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SPECIFIC ENERGY CONSUMPTION IN ANODE BAKE FURNACES

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Abstract

For anode baking the specific energy consumption is one of the important cost elements. When evaluating a new furnace, guarantees regarding specific energy consumption are always prime questions that have to be answered by the supplier of the process control system. However, specific energy consumption is a function of numerous variables of which most are beyond the influence of the process control system. This paper discusses the main factors which influence the specific energy consumption for anode bake furnaces.

Introduction

The specific energy consumption will be discussed for a state-of-the-art open top anode bake furnace. Such a furnace, as shown in Figure 1, has a standard flue design with three baffles per flue. Anodes are placed in the pits with bottom and top facing the flue walls.

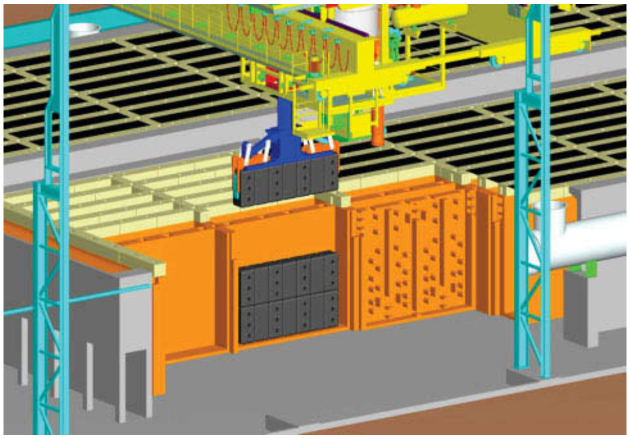


Figure 1: Open top furnace with three baffles flues and anodes loaded in the pits with top and bottom facing the flue walls.

When evaluating a new bake furnace guarantees regarding specific energy consumption are always a prime question that has to be answered by the supplier of the process control system. However, other factors as e.g. furnace design and operating parameters have a much bigger impact on the specific energy consumption than the process control system. Extended calculations validated on furnaces in full operation have been used to identify and quantify the key factors that influence the specific energy consumption. With such information and results it is possible to predict in advance the specific energy consumption of new anode bake furnaces. This allows also to adapt or change the design if the outcome of the calculations is unsatisfactory.

Factors Influencing the Specific Energy Consumption

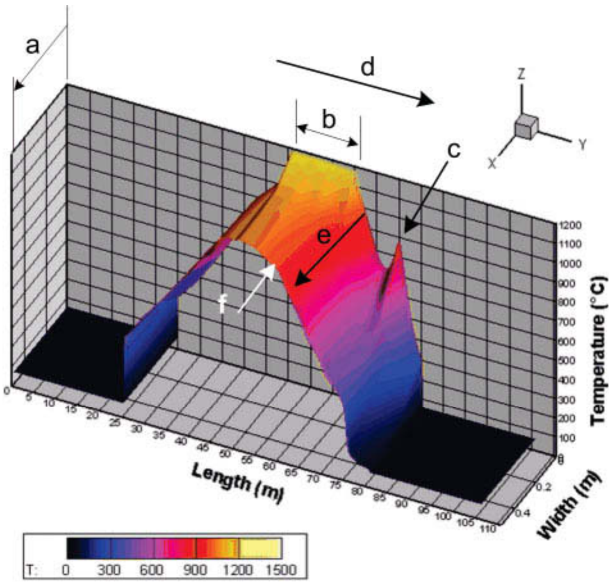
For undisturbed furnace operation, a number of boundary conditions have to be observed. If those conditions are neglected a poor furnace behavior may result, as, e.g. soot formation. The following boundary conditions have to be checked:

- <u>Oxygen content</u>: Based on our experience we know that a stoichiometric pitch volatile combustion is not possible. To be on the safe side, an oxygen concentration of 8 % has to be continuously maintained in the flue cavities of all heating sections to achieve a soot- and tar free pitch volatile matter combustion.
- <u>Under pressure</u>: For cost and for practical reasons (e.g., false air infiltration) the under pressure in the flues is limited. Based on our experience the under pressure should not exceed - 400 Pa (- 4 mbar) measured in the flue cavity just upstream of the exhaust manifold.
- <u>Heat-up rate:</u> Too high a heat-up rate may result in cracked anodes. Typically, a maximum anode heat-up rate of 15 °C/hour should not be exceeded.
- <u>Soaking time:</u> The soaking time should be long enough to allow the heat wave to penetrate from the flue cavity to the center plane of all anodes.
- <u>Refractory maintenance cost:</u> Actions meant to reduce specific energy consumption shall not result in increasing refractory maintenance cost through e.g. too thin refractory walls, as the overall impact of substandard refractory design will be negative.
- <u>Anode quality:</u> The specific energy consumption must never be optimized at cost of the resulting anode quality, as the inferior anode performance in the pots will greatly outweigh the gains of the energy saved.

Note that in this paper (and as common in the industry) "Specific Energy Consumption" means the amount of fuel (i.e. gas or oil) supplied to the process through burners, i.e. excluding the energy provided by the pitch volatile matter. Taking these conditions into account, the following relationships have been established:

<u>Pit Width</u>

Due to potroom requirements a trend to higher anodes is observed. Consequently broader pits are needed to accommodate such anodes. As a consequence a longer soaking and longer cycle time is needed to allow the heat wave to migrate the (longer) way from the flue cavity through the flue wall, the packing material layer and through half of the anode height to the pit symmetrical plane as shown in Figure 2.



Legend:
a: Half pit width, flue wall to anode center plane
b: Soaking time
c: Pitch volatile matter combustion
d: Direction of heat wave (combustion gas)
e: Direction of heat wave from flue to anodes
f: Anode temperature

Figure 2: Heat wave traveling the fire length and from flue to pit.

The increase in the required cycle time with wider pits is significant as can be seen in Figure 3.

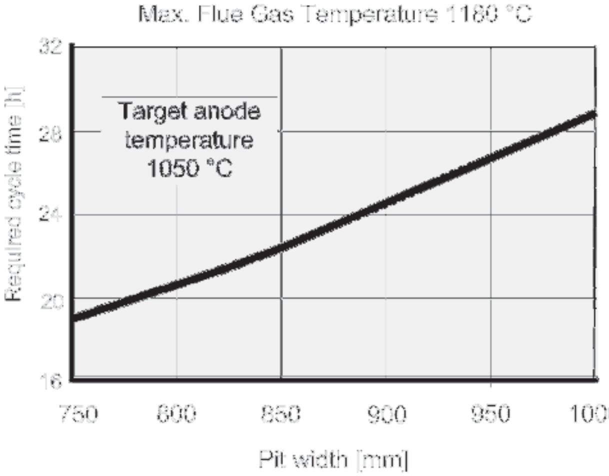


Figure 3: Relationship between pit width and required cycle time; flue gas temperature 1180 °C; target anode temperature 1050 °C.

Shorter cycle times can be achieved by increasing the flue gas temperature. This, however, is only possible within narrow ranges as not to endanger the flue wall refractory bricks.

Longer cycle times for larger pits (required for higher anodes) strongly influence the fuel consumption as shown in Figure 4. The calculation is based on a flue width of 320 mm and a soaking time of two cycles (i.e. flue gas temperature held constant) in the two most upstream heating sections. Under pressure boundary conditions may further create restrictions regarding combinations of flue and pit dimensions and cycle times.

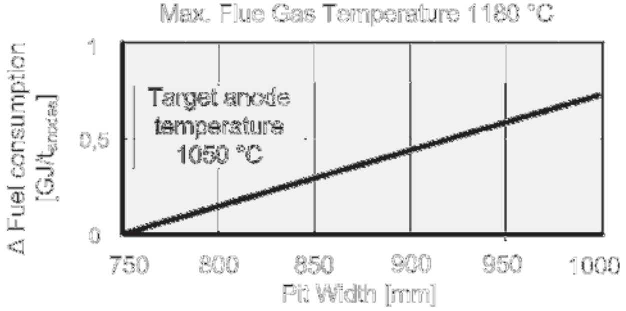


Figure 4: Typical relationship between pit width and extra energy consumption; flue gas temperature 1180 °C.

Hence furnaces with large pits to accommodate higher anodes require longer cycle times and show higher specific energy consumption compared to similar furnaces with smaller pits.

Flue Cavity Width

In designing a new furnace, flue cavity width is the most important boundary condition that can be varied in a rather vast range. In determining optimum cavity width, the following facts have to be considered:

- If the cavity is too small, available under pressure (by definition limited to - 400 Pa) will not be able to provide the required amount of combustion air (and thus O_2) to maintain an oxygen content of 8 % in all heating sections at all times.
- If the cavity is too large, air mass flow will increase unnecessarily, resulting in extra energy consumption required to heat up the higher quantity of combustion air as shown in Figure 5.

Defining the optimum flue cavity width is most important as too small cavities prevent complete pitch volatile matter combustion and too large cavities not only result in higher energy consumption but also in higher building cost.

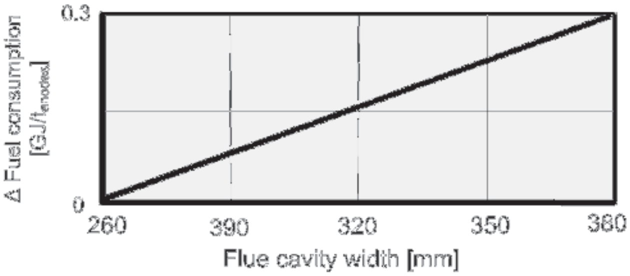


Figure 5: Typical relationship between flue width and extra energy consumption.

Hence the optimum cavity has the smallest width that allows to maintain the required oxygen levels continuously in all heating sections. The absolute value for the optimum flue width has to be calculated taking into account the boundary conditions regarding all relevant furnace- and anode dimensions, including probable future modifications of anode dimensions.

Section Length

Sections are separated from each other by a headwall, typically with a thickness of 0.4 to 0.5 m. Sufficient space between the headwall and the anode pack is required for the anode clamp and the packing material suction pipe. As a consequence the thickness of the packing material layer in the direction of the pit length will be in the range of 0.25 m to 0.3 m. The thickness of the headwall and the thickness of the packing material layer are virtually independent of the section length [1] and the ratio between anode pack length and section length is more favorable for longer sections. This means that the relationship of anodes to be heated up compared with the "dead material" is more favorable for longer sections as shown in Figure 6.

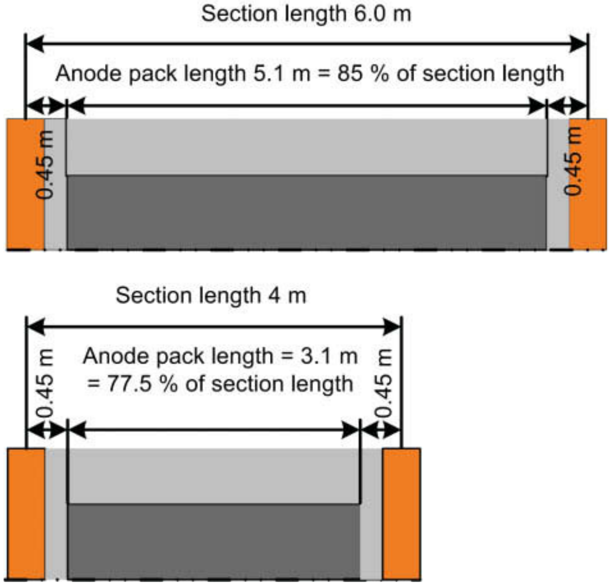


Figure 6: Share of anodes compared with "dead material", for long and short sections. Share of the anode pack length 85 % for the longer section compared with 77.5 % for the shorter section.

Figure 7 describes the relationship between section length and fuel consumption. The example has been calculated for an anode temperature of 1100°C in the pit center plane.

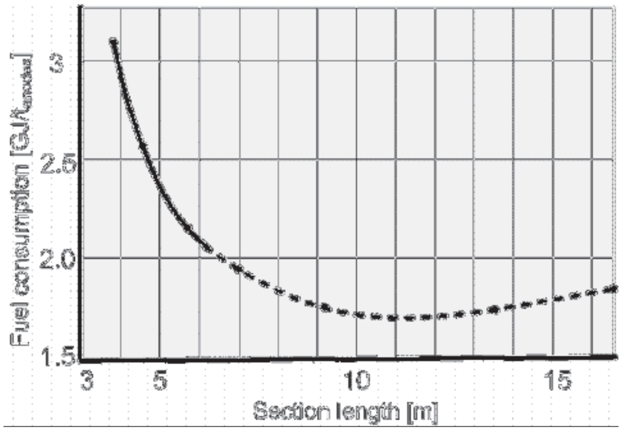


Figure 7: Impact of the section length on the fuel consumption. Dotted line: not feasible, due to refractory instability and excessive under pressure required.

The fuel consumption increase on the right hand side of the graph is irrelevant. Section lengths of more than approximately six meters are not feasible due to the instability of the refractory material. Furthermore, longer sections would require excessive under pressure values, resulting in extreme false air infiltration and a sharp fuel consumption increase.

As a consequence, longer sections are favorable regarding specific energy consumption. The section length is, however, limited by refractory instability and too high under pressure values.

Final Baking Temperature

The optimum final baking temperature is mainly a function of the petroleum coke grade used for the production of the anodes. It is obvious that increasing the target temperature will also increase the specific fuel consumption. Measurements on full size furnaces have shown that a baking temperature increase by 50 °C will increase the energy consumption by 0.2 GJ/t_{anodes}, equivalent to approximately 10 % of the nominal fuel consumption (Figure 8).

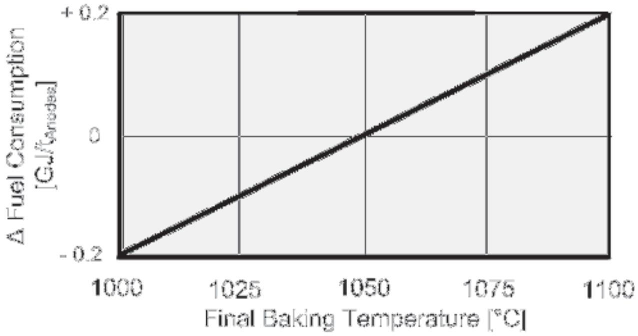


Figure 8: Relationship between anode baking temperature and fuel consumption.

Under baking is always detrimental for anode quality reasons. Over baking may be detrimental too, but is certainly unfavorable in view of energy consumption and refractory life [2].

As a consequence, every prediction regarding specific energy consumption is meaningless if the baking temperature has not been defined.

Pitch Content in Anodes

Energy supply from pitch volatile combustion is in the same order of magnitude as through the contribution from the fuel (gas or oil) supplied through the burners. Accordingly changes in the anode raw material characteristics and/or green mill processing parameters can have a substantial influence on the baking process. In fact a "Dynamic Process Optimization" (DPO) in the green mill as developed and conducted by R&D Carbon [3, 4] may reduce the pitch content from e.g. 15 to 13 %. As a consequence the energy supply from the green anodes is reduced by 13.3 %. If the modified anode formulation, however, requires the same baking temperature as before optimization, the missing energy has to be supplied by additional fuel of about 0.3 GJ/t_{anodes}. As shown in Figure 9 the total energy input has to remain constant.

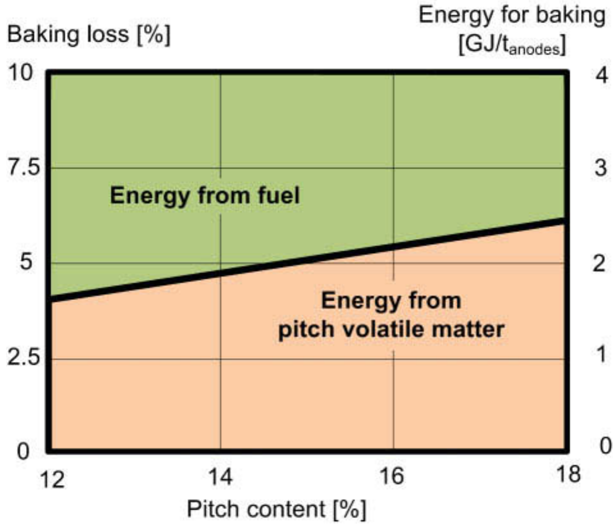


Figure 9: Relationship between energy supply from tar and fuel in function of the pitch content.

For anode quality considerations, the pitch content should always be determined for optimum anode quality and never for bake furnace fuel supply minimization.

Therefore, the pitch content has to be considered as a boundary condition governed by anode quality criteria, even if this will require an increase in the specific fuel consumption.

Combustion Efficiency

In a properly designed ring type furnace nearly 100 % of the pitch volatile matter is burnt in the furnace. Furthermore, most of the energy stored in the cooling area is transported to the heat-up area, significantly reducing the amount of energy to be supplied through the burners. Incomplete combustion of either pitch volatiles or fuel has been observed in furnaces being operated above their nominal capacity and in older, mainly hand-regulated furnaces with too small flue cavities. In both cases the required minimal oxygen level of 8 % may then not be continuously maintained in all heating sections.

Additionally a significant amount of solids (refractory material, packing material and anodes) has to be heated up. If the amount of solids could be decreased an increase of the combustion efficiency would result, This however, would result in higher refractory maintenance cost.

Both for a new or an existing bake furnace, a process optimization may nevertheless be very beneficial. Thereby parameters like heat-up rate, final baking temperature and soaking time will be adapted. The primary goal of such an optimization [2] usually is the increase of the furnace productivity and/or the anode quality. In some cases the goal may also be to increase the refractory life, reduce the emissions and/or increase the production rate. However, no process control system will be able to substantially compensate for inherent furnace design deficiencies. Increasing the output may result in a higher specific energy consumption. Depending on the anode demand, operating the furnace in such a way may be a smart strategy, considering the overall plant efficiency.

Considering the fact that the amount of solids to be heated is a boundary condition, process optimization has to focus on complete pitch volatile combustion and on optimum usage of cooling air for the combustion process. Furthermore, the specific energy consumption must never be optimized at cost of the resulting anode quality, as the inferior anode performance in the pots will greatly outweigh the gains of the energy saved [5]. Operating the furnace at a higher than minimal specific energy consumption, e.g. to increase the production can be a smart strategy taking into account the overall plant efficiency.

False Air

False air, i.e. ambient air sucked into the flue cavities through packing material and peephole covers is mainly a function of the following furnace properties:

- Flue wall construction
- Peephole construction
- Packing material granulometry
- Level of under pressure applied to the furnace
- Quality of refractory maintenance
- Furnace top sealing applied by, e.g., plastic sheets
- Port plate (obturator) design.

Typically, waste gas quantities in the range of 3000 to 5000 Nm^3/t$_{anodes}$ will be observed. It can be shown that 3000 Nm^3/t$_{anodes}$ has to be considered the minimum off-gas quantity for the operation of a typical furnace. In poorly operated and maintained furnaces, figures as high as 7000 Nm^3/t$_{anodes}$ have been found. Such furnaces have to be considered to be out of control. As shown in Figure 10, already an increase of 1000 Nm^3/t$_{anodes}$ will result in an extra specific fuel consumption in the order of magnitude of up to 0.5 GJ/t$_{anodes}$. Also, the level of energy consumption will rise with increasing waste gas temperature. As a consequence, for maximum energy efficiency, keeping false air quantities as low as possible is of paramount importance.

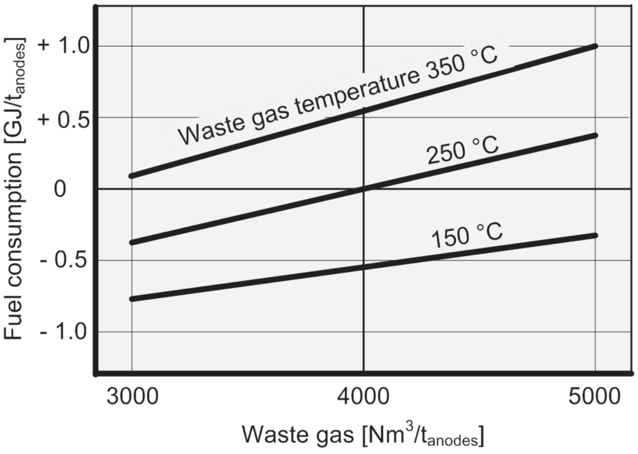


Figure 10: Fuel consumption differences in function of the waste gas quantity and of the waste gas temperature.

Hence poor furnace design, operation and/or maintenance, resulting in a higher than optimum waste gas quantity may increase specific energy consumption by up to 1 GJ/t$_{anodes}$.

Number of Sections in Heat-up

Furnaces with four to nine sections in heat-up have been observed. In modern furnaces, however, typically six sections in heat-up and 16 sections per fire are the rule. Designing the furnace with 17 sections per fire (7 in heat up) can be an interesting option to increase the production per fire by about 15 to 16 %. If, e.g. 168 hours are considered for heat treatment of the anodes, this can be achieved either with a cycle time of 6 x 28 hours or 7 x 24 hours. In the six sections heat-up arrangement, three sections are equipped with burner bridges. In the seven sections arrangement, four burner bridges are installed. As the furnace output for a given section load is inversely proportional to the cycle time, the 7 x 24 hours option will result in a production increase of 16 % compared with the 6 x 28 hours operation. As shown in Figure 11, the 7-section operation (with four instead of three burner bridges) has a higher under pressure demand to guarantee the required 8 % oxygen level. As a third possibility to accomplish a 168 hours baking period, a furnace can be operated with again four sections equipped with burner bridges and four (instead of three) sections in preheat. With a cycle time of 21 hours, the output will be even 30 % higher than in the 6 x 28 hours configuration, of course at the price of higher investment for an extra section per fire, and of a higher under pressure to be maintained in order to provide 8 % oxygen at all times and places.

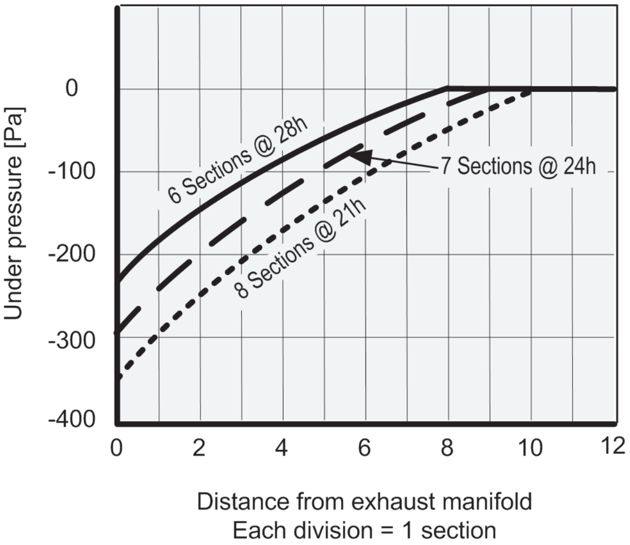


Figure 11: Under pressure profiles for furnace operation with 6, 7 or 8 sections in heat-up and with 8% oxygen continuously in all heating sections.

Depending on the operational parameters, furnaces operated with identical baking periods but different numbers of heating sections may show specific energy consumption differences of up to 10 %.

Summarizing, the number of sections in heat-up may influence the specific energy consumption with up to 10 %. Increasing the number of sections in heat-up is of course possible only if the number of sections per fire allows such a configuration.

Crossover Heat Loss Compensation

To compensate at least partially for the heat losses in the crossover channel, a certain amount of "over baking" is sometimes programmed for the last two sections upstream of the crossover channel. Such an action helps to avoid under baking of the anodes in the first and second section downstream of the crossover channel. As the extra energy input required for the over baking does not result in extra production this amount of energy contributes to the overall specific energy consumption of the furnace. As a rule of thumb the full compensation of the heat sink of the crossover would require an extra fuel equivalent to one furnace section. Supplying such an extra amount of fuel through the burner bridges is not feasible; 50 % is more realistic.

As a consequence, in a 2-fire furnace with typically 32 sections, crossover heat loss compensation increases the specific energy consumption by approximately 3 % and in a 4-fire furnace the increase equals to 1.5 %.

Impact of Poor Operation Practices

With all statements made in this paper it is supposed that the anode bake furnace is well maintained and well operated [6]. The most serious operational shortcomings observed in real life can be summarized as follows:

- Fire change delayed
- Not all baked anodes unpacked

Not unpacking baked anodes and delaying any fire change *always* results in a reduction of the anode production rate.

As a first approximation, the energy consumption increases with the same percentage as the production rate decreases.

Impact of Poor Refractory Maintenance Practices

Poor refractory maintenance practice may be the cause for delayed fire changes and for the impossibility to unpack all baked anodes. Furthermore, extreme quantities of false air may be observed. In most if not all cases of poor refractory maintenance an increased percentage of rejects will result. As the specific energy consumption is always related to the production of good anodes, the increase of the reject rate also increases the specific energy consumption. Energy consumption figures in the range of 3 - 4 GJ/t_{anodes} have been reported for such cases. Poor refractory maintenance may even result in a risk of explosions.

If such a situation is observed the furnace is out of control! Management concern should then not be to optimize specific energy consumption but to restore proper operation first.

Specific Energy Consumption Prediction

As discussed above the prediction of the specific energy consumption is now possible for any given furnace design and operation. Once the key dimensions and the main operating parameters have been identified, it is strongly recommended to calculate the expected specific energy consumption using numerical models. In such a way the risk of constructing substandard furnaces can be eliminated. This is of paramount importance as modifying existing furnaces is virtually impossible. Details of this approach will be presented in the near future in a separate paper.

Optimization of Bake Furnace Operation

Taking into account the information given in this paper it can be concluded that every furnace operator is confronted with at least the following competing or even conflicting goals:

- Anode quality
- Specific energy consumption
- Furnace output
- Environmental impact
- Maintenance cost

After analyzing the operational results of a significant number of furnaces, including the evaluation of the anode behavior in the electrolysis, we feel that the following statements can be made:

- The goal of any bake furnace optimization program must be to minimize smelter production cost and not bake furnace operation cost, as, e.g. through minimization of the specific energy consumption [5]. Due to the fact that additional energy is more often beneficial than detrimental for the resulting anode quality, a baking optimization to reduce the energy consumption is delicate. Substantial losses due to inferior pot performance can easily outweigh the gains.
- For a given furnace and cycle time, the final baking temperature, the heat up rate and the soaking time have a direct relationship with anode quality. Within the limits given by over baking, O_2 shortage and refractory brick temperature, accepting a higher specific energy consumption may be advantageous.
- Provided that a furnace is under control regarding all operational and maintenance aspects, optimization programs will then focus on balancing between anode quality, output, maintenance cost and environmental impact.

Concluding it can be said that typically specific energy consumption is not a goal as such, but a resultant of primary goals as the anode quality.

Conclusions

When evaluating a new furnace, guarantees regarding specific energy consumption are always prime questions that have to be answered by the supplier of the process control system. However, as shown in this paper, specific energy consumption is a function of numerous variables of which most are beyond the influence of the control system.

Thermal calculations verified through on-site measurements on anode bake furnaces allowed identifying the following key factors that influence the specific energy consumption:

- Pit width
- Flue cavity width
- Section length
- Final baking temperature
- Anode pitch content
- Furnace production rate
- Amount of false air
- Number of sections in heat-up
- Crossover heat loss compensation
- Operation practices
- Refractory maintenance practices.

With a typical specific energy (i.e. fuel) consumption of 2 GJ/t_{anodes} as a starting point, the impact of each factor mentioned above is in the range of 1 % - 10 % *per factor*! If by chance several factors are on the unfavorable side, a specific energy consumption as high as 3 GJ/t_{anodes} may result. As the energy consumption is always an important cost element, operating a furnace under such conditions will significantly increase baking cost. Even worse, poor operation and maintenance practices may create a significant risk of explosions. The furnace is then out of control and this situation has to be corrected first.

In the design phase of a new furnace it is now possible to calculate and predict the expected energy consumption. In doing so, the risk of constructing furnaces with sub-standard performance regarding specific energy consumption can virtually be eliminated.

For both a new and an existing furnace a process optimization may be very beneficial mainly to increase the furnace productivity and/or to improve the anode quality. In some cases the furnace process optimization may focus on increasing the refractory life, reducing the emissions and/or improving the combustion efficiency. However no process control system will be able to substantially compensate for inherent furnace design deficiencies. Furthermore, the specific energy consumption must never be optimized at cost of the resulting anode quality, as the inferior anode performance in the pots will greatly outweigh the gains of the energy saved.

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