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Experimental investigations for the development of burners for low scale reheating of semi-finished metal products

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Abstract

Industrial furnaces for the reheating of 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 for direct fired reheating furnaces, which reduces scale formation, was developed. It involves fuel rich combustion, post-combustion of the unburned off-gas and efficient preheating of the combustion air. Based on this concept a prototype-burner was developed which produces a low oxidizing atmosphere in the furnace. The concept is realized by a recuperative burner generating a reducing furnace atmosphere with fuel rich combustion of natural gas and air. The complete combustion of the furnace atmosphere is ensured by the injection of additional air and takes places in an open radiant tube as part of the burner resulting in a high energy efficiency.

In order to investigate the process an experimental system is set up, consisting of a model of the burner and a combustion chamber for temperature and off-gas measurements. The experimental investigations focus on the reheating of copper and steel in direct fired furnaces with recuperative burners. This paper presents the influence of furnace atmosphere, especially the air ratio of the combustion of natural gas and air in the furnace, on the metal loss of copper and steel samples due to surface oxidation. In addition, the parameters for a stable post-combustion and the efficiency of the process are investigated. The experimental results show the impact of different parameters on the temperature distribution and heat transfer in the open radiant tube and off-gas emissions.

Keywords: recuperative burner; fuel rich combustion; direct fired furnace; scale reduction; radiant tube

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1. Introduction

Direct fired reheating furnaces are used to heat slabs or billets prior to the hot rolling or forging process. These furnaces are usually fired with natural gas and have to be operated with a high efficiency. The complete combustion of the fuel is an essential step to get the maximum heat input into the furnace, which is usually realized by an operation with excess air [1]. The furnace atmosphere contains free oxygen, carbon dioxide and water vapor, leading to an oxidation on the surface of the product [2, 3].

A possibility to prevent scale formation is the usage of a protective gas atmosphere in the furnace. Usually these types of furnaces are equipped with radiant tubes or electric heating elements. Typical atmospheres can be produced by oxidizing fuel gases and drying or cracking of ammonia [4]. Another way to decrease the formation of scale is the fuel rich combustion of natural gas [5-8]. It delivers atmospheres containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), water vapor ($H_2O_{(g)}$) and nitrogen (N_2) [9]. The flammable components like CO and H_2 result in an incomplete usage of the fuel energy content in the furnace. Furthermore, CO is a toxic gas and its emission is regulated by law for example in [10]. In consequence, a post-combustion of the off-gas is necessary.

The aim of the presented research is the development of a burner that produces a low oxidizing / reducing atmosphere in the furnace with a thermal efficiency comparable to state-of-the-art recuperative burners. This article introduces a concept for low scale reheating of semi-finished metal products with decentralized air preheating with recuperative burners based on the results of [6-8, 11-13]. The concept, shown in Figure 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 the combustion air.

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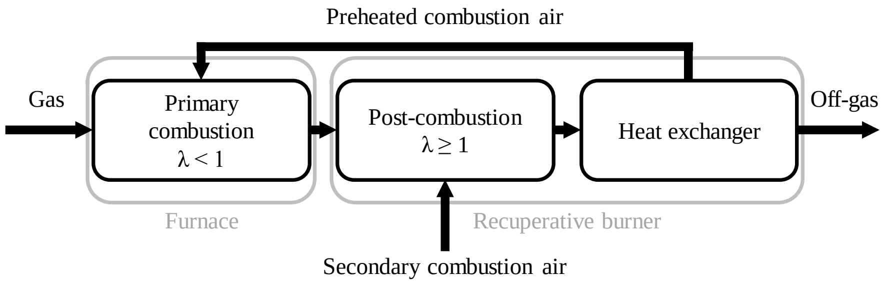

Figure 1: Concept for low scale reheating of semi-finished metal products [11]

Based on the concept of low scale reheating, a new burner was developed which combines direct fuel rich firing and indirect heating with a open radiant tube in a recuperative burner. This concept is shown in Figure 2. The burner operates in flameless mode with a primary air ratio $\lambda_{primary} < 1$ allowing a uniform temperature distribution in the furnace and a low oxidizing / reducing atmosphere. In this paper 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.

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

Unlike existing recuperative burners, the burner is equipped with an open radiant tube (ORT) forming an annular gap between the burner and the tube, where the off-gas is post-combusted by the addition of secondary air. The heat of the reaction is transferred to the furnace by radiation of the ORT and recuperated to heat up the primary and secondary combustion air.

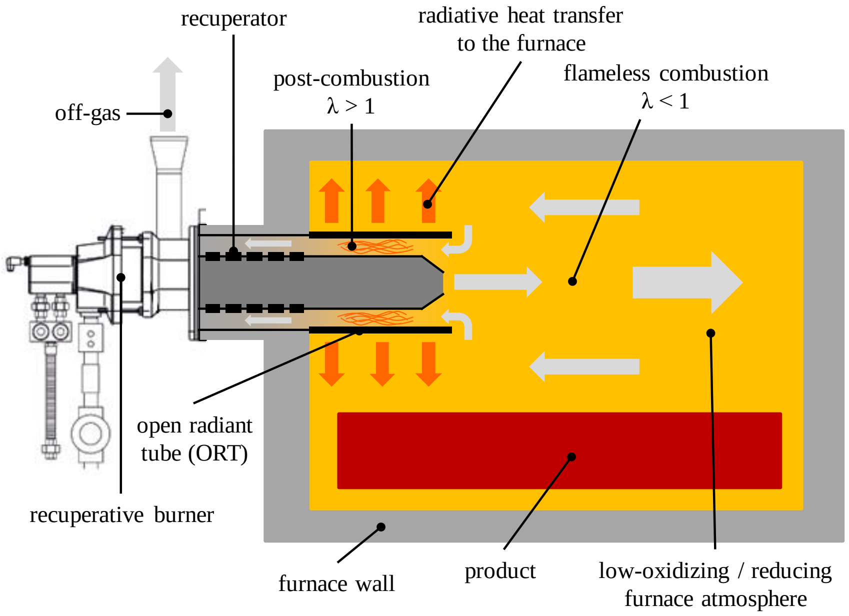

Figure 2: Concept of direct fuel rich firing and radiant tube heating [14, 15, 16]

The intended operating range of the burner is shown in Figure 3. The diagram illustrates the equilibrium concentration of the off-gas components for the combustion of natural gas with air depending on the primary air ratio for a temperature of T = 1000 °C and a pressure of p = 101325 Pa. The primary air ratio is set between $\lambda_{primary} = 0.7$ and $\lambda_{primary} = 0.95$. The maximum concentration of CO is 6 vol.-% in the moist off-gas. After the post-combustion step the total air ration is in a range between $\lambda_{total} = 1.1$ and $\lambda_{total} = 1.2$ [14].

To design a prototype of the burner the post-combustion is investigated numerically with CFD methods [15], determining the influence of different parameters like primary or total air ratio on combustion and energy efficiency of the burner. In addition, the post-combustion in the annular gap, the operation limits and the performance of heat recovery are studied experimentally using an experimental set up consisting of a combustion chamber and a concept-burner [16]. Based on the experimental results the numerical model is validated and used for the further design of a prototype of the burner. The maximum operation temperature of the concept-burner is 1050 °C. The recuperator and the ORT made of heat-resistant steel. The prototype of the burner is made of SiSiC for operation temperatures up to 1250 °C.

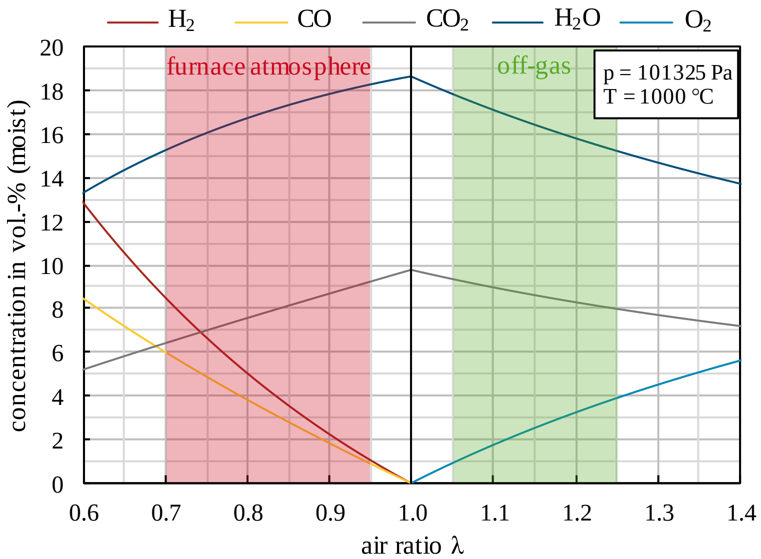

Figure 3: Operating range of the new burner [14]

2. Scale formation on copper and steel

One part of the research was the quantification of the mass change due to scale formation depending on the air ratio of the reheating process which were discussed in detail in [7, 8, 11, 12]. In the presented 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 was 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 [7, 12, 17].

According to the investigations in [7, 17] copper forms the stable oxides CuO and Cu_2O with oxygen. 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 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.

According to the investigations in [7] 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 $\lambda_{primary} \leq 1.0$. For the investigated steel a primary air ratio of $\lambda_{primary} = 0.95$ was figured out as a good compromise between material loss and energy efficiency.

For the determination of the economic effects the specific metal loss caused by scale formation was investigated. Based on these investigations the specific costs for fuel and metal loss were calculated and the cost reduction due to low scale reheating, instead of fuel lean reheating with $\lambda_{primary} = 1.15$, was determined. Detailed results are presented in [11]. Thereby the metal loss per product input is defined according to Eq. (2). In this equation $x_{metal/oxygen}$ is the ratio of metal mass and oxygen mass due the reactions for the formation of Cu_2O, CuO and FeO. The mass change due to scaling is defined as Δm, the surface area is defined as A and the mass of the product before reheating as $m_{product\ input}$. According to [18], the scale on copper consists of 96 % Cu_2O and 4 % CuO. The scale on the steel is assumed as 100 % FeO, according to the investigations of [17].

$$x_{metal\ loss/product\ input} = x_{metal/oxygen} \cdot \left(\frac{\Delta m}{A}\right) \cdot \left(\frac{A}{m_{product\ input}}\right) \tag{2}$$

A key indicator for the material output is the metal yield η_{metal}, according to Eq. (3). As copper product a billet with length of 80 cm, a diameter of 35 cm and a density of 8930 kg/m³ is assumed. As steel product a billet with a length of 8 m, a width of 1.25 m, a thickness of 0.2 m and a density of 7874.0 kg/m³ is assumed. The specific mass change Δm/A and the operating conditions of the experiments according to the experiments of [17] for a process time of approximately 1.5 h are shown in Table 1. To compare the results of the measured mass change depending on the air ratio, all other operating parameters remain constant. The detailed results are shown in [11].

$$\eta_{metal} = 1 - x_{metal\ loss/product\ input} \tag{3}$$

Table 1: Specific mass change for different operating conditions according to [11]

Sample	Temperature T_{max} in °C	Process time in h	Air ratio $\lambda_{primary}$	Mass change in mg/cm²	Metal yield in %
Cu-ETP	950	1.5	1.15	8	99.903
Cu-ETP	950	1.5	0.96	2	99.976
Steel 1.2367	1200	1.5	1.15	52.5	99.724
Steel 1.2367	1200	1.5	0.95	22	99.884

3. Experimental setup and burner designs

The experimental setup for the development of the new burner is shown in Figure 4. It is described in detail in [15, 16, 19]. It consists of the concept-burner, gas and air supply acc. to DIN EN 746-2 [20], a primary combustion chamber with indirect air-cooling and measurement equipment. The height of the primary combustion chamber is 950 mm with a diameter of 600 mm. The concept-burner is installed at the bottom of the chamber and modified with special access spots for measurement equipment like an off-gas sample probe and a suction pyrometer for the measurement of the gas temperature. Furthermore, the inner wall temperature of the furnace is measured with several thermocouples. The nominal power at $\lambda_{primary}$ = 1.0 is approximately 40 kW. The capacity of the prototype-burner will be in the range of 40 to 80 kW, so the concept-burner shows the operation limits for low capacities of the prototype-burner.

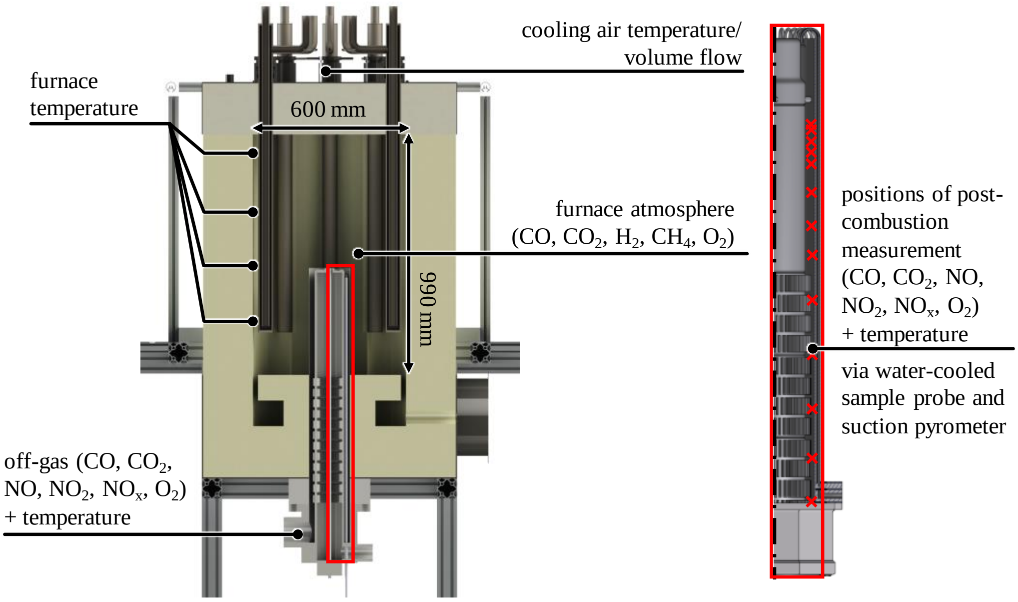

Figure 4: Experimental setup [19]

The concept-burner consists of an extended recuperative burner modified with an open radiant tube (ORT), forming an annular gap of 15 mm for the post-combustion. Figure 5 illustrates the modified burner, showing a cross section. The ORT has a length of 425 mm in the furnace and an outer diameter of 145 mm, while the recuperator, placed inside the furnace wall, is about 400 mm. Air, preheated by the recuperator, and natural gas are used for the primary flameless combustion (FLOX®). The combustion generates a homogeneous temperature distribution within the furnace atmosphere [21]. The off-gas flows through the annular gap between the ORT and the burner and is post-combusted with secondary air. This air is injected by small pipes at a defined angle, causing a swirl and increase mixing between the off-gas and the air.

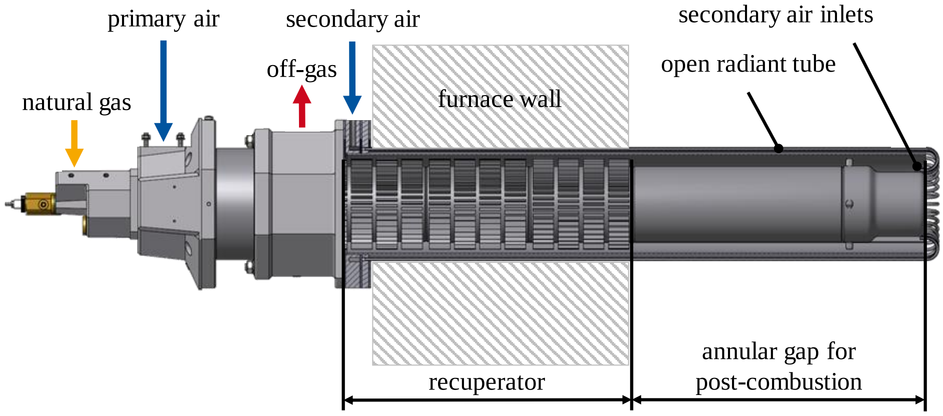

Figure 5: Cross section of the concept-burner [16]

After the post-combustion, the off-gas only contains sensible enthalpy, which is transferred to the furnace by the ORT through convection and radiation and to the combustion air on the inner side of the recuperator. The combination of heat transfer to the furnace in the radiant tube and recuperative air preheating results in low off-gas temperature and a combustion efficiency, defined in Eq. (4) according to [1], which is comparable to state of the art recuperative burner. This results in a high thermal efficiency of the system.

$$\eta_{combustion} = \frac{\dot{H}_{fuel} - \dot{H}_{off\text{-}gas}}{\dot{H}_{fuel}} \quad (4)$$

The mass flows of natural gas and primary combustion air are controlled automatically. The primary off-gas-composition is continuously measured at a defined position in the combustion chamber. The off-gas is taken out with a heated sample probe and transported to the gas conditioning in a heated sample line. After passing filters and a cooling trap, the species CO, CO_2, CH_4, H_2 and O_2 are detected by infrared and paramagnetic analyzers in the dry off-gas.

In the annular gap temperature and gas-composition are measured to characterize the post-combustion. Therefore, the off-gas is taken out with a water-cooled probe and the species CO, CO_2, NO (all infrared), NO_2 (ultraviolet), O_2 (paramagnetic) are detected in the dry off-gas. After the off-gas passes the recuperator another off-gas sample is taken and the concentration of CO, NO, NO_2 and total concentration of nitrogen oxides (NO_x) as well as the concentration of CO_2 and O_2 is analysed continuously. In addition, the off-gas temperature is detected with a thermocouple (typ K).

4. Results

The main aim of the prototype construction process, described in [14], is a burner design for ceramic recuperative burner, which makes the new burner suitable for process temperatures up to 1250 °C. For the design and construction of the prototype-burner the results of the experimental and numerical investigations of the concept-burner are used [15, 16, 22].

The capacity of the prototype-burner is 80 kW instead of 40 kW of the concept-burner. Therefore the capacity of the prototype-burner is in the range of the planned final product. Figure 6 shows the prototype-burner in a test furnace. Due to the ceramic construction of the prototype-burner the width of the annular gap in the ORT is 32 mm, which is twice the diameter of the concept-burner. In the recuperator of the burner the annular gap is reduced to a diameter of conventional recuperative burner, resulting in high off-gas velocity and heat transfer. Due to the ceramic construction of the recuperator and less space for the temperature and off-gas measurement equipment used for the investigations of the concept-burner, the experimental investigations of the prototype-burner focus on the operating range ($\lambda_{primary}$, λ_{total}) and the off-gas emissions especially CO und NO_x. Besides the temperature distribution in the annular gap of the ORT and the recuperator is measured with typ K thermocouples.

The prototype-burner has a characteristic ratio of the volumetric flow rate of the primary and secondary combustion air due to the ceramic construction with defined air inlets. Therefore the total air ratio depends on the primary air ratio. The investigations focus on two different configurations of the prototype-burner (configuration 1 and configuration 2). The results are shown in Figure 7. There is a linear correlation between the primary air ratio $\lambda_{primary}$ and the total air ratio λ_{total}. The green area illustrates the main operation range of the new burner. The grey area illustrates the tested range of the prototype-burner. The operation range of the new burner can be adapted to the intended furnace or process conditions. A modification is done by a variation of the burner geometry.

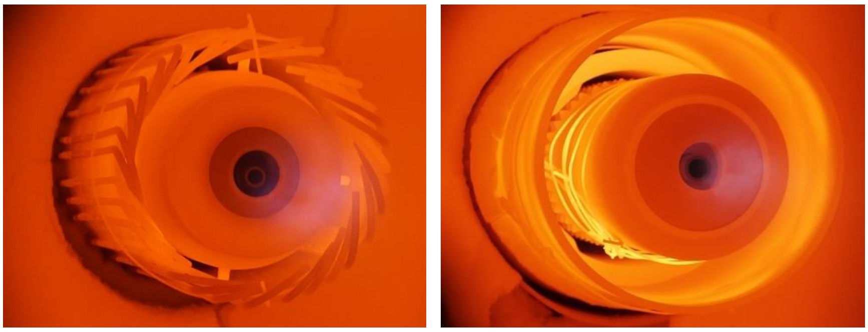

Figure 6: Picture of the concept-burner (left) and the ceramic prototype-burner (right) in a test furnace [14, 15]

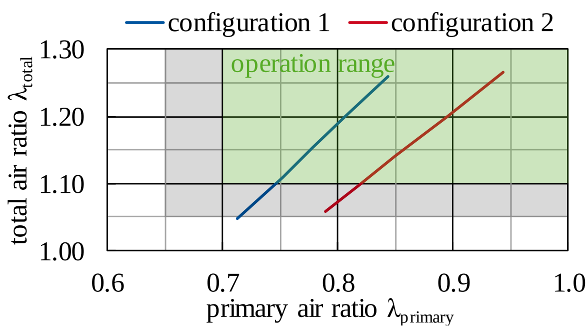

Figure 7: Operation range of the ceramic prototype-burner in a test furnace [14]

Figure 8 shows the temperature distribution in the ORT and the recuperator of the prototype-burner depending on the distance from the primary off-gas inlet for configuration 2. The figure shows the experiments and numerical calculations. For the numerical simulations, steady-state CFD calculations including combustion and heat transfer are carried out. The simple model only includes the post-combustion in the annular gap [15, 16], while the coupled model takes the combustion air flow on the inside of the annular gap as well as the heat transfer in the recuperator into account [19]. Depending on the used numerical model the calculations are a useful indicator for the temperature distribution. The temperature measurements are the basis for the calculations of energy efficiency [19].

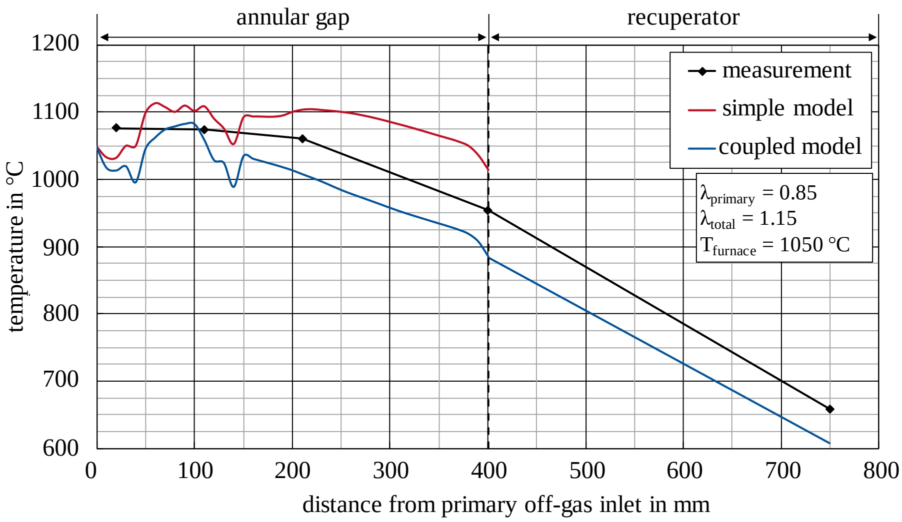

Figure 8: Temperature in the annular gap of the prototype-burner, burner configuration 2 [19]

Figure 9 shows the CO-concentration, the total NO_x-concentration in the dry off-gas and the combustion efficiency depending on the total air ratio λ_{total} for the experimental investigations of the prototype-burner in configuration 1. The temperature in the furnace is T = 1050 °C and the burner capacity is 80 kW. The primary and post-combustion is flameless. Therefore the formation of thermal NO_x is low. The NO_x-concentration decreases with an increasing total air ratio from 38 ppm at λ_{total} = 1.04 to less than

15 ppm at λ_{total} = 1.27. At a total air ratio of λ_{total} = 1.10 the CO-concentration is less than 50 ppm. With an optimization of the burner design a further decrease of the CO-concentration in the off-gas is possible. The combustion efficiency in the experiments, calculated according to Eq. 4 is in a range of 65 % and therefore in a range of conventional recuperative burner. A further improvement of the energy efficiency of the burner can be obtained by changing the heat exchanger concept and design.

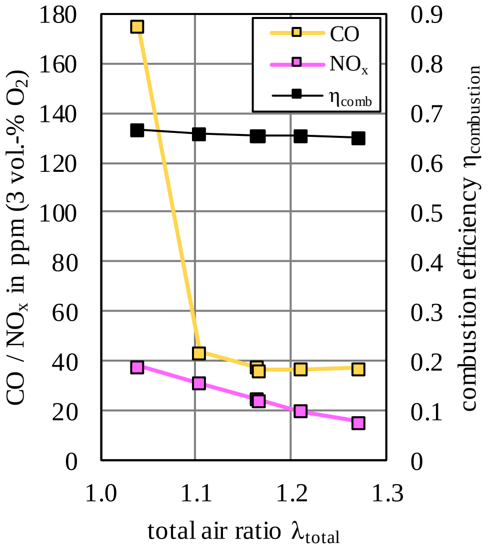

Figure 9: Measured off-gas emissions and thermal efficiency of the prototype-burner in configuration 1 [14, 19]

5. Conclusion

Reheating slabs or billets in a low oxidizing / reducing atmosphere due to fuel rich combustion of natural gas and air results in less scale formation and lower material loss. In this paper, the design and development of a new burner combining fuel rich combustion, post-combustion in an open radiant tube and recuperation of the off-gas is presented.

In a first step, the potential of a concept for low scale reheating of semi-finished copper and steel product due to fuel rich combustion and post-combustion of the unburned off-gas was analyzed. The experiments show a significant reduction of scale for a primary air ratio of $\lambda_{primary}$ = 0.96 for copper and of $\lambda_{primary}$ = 0.95 for steel.

In a second step, a metallic concept-burner was developed, using flameless oxidation (FLOX®) and fuel rich combustion to create an oxidizing / reducing off-gas. For the post-combustion, the burner is extended and modified by an open radiant tube (ORT) which forms an annular gap and transfers the heat to the furnace by convection and radiation. After post-combustion the heat of the off-gas is used for recuperative air preheating.

Based on the experimental investigations of the concept-burner a ceramic prototype of the new burner for temperatures up to 1250 °C was developed. The investigations in a test rig show a stable flameless primary and post-combustion, which results in a low NO_x-concentration of less than 40 ppm in the off-gas. The CO-concentration at a total air ratio of λ_{total} = 1.10 is less than 50 ppm. The combustion efficiency in the experiments was in a range of 65 % and therefore comparable to the combustion efficiency of conventional recuperative burner. With further optimization of the prototype after the project, the new burner is suitable for several furnace and process applications with a high thermal efficiency and low off-gas emissions.

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References

[1] **Pfeifer, H.; Nacke, B.; Beneke, F.:** Handbook of Thermoprocessing Technologies Volume 1: Fundamentals, Processes, Calculations, 2nd Edition, Vulkan-Verlag, Essen, 2010

[2] **Abuluwefa, H. T.; Guthrie, R. I. L.; Ajersch, F.:** The Effect of Oxygen Concentration on the Oxidation of Low-Carbon Steel in the Temperature Range 1000 to 1250 °C, Oxidation of Metals Vol. 46 (1996), No. 5/6, pp. 423-440A

[3] **Birks, N.; Meier, G. M.; Petit, F. S.:** High-Temperature Oxidation of Metals, Cambridge University Press, Cambridge, 2006

[4] **Nemenyi, R.:** Controlled Atmospheres for Heat Treatment, 1st Edition, Pergamon Press, 1984

[5] **Schmidt, R.; Winning, G.; Bender, W.; Hatzfeld, O.; Adler, W.:** Weiterentwicklung und Betriebseinführung von Verfahren zur Umweltentlastung am Beispiel Schmiedeöfen durch Einsatz neuartiger Beheizungs- und Prozesstechnologien bei Hochtemperatur, Final Technical Report, Betriebsforschungsinstitut (BFI) VDEh-lnstitut für angewandte Forschung GmbH, Wiehl, 2004

[6] **Schwotzer, C.; Schnitzler, M.; Pfeifer, H.; Ackermann, H.; Lucka, K.:** Experimental investigation of a concept for scale free reheating of semi-finished metal products, Proceedings of the 7th European Combustion Meeting, 30. March - 2. April 2015, Budapest

[7] **Schwotzer, C.; Balkenhol, T.; Schnitzler, M.; Pfeifer, H.; Ackermann, H.; Lucka, K.:** Experimental investigation of a concept for scale free reheating of semi-finished metal products, Proceedings of the 10th European Conference on Industrial Furnaces and Boilers, 7.-10. April 2015, Porto Gaia, Portugal

[8] **Schwotzer, C.; Schnitzler, M.; Pfeifer, H.:** Zunderarme Wiedererwärmung von Metall-Halbzeugen mit Rekuperatorbrennern, Gaswärme International Vol. 65 (2016), No. 3, pp. 67-72

[9] **Wuenning, J.G.; Milani, A.:** Handbook of Burner Technology for Industrial Furnaces, 2nd Edition, Vulkan-Verlag, Essen, 2016

[10] Erste Allgemeine Verwaltungsvorschrift zum Bundes-Immisionsschutzgesetz (Technische Anleitung zur Reinhaltung der Luft – TA Luft) of 24th of July 2002 (GMBI. p. 511), 2002

[11] **Schwotzer, C.; Schnitzler, M.; Pfeifer, H.:** Low scale reheating of semi-finished metal products in furnaces with recuperative burners, Applied Thermal Engineering Vol. 128 (2018), pp. 586-594

[12] **Schwotzer, C.; Schnitzler, M.; Pfeifer, H.; Ackermann, H.; Diarra, D.:** Low scale reheating of semi-finished metal products in furnaces with a central recuperator, Heat Processing Vol. 14 (2016), No. 3, pp. 83-89

[13] **Schwotzer, C.; Schnitzler, M.; Pfeifer, H.:** Untersuchung der Abgasnachverbrennung für ein Verfahren zur zunderarmen Wiedererwärmung von Metall-Halbzeugen, 27th VDI Flammentag, 16.-17. September 2015, Clausthal-Zellerfeld

[14] **Schmitz, N.; Schwotzer, C.; Pfeifer, H.; Wuenning, J. G.; Cresci, E.; Schneider, J.:** Entwicklung eines energieeffizienten Brenners mit reduzierender Schutzgasatmosphäre, Gaswärme International Vol. 67 (2018), No. 1, pp. 72-78

[15] **Schmitz, N.; Schwotzer, C.; Pfeifer, H.; Schneider, J.; Cresci, E.; Wuenning, J. G.:** Development of an Energy-Efficient Burner for Heat Treatment Furnaces with a Reducing Gas Atmosphere, HTM Journal of Heat Treatment and Materials Vol. 72 (2017), No. 2, pp. 73-80

[16] **Schmitz, N.; Schwotzer, C.; Pfeifer, H.; Wuenning, J. G.; Cresci, E.; Schneider, J.:** Numerical investigation on post-combustion in a burner for heat treatment furnaces with a reducing gas atmosphere, Energy Procedia Vol. 120C (2017), pp. 112-119

[17] **Ackermann, H.; Diarra, D.; Wuenning, J. G.:** Zunderwachstum von Kupfer und Stahl bei direkter Befeuerung mit Brennstoffüberschuss, Gaswärme International Vol. 65 (2016), pp. 33-39

[18] **Zhu, Y.; Mimura, K.; Lim, J.-W.; Isshiki, M.; Jiang, Q.:** Brief review of oxidation kinetics of copper at 350 °C to 1050 °C, Metallurgical and Materials Transactions A Vol. 37 (2006), pp. 1231-1237

[19] **Schmitz, N.; Giesler, L.; Schwotzer, C.; Pfeifer, H.; Schneider, J.; Cresci, E.; Wuenning, J. G.:** Numerical investigation on post-combustion and air preheating in a recuperative burner producing a low oxidizing gas atmosphere, IFRF Conference, 30.-31. May 2018 Sheffield, United Kingdom

[20] **DIN EN 746-2:** Industrial Thermoprocessing Equipment – Part 2: Safety requirements for combustion and fuel handling systems, 2011

[21] **Wuenning, J.G.:** FLOX® - Flameless Combustion, Thermprocess Symposium, Duesseldorf, 2003

[22] **Schmitz, N.; Schwotzer, C.; Schneider, J.; Cresci, E.; Pfeifer, H.; Wuenning, J. G.:** Development of an Energy-Efficient Burner for Heat Treatment Furnaces with a Reducing Gas Atmosphere, 6th International Conference on Hot Sheet Metal Forming of High Performance Steel (CHS²), 04.-07.06.2017, Atlanta, USA