THERMAL BEHAVIOR OF ACHESON FURNACE BY ITS CURVE OF ELECTRICAL RESISTANCE

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Abstract. *The silicon carbide, SiC, has important physic and chemical properties, such as high hardness, high abrasion resistance, low coefficient of thermal expansion and high thermal conductivity. Such applications make the silicon carbide an important material in the foundries, steel industries, and machining of materials as well. SiC is formed by extremely endothermic reaction between carbon and silica and its industrial process has an intense energetic impact on society. Acheson Furnace is the only process of SiC which makes possible their production on an industrial scale. It is applying a voltage between terminals of a graphite electrode surrounded by a stoichiometric mixture composed of sand and pet coke. Then a current flows through the electrode, generating heat and transforming the mixture into a cylinder of SiC concentric to the graphite electrode. The thermal behavior of this kind of furnace is relatively unknown by the scientific and industrial communities due to several factors, mainly the difficulty of measuring temperature at different points inside furnace. In larger plants, the run time of these furnaces ranges from 3 to 8 days. Daily in some plants, runs are interrupted for 3 hours due to power peak time. Knowing the difficulties of thermal control, the curve of electrical resistance becomes a great ally to interpret the thermal behavior of furnace. It was observed that the equation relating the electrical resistance with the resistivity and length of conductor, and with inverse of its sectional area, as well, can be used in order to interpret the thermal behavior of the furnace. From a typical operation of Acheson furnace, were collected the values of electrical parameters such as current, voltage and power to determine and plot the curve of resistance. The length of the conductor remains constant throughout the run. Due SiC has excellent conductivity, their formation increases the sectional area of conductor, causing the fall of electrical resistance gradually throughout the run. The resistivity of graphite varies greatly with temperature and its influence may be observed mainly in hours after the peak time, when there are largest thermal oscillations. Experiments were performed in order to analyze the behavior of resistance curve when a partial power is applied to the furnace, comparing with the behavior of the furnace when it's off for three hours. Using the interpretation of thermal behavior from the curve of electrical resistance was possible to analyze the energetic impacts of shutdown for three hours at peak time. The experiments were conducted in different furnaces, with different power. The energetic balances of them were similar, confirming the efficiency of thermal analysis of Acheson furnace through the curve of electrical resistance. With the efficiency of this method confirmed, it was possible to determine the feasibility of hiring power demand during peak time. Due the high price of power at peak time, it was deemed unfeasible.*

Keywords: *Acheson Furnace; Silicon Carbide; SiC; Electrical Resistance;*

1. INTRODUCTION

The silicon carbide, SiC, has important physic and chemical properties, such as high hardness, high abrasion resistance, low coefficient of thermal expansion and high thermal conductivity. Such applications make the silicon carbide an important material in the foundries, steel industries, and machining of materials as well. (Semeghin, Magliano, 2010)

SiC is formed by extremely endothermic reaction between carbon and silica and its industrial process has an intense energetic impact on society

According to (Abel 2007), SiC has two phases, alpha and beta. Among these two phases, different types of applications are known. This variety provides the existence of different production routes for obtaining SiC, which influence the application and the product cost.

Acheson Furnace is the only process of SiC which makes possible their production on an industrial scale. It is applying a voltage between terminals of a graphite electrode surrounded by a stoichiometric mixture composed of sand and pet coke. Then a current flows through the electrode, generating heat and transforming the mixture into a cylinder of SiC concentric to the graphite electrode. (Lindstad, 2002)

The thermal behavior of this kind of furnace is relatively unknown by the scientific and industrial communities due to several factors, mainly the difficulty of measuring temperature at different points inside furnace. In larger plants, the run time of these furnaces ranges from 3 to 8 days.

2. METHODOLOGY

In some plants of Silicon Carbide, the runs are not continuous from the beginning to end, they are interrupted during peak time and the furnaces are shut down completely for three hours. The distribution of power demand in the Brazilian electrical system, allows for two days of the week, the furnaces work without interruption. As the furnaces are shut down and a modulation occurs in the power curve of the furnaces, this period of interruption is also called the time of modulation.

Knowing the difficulties of thermal control, the curve of electrical resistance becomes a great ally to interpret the thermal behavior of furnace.

It was observed that the equation relating the electrical resistance with the resistivity and length of conductor, and with inverse of its sectional area, as well, can be used in order to interpret the thermal behavior of the furnace. Fig.1 shows a typical curve of electrical resistance to this process.

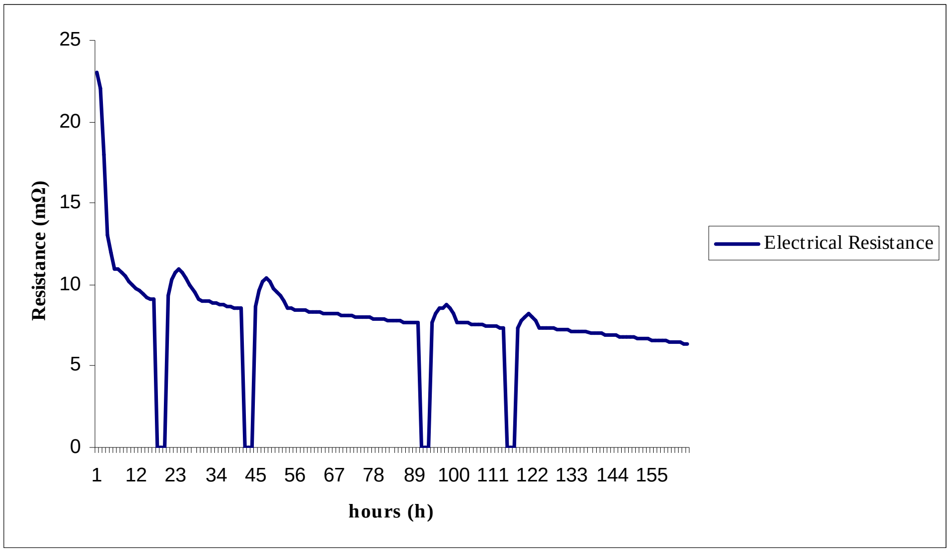

Figure 1. Typical curve of electrical resistance of an Acheson run with Peak Time

In the early hours there is a reduction of resistance, followed by a phase of instability. This initial period is called warm up time.

Interruptions due to peak time are clearly shown in the figure, where it is also possible to see the days when the furnaces are not interrupted.

During 170 hours of a run of an industrial Acheson furnace, were collected hourly the following electrical quantities, with their respective units inside the brackets. The furnace's run occurred in seven days and was interrupted for three hours on four occasions.

- Voltage (V) applied to electrodes
- Current (KA) flowing through the graphite electrode
- Power (KW) supplied to the furnace
- Accumulated energy consumption (KWh)

With the values of voltage and power, you can get the value of electrical resistance (R) of the furnace through the eq.1:

$$R = \frac{V^2}{P} \tag{1}$$

Where V is the voltage applied between the electrodes of the furnace and P is the power supplied to the furnace.

With the electrical quantities collected during the run, it was possible to calculate the resistance values for each hour of run and consequently plot the graph.

Equation 2 involves the physical properties of a conductor and would be used to interpret the thermal behavior of the furnace.

$$R = \frac{\rho L}{A} \tag{2}$$

Where ρ is the electrical resistivity of the material, L is the length of the furnace and A is the area of the conductor section.

For this analysis, the conductor length is constant throughout the run. Therefore, we will analyze only the variation of resistivity of the material and the conductor section.

Resistivity is a property that varies greatly with the temperature of the material. Graphite has a property that approximates the semiconductor, because its resistivity, relatively high at normal conditions of temperature tends to decrease with increasing of temperature. (Filho, et al. 2006).

In the early hours of the heating, it is expected an abrupt decrease of the resistance due to the decreasing of resistivity with the increasing of temperature.

From the moment of begining the formation of SiC, it also begins to conduct current, according to its physical properties. Thus, as SiC is forming around the graphite, the conductor section increasing gradually. Therefore, it is expected that the electrical resistance decreases slowly due the increased section, as shown in figure.

Figure 2 shows the product formed in the cylinder. In the central part is located the graphite. Crystallized SiC is in areas close to the center and in peripheral regions, the β SiC is found, also known as metallurgical SiC.

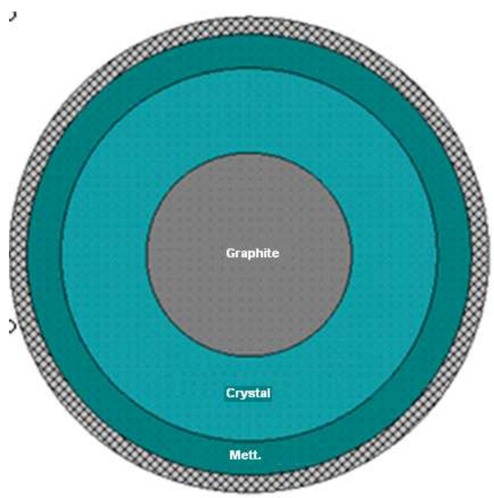

Figure 2. Product in the cylinder, formed concentric to the graphite conductor

During the peak time, the furnace is off for 3 hours, and consequently the conductor (graphite + SiC) is cooled. Therefore, it is considered that in this scenario, the value of resistivity is changed by the reduction of temperature. It was observed an increase in resistance value when the operation was resumed. An important definition will be used for the analysis of this study will now be set: the reheating time after peak time.

The reheating time after peak time, will be the time elapsed since the restart of the furnace and the moment when the resistance reached a value of the last reading before the last interruption. It is believed that at this moment, the thermal characteristics of the furnace are similar to the previous stop.

Analyzing the data collected in the run, it is observed that the resistance value before the interruption is 9.2 mΩ. After the restart, this value was reached after approximately seven hours of reheating. Therefore, the period of reheating after the first peak time is approximately 7 hours.

3. EXPERIMENTS

The goal of the experiment is to analyze the behavior of the resistance curve of the furnace with a source of partial power applied for three hours, compared with the behavior of the furnace when it's off for three hours. To collect the data of experiments we used the same methodology previously demonstrated with readings of electrical performed every hour.

For the analysis of results be more reliable, the experiments were performed in furnaces with distinct powers. To ensure the same reliability, the data analyzed are outside of the instability period of early hours of the runs.

3.1 EXPERIMENT 1

The resistance curve was stable during the run, and the furnace was turned off at peak time for 3 hours. The resistance reading at the time of the shutdown was 6 mΩ.

Three hours later the furnace was on again and the readings were taken. Resistance values were calculated. The table 1 shows the resistance values calculated and measured power:

Table 1 – Resistance values calculates and power measured

	Resistance calculated (mΩ)	Power measured (KW)
Reading before shut down	6,00	9130
1 hour after peak time	7,11	9880
2 hours after peak time	7,27	9300
3 hours after peak time	7,32	9450
4 hours after peak time	7,38	9300
5 hours after peak time	7,42	9390
6 hours after peak time	7,29	9350
7 hours after peak time	7,02	9780
8 hours after peak time	6,49	9400
9 hours after peak time	6,06	9340

The reading of the tenth hour after the restart was disregarded because the calculated value of resistance is lower than the level before the shutdown. Therefore, it is considered that at the tenth hour after the restart, the furnace returned to the same thermal conditions before the interruption. As expected, with the subsequent cooling after the shutdown of the conductor and increasing of the resistivity, resistance values were high. Therefore it is believed that during reheating, part of the energy supplied to the furnace is not utilized in the process of SiC formation, being addressed to the process for reheating and recovery of the previous condition.

To measure the amount of power intended for reheating, it was calculated the differences between the resistance value and value in the reheating before the interruption, in this case, 6 mΩ. It was also calculated the percentage that represents the difference compared to the previous value, according to table 2.

Table 2 – Difference between resistances

	Resistance calculated (mΩ)	Power measured (KW)	Difference between resistances	% relattive R before
Reading before shut down	6,00	9130		
1 hour after peak time	7,11	9880	1,11	18,46%
2 hours after peak time	7,27	9300	1,27	21,15%
3 hours after peak time	7,32	9450	1,32	21,99%
4 hours after peak time	7,38	9300	1,38	23,02%
5 hours after peak time	7,42	9390	1,42	23,71%
6 hours after peak time	7,29	9350	1,29	21,43%
7 hours after peak time	7,02	9780	1,02	16,98%
8 hours after peak time	6,49	9400	0,49	8,17%
9 hours after peak time	6,06	9340	0,06	1,08%

Assuming that the percentage of increasing of resistance corresponds to the portion of the energy for reheating, it is possible to measure the total energy for the reheating furnace. The table 3 shows a column with the share of power for the reheating furnace.

Table 3 – Share of power for reheating furnace after peak time

	Resistance calculated (mΩ)	Power measured (KW)	Difference between resistances	% relattive R before	Reheating Power (KW)
Reading before shut down	6,00	9130			
1 hour after peak time	7,11	9880	1,11	18,46%	1824
2 hours after peak time	7,27	9300	1,27	21,15%	1967
3 hours after peak time	7,32	9450	1,32	21,99%	2078
4 hours after peak time	7,38	9300	1,38	23,02%	2141
5 hours after peak time	7,42	9390	1,42	23,71%	2226
6 hours after peak time	7,29	9350	1,29	21,43%	2004
7 hours after peak time	7,02	9780	1,02	16,98%	1661
8 hours after peak time	6,49	9400	0,49	8,17%	768
9 hours after peak time	6,06	9340	0,06	1,08%	101
Energy consumption (KWh)		85190			14769

As readings are taken every hour, it is possible to transform directly the values from power (KW) to energy consumption (KWh).

Therefore, it is clear that from the 85,190 KWh consumed in 9 hours after the restart of the furnace, a portion of 14,769 kWh, or 17.33%, were used for reheating furnace and the restoration of conditions before the shut down.

In the same run, the next day, it was initiated the partial supply of power for three hours. The partial power supplied equals approximately 33% of the total power of the oven before the power reduction. The table 4 shows: the values of the last reading prior to the reduction, the three readings of the partial supply and subsequent readings until the restoration of conditions prior to test as well.

Table 4 – Share of power for partial supply

	Resistance calculated (mΩ)	Power measured (KW)	Difference between resistances	% relattive to R before	Reheating Power (KW)
Reading before shut down	5,66	9100			
1 hour with partial supply	6,10	2900			
2 hour with partial supply	6,27	2780			
3 hour with partial supply	6,63	3000			
1 hour after normal supply	6,59	9410	0,93	16,36%	1539,35
2 hour after normal supply	6,65	9400	0,99	17,42%	1637,47
3 hour after normal supply	6,48	9800	0,82	14,44%	1414,78
4 hour after normal supply	6,35	9380	0,68	12,09%	1134,03
5 hour after normal supply	5,94	9540	0,27	4,86%	463,31
6 hour after normal supply	5,72	9170	0,06	0,99%	91,06
Energy consumption (KWh)		56700			6280

The furnace was kept with partial power for three hours supplied by approximately 3 MW. It was observed that after the resumption of full power, the increasing of resistance was much lower than the furnace was off during the peak time, being 0.99 mΩ, the biggest difference compared with the previous resistance.

The table also shows the share of energy for the reheating furnace, which corresponds to 6280 KWh, equivalent to 11.08% of 56,700 kWh consumed by the furnace after the resumption.

It is observed that the share of energy for the reheating is lower for the partial contribution, 6280 kWh, than to the state shutdown, 14,769 kWh.

However, from the energetic efficiency view, this analysis is incomplete because it was provided a partial power to the furnace in the second case, while int the first case, the furnace was shut down completely during peak time. So, the energy supplied from the partial supply must be added to energy for reheating.

- Energy delivered during the three-hour partial contribution: 8680 KWh.
- Energy for the reheating after partial contribution: 6280 KWh.
- Total energy consumed be the furnace to recover the previous conditions:

8680 KWh + 6280 KWh = 14,960 kWh

Therefore, the amount of power supplied to keep the furnace with supply partial power, added to energy for reheating during recovery is approximately the same energy required to reheat the furnace after the peak time.

$$14960 \cong 14769 \, \text{KWh}$$

3.2 EXPERIMENT 2

The same methodology used in Experiment 1 was applied for this second experiment, with only two changes:
• Power supplied higher, about 14 MW
• Supply of partial power is 25%, which equates to approximately 3.5 MW

The following tables show the results for the peak time with power off, and the next day, for three hours of partial power supply.

Table 5 – Share of power after peak time of experiment 2

	Resistance calculated (mΩ)	Power measured (KW)	Difference between resistances	% relattive R before	Reheating Power (KW)
Reading before shut down	6,55	14100			
1 hour after peak time	7,57	13960	1,02	15,52%	2166
2 hours after peak time	7,65	14500	1,10	16,76%	2430
3 hours after peak time	7,85	14460	1,30	19,91%	2879
4 hours after peak time	7,94	15000	1,39	21,15%	3172
5 hours after peak time	8,04	14810	1,49	22,70%	3362
6 hours after peak time	7,85	14730	1,30	19,82%	2919
7 hours after peak time	7,55	14600	1,00	15,26%	2228
8 hours after peak time	6,89	14670	0,34	5,24%	769
9 hours after peak time	6,56	14000	0,01	0,12%	17
Energy consumption (KWh)		130730			19940

Table 6 – Share of power for partial supply of experiment 2

	Resistance calculated (mΩ)	Power measured (KW)	Difference between resistances	% relattive R before	Reheating Power (KW)
Reading before shut down	6,16	13660			
1 hour with partial supply	6,46	3530	0,30	4,91%	
2 hour with partial supply	6,66	3560	0,51	8,20%	
3 hour with partial supply	6,78	3410	0,62	10,05%	
1 hour after normal supply	6,96	14430	0,81	13,11%	1892
2 hour after normal supply	7,06	14510	0,90	14,63%	2122
3 hour after normal supply	7,03	14930	0,87	14,20%	2121
4 hour after normal supply	7,02	14400	0,87	14,06%	2025
5 hour after normal supply	6,69	14000	0,53	8,63%	1209
6 hour after normal supply	6,37	13750	0,22	3,50%	481
Energy consumption (KWh)		130730			9850

It was observed that for the test with total shutdown, the energy required for reheating is measured at 19,940 kWh.

In the partial power testt, it was observed that the furnace reheated more quickly, being a period of approximately 6 hours of reheating. The share of energy for the reheating is lower for this case, 9850 MWh.

Similarly to experiment 1, the analysis is still incomplete, 10500 KWh were consumed by the furnace during the three hours of partial supply.

- Energy delivered during the three hours of partial supply: 10500 KWh
- Energy for the reheating after partial supply: 9850 KWh
- Total energy consumed by the furnace to return to previous conditions:
- 10500 KWh + 20,350 KWh = 9850 KWh

Therefore, experiment 2 confirms the results of experiment 1, because the amount of power supplied to keep the furnace with supply partial power, added to energy for reheating during recovery is approximately the same energy required for reheating furnace after peak time.

$$19940 \cong 20350 \text{ KWh}$$

4. CONCLUSIONS

After analyzing the results of both experiments it was observed that:

- The energy used to restore the previous conditions when the furnace is off for 3 hours is about the same energy needed to keep the furnace on with partial power supply added to energy recovery after resumption of full power.
- The energy balance was confirmed for the two experiments in different furnaces and different power for partial supplies.
- Considering the results, analysis of thermal behavior of the Acheson furnace through the curve of electrical resistance was efficient.
- Analyzing the scenario where the energy at peak is much more expensive than the normal time, it becomes uneconomical to hire demand for that time, due the energetic balance be equal in every experiments.
- Hiring demand at peak time would be an alternative just to increased energy consumption and consequently the volume produced without the need to increase the run time, due the relation tons of SiC per energy in MWh be linear a constant.

5. REFERENCES

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