



Modelling and control of pollutant formation in blast stoves



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ABSTRACT

The formation of nitrogen oxide NO is investigated for the combustion of enriched blast furnace gas in a blast stove of the voestalpine Stahl GmbH Linz.

The pollution formation is modelled with Computational Fluid Dynamics (CFD) considering detailed reaction chemistry. The non-adiabatic numerical calculations investigate the turbulence–chemistry interaction in the combustion chamber using the Eddy Dissipation Concept in combination with a multi-step chemical reaction mechanism. Sub-models are implemented to investigate turbulence of flow, radiative heat transport, flame characteristics and reaction kinetics of participating species in order to calculate the emission load in dependence on the operating conditions. The results confirmed the generally known trend that the NO emissions strongly depend on the temperature level of the stove's dome. A NO emission load of about 16.1 mg/m³ (STP) (at 3 volume % of dry O₂) was calculated for the base operating case showing promising agreement with real plant data and literature trends. The numerical results can be used by plant operators to generate operational measures in terms of control for temperature level and gas feed ensuring compliance with legal pollution limits. In this context a dome temperature of ~1360 °C turns out to define the plant's peak temperature to hold the permissible NO_x offgas concentration.

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1. Introduction

Hot blast stoves (also known as cowpers; cf. Fig. 1) are auxiliary installations in metallurgical plants being used to preheat the air for the blast furnace process. They consist of an upward flow burning and a downward flow regenerator shaft. A dome forms the horizontal connection between the shafts. The blast process consists of two main periods being interrupted by changeover periods (pressure swings). In the heating period (duration approximately 50 min) the stoves are heated up by burning gases (enriched blast furnace gas, BFG) until the dome reaches the desired process temperature (approximately 1300 °C–1350 °C; acc. to [BAT Iron and Steel Production, 2012](#)). The dome temperature represents an important control parameter. The combustion starts in a ceramic burner at the bottom of the burning shaft. The flue gas streams upwards through the burning shaft and later through the dome into the regenerator shaft. The flue gas outlet is situated at the

bottom of the regenerator shaft. The shaft interior contains refractory brickwork equipped with vertical gas channels. The refractories contact with the flue gas and store the gas heat which is used for the preheating of cold air in the second period (blast period, duration ~40 min). Therefore the combustion gas flow is cut off and by reversing the flow direction the stove is filled with compressed preheated air (5–6 bars absolute pressure and ~220 °C respectively), which enters the stove at the bottom of the regenerator shaft pressurizing the stove up to 5 bar (gauge pressure). The air passes the hot bricks by heating up to approximately 1350 °C. Afterwards the so called hot blast leaves the stove via the hot blast outlet above the burner and is subsequently transported to the blast furnace.

Higher combustion temperatures in the stove increase the blast temperature, which results in a reduced coke requirement for the iron production ([BAT Iron and Steel Production, 2012](#)). On the other hand higher temperature levels in the dome and the entire blast stove respectively enforce the formation of nitrogen oxides ([Sucker et al., 1981](#)). NO_x emissions in blast stoves increase exponentially for dome temperatures above 1300 °C ([Kalfa and Bühler, 1984](#)). Control of emission is demanded by stringent legislation and furthermore in order to reduce corrosive impacts at the blast stove steel shell.

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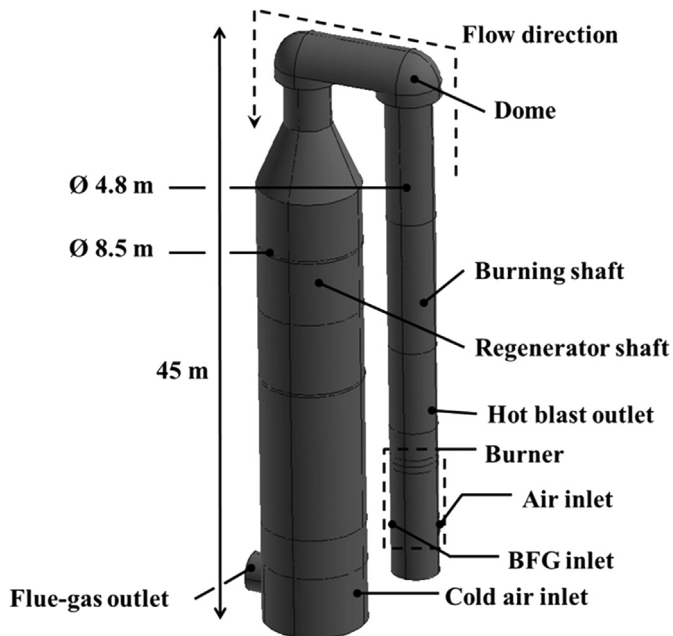


Fig. 1. Blast stove geometry: Specification of the flow domain and the inlet boundaries for the combustion air and the blast furnace gas (BFG). Description of Fig. 1: The figure shows the geometry of the blast stove including dimensions, the gas flow inlets and outlets and the flow direction during the combustion process respectively.

The formation of NO strongly depends on the blast stove operating periods. Several prior studies confirmed for the heating period the NO formation preferentially to take place in the upper part of the burning shaft where the dome was identified as the high temperature combustion zone of the blast stove (Sucker et al., 1981). Harp et al. (1990) were one of the first to analyze the influence of changing blast stove operating conditions on the NO formation. This work confirmed Sucker's theory on the position of the NO formation maxima in the stove. Numerical modelling based prediction of pollution formation was realized as a useful and relatively cheap method to perform a combustion process control with respect to NO formation also by Khiari et al. (2008).

Under certain conditions pollutants such as nitrogen oxides are the starting point for severe stress corrosion cracking. During the air filling process of the stove after the heating period flue gas species e.g. NO diffuse through the slits of the refractory lining to the relatively cold outer steel casing. This mass transfer occurs because of pressure swings being associated with load changes of the blast operation when switching from the heating period to the blast period (Huijbregts and Leferink, 2002). During the following blast period the flue gas cools down at the steel shell and NO is converted into NO₂ under presence of residual O₂. Nitric and sulfuric acid, both formed by sour gas hydrolysis, increase the acid dew point of the entire combustion gas. Condensation results in formation of aqueous wall films during the blast period (Leferink and Huijbregts, 2004). In further acid and sour gas reactions at the steel casing nitrite is partially reduced forming ammonia. By salt formation ammonia and nitric acid convert into ammonium nitrate (NH₄NO₃) introducing a strong stress corrosion cracking potential. Corrosion takes place in the lower section of the regenerator shaft preferentially in the vicinity of flue gas outlet, where the welded areas of the steel shell are exposed to considerable tensile stresses.

In the present study Computational Fluid Dynamics (CFD) is used to investigate the pollution formation during the heating period in a blast stove of the voestalpine Stahl GmbH in Linz with

specific focus on BFG combustion. The paper summarizes the calculated results concerning the NO and CO emission loads due to changing operating conditions. Preheating of the combustion gas and the combustion air will be analyzed in detail as a mean to control dome temperature levels. In a further step excess air increase is studied as a potential strategy to reduce NO_x emissions in the stove. During the heating period temperature and air excess influence the NO and CO concentration levels of the offgas considerably and therefore represent important blast process control parameters. Since the offgas composition and the pollutant load result directly from our simulations the study aims to analyze the restrictions induced by environmental regulations on the thermal utilization of BFG in hot blast production. To the authors' knowledge such a type of investigation has not been performed for high temperature combustion systems of integrated steel plants to such an extent before. Our motivation is to generate a link between emission modelling with respect to legal pollution limits and changing operating conditions such as flow rate and preheating temperature. The investigation demonstrates means for plant operators to optimize the stove operation simultaneously considering the constraints of the plant's current emission limits. The results of our simulations are evaluated by a comparison with real plant emission data.

2. Numerical approach and model setup

Since the blast stove possesses separate fuel gas and air supply channels the combustion gases do not mix until reaching the ceramic burner. Under these conditions a non-premixed combustion model represents the basis for the description of the reactive species transport during the blast stove heating process. Fig. 1 shows the geometry of a blast stove of the Blast Furnace A (BF-A) at the voestalpine Stahl GmbH Linz with an overall height of approximately 45 m. The diameters of the burning shaft and the regenerator shaft are 4.8 m and 8.5 m respectively. The dome has a length of approximately 13 m. Operating on cyclical basis four stoves provide a continuous air supply for the BF-A.

2.1. Turbulence

The changing operating conditions during the blast stove process (periodic change of hot and cold air, pressure swings and changes of flow direction) produce strongly unsteady conditions in the stove. A simplified quasi-steady state for the flow was used in for the CFD-investigation with the Reynolds-Averaged Navier–Stokes equations (RANS) chosen as a basis for the conservation of mass, momentum, energy and species.

In the stove's confined flow situation our standard operating case is defined by a high Reynolds-number of ($Re = 1.7 \times 10^6$). Since the flow includes no recirculation or swirling effects the $k-\epsilon$ model was decided as accurate enough for turbulence description. Therefore two additional transport equations for the turbulent kinetic energy k and the dissipation rate ϵ have to be solved.

2.2. Turbulence chemistry interaction and species transport

The challenge in numerical calculation of BFG combustion lays in the simultaneous conversion of species involving fast as well as slow chemical kinetics. Oxidation of hydrogen and carbon monoxide with different reaction time scales induce temporal fluctuations in scalar quantities such as temperature and species concentrations. Simplified fast chemistry approaches as well as mean scalar quantities are not sufficient for a representative determination of pollutant species levels.

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