaching time of 6 hours. As fly ash compositions were combined with main different components in TABLE 1, the leaching time was the key condition to ensure the dissolution of yttrium and neodymium to be the desired leaching reaction, otherwise excessive impurities such Ca^{2+} , Mg^{2+} , Na^+ , etc., dissolved and then precipitated sulfate compound.

The simultaneous leaching efficiency of yttrium and neodymium from fly ash was about 26% and 24% [Fig. 3], respectively, in case of the only heating process at temperature of 90°C for 7 hours whereas it was significantly increased by more than 2.5 times to about 65% and 63%, respectively, as two-step leaching process with the aid of ultrasonic wave carried out under temperature of 90°C for 4 hours after the first leaching at room temperature of 30°C for 3 hours.

Fig. 10 shows the simultaneous leaching efficiency by two-step leaching process at various ultrasonic powers of 25~200 W with temperature of 90°C for 4 hours, after the first leaching at room temperature of 30°C for 3 hours with solid loading of 250 g ash/l of 2.0 N H_2SO_4 . Fig. 10 shows that the leaching efficiencies of yttrium and neodymium from fly ash increased with ultrasonic power from 25 W to 75 W, and 100 W, respectively, but declined from 125 W and 150 W. The simultaneous leaching efficiencies of yttrium are positively correlated with the ultrasonic wave and reach up to 66% and 63%, respectively, when the power of ultrasonic wave was 100 W. Generally speaking, optimal ultrasonic powers for the simultaneous leaching of yttrium and neodymium was 100 W under the condition of two-step leaching process. Although the complete leaching of yttrium and neodymium in fly ash will be further developed, the ultrasonic wave was chosen as the most appropriate method to assist the yttrium and neodymium leaching. Particle size of all raw fly ashes had less than $10\text{ }\mu\text{m}$ and it changes of size was not



(a)

(b)

Fig. 11. Surface morphology of (a) raw ash samples before and (b) residues after the two step leaching of yttrium and neodymium.

TABLE 3
Pore and Surface Area Properties of Raw Ash Samples and Residues After Leaching.

Samples	BET surface area (m^2/g)	Total Pore Volume (cm^3/g)	Average Pore Size (\AA)	Mean particle size (μm)
Raw fly ashes	1.58	0.0029	74.32	6.21
Residues*	16.75	0.0137	32.75	5.93

* residues precipitated by two-step leaching process at ultrasonic powers of 100 W with temperature of 90°C for 4 h, after the first leaching at room temperature of 30°C for 3 h with solid loading of 250 g ash/l of 2.0 N H_2SO_4 .

noticeable before and after two-step leaching process as shown in Fig. 11. It was ascertained that mean particle sizes(d_{50}) of raw fly ashes and residues after two-step leaching were about $6.21\text{ }\mu\text{m}$ ($n=5$, $\sigma=0.21\text{ }\mu\text{m}$) and $5.93\text{ }\mu\text{m}$ ($n=5$, $\sigma=0.18\text{ }\mu\text{m}$), respectively, as shown in TABLE 3.

It can be seen that raw ashes [Fig. 11(a)] are composed of spherical smooth particles whereas after the leaching, the ash residues [Fig. 11(b)] become more mainly consisting of rough and microporous particles. According to analysis of N_2 adsorption and desorption, average BET surface area of raw fly ash was about $1.58\text{ m}^2/\text{g}$ ($n=5$, $\sigma=0.079\text{ m}^2/\text{g}$) before the leaching but it of the residues after the two-step leaching was increased more than 10.6 times, about $16.75\text{ m}^2/\text{g}$ ($n=5$, $\sigma=0.18\text{ m}^2/\text{g}$) as shown in TABLE 3.

In the case of initial fly ash, pore volumes were very low whereas it of residues after the two-step leaching was significantly increased from $0.0029\text{ cm}^3/\text{g}$ to $0.0137\text{ cm}^3/\text{g}$ because ash surface was converted from smooth nonporous state to rough porous state by dissolved most soluble components contained yttrium and neodymium in fly ash at H_2SO_4 solvent. As the micro-pores were newly formed by the leaching of soluble materials, the average pore size calculated by BJH method was definitely decreased from 74.32 \AA to 32.75 \AA . This result conforms that most silica (SiO_2) and alumina (Al_2O_3) components of main components in fly ash were not leachable, but yttrium and neodymium of desired target components were selectively leachable with the SEM result [Fig. 11].

IV. Conclusion

The results obtained in this study was be summarized as follows. Effects of the ultrasonic wave to increase the leaching rate of yttrium and neodymium from fly ash were demonstrated. Leaching efficiency of yttrium and neodymium from fly ash by two-step ultrasonic process combined with the conventional heating mantle was significantly increased than the only conventional heating

process. The first step leaching at room temperature was required to dissolve the yttrium and neodymium in presence of surface layer of fly ash and the second step leaching with aid of ultrasonic power combined to heating mantle was used to speed up significantly the leaching rate of yttrium and neodymium of ash inner layer. Leaching efficiencies of yttrium and neodymium of two-step leaching process have about 66% and 63%, respectively. The optimum conditions for the maximum leaching of yttrium and neodymium from fly ash were ascertained to be the solid loading of 250 g ash/l of H₂SO₄, solvent concentration of 2.0 N H₂SO₄, second step process of temperatures of 30°C for 3 hours and then 90°C for 4 hours with ultrasonic intensity of 100 W.

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