A numerical modelling of non-recovery/heat-recovery coke ovens

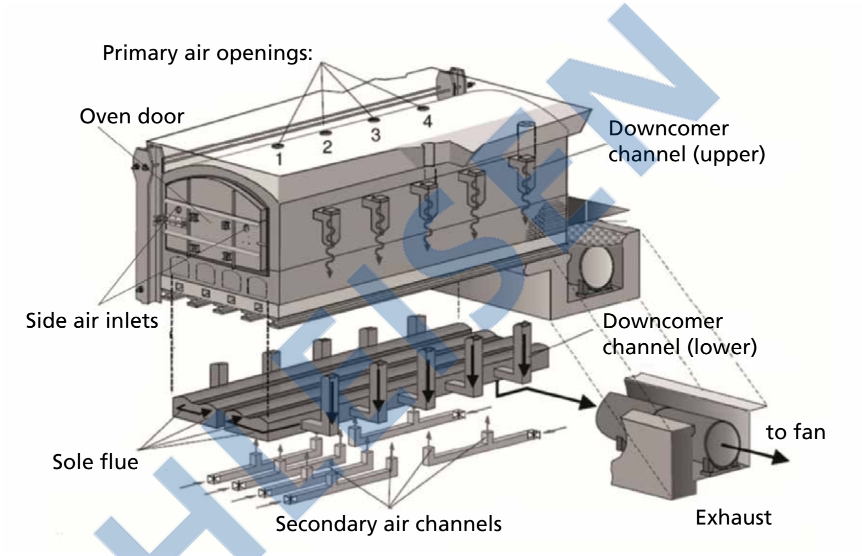
Numerical calculations of the combustion process inside the coke oven were carried out in order to gain an improved understanding of the internal thermodynamic behaviour. In doing so, scientific/engineering tools are created which help both improve the oven design and optimize the coking process.

In the heat-recovery/non-recovery (HR/NR) coke ovens the coal/coke bed is located in the large oven chamber in the upper part of the oven. The coal/coke fixed bed is of a parallelepiped shape, the typical dimensions being approx. 1 m in height, 4 m in width and 15 m in length. The carbonization process of the coal begins at the top and at the bottom of the fixed bed. Then the carbonization front will move continuously through the bed. The heat required for thermal decomposition and carbonization is generated by combustion of volatiles released from the coal bed. The volatile matter is partially combusted in the free space above the fixed bed using air entrained through the various ports/openings (channels) located in both side doors and the oven roof.

The gas formed in the upper oven is transported through “downcomer” passages to the sole flue (bottom part of the oven). Additional channels in the sole flue provide the required amount of air to complete the combustion process [1 – 4].

In the course of a coking process (which proceeds under negative pressure) the amount of air provided to the spaces above and below the coal bed is controlled by under-pressure (suction) generated using either a fan or through natural draft caused by a stack. The entire coke making process can be controlled just by varying the suction at the outlet of the oven. This is usually not enough to obtain the same high quality product (coke) in the entire coke bed.

Dr. Ronald Kim, Dr. Patrick Schwöppe; ThyssenKrupp Industrial Solutions AG, Dortmund, Germany;
Dr. Rafat Buczyński, Technical University Clausthal, Clausthal, Germany
Contact: www.thyssenkrupp-industrial-solutions.com
E-mail: ronald.kim@thyssenkrupp.com



Geometry of a heat-recovery/non-recovery coke oven

To improve the homogeneity of the coke product, a uniform heating rate of the fixed bed has to be ensured. In the upper part of the oven (above coal bed), heat is transferred to the bed mainly through radiation from the oven walls and from hot gases, which are products of partial combustion of volatiles. The heat produced in the sole flue is transferred to the coal charge through the sole flue brick ceiling. The uniform heating rate of coke charge through the sole flue ceiling can be obtained if the temperature profile in the sole flues is uniform. This can be achieved by changing the size and position of the gas and air channels.

3D numerical model of the coke oven

Numerical simulations using computational fluid dynamics (CFD) are considered a perfect method for engineering and optimizing the design of the NR/HR-coke ovens. CFD-simulations of processes occurring in both the upper and the lower part of the oven, allow both identify the reasons for uneven heating and propose remedies.

The coke making process is transient and requires typically around 48 to 72 hours until the coal has been completely transformed to coke. Performing time-dependent CFD-simulations of the entire process would require an unreasonable amount of CPU time. Consequently, the CFD is used to simulate the furnace performance at selected, characteristic coking phases, assuming pseudo steady state conditions. Such an approach produces useful results in a reasonable time.

In the numerical simulations, only half of the entire oven has been considered, due to its symmetrical design. It is imperative to include a large chamber volume above the coal/coke bed as well as a sole flue. A coke making oven is in fact a hydraulic network where the driving force is the under-pressure generated by a fan and, therefore, while performing CFD simulations the oven cannot be divided into segments.

A non-structural mesh consisting of around 10 million hexa/tetrahedral elements has been generated. Only CH_4,

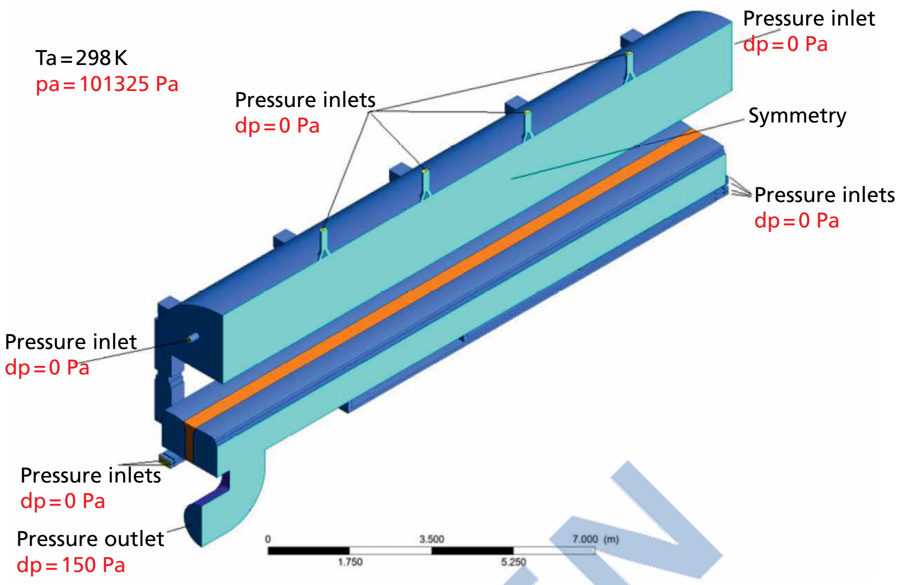
CO_2, CO, O_2, H_2, H_2O and N_2 have been considered as components relevant in the gas phase reactions. In order to save computation time, three characteristic instants of the coking process have been selected, corresponding to 10%, 50% and 90% of the total coking time. This article is limited to the discussion of results obtained for 10% of the coking time. The numerical calculations are performed by means of the commercial CFD software package FLUENT.

The amount of air entrained through ports (air channels) into the analyzed oven depends on:

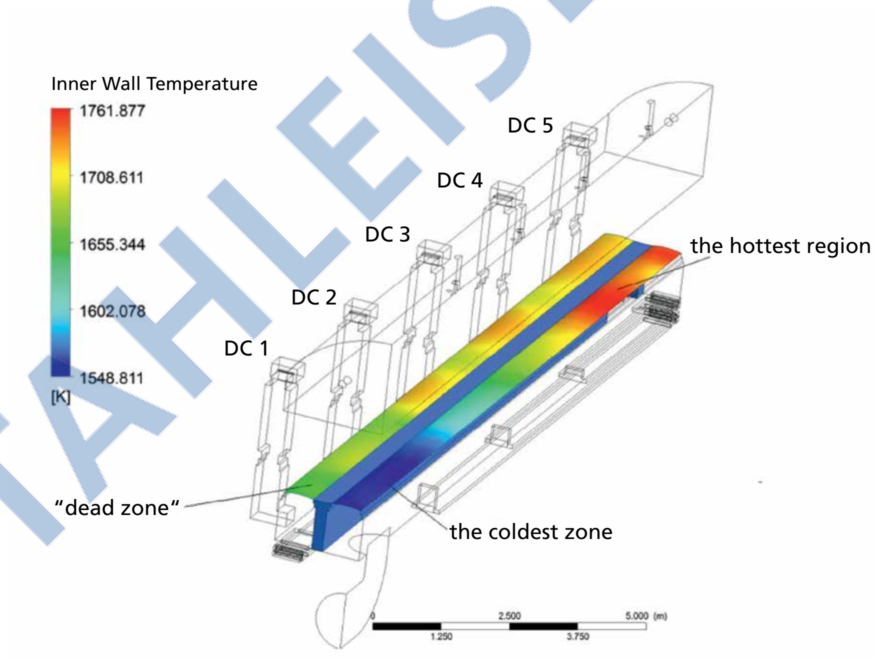
- the applied suction (at the outlet),
- external conditions (mainly air temperature),
- mass flow rate, gas composition, temperature of the raw gas released during the carbonization process.

The pressure inlet boundary condition was provided by the air inlets and the pressure outlet boundary condition by the oven outlet. At the top of coke charge a mass flow inlet is provided. The suction (negative pressure) at the outlet, gas composition, temperature and mass flow rates of raw gas released from the coal bed were taken from measurements.

It is important to note that above the fixed bed, combustion of volatiles takes place under a deficiency of oxygen (excess air ratio is in the range of 0.3 to 0.6). In the outer sole flue, the air excess ratio is in the range of 0.9 to 1.3. In the inner sole flue the ratio is equal to 1.5 to 1.8. In the simulations, the oxidation of methane (CH_4), carbon monoxide (CO) and hydrogen (H_2) has been modelled. Methane is mainly consumed in the upper part of the oven under under-stoichiometric conditions. The carbon monoxide and hydrogen is oxidized in the sole flue (air excess ratio > 1).



General conditions



Computed ceiling temperature profile for the HR/NR design at 10% coking time

Results of the 3D calculations

Reflecting about the calculated temperature distribution in the sole flues for the HR/NR design at 10% coking time, the non-uniformity in the temperature distribution is apparent. Moreover, the temperature near the U-tube is close to the safety limit (< 1,500°C). The sole flue ceiling temperature should be lower than 1,500°C since excessive temperatures damage the silica-based refractory.

Three characteristic temperature regions are apparent in the results. The "dead zone" (zone 1) appears in the outer sole flue near the first downcomer (DC1). The region called "dead zone" is colder than other regions of the outer sole flue and this is due to deficiency of air in this region. The deficiency occurs because air is introduced to the sole flue downstream of the first downcomer. Thus, little combustion occurs in this part of the flue which is located upstream of the first air inlet.

In the hottest region (zone 2) located near the U-tube, very high temperatures close to the safety limit (> 1,500°C) occur. In this region damage to the silica refractory may occur. The problem is caused by:

- the combustion conditions – excess air ratio in this region reaches a value of around 1.0,
- the design of the sole flue – all the gas which flows into the outer sole flue accumulates in the region near the U-tube. The U-tube intensifies the mixing so the remaining fuel burns rapidly leading to an intensive heat transfer to the ceiling.

The "coldest region" (zone 3), where the problems have been noticed, is the region in the inner sole flue near the outflow. The gas in the inner sole flue is gradually cooled down by the entering cold air. The excess air ratio increases from 1.0 near the U-tube to the value of 1.5 to 1.8 at the end of the sole flue.

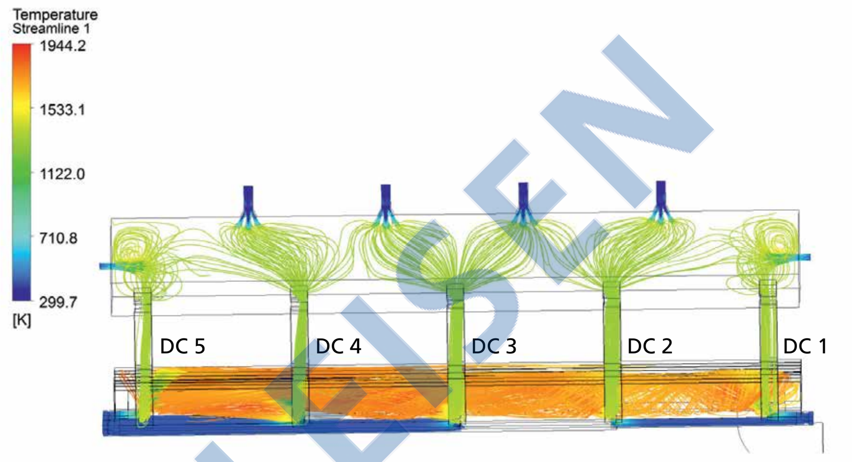
Temperature non-uniformity of the sole flue ceiling may also be caused by the air supply installation above the coal deposit (in the upper oven). The gas containing combustible compounds such as CO and H_2 is transported to the sole flue through five downcomers per wall. The gaseous fuel is produced by partial combustion of volatile matter released from the coal bed located in the upper oven. Primary air required for partial combustion flows through the top (primary) air channels and side air channels. The side air channels may disturb the uniformity of the air supply. Gas transported in downcomers DC 1 and DC 5 has a different composition than gas flowing through the other downcomers DC 2, DC 3 and DC 4. Differences in flow rates, temperatures and composition of the gas in downcomers may worsen the uniformity of the sole flue temperature.

The gas-flow in the downcomers and in the sole flue is generated by the suction fan located at the plant exit duct. The secondary air is entrained via eight air inlets. There is marked non-uniformity in the distribution of the gas flowing through the downcomers; the largest amount is transported through the 5th downcomer whilst the smallest amount flows in the 1st downcomer. Different amounts of air are entrained through the air inlets so that different, highly non-uniform, combustion conditions (stoichiometry and mixing) occur. Consequently, the ceiling of the sole flue is exposed to non-uniform heat transfer rates, which invoke non-uniformity of ceiling temperatures.

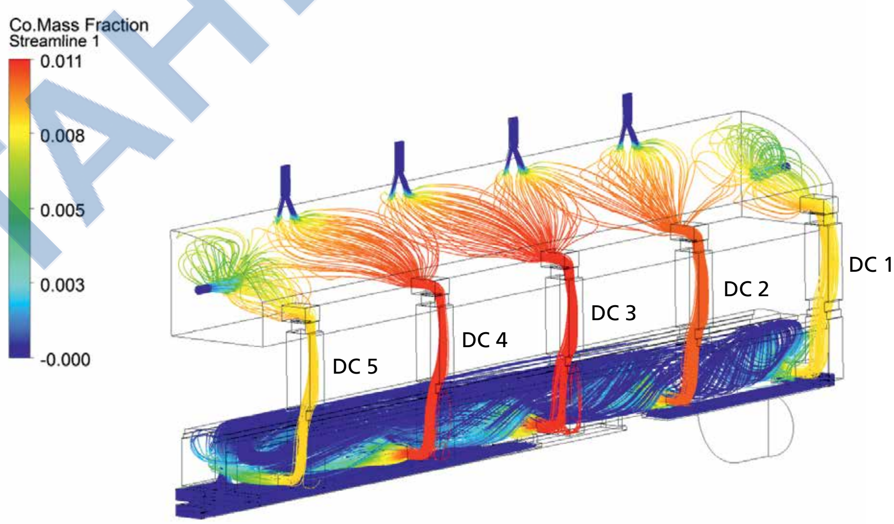
To improve the temperature distribution in the sole flue, one has to understand how the gas produced in the upper oven behaves when entering the sole flue. It is also necessary to understand the air behaviour. After igniting, the gas leaving the downcomer is heated up, it then hits the side wall (sole flue partition) and flows upwards to the sole flue ceiling. The calculation clearly shows that the gas recirculates in the sole flue. The behaviour is similar for all downcomers.

The secondary air flows differently. The air entrained from the surroundings enters the sole flue using ports (channels) placed at the sole flue bottom. The air flows upwards and hits the sole flue ceiling near the downcomers 1 and 2. In the vicinity of the downcomers 3, 4 and 5 the air streams are entrained by the main flow and do not hit the ceiling.

The existence of the hottest region of the sole flue can be explained by the above-described behaviour of the gas entering the sole flue. The hot combustion products of gas leaving downcomer 5 (and other downcomers) pass by the U-tube and flow upwards to the region near the sole flue ceiling. The gas stream impinges on the ceiling in the "hottest area" of the sole flue ceiling. The main flow and the sole flue ceiling near the oven outlet are cooled by the air entering the oven through air channels located at the bottom of the sole flue.



Gas path lines coloured by temperature



Gas path lines coloured by carbon monoxide mass fraction

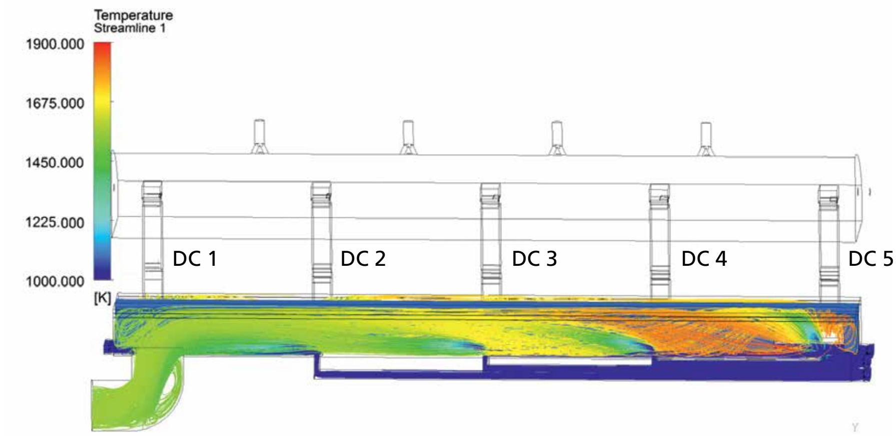
1D numerical model of the coke oven

FLUENT is a useful software tool which helps to understand processes inside the oven. The knowledge gathered from the FLUENT calculations is very helpful when the oven design and construction have to be optimized. When it comes to controlling the coking process, a one-dimensional model may be a better choice since results are obtained (significantly) faster compared to FLUENT.

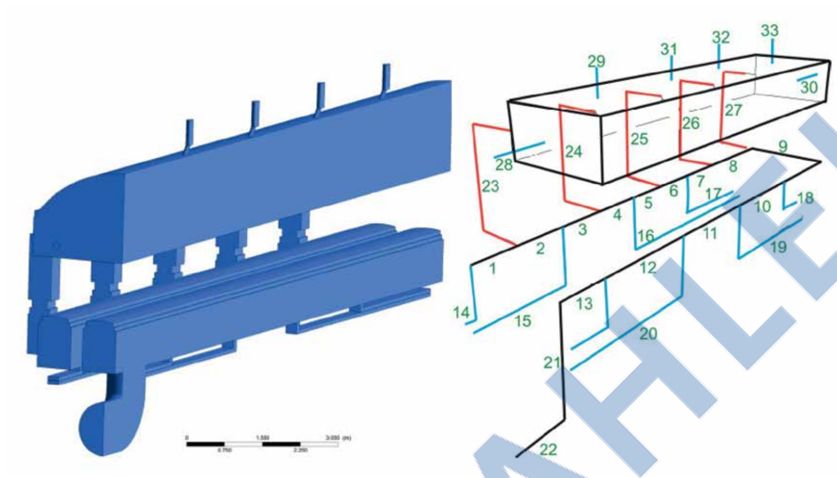
A single CFD calculation takes about three weeks. It is possible to develop a one-dimensional (1D) network model, which would provide simplified simulations of the whole coking process (about 70 hours) in two to three days. Such a model, described below, is currently under development.

The one-dimensional model consists of four main parts:

- hydraulic network – for calculation of the downcomer flow rates and the amount of entrained combustion air,
- gas combustion sub-model – to simulate gas combustion inside the branches of the hydraulic network. The sub-model is coupled with the hydraulic network,
- chamber sub-model – equilibrium calculations to predict gas composition in the upper oven, above the coal/coke bed,
- coke sub-model – to simulate heat conduction through the coal bed, evaporation, condensation phenomena and the devolatilization process using "Merrick's model" [5].



Inner sole flue path lines coloured by temperature



Hydraulic network

Because the 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 within the oven, an optimized instruction schedule was prepared based on the above investigation, meeting various operational conditions. Its multiple benefits are permanently validated during operation of a HR-plant in Brazil, where the adjustment schedule is part of an automatic installation. One of these benefits is the avoidance of melting processes of sole or wall refractories caused by any incorrect adjustment of the cross section of the secondary air inlet devices below the oven sole.

Based on the investigations described above, ThyssenKrupp Industrial Solutions has optimized the overall design and process control of its NR/HR-oven, resulting in a uniform heat flux distribution both above and below the oven charge. It is associated with short gross coking times of less than 58 hours using compacted coal charges with a density of d = 1,100 kg/m^3, thus guaranteeing high process efficiency and low investment costs at the same time.

Relatively quick calculations allow for the determination of a number of parameters necessary for improved oven performance. The 1D model may provide information concerning parameters such as “required oven (under-pressure) suction”, “end of coking process” or “required channel diameter”.

The hydraulic network model and gas combustion model are coupled. Mass flow rates, gas composition and temperature in each branch are exchanged between both the hydraulic network model and the combustion model.

The raw gas (volatiles) composition comes from the Merrick sub-model [5].

The comparison of the mass flow rates entrained (sucked) through the primary air inlets and the secondary air inlets shows that both models (one-dimensional and FLUENT calculations) produce very similar results. The temperatures in the upper oven and in the sole flue are also in good agreement.

Conclusions

The 3D flow simulation model developed for NR/HR-ovens, corresponding to state-of-the-art design of TKIS-PT, enables the mixing and combustion process within the oven chamber and sole flues to be observed through graphical animation and lead to an evolutionary improvement in the understanding of mixing and combustion laws within all combustion chambers of the oven. Moreover, the model allows the application limits of this coking technology to be determined with respect to important process parameters like characteristic temperature and pressure profiles in the upper and lower parts of the oven. It is also possible to illustrate any geometric point with differently adjusted primary and secondary air fractions, taking into account all aspects of process and geometric coupling between the upper and lower parts of the oven.

References

[1] Kim, R., Ein Prozessmodell zur Kokserzeugung mit direkter Beheizung, Dissertation, TU Clausthal, 2010

[2] Quanci, J., Recent Trends in Heat Recovery Coke making Processes, SunCoke Energy, ABM Brasil, 2011

[3] Zheng, Q., and Wei, H., Three-Dimensional Numerical Simulations and Analysis of a Heat-Recovery Coke Oven, School of Chemical Engineering and Technology, Energy Fuels, 27 (6), pp 3570 – 3577, 2013

[4] Austin, G.T., “Coal Chemicals” Shreve’s Chemical Process Industries Fifth Edition edited by George T. Austin McGraw Hill International editions, p. 70, 1984

[5] Merrick, D., and Atkinson, B., Mathematical models of the thermal decomposition of coal. National Coal Board, Coal Research Establishment, Stoke Orchard, Cheltenham, Glos., GL52 4RZ, UK, 1982