RECENT DEVELOPMENTS IN ANODE BAKING FURNACE DESIGN

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Abstract

Today, furnace design still proceeds mainly by extrapolation from existing furnaces. Investigating existing furnaces shows the dangers of underestimating the impact of apparently small modifications: e.g., larger pits to accommodate higher anodes can result in furnaces with substandard performance. Side effects such as soot creation have then to be accepted. This paper presents an approach to bake furnace design which completely eliminates extrapolation from existing furnaces. The same approach can be used to estimate the optimization potential for existing furnaces.

Introduction

This paper discusses the design of open top ring type furnaces (Figure 1) with typically six to seven sections in heat-up and 16 to 18 sections per fire.

A modern and well-designed anode bake furnace should fulfill simultaneously the following goals [1]:

- Produce anodes with high and uniform quality, fulfilling the requirements of the potroom
- Production at design capacity even at the highest baking temperature.
- Soot free combustion.
- Lowest possible NOx generation.
- Low maintenance cost, high flue wall life time.

Figure 1: Open top ring type furnace under construction

In this paper, two different situations will be discussed:

- Design of new furnaces.
- Optimization of existing furnaces.

At TMS 2010 a paper has been presented discussing the factors influencing the specific energy consumption of anode bake furnaces [2]. This document now presents a method to design a furnace in such a way that all boundary conditions for optimum furnace operation as listed above are fulfilled. A similar approach allows identification of possible improvements for existing furnaces not performing as expected. Note that the specific energy consumption is not a characteristic furnace parameter that can be chosen freely but a result of the furnace design and operating parameters [2 and 3].

Boundary Conditions to be Observed

For typical anodes produced from calcined petroleum coke (CPC) and coal tar pitch, experience shows that a furnace should be able to fulfill the following boundary conditions in order to be able to properly bake all brands of raw material that may be expected:

- Maximum anode heat-up rate of approximately 15 °C/hour, in order to avoid anode cracking.
- Maximum final anode baking temperature of 1150 °C, measured by the Xylene density method according to ISO-9088. Note however that 1150 °C is an extreme baking temperature, possibly resulting in "over baking" with poor air reactivity properties as a consequence. Depending on the coke properties, a lower baking temperature in the range of 1050 °C to 1100 °C is most often sufficient without any significant quality loss but with the advantage of a lower energy consumption. However, the furnace has to be able to reach the maximum temperature level mentioned as certain CPC's may call for a high baking temperature level in order to reach the required quality level. Applying the method ISO-9088 is recommended, as experience shows that this method gives the most accurate results. The method is based on the fact that the Xylene density (or true density) correlates strongly with the baking temperature. In the practical application the method has to be calibrated by baking bodies of the same green formulation as the anodes in pilot plant furnaces to different baking levels.
- Experience shows that for soot free combustion a minimum oxygen level of 8 % has to be maintained in all flues at all times and at all places.
- Experience shows that for acceptable temperature homogeneity over the length and depth of a pit a "soaking time" (i.e. the time where the combustion gas temperature is held constant at the maximum level) should be not less than 1.5 times or preferably two times the nominal cycle time duration.
- For refractory construction stability reasons and for anode deformation reasons, pit length and depth is limited to approximately 6 meters each.
- For the sake of a high refractory service life, most refractory material suppliers ask for a maximum refractory surface temperature in the burner area in the range of approximately 1250 °C to 1320 °C. In a standard arrangement with a

thermocouple one baffle in front of a burner, a maximum refractory surface temperature of 1300 °C will typically be reached with a maximum combustion gas temperature somewhere in the range of 1150 °C to 1250 °C. Note that the acceptable refractory *surface* temperature is significantly lower than the maximum *service* temperature of the bricks applied as given in the data sheets. The maximum service temperature will typically be in the range of 1400 °C to 1500 °C.

- To keep the required ring main under pressure within reasonable limits, the under pressure in the flues in the first peephole just upstream of the exhaust manifold is typically limited to approximately 400 Pa.

From the customer, the following information has to be submitted:

- Maximum and minimum output in tons per year, defining the shortest and longest cycle time to be considered. For a given furnace and anode load the output is a function of the cycle time only, with the highest output determined by the shortest cycle time.
- Anode size, nominal and maximum. Experience shows that more often than not, the reduction plant will ask for longer and/or higher anodes. If this has not been taken into account when designing the furnace, experience shows that increasing the anode size will have a significant negative impact on pitch volatile matter combustion and on refractory maintenance cost.

Proposed Furnace Design Approach

Today, furnace design is all too often still done by extrapolating from existing furnaces, complemented by Computational Fluid Dynamics (CFD) calculations for the flue cavity design [4] among other aspects [5] and [6]. With a trend to higher anodes and thus wider pits simply adapting existing designs may result in unsatisfactory furnace behavior. This document describes a new approach for the determination of all key dimensions required to design a new furnace. It is assumed that the anode size, the required output and the desired maximum anode baking temperature is all that is given as a "starting point" for the calculations aimed to design the furnace. Unfortunately, the number of variables is too high to calculate all possible combinations of key dimensions. Extensive test calculations on existing furnaces allowed to prove that the job could be massively simplified by:

- Treating several variables as constants.
- Determination of furnace parameters by iteration.

After years of development and validating the calculations on a significant number of anode bake furnaces with different designs, the approach can now be launched for application in the industry. Furthermore it could be proven that a simplified approach also allows an estimate of the optimization potential of existing furnaces.

<u>Numerical Models Used</u>

The numerical models used in this paper are a combination of a 3D detailed model (1 section) with a global (all sections) 2D mass and energy balance model.

The 3D model was presented in [4] using a computational commercial code. It is useful to study gas flow patterns, pressure drop and thermal insulation options, considering detailed geometry. Figure 2 and Figure 3 present examples of 3D calculation results of fluid flow patterns, anode temperature distribution and gas temperature in the fire section.

The 2D global model was developed by CAETE to study the entire baking process simultaneously. Balance equations for heat transfer, species concentrations and pressure distribution are solved by a dedicated software, built up in a Fortran platform.

The anode baking furnace can be understood as a counter-flow heat and mass exchanger. The gases flow from the cooling sections to the preheating sections at a certain velocity determined by local pressure, temperature and infiltration conditions.

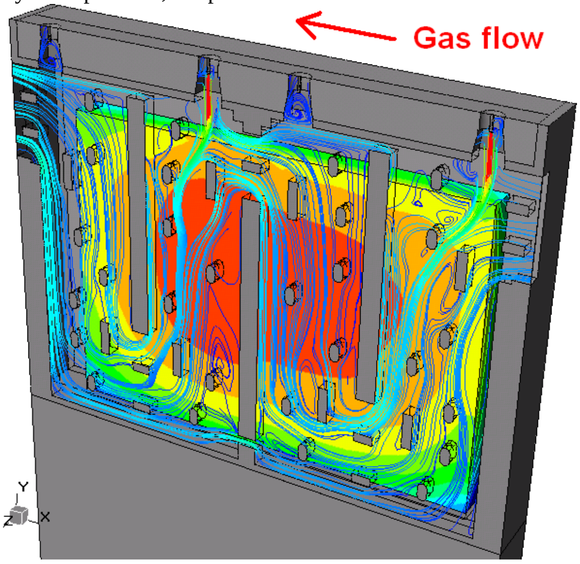

Figure 2: Gas flow streamlines and anode temperature distribution calculated by the 3D model

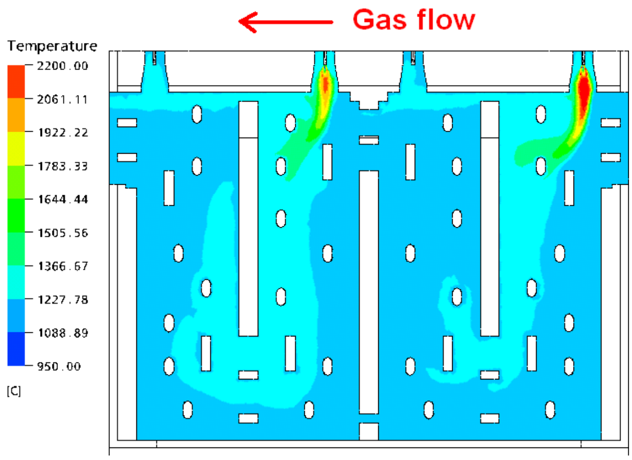

Figure 3: Temperature of the gas in the fire section showing gas natural flame inside the flue calculated by 3D model

The solids "flow" in a discrete step equal to 1 section per cycle time in the opposite direction of the gas flow. This model is inspired in the models presented R.T. Bui et al. [7] and R. Ouellet et. al [8], incorporating some improvements. The real transient effect of the fire and manifold movement is taken into account as the model is a true transient model inside each fire cycle and the fire movement occurs in a discrete way. The finite volume method is used for the evaluation of the balance equations.

The global model uses a 2-dimensional mesh representing a horizontal slice of the sections directly involved in the process (preheating, firing, cooling). Heat conduction inside the solids is calculated in 2D, but heat balance, oxygen concentration (and also CO_2, H_2O), inside the flue is evaluated in one-dimensional form, as it is considered that variations are small in the flue width direction. Heat losses to environment occur at furnace top, as well part of the heat is lost to the ground. These losses are taken into account in the modeling by imposing appropriate heat loss coefficients.

Treating Variables as Constants

Preliminary calculations have shown that a significant number of variables can be treated as constants, greatly reducing the number of alternatives to be considered. As an example, it can be shown that specific energy consumption decreases when increasing anode pack length (Figure 4) and height. Therefore, these variables are limited by the maximum allowable value compatible with refractory stability. The variable will thus be set to the limit given by the refractory restrictions.

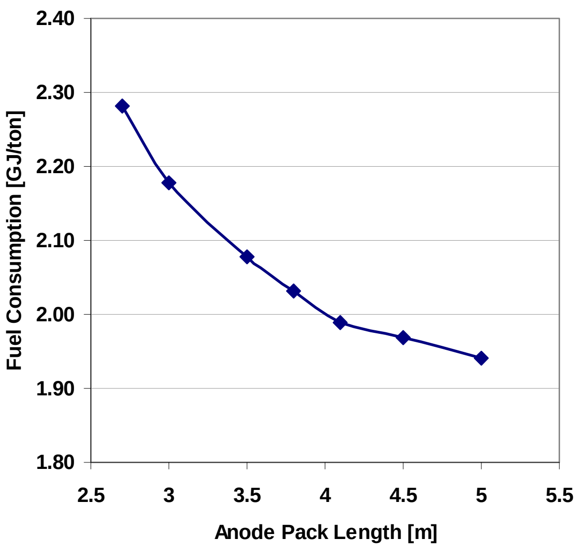

Figure 4: Specific energy consumption in function of the anode pack length

Similar considerations are valid for parameters such as pit height, top packing material layer thickness, headwall thickness, maximum combustion gas temperature and maximum refractory surface temperature.

Furnace Dimensioning by Iteration

Within certain limits, the number of sections in heat-up and the number of pits per section can be varied. Typically, six to eight sections in heat-up with three to four sections equipped with burner bridges will be found. The number of sections in heat-up will have an impact on properties as, e.g. the specific energy consumption, the optimum flue cavity width and the required under pressure. Separate calculation runs will be required for different flue designs and flue cavity widths. As the amount of computer time per run is within reasonable limits, this approach is considered adequate.

In a first step it will be possible to identify the optimum configuration regarding the number of sections in heat-up, the required flue cavity width for a given flue design and the necessary cycle time and soaking time for a given baking temperature.

In a second step, the availability of the draught required to produce soot free combustion under all circumstances is checked. The fuel consumption for this situation is also calculated. Soot free combustion is generally achieved if the oxygen concentration is 8 % or more in all heating sections at all times. A second calculation loop may be required, including the first step, if the oxygen check shows that the required minimum concentration cannot be achieved with an acceptable level of draught or if the fuel consumption is too high. Graphically, the calculation sequence is shown in Figure 5.

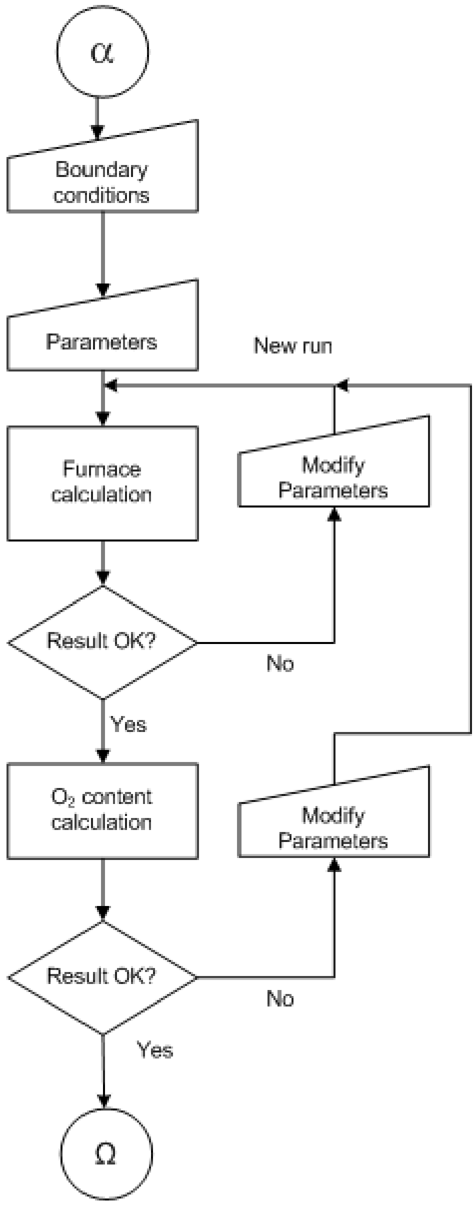

Figure 5: Basic calculation flow sheet

As an example, the significant impact of the baffle design and of flue cavity width on the minimum O_2 concentration in the flues for different under pressure levels has been calculated. Regarding baffle design, typically one of the two arrangements shown in

Figure 6 will be found. In the design on the left side, at the first and third baffle an opening with the height of one brick (approximately 0.09 m) is arranged. In the design on the right side no such gap is provided. Figure 7 shows the impact of the baffle arrangements depicted in figure 6 on the gas flow pattern.

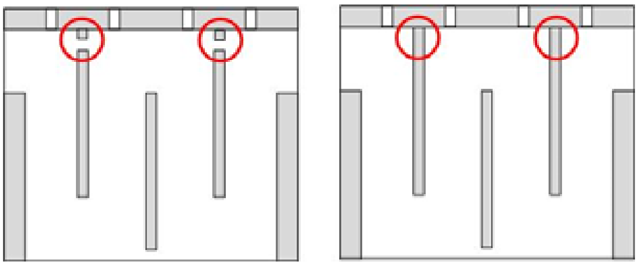

Figure 6: Typical baffle arrangements; left with gap on top of first and third baffle, right with closed baffles

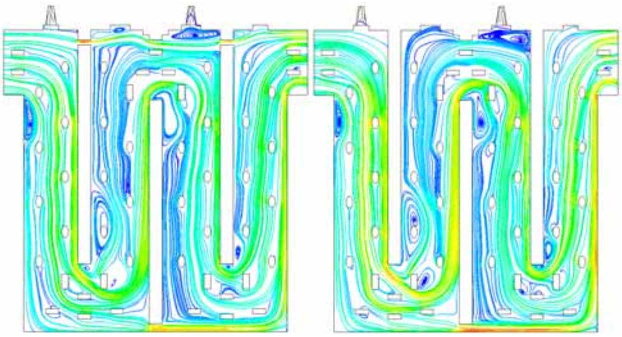

Figure 7: Gas flow streamlines calculated for the baffle arrangements shown in figure 6

Figure 8 gives the resulting minimum O_2 concentration for two different draught levels and for baffles with and without gap on top.

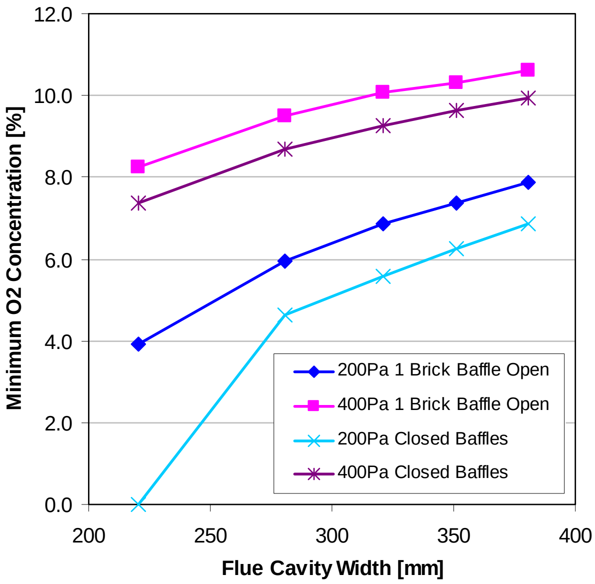

Figure 8: Minimum O_2 content in function of the flue cavity width, the baffle construction and the draught applied

Depending on the furnace construction the O_2 concentration may vary heavily over the duration of the fire cycle. Figure 9 shows an example of the O_2 distribution over the total heat-up area and over the full cycle time in intervals of 6 hours, for a configuration with 6 sections in heat-up.

In the example shown in figure 9 the target flue gas temperature is reached at the end of the cycle time and in the section equipped with the back burner bridge only (i.e. between the points 5 and 6 on the x-axis). The extra energy required in this section is the reason for the steeply decreasing oxygen concentration. The fast rate of oxygen level decrease observed between the points 1 and 2 on the x-axis is a result of the combustion of pitch volatile matter released from the anodes. In the first section upstream of the exhaust manifold (i.e. between the points 0 and 1 on the x-axis) most often an increase of the oxygen concentration is observed, due to fresh air infiltration. If pitch volatile matter combustion is already observed in the section mentioned (typically in the last few hours before the fire change) a decreasing oxygen content may result, as depicted in the 24 hours line shown in figure 9.

Similar calculation runs will be made for different combinations of parameters until a satisfying combination has been found.

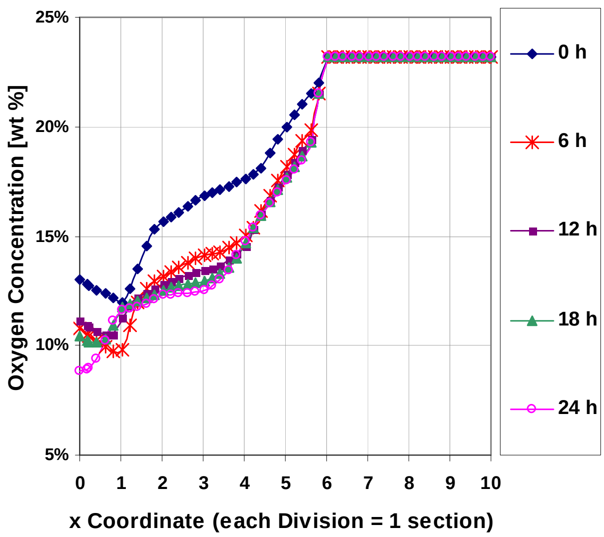

Figure 9: Oxygen concentration over heat-up area and one fire cycle, for a given baffle construction and draught level. Sections counted from the exhaust manifold

Impact of Higher Anodes on the Furnace Design

In the past, reasonable results regarding furnace behavior have been achieved by extrapolating the dimensions from existing furnaces. Such an approach is of course fast and cheap. There is however a significant risk of a pitfall. For example, in the last few years a trend to higher and higher anodes can be observed. In most furnaces the anodes are set in the pits with anode top and bottom facing the flue walls. In order to accommodate such anodes, the furnace design results in larger pits. Analysis of existing furnaces has shown that the impact of larger pits on the cycle time is often underestimated.

Figure 10 shows the massive impact of the pit width on the shortest possible cycle time required to reach a given anode temperature. In wider pits more time is needed by the heat wave to penetrate into the center plane of the pit. Increasing the cycle time is then the only option to reach the required baking level. Such an action has however as drawback a lower production as the furnace output is inversely proportional to the cycle time. In order to reach simultaneously a sufficient time for the heat wave to penetrate the pit *and* to maintain an acceptable output (i.e. to operate the furnace with a "short" cycle time) increasing the number of sections in heat up from six to seven or even eight sections instead of increasing the number of fires may be a solution. The different configurations will also differ in the achievable specific energy consumption.

It is a wise and cost effective approach of the furnace buyer to request from the supplier of the furnace and/or of the firing system during the bid phase a numerical furnace simulation to prove that the furnace is functional under the current and future conditions.

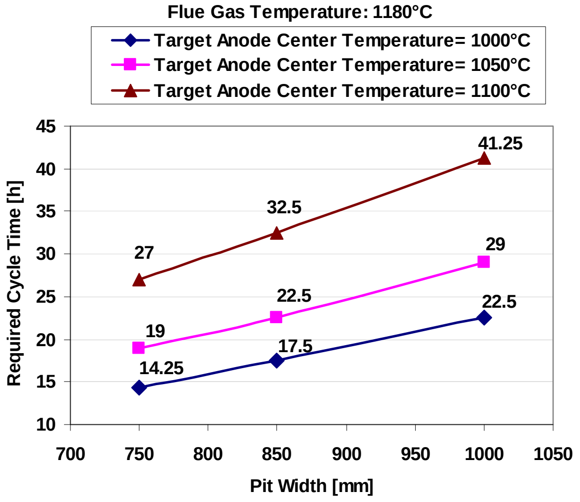

Figure 10: Impact of pit width on the required cycle time; six sections in heat-up

Discussion of Predicted and Achieved Results

The furnace operation data and measurements from several plants cooperating with the authors have been compared with the behavior predicted by numerical models in different aspects. These data were used for the fine tuning of the models.

The Figure 11 shows measured underpressure inside the flue cavities versus calculation results. The calculated underpressure profile was obtained by the 3D model using appropriate resistance parameters between flue chamber and atmosphere.

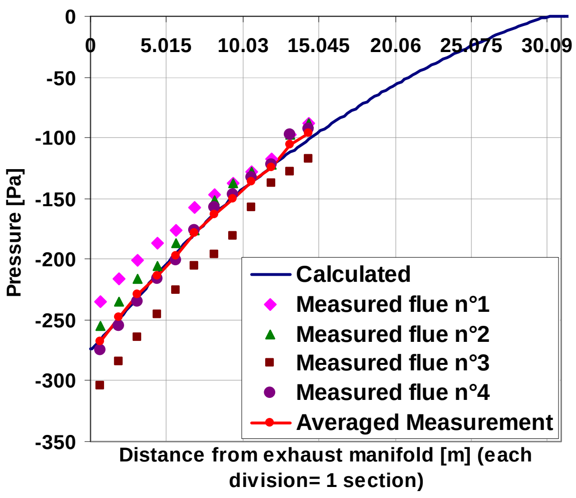

Figure 11: Comparison of measured and calculated draught profiles inside the flues at preheat

Anode temperatures inside the furnace were measured during the process by thermocouples installed inside the packing coke between fluewall and anodes. The Figure 12 shows the comparison between the averaged measured and model temperatures. Note the excellent agreement between the curves including the volatiles peak (after ~60h).

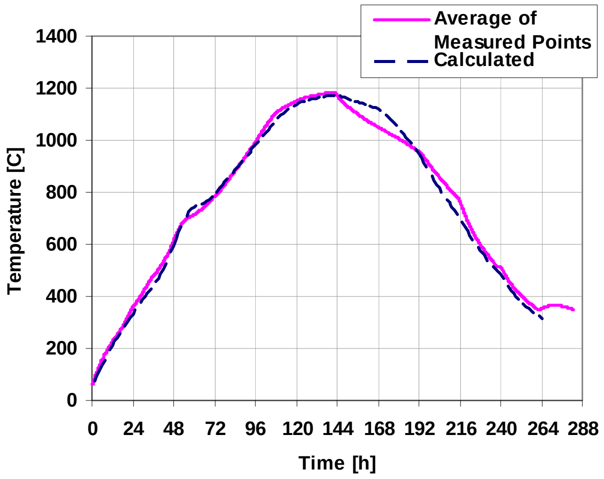

Figure 12: Comparison of measured and calculated temperatures inside the packing coke during the baking process

Designing New Furnaces

Using the calculation tools available today, it is possible to design and to predict the behavior of a furnace in such a way that the expected results can be achieved as well as regarding output, quality, energy consumption and combustion quality. The supplier of the furnace and/or the firing system should be requested in the bid phase to prove with a numerical furnace simulation the correct functionality under the current and future conditions.

Optimizing Existing Furnaces

If a furnace does not perform as expected, the tools developed allow pinpointing of the critical items and identifying possible actions to improve the situation. As the "starting point" is an existing furnace, the number of variables is extremely small. Measurements on the furnace can be used as input values, reducing heavily the amount of calculation work to be done. As an example, in designing a new furnace, the under pressure profile from the exhaust manifold to the zero pressure point upstream of the back burner bridge has to be calculated. In an existing furnace, this profile can easily be measured and applied as input for the calculations. Knowing the possible improvements makes it much easier to justify the required optimization tests [9].

Conclusions

A new approach regarding the design of new anode bake furnaces has been developed. Although the baking process is quite complex, it has proven possible to simplify the calculations by treating some variables as constants. Key dimensions can then be optimized within a reasonable number of iterations. In doing so, a furnace can be designed, to fulfill all important goals, i.e. output, quality, energy consumption, soot free combustion and operating cost at the same time. The supplier of the furnace and/or the firing system should be requested in the bid phase to prove with a numerical furnace simulation the correct functionality under the current and future conditions. Finally, this same approach can be used for the estimation of the optimization potential of existing furnaces.

Acknowledgements

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