A 90 MW CALCIUM CARBIDE FURNACE – PROCESS AND ELECTRICAL SCALE-UP

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Abstract

Circular 3-electrode furnaces of up to about 55 MW or 75 MVA capacity for calcium carbide production are well established having been built by several designers by the 1960s and have remained the state-of-the-art for over 50 years. Electrode sizes are at or near practical limits in these furnaces, so only incremental capacity improvements could be made without more electrodes per furnace. Rectangular, 6-electrode furnaces are in common use in other metallurgical applications and allow a step change in capacity with limited technical risk for the calcium carbide application.

This paper describes the scale-up for a furnace design rated at 90 MW active (real) power for calcium carbide production. The basis for the scale-up is Carbide Industries' (CI) well established 50 MW furnace and process in Louisville, KY. Working closely with CI, Hatch has adapted the design to a 6-electrode furnace configuration. Topics for the scale-up include adaptation to the 6-electrode electric circuit, power supply ratings, electrical provisions for variability in raw materials characteristics, vessel sizing, feeding and tapping arrangements, as well as mass and energy balance control.

The first application of the system is at the Qinghai Salt Lake Industry Co. (QSLIC) smelter in Golmud. Future application of the 90 MW furnace for ferroalloy production is a long term objective.

Introduction

Hatch has worked with partner Carbide Industries (CI) to scale up CI's circular, 3-electrode furnace to a rectangular, 6-electrode closed furnace design with twice the production capacity of CI's furnace. The new furnaces are guaranteed for 90 MW (real power) operation, with a maximum design capacity of 100 MW. The first application of these furnaces is four units for Qinghai Salt Lake Industry Co. Ltd. (QSLIC) in Golmud, Qinghai Province, P. R. China. Another furnace is being built for Qinghai Salt Lake Haina Chemical Industry Co. Ltd. near Xining, also in Qinghai Province. In addition to the furnaces, associated dry furnace off-gas cleaning and calcium carbide handling systems have also been designed by Hatch. At the time of writing, the furnaces are under construction. Further details of the overall process and associated projects are given in separate papers [1, 2].

The fundamental process and electrical aspects of scaling-up a 50 MW, 3-electrode, round calcium carbide furnace, to a 90 MW, 6-electrode, rectangular closed furnace configuration are outlined in this paper. CI's furnace has a long history of efficient, steady and reliable operation with a well-proven process and safe operating practices. The scale-up approach was therefore to maintain these well-established process characteristics, but adapt the equipment to doubled capacity.

CI's Furnace in Louisville, Kentucky

CI's 50 MW furnace has been operating continuously in Louisville, Kentucky since 1968, with major rebuilds required in 1975, 1982 and 2011. The furnace was originally built according to an Elkem design, and the original equipment and operating conditions were described by Frye in 1970 [3]. Numerous upgrades and design changes to the equipment have been made through the rebuilds and over the years, but the basic chemical and electrical process and configuration of the furnace remain the same.

The furnace is choke-fed with a carefully proportioned charge mix of lime and coke, which react at about 2,000°C to produce molten calcium carbide product and carbon monoxide off-gas co-product. Tapping practices and equipment have changed over the years, but continuous tapping was and remains the operating basis. The purity of the calcium carbide produced is in the range of 300-320 L/kg gas yield or around 80 weight % contained CaC_2. (The gas yield refers to the Chinese standard [4].) Furnace specific energy consumption is approximately 3.0 MWh/t of produced calcium carbide.

As described by Frye in 1970, the vessel was refractory lined, with an approximately cylindrical steel shell of about 10 m diameter and a water-cooled roof (or cover). Three Soderberg electrodes supplied power to the furnace, with nominal electrical operating parameters being 45 MW real power, approximately 115 kA electrode current and a secondary voltage of approximately 300 V. Power was supplied at a primary voltage of 13.8 kV through three 22 MVA, single phase transformers, equipped with on-load tap changers. Secondary voltage taps ranged from 180 to 380 V in delta-delta connection. Power factor was about 0.75.

Electrode and Reaction Zone Coupled

In a calcium carbide furnace, the chemical reaction is generally understood to occur in a zone around and below the electrode tip. It is thought that this zone is a packed bed of coke with its voids filled by molten calcium carbide and evolving reaction gas. The calcium carbide drains to the furnace hearth from where it is tapped adjacent to the electrode, while the gas percolates up out of the reaction zone and through the overburden into the furnace freeboard. As the reaction proceeds and calcium carbide is tapped, fresh charge mix descends into the reaction zone from the choke fed bed of charge above. The energy driving the endothermic calcium carbide production reaction and supplying the heat to melt the materials derives from submerged arc electrical resistance heating as high current passes through the reaction zones from one electrode to another.

The reaction zones form a crucible within the charge bed contained in the furnace cavity, and if close enough to adjacent electrodes, the reaction zones may overlap. In case of reaction zones overlapping, a larger crucible containing multiple electrodes exists. This condition allows for calcium carbide produced below one electrode to flow to and be tapped from a taphole adjacent to another electrode (liquid communication). Since it is not practical to tap at each electrode at all times, overlapping reaction zones that provide good liquid communication is a primary design requirement for a multi-electrode calcium carbide furnace [5].

The basic unit of the calcium carbide furnace as a multi-part reactor is the electrode and reaction zone pairs. Referencing again Frye's description of CI's furnace in Louisville in 1970, each part reactor has a power of 15 MW, sees a typical 115 kA current and from Ohm's Law, it can be inferred that the electrode resistance is approximately 1.1 m□. At this power level, based on 3.0 MWh/t, calcium carbide production is 5 t/h per electrode. 3.0 MWh/t is achievable with high quality feeds, efficient equipment design and steady plant operation. For clarity, the mass unit here is a Metric tonne, i.e. 1,000kg.)

To increase the capacity of the furnace as a whole, one must either increase the power through each electrode, or increase the number of electrodes. Calcium carbide production increases correspondingly. In 3-phase AC electric smelting furnaces, the normal electrode arrangements are three electrodes in a delta within a circular vessel, or six electrodes in a line within a long rectangular vessel. So to double capacity, the choice is between three electrodes with doubled power, or six of the same size.

Selection of Number and Configuration of Electrodes

As noted earlier, CI's Louisville furnace has operated well since the late 1960s with a steady and generally well understood smelting process. The operating parameters per electrode are well known and proven, and the relevant dimensions of the furnace are also known, of course. As a starting point for a scale-up, simply increasing the number of electrodes means that the main process and electrical parameters per electrode are known, as are key dimensions such as electrode diameter, electrode-to-sidewall distance and electrode tip-to-hearth distance.

Relative to these known parameters, increased power per electrode requires adjustments to many other parameters, mainly in furnace dimensioning, electrode sizing and electrical parameters. Westly [6] was able to determine generally for scaling submerged arc furnaces that:

$R \propto P^{-1/3}$, where R is electrode resistance to ground (or hearth) and P is electrode power, or

$I \propto P^{2/3}$, where I is electrode current.

Westly also builds on well-known earlier work which established that for submerged arc furnaces, the following relationship exists:

$k = R\pi D$, where k is a process specific factor known from reference installations, and D is electrode diameter.

Using these formulae, values for resistance, current and electrode diameter have been calculated for electrode power levels scaled up from Frye's description of CI's operation in 1970. These are summarized in Table 1. Also included in the table is estimated power factor for each case assuming inductance is unchanged from the base case. Finally, furnace diameter is also given, estimated based on a constant hearth power density.

Table 8: Scale Up Comparison for Higher Power Per Electrode for a 3-Electrode Furnace

Fraction of CI's Capacity (%)	100	133	167	200
Power per Electrode (MW)	15	20	25	30
Electrode Resistance (m□)	1.13	1.03	0.95	0.90
Electrode Current (kA)	115	139	162	183
Electrode Diameter (m)	1.58	1.73	1.87	1.99
Power Factor (%)	0.75	0.72	0.69	0.67
Furnace Diameter (m)	10	11.5	12.9	14.1

The comparison shows that as power is scaled up, electrode current rises. Although the current rise is less than in direct proportion to the power increase, it does quickly rise beyond precedents so far set in the industry. Electrode size is within the range of precedent, although near its limit. Furnace diameter is well within the range of precedent for circular smelting furnaces. Power factor goes down.

These results appear to suggest that such a scale-up to double capacity (30 MW/electrode) is possible provided that one can design suitable power supply equipment for the high current (183 kA). However, all of these cases represent significant extrapolations from prior practice based on scale-up formulae for which electrode power levels of not more than about 17 MW have been considered. It is unknown what new phenomena may manifest at the higher power levels, so these cases carry great uncertainties.

Additionally, the extrapolation is from a known operation (CI's) with consistent, high quality, well known and well controlled feed materials. For the scale up to be commercially useful, it should be broadly applicable in the calcium carbide industry, i.e. for a variety of raw materials possibilities. As will be seen later in this paper, making provision for the likely range of raw materials resulted in significant design margins being needed, especially with respect to resistance (allowing for lower values) and current (allowing for higher values). For a 30 MW/electrode scale-up, this implies design provision for electrode currents in excess of 200 kA.

Ultimately, a judgement was made that uncertainties in the process and electrical performance at very high electrode power levels were too great without some form of large-scale testwork. Instead, it was decided to increase the number of electrodes per furnace from three to six, and this led naturally to the well-established rectangular 6-electrode-in-line furnace configuration. It was judged that the challenges of developing completely new equipment designs could be managed by the design team. Hatch and CI's partnership allowed the two companies to make complimentary contributions to the new design: CI's process and operational knowhow was combined with Hatch's expertise in custom furnace design.

Vessel Scale-Up

The traditional approach to sizing 3-electrode submerged arc furnaces based on partially overlapping reaction zones is illustrated in Figure 1, taken from Kelly.**Ошибка! Закладка не определена.** Figure 2 shows how this concept has been applied for the scale-up to a 6-electrode-in-line furnace. Reaction zones between electrodes overlap in the same way as in the 3-electrode furnace.

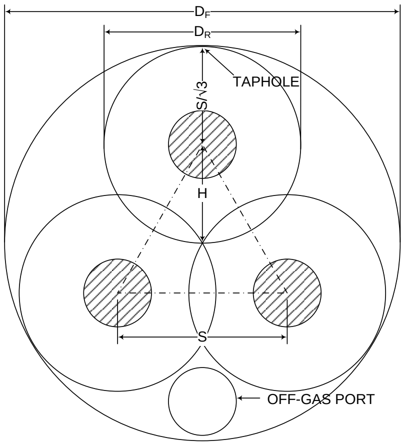

Figure 15: Traditional 3-Electrode Circular Furnace Sizing

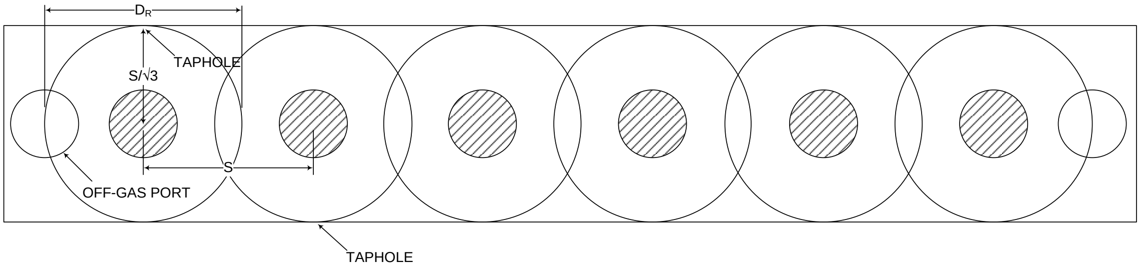

Figure 16: Adaptation of Traditional Sizing Approach for 6-Electrode Rectangular Furnace

Note that for the in-line electrode arrangement, there is no corresponding hot spot in the centre of the furnace between three electrodes. It was thought that the central hot spot tends to ensure flow of the carbide in the furnace between the reaction zones. As a result, for the in-line furnace, a small adjustment was made to decrease electrode spacing to provide greater overlap between electrodes to compensate for the absence of the hot spot and thereby ensure good liquid communication between the reaction zones.

Off-gas ports on circular furnaces are normally located in the dead zones towards the shell between electrodes, as shown in Figure 15. For the rectangular furnace, these zones are too small, so off-gas ports have been located at each end of the furnace, as shown in Figure 16, thus extending its length relative to the minimum required by the reaction zones. Considering the foregoing, the resulting furnace size is about 6.5 m across and 27 m long at the shell. In comparison to CI’s reference, hearth area is slightly more than doubled, mainly because of the extra space required to accommodate the off-gas ports.

Overall vessel height was based on the precedent at CI. However, the furnace was made slightly higher to allow for greater freedom to set electrode burden depth above the electrode tip to adapt to different feed materials and application of the technology at higher than sea level elevation. (QSLIC’s Golmud project is located at 2,800 m above sea level where atmospheric pressure is about 71 kPa.) Magnesium recirculation within the furnace is the main consideration. Mg crusting within the furnace charge may lead to lost charge permeability and when severe, can cause furnace disruptions that may include over-pressurization, blows, and in extreme cases, eruptions.

Mg recirculation results from formation of Mg vapour in the hot reaction zone of the furnace ($MgO + C \rightarrow Mg + CO$) and its reoxidation in the charge above the electrodes or in the furnace freeboard ($Mg + CO \rightarrow MgO + C$). It is likely that higher levels of Mg in the feed and higher elevation are competing factors which affect the equilibrium of these reactions. With a somewhat higher furnace, the operators have greater freedom to raise or lower electrodes to adjust off-gas temperature and the equilibrium. Of course, such adjustments have secondary electrical effects on resistance, so adjustments must be made with consideration for these effects as well.

Mass and Energy Balances

In terms of mass and energy balance, the furnace process scales directly on a per electrode basis. Thermal and electrical energy losses have been estimated for both CI’s 3-electrode circular furnace and for the 6-electrode rectangular furnace. Overall, these losses are the same in both cases and there is no net change in furnace specific energy consumption. In both cases, specific energy consumption is about 3.0 MWh/t for good quality feed, i.e. metallurgical coke with 88% fixed carbon (moisture free basis) and burned lime with 96% CaO. The balances are summarized in Table 2 both on specific and absolute bases.

Table 9: Mass and Energy Balances

Input / Output (Mass / Energy)	**Temp (°C)**	**Specific Value**		**Typical – 45 MW**		**Scaled-Up – 90 MW**	
		Mass (t/t CaC_2)	**Energy (MWh/t CaC_2)**	**Mass Flow (t/h)**	**Power (MW)**	**Mass Flow (t/h)**	**Power (MW)**
Inputs							
Charge Mix	25	1.45	-	21.8	-	43.5	-
Electrical Energy	-	-	3,000	-	45.0	-	90.0
Total	**-**	**1.45**	**3,000**	**21.8**	**45.0**	**43.5**	**90.0**
Outputs							
CaC_2 (300 L/kg)	2,000	1.00	740	15.0	11.1	30.0	22.2
Off-Gas & Dust	800	0.45	120	6.8	1.8	13.5	3.6
Chemical Reaction	-	-	1,840	-	27.6	-	55.2
Electrical & Thermal Losses	-	-	300	-	4.5	-	9.0
Total	**-**	**1.45**	**3,000**	**21.8**	**45.0**	**43.5**	**90.0**

Data presented in the Table will vary for differing raw materials characteristics and detailed calculations that must be prepared for any particular new application. Specific energy consumption can be significantly increased, and furnace productivity decreased, if low quality raw materials are used.

Tapping

Tapping of a choke fed calcium carbide furnace is its primary means of mass and energy balance control. Once the power is turned on and material is heated, reactions occur and feed is consumed. If the calcium carbide pool is over-tapped, tapping naturally stops because there is insufficient liquid remaining. On the other hand, if tapping does not keep pace with the rate at which the calcium carbide is produced, then the calcium carbide accumulates, electrode currents increase rapidly and the liquid pool overheats. This can lead to troublesome liquid boil-ups and dangerous gas blows. For large, high production rate furnaces, it is continuous tapping that keeps the furnace in balance by ensuring that liquid calcium carbide is removed at approximately the same rate at which it is produced, and thus is prevented from overheating.

Tapping at CI uses three tapholes, one adjacent to each electrode, and is continuous. Each taphole is worked in sequence around the furnace and tapping shifts from one hole to the next, with the tapping frequency varied depending on furnace conditions. Normally, as one taphole is being closed, then the next is being opened. Two tappers are required. If tapping must be interrupted for an extended period of time, then power must be shut off. The tapping sequence at CI is illustrated in Figure 3 below.

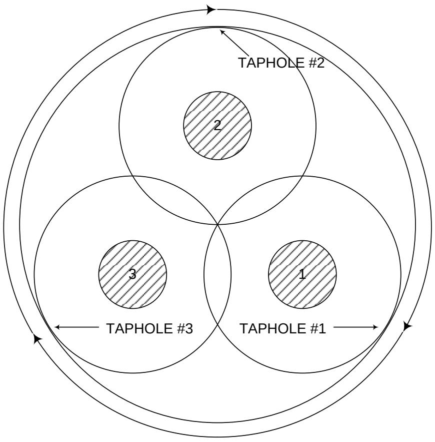

Figure 17: Tapping Sequence at CI

For the 6-electrode furnace, it was intended to match this approach as closely as possible to achieve the same objectives. Consequently, the furnace is provided with six tapholes, one adjacent to each electrode. For the circular furnace, tapholes are located approximately 10.5m apart along the perimeter of the shell. This leaves plenty of space available to accommodate the tapping components on the furnace and the ancillary equipment on the adjacent tapping floors. However, for the rectangular furnace with electrodes on less than 4 m spacing, it is impractical to locate all tapholes along one side of the furnace. Instead, three tapholes are located on each sidewall at the Electrode #1, 3 and 5 positions on one side, and on the Electrode #2, 4, and 6 positions on the other side. This is illustrated in Figure 4.

With three tapholes on each side of the furnace, it was natural to follow CI's tapping rotation among three tapholes, except in this case two tappers work on each side of the furnace and circulate among their tapholes. This is also illustrated in Figure 4.

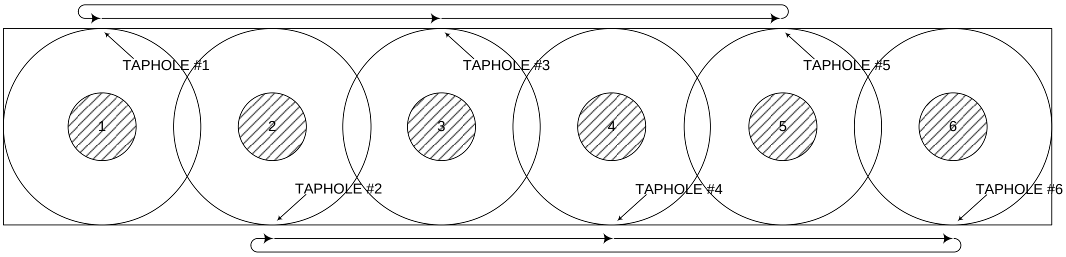

Figure 18: Tapping Sequence for the 90 MW 6-in-Line Furnace

Electrical Scale-Up

The choice to proceed with six electrodes leads to selection of electrodes of the same size as the precedent, i.e. CI's 1,575 mm diameter. However, Hatch's current generation electrode column system has been recently built for 1,600 mm diameter electrodes, so this was selected to avoid unnecessary redesign. It has been determined that this has negligible impact on the process and electrical characteristics of the furnace.

The 3-phase AC electrical circuits differ between the 3-electrode and 6-electrode furnaces. In the 3-electrode case, the furnace comprises a single 3-phase electrical circuit supplied through three electrodes, one for each phase, from three single phase transformers connected in delta or star configuration or from a single three-phase transformer. In the 6-electrode case, the furnace comprises three single phase circuits, each supplied by a single phase transformer connected to an electrode pair. The two arrangements are shown schematically in Figure 5 below. Note that the electrode to hearth resistance of 1.1 mΩ quoted for the 3-electrode furnace is equivalent to 2.2 mΩ per electrode pair for the 6-electrode furnace. Note also that the 6-electrode furnace has been designed for the higher primary voltage of 110kV available for the QSLIC project in Golmud.

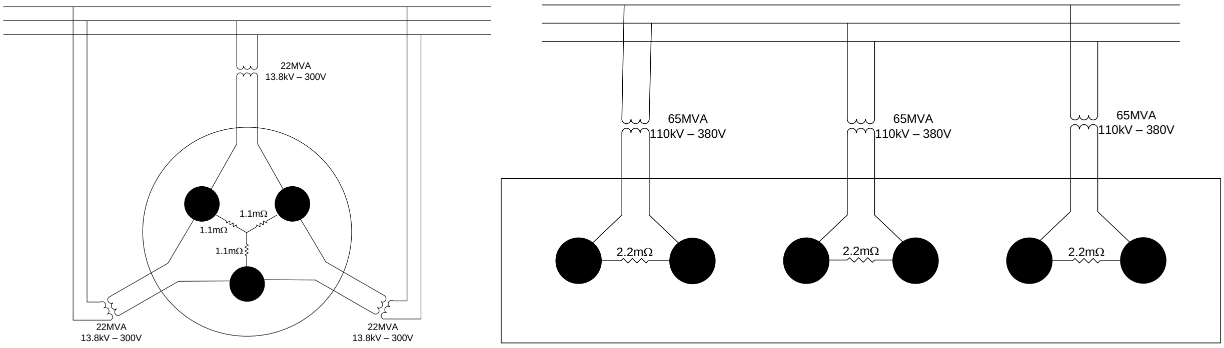

Figure 19 – Furnace Electrical Circuit Comparison

The operating resistance in a calcium carbide furnace is influenced by a number of factors including the furnace design and dimensioning, as well as the raw materials. In particular, particle size of lime and coke, chemical composition of lime and coke, and resistivity of coke are known to affect the operating resistance. There is no systematic way to calculate precisely the operating resistance of a calcium carbide furnace based on quantification of these parameters. In fact, even in cases of consistent furnace feeds at any particular plant, the operating resistance varies significantly over time.

In principle, Hatch's 6-electrode furnace power supply sizing is based on Westly's C3 curves [7], along with Carbide Industries' and another producer's operating data. Figure 20 shows the Power-Voltage-Current (PVI) diagram of the 90MW furnace. The diagram indicates the relationship between the furnace power and electrode currents for each transformer tap position. These operating points can also be correlated with the electrode resistance values shown in black lines. The target operating setpoint of the furnace, 90 MW at 115 kA, which corresponds to 2.2 mΩ resistance per electrode pair is indicated on the diagram. The Westly curves for calcium carbide with different confidence levels are also shown.

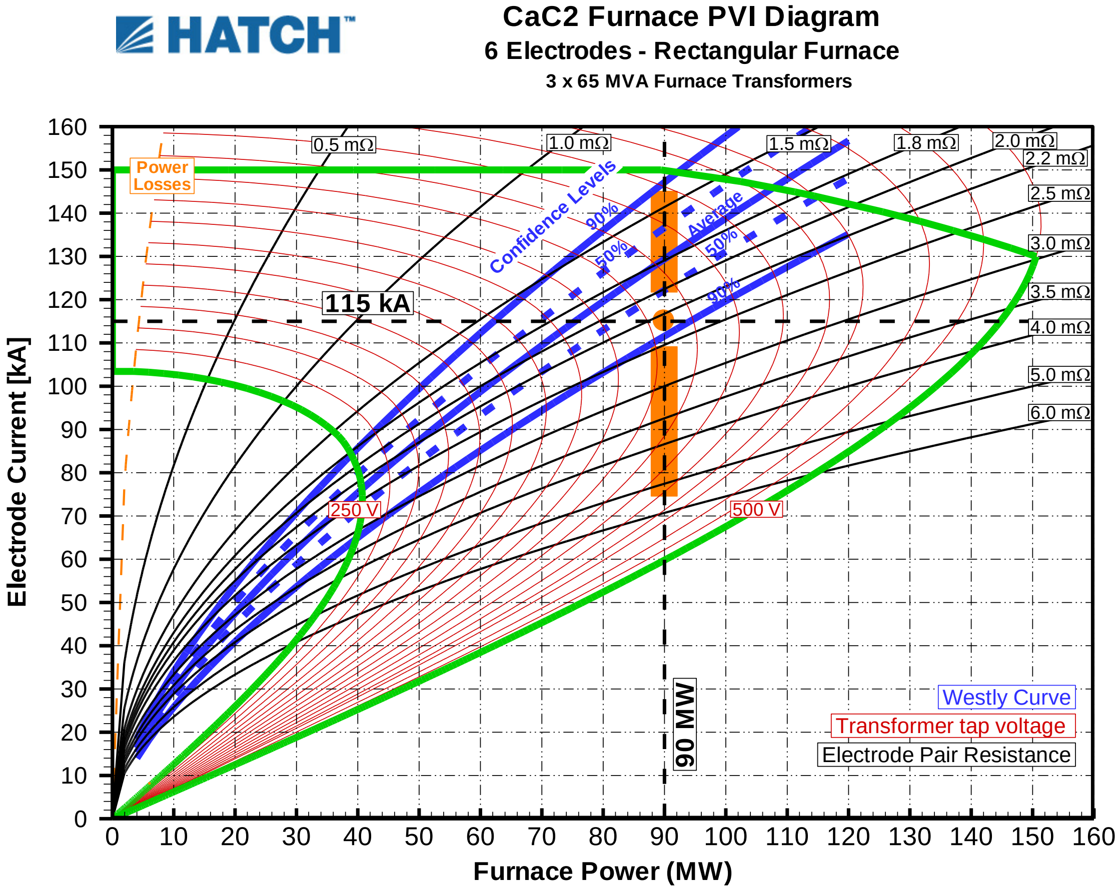

Figure 20: PVI for the 6-Electrode, 90 MW Furnace

While the target operating point is based on Frye's description of CI's furnace, one can see from inspection of the PVI diagram that it sits favorably near the lower edge of the range of Westly's curves. It is a favourable position within the range since its relatively high electrode pair resistance reduces current and increases power factor. This is reflective of CI's careful management of the raw materials and operating practices.

For the scale-up to the 6-electrode furnace to be commercially useful, it should be broadly applicable in the calcium carbide industry, i.e. for a variety of raw materials possibilities. So, one can note in the PVI that the furnace operating envelope (shown in green) allows for a wide variation of the operating parameters, including the likely range of potentially observable resistance at 90 MW according to Westly. Since furnace power supply cannot usually be easily upgraded, the operating envelope was sized such that it provides enough room for any future variation in the raw materials as well as for operational improvements. This is indicated with the orange rectangular boxes above and below the design 90 MW, 115 kA, and 2.2 mΩ electrode pair resistance operating point.

Since the operating power factor of such furnaces can be as low as 0.50, the power supply needs to be designed with adequate power factor correction equipment to ensure not only an acceptable power factor to the power supply utility but also to ensure that the voltage drop of the furnace transformers' supply bus is managed adequately. Depending on the actual objective, the power factor correction capacitor bank should be able to supply a capacitive reactive power of around 100 MVAr. Depending on the actual system, this can be achieved by using switchable capacitor banks, or, if a more sophisticated control is required, even a STATCOM [8] system may be used.

Based on the available operating envelope (the green line) the power supply system will allow production with a power level of up to 100-105 MW, which is the present upper limit considering the physical size of the furnace. However, in later stages even higher power levels may be possible with experience and/or mechanical upgrades which may be considered in the future.

Conclusion

A new 6-electrode rectangular 90 MW calcium carbide furnace design has been developed. Its process and electrical scale-up has been developed using information obtained from the furnace operated by Carbide Industries in Louisville, Kentucky since 1968. The scale-up approach is to maintain a 15 MW electrode and reaction zone as a basic element of the furnace, and to increase the number of electrodes and reaction zones within the vessel. This approach minimizes uncertainties in the operation of the process and of the main electrical parameters, since these factors are based on extensive proven industrial operating histories. This approach required an entirely new equipment design, both in terms of the configuration of the furnace vessel and its associated power supply circuit.

Allowance has been made in the design for a range of likely raw materials characteristics to give the furnace broad industry applicability. Eventually higher power operation is forecast as operating experience is gained.

The first five of these new furnaces are under construction in China for QSLIC at the time of writing. After commissioning, these will be by far the largest calcium carbide furnaces ever operated.

A longer term objective for Hatch is to apply the design for ferroalloy production.

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