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Transient Thermal Analysis Using FEA for Metallurgical Coke-Making Process

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ABSTRACT

Metallurgical coke is a primary fuel source integral to steel production, achieved through the carbonization of coal in coke ovens at elevated temperatures. Ensuring optimal coke quality necessitates a uniform temperature distribution within these ovens to prevent incomplete carbonization or over-coking. The case study is presented herein leverages Finite Element Analysis (FEA), a potent computational technique, to execute a transient thermal analysis on a coal bed in a horizontal metallurgical coke oven. This analysis aids in understanding temperature variations over time during the coking process. This research underscores the pivotal role of transient thermal simulations in achieving consistent coke quality, improved yields, and efficient coke-making operations.

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Introduction

Metallurgical coke is vital for steel production, it is the primary fuel source in the blast furnace to produce high temperatures for smelting iron ore. Metallurgical coke is the pure form of carbon That reacts with oxygen in iron ore and produce molten iron. The high temperatures in the blast furnace cause impurities in the iron ore to migrate to the molten slag. The alkaline nature of coke ash helps in binding silica and other acidic impurities, ensuring a cleaner molten iron.

The selected coal is crushed and screened to achieve a uniform size. This is essential for consistent coking operations. In the carbonization process coal is heated in the absence of air (anaerobic conditions) in coke ovens. As the temperature rises (usually to around 1000°C-1100°C), the coal softens, liquefies, and then resolidifies into a solid, porous mass called coke. This process drives off volatile matter, moisture, and other impurities, leaving almost pure carbon. The process emits potentially harmful gases, and byproducts can be hazardous. Modern coke plants, redirect these byproducts to recovery units where valuable chemicals like tar, ammonia, and benzene are extracted and sold, thereby reducing environmental impact.

To achieve optimal coke quality, a uniform temperature distribution within the coke oven is desired. Cold spots can lead to incomplete carbonization, producing coke with inferior strength and higher impurities. On the other hand, hot spots can cause over-coking, leading to reduced coke yield and increased ash. By analyzing burn profiles, you can gain insights into the combustion characteristics of the coal being used. This includes the rate at which volatiles are released, the amount of heat generated, and the time taken for the coal to fully carbonize. By simulating different burn profiles, charge compositions, and oven operating conditions, you can optimize the process for maximum yield and quality. This might involve adjusting parameters like oven pressure, heating rate, or coal blend. Leveraging transient thermal simulations and other advanced tools can offer a more detailed understanding of the coking process, ensuring consistent coke quality, improved yields, and efficient operations.

Background

A typical Horizontal metallurgical Coke oven is shown in Figure 1. This oven wall and arches are built using silica-cast slabs and silica bricks. These bricks can resist high temperatures above 1650^{0}C [1]. After loading the coal into the hot oven and closing its doors, the combustion process begins. The partially combusted flue gases are removed through the uptake and sole flue drafts by adjusting the dampers. The oven temperatures can be regulated by opening and closing these dampers. The cooking duration for these horizontal ovens is set at 48 hours [2]. At the beginning of the cycle, the coke oven is fuel-rich because of high flue gases gradually it goes down closer to the finished coke cycle. These flue gases are taken out using negative pressure using an upstream fan. The surplus heat is harnessed to produce electricity. Within the coke oven setup, temperature sensors are strategically positioned both in the crown and in the sole flues. These sensors monitor temperature variations throughout the combustion process. Utilizing this temperature data, a transient thermal simulation is conducted to evaluate the uniformity of coal heating and pinpoint any potential cold or overheated zones. This analysis assists in determining the quality of the produced Coke and adjusts the necessary processing time for different coal quantities loaded into the oven.

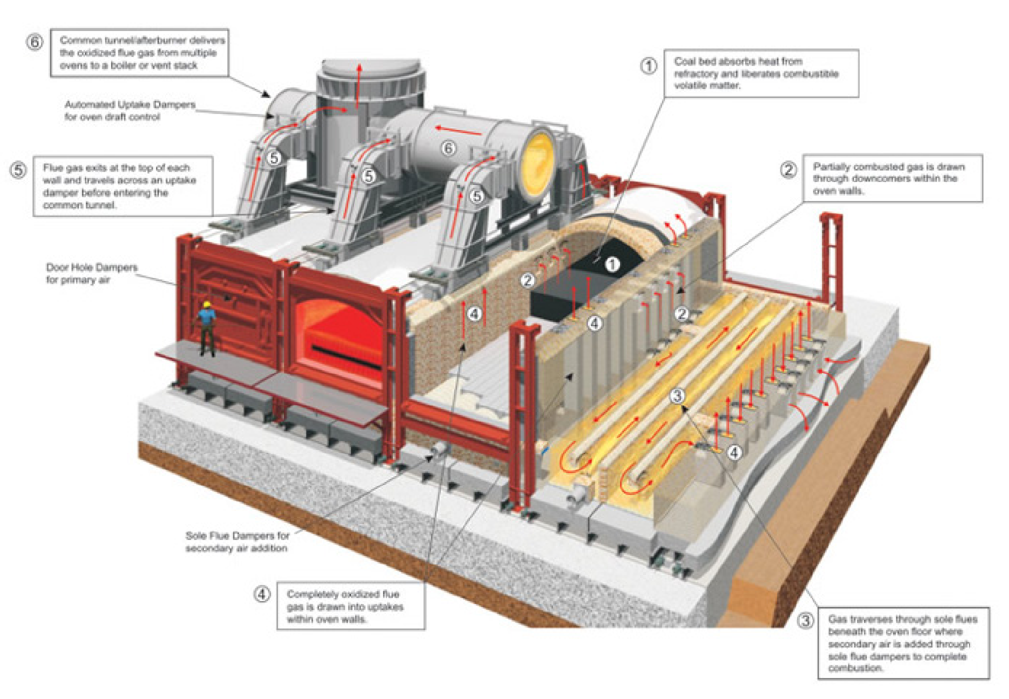

Figure 1: Horizontal Coke-Making Oven Structure and Gas Flow (Suncoke Energy) [2].

Finite Element Analysis (FEA) is a powerful computational method used to gain approximate solutions to boundary value problems. In simple terms, it's a way to simulate the physical behavior of structures and materials by breaking them down into smaller, simpler pieces (called "elements") to understand how they'll behave under different conditions. The predictions made by FEA can assist in making design decisions, assessing performance, or predicting failure points.

Given the complex geometries and boundary conditions typical of coke ovens, FEA becomes essential. It can accurately predict the behavior of the system, helping in the design, optimization, and troubleshooting of coke ovens. Moreover, with FEA, engineers can ensure uniform heating, proper gas flow, and ideal conditions for coke production, reducing waste and inefficiencies.

Case Study

In this case study, a transient thermal simulation is demonstrated to determine the optimal cooking time. For this demonstration a coal bed that measures approximately 1 meter in depth, 4 meters in width, and 14 meters in length. The focus is on elucidating how to set boundary conditions effectively for transient thermal analysis using the Abaqus FE solver.

Transient thermal analysis is the study of how heat transfer changes over time. Unlike steady-state analysis, which only considers situations where conditions remain constant over time, transient analysis captures the dynamic changes that can occur, making it suitable for scenarios where temperatures vary

Geometry and Meshing

An approximated 3D CAD model of the coke oven is created to fit a coal charge of 1m depth, 4m width, and 14m long. This model represents the physical structure of the coal bed and refractory bricks. This CAD model is discretized using hexahedral C3D8R elements.

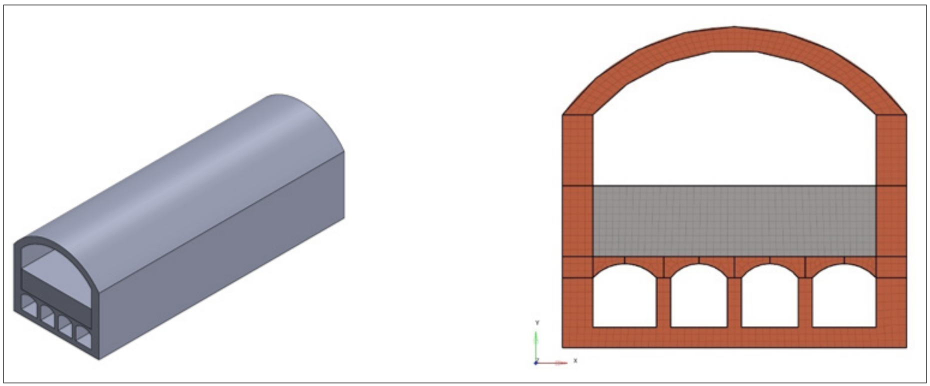

Figure 2: Horizontal Oven Geometry and Mesh Model

Boundary and Initial Conditions

Initial conditions for the coke oven is heated to 1832^{0}F using steady state heat transfer analysis to represent the previous cycle. In the second step, add the coal to the oven using the "Model change" option in Abaqus. Applying the heat transfer co-efficient refractory bricks boundary conditions can include details about temperature. Crown and Sole-Flue temperatures are applied over time [2]. The top of the crown and bottom base are exposed to ambient temperatures.

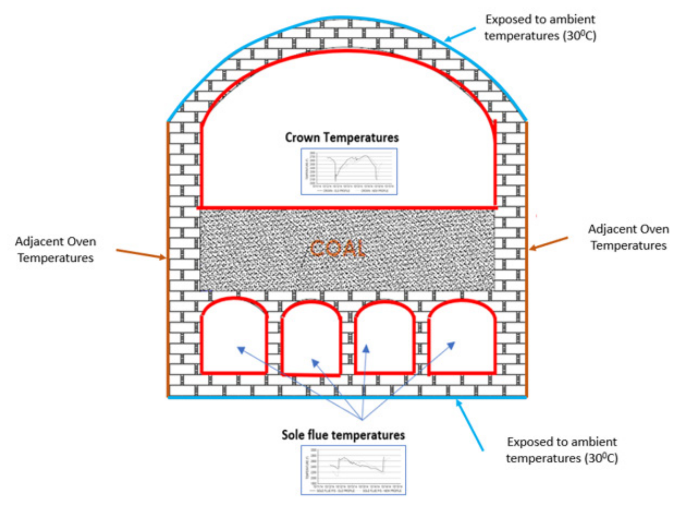

Figure 3: Boundary Conditions

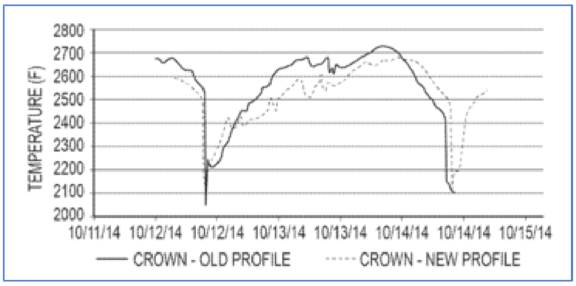

Figure 4: Crown Temperatures [2].

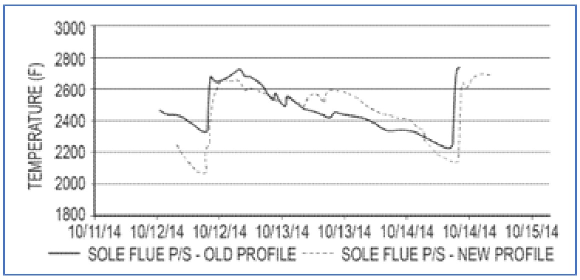

Figure 5: Sole Flue Temperatures [2].

Material Properties

One of the most crucial steps is defining the material properties for the components involved. This would involve defining properties for both coal and refractory silica brick. Parameters like thermal conductivity, specific heat, density, and more play a pivotal role in how the material responds to heating. Silica brick material properties are detailed in Figure 6. The thermal conductivity of bituminous coal is typically in the range 0.17 W/(m. K) to 0.29 W/(m. K) [1].

Table 1: Material Properties

	Thermal Conductivity (Btu/(h•ft•°F))	Specific heat (Btu/(lbm 0F))	Density sl/ft³
Refractory	1.155	0.18	1.15
Coal [3].	0.144	0.33	2.61

Results and Discussion

Transient thermal analysis was conducted to understand how the temperature varies across the coal charge as time progresses. As depicted in Figure 6 details the initial conditions of the coal charging. Figure 7 describes the thermal distribution on the coal was examined in every 12-hour intervals of the coking cycle, providing detailed insights into the temperature changes over time. Towards the conclusion of the testing cycle, the coal's temperature surpassed a remarkable 2000°F. This elevated temperature, exceeding 2000°F, is a definitive indicator of the transformation of coal into final metallurgical coke. The results confirm that the thermal behavior of the coal is consistent with the expected characteristics for producing high-quality metallurgical coke. The consistent rise in temperature, as shown in the 12-hour snapshots in Figure 7, underscores the significance of monitoring the thermal distribution throughout the coal charge's processing [3].

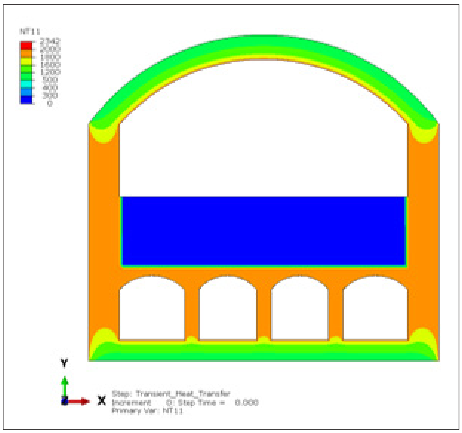

Figure 6: Nodal Thermal Distribution of Coke Oven Immediately after Coal is Loaded

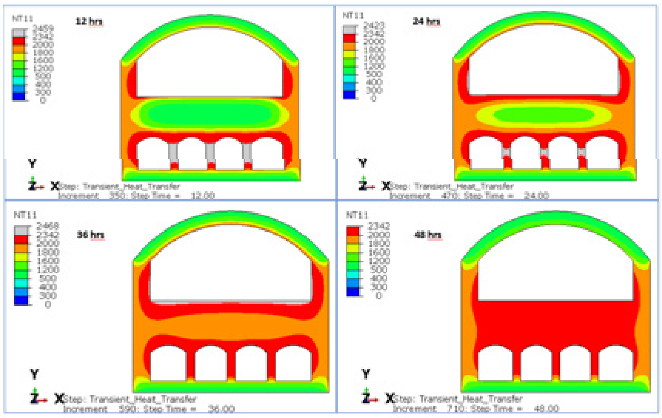

Figure 7: Nodal Thermal Distribution Coal with Oven over Time

Conclusion

This research effectively utilized Finite Element Analysis (FEA) to conduct a transient thermal analysis on a coal bed within a horizontal metallurgical coke oven. The application of this technique allowed for a comprehensive understanding of temperature dynamics during the coking process. Through the simulation, insights were gathered about potential temperature distribution inconsistencies that could result in incomplete carbonization or over-coking. This technique can used to predict the coking time at different climatic conditions.

With modern coke-making plants striving to minimize environmental impact by redirecting byproducts to recovery units, achieving a high degree of efficiency in the coking process becomes even more critical. Hence, the findings from this study underscore the indispensable role of transient thermal simulations. When used effectively, such simulations not only ensure high-quality coke production but also improve overall yields and streamline coke-making operations. Future endeavors in the metallurgical coke production sector would benefit significantly from the incorporation of advanced computational methods, such as the FEA used in this research, to optimize and maintain a consistently high standard in their operations.

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