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RESEARCH ON THERMAL PROCESS TECHNOLOGY OF NON / HEAT RECOVERY COKE OVENS[1]

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Abstract

UHDE has decided to validate and broaden the design criteria for heat recovery technology with an in-depth theoretical investigation of the process using various mathematical models. A two-dimensional, transient coking model was developed for industrial application to allow key influencing quantities of the heat recovery coking process to be recorded and the main process parameters, such as “end of coking process”, to be predicted. The thermo-physical properties which characterise the coal/coke cake and ash - i.e. thermal conductivity, specific heat capacity cp and density – were determined on a temperature-dependent, effective basis by means of heat flow balance calorimeter measurements and LFA analysis. The model also enabled the limits of application for this coking technology to be worked out with respect to the process parameters, and characteristic temperature profiles in the upper and lower parts of the oven to be illustrated dependent on the primary and secondary air adjustment as well as the total excess air amount specified, taking into account full process and geometric coupling between the upper and lower parts of the oven. Two ovens based on the UHDE design at ICC’s non-recovery plant were used for practical validation of the computed temperature profiles in the coal/coke cake by means of tar joint measurements. In order to achieve an optimized design for the air inlets and downcomers with respect to an even surface heating of the cake, a complex mathematical flow and staged combustion model based on a finite volume analysis was designed. This enabled the mixing and combustion process inside the oven chamber to be observed through graphical animation and led to an evolutionary improvement in understanding of mixing and combustion laws within the oven.
Key words: Transient process model; Combustion and flow simulation; Measurement of the thermo-physical properties of coal and coke; Measurement of temperature distribution; Design of primary air supply.

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In the past decade heat recovery (hr) coke ovens have been the subject of much discussion among coke oven experts. A review of estimated gross coking times from published literature, company brochures and bid information reveals an enormous spread of data. However, it is crucial to have a reliable estimate of the gross coking time relative to oven capacity as a key coke oven design parameter. With the quasi-steady-state computational models previously available, it was only possible to solve problems regarding steady-state heat conduction with no internal heat sources (Figure 1). UHDE has used them to assist in developing oven design and in selecting refractory materials.

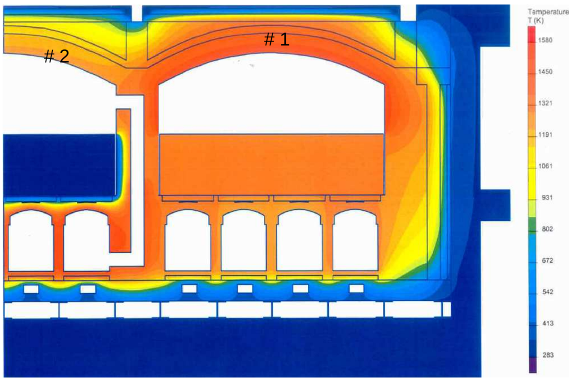

Figure 1: Quasi-steady-state 2d temperature profile with no internal heat sources, “end oven # 1 before pushing”, “oven # 2 after charging”.

The special feature of heat recovery coking technology is that the energy supplied by the raw gas released from the coal in connection with the combustion process cannot be greatly influenced.

Against this background UHDE decided to validate and broaden the design criteria for the technology with an in-depth theoretical investigation of the process using mathematical models, breaking the task into several phases involving the following sub-models:

(1) Development of a two-dimensional, transient coking and combustion model in order to determine the gross coking time as well as to illustrate characteristic oven temperature profiles, taking into account full process and geometric interaction between the upper and lower parts of the oven. The aim was to develop a dynamic simulation model for industrial application which allows the main process parameters, such as gross coking time, to be predicted based on the input of specific process information, i.e. the volatile matter (VM) content of the coal, the air distribution and the effective thermal diffusivity of the coal, coke and ash.

(2) Practical validation of process assumptions and computed temperature profiles in the coal cake by means of tar joint measurements for top-charged and compacted oven operation in two ovens based on the UHDE heating design at ICC’s non-recovery coke oven plant at Coalcliff (NSW /Australia).

(3) Fluid mechanical optimization of the mixing and combustion processes in the oven chambers with the aid of a three-dimensional, steady-state finite volume analysis to guarantee the most uniform air supply and heating of coal and coke cake surfaces in the direction of the oven length and to provide the theoretical basis for the above-mentioned transient coking model. Based on this, oven design principles with regard to the location of air inlets and downcomer channels were deduced under the assumption of an oven chamber design which ensures complete air tightness.

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1 DESCRIPTION OF THE TWO-DIMENSIONAL, TRANSIENT COKING MODEL

The oven geometry represented by the two-dimensional, transient coking model, as shown in Figure 2, takes into account geometric and thermal coupling between the upper and lower parts of the UHDE-type hr oven. The upper section above the top of the oven sole contains the coal/coke cake and the primary combustion chamber, while the lower section has the characteristics of an air-staged twin-flue heating system. The geometry also considers the lower lateral heating wall flues as well as the U-shaped heating flues located under the oven sole. In this model raw/waste gas mixture results from primary combustion triggered in the combustion chamber, and the secondary combustion processes taking place in the heating flues under the oven sole through the addition of secondary air represent an additional energy source. The secondary air stream is further divided into two sub-streams in accordance with the horizontal heating flue geometry.

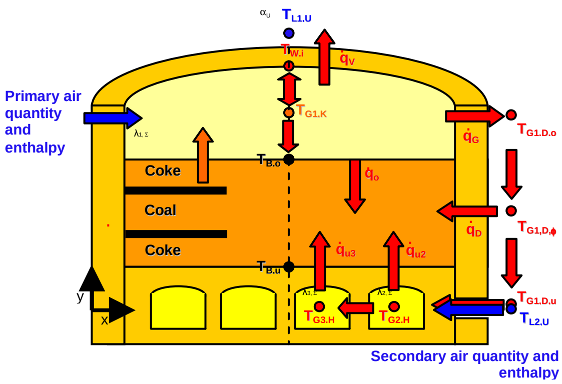

Figure 2: Coke oven model, taking into account geometric and thermal coupling between the upper and lower parts of the oven.

The combustion process in the oven chamber largely depends on the quantity of raw gas that is generated under the influence of the temperature as well as the coal characteristics. The profiles applied for the model are mainly based on measurements taken at a plant in operation.[1] The model takes into account the time-dependent formation of raw gases and their components. These data have been converted to a wet basis by including the specified water vapour content, and adjusted to the relevant coking time for the hr process of approx. 50 h – 60 h.
The radiation processes between the oven chamber zones result from the combustion of these raw gases. Spectral emission factors of used Silica bricks were measured at a temperature of 1200 ℃ as a function of the wave length (0 µm – 16 µm) and incorporated into the radiation sub-model.
The thermo-physical properties which characterise the coal/coke cake - i.e. thermal conductivity □, specific heat capacity c_p and density □ – were determined on a temperature-dependent, effective basis using an Australian coal blend with a VM content of approx. 19,3 % (db). First, the specific heat capacities of the coal and coke were determined by means of a heat flow balance calorimeter. The thermal conductivity of the coal and coke was calculated from the measured thermal diffusivity a (t) and specific heat capacity c_p (t) according to equation (1):

$$\lambda_{coal/coke}(t) = \rho \times c_p(t) \times a(t) \qquad (1)$$

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The transition from coal to coke properties (□, c_p) was carried at a temperature of 750 ℃. The initial density of the compacted cake was set at 1100 kg/m^3 and was reduced non-linearly during the course of the coking process. Radiation heat transfer as well as water evaporation and condensation fronts in the coal cake were not modelled separately, but were taken into account by the transformation of the above-mentioned parameters into an effective state.
The coal bed height was set at 1000 mm. An insulating layer of ash, which is known from practical experience to form on the top of the coal a few hours after charging, was taken into account. The porosity and thermal diffusivity of this oxide conglomeration were measured as a function of the temperature t_{Ash} (25 ℃-1100 ℃).
The initial surface temperature of the oven crown was specified using the results of a quasi- steady–state model (Figure 1). The temperature profile of the oven is strongly influenced by the division of the combustion air into primary and secondary streams. The calculation presented in this paper is based on a non-linear increase in the quantity of primary and secondary air during the coking process. To support this assumption, the waste gas quantity and oxygen content (8 %) was determined, and resulted in confirmation of this hypothesis. It is common practice to adjust the primary and secondary air streams by means of dampers during the course of the coking process. The choice of a suitable point in time for this adjustment was influenced by practical experience and considerations which have shown the least possible number of adjustments to be desirable. In the model under discussion, it is assumed that the secondary air inlet is closed after a certain period through the coking process.
In specifying the total quantity of combustion air, practical experience with the UHDE oven system was applied, taking into account the specific mixing characteristics in the oven. For this model, the already partially combusted raw gases in the sole heating flues were considered to be fully mixed for the purposes of generating the final combustion reactions. Therefore, the total air quantity was determined by specifying the total oxygen concentration in the waste gas at the oven outlet to within 6 – 8 %.

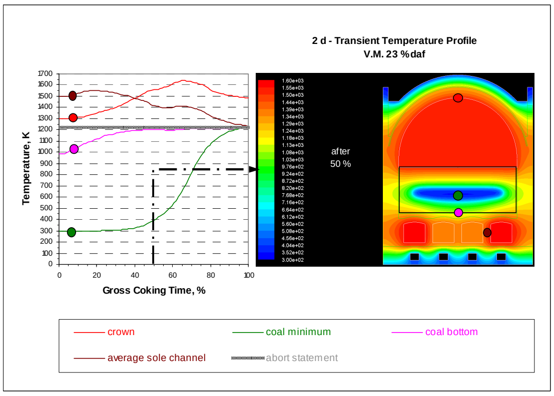

Figure 3: Calculated two-dimensional temperature profile “intermediate profile, Gross Coking Time = 50%”.

Figure 3 illustrates the calculated temperature profile for selected oven sections over time during the coking cycle. These oven sections are shown as a two-dimensional profile on the right. As expected, the charging operation causes a drop in the average crown temperature which, however, quickly rises again to an adequate temperature level once primary combustion starts. In comparison, the average temperature of the sole flue surface is higher during the first 50 % of the coking cycle due to the enthalpy

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of the primary waste gas exhausted into the lower part of the oven and the intensive secondary combustion processes. For this calculation example it can be seen, that approximately halfway through the coking period the average crown and sole flue temperatures are approached, i.e. the intensity of the secondary combustion weakens although the air intake remains the same. In order to prevent the sole flues cooling, the secondary air inlets are closed completely at this time. Shutting off the secondary air feed increases the negative pressure in the upper part of the oven, thus increasing the amount of air drawn in through the primary air inlets and triggering intensive primary combustion, which results in a rapid temperature rise at the crown. The enthalpy of the hot waste gases from the primary combustion processes prevents further cooling of the heating flues. The thermal relationships described here are borne out by practical experience.

Using the thermo-physical coal data specified above and the special ICC oven geometry, an “end of coking process” of less than 60 h was calculated for this example, dependent on the pri-mary and secondary air adjustment as well as the total excess air amount specified. The simulation runs were stopped when the abort criterion defining the end of the coking process was exceeded throughout the entire bed height. The specified criterion 950 ℃ correspo nds to a final VM content of less than 1 % within the coke. As expec-ted, the maximum temperature is reached at the top of the cake. The calculation example shows that the minimum cake temperature shifts in the direction of the oven sole over the course of the coking cycle. The location of the minimum temperature at the point “Gross Coking Time = 100 %” corresponds to the tar joint familiar from con-ventional coke ovens. The asymmetrical carbonisation can be explained by the thermal resistance of the oven sole. The effective heat flow density at the bottom of the cake is therefore lower than the effective heat flow density resulting from the radiant heat transfer at the top of the cake.

2 PRACTICAL MODEL VALIDATIONS

For practical validation of the model premises, time-dependent temperature measurements were taken in compacted and top-charged oven charges. A box-shaped device was designed for the production of hydraulically compacted coal briquettes with a density of up to 1200 kg/m^3 so that one oven could be filled with compacted coal. The oven charge prepared on a steel plate on the coke side of the oven comprised up to 16 briquettes. The pusher machine performed the task of pulling the coal charge through the door in the oven during charging. Following this, heat-resistant thermo-wells were put through the four charging holes in the oven top and placed in the coal charge.

The temperature in the charge was measured vertically using type N thermocouples, which were removed again prior to the pushing operation. The length of the four thermocouples was determined by the need to derive a vertical temperature profile in the charge from the data. The temperature measurements show sufficient correlation with the calculated data and validate both the model premises for top-charged operation and those for compacted operation. To reconcile theory with practice a so-called effective thermal conductivity of the coal was deduced, which takes into account both the radiant heat transfer as well as the flow configurations in the cracks and pores of the charge.

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3 FLUID MECHANICAL OPTIMIZATION OF THE OVEN DESIGN

A three-dimensional flow and combustion model based on a finite volume analysis was developed to determine an optimized design for the air inlets and downcomer channels to ensure that the surface of the cake is heated as evenly as possible. In so doing, it was assumed that the raw combustible gases escape from the coal cake homogenously and spread evenly across the surface. The steady-state model is based on partial combustion of the raw gas which rises up at the point “coking progress approx. 10 %”, which is when the maximum raw gas formation is to be observed, as well as the primary excess air parameter (□$_P$ □1.0).

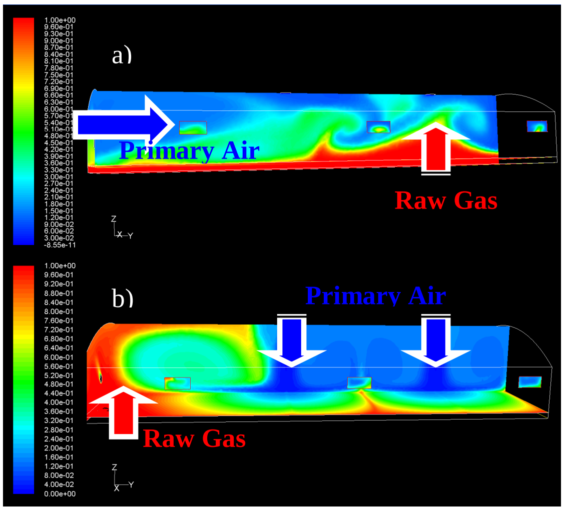

Figure 4: Mixing scalar inside half an oven: a) primary air supply through oven door inlets, b) primary air supply through oven top inlets.

Figure 4 shows a comparison of the mixing scalar for the geometry of half an oven between the oven doors and the centre of the oven. The raw gas emitted (S = 1) is shown in red and the primary air (S = 0) in blue.

Figure 4 a) shows the mixing within a combustion chamber supplied horizontally with primary air through the oven door inlets only. It can be seen that there is insufficient mixing of the combustion fluids in the oven chamber and that there is almost no effect on the upwards flow of unburned raw gas in the middle zone of the oven.

Figure 4 b) illustrates the results of a simulation in which the primary air was supplied through the inlets in the oven top only. In the oven door area it can be seen that there is almost no effect on the upwards flow of raw gas, i.e. the air flowing in through the oven top does not reach the edges of the oven. The raw gas is returned to the oven interior by a recirculation mechanism acting in y direction at the door and oven crown and then it is mixed and combusted with the primary air. The outer zone of the oven is inadequately heated though on the whole a greater heat flow density is transferred to the surface of the coal compared with 4 a). Figure 5 shows the corresponding heat flow flux distribution for this oven segment.

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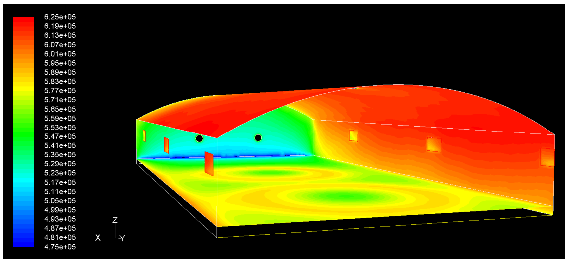

Figure 5: Incident radiation inside half an oven, W m^{-2}.

4 CONCLUSIONS

(1) This paper presents for the first time a simulation model for hr coke ovens which, taking into account the specific oven geometry and the coal-specific thermo-physical properties, can be used to calculate two-dimensional, transient temperature profiles in the coal charge and oven walls and to draw reliable conclusions regarding the gross coking time. The premises of the model have been validated by practical measurements.
(2) Hr coke ovens must be kept at as high a temperature as possible if the optimum gross coking times are to be achieved. Therefore, the VM content in the coal blend is limited to achieve an adequate heat balance in a high-performance hr coke oven which operates with a bed height of 1m, densities higher than 1050 kg/m^3 and gross coking times less than 60 h.
(3) Therefore, hr coke oven must be airtight.
(4) Adjustment of the primary and secondary air flow quantities at the correct points in time is of great significance with respect to the temperature regime in the oven.
(5) Supplying the primary air through the oven top promotes the surface heating of the charge in ovens longer than 10 m and is an advantage over air supplied through the oven doors at the sides.
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