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ENERGY IN ALUMINA REFINING: SETTING NEW LIMITS

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Abstract

Enormous emphasis is placed on the specific energy consumption from the refining of alumina from Bauxite. The current spread of specific energy consumption of the industry varies from 7 GJ/tonne to 21 GJ/tonne. Energy consumption is highly technology specific with digestion and calcination accounting for sixty percent of refinery thermal energy consumption. With Greenfield projects placing a high importance on fuel consumption in order to make their projects viable, careful selection of the technology will have an immediate impact on the energy consumption and in turn the fuel consumption which could ultimately determine the financial viability of the refinery throughout the lifetime of the project. This paper seeks to analyze the energy consumption requirements for different digestion and calcination configurations, such as single vs split stream digestion along with alternative methods of final stage heating; as well as calcination technology options and also their impact on the financial viability of the refinery itself.

Introduction

Energy is arguably one of the most debated topics in the production of alumina from bauxite and/ or alternative sources, such as Nepheline and has been widely discussed amongst technology suppliers, operators and authors in the literature [1, 2 and 3]. There are approximately 87 refineries in operation worldwide 80 % of which use some variation of the Bayer process, 14 % a sintering or combined Bayer sinter technique and 3 % use raw material other than bauxite or low grade bauxite [4].

Breakdown of Refinery Energy Consumption

The production of alumina, is an energy intensive process. Unlike other metals, such as Copper, Zinc and Nickel there is little incentive to pre-treat Bauxite via a pyrometallurgical process such as roasting, nonetheless copious amounts of energy are supplied to the Bayer process in order to meet the product requirements. The two most energy intensive process steps are Digestion and Calcination which each are responsible for about 30 % of refinery energy consumption, 20 % of refinery energy consumption is dedicated to evaporation and the remainder for minor consumers such as caustcisation, oxalate destruction, caustic and acid cleaning heating (for a modern plant using some 10 GJ/ton alumina produced).

Theoretical Requirements to Produce Alumina

The theoretical energy requirements to produce alumina from bauxite are quite modest, the main chemical reactions that take place are: the dissolution of gibbsite or boehmite in digestion (endothermic), the dissolution of kaolinite (exothermic) and the re-transformation into sodalite based de-silication products (endothermic), the precipitation of gibbsite (exothermic) and the calcination of gibbsite to smelter grade alumina (endothermic). Based on a typical bauxite with the composition indicated in Table 1, the chemical requirements to produce 1 tonne of alumina are illustrated in Figure 1, and results in a net value of around 2 GJ/tonne, hence the question is asked why is it that actual operation and design is so afar from the theoretical value? One answer to this question is that there are pre-existing thermal requirements for these reactions to take place to begin with, for example dissolution of gibbsite or boehmite require relatively high temperatures and concentrations of caustic [5], this means that large volumes of inert material needs to be heated, from which the heat may (or may not) be recovered, and with large flows come large vessels, heat exchangers and equipment that also incur relatively large heat losses. Likewise in calcination, the calcination reactions and final determination of product quality is also facilitated by high operating temperatures.

THA	41%
Al_2O_3	44%
$RSiO_2$	1%
$TSiO_2$	2%
TiO_2	8%
Fe_2O_3	21%
Trace	2%
Total	78%

Table 1. Fictional bauxite used for the purpose of this study.

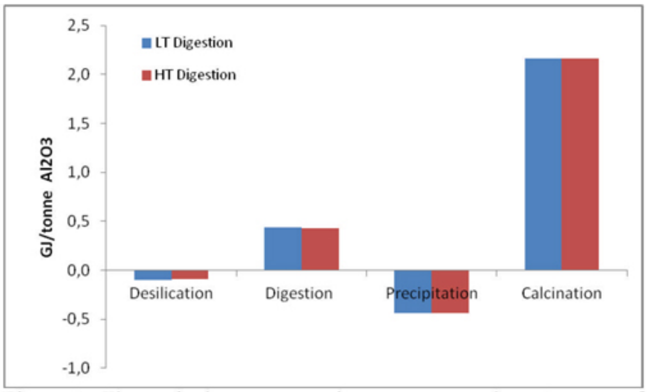

Figure 1. Theoretical energy requirements to produce 1 tonne of smelter grade alumina from bauxite.

Review of Current Situation in the Industry

As already stated above, digestion and calcination are the current biggest consumers of energy. In addition to the bauxite type, technology selection of different types of digestor designs have had a large impact on energy consumption such as single stream tube digestion with the use of jacketed pipe units [6, 7, 8, 9, 10 and 11] over split stream digestion or direct versus indirect steam injection digester designs. Likewise varying calcinations technologies such as circulating fluidized bed [12], gas suspension calcination techniques [13] and rotary kilns will also have a varying effect on total plant energy consumption. Although there are cases where the above mentioned technologies have shown improved energy consumptions over the other, there has not been a holistic overview over the whole alumina production industry in its entirety.

The Effect of Refinery Technology on Energy Consumption

The average energy consumption for all refineries is approximately 13.8 GJ/tonne of calcined alumina, with a range from 7.2 to 43 GJ/tonne. The average energy consumption of Bayer refineries is 12 GJ/tonne and ranges between 7.2 and 21.9 GJ/tonne. Not surprisingly, those refineries that use some form of sinter, Bayer sinter or alumina extraction from non-bauxitic ores have an average energy consumption of 22 GJ/tonne ranging from 14 to 43 GJ/tonne.

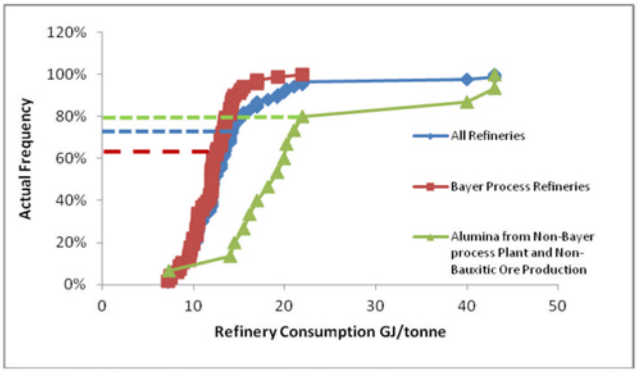

Figure 2. Distribution of Alumina refinery energy consumption for all refineries in operation, refineries using Bayer and non-Bayer Techniques to produce smelter grade alumina [4].

The effect of digestion technology on energy consumption of 19 known refineries is highlighted in Table 2 which shows although on average the low temperature refineries use less energy than high temperature ones, however the large standard deviation in refineries using high temperature digestion reveals there are cases of high temperature refineries having lower energy consumption than refineries using low temperature digestion technology. Statistically speaking however, there is little difference between the two data sets when conducting a two tail t-test using a critical probability of 0,05.

Table 3 compares the overall energy consumption of refineries using different types of digestion technologies such as Atmospheric digestion, Double Digest, Single and Split stream digestion technologies [4].

Digestion Technology	Average Energy Consumption	Stdev in Energy Consumption	Two Tail P-Value
LT Energy Consumption	10,440	2,239	0,51
HT energy Consumption	11,400	3,652	

Table 2. Statistical evaluation of the difference in energy consumption between high and low temperature digestion [4].

Digestion Technology	Average Energy Consumption	Stdev in Energy Consumption
Atmospheric Digestion Energy Consumption	12,500	0,707
Double Digest Energy consumption	11,400	1,556
Single Stream Digestion Energy Consumption	11,250	4,593
Split Stream Energy Digestion Consumption	11,440	2,448

Table 3. Average energy consumption of 19 refineries using different digestion technologies [4].

In addition to digestion the effect of different calcination technology on 68 refineries was also observed in Table 4, such technologies include circulating fluidized bed (CFB), Gas suspension calciners (GSC) and rotary kilns.

Calcination Technology	Average Energy Consumption	Stdev in Energy Consumption
CFB Energy Consumption	9,843	2,152
GSC Energy Consumption	11,800	2,108
Kiln Energy Consumption	13,593	3,371

Table 4. The average energy consumption of 65 refineries using different calcinations technologies.

Investigation into requirements, alternatives and New Designs

Many improvements have been made on Bayer Energy consumption over the years such as improved de-scaling methods, chemical scale inhibitors, falling film evaporation, improved yield in precipitation and increased number of flash stages in digestion and evaporation [2].

Pushing towards the 7 GJ/tonne mark is a feat only achieved by few refineries but completely feasibile given the correct design, technology and operating experience.

Effect of Different Calcination Designs on Overall Refinery Energy Consumption

Energy consumption in calcination has certainly evolved throughout the 20th century with conversion of rotary kilns to complex plants with heat recovery systems [14] to the inception of stationary calciners such as gas suspension units and Circulating Fluidized Beds. The latter of the two stationary units is considered one of the benchmarks in energy consumption evolving over the last 50 years, such improvements include:

1) additonal cooling stages for increased air pre-heating and recovery of heat with the alumina,
2) additon of the hydrate baypass so as to use the heat capacitance from the alumina discharged from the furnace as a heating agent to calcine a small percentage of the incoming hydrate.
3) the addtion of a Hydrate drier which uses waste heat via re-circulation of water from the product fluid bed cooler to dry incoming hydrate.
4) additional Hydrate pre-heating stages.

Such Modifications have allowed this calciner design to fall below 3 GJ/tonne to 2.7 GJ/tonne of calcined alumina [12]

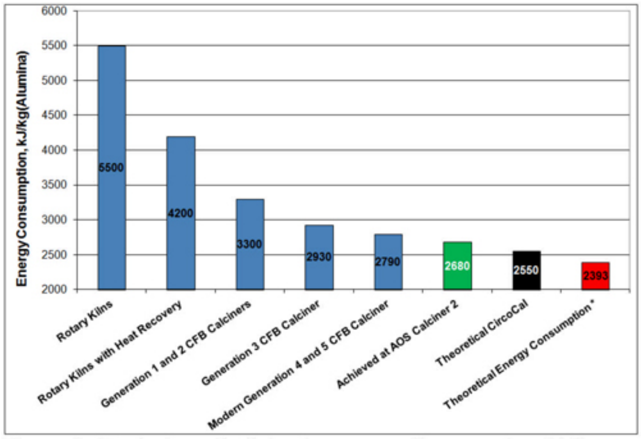

Figure 3. Evolution of calcination energy Consumption [15]

Effect of Different Digester Designs on Overall Refinery Energy Consumption

Five different different refineries using different digestion configurations were studied and their effect on energy consumption using the Outotec syscad models and their capital requirement assessed respectively;

Plant 1: High Temperature Split stream digestion with direct steam injection, evaporation and Circulating Fluidized Bed Calciner

Plant 2: Low Temperature Split stream digestion with direct steam injection, evaporation and Circulating Fluidized Bed Calciner

Plant 3: High Temperature Single stream digestion with indirect steam heating, evaporation plant and Circulating Fluidised Bed Calciner.

Plant 4: High Temperature Single stream digestion with indirect steam heating without evaporation, red mud filtrate recycle back to plant and Circulating Fluidized Bed Calciner.

Plant 5: High Temperature Single stream digestion, with alternate heating source, without evaporation, red mud filtrate recycle back to plant and Circulating Fluidized Bed Calciner.

The technologies include High and low temperature split stream digestion plants with direct steam injection, high temperature single stream tube digestion with indirect steam heating using jacketed pipe unit technology typically designed by the Hatch – Outotec Joint venture [6 and 8] and single stream digestion technology using alternate forms of heating other than steam such as heating oils or molten salts [16].

In addtion considerations have been made to remove evaporation and de-water red-mud and recycle the caustic filtrate back to the process thus eleiminating a major source of water ingress and reyling soley on the recuperable heating stages as the source of water extraction. In order to compensate for contaminat build up such as organics and salt, wet oxidation and simple salt crysallisers have been considered, with the former, well siuted to high temperature tube digestion plants [17].

In order to keep consitstent comparision between the plants the bauxite used was that illustrated in Table 1 to produce 2 Million tonnes per annum of smelter grade alumina and a average specific heat transfer surface area in digestion of 1076 m^2 per recoverable heating stage was employed, consistent heat transfer coefficient profiles, an evaporation economy of 4.0 was targeted for plants 1 to 3 and a specific energy consumption in calcination of 2.75 GJ/t was used.

Table 5 illustrates the performance from an energy view point the of the five suggested plant configurations. The extra 2-3 % beohmite highlights a drop in specific bauxite consumption, but significant rise in process energy requirements when comparing Plant 1 and Plant 2, with more than 2 extra GJ/t required, mainly due to the additional water ingress associated with direct steam injection. That additional energy consumption required to achieve the high temperature conditions can be offset to about 8.5 GJ/tonne by employment of single stream tube digestion technology (Plant 3), which concept makes use of simultaneous bauxite and liquor pre-heating in the recoverable heating stages in digestion, also using indirect steam heating thus considerably reducing evaporation requirements. These changes reduce overall energy requirements by 3 GJ/t when compared to Plant 1 and 0.8 GJ/t when compared to Plant 2.

Further energy reductions of 1.2 to 1.3 GJ/tonne can be made (comparison between plant 3, 4 and 5) by removing evaporation and using red-mud caustic filtrate as a source of wash water, thus eliminating a major source of water ingress and solely relying on digestion as the source of water extraction in order to maintain a viable plant water balance.

	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5
Bauxite Consumption, t/t	2,40	2,54	2,40	2,400	2,40
Total Energy Consumption, GJ/t	11,55	9,25	8,45	7,17	7,14
Steam Consumption Oxalate Destruction, t/t	0,01	0,01	0,01	0,01	0,01*
Steam Consumption Mill liquor, t/t	0,09	0,09	0,09	0,07	0,08*
Steam Consumption Pre-Desilication, t/t	0,07	0,08	0,07	0,07	0,07*
Steam Consumption Causticisation, t/t	0,15	0,12	0,28	0,15	0,16*
Steam Consumption Digestion, t/t	2,52	1,22	1,93	2,36	0,00*
Steam Consumption Evaporation, t/t	0,75	0,91	0,69	0,00	0,00*
Total Specific Steam consumption	3,58	2,42	3,08	2,66	0,31*

Table 5: Specific Bauxite, energy and steam consumption for different plant configurations using identical bauxite, values are reported as per tonnes of calcined alumina. *export steam from digestion to other plant consumers.

Temperature Parallelograms were also developed for all five plants so as to comprehend the thermal efficiency of each plant. Figure 4 illustrates the temperature parallelogram for Plant 2, the low temperature scenario, highlighting heat inefficiencies associated with blow-off and overheating in evaporation. Likewise comparisons between plants Plant 1 and 3 in Figure 5 with same heat transfer areas in digestion show distinct differences between one another, namely the blow off tank where large amounts of steam are released due to the relatively high last flash tank pressures, implying that in order to achieve the same blow off conditions as per the single stream case (Plant 3) additional heat transfer area is required. Figure 6 shows little difference in thermal conditions, between all single stream scenarios, however it is worthy to point out that due to the fact the evaporation circuit has been removed in Plants 4 and 5, there is no risk of thermal overheating or excessive cooling in evaporation, due to the fact that liquor is directed straight from the heater interchange department (HID) to digestion.

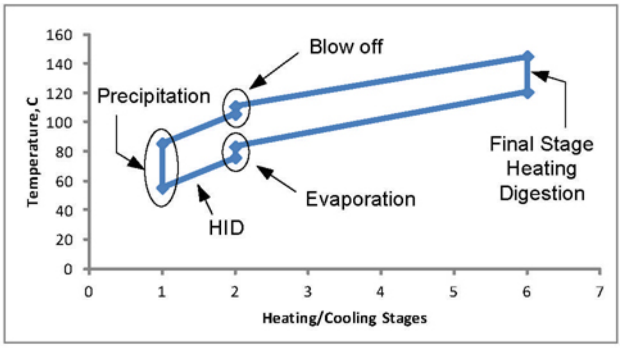

Figure 4: Temperature Parallelogram for Plant 2

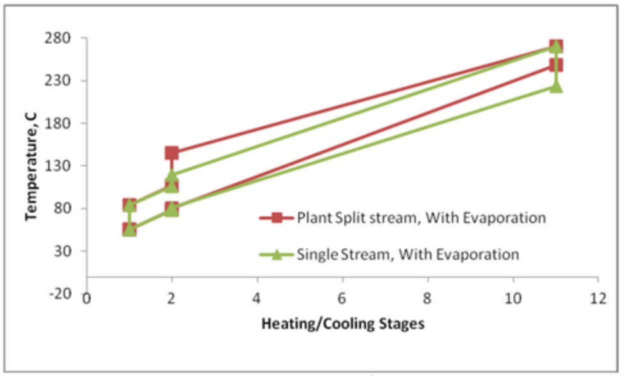

Figure 5: Temperature Parallelogram for Plant 1 and 3

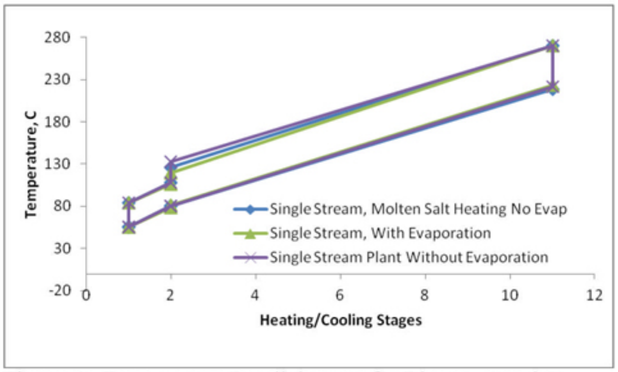

Figure 6. Temperature Parallelogram for Plant 3, 4 and 5.

Addressing the Additional capital costs of a High Temperature Digestion Installations

Throughout the industry there is much speculation about the benefit of high temperature digestion units using bauxites with low percentages of boehmite. Although it is well recognized a high temperature system is inherently more expensive due to the fact that more recoverable heating stages are required, the need for high pressure equipment and in some cases special lining to resist caustic embrittlement, it can be effectively demonstrated that the extra capital investment for such an installation can be amortized by alternate technological arrangements. Table 6 is the comparison in specific capital cost of the five plants. The capital estimates were based on a green field site in a zone “0” earthquake rated area, and on installed equipment basis.

The most immediate comparison is between Plant 1 and 2, as they illustrate the difference in costs between a plant using high temperature split stream digestion with direct steam injection and a plant using low temperature split stream digestion also with direct steam injection, this can be attributed to increased number of vessels for heat recovery, the need for high pressure equipment, the higher steam requirements which in turn require larger steam generation plants, which in turn requires increased evaporation capacity and not to mention the need for nickel lining to protect against caustic embrittlement. Unlike Plant1, Plant 3 conversely requires marginally less capital, due to the reduced steam generation and evaporation requirements in maintaining a closed water balance which is associated with the higher recoverable energy associated with single stream systems.

One of the major sources of water ingress into the Bayer circuit is wash water, by de-watering red mud using filter press technology [18] and recycling caustic filtrate back to the Bayer circuit a reduction in the plant evaporative requirements is gained, with the possibility of making the evaporation plant redundant, this scenario is reflected in the capital requirements for plant 4. Further capital expenditure improvements can be made from plant 4 to 5, with the addition of alternative heating mediums such as molten salt or thermal oils. Typically these systems require gas fired coiled vessels to achieve their operating temperature and are relatively inexpensive compared high pressure steam generation plants, not to mention they can be handled at atmospheric conditions at their operating temperatures without the need for high pressure piping or equipment.

Plant Area	Plant1	Plant 2	Plant 3	Plant 4	Plant 5
Specific Capital Cost, USD/t	1380	1250	1362	1338	1283

Table 6. Specific capital costs of Plants 1 to 5.

Conclusion

There is quite a large variation in energy consumption in the industry, and can be seen from data gathered from sites, however it is important to note that technological selection will have a large bearing on the definitive energy consumption is going to be for a future Greenfield refinery. The largest energy consumers in the onsite are Digestion, Calcination and Evaporation in this specific order. Selection of technologies such as circulating fluidized bed calcination and single stream digestion technology can have significant impacts on refinery energy requirements. The substitution of wash water with red mud filtrate by using filter press technology, leaves the option for either reduced evaporation requirements or elimination of the evaporation plant altogether. These progressive changes can amortize the extra capital requirements associated with the installation of a high temperature versus a low temperature refinery for the same bauxite, and can be further optimized via the substitution of steam as a heat transfer medium with thermal oils or molten salts. In conclusion this paper demonstrates that plants using high temperature digestion technology can achieve extremely low overall refinery energy consumption, and that the extra capital expense in their installation can be quickly recovered provided that necessary steps are taken to ensure this in terms of technology selection.

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