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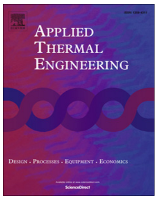

Research Paper

Low scale reheating of semi-finished metal products in furnaces with recuperative burners

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HIGHLIGHTS

- Low scale reheating of copper and steel products applying fuel rich combustion.
- Post-combustion and heat transfer in recuperative burners.
- Low NO_X emissions due to fuel rich combustion and post-combustion.
- Cost reduction for reheating of high-priced metal products.

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ABSTRACT

Industrial furnaces for reheating semi-finished metal products are often direct fired with natural gas and air. Oxidation of the metals exposed to the furnace atmosphere causes significant material losses and additional work during furnace operation and in further processing. A reheating concept, which reduces scale formation, was developed for direct fired reheating furnaces. It involves fuel rich combustion, post-combustion of the unburned off-gas and efficient preheating of the combustion air. This paper focuses on the reheating of copper and steel in direct fired furnaces with recuperative burners. Therefore, the post-combustion in an annular gap, according to a recuperative burner was examined, concerning temperature profile in the gap and off-gas emissions, to determine technical limits of the concept. Based on energy balances and scale formation the costs for fuel and metal loss were calculated to determine economic impact on the reheating process. The results show economic potential of the concept in terms of cost savings for the reheating of copper with a fuel rich combustion but no significant cost savings for the reheating of steel.

1. Introduction

Direct gas fired reheating furnaces are often used to heat slabs or billets prior to hot working. Excess oxygen, carbon dioxide and vapor in the furnace atmosphere lead to scale formation on the surface of the metal products, especially at high temperatures. This causes significant amounts of material losses. This article introduces a concept for low scale reheating of semi-finished metal products with decentralized air preheating with recuperative burners. The concept, shown in Fig. 1, consists of three steps, which are the primary fuel rich combustion, the post-combustion of flammable off-gas components, such as H_2 and CO, with excess air and the heat-transfer in a heat exchanger for preheating of the combustion air.

Heating with fuel rich combustion is a common approach to reduce scale formation. Although, most of the furnaces are fired fuel lean, there are several concepts for low scale reheating with fuel rich combustion in literature, especially for the scale free reheating of steel. Several investigations describe the reduction of scale due to a separation of the furnace atmosphere into high temperature, fuel rich sections and low temperature fuel lean sections [1–6]. Other investigations focus on a fuel rich combustion and post-combustion in separate combustion chambers to use the heat of the post-combustion as radiation of the hot walls in the furnace chamber [7,8]. In addition, there are applications using the heat of the post-combustion for centralized combustion air preheating with a central recuperator [9]. But, also furnaces with combined concepts are described, like rotary hearth furnaces [10,11] or galvanizing lines [12].

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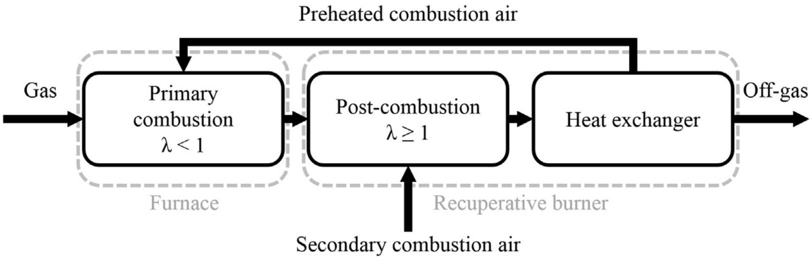

Fig. 1. Concept for low scale reheating of semi-finished metal products.

In contrast, there are less decentralized concepts for the reheating of steel reported in literature. Concepts of a regeneratively heated chamber furnaces are described in [7,13]. A concept with recuperative burners, similar to the investigated concept in this article, is described in [1,14]. However, these investigations do not focus on the post-combustion of the off-gas or technical limits of the concept.

Besides, for the reheating of copper the main concepts are gas fired reheating and fast inductive reheating. However, most of the investigations only focus on the oxidation behavior of copper samples and its alloys in an atmosphere containing excess oxygen [15–22]. There is less documentation about reheating concepts in furnaces. In [23] the reheating of copper billets with gas fired billet heaters or chamber furnaces is described. To avoid scale formation the air ratio is controlled to an oxygen content of 1 vol-% with a maximum reheating time of 1.5 h.

Although, there are investigations on the concept of fuel rich combustion and post-combustion for especially scale free reheating of steel, there are no information about concepts of low scale reheating with recuperative burners, its technical limits and economic impact on the production process. But, recuperative burners are often used as an application for continuous air preheating with high energy efficiency, for example in the forging industry [24]. Therefore, the main aims of this research project are the quantification of the scale reduction due to fuel rich combustion for different reheating processes, the effect of fuel rich combustion and post-combustion on the thermal load, the off-gas emissions of the concept for recuperative burners and the economic effects compared to conventional reheating concepts with fuel lean combustion.

This article presents the results of the examination of the concept for the reheating of copper and steel in furnaces with metallic ($T_{furnace} = 950\,°C$) and ceramic ($T_{furnace} = 1200\,°C$) recuperative burners. The post-combustion in an annular gap was investigated to localize the maximum thermal load on the recuperator material and the off-gas emissions depending on the temperature of off-gas and air. The economic potential of the low scale reheating concept was compared to a conventional reheating process with fuel lean combustion based on the costs for fuel and metal loss which results from the energy balances of two idealized reheating processes and the mass change due to scale formation based on experimental data of [25].

2. Scale formation on copper and steel

One part of the project is the quantification of the mass change due to scale formation depending on the air ratio of the reheating process. The air ratio λ is defined in Eq. (1) as the inverse of the equivalence ratio φ with l as the provided combustion air and l_{min} as the exactly needed combustion air. In this paper an off-gas atmosphere of $\lambda < 1$ is defined as fuel rich and an off-gas atmosphere of $\lambda > 1$ is defined as fuel lean, whereby $\lambda_{primary}$ describes the air ratio of the primary combustion and λ_{total} the total air ratio, including primary combustion and post-combustion.

$$\lambda = \frac{1}{\varphi} = \frac{l}{l_{min}} \tag{1}$$

In this research project the scale formation on copper, a copper-nickel alloy and the hot forming tool steel 1.2367 (X38CrMoV5-3 according to EN ISO 4957) was studied in a synthetic off-gas. Main focus of the investigations is the mass gain depending on air ratio, temperature and time for the different metals.

The oxygen partial pressure of the surrounding atmosphere, which is adjusted by the air ratio, strongly affects the formation of oxides on a metallic surface, depending on the thermodynamic stability of the oxides. Instead, the temperature and time of a process affects the kinetic of the oxide growth. The experiments and results for copper, a copper-nickel alloy and steel samples as part of this project are described in [25–27].

Copper forms with oxygen the stable oxides CuO and Cu_2O. Cu_2O is thermodynamically more stable. Therefore, it decays at a lower equilibrium partial pressure of oxygen into copper and oxygen rather than CuO. In natural gas direct fired furnaces the oxygen partial pressure at equilibrium falls below the stability limit for the three oxides at an air ratio of $\lambda_{primary} = 0.98$. As a result, the growth of oxide scales on copper is not possible in an off-gas atmosphere with $\lambda_{primary} \leq 0.98$. In the experiments in this project an air ratio of $\lambda_{primary} = 0.96$ is used considering measurement uncertainties [25,26].

The most stable oxide of iron is FeO, which is considered for further calculations. Other oxides from iron are Fe_3O_4 and Fe_2O_3. Alongside iron, chromium, molybdenum, vanadium, silicon and manganese are the further alloying elements of the investigated alloy 1.2367. Therefore, oxides of these elements, as well as mixed oxides from more than one metal, may also form. Scale free reheating of steel is only possible with a combustion of natural gas and air with an air ratio of $\lambda_{primary} \leq 0.48$. Instead, low scale reheating is possible with a moderate air ratio of $\lambda_{primary} \leq 1.0$ [25].

3. Experimental setup

The experimental setup is described in [26,28]. The primary, fuel rich combustion takes place in a combustion chamber with a diameter of 600 mm and a height of 940 mm. Therefore, a conventional burner, fired with natural gas and cold air, is used, which operates with a burner capacity P_{burner} of 10 kW to 40 kW with an air ratio from $\lambda_{primary} = 0.7$ to $\lambda_{primary} = 1.15$ and provides fuel rich and fuel lean furnace atmospheres.

This article focusses on the processes in the post-combustion chamber, shown in Fig. 2. The post-combustion chamber is structured similar to the off-gas channel of a recuperative burner, where post-combustion and heat transfer are accomplished simultaneously. Therefore, the inner tube can be cooled with cooling air to include the influence of the heat transfer to the recuperator. To analyze the post-combustion and the emissions of the process