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Apatite/Salt Slurry Emission Control of Post Combustion Flue Gas of Lignite and Coal in Fluidized Bed - Double Circulation Microwave Column Adsorber

Yildirim İsmail Tosun

Abstract

Heated Ca apatite slimes in microwave radiated salt slurries are one of the most promising technologies for advanced fuel energy storage with favorable economic potential and intrinsic properties. The development of solid pellet technology for molten salt is a key issue in the heat transport processing. The apatite phosphate, slurry salt in the slime-salt bath mixes was investigated under microwave radiation heating to result in insoluble sorbent fines dissolved in porous basket. The insoluble consists of noble metal fission products, such as Pb, Zn, Cu. In this study, there have been very few transport studies of wet steam alkali slurry (metal fines-molten alkali salt mixture). Bath ferrite/apatite particle size changed the heat conductivity to salt bath. A major reason is that the retention time in fixed film processes is longer than in solid-gas processes. This allows more time to the heat absorption for cracking to the desorbed persistent compounds. Furthermore, radiated ferrite by microwave allows a sufficient intimate contact between coal and biomass surface pores and gas atmosphere in the furnace due to more pyrolysis gas desorption. Bubbling slurry of sorbent porosity decreases while temperature decreases. There was a critical porous structure of bubbling sorbent bath which is a factor that determines to a great extent both the sorbent rate and degree of boiling it was found that, a porous slurry bath over 45% was more efficient with radiated a low amount ferrite below weight rate of 15% in microwave column.

Keywords: apatite, Ca phosphate, microwave radiation, salt slurries, metal sorption, energy, risk assessment, hybrid sorbent, apatite compost, salt slurries, microwave, column adsorber, toxic emission, phosphate composts

1. Introduction

Exhaust toxic gases coming out of the chimneys in the highly industrialized locations cause hazardous environmental issue. The factories using combustion boilers pollute the fresh air in nature. The industrial development and urbanization and transportation opportunities harm the environment and living things due to combusted fuels. In many countries, power generation is the leading source of air

pollution. While thermal power plants using coal make a significant contribution part of air pollution, diesel generators are also another major ecological concern. Industrial processes in the chemical and mining industries are related with use of solvents producing hazardous emissions as a result of the volatile properties of those chemicals and the combustion outputs pollute the air. In Turkey, The policies and programs that aimed to increase energy efficiency and production from renewable sources have a direct impact on a country's air quality [1].

In environmental impact assessment processes since 2012, the Turkish Ministry of Environment and Urbanization request risk assessment supported financially the project owners to make calculations using owning and operating modeling programs that take into account the long-range and cumulative reducing effects on air pollution in the country [2].

Privatized owning resources for 50 years period income owing and tax free income quarentee for renewable resource use was eliminating incentive uses for fossil fuels, especially coal, and developing policies and incentive mechanisms to prioritize other alternative energy sources instead of fossil fuels.

2. Pollution control on post combustion shower sorption

Conventional coal combustion systems using Stokers or grate chambers are not designed to treat potentially low quality coal and waste in combustion [3–12]. In order to prevent air pollution, combusted boilers with post combustion was become the potential choice eliminate to spread of toxic emissions of coal and wastes [13–15]. The polluting matter of combusted emissions in stack should be controlled for Pb and Hg flue emissions, even as radioactive dust control. Sorbent use as the charcoal was offered and the sorptive property on porosity and the effect of char content was advantageous. The toxic waste and the reactive washing solutions utilized active carbon which resulted in the followed washing equations as below: [6–8].

The dissolution kinetics of sludge/mud particle for Pb heavy metal is followed by equation

$$\frac{dP_{Pb}}{dt} = k_i e^{-t/c} dc \quad (1)$$

Where c_{Pb} Lead contamination mg/l, k the rate of dissolution of lead, i is the reaction style, t is time, Lead matter of coal would affect mainly emission increase pressure content.

The different type of solid sorbents such as Tatvan Pumice, salted pumice and borax, the popped borax soaked CaO were studied in elimination of toxic emissions in high sulfur asphaltite coal combustion [15, 16]. It was found that the reduction of toxic gas emissions can reach as high as 94.52% with soaking CaO and 90% with soaking CaO and oil slurry after 1 h combustion at 750°C, with a 100:1 weight ratio of clay pellet to fuel, 21 wt. % CaO/borax.

2.1 Sorption matter

The large surface used for industrial purposes natural materials [17–20]. Absorbents and adsorbents generally used bentonite; Simectite, Atapulgit, Sepiolite. It can be classified as montmorillonite. The smectite group is one of clay minerals or fire clay activated more called bentonite. Bentonite base mineral montmorillonite is common for the killer and is a commercially used term, at least soft, containing 85% montmorillonite, is an aluminum hydrosilicate with a colloidal

property. When mixed with water, density of a few solid swelling bentonite about 2.5 g/cm^3 . Montmorillonite is calcium clay in common use. Bentonite is a given name on the main content which cation of montmorillonite change mainly with Ca; Atapulgit, $2\text{MgSi}_8\text{O}_{20} \cdot 4(\text{H}_2\text{O}) (\text{OH})$. The palygorskite expressed by the formula $4\text{H}_2\text{O}$ aqueous magnesium, aluminum silicate. Sepiolite is $(\text{OH})_6 \text{Mg}_9 \text{Si}_{12} \text{O}_{30} (\text{OH})_4 \cdot 6\text{H}_2\text{O}$ group is aqueous Mg silicate. In these clay minerals, the channel-shaped pore water bound to crystal structure with layered silicate molecules. The activated clay minerals by dehydrated crystal cavities contain micropores and channels and large surface area due to the possession of various cavity surfaces adsorbing heavy metals and high adsorbing capacities [20–30].

2.2 Sorbent type and utility

The diffusion rate of combustion gases with solid sorbents may influence the adsorption of toxic emissions amount. Especially, increased combustion temperature will reduce the time of solid sorbent diffusion [13–20].

The gas stream amendments, such as shale char carbonized from Şırnak asphaltite containing 52–60% shale by columns under microwave radiation as geo material composted for waste gas treatment should control contaminated effluents concentration. The field studies to evaluate the stability of heavy Hg and Pb SO_x concentrations and salts were balanced as weight increase. The initial objective of this study was to determine the effects of gas flow to sorbent column from the industrial discharge under certain pressure and temperature. In this study, important investigations have been made on composite granules production with Şırnak shale char and apatite ore of Mazıdağ, Mardin, as Ca phosphate feed in order to salt slurry shower in microwave oven 2 M HCl dissolution. The double stage compost sorbent for high level high gas sorption in laboratory water packed bed column adsorption compost system. Although the changes in the structural properties of bentonite after acid activation have been studied extensively in the literature, the studies on Pb adsorption of these samples are rather limited [30–33]. For this reason, the aim of this study is to investigate the thermal Pb and Hg washed adsorption properties of shale after acid modification and microwave activation.

In this study, bentonite and other clays, shale and marly shale of Şırnak utilized regarding absorbance properties, areas of use, production and market conditions. The bulk density of absorbent apatite phosphate changed the amount of moisture and the absorbent capacity. Bentonite and atapulgit absorbance by passing through certain processes was performed and the absorbance was measured at the mechanical strength change has been studied [25–30].

Bentonite with desired surface properties, porosity and hence retention capacity was mainly produced by dry or wet acid activation using mineral acids such as H_2SO_4 and HCl [31–34]. The main purpose in acid activation is to reach the desired structure without disrupting the layered crystal structure of the clay. For this reason, the acid/clay ratio, temperature, acidity, acid concentration, type and duration of activation, clay type and physical properties and amount of activation were important considerations to be taken into account when performing the appropriate activation [35–40].

2.3 Phosphate - clay compost

The Mazıdağı phosphate waste was Ca salt form of the phosphate mineral and limestones with even fluorine apatite [41–45]. The dust waste of calcinations was utilized as necessary to prevent the joint reactive of CaO and F in order to sorptive washing process. The obtained slurries at 10% waste dust by using such as $\text{CaO} \cdot 2\text{H}_3\text{PO}_4 \cdot 5\text{OH}$.

xP_2O_5 and $NaCO_3$. The calcinations product is subjected to acid treatment for artificial fertilizer fabrication. The acid dissolution characteristics after calcinations, Mazıdağı apatite phosphate was mostly acid-soluble in their natural state compared to other phosphate minerals. The study utilized the fine waste, compost 32.81% P_2O_5 –30.98% P_2O_5 , soluble% P_2O_5 27.16%% P_2O_5 parts - calcination at 625°C at last 1/2 hour [38–40].

2.4 Ca phosphate/Asphaltite shale char composite

In this study, bentonite type clay is used as salt slurry with char fine for emission control. The substrate fine of the bentonite/ P_2O_5 granules use as absorbent in 2020s show improved treatment [24–30]. The industrial waste sludges in some tanning and wood board plants, airplane hangars, ship building bench, other production facilities required neutralization and further treatment. In the workshops, grease, oil, water, chemicals and other undesirable substances absorbed by compost of apatite waste/zeolite and char and cleaned [31–37].

2.5 Microwave treated biomass char/apatite phosphate compost

Washing of hazardous waste waters by microwave action efficiencies exceeding the total Fe Pb and Hg contents of sludge increased fast on coal char and wood char were also reported by Tosun [6–10]. Material to be used as powder at porous granule at ultrafine grain size, basic as absorption capacity by the gas emission and other fluids reactive and solvents. High absorption capacity having clay, only to absorb the urea not ventilated, but bad reduce smell and bacteria should avoid. The packed grain size distribution of clay granules it is important that it is usually between 1 and 6 mm is required.

3. Material and methods

3.1 Physical surface properties of sorbent/char

BET specific surface areas of sorbent as tested by N_2 gas permeability. The sorbent was critical on the base of surface properties such as total surface activity, oxygen functional groups, total surface impurities, metal concentrations, dielectric value, free radical concentration and reactivity. The main chemical texture was related to the stimulation of oxidation reactivity. However, in some investigations, the pore size distribution of activated carbon is also likely to affect desorption kinetics.

The salt slurries were mixed with activated clay bentonite at weight rates of 1/8. The head tests are carried out by $CaCl_2$ added 10000ppm slurries to 80 gr bentonite solid. The suspension of 80 gr slurry of clay and apatite was mixed in 1lt water as slurry and give through shower in 5 cm diameter glass columns. Finally microwave radiated glass showered to flue gas compressed at 2 bar retained by exposure to at 160 °C for 4 hours. In addition, these samples were further dried at the same temperature for 1 hour to remove vapor species. The experimentation unit as shown in **Figure 1**. The microwave salt slurry washing tests are followed by flowsheet as seen in **Figure 2**. The surface areas of the apatite, coal char, activated compost and shale clay samples were measured with a Quanta Chromosorb surface analyzer. The surface area was determined by measuring the thermal conductivity using a gas mixture prepared in N_2 and Ar composition and taking into account the BET equation. The sorbent solids compositions and physical quality are given in **Tables 1** and **2**.

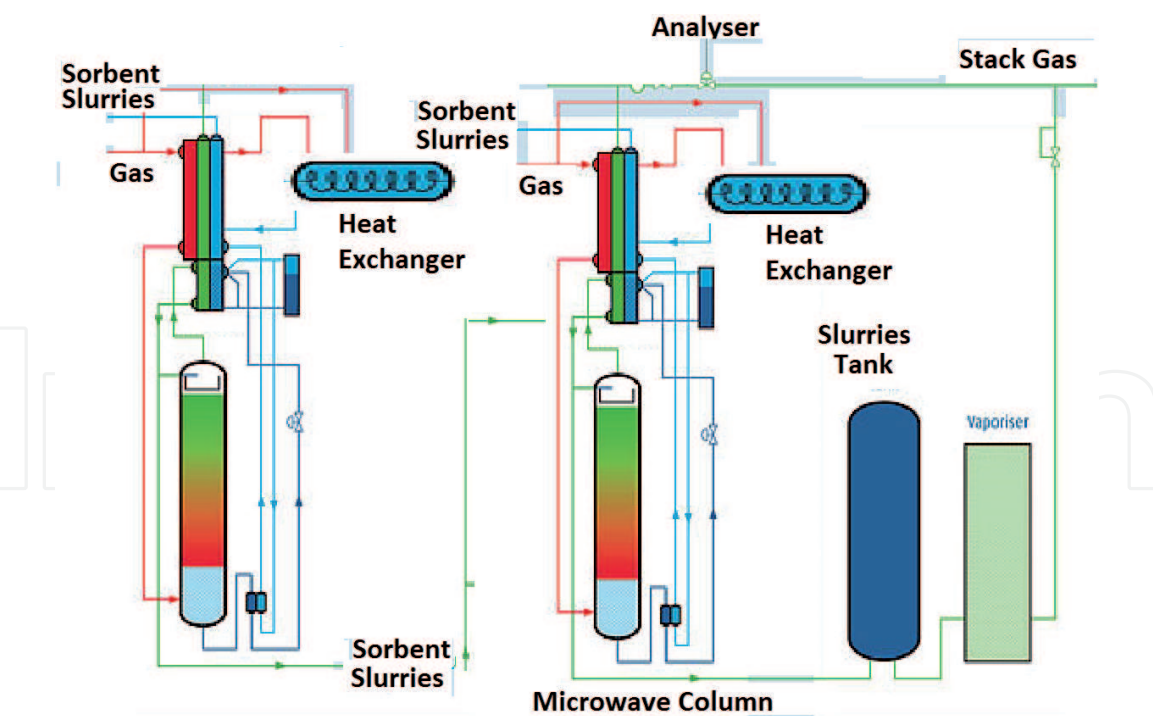


Figure 1.
The schematic view of an washing with microwave recycled by microwave sorption technique.

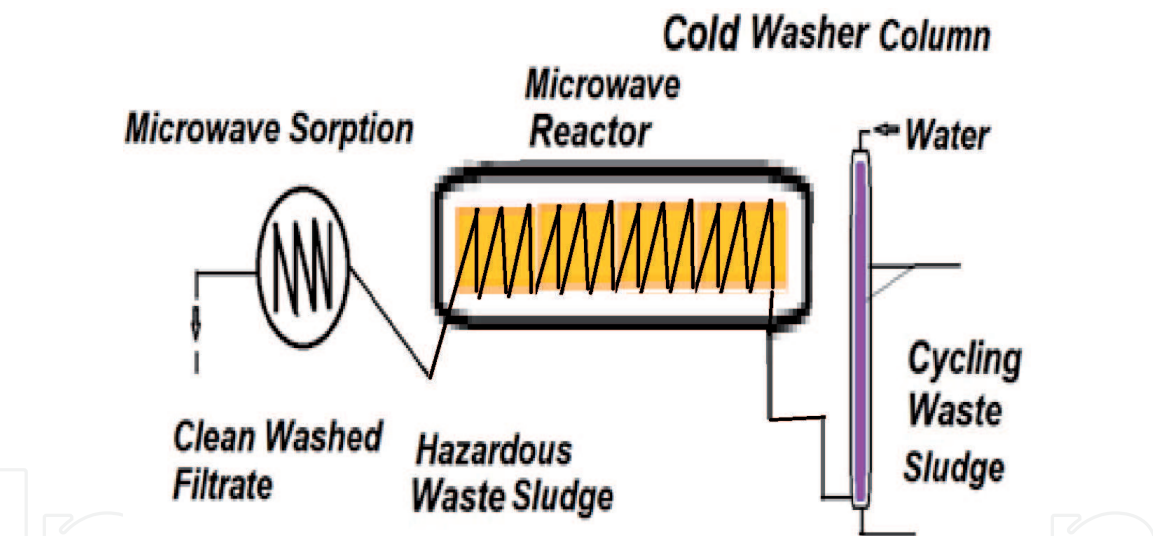


Figure 2.
Studied washing by microwave sorption technique.

	SiO ₂	Al ₂ O ₂	Fe ₂ O ₂	MgO	K ₂ O	CaO	P ₂ O ₅	TiO ₂	LOI*
Kaolin (%)	47.85	37.60	0.83	0.17	0.97	0.57	0.2	0.2	11.27
Şirnak Asphaltite Char Shale	27,4	7.70	10.83	2.17	1.97	10.5	1.4	1.74	5.47
Bentonite	50.45	17.80	6.83	12.17	4.97	3.57	0.1	0.4	7.37
Marly Shale	17.85	11.60	0.83	5.17	3.97	20.57	0.2	0.4	5.27
Fly ash	27.8	13.60	17.83	4.17	2.97	10.7	1.6	1.4	17.27
Apatite Phosphate	0,2	0,1	2,3	2,3	4,3	11,3	23,5	0,1	6,5

*LOI: Loss on Ignition at 1000°.

Table 1.
Sorbent types for washing treatment.

Waste Sorbent Granule	Active Matter,%	BET Area, density
Bentonite	CaO, 23	122, 800–980 kg/cm ³
Sepiolite	NaO, 12	45, 400–700
Apatite Phosphate	P2O5, 16	23, 700

Table 2.
Phosphate, shale and Marly shale granules, physical packed properties.

3.2 Ca phosphate/carbon compost sorbent applications

During the experimental studies bentonite and phosphate samples, Ünye region, was investigated with intermediate type bentonite; pure, purified, tap water and CaCl₂.2H₂O, NaCl, MgCl₂, KCl, FeCl₃ at concentrations ranging from 125 mg to 1000 ppm. Bentonite suspensions prepared by adding waters such as suspensions decanted by sedimentation method for 30 minutes in a 2 lt scale and bentonite slurries were obtained and then necessary test and characterization procedures were applied afterwards.

Decantation was carried out in 2000 ml mills by adding 75 gr bentonite to 1900 ml of water. For a homogeneous suspension mortar, the bentonite water mixture was first subjected to salt slurry mixing cell for 5 minutes.

After the scurvy, the suspension was allowed to stand for 30 minutes after being agitated so that the impurities were precipitated. At the end of the period, suspended bentonite concentrate was removed by titration method and etch was dried.

The same procedure was repeated with synthetic waters prepared by adding salts at concentrations ranging from 125 ppm to 1000 ppm, until the bentonite slurry were obtained in sufficient quantities with salt slurry mixing water.

The layout of the washing cycle is somewhat simpler than that of the lime slurry: there was no water–compost washing column towers connected to the waste sludge, and the washing unit contained one single microwave radiation column can be used to perform the three decantation washing phases: roughing, scraping and cleaning. The variation of the third cycle washing was also more limited recycled by decantation.

The simple production presented as adapted and optimized depending on the target application. The main applications are briefly described in the following sections. Although this review only focuses on state-of-the art commercially available pellet plants, it should be noted that some prospective advanced applications for heat melting of binder are currently being studied, mainly in the form of prototypes proposed as seen in **Figure 3**. These innovative applications include:

- Compost systems, in which the extrusion mold system takes advantage of temperature gradients in wet gradient.
- Compression press systems, where the high load press is used to drive the forming sludge in plant.
- Continuous conversion systems, utilizing the high temperature binding gradients and amounts (of at least 20 C) in slurries to drive a recycle.
- Hot production, where the scraping power of the load system is used to drive the compressive form of hot system.

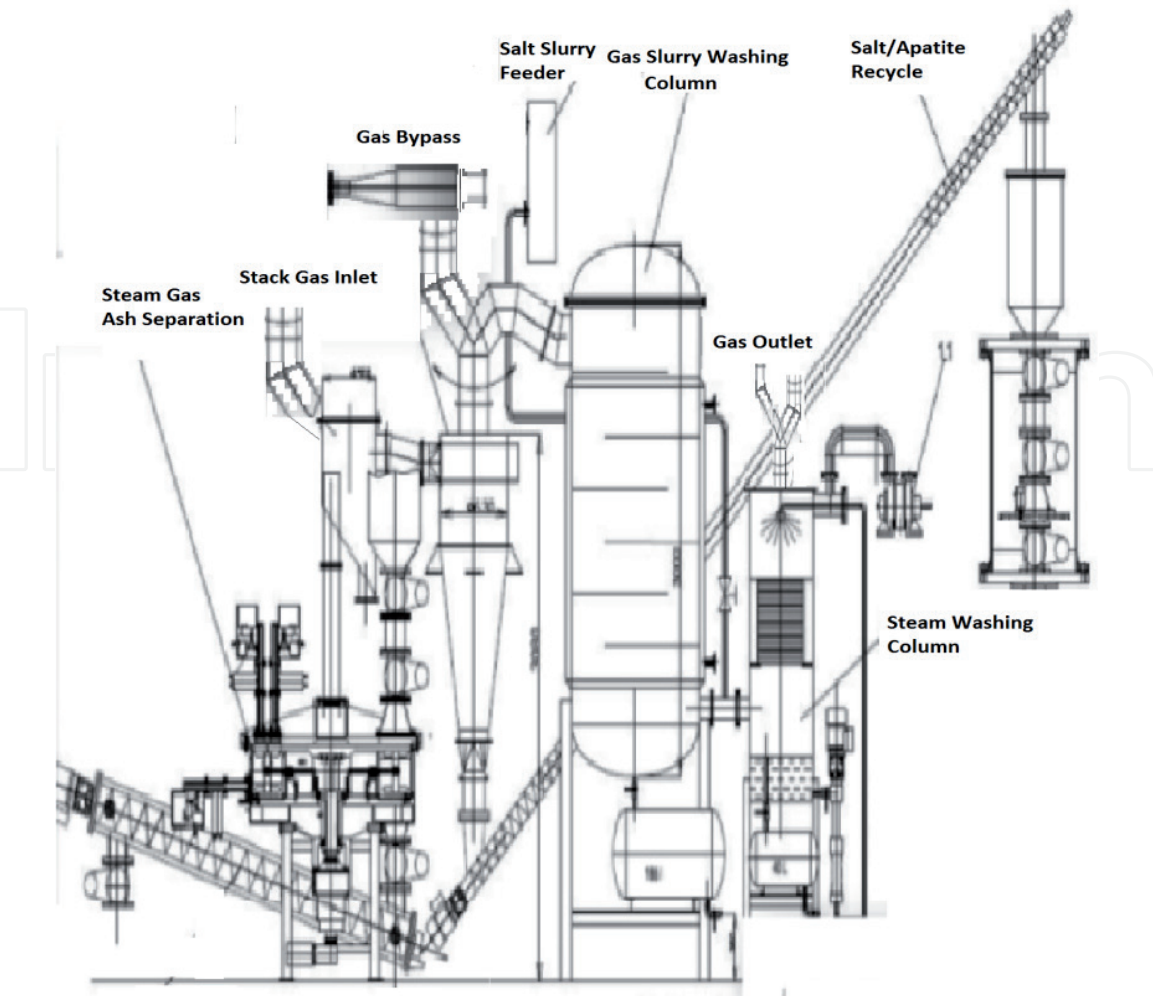


Figure 3.
Apatite and salt slurry gas washing plant for emission control of flue gas, proposed for silopi power plant.

4. Langmuir absorption model

For an overview of these more innovative and prospective applications, the general common method can be given in first order linear concentration change. However sequential sorption cycles changed that trend in sorption of heavy metal contents of gases.

The first order sorption concentration at three stage cycling counted as t time depended by the Eq. 3 below:

$$\ln c_{pb}^{(Ca,PO_3,S_2O_3)} = a + b \left(\frac{k_{1Ca}t}{1!} + \frac{k_{2PO_3}t^2}{2!} + \frac{k_{3S_2O_3}t^3}{3!} \right) \quad (2)$$

$$\frac{dQ}{dt} = k^{(Ca,,PO_3,S_2O_3)} (Q_e - Q) \quad (3)$$

$$Q = Q_e(1 - e^{-kt}) \quad (4)$$

Q_e : Equilibrium adsorption capacity (mg/g)

Q : Time adsorption capacity (mg/g)

t: Time (min)

k1: First-order rate coefficient (l/min)

Apatite phosphate was known to react easily at low pH of 5–6 by a considerable dependence on the layer charge and edge charge pH. Therefore, a decrease in the cation exchange capacity should be expected in locked cavity texture of char with the decrease in pH. Acidic washing was so efficient reaching by Fe holdup of 70 ppm and Lead holdup of 65 ppm with 55% highest yield at 18 hours (Figure 4).

Cation exchange ability was so effective in metal sorption manner. The acidic pH was efficient at criteria in the washing column sorption. It can be seen in the above graph, the pH decreases inversely proportional to the amount of salt added to bentonite suspension, which is much more noticeable when FeCl₃ as activation cavity sites developed.

Bentonite is known to have a considerable dependence on the layer charge and edge charge pH. Therefore, a decrease in the cation exchange capacity should be expected in parallel with the decrease in pH. Acidic washing was so efficient reaching by Fe holdup of 60 ppm and Lead holdup of 41 ppm with 45% highest yield at 18 hours (Figure 5).

The FeCl₃ 20 mg added bentonite solutions showed the change in cation exchange capacity (CEC, milliequivalent gram/100gr) found in the bentonite concentrates and suspensions obtained using the precipitation-siphoning technique, depending on the salt concentration added.

Zeolite exchange ability was so effective in metal sorption manner. The pH was efficient criteria in the washing column sorption. It can be seen in the above graph, the pH decrease improved the amount of lead and Hg char suspension, pH 4 was more noticeable when Pb 65 ppm at high cavity sites developed (Figure 6).

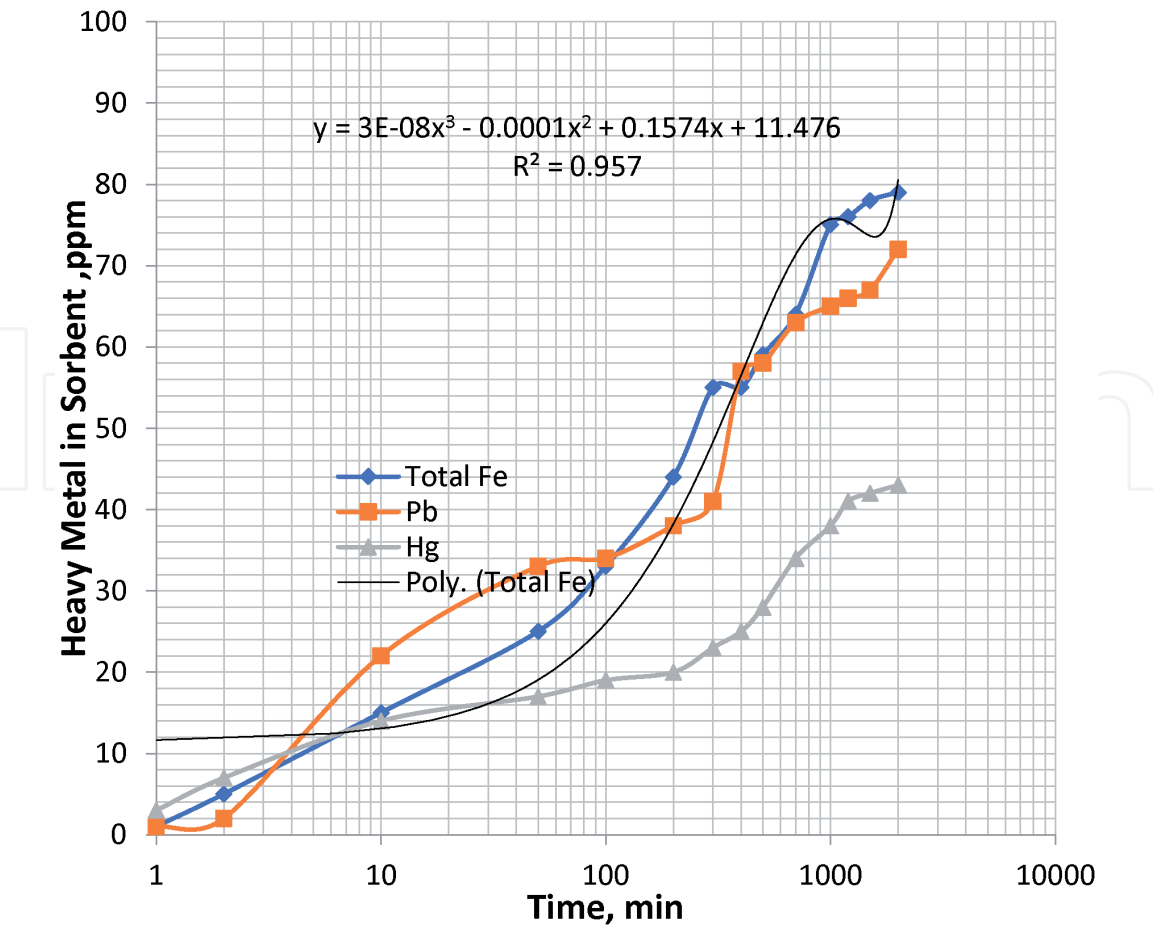


Figure 4. The change in metal sorption depending on the metal concentration incorporated in the phosphate char suspensions.

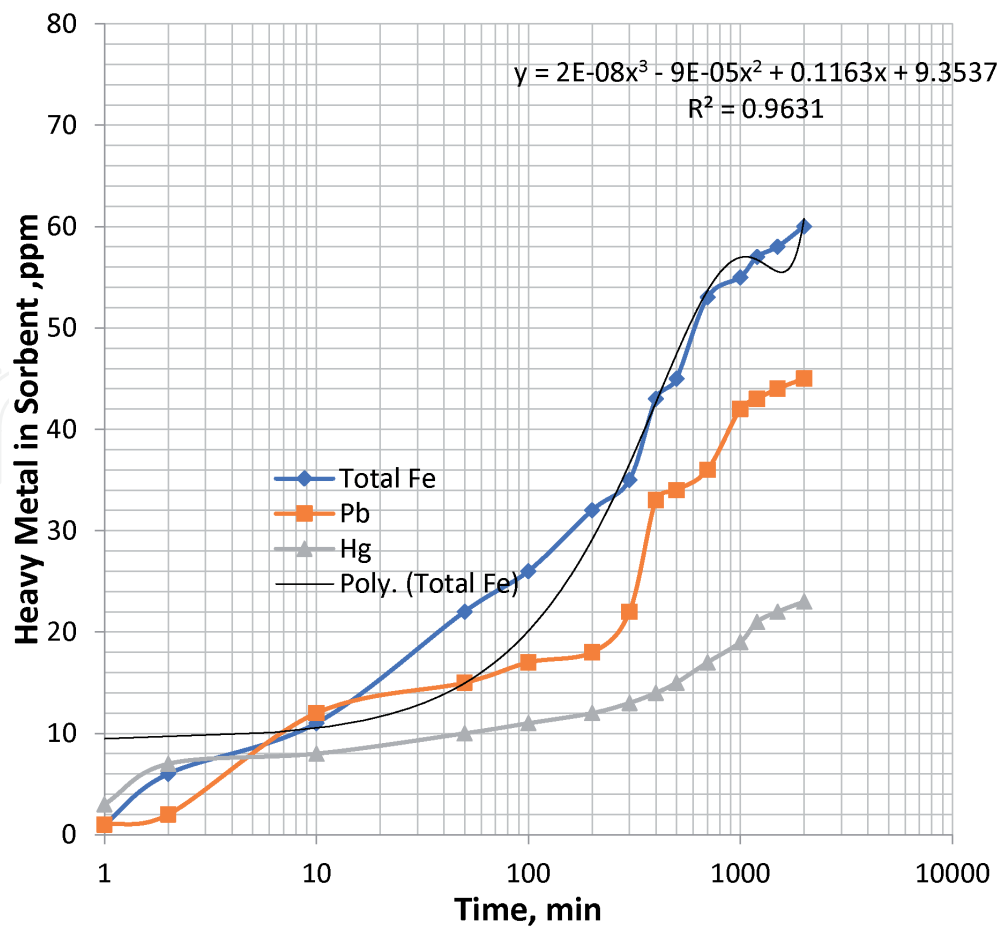


Figure 5.
The change in metal sorption depending on the metal concentration incorporated in the bentonite char suspensions.

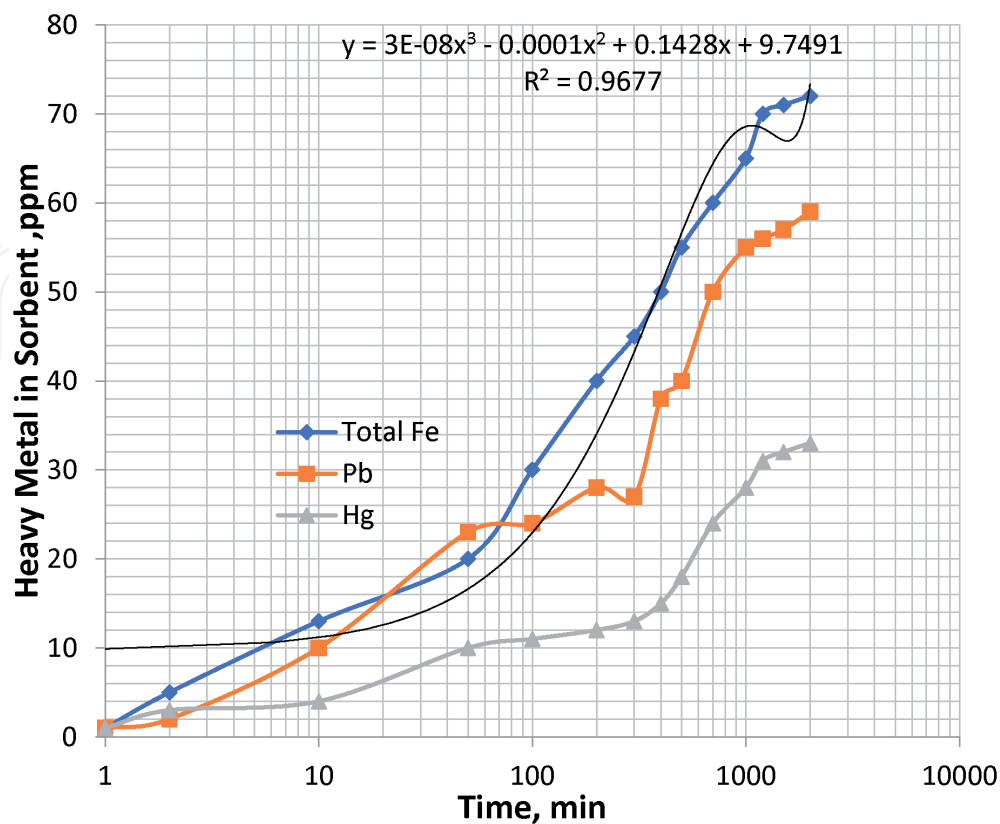


Figure 6.
The change in metal sorption depending on the metal concentration incorporated in the zeolite char suspensions.

Zeolite was known to have a considerable dependence on the layer charge and a decrease in the cation exchange capacity should be expected in parallel with the decrease in pH. Acidic washing was so efficient reaching by Fe holdup of 60 ppm and Lead holdup of 65 ppm with 45% yield at 18 hours.

4.1 Double shower by microwave radiation

The bentonite sample was sieved and a small part of 45 μm was used for the operation. Bentonite samples were activated with 1 and 2 M HCl solutions for 2 h at 90° C using the Batch method (using 100 ml acid solution for 5 g sample). The acid-treated samples were washed with hot deionized water to remove Cl-ions and dried in room condition. 125-1000 ppm salt CaOH_2 , CaCl_2 , NaOH, NaCl, KCl, FeCl_3 was mixed by activated clay samples are mixed in 2 lt slurry mixing cells by tap water.

5. Results and discussion

The current use of absorbent bentonite and new areas of use increase in demand due to outflow. The phosphate resources of Mazıdağı Mardin was gaining in sorbent production and phosphoric acid use in copper ore leaching recently in Turkey, The local sobent alkali and reactive alkali matters is limited due to instead of clay consumption. For this purpose, apathite resources as high rock salt reserves existing in Turkey provided high advantage in use as absorbent and waste mixtures with clay beds. These phosphate waste materials must be fully identified, potential sources should be determined, absorbent purpose should be investigated. In this market, the country economy will provide significant benefits in desulphurization and air pollution control in terms of apathite phosphate instead of fertilizer acid production.

Effective sorptive char in pyrolysis process depend on numerous factors including coal rank in carbonization, the volatile gaseous matter of coal such as presence of hydrogen, carbonyl gas. Char oxidation rate was so stabilizing the desorbence, the settings of optimal diffusion conditions including structure defects (nitrogen, phosphorus, sulfur, etc.), temperature, oxygen content of coal. The optimization of reactivity and cavity concentration ratios improved the adsorption–desorption balance, the residence time and the reactive spatial distribution of sorbent molecules in coal amorph texture. The acidified washing was other parameter determining the sorbent efficiency of carbonized char. The extent of carbonization was much dependent on the site activation affecting sorption rate, its desorption properties and bed meso porosity. As seen in **Figures 3–5**, the carbonized char was a prerequisite step for sorption substrate.

The apathite content rate was widely used to improve the adsorption and catalytic properties of natural bentonites. The impurities, such as calcite and dolomite, are removed from the structure by the treatment of montmorillonite with inorganic acids, the interchangeable cations are replaced by hydrogen ions, and some of the Al ions in the tetrahedral layer dissolve certain cations of Fe, Al and Mg in the octahedral layer.

As a result, acid activation increases the pore diameters of the bentonite surface and the surface area and adsorption capacity up to a certain amount of this application. If the amount of acid used during the acid activation process is excessively high, the Al ions found in the octahedral layer dissolve more and as a result, the mineral structure collapses, leaving a skeleton structure composed of silica solids. This reduces the adsorption capacity of the clay and disrupts its selectivity. Pb is a colorless and Hg. The main sources are fossil fuels such as Pb, acidic mine waters and toxic metal sludges, which are industrial plants and industrial steel washings. During the metal smelting processes and other industrial processes.

The compost of apatite, char and salts has substantially oxidized, resistant to forming crystal crack underway service. This pressurized fluid provides precise, uniform temperature control to 500°C in closed-loop microwave systems where the heat transfer fluid is more than occasionally exposed to air. The fluid is comprised of a unique high-stability base plus high-performance oxidation inhibitor/stabilizer.

5.1 Carbon surface activation

In the sorbent size distribution, 80% of weights of samples were less than 3 mm. The lignite samples were mainly distributed between 1 mm and 3 mm size fractions. The effect of particle size of solid sorbents were investigated over the combustion of Şırnak Asphaltite char shale and bentonite carried out well on acidic mine water of copper mine in Siirt substance subjected to reaction with salt/char slurry in sorp-tion, as shown in **Figure 7**.

Although metal diffusion on sorbent from salt slurry was believed to be the primary mass transport process in the absorption chamber, complex reactions proliferated the alkali clusters below 1-2 mm size and exothermic oxidation reac-tions increased toxic substances in the effluent form, a relatively porous structure of bentonite clay interstitial spaces and cracks reduced below 1 mm size. The hazard-ous heavy metal concentrations reacted adsorbate then adsorbs to the sorbent in a certain amount that is equal to the amount of previous adsorbate that was partially degraded on the surface of the bentonite clay and stuck covered toxins, along with avoiding chelating organic matter related carbonyl and amine.

Initially, most of the toxin removal occurs through chemical adsorption of the toxins to the apatite fine at weight rate of 5 % in fluidized bed where the combus-tion temperature was in the combustion phase below 750°C that lasts approximately 2–3 mins.The removal efficiency of 40–90% were reported during this temperature range. Total organic toxin substances were completely slightly at efficiencies of 75–90% in the late combustion phase. A common industrial combustion to control the emissions pro combustion stage lime washing involves backwashing with air and hydrated lime water rinse. Process variables include the control backwash rate,

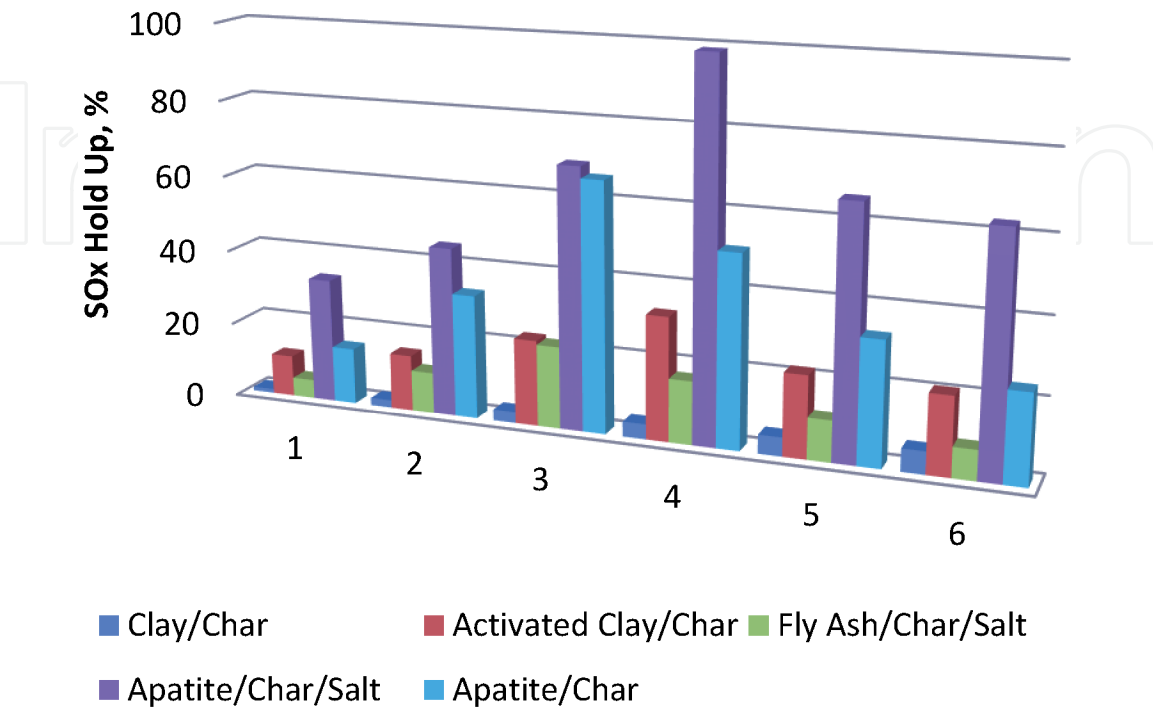


Figure 7.
Apatite and salt act on emission control for flue gas.

surface wash rate/duration, time sequence and duration of backwash. Clean filtrate is pumped back into the bottom of the column during backwashing.

6. Conclusions

The stack gas washed and ESP dust controlled exhaust gas given to vertical column washing by the slurry salt providing toxic metal washing on based acidified digestive mass transfer. This was provided by microwave heating on reactivity of different absorbent materials and amount conditions on activated cavity at Langmuir linear trend. The same situation was also available in the case of other sorbent char lead and CS, COS gas. The apathite material improved packed bed sorption reaction rate. The zeolite activated cage was influenced by the unit surface area, which varied with the internal pore type of the zeolite sorption reaction and the adsorption metal washing cycle.

The power plants using Şirnak asphaltite in fluidized bed combustion chamber produced fly ash slurries contaminated water control, management practices and emission control water washings and metal solutions in treatment system.

The column activated by microwave dissolved washing of exhaust gas at atmospheric pressure happened in porous basket column. The insoluble consists of metal outputs, such as Pb, Zn, Cu. In this study, there have been very few transport studies of apatite char salt slurry (exhaust gas- salt mixtures. There is a great green concern prompting clean air in order to control air and washing waters so that the research study controlled and avoided hazardous toxicity limits of residual gas streams and contaminants of heavy streams by sorption local clay and Ca phosphate compost. The contamination rate changes to those based on weight concentrations and wetness.

In the pH measurements made, the pH value of 5–3 in washing hazardous waste water finally at the last washing column decreased to 5, depending on the concentration of salt content of sorbents in the water.

In the three cycled stage microwave activated washing test measurements made with tap water, it was found that 73 mg/l(ppm) in apatite salt slurries/asphaltite char shale decreased to 53 mg/l(ppm)/in last column output. Likewise, the washed waste waters obtained after 100 min washing by microwave activity using sodium salts softened flow with below 1 mm sized sorbent packages showed reductions in Pb,Hg and Fe at 47% performance.

In water aliquate had the 24 ppm Pb,5 ppm Hg and 57 Fe values, which Pb reduction rates of sorption at Langmuir model with nitrate washing rate was 0,73 ppm/min.l, Hg and total Fe reduction rate decreased to 0,43 ppm/min.l and 0,23 ppm/min.l,respectively.

The pH increased at washing was efficient in heavy metal sorption, the swelling index decreased, the loss of filtration increased negatively, and viscosity decreased by the addition of sodium. In the obtained data, it was observed that sorption manner of bentonite negatively affected by foreign ions in washing water for the activation especially total iron ion.

Abbreviations

Greek symbols

a	affinity parameter of the Langmuir isotherm ($L\ mg^{-1}$)
b	stoichiometric constant defined by

B	reactant solid defined
Bi_m	Biot number for mass transfer
C_i	concentration of manganese in the bulk external phase of stage i (mg L^{-1})
C_0	feed concentration of manganese in the column (mg L^{-1})
D_{ef}	effective diffusion coefficient ($\text{m}^2 \text{s}^{-1}$)
F	objective function
h	fixed bed height (m)
k_e	mass transfer coefficient in the bulk external phase (m s^{-1})
k_r	reaction rate constant for heterogeneous systems (m s^{-1})
N	number of stages
Q	volumetric flowrate ($\text{m}^3 \text{s}^{-1}$)
q_i	concentration of immobilized manganese within the adsorbent particle at stage i (mg g^{-1})
q_m	theoretical maximum adsorption capacity of the Langmuir isotherm (mg g^{-1})
r	radial distance from the center of the particle, $0 < r < R_p$ (m)
R	radius of column (m)
R_p	radius of adsorbent particle (m)
R^2	determination coefficient (–)
$r_{c,i}$	unreacted core radius at stage i (m)
t	time (s)
V_i	volume of stage i (L)
α	backmixing coefficient (–)
φ	column hold-up (–)
ρ	density of adsorbent particle (g m^{-3})
τ	mean residence time of fluid in the column (s)

Author details

Yildirim İsmail Tosun
Şırnak University, Engineering Faculty, Mining Engineering, Department, Şırnak,
Turkey

*Address all correspondence to: yildirimismailtosun@gmail.com

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