

Light Metals 2012

ALUMINA and BAUXITE

**Hydrate Precipitation,
Calcination and Environment**

SESSION CHAIR

Hans-Werner Schmidt

Outotech GmbH

Oberreusel, Germany

Growth and agglomeration of boehmite in sodium aluminate solutions

Zhi Wang¹, Juan Zhang^{1,2}, Rongguang Xu^{1,2}, Zhancheng Guo¹

1. National Engineering Laboratory for Hydrometallurgical Cleaner Production Technology,
Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, China;

2. Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Keywords: Sodium aluminate solutions, Boehmite, Agglomeration degree, Attrition index, Precipitation ratio

Abstract

Boehmite precipitation is a new alternative way from sodium aluminate solutions to alumina, however, the too small particle size becomes one bottleneck for this methods replacing the current production route. Growth and agglomeration of crystals are the main factors influencing product size. The results show that the growth rate of boehmite is in a low range from 0.08 to 2.4 $\mu\text{m}/\text{h}$. Thus, agglomeration of boehmite is a major means to enlarge the particle size of precipitation products from sodium aluminate solutions. By means of laser particle size analyzer and powder attrition index analyzer, the agglomeration efficiency was represented by combining agglomeration degree and attrition index. The influences of seed ratio, temperature, the molar ratio of Na_2O to Al_2O_3 and organic additives on agglomeration were investigated. The alcohol type additives PPG increases precipitation ratio and agglomeration degree, but reduces the strength of products and makes attrition index increase.

Introduction

Both boehmite and gibbsite can be precipitated from sodium aluminate solutions for production of alumina [1]. Precipitation of boehmite instead of gibbsite is an energy saving option due to lower enthalpy of boehmite dehydration during calcinations [2]. Furthermore, electrolytic production of aluminium requires sandy alumina, owing to the wide utilization of large amperage pre-baked cell and dry cleaning of aluminum smelting gas system [3, 4]. Sandy alumina asks for the particle size and strength of boehmite to be improved [5]. Particle size can be enlarged by crystal growth and agglomeration. Agglomeration is the major effective means to improve particle size of gibbsite [6]. In addition, the agglomeration products should have some resistance to attrition in order to avoid grain breakage in transportation. Therefore, improving the particle size and strength of boehmite becomes a problem to be solved urgently.

During the crystallization step, aggregation and growth of the crystals occur simultaneously; this phenomenon has been defined as agglomeration in previous work [7, 8]. Agglomeration process is generally divided into two or three steps: encounter and association between particles, consolidation or cementation by crystal growth [9]. Over the last 40 years, many studies on gibbsite not boehmite agglomeration have been done, including process parameters and kinetics. Researches show that agglomeration can be affected in many ways. For example, high supersaturation or temperature favors the agglomeration kinetics constant. On the other hand, the smaller size or less mass particles agglomerate proceeds better [10-12]. The agglomeration of boehmite in sodium aluminate solutions is badly insufficient at present. Existing studies of boehmite focus particularly on precipitation kinetics. However, it seems to be short of research on controlling boehmite size.

The present work concerns particle size of boehmite products, especially investigates the effect of process parameters on agglomeration degree and attrition index. The varying parameters

are seed mass, temperature, MR of sodium aluminate solutions and organic additives.

Materials and Methods

Growth of boehmite was observed in situ using an Axio Imager A1 microscope (Carl Zeiss) with a modified crystallizer. The original precipitation set up used in this work, has been described in a previous work [1]. The crystallizer was loaded with 400 ml supersaturated sodium aluminate solution with pre-adjusted Al_2O_3 and Na_2O concentrations. When the solution was heated to the required temperature, the appropriate amount of boehmite seed was added. Samples were taken from the reactor to a centrifuge for solid-liquid separation periodically. Liquid samples were analyzed for their alumina and caustic concentrations using the titration method. The solids were washed and then dried at 105 $^\circ\text{C}$ for 48 h for characterization.

The crystallography of the precipitates was identified by X-ray Diffractometry (SIEMENS D5000). The particle size of the precipitates was analyzed by the Laser Particle Size Analyzer (MALVERN MASTERSIZER). Attrition index of boehmite was determined by Powder Attrition Index Analyzer (BJ-INSPECT ISPF-1). Seeds for agglomeration experiments are industrial grade boehmite (Aluminum Ltd Co, China). More than 60 percent of seed is fine particles less than 10 μm , and the particle size distribution is presented in Fig. 1.

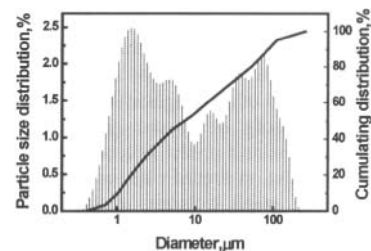


Figure 1. Particle size distribution of boehmite seed

In agglomeration process, fine seeds added to sodium aluminate solutions are cemented into coarse particles. As a result fine seeds decline in number, however, particle size increases. Accordingly, agglomeration degree of boehmite can be defined as follows. Before agglomeration the mass of particles coarser than 45 μm is $1.18C \cdot SR \cdot X_1$; after agglomeration the mass of products coarser than 45 μm becomes $1.18C \cdot (SR + \eta) \cdot X_2$. By means of agglomeration the mass increment of products coarser than 45 μm is

$$1.18C(SR + \eta)X_2 - 1.18C \cdot SR \cdot X_1 = 1.18C[(SR + \eta)X_2 - SR \cdot X_1]$$

So agglomeration degree is given by

$$E = \frac{1.18C[(SR + \eta)X_2 - SR \cdot X_1]}{1.18C \cdot SR \cdot X_1} \times 100\% = \left(\frac{SR + \eta}{SR} \cdot \frac{X_2}{X_1} - 1 \right) \times 100\% \quad (1)$$

Where

C : alumina content of sodium aluminate solutions, g/L;
 SR : seed ratio;
 η : precipitation ratio of sodium aluminate solutions, %;
 X_1 and X_2 : before and after agglomeration the percentage composition of boehmite coarser than 45 μm respectively, %;
 E : agglomeration degree, %.

From the formula it can be seen that both seed and precipitation ratio affect agglomeration degree, which can characterize the apparent effectiveness of agglomeration.

Attrition index, a major parameter to evaluate the strength of sandy alumina, is used for boehmite here in order to measure the real agglomeration state. Attrition index of boehmite was measured with the following method: 50 g boehmite sample was blown using dry compressed nitrogen under 0.4 MPa pressure for 15 minutes, and then analysed the change of particle size distribution. The computational formula of attrition index is given by Eq. (2)

$$I_A = \frac{w_b - w_a}{w_b} \times 100\% \quad (2)$$

where

I_A : attrition index, %;

w_b and w_a : before and after attrition test the percentage composition of boehmite coarser than 45 μm respectively.

Results and Discussion

Observation of Boehmite Crystal Growth

Growth and agglomeration of crystals are the main factors influencing product size in the precipitation of sodium aluminate solutions. Agglomeration makes fine particles become coarse ones, while growth can improve the strength of aggregation thus make it harder to break. Therefore, crystal growth is critical for alumina hydrate transformation from liquid to solid phase, which influences size and strength of the product directly.

The growth of boehmite was recorded online by modified crystallization observation microscope, with transmission light and magnification of 500. Fig. 2 shows the growth change of boehmite at 70°C, and crystal shape is various, such as square, diamond, triangle and other irregular shape, which is relevant to variety and complexity of crystal growth defects (twinning, hemitrope, dislocation and crystal internal boundary). Crystal size ranges from 1 to 6 μm , in accord with results obtained from SEM. From the scale of graph software of the microscopy, we can calculate the mean growth rate of boehmite within a fixed time. As showed in Fig. 3, growth rate of boehmite has dispersive feature and is different for its initial size, and at the same temperature the growth rate is not related to the initial size of seed, i.e. obeying ΔL law. Growth rate is less than 0.3 $\mu\text{m}/\text{h}$ at 70°C and concentrates on 0.5 $\mu\text{m}/\text{h}$ at 80°C, while lies in 0.08-2.4 $\mu\text{m}/\text{h}$. So on the whole the growth rate at 80°C is faster than that at 70°C, and raising temperature can improve crystal growth rate. Growth rate of gibbsite observed by Sweegers et al. [13] was generally 2.0 $\mu\text{m}/\text{h}$, even reached 10 $\mu\text{m}/\text{h}$, and ranged from 0.3 to 7.2 $\mu\text{m}/\text{h}$ by Sawsan et al. [14] using atomic force microscopy. So the growth rate of boehmite is 4-10 times less than that of gibbsite, which may be determined by crystal structure, growth mechanism and growth rate constant of boehmite.

Effects of Seed Ratio on Agglomeration of Boehmite

Seed is an important influence factor of agglomeration, and hence precipitation experiments were carried out under different seed ratio (SR) with Bayer liquor concentrations of 150 g/L Al_2O_3 and molecular ratio 1.46 (MR , presented by the ratio of alumina to caustic of sodium aluminate solutions), at the temperature of 90 °C for 8h.

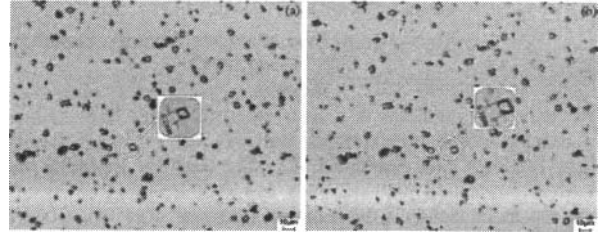


Figure 2. In situ observation the growth of boehmite crystal: (a) $t=0$ h; (b) $t=6$ h

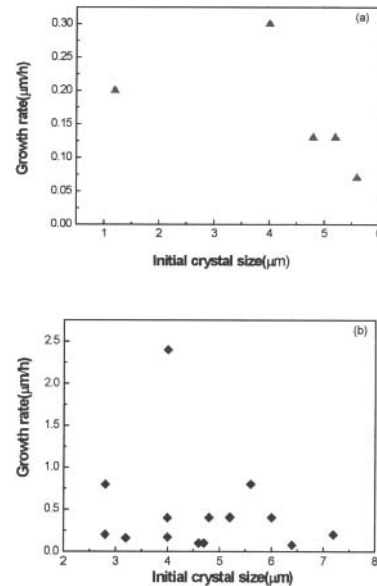


Figure 3. The growth rate of boehmite at different temperatures: (a) 70°C; (b) 80°C

Agglomeration degree and attrition index under different SR are shown in Figure 4. It shows that agglomeration degree decreases as SR increasing on the whole, but there is an inflection point at SR of 0.6. The increase of SR results in the increase of attrition index, which indicates that large seeds amount have disadvantage for the strength of products. Just as mentioned above, during agglomeration process fine particles are encountered and then cemented by accompanying products precipitated. When SR is high, the products as adhesive become relatively not enough and hence agglomeration degree decreases. On the other hand, inadequate adhesive generates loose products and leads to the increase of attrition index. Due to the fine seeds used in this experiments, the sizes of products are also smaller than normal products, which leads to the attrition index was in a higher value range.

There is another explanation just like gibbsite, an increase of the seed mass induces two opposite effects [9]. On one hand, it corresponds to a decrease of the distances between them, which

increase both the frequency of encounter between particles, and their association by Van der Waals attraction forces. On the other hand, the higher the number of particles, the higher the number of shocks attempting to disagglomerate the particles. When the seed mass is low, for instance SR is 0.2, adding seed only increases the frequency of encounter between particles and their association forces, while the number of shocks does not change evidently, so agglomeration degree increases. With SR increasing, the influence of shocks among particles leading to disagglomerate becomes obvious.

In the sodium aluminate solutions boehmite particles are covered by free hydroxyl (OH^-) and the surfaces become negatively charged. As a result, repulsive forces between the boehmite and aluminate ions will inhibit the precipitation process [15, 16]. With the seed amount increases, the unit negative charge on the boehmite surfaces reduces. The inhibition is eliminated and precipitation process is improved. Due to the increase of precipitation ratio with SR increasing, both agglomeration particles and adhesive increase, so agglomeration degree is determined by SR and precipitation ratio just as presented in Equation 1. Combining agglomeration degree and attrition index, with SR of 1.0 the boehmite agglomeration is most effective in the SR range of 0.2 to 1.4. Seyssiecq etc. [9] showed that there was an optimum seed mass for maximum agglomeration of gibbsite, approximately 50-140 g/L.

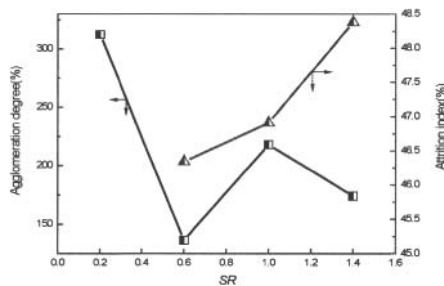


Figure 4. Effect of SR on agglomeration degree and attrition index of products

Effects of Temperature on Agglomeration of Boehmite

Temperature is an important factor to affect transfer and reaction of ions, so at different temperatures the agglomeration process of boehmite was investigated under experimental conditions: $C(\text{Al}_2\text{O}_3)=106$ g/L, $MR=1.5$, $SR=1.0$, $t=8$ h. The precipitation ratio of sodium aluminate solutions at different temperatures was shown in Figure 5. There appears to be a trend, that higher precipitation ratio was obtained at higher temperature from 45 °C to 95 °C. Below 55 °C the precipitation ratio was lower than 8%, however, when temperature was elevated to 65 °C precipitation ratio had a rapid rise to 20% approximately. The precipitation of sodium aluminate solutions is a reaction process of crystallization, and thus higher temperature contributes to the increase of the reaction rate constant. Then with the increase of temperature the viscosity of sodium aluminate solution is decreased, and therefore the transfer speed of aluminium ions is accelerated. According to above two reasons precipitation ratio increased with temperature elevating.

In Figure 5 the XRD patterns indicate that precipitation products are all boehmite in the range of experimental temperature from 45

°C to 95°C. Panias etc. [16-18] have done many researches on the thermodynamics and kinetics of boehmite precipitation. According to the thermodynamic data boehmite can be formed at temperatures as low as 50 °C, however, the experimental results prove that boehmite precipitation from sodium aluminate solutions is available with concentration 120 g/L Na_2O at temperature higher than 90 °C, whilst a decrease of the total sodium hydroxide concentration from 120 g/L to 65 g/L results in the boehmite precipitation at temperature as low as 70 °C [17, 18]. Boehmite precipitation needs higher temperature, because the activation energy of boehmite precipitation is 89 kJ/mol, much higher than 50-59 kJ/mol of gibbsite [16]. The present results are not accord with panias outcomes, maybe owing to the differences between boehmite seeds [19], which indicates that the thermodynamics of boehmite precipitation are relevant to not only the seed adding amount, but also the prepared method and seed surface activity.

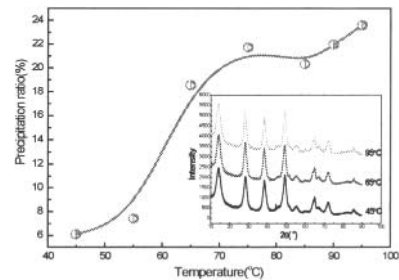


Figure 5. Effect of temperature on precipitation ratio of sodium aluminate solutions

Agglomeration degree and attrition index obtained at different temperatures are shown in Figure 6. The curve of agglomeration degree indicates that as temperature lower than 55 °C the agglomeration degree of products is about 70%. When the temperature is elevated to 65 °C the agglomeration degree increases to above 240% and then there is a plateau from 65 °C to 90 °C. Keeping raising the temperature to 95 °C, however, the agglomeration degree has a decrease. Gibbsite agglomeration is best at 75 °C from 65 °C to 95 °C [12], which is similar to boehmite. As to attrition index, minimum value can be got at 75 °C. As temperature down to 65 °C or up to 95 °C, the attrition index increases and thus the strength of products decreases.

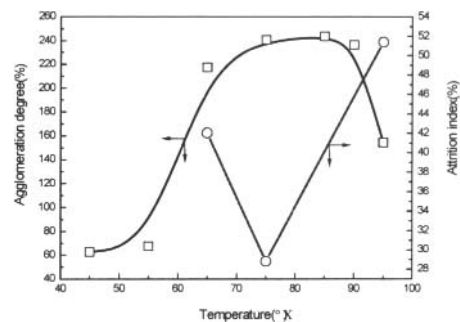


Figure 6. Agglomeration degree and attrition index of products at different temperature

Higher temperature can promote the agglomeration process owing to the increase of particles effective collision and the spread of active sites across particle surface. On the other hand, higher temperature reduces the supersaturation of sodium aluminate solutions, resulting in the decrease of agglomeration driving force. That is, agglomeration process is affected by both positive and negative factors. As temperature lower than 55 °C the frequency of particle collision is also low, so the agglomeration efficiency is poor. When temperature increasing from 65 °C to 90 °C, the two opposing factors cancel each other thus the agglomeration degree remains virtually unchanged. As temperature is elevated to 95 °C, the supersaturation of solutions decreases thus the negative factor plays a leading role on agglomeration, so the agglomeration degree has a decline. Attrition index at 65 °C is higher than that at 75 °C, because the precipitation ratio at 65 °C is lower than that at 75 °C, thus the adhesive reduction leads to the lower strength of products. At 95 °C the enhancement of particles collision probably changes the inlay mode and structure, affecting the strength of products. In a word, the agglomeration degree of boehmite has an optimal temperature range between 65 °C and 90 °C under the experimental conditions. Combining with attrition index, the optimal temperature for effective agglomeration is 75 °C

Effects of Molar Ratio on Agglomeration of Boehmite

The effect of initial *MR* on boehmite agglomeration is investigated under the conditions: $C(\text{Al}_2\text{O}_3)=106 \text{ g/L}$, $SR=1.0$, $T=90^\circ\text{C}$, $t=8 \text{ h}$. Figure 7 depicts the relationship between precipitation ratio and *MR*. The smaller *MR* is, the higher precipitation ratio can be got. *MR* has key influence on the supersaturation of sodium aluminate solutions, which is the driving force for crystallization and presents the chemical potential differences between solid and liquid phases. The supersaturation of solutions with low *MR* is high, so precipitation ratio is improved. The XRD analyses show that the products are boehmite except *MR* of 1.4, at which gibbsite precipitated also. A study by Dash et al. [19] suggests that the important factor whether boehmite or gibbsite is precipitated from sodium aluminate solutions is A/C ($A/C=1.645/MR$), because A/C can affect the supersaturation of solutions. Low *MR* facilitates gibbsite precipitation, just like the present results, therefore inhibiting gibbsite precipitation should adequately control *MR* of solutions.

The particle size distribution of products with different *MR* is shown in Figure 8. Boehmite seeds are multi-peak distribution, however, agglomeration process leads to the remarkable decrease of fine particles thus the particle size distribution becomes close to single-peak distribution, indicating that agglomeration has played a very significant role. These curves also demonstrate that the main peak positions of particle size distribution move from right to left with *MR* increasing, suggesting coarse products can be formed under low *MR* condition. The size and distribution of agglomerate are affected by initial *MR*. Lower *MR* solutions have stronger driving force for agglomeration and then coarser products are got.

Figure 9 shows the agglomeration degree and attrition index of products with different *MR*. When *MR* shifts from 1.4 to 2.2, the agglomeration degree has the maximum value at *MR* 1.6, and decreases when *MR* is either lower or higher than 1.6. However, attrition index increases and product strength decreases with the increase of *MR*. The main reason for that agglomeration degree and attrition index are affected by *MR* is that the initial supersaturation of solutions is different.

The initial supersaturation of *MR* 1.4 solutions is very high, so second nucleation occurs easily. Just as the XRD patterns presented in Figure 7, with *MR* 1.4 gibbsite is precipitated. The differences of crystal form, between boehmite and gibbsite, are not favourable to agglomeration. With other *MR* the products are only boehmites, and it is easy for boehmite to agglomerate among one another. As a result the agglomeration degree with *MR* 1.6 is higher than that with *MR* 1.4.

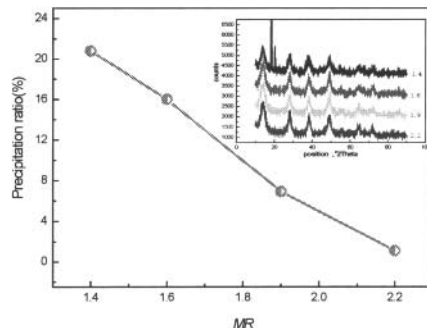


Figure 7. Precipitation ratio and initial relative degree of supersaturation with different *MR*

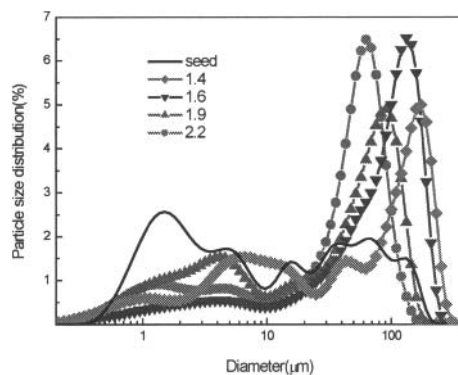


Figure 8. Particle size distribution of products with different *MR*

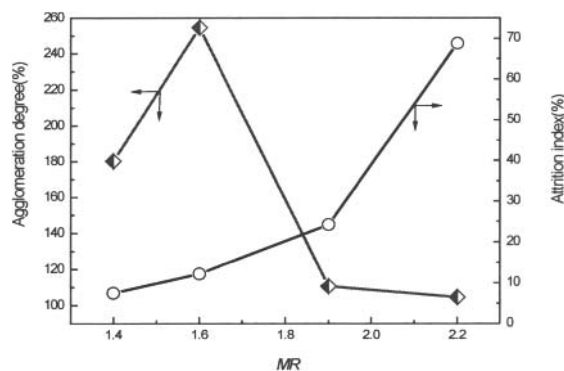


Figure 9. Agglomeration degree and attrition index of products with different *MR*

When MR is higher than 1.8, agglomeration degree decreases dramatically. This can be explained by critical diameter of agglomeration proposed by M. L. Steemson [20]. Only particles which are finer than critical diameter agglomerate together. Conditions of agglomeration are different, thus the diameters of agglomerate particles are different. The critical diameter of agglomeration can be described by the following equation:

$$D_c = G^{2/3} [2.1 - 3.5 \log(\varepsilon) + 1.5 \log(M_T)] \quad (3)$$

Where

D_c : critical diameter of agglomeration, μm ;

G : critical rate of growth, $\mu\text{m/h}$;

ε : power consumption of unit volume suspension, kw/m^3 ;

M_T : solid content in suspension, g/L .

With MR increasing, the supersaturation of sodium aluminate solutions and crystal growth rate decrease. In addition, the increase of MR results in the decrease of precipitation ratio and precipitated solids. Because G and M_T decrease, D_c decreases and the quantity of agglomerate particles reduces. So agglomeration degree decreases with MR increasing.

From Figure 7 above, it is shown that precipitation ratio is high with low MR . The more adhesive is precipitated, the more strongly particles are cemented with the same seeds amount, so the agglomeration degree becomes higher with lower MR except MR of 1.4. Because gibbsite is precipitation with MR of 1.4, and the different crystal types between gibbsite and boehmite go against agglomeration between them. So agglomeration degree of products with MR of 1.4 is lower than that with MR of 1.6. However, products with higher agglomeration degree do not always have better strength. Although particles with MR 1.6 are agglomerated to sandy products, the strength is poor and agglomerates are broken to fine particles under attrition conditions, indicating that products with MR 1.4 are denser and tighter compared to those with MR 1.6. Because of gibbsite by-product formed with MR 1.4, the effective agglomeration for boehmite can be obtained with MR 1.6.

Effects of Additive on Agglomeration of Boehmite

Organic additives are important factor in crystallization from sodium aluminate solutions and have several influences on the precipitation process, including promoting or inhibiting precipitation ratio, changing particle size and morphologies [21]. The amount of organic additives is small, but the effect is significant. The mechanism of additives was through changing the seed surfaces by absorption or altering the sodium aluminate solutions characters [22]. In order to investigate the effects of additives on boehmite agglomeration, several alcohols were proposed as additives. Experimental conditions are as follows: $C(\text{Al}_2\text{O}_3)=150 \text{ g/L}$, $MR=1.5$, $SR=1.0$, $T=80 \text{ }^\circ\text{C}$, and the concentration of additive was 20 mmol/L .

The precipitation ratio with additives is given in Fig. 10. The blank precipitation ratio without additives is approximately 15% for 8 hours. Precipitation ratio adding 1, 2-propanediol and PPG is increased to 17% and 19% respectively, however, other alcohols inhibit precipitation. The extent of inhibition from strong to weak is: mannitol > n-octyl alcohol > n-propyl alcohol > glycerol. Differences of alcohols, including length of carbon chain and the number and position of their hydroxyl groups, determine their effects in boehmite precipitation.

The effect of alcohol additives on agglomeration degree and attrition index is shown in Figure 11. All of alcohols reduce agglomeration degree excepting PPG. Although 1, 2-propanediol and PPG can improve precipitation ratio, make attrition index

increase and reduce the strength of products. It might the reason that alcohols could decrease surface tension of the solution, which makes fine particle much steady, and it is difficult for alcohol additives to promote both size and strength of agglomerate.

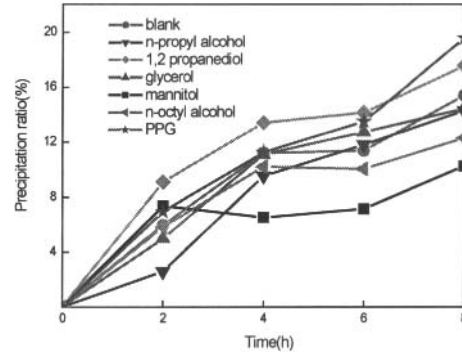


Figure 10. Precipitation ratio of sodium aluminate solution with alcohol additives

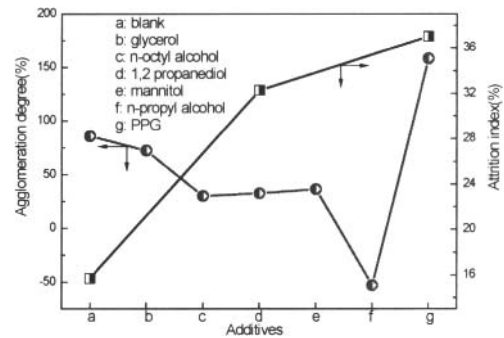


Figure 11. Effect of alcohol additives on agglomeration degree and attrition index

Conclusion

The growth of boehmite crystal was recorded online by modified crystallization observation microscope. The growth rate of boehmite ranges from 0.08 to $2.4 \mu\text{m/h}$, and concentrates on $0.5 \mu\text{m/h}$, slower than that of gibbsite 4-10 times; raising temperature favors the growth rate of boehmite, and at the same temperature the growth rate is not related to the initial size of seed. Boehmite seeds promote precipitation, however, too high SR has disadvantage to agglomeration. Combining agglomeration degree and attrition index, with SR of 1.0 the boehmite agglomeration is most effective in the SR range of 0.2 to 1.4. The optimal temperature for effective agglomeration is $75 \text{ }^\circ\text{C}$. Low initial MR promotes precipitation ratio, gibbsite formation, coarse products and agglomerate strength when MR shifts from 1.4 to 2.2, but the agglomeration degree have the maximum value with MR 1.6. Several alcohols were proposed as additives, only PPG develops precipitation ratio and agglomeration degree, but makes attrition index increase and reduces the strength of products.

Acknowledgments

The financial support of the National Natural Science Foundation of China (Contract No. 50704030) and the Knowledge Innovation Program of the Chinese Academy of Sciences (Contract No. KG CX2-YW-321-2) is gratefully acknowledged.

References

1. Wang Zhi, et al., "Adjustment on gibbsite and boehmite coprecipitation from supersaturated sodium aluminate solutions", *Trans. Nonferrous Met. Soc. China*, 20(2010), 521-527.
2. Filippou D and Paspallaris I., "From Bayer process liquors to boehmite and then to alumina: an alternative route for alumina production", *Light Metals*, (1993), 119-123.
3. Arnswald W, Lalla A and Vollmers G., "Improved AOS technology to produce sandy alumina in a plant originally designed for the floury type", *Light Metals*, (1995), 171-175.
4. Yan Li et al., "Precipitating sandy aluminium hydroxide from sodium aluminate solution by the neutralization of sodium bicarbonate", *Hydrometallurgy*, 98(2009), 52-57.
5. Zhi Wang, et al., "Evolution of particle size and strength of hydrargillite from carbonization in seeded sodium aluminate liquors", *Journal of Crystal Growth*, 274(2005), 218-225.
6. Veessler S. and Boistelle R., "About supersaturation and growth rates of hydrargillite $\text{Al}(\text{OH})_3$ in alumina caustic solutions", *Journal of Crystal Growth*, 130(1993), 411-415.
7. Seyssiecq I. et al., "Modelling gibbsite agglomeration in a constant supersaturation crystallizer", *Chemical Engineering Science*, 55(2000), 5565-5578.
8. Seyssiecq I., Veessler S. and Boistelle R., "A non immersed induction conductivity system for controlling supersaturation in corrosive media: The case of gibbsite crystals agglomeration in Bayer liquors", *Journal of Crystal Growth*, 169(1996), 124-128.
9. Seyssiecq I. et al., "Agglomeration of gibbsite $\text{Al}(\text{OH})_3$ crystals in Bayer liquors. Influence of the process parameters", *Chemical Engineering Science*, 53(1998), 2177-2185.
10. Ilievski D. and Livk I., "An agglomeration efficiency model for gibbsite precipitation in a turbulently stirred vessel", *Chemical Engineering Science*, 61(2006), 2010-2022.
11. Johnston J. R. R. and Cresswell P. J., "Modelling alumina precipitation: dynamic solution of the population balance equation", Proceedings of the 4th International Alumina Quality Workshop (Darwin, Australia), 2 (1996), 281-290.
12. Zhang Bin et al., "Effects of temperature and initial ratio of Na_2O to Al_2O_3 on agglomeration of fine $\text{Al}(\text{OH})_3$ seed in synthetic Bayer solution", *J. Cent. South Univ. Technol.*, 15(2008), 786-790.
13. Sweegers, C., Meekes, H. and van Enckevort W. J. P., "Growth rate analysis of gibbsite single crystals growing from aqueous sodium aluminate solutions", *Crystal Growth & Design*, 4(2004), 185-198.
14. Sawsan J. et al., "Direct observation of the growth of gibbsite crystals by atomic force microscopy", *Journal of Crystal Growth*, 260 (2004), 232-242.
15. Panias, D. et al., "Boehmite process: an alternative technology in alumina production", *Light Metals*, (2001), 97-103.
16. Skoufadis C., Panias D. and Paspallaris I. "Kinetics of boehmite precipitation from supersaturated sodium aluminate solutions", *Hydrometallurgy*, 68(2003), 57-68.
17. Panias D. and Paspallaris I. "Thermodynamic Determination of the Stability Area of Boehmite in Al_2O_3 - Na_2O - H_2O and Al_2O_3 - H_2O System", *Erzmetall*, 52(1999), 585-590.
18. Panias D. and Krestoul A. "Effect of synthesis parameters on precipitation of nanocrystalline boehmite from aluminate solutions", *Powder Technology*, 175(2007), 163-173.
19. Dash B. et al., "Effect of temperature and alumina/caustic ratio on precipitation of boehmite in synthetic sodium aluminate liquor", *Hydrometallurgy*, 88, (2007), 121-126.
20. Steemson M. L., White E. T. and Marshall R. J. "Mathematical model of precipitation section of a Bayer plant", *Light Metals*, (1984), 237-253.
21. Bronswijk W. van, Watling H. R. and Yu Z., "A study of the adsorption of acyclic polyols on hydrated alumina", *Colloids and Surfaces*, 157(1999), 85-99.
22. Loha J. S. C., Watling H. R. and Parkinson G. M., "The effect of isotopic substitution of deuterium for hydrogen on the morphology of products precipitated from synthetic Bayer solutions", *Journal of Crystal Growth*, 237(2002), 2178-2182.