Combustion processes inside a direct-fired continuous strip annealing furnace

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Abstract: The combustion process inside a direct-fired continuous strip annealing furnace for steel is analyzed. Here, the fuel-rich combustion of natural gas is modeled by two chemical reactions: first, the oxidation and, second, the water-gas-shift reaction, which leads to a chemical equilibrium inside the furnace. Based on the combustion process, the flue gas dynamics are modeled by the mass and the enthalpy balance. A measurement campaign conducted at a real plant is used for verification of the mathematical model. This model is appropriate for real-time applications in control and optimization due to its low computational effort and high accuracy.

Keywords: Direct-fired strip annealing furnace, heat treatment of metal strips, two-step fuel-rich combustion of natural gas, water-gas-shift reaction, first principles.

1. INTRODUCTION

1.1 Objective of this work

In this work, a direct-fired continuous counter-flow strip annealing furnace (DFF) with focus on the combustion processes is considered. The furnace is part of a hot-dip galvanizing line at voestalpine Stahl GmbH, Linz, Austria. It is used for heat treatment of metal strip products. This processing step helps to control material parameters of the strip and is a preparation for subsequent surface treatment. The temperatures during the heat treatment process are crucial for the product quality. Moreover, the oxygen content of the furnace atmosphere is an important process parameter because an inert gas atmosphere is required to avoid scale formation. Fig. 1 shows an outline of the considered furnace.

Due to locally varying combustion mechanisms inside the furnace, the control of the strip temperature is a demanding task. This task is further complicated by time-varying process parameters (steel grade, strip thickness, and width) and by the fact that the strip temperature can only be measured by one pyrometer (cf. Fig. 1). Further control objectives are high product quality, minimum energy consumption, minimum flue gas emissions, minimum operating costs, and maximum throughput. To reach these control objectives, a model-based control concept has to be developed. This is why a detailed analysis and an accurate mathematical model of the DFF are required. The model should capture the most important nonlinearities, the dynamical interaction, and the combustion processes inside
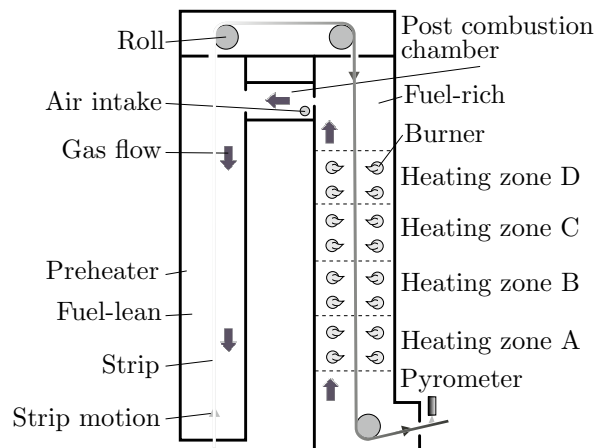
Fig. 1. Direct-fired counter-flow strip annealing furnace.

the furnace. As model-based furnace control has to be performed in real-time, the model should be computationally efficient and sufficiently accurate.

1.2 Direct-fired furnace

The steel strip moves with a velocity up to $3\,\text{m/s}$ through the considered furnace. The range of the strip thickness is $0.35 - 1.2\,\text{mm}$ and of the width $0.8 - 1.7\,\text{m}$. The strip enters the furnace with ambient temperature and is guided through the furnace by three rolls made of high-temperature alloy. The flue gas composition varies locally along the furnace duct. The combustion of natural gas takes place in four heating zones (HZ A – D). The burners of each HZ are supplied with natural gas and combustion air. The air for the HZ C and D is preheated by a recuperator. In general, the air-fuel equivalence ratio is a crucial process parameter that influences the product quality. It is controlled to be smaller than unity. Therefore, the combustion is called fuel rich. This means that the flue

gas inside the HZs does not contain oxygen and oxidation of the strip is avoided. The flue gas which leaves the HZ D contains unburnt elements. As these harmful products must not leave the furnace, they are oxidized in a post combustion chamber (PCC). Here, fresh air is added to the flue gas. For safety reasons, burners that are switched off are flushed with nitrogen. However, the flushing causes a drop of the flue gas temperature and thus, the heat input into the strip is reduced. The post combustion changes the composition of the hot flue gas to fuel lean, i.e., the flue gas contains oxygen. After the PCC, the hot flue gas is used for preheating the strip in the preheater. Finally, the remaining enthalpy of the flue gas, which leaves the furnace through the funnel, is used for preheating the air of the HZs C and D.

1.3 Existing models

A frequent motivation for physical or empirical models is their use in model-based real-time control, see Jiang et al. (2004) for empirical models and Yoshitani (1993) for a semi-analytical model. Although, these approaches are characterized by a low computational effort, a physical interpretation of the parameters may be difficult. Physics-based models in combination with linearization are often suggested for real-time applications, e.g. Tian et al. (2000). Models that are based on balances and constitutive equations are particularly interesting. Generally, gas radiation is the dominant heat transfer mechanism in a DFF. Depending on its composition, the flue gas is either participating or non-participating for thermal radiation. In the considered furnace, the flue gas is participating, see Viskanta and Mengüç (1987).
In (Strommer et al., 2014), a mathematical model of the considered DFF is proposed. The dynamic model captures the bulk fluid flow, the temperature of the wall, the strip, and the rolls, and the combustion of methane. Here, a simplified one-step combustion reaction and the water-gas-shift reaction (WGSR) define the stoichiometric coefficients (SCs) of the combustion products. The chemical equilibrium (CE), which is determined by the WGSR, is considered to be reached right at the burner nozzles, i.e., at the entry of the corresponding volume zone. Due to the gas flow coming from the upstream volume zone, a change of the CE occurs in the volume zone, which however is not considered in (Strommer et al., 2014). Hence, the enthalpy, which is related to this chemical process, is not captured. This causes an erroneous calculation of the flue gas temperature. Furthermore, if the burners are switched off, they are flushed by nitrogen, which decreases the flue gas temperature bringing along a shift of the CE. This is not considered in (Strommer et al., 2014).
In this furnace, the combustion is controlled to be fuel rich. This fact and the high flue gas temperature are the reasons why the WGSR occurs in this furnace (Moe, 1962). Therefore, the chemical reactions should be captured by a sufficiently accurate model. Moreover, the composition and the temperature of the flue gas are required for accurate calculation of the heat transfer inside the furnace.
In literature, there exist different approaches for modeling the combustion mechanism of methane. They vary significantly in terms of complexity and level of detail. The general combustion mechanism of methane is presented in (Montgomery and Kosály, 1997; Turns, 2006).

A reduced model with only four chemical reactions is presented in (Bilger and Starner, 1990; Peters and Kee, 1987; Turns, 2006). This combustion mechanism can be further simplified by assuming a stationary condition for the hydrogen radical. Then, the combustion of methane can be modeled by three chemical equations (Bilger and Starner, 1990; Peters and Williams, 1987). Typically, the combustion mechanisms and the flue gas composition are neglected in models of such furnaces (Banerjee et al., 2004; Marlow, 1996; Tian et al., 2000; Yoshitani, 1993). However, the flue gas composition is an important process parameter with respect to the product quality. Moreover, the furnace efficiency can be increased by reducing the amount of excess air, which is supplied to the PCC. Therefore, an accurate model of the combustion and the flue gas composition is necessary.
In literature, various mathematical models of DFFs have been presented. But these approaches are not directly applicable to the furnace considered in this work, mainly due to the following reasons:

- Strommer et al. (2014) considered the CE only at the nozzles of the burners but not in the flue gas moving through the furnace.
- If burners are switched off, they are flushed with nitrogen. This entails a change of the enthalpy and of the flue gas composition. Hence, the CE is also influenced by the flushing.
- Using a more sophisticated combustion mechanism (e.g., four chemical reactions), a lot of species have to be considered (Turns, 2006). This leads to high computational effort and complexity, which is cumbersome in view of the desired real-time capability.

1.4 Contents

The combustion of natural gas and the flue gas dynamics are described in Sec. 2. The combustion is modeled by a two-step combustion mechanism, cf. Sec. 2.1. Based on the reaction kinetics and the mass balance, the mass and the composition of the flue gas is found in Sec. 2.2. In Sec. 2.3, the enthalpy balance is used for calculating the flue gas temperature. In Sec. 3, the accuracy of the model is verified based on measurements from the plant.

2. MATHEMATICAL MODEL

The mathematical model of the DFF consists of submodels for the combustion, the flue gas, the roll, the strip, the wall, and the heat transfer mechanisms. In the following, the combustion of natural gas and the flue gas dynamics are analyzed. The remaining subsystems are discussed in (Strommer et al., 2014). It is assumed that the flue gas is an ideal gas consisting of carbon dioxide CO_2, carbon monoxide CO, water H_2O, hydrogen H_2, oxygen O_2, and nitrogen N_2. The abbreviations of these elements are summarized in the set $\mathcal{S} = \{CO_2, CO, H_2O, H_2, O_2, N_2\}$. The flue gas composition is defined by the fuel-rich combustion in the HZs and the fuel-lean combustion of CO and H_2 in the PCC. The furnace is discretized into N volume zones. It is considered that each zone is a well-stirred reactor and that the gas streams only in the direction opposing the strip motion. The mass and the enthalpy balance are applied to determine the total gas mass M_i, the mass fraction