

# Experimental investigation of a concept for scale free reheating of semi-finished metal products

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## Abstract

The heat treatment of semi-finished metal products in direct fired furnaces with excess air causes significant metal loss due to the formation of an oxide scale on the surface of the product. The approach of this study is the reduction of scale loss by fuel-rich combustion using a conventional burner. To ensure complete combustion the off-gas is burned with secondary air before it passes a heat exchanger. This study focuses on the stability limits of the combustion at different operating conditions. Therefore the visualization of OH\*-chemiluminescence is used. Results show a stable combustion for an equivalence ratio smaller than 1.43 and a burner capacity larger than 50 %.

## Introduction

Direct fired reheating furnaces are used to heat slabs or billets prior to hot working. To achieve high energy efficiency and profitability these furnaces are fired with natural gas. Usually the furnaces operate with excess air in order to ensure a complete combustion of the fuel. Free oxygen, carbon dioxide and vapor in the furnace atmosphere lead to scale formation on the surface of the metal. Especially at high temperatures the oxidation of the workpiece in the atmosphere is significant. To prevent surface defects the scale has to be removed prior to the subsequent process. Therefore the scale formation causes serious material losses.

Heating with fuel-rich combustion may reduce the scale formation significantly, but the off-gas contains flammable components such as CO and H<sub>2</sub>. In this case the energy content of the fuel is not fully exploited and the off-gas contains toxic components. This leads to the necessity of a post-combustion of the off-gas.

The aim of the presented research project is a reduction of the oxygen partial pressure in the furnace atmosphere by control of the equivalence ratio in order to decrease the formation of metal oxides. To ensure complete combustion and increase the efficiency of the process the flammable components in the off-gas are burned using secondary air in a post-combustion process step. The heat of the off-gas is transferred in a heat exchanger to the combustion air.

In the presented study a conventional burner is used to create an atmosphere with low oxygen partial pressure and investigate the parameters for a stable fuel-rich combustion, post-combustion and the oxidation behavior of the metals in the furnace atmosphere. In order to characterize the combustion of the burner at different operating conditions the distribution of OH\*-chemiluminescence in the flame is measured with an intensified CCD camera. In addition the off-gas composition is measured. Presented is the influence of furnace temperature, burner capacity and equivalence ratio on the combustion.

The experiments show a stable combustion for a burner capacity of 50 % to 100 % with an equivalence ratio of 0.87 to 1.43. A significant reduction of scale

formation is achieved for copper and copper-nickel alloys.

## Principle of the process

The process consists of three steps: The primary combustion, the secondary combustion and the heat exchange. Figure 1 shows the principle of the process.

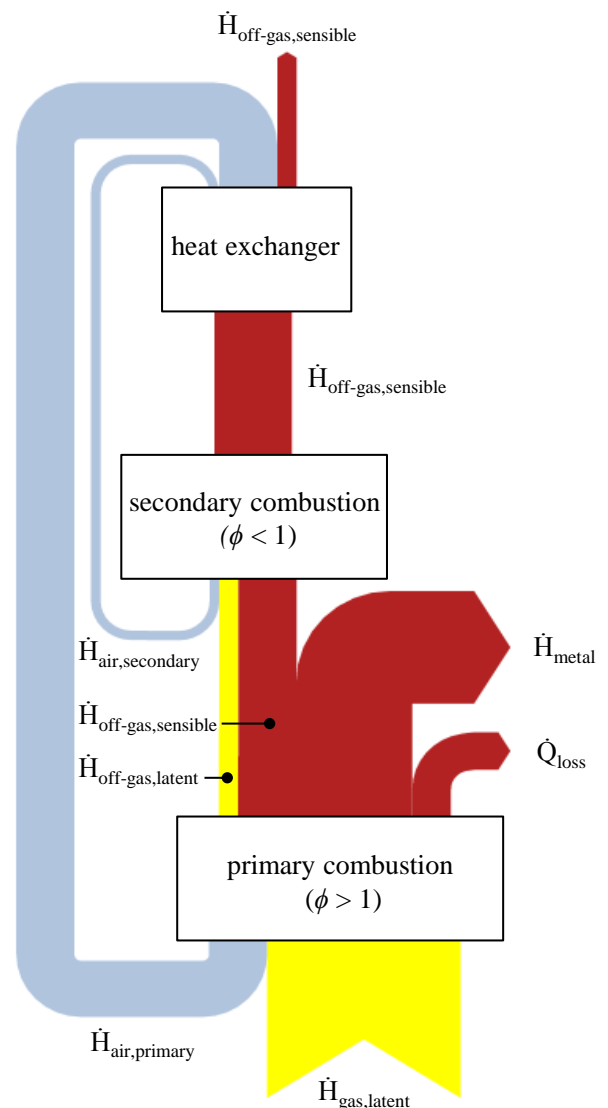


Figure 1: Principle of the process

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The first process step is the primary combustion. During the primary combustion natural gas is burned with preheated air. The primary combustion is fuel-rich. So there is a low partial pressure of oxygen in the furnace atmosphere.

Due to the fuel rich combustion there are unburned species like CO, H<sub>2</sub> and CH<sub>4</sub> in the off-gas of the burner, which results in a latent enthalpy part of the off-gas besides the sensible enthalpy part (due to the temperature of the off-gas).

To use the part of the latent enthalpy of the off-gas of the primary combustion it is completely burned with secondary air in the post-combustion step. This raises the temperature and the amount of the off-gas volume flow.

After the post-combustion process step the burned off-gas passes a heat exchanger to heat up the combustion air of the primary and secondary combustion.

### Oxidation behavior of copper-alloys

Copper forms with oxygen the oxides CuO and Cu<sub>2</sub>O. Cu<sub>2</sub>O is the more stable oxide, therefore it decays at a lower partial pressure of oxygen into Cu and O<sub>2</sub>. The oxidation behavior of copper is discussed in several studies. In air and 1 bar oxygen the change in mass due to the formation of scale follows a parabolic law [1-3].

$$\left(\frac{\Delta m}{A}\right)^2 = k_p t$$

Where  $\Delta m$  is the change in mass, A is the surface of the sample, t is the time and  $k_p$  is a constant depending on the material.

Calculations based on the thermodynamical data of Froberg [4] and Pankratz [5] show that in a natural gas fired furnace the oxygen partial pressure falls below the stability limit for the oxides CuO and Cu<sub>2</sub>O at an equivalence ratio of  $\phi = 1.02$ . As a result the growth of scales is not possible in an off-gas atmosphere with an equivalence ratio larger than  $\phi = 1.02$ .

For further investigation an experimental setup with an electrically heated tube reactor at the Oel-Waerme-Institut GmbH was used to investigate the oxidation behavior of copper in an ideal synthetic off-gas. A single Cu-sample with the dimensions of 20 mm x 18 mm x 5 mm was heated in the tube reactor in a synthetic atmosphere to a temperature of 950 °C within a time of 1.5 h. Afterwards it was rapidly cooled in nitrogen. The generated atmospheres had the composition of the off-gas at thermodynamic equilibrium. This was 19.64 vol.-% H<sub>2</sub>O, 9.26 vol.-% CO<sub>2</sub>, 0.51 vol.-% CO, 0.7 vol.-% H<sub>2</sub> and rest N<sub>2</sub> for an equivalence ratio of  $\phi = 1.04$  and 2.47 vol.-% O<sub>2</sub>, 17.68 vol.-% H<sub>2</sub>O, 8.31 vol.-% CO<sub>2</sub> and rest N<sub>2</sub> for an equivalence ratio of  $\phi = 0.87$ .

Figure 2 shows a Cu-sample before the experiment and after the treatment in the tube reactor with an

equivalence ratio of  $\phi = 0.87$  and  $\phi = 1.04$ . During the heat treatment in an atmosphere containing oxygen there is scale formed on the surface of the sample. The measured change in mass is 8 mg/cm<sup>2</sup> including the flaked off scale.

In comparison the sample after a treatment with an equivalence ratio of  $\phi = 1.04$  shows no formation of scale on the surface. The change in mass is below the detection limit of the balance. So there is no oxidation of copper under the conditions of a fuel rich combustion with an equivalence ratio larger than  $\phi = 1.04$ .

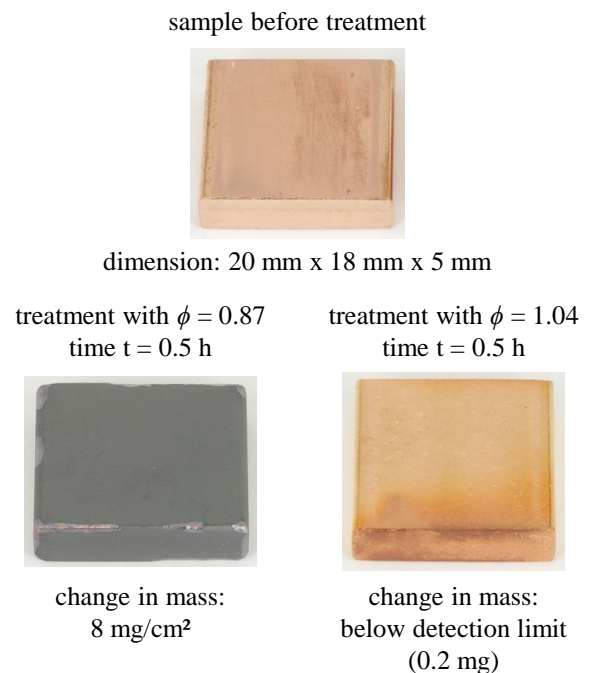


Figure 2: Oxidation behavior of copper at different equivalence ratios

### Experimental setup

For the investigation of the process of primary and secondary combustion an experimental setup at the Department for Industrial Furnaces and Heat Engineering at the RWTH Aachen University is used. A cross-sectional sketch of the experimental setup is shown in figure 3. The experimental setup consists of a primary combustion chamber, a post-combustion chamber, an exhaust tube, an air cooling system and a camera system for flame diagnostics.

The primary combustion takes place in the combustion chamber with a height of 940 mm and a diameter of 600 mm. The primary combustion chamber is fired with a conventional burner with a nominal power of 40 kW. The burner is fired with natural gas and cold air. Via the adjustment of the air and the gas flow the burner operates in a range of 10 kW to 40 kW with an equivalence ratio from  $\phi = 0.87$  to  $\phi = 1.43$ .

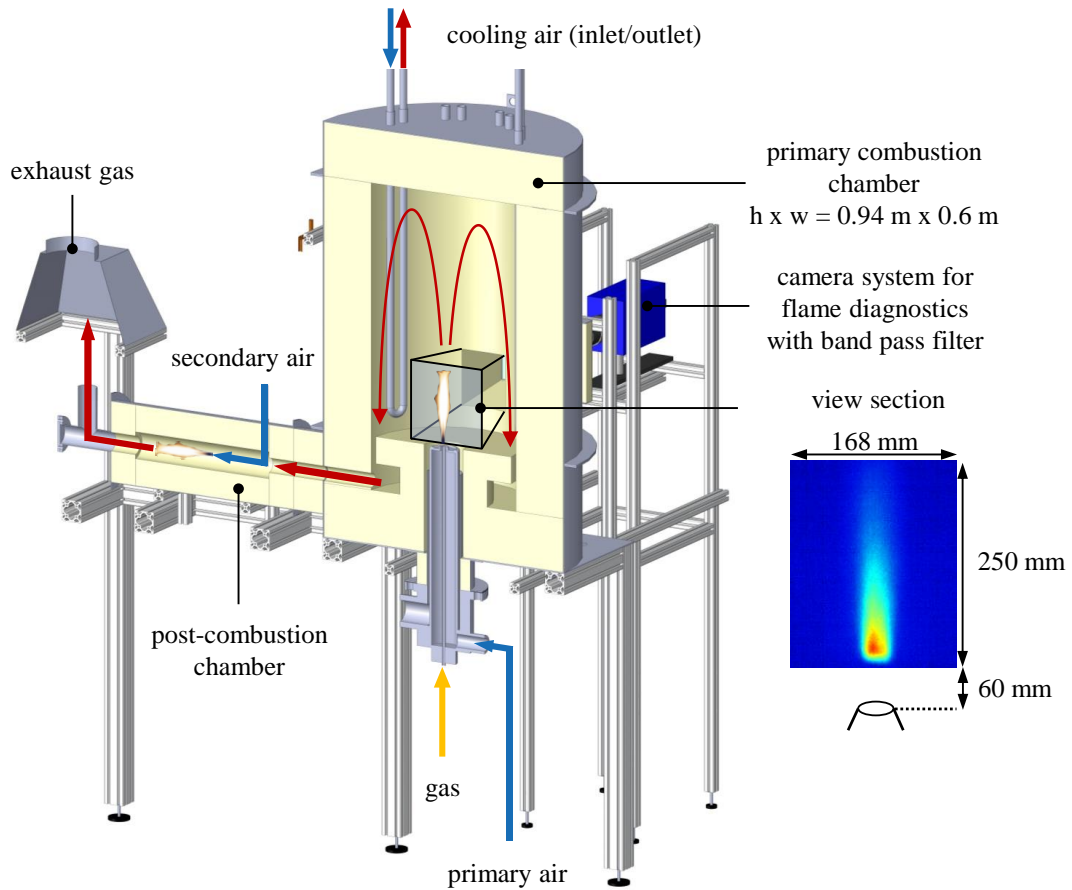


Figure 3: Cross-sectional sketch of the experimental setup

The off-gas of the primary combustion flows through an annular gap and a channel into the post-combustion chamber. After that the completely burned off-gas leaves the experimental setup through the exhaust tube.

This study focuses on the investigation of the primary combustion. Therefore different measurement techniques are used. To characterize the combustion at different operating conditions a camera system with an intensified CCD-sensor and a band pass filter (peak transmission at 308 nm) for the detection of OH\*-chemiluminescence is used. The OH\*-radical is an intermediate product of the combustion reaction. OH\*-chemiluminescence is widely used as an indicator for the global heat release in flames. It is an inexpensive way to provide information with effective spatial-resolution for the reaction zone of the combustion [6-9].

## Results and Discussion

### Influence of furnace temperature on the combustion

As mentioned before the measurement of the OH\*-chemiluminescence is a useful tool for the visualization of the reaction zone of the combustion. Figure 4 shows a photo of the flame with an exposure time of 1/60 seconds at a temperature of 900 °C and 1100 °C.

The burner capacity is 30.5 kW and the equivalence ratio is 0.87.

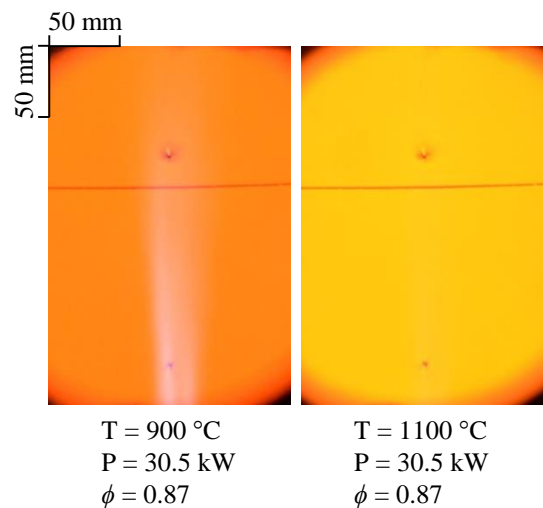


Figure 4: Photo of the flame at different temperatures

At a temperature of 900 °C the blue gas flame of the burner is visible in front of the furnace wall. At a temperature above 900 °C the blue flame disappears in front of the background because of the radiation of the hot furnace wall.

In contrast figure 5 shows the measured OH\*-intensity at the same operating conditions. The figure is obtained by calculating the average of 300 exposures that were recorded in 30 seconds. Zones with a high intensity of OH\* are marked in red. Zones of not detectable OH\*-Intensity are marked in blue. Due to the transmission of the band pass filter the measurement of the OH\*-chemiluminescence is not affected by the heat radiation of the hot furnace wall. The OH\*-distribution shows nearly the same spatial extension for a temperature of 900 °C and 1100 °C. The reaction zone is long and small like the blue gas flame from figure 1. The highest intensity is in the centre of the flame. With increasing temperature the length of the reaction zone increases. But this increase is not relevant for further investigations.

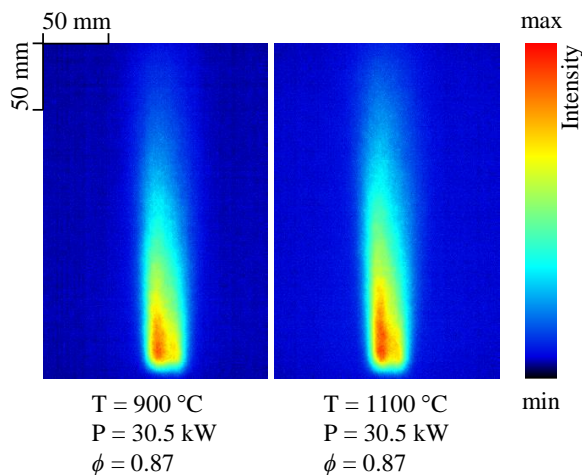


Figure 5: OH\*-chemiluminescence at different temperatures

#### Influence of burner capacity on the combustion

Figure 6 and figure 7 show the distribution of the OH\*-radical for an increasing burner capacity from 10.4 kW to 40.5 kW at an equivalence ratio of 0.87 and a furnace temperature of 900 °C.

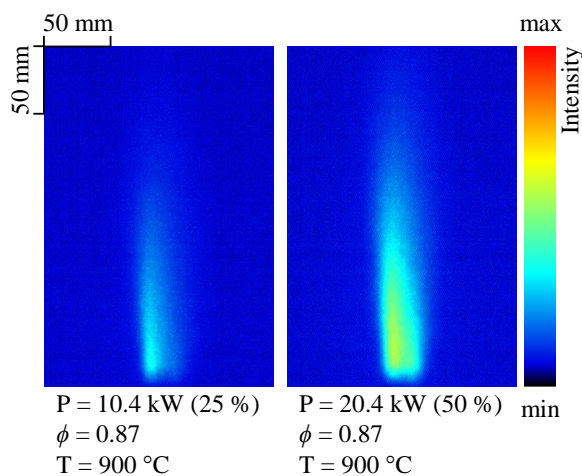


Figure 6: OH\*-chemiluminescence at different burner capacities

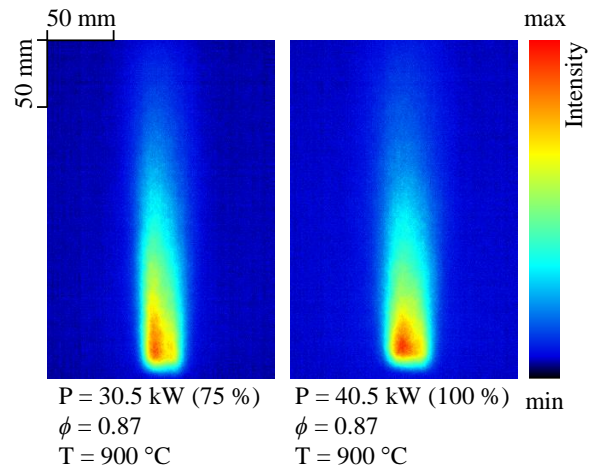


Figure 7: OH\*-chemiluminescence at different burner capacities

With increasing burner capacity the measured intensity of the OH\*-chemiluminescence increases, too. Up to a burner capacity of 75 % mainly the length of the reaction zone decreases, whereas at a burner capacity between 75 % and 100 % the increases in length stagnates and the region of the maximum intensity becomes broader. Besides the reaction zone becomes more symmetric. The centre of the combustion reaction remains at a position between 60 mm and 80 mm above the outlet of the burner. For the investigated range of burner capacity between 10.4 kW and 40.5 kW there is a stable reaction zone of the flame visible. But with decreasing burner capacity the mixing of fuel and gas becomes worse and there is the tendency of the formation of soot, which was found in the exhaust gas tube, at a burner capacity lower than 50 % (20 kW).

#### Influence of equivalence ratio on the combustion

Figure 8 and figure 9 show the distribution of the OH\*-chemiluminescence at different equivalence ratios at a furnace temperature of 1050 °C. Because of the formation of soot at low burner capacities the influence of the equivalence ratio on the combustion is only investigated at a minimum burner capacity of 50 %.

In the case of fuel lean combustions the volumetric flow rate of gas remains constant at a value of 2.0 m<sup>3</sup>/h and the volumetric flow rate of the air is changed. In the case of fuel rich combustion the volumetric flow rate of the air remains constant at a value of 20.1 m<sup>3</sup>/h and the volumetric flow rate of the fuel is changed. Therefore there is a heat release of the combustion of around 20 kW for the investigated equivalence ratios.

For the fuel rich combustion the measurements of the OH\*-distribution show a decreasing length of the reaction zone with increasing equivalence ratio, whereas the position of the maximum intensity remains constant. Also the reaction zone becomes more asymmetric with increasing equivalence ratio.

For the fuel lean combustion the length of the reaction zone remains constant. Instead the region with

a high intensity spreads. At all investigated equivalence ratios the flame remains stable.

The measured off-gas composition for the different equivalence ratios is shown in figure 10. The species  $O_2$ ,  $CO_2$ ,  $CO$ ,  $H_2$  and  $CH_4$  are measured in the dry off-gas. The mean values over a time of 60 seconds are shown at a steady state. The measurements correspond the measurements of the  $OH^*$ -distribution illustrated in figure 8 and figure 9.

In the case of fuel lean combustion the dry off-gas mainly consists of  $CO_2$ ,  $O_2$  and rest  $N_2$ . Due to complete mixing of gas and fuel there are no concentrations of  $CO$ ,  $H_2$  and  $CH_4$  measured. With decreasing equivalence ratio the concentration of  $O_2$  increases due to more excess air.

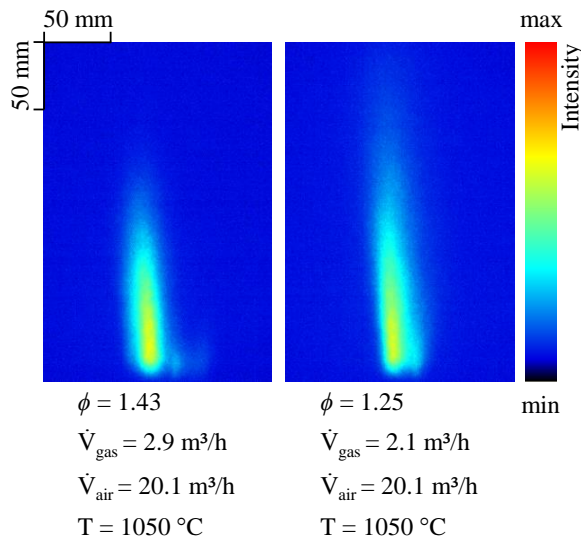


Figure 8:  $OH^*$ -chemiluminescence at different equivalence ratios

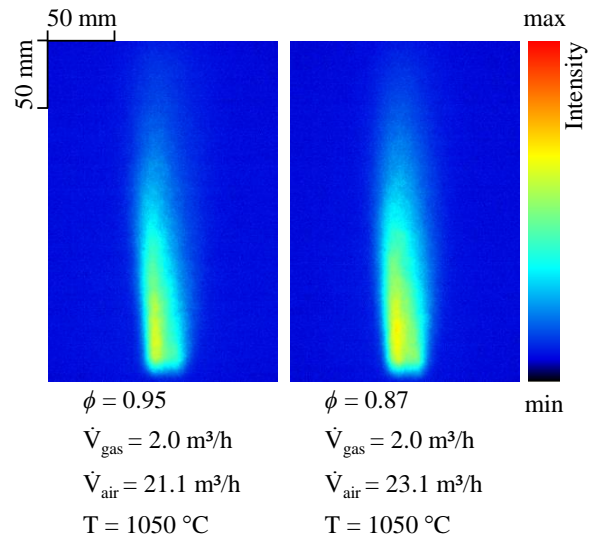


Figure 9:  $OH^*$ -chemiluminescence at different equivalence ratios

In the case of fuel rich combustion the dry off-gas consists besides  $CO_2$  and  $N_2$  also of  $CO$ ,  $H_2$  and  $CH_4$  due to the excess of fuel. Therefore the combustion is incomplete. The whole amount of oxygen is consumed so there is no  $O_2$  in the off-gas measured. With increasing equivalence ratio the amounts of  $CO$  and  $H_2$  increase. Due to the change in the mixing behavior of the burner the off-gas also consists of  $CH_4$  up to 1.14 vol.-% at high equivalence ratios, which differs to the concentration at thermodynamic equilibrium with a  $CH_4$  concentration of less than  $10^{-5}$  vol.-%.

The influence on the mixing behavior of the burner is also shown in the formation of soot, which was found in the exhaust gas tube. But the influence on the soot formation due to a change in the equivalence ratio is not significant compared to a change in burner capacity. For quantitative measurements there would be further investigations necessary.

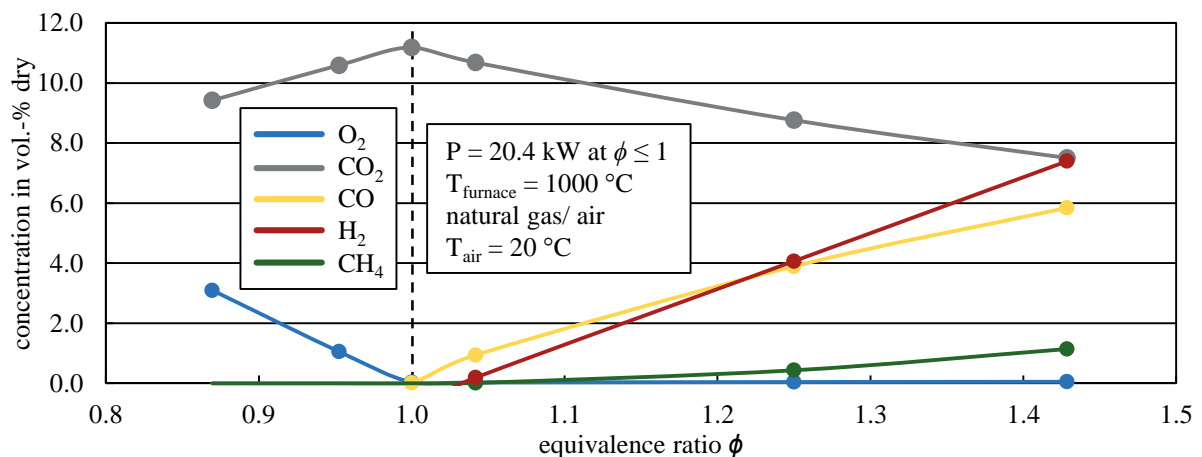


Figure 10: Off-gas composition (dry) at different equivalence ratios

## Conclusion and Outlook

In this study the chemiluminescence of OH\*-radicals is used to visualize the spatial expansion of the flame of a conventional natural gas fired burner with a capacity of 40 kW. This measurement technique can be used in high temperature conditions, whereas conventional photographic systems can only be used up to a furnace temperature of 900 °C. In this case at higher temperatures the blue gas flame is not visible in front of the hot furnace walls.

The combustion was investigated at different operating conditions. The influence of furnace temperature, burner capacity and equivalence ratio on the expansion of the reaction zone was investigated.

The influence of the furnace temperature on the dimensions of the reaction zone is not significant. For a range in temperature from 900 °C to 1100 °C the reaction zone is long and small with the maximum of the intensity in the centre of the flame.

The influence of the burner capacity instead is significant. At 25 % of the burner capacity the measured OH\*-intensity is low. With increasing burner capacity the intensity increases. Up to a burner capacity of 75 % the length of the reaction zone increases to the maximum length of around 260 mm. In the range of a burner capacity between 75 % and 100 % the reaction zone becomes broader.

Also the equivalence ratio, which was investigated in a range between 0.87 and 1.43 has an influence on the dimension of the distribution of the OH\*-radicals. In the case of fuel rich combustion the length of the reaction zone decreases with increasing equivalence ratio and the OH\*-distribution becomes more asymmetric. The concentration of the species CO and H<sub>2</sub> in the dry off-gas increases with increasing equivalence ratio. At high equivalence ratios there is also CH<sub>4</sub> measured in the off-gas due the change in mixing behavior of the burner.

In the case of fuel-lean conditions the reaction zone of the flame becomes broader. The length of the flame remains constant. There are no unburned species measured in the off-gas.

The visualization of the OH\*-chemiluminescence shows a stable reaction zone for a burner capacity from 25 % to 100 % with an equivalence ratio of 0.87 to 1.43. The conventional burner can be used to generate a fuel-rich furnace atmosphere. This atmosphere can be used for further investigations of the oxidation behavior of copper and the post-combustion of the off-gas.

It was found that below a burner capacity 20 kW there is the formation of soot, which was found in the exhaust gas tube. Besides, there is the tendency of soot formation at a fuel-rich combustion with increasing equivalence ratios. Therefore the process window for the operating conditions of the burner is limited.

## Acknowledgements

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