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Highly Attrition Resistant Zinc Oxide-Based Sorbents for H₂S Removal by Spray Drying Technique

Key Words: Hot Gas Desulfurization, Attrition, Sorbent, Spray Dry, Fluidized-bed.

Introduction

Coal-fired power plants dominates electricity generation in Korea taking 29.4% of the total generation (54.3 GW) as of 2002. Coal will play an equally important role in electric power generation for the next 15 years, which is based on the 5th long-term electric power supply plans established in 2000 by the Ministry of Commerce, Industrial, and Energy of Korean Government. Korea emphasizes on the use of alternative energies including CCT to resolve emissions from the use of fossil fuel, especially coal. Korea has plan to construct three 300

MWe scale CCT power plants in 2007, 2013 and 2014. IGCC project, as an alternative energy policy, mainly sponsored by government and Korea Electric Power Company (KEPCO) was initiated in 1994, which focused on the key technology developments in IGCC. Hot gas desulfurization was selected as a key technology, which will have benefits including higher plant efficiency (>45%), lower capital cost, and less environmental impact (DOE, 1995)

Hot gas desulfurization in Korea has focused on a fluidized-bed hot gas desulfurization process and its sorbent development. The desulfurization process of fluidized-bed/transport reactor has several potential advantages over fixed-bed and moving-bed processes. These advantages include excellent gas contact with smaller sorbent particle, ease of sorbent refill and removal, ease control of exothermic regeneration reaction temperature, and continuous steady operation (Gupta et al, 1996). Gupta and coworkers (Gupta et al, 1996 & 1998) suggested that the sorbents for transport reactor applications must be highly attrition resistant, good sorption capacity with fast chemical reactivity within a few contact time (1-2 sec), low temperature initiation of regeneration and good regenerability, and good flowability.

With adaptation of fluidized-bed/transport reactor technology to hot gas desulfurization, spray-drying technique not only provides sorbent particles of highly uniform size, spherical shape and texture, but also is readily accessible to addition of sorbent ingredients during slurry preparation steps and scale up to industrial production.

KEPRI has been tried to prepare a series of spray-dried regenerable ZnO-based sorbents which are suitable for fluidized/transport desulfurization process (Ryu et al, 2001). This paper will describe ZAC 32N (2 kg scale) and ZAC 32SU (16 kg scale) sorbents recently developed at KEPRI.

Objectives & Approach

Primary issues for the fluidized-bed/transport reactor process are high attrition resistant sorbent, its high sorption capacity and regenerability, durability, and cost. The overall objective of this project is the development of a superior attrition resistant zinc oxide-based sorbent for hot gas cleanup in integrated coal gasification combined cycle (IGCC). Sorbents applicable to a fluidized-bed hot gas desulfurization process must have a high attrition resistance to withstand the fast solid circulation between a desulfurizer and a regenerator, fast kinetic reactions, and high sulfur sorption capacity. The oxidative regeneration of zinc-based sorbent usually initiated at greater than 600°C with highly exothermic nature causing deactivation of sorbent as well as complication of sulfidation process by side reaction.

Focusing on solving the sorbent attrition and regenerability of zinc oxide-based sorbent, we have adapted multi-binder matrices and direct incorporation of regeneration promoter. The sorbent forming was done with a spray drying technique that is easily scalable to commercial quantity.

Project Description

This project mainly sponsored by Korean government is a joint effort with the Korea Institute of Energy Research (KIER), where develop fluidized-bed reactor processes for hot gas desulfurization, and other universities subcontracted to KIER support either sorbent and process development. KEPRI and KIER both are subcontractors to Institute of Advanced Energy (IAE). IAE, now non-profit independent organization and a main contractor of government at Phase III stage of IGCC project, has developed a 3 ton coal /day scale gasifier system. This project entered final year of Phase III stage (2000-2002).

Requirements of commercial grade sorbents. Because of the competitive nature of electric generation technology, and the limited industry confidence in dry sorbent technology, a steady performance and low cost of sorbents are essential for an advanced IGCC plant industry to adopt hot gas desulfurization technology. Comprehensive analysis of literatures regarding to the fluidized-bed processes and our own experiences indicated that current technical challenges in the development of sorbents for fluidized-bed application are the sorbent attrition and high H₂S sorption capacity with fast reaction kinetics, followed by a smooth regeneration reaction.

Such properties of sorbents are necessary to minimize the impact of sorbent costs on operation of hot-gas desulfurization process in an IGCC plant. Among the sorbent properties, Table 1 summarized the basic requirement of commercial grade sorbents for fluidized-bed applications (Gupta et al, 1998).

During regeneration, the sorbent should be able to initiate regeneration reaction at lower temperature (i.e. ≤ 500 °C) than that of desulfurizer and proceed smoothly to maintain sorbent activity during continuous solid circulation modes. It would be better that desulfidation and regeneration reactions proceed at similar temperature (i.e. 550 °C) to make the process operation easy.

Sorbent Preparation. We have adapted multi-binder matrices and direct incorporation of regeneration promoter to improve attrition and regenerability of sorbent. The sorbent forming was done with a spray drying technique that is easily scalable to commercial quantity. A spray drying process of sorbent includes the selection of raw material, the comminution of raw materials, a colloidal slurry preparation, a spray drying, and calcination steps. Among these steps a colloidal slurry preparation is of most importance to yield sorbent particles suitable to fluidized-bed application. A colloidal slurry have to be flowable, homogeneous, dispersed and stable, which are controlled by concentration, viscosity, pH, and zeta potential of slurry with an addition of organic additives such as dispersants. With the direct incorporation of regeneration promoter into slurry, a number of formulations with multi-

binder matrices prepared by spray drying met the criteria of fluidized-bed application. One of them identified to ZAC 32N (2-kg base) and 32SU (16-kg base) sorbents.

Sorbent Characterization: Physical properties of sorbent prepared by spray-dried technique were characterized and screened based on the criteria in Table 1 by microscope or SEM, attrition tester (ASTM 5757-95), tap density meter (ASTM 4164-88), and size analyzer (or sieve). Once they meet the criteria in Table 1 and then chemical reactivities of sorbents are investigated by a TGA and a high-temperature and high-pressure micro-reactor.

TGA Chemical Reactivity. Chemical reactivity of sorbents was assessed using a simultaneous thermal analyzer (Rheometric Scientific STA 1500) that has dual functions of thermogravimetric analysis and differential scanning calorimetry. Scope test for sulfidation were done in the range of 300-800 °C with heating rate of 5 °C /min while scope test for regeneration in the range of 300-850 °C with heating rate of 10 °C /min. The base line test was done with the similar method to the scope test except the temperature of sulfidation (500 °C) and regeneration reaction (650 °C). During the 1.5 cycle TGA baseline test, the first 30 min before each sulfidation correspond to expose to simulated clean coal gas (without H₂S) to establish a weight baseline. Amount of samples used for scope and base line tests were 10 mg and total flowrate was 50 ml/min. TGA test conditions and gas compositions were summarized in Table 2.

Micro Reactor. KEPRI's micro reactor facility is shown in Figure 1. Micro reactor is house-designed for 1-3 ml (\leq 4g) scale reaction tests up to 850 °C and 35 bar under corrosive environmental atmosphere. Two 10 ml reactors that have coned and treaded nipples at both ends are connected by coned and treaded union coupling with grands and colors. The threads of grand are right-hand while the threads of the collar are left-hand to prevent rotation of the collar during assembly. It is very simple and easy to disassemble and retighten indefinitely. Micro reactor system did not have a separate preheater but the double deck reactor in an electric furnace. Depending on the gas flow direction such a configuration can be used for fixed-bed (down-flow) or fluidized-bed (upflow) mode being one of reactor acted as a preheater. The inlet or out H₂S gas was measured by using a H₂S continuous analyzer, Advance Optima Limas-11UV (ABB-Hartmann Braun) that automatically switch from 0-1000 ppmv range to 0-3% range. The continuous H₂S analyzer also have built-in SO₂ detector and software program (Model Optima SMT & Optima Plant Pilot) to correct H₂S signals for interference induced by SO₂ signals into H₂S signals. However this model did not have any way to compensate for the interference induced by COS. The SO₂ and O₂ gases were measured by using a continuous SO₂ & O₂ analyzer, Advance Optima Limas-11UV & paramagnetic Magnos 16 model. The respective continuous SO₂ and O₂ analyzer has a

function of automatic range switching from 0-1000ppm to 0-2vol% to 0-15 vol% for SO₂ and from 0-10vol% to 0-25 vol% for O₂. H₂S, COS, and SO₂ gases were also measured every 5min for H₂S and COS gases and every 7 min for SO₂ gas in order to check more accurate concentrations of gases using GC with a flame photometric detector with detection limit of 1ppmv H₂S level.

The multicycle micro reactor tests were performed with test conditions and gas compositions summarized in Table 3 and Table 4, respectively.

Results and Discussions

Preparation. The dispersion and zeta potential of slurry are of important parameters to predict the sorbent shape and attrition properties at a given binder matrix. As a rule of thumb, a zeta potential of at least of ± 30 mV is necessary for long-term dispersion stability of slurry. Zeta potentials of ZAC 32N and 32SU slurries are -129 and -3 mV, respectively. The rather low value of zeta potential was mainly attributed to the improper mixing of a large amount of slurry in the lab. It turned out that the shapes of ZAC 32N particles are spherical while those of ZAC 32SU particles are partly doughnut-like as shown in Figure 2. It is very plausible that there is close relationship between stability of slurry and the shape of spray-dried sorbents since the low absolute value of zeta potential tend to coagulate or agglomerate particles in the slurry.

The spray-dried ZAC32N and ZAC 32SU sorbents were calcined at several different temperatures. For clarity and comparison purpose, the calcination temperature of sorbent is represented by ZAC 32N(650) that means the 650 °C calcined ZAC 32N sorbent.

Physical Properties. The Table 5 shows the physical properties of ZAC 32N and ZAC 32SU sorbents. The scope test for calcination was performed in the temperature range of 80 - 1000 °C with heating rate of 5 °C/min. The calcination curve (not shown) revealed a multi-stage endothermic weight loss occurring in the temperature region of 80-650 °C due to the dehydration and decomposition of organic additives. The steady state was observed in the range of 650-850 °C and a slight weight gain occurred thereafter. Thus ZAC 32N sorbent was calcined at the three different temperatures to investigate the possible thermal impact encountered the actual operations. ZAC 32SU sorbent was calcined only at 700 °C based on the performance of ZAC 32N sorbent. The morphology and size of fresh sorbents govern by the great extent to what the temperature employs at calcination steps. For example, the size and BET surface area of ZAC 32N(850) sorbent markedly reduced by 30% and 90% relative to those of ZAC 32N(650). The porosity of ZAC 32N sorbent is not much affected by the calcination temperature and maintains more than 60%. The porosity of ZAC 32SU is much higher than that of ZAC 32N.

The attrition resistance of catalysts or sorbents for fluidized-bed application is used to

measure using a three-hole air-jet attrition tester based on the ASTM 5757-95. The attrition was determined at 10 slpm over 5h as described in the ASTM method. The attrition index (AI) is the percent fines generated over 5h. The corrected attrition index (CAI) is the percent fines generated only over 4 h, that is, the fines generated over the first 1h was subtracted from a total fine generated over 5h and from a total amount of sample used initially. The AI (CAI) of Akzo and Davison FCC catalysts as references are 22.5(18) and 18.4(13.1), respectively. With multibinder matrix, attrition of sorbent is greatly improved. One of features for ZAC 32 and 32SU sorbents is that the attrition resistance along with other important parameters such as bulk tap density also increases as the calcination temperature increases. AI and CAI of sorbents are comparable to that of the reference FCC catalyst as shown in the Figure 3. Overall the important physical parameters of ZAC 32N and ZAC 32SU sorbents satisfy the criteria (Table 1) of fast fluidized-bed applications.

TGA. The TGA scope test for sulfidation reaction was performed with heating rate of 5 °C/min in the range of 300-800°C as shown in Figure 4(top). The sulfidation reaction of ZAC 32N(650) sorbent initiated at 340 °C and reached the target sorption capacity (10 wt% S) at 450 °C. The 800 °C sulfur load of ZAC 32N(650) was 20.2 wt% S close to the theoretical value. The sulfidation reaction of ZAC 32N(750) initiated at 440 °C and its 10 wt% S sulfur load occurred at 530 °C. The 800 °C sulfur load of ZAC 32(750) was 19.6 wt% S. The TGA chemical reactivity of ZAC 32N(750) was less reactive than that of ZAC 32N(650) sorbent (see Figure 4). From the sulfidation scope test, sulfidation temperature can be in the temperature range of 450-600 °C.

Figure 4 (bottom) also shows the TGA regeneration scope test with heat flow for ZAC 32N(750). The ZAC 32N(650) sorbent also showed a similar regeneration profile. The TGA regeneration scope test with neat air was performed in the range of 300-850 °C with heating rate of 10 °C/min. The regeneration profile in Figure 4 shows unusual features that are not observed in other sorbent formulations at KEPRI. The onset of regeneration reaction occurred at the rather low temperature around 400 °C. Such initial regeneration reaction accompanied with progressive weight gain rather than weight loss which is usual case for the most of formulated ZnO-based sorbents. The vigorous exothermic regeneration reaction begin at around 500 °C and within 15 min or so the heat flow reaches its maximum value at near 650 °C. As the heat of reaction vigorously evolves the TGA weight loss become obvious but again weight gain become dominant beyond 680 °C. This results indicate that the regeneration reaction with heating rate of 10 °C/min is complete within 15 min or so and the ZAC 32N sorbent formulation has at least one component that is responsible to the competitive weight gain channel against the weight loss one. The weight gain channel should be closely related to the formation of metal sulfate that might not easily decompose below 850 °C. The rate of metal sulfate formation seems to depend proportionally on the SO₂

evolution and temperature in the regeneration reaction. The heat flow profile during the regeneration scope test suggests that the regeneration reaction at steady temperature can proceed at the temperature range of 500 –650 °C.

The 1.5 cycle TGA base line test was performed base on the scope test described above. The sulfidation and regeneration temperatures were 500 and 650 °C, respectively. The simulated dry KRW gasifier gas compositions containing 3vol% H₂S was used for sulfidation reaction and neat air for regeneration reaction. The 650 °C regeneration temperature was chose to investigate the performance of sulfidation reactivity of ZAC 32N(750) sorbent. Figure 5 shows the initial 1.5 cycle TGA chemical reactivity and the following 3 cycle TGA chemical reactivity to demonstrate the unusual behavior of regeneration reaction observed at the scope test. As the first regeneration reaction performed right after 1 cycle sulfidation reaction, TGA curve did not come back to its baseline but it rather slightly increased and reached the steady state. The second sulfidation reaction leaded to a weight gain as much as the first sulfidation reaction. After manually resetting the second sulfidation TGA curve to the baseline, the successive 3 cycle sulfidation-regeneration reactions were performed. From the second regeneration reaction, typical TGA weight loss curves were observed although the respective baseline tends to increase at every regeneration step possibly due to residual sulfate formation. During the 4.5 cycle TGA test, the respective sulfur load was not changed much and maintained 11.4 ± 0.5 wt%. These results lead to the conclusions that the sulfate formation did not adversely affect the chemical reactivity of ZAC 32N(750) sorbent and the sulfate formed by other metal components that is neither active metal oxide or regeneration promoter. It also indicate that sulfate formed during regeneration step did not decompose at near 650 °C. The 1.5 TGA sulfur loads at 500 °C for ZAC 32N(650, 750, 850) and ZAC 32SU were 19.6, 13, 12, and 15 wt% S respectively. All the TGA sulfur loads of sorbent developed meet the target value of 10 wt% S although the TGA sulfur load tend to decrease proportionally as the calcination temperature increases.

Multicycle Micro Reactor Test. The multicycle tests were carried out with ZAC 32N(650) and ZAC 32N(750), and ZAC 32SU(700). The multicycle tests of sulfidation and regeneration reaction at 550 °C and 294 psig were performed in a fluidized-mode to investigate the adaptability of the fluidized-bed applications and to reduce the thermal impact on sorbents during the regeneration cycles. The space velocity and the contact time were 2.53 cm/s and 2 s. Regeneration for ZAC 32N(650) was performed with dry neat air at 550 °C except the 2nd cycle with 11% O₂, the 3rd cycle with 7% O₂, 7th – 10th cycles with 10% H₂O and air. The main purpose of the changes of regeneration gas was to determine an appropriate set of test conditions for successful regeneration. The representative H₂S breakthrough curves for ZAC 32N(650) are shown in Figure 6. The breakthrough time defines as the time at which the effluent total sulfur gas or H₂S concentration reaches at 200 ppmv. At every sulfidation

cycle, introduction of H₂S gas was turned off right after the effluent H₂S concentration reached at 200 ppmv. The 1st cycle sulfidation showed the 21 min breakthrough time corresponding to the sulfur sorption capacity of 8.3 wt% S. But more than 30% reduction of sorption capacity was observed at the 2nd cycle sulfidation. Modification of regeneration procedure, reduced oxygen content from 21% to 11% for 2nd regeneration to 7% for the 3rd regeneration, did not improve or recover the initial sulfur sorption capacity. For the 4th –6th regeneration cycle, dry neat air was used again and 5.6 wt% S sulfur sorption capacity was maintained throughout this period of cycle test. The 7th sulfidation reaction followed by three successive dry air regenerations nearly recovered the initial sorption capacity. When 10% steam with neat air balance was used for the 7th-10th regeneration cycles, sorption capacity was dropped to 3-4 wt% S. Some agglomerates found from the sample after the 10th cycle regeneration although sorbent particles were intact by visual examination through the microscope.

The temperature rise in sorbent bed during each regeneration cycle was in the range of 5-20 °C. The abrupt temperature increase of sorbent bed due to the vigorous exothermic regeneration reaction is observed within a couple minute after introduction of regeneration gas. The sorbent bed temperature was stabilized back at 550 °C within 5 min or so. The temperature increase, less than 20 °C in a short period of time, would not be enough to degrade sorbent. The pre-breakthrough concentrations of H₂S were less than 10 ppmv and tended to increase toward the breakthrough point at each sulfidation cycle. We did not observe any obvious SO₂ slippage in the sulfidation reaction. Considering agglomerate formation and other possible deactivations such as sintering caused by chemical transformation and thermal impact, the performance of ZAC 32N(650) showed excellent promises maintaining sorption capacity more than 5 wt% S except 9th and 10th cycle.

Figure 7 shows the envelope of the breakthrough curves for ZAC 32N(650), ZAC 32N(750), and ZAC 32SU sorbents. Regeneration for ZAC 32N(750) was performed with dry neat air at 550 °C except the 7th cycle with 10% H₂O and air, the 8th & 10th with 10% H₂O and 3% O₂, and the 9th with 7% O₂. Regeneration for ZAC 32SU was also performed with dry air at 550 °C except the 8th with 10% H₂O and air. The temperature rise in the regeneration reactions was below 15 °C (max. 32 °C at the 3rd regeneration cycle) for ZAC 32N(750) sorbent and was relatively high for ZAC 32SU sorbent, which often reached at about 40 °C. It is not clear at this time why the higher temperature rise occur during the regeneration reaction even if the sorption capacity of ZAC 32SU is relatively lower than others. The performance of ZAC 32N(750) and ZAC 32SU were by and large similar to ZAC 32N(650) as described above.

Post-Test Characterization. Table 6 shows physical and chemical properties of fresh sorbent and sorbent removed after 10-cycle regeneration in the KEPRI micro reactor. One of the

features for reacted sorbents is the reduction of the BET surface area that could be attributable to the chemical transformation and thermal sintering. As discussed before (see Table 5), the BET surface area of the ZAC 32N(850) is reduced as much as 90% of the ZAC 32N(650) indicating that the thermal sintering is one of the dominant paths. But this is not the case under 10 cycle micro reactor tests since the maximum temperature during the regeneration is usually less than 40 °C and all the sorbents tested here were calcined at higher temperature than the reaction temperature. The BET surface area reduction observed here is more likely attributable to chemical transformations that could lead to pore plugging and the secondary pore development due to the formation of metal sulfide, metal sulfate, and others. Despite of the marked BET reduction, Hg porosities for reacted sorbents were well over 55%, which is the good indication of accessibility of active sites.

Application

We have demonstrated that the highly attrition resistant sorbents applicable to transport reactor can be successfully prepared by spray drying technique with multibinder matrix. We are routinely used to prepare the 2 kg solid base scale sorbents and with some limitations of lab equipment we can scaled up 32 kg solid batch of sorbents. The ZAC 32N (2 kg batch) and ZAC 32SU(16 kg) were extensively characterized and showed a good promise to be suitable for transport applications. For examples, the shape, size and size distribution, bulk tap density, and attrition resistance all are well qualified for transport-reactor process. The chemical reactivity also appears to have desirable characteristics for effective desulfurization of syngas stream in the temperature range of 450-550 °C. The bench scale test of ZAC 32SU at KIER's transport-fluidized bed desulfurization process were successfully carried out for continuous 160 h with steady solid circulation (54.6 kg/h), which showed a 99%+ desulfurization and reasonable regenerability (Yi et al, 2002).

Future Activities

Sorbent development work will continue with particular emphasis on the inhibition and/or retardation of shrinkage by modifying preparation methods and improvement of regenerability by modifying compositions and morphology control.

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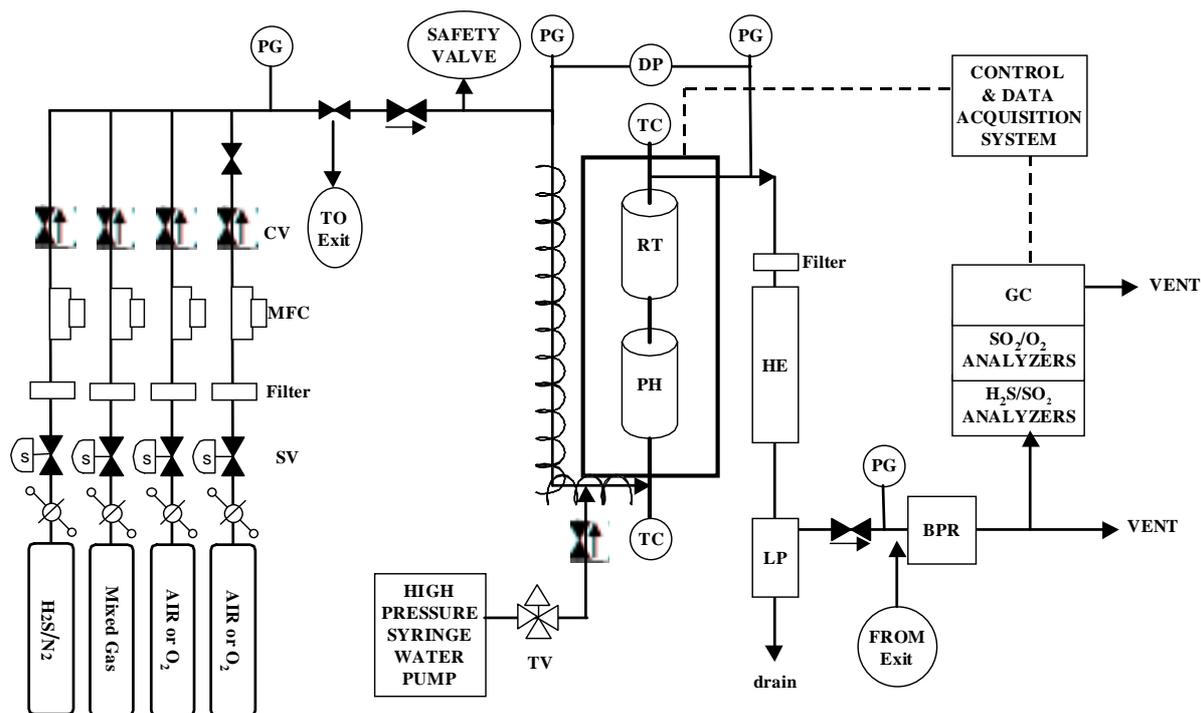


Figure 1. The Schematic diagram of KEPRI Micro Reactor System

SV: solenoid valve, MFC: mass flow controller, CV: check valve, TV: three way valve, HE: heat exchanger, LP: lockout port, RT: reactor, PH: preheater, TC: thermocouple, PG: pressure sensor, BPR: backpressure regulator or automatic pressure control valve, DP: differential pressure.

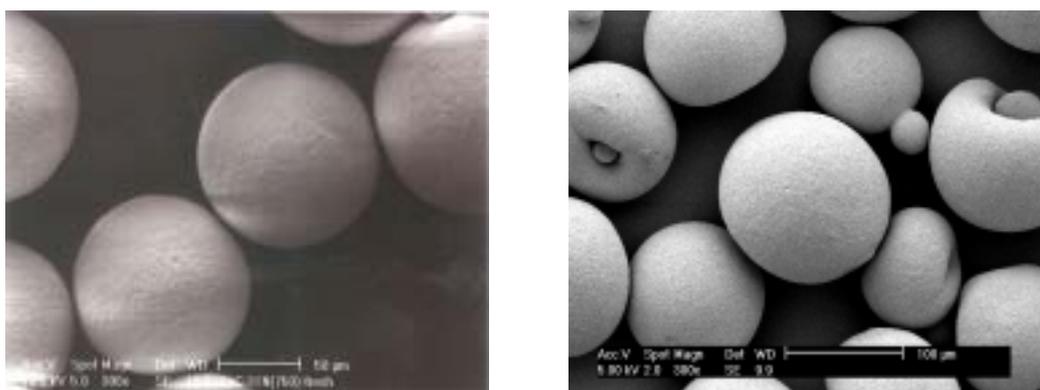


Figure 2. SEM Photographs of ZAC 32N(750) Sorbent (left, top 300x, bottom 5000x) and ZAC 32SU(700)(right, top: 300x, bottom: 5000x)

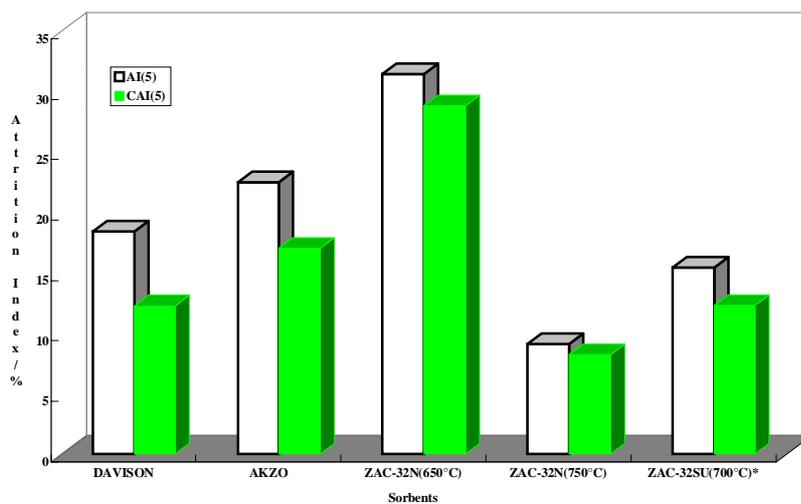


Figure 3. Comparison of Attrition Resistance of Sorbents with Reference FCC Catalysts

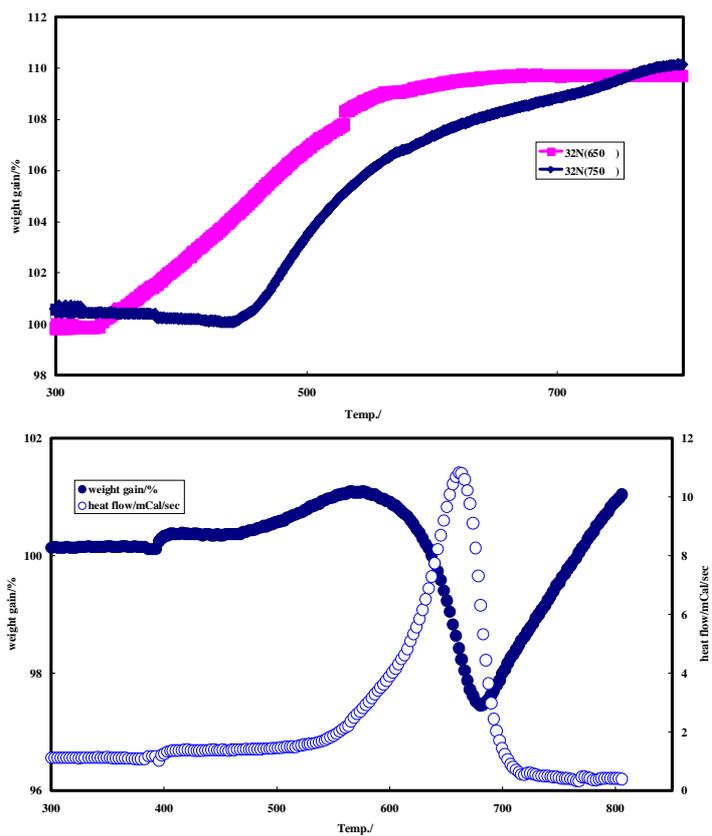


Figure 4. The Sulfidation (top) and Regeneration (bottom) Profiles of the Scope Test for ZAC 32N(750) Sorbent

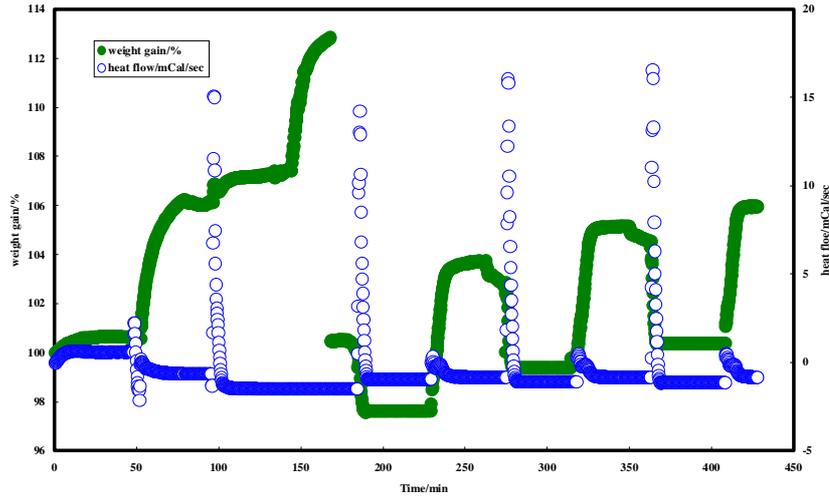


Figure 5. The 4.5 cycle TGA Chemical Reactivity of ZAC 32N

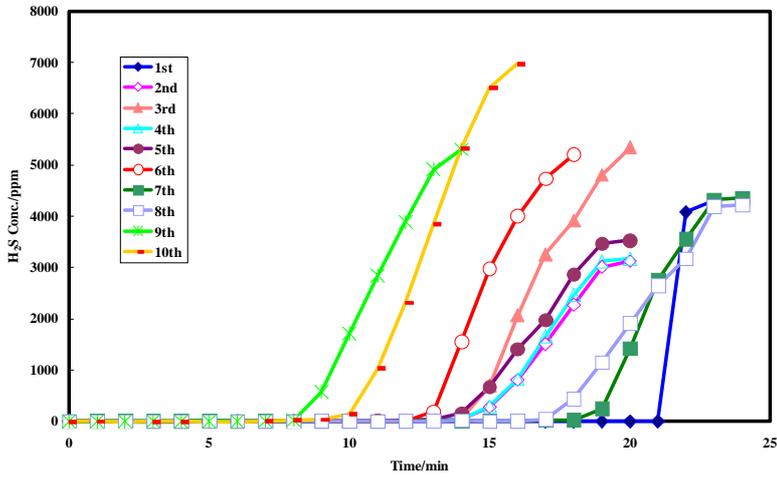


Figure 6. H₂S Breakthrough Curves for ZAC 32N(650) Sorbent

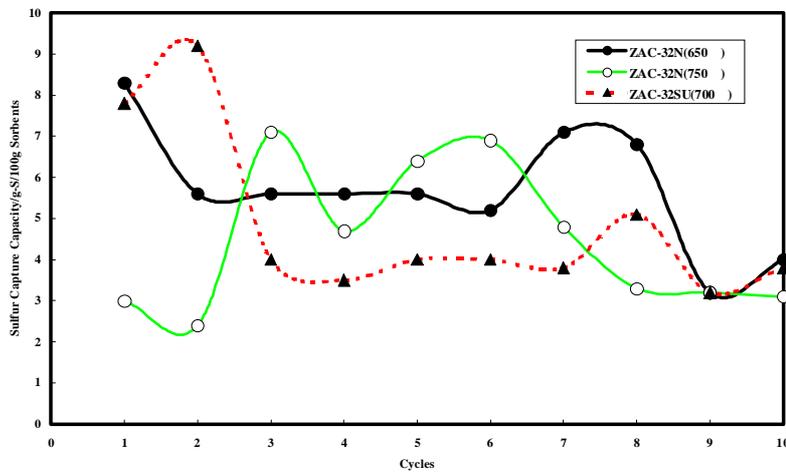


Figure 7. Envelope of the Breakthrough Curves for ZAC 32N(650, 750) and ZAC 32SU Sorbents

Table 1. Requirements of Commercial Grade Sorbents for Fluidized-Bed Reactors

Properties	Requirements	Remarks
Gas compositions	Air-/oxygen-blown gasifier	-
Operational temp. & press.	450-600 °C(500 °C) & 20-30 bar	-
Active component	ZnO	-
Shape	Semi-sphere	-
Average size	75-120 μm(100 μm)	-
Size distribution	40-300 μm	-
Packing density	≥ 1 g/cc	ASTM 4164-88
Attrition index at 10 slpm	AI(5) ≤ 20 %	ASTM 5757-95
TGA sulfur load	> 10 wt% S	Ambient TGA
H ₂ S leakage	≤ 20 ppmv	Microreactor or BSU
SO ₂ slippage	≤ 10 ppmv	Microreactor or BSU

Table 2. TGA Test conditions and Gas Compositions

Conditions	Sulfidation	Regeneration
Gas composition /vol%	H ₂ S	3
	H ₂	9.7
	CH ₄	0.4
	CO	17.5
	CO ₂	6.1
	N ₂	Balance
Neat air	-	100
Temperature/°C	-	500
Pressure	-	650
Sample load/mg	-	Ambient
Total gas flowrate/(ml/min)	-	10
	-	50

Table 3. Micro Reactor Multicycle Test Conditions

Condition	Sulfidation	Regeneration
Sorbent loading volume /ml	2.5	2.5
Contact time/s	2	2
Temperature/°C	550	550
Pressure/psig	294	294
Total gas flowrate/sccm	534	534

Table 4. Gas Compositions for Micro Reactor Tests

Gas	Sulfidation
H ₂	8.5
CO	21.4
CO ₂	7.1
CH ₄	0.4
H ₂ O	10
H ₂ S	1.0
N ₂	51.6

Table 5. The Physical Properties and TGA Reactivities of ZAC 32N and ZAC 32SU Sorbents.

Properties	ZAC 32N		ZAC 32SU	
Calcination temperature/	650	750	850	700
Average particle size / μm	111	83	77	87
Size distribution / μm	38-250	38-212	38-180	38-212
Bulk tap density /(g/ml)	0.77	1.38	1.60	1.135
BET surface area /(m ² /g)	39.3	9.74	3.82	26.036
Hg total pore volume /(ml/g)	0.467	0.5595	0.2425	0.9222
Porosity/%	69.3	70.6	63.6	81.9
5h Attrition resistance				
AI(CAI)/%	31.42(28.8)	9.1(8.2)	4.8(4.4)	15.4(-)
Fresh TGA sulfur capacity /wt%	19.6	13	12	15

Table 6. Comparison of Physical Properties of Fresh and Used ZAC 32 Sorbents.

	ZAC 32N(650)		ZAC 32N(750)		ZAC 32SU(700)	
	Fresh	Used	Fresh	Used	Fresh	Used
BET/(m ² /g)	39.3	8.03	9.74	9.74	26.03	8.76
Porosity/%	69.3	66.01	70.6	56.5	81.9	65.6
APD(4V/A)/nm	65.8	61.3	120.5	100.4	73.9	65.7