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Numerical and experimental investigations on an innovative, regeneratively heated radiant tube with compact dimensions

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Abstract

The presented, public funded research cooperation project of the Department for Industrial Furnaces and Heat Engineering at the RWTH Aachen University and the WS Wärmeprozesstechnik GmbH main aim is the development of an innovative, regeneratively heated radiant tube with compact dimensions.

The main components are the I-shaped radiant tube with regenerators and an inner gas tube with 36 gas outlets over the entire tube length. Due to fuel-staging and a desired flameless combustion, low NO_x-emissions are ensured. A high thermal efficiency is ensured by a regeneratively operated air preheating system. Ceramic honeycomb modules (regenerative module) are installed on both sides of the radiant tube in the furnace wall, which preheat the combustion air in alternating operation. By that, preheating temperatures of around 1050 °C are possible.

Numerical simulations for different gas tube diameters were performed to figure out the most suitable diameter for a uniform temperature distribution at the radiant tube surface. With this information, a test model was developed and investigated in a test bench. The temperature homogeneity and the off-gas composition are the main parameters examined. In this paper, numerical and experimental results of the test model and the design of a prototype, based on the results of the test model, are presented.

Keywords: heat treatment; radiant tube; regenerative heating; staged combustion

1. Introduction

The aim of heat treatment is to create certain properties in the workpiece. To avoid oxidation of the material's surface during heat treatment, indirect heating concepts are used. These especially include electrical heating elements and gas-heated radiant tubes [2]. The electrical heating is realized with resistance heating elements. By setting the current intensity, an exact temperature in the furnace chamber can be set. Temperatures between 600 °C and 1200 °C can be achieved [5]. Gas-heated radiant tubes are an alternative to electrical heating elements. Recuperative or regenerative air preheating is often used to increase combustion efficiency [2]. In recuperative air preheating systems, air and exhaust gas are separated from each other by a heat exchanger surface. To enlarge the heat exchanger surface, fins or corrugations are often applied to the surface. A combustion efficiency of up to 75 % at off-gas temperatures of 1250 °C can be achieved [6]. Another possibility is regenerative air preheating. The transferred energy is temporarily storaged in regenerators. Storage elements for small burners are often cordierite or SiC honeycomb blocks. The burners are operating in pairs. While one burner fires, the storage elements of the other are warmed up. After a certain

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time, the previously heated burner is started and the air is preheated via the hot storage elements. Meanwhile, the cooled burner is reheated with the off-gas. Combustion efficiencies of up to 90 % at a flue gas temperature of 1250 °C can be achieved [1]. The heat treatment of small components in an inert gas atmosphere is often carried out in roller hearth furnaces or chamber furnaces. Due to limited installation space, heating with compact electrical heating elements or radiant tubes with recuperative air preheating is state of the art.

The current research project of the Department for Industrial Furnaces and Heat Engineering and WS Wärmeprozesstechnik GmbH focuses on the development of innovative, regeneratively heated radiant tubes with compact dimensions for the integration in furnaces with limited space. The innovative heating concept enables the usage of regenerative air preheating in radiant tubes with a diameter of less than 50 % compared to conventional radiant tubes. Therefore, an increase of the combustion efficiency compared to conventionally used recuperative burners is possible. Furthermore, the combination of electrical heating elements and the regeneratively heated radiant tubes is possible in order to obtain a hybrid heating concept to react on possible fluctuations in the future energy market.

Figure 1 shows the concept of the innovative radiant tube. The radiant tube with integrated gas tube is located in the furnace. Staged, flameless combustion over the entire length of the tube is achieved by holes in the gas tube and enables a homogeneous temperature profile on the surface. The fuel staging as well as the flameless combustion allow a decrease of the flame temperature and thus a reduction of the nitrogen oxide emissions. On the left and right side of the tube regenerators for air preheating are installed. Switching the flow direction of air and exhaust gas enables the regenerators to be heated and thus the air to be preheated. Natural gas is always supplied from one side. In the entrance section the combustion takes place with a strong excess air of $\lambda >> 1$, whereas in the outlet section the air ratio λ is about $\lambda \approx 1$.

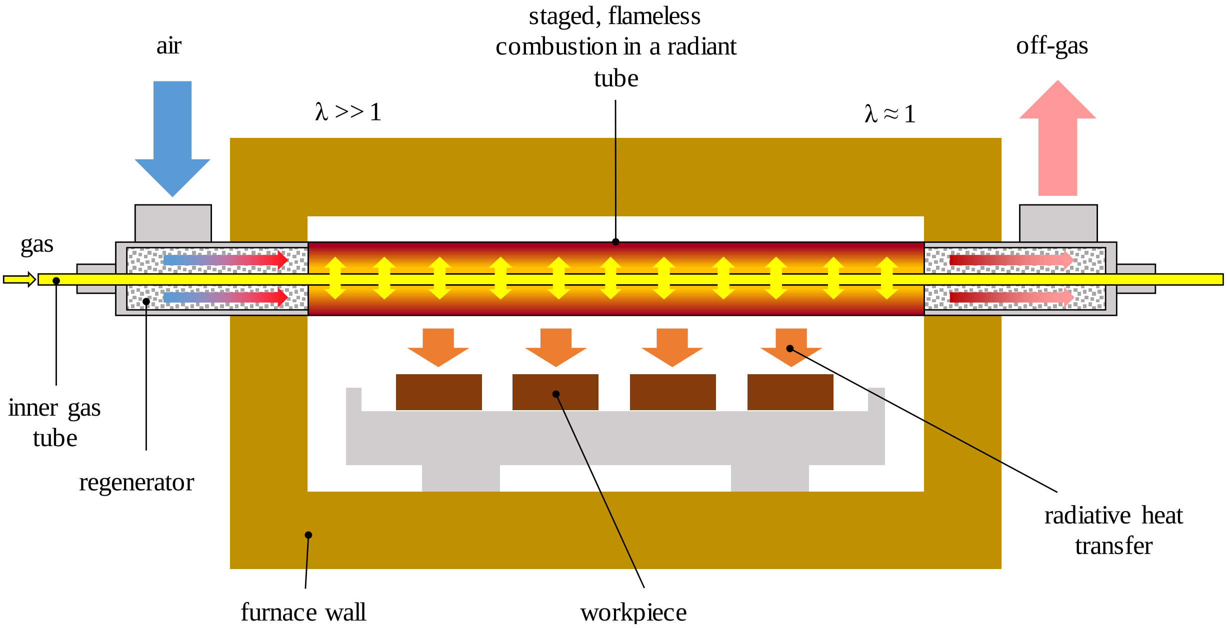

Figure 1: Concept of the innovative radiant tube

Previous investigations have shown that a gas tube with 36 holes (Ø = 1,6mm) and a diameter ratio of gas tube diameter d to radiant tube diameter D of d/D = 0.27 provides a homogeneous temperature profile on the surface. A numerical model was successfully validated [3]. Furthermore, an air injection into the gas tube using a mass flow controller (MFC) was installed in order to avoid cracking of natural gas in the gas tube and to decrease the temperatures in the tube. Temperatures of up to 1300 °C were achieved without primary air injection in the gas tube and led to damage to the radiant tube as well as to the gas tube and the ceramic modules. A large influence of the air injection on the formation of pollutants like NO_x and CO was determined. With increasing primary air injection, a reduction in nitrogen oxide formation can be observed. The influence on the formation of CO has not yet been fully clarified and requires further investigation. Moreover, the formation of Hot-Spots could be observed during primary air injection in the gas tube with $\lambda_{primary} \geq 0.15$ [4].

2. Test model and experimental setup

An I-shaped test model has been set up, using the information of the results of the numerical simulations [3]. Figure 2 shows the test model and its implementation. The middle part shows the gas tube as well as the regenerative honeycomb modules on both sides of the tube. The air supply alternates between both sides. The switching time for all tests is 15 seconds. Natural gas is supplied via the left side. The tube length is about 2000 mm. The gas tube has 72 holes distributed on four holes over the perimeter. Burner capacities between 15 kW and 25 kW are investigated as well as the primary air injection for setting a primary air ratio of $0.15 \leq \lambda_{primary} \leq 0.25$. The total air ratio in all tests is $\lambda_{Total} \approx 1.3$ for a residual oxygen content of 5 vol. % (dry) in the off-gas. Air-preheating temperatures of up to 1050 °C are possible, depending on the off-gas temperatures. The furnace chamber temperature is set to 950 °C by indirect air cooling. The cooling air is supplied from the left side via four cooling tubes. The radiant tube is only operated above self-ignition temperature (T > 850 °C). The temperature distribution on the radiant tube surface is measured with 24 thermocouples and is recorded continuously. Additionally, a continuous off-gas analyser is used for recording the off-gas composition (CO, CO_2, NO_x, O_2).

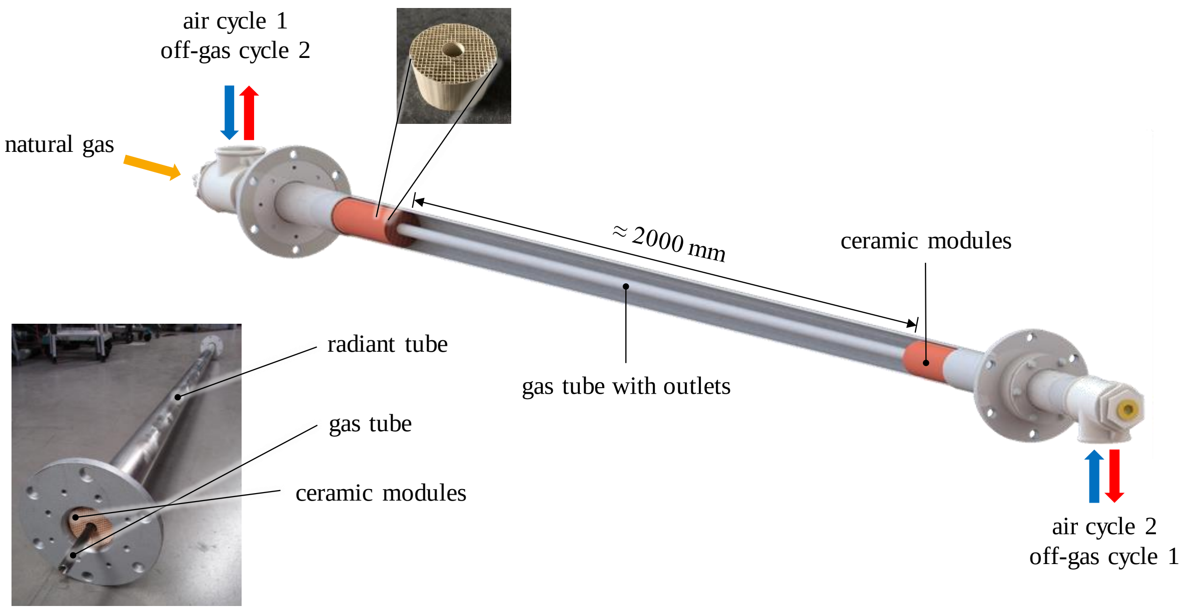

Figure 2: test model

3. Numerical calculations of staged combustion in the tube with air injection

The numerical model includes the area between the gas tube and the radiant tube, figure 3. Due to the symmetry in the tube, only a quarter of the tube is modeled. The holes in the tube are considered as inlets for the supply of natural gas and the injection of air. The number of cells for the whole model is approx. 2 million. For turbulence modelling, the k-ε model is used. The Discrete-Ordinates (DO) model with the weighted-sum-of-gray-gases (WSGG) model is applied for radiation. The Eddy-Dissipation-Concept (EDC) model in combination with the DRM19 mechanism is applied to model combustion in the tube. In preliminary investigations it was found that simple combustion models in relation to turbulence/chemistry interaction are not able to accurately represent the complex conditions in the tube. The requirement for the numerical model is to predict the flow in the tube and the temperature profile on the surface of the radiant tube with adequate computing time. For this reason, all numerical investigations are carried out under steady-state conditions.

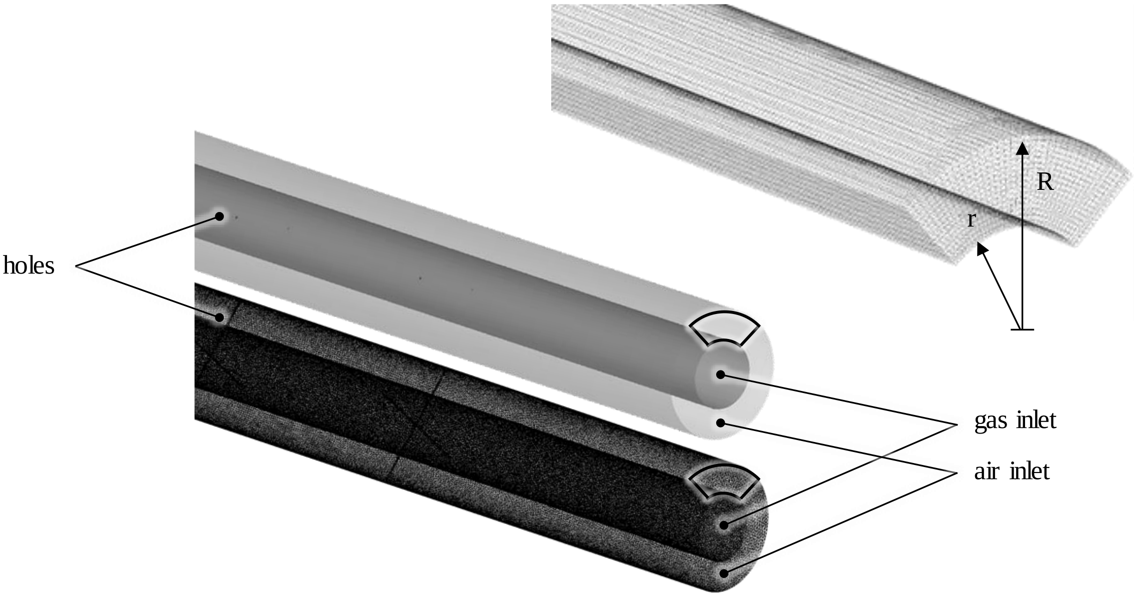

Figure 3: numerical model domain

The air injected via the holes in the gas tube is called primary air and is adjusted by a primary air ratio $\lambda_{Primary}$. Primary air ratios between $\lambda_{Primary} = 0.15$ and $\lambda_{Primary}$ 0.25 are investigated. The secondary air, which enters the tube directly, is set to a temperature of 1050 °C. The ambient temperature on the outside of the radiant tube is $T_\infty = 950$ °C and convection and radiation are taken into account. The gas inlet temperature is $T_{gas} = 150$ °C and a burner capacity of 20 kW is assumed. The boundary conditions are based on previous experimental investigations [3, 4].

4. Results

The numerical results show that by increasing the number and reducing the diameter of holes, the formation of hot spots can be prevented. Figure 4 shows the temperature distribution on the surface of the radiant tube with a primary air ratio of $\lambda_{Primary} = 0.2$ for a) 36 holes with Ø = 1.6 mm and b) 72 holes with Ø = 1.2 mm. In the inlet area of configuration b), the temperatures are about 950 °C due to the preheated air. First, the temperature decreases to 900 °C, rising up to 1100 °C over the length. The drop in temperature at x = 100 mm is due to the position of the gas holes. The first hole is at x = 250 mm, from where the natural gas ignites. Air switching is neglected in the numerical model, as steady-state simulations are performed. Because of that, the temperature in the outlet area is quite high. In experimental investigations, the occurrence of slight hot spots at $\lambda_{Primary} > 0.2$ could be observed.

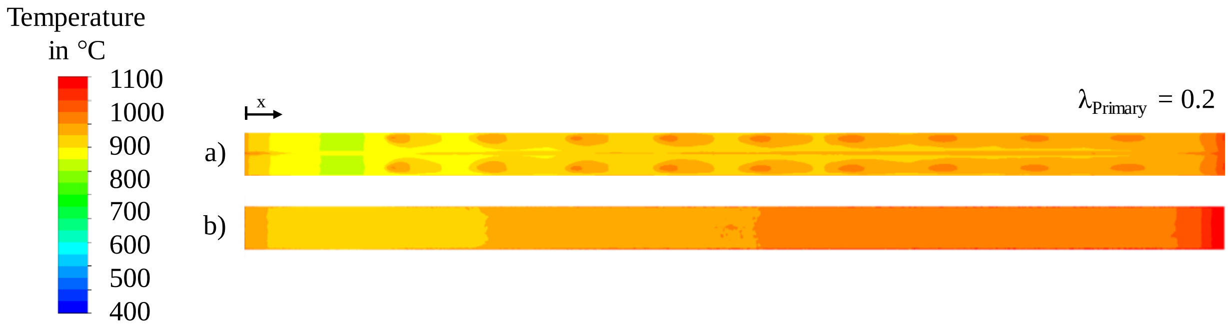

Figure 4: numerical temperature distribution on the radiant tube surface for $\lambda_{Primary} = 0.2$
a) 36 holes with Ø = 1.6 mm b) 72 holes with Ø = 1.2 mm

Figure 5 shows the temperature distribution averaged over the perimeter on the radiant tube surface for different primary air ratios $\lambda_{Primary}$ at 20 kW burner capacity. The vertical lines show the position of the holes in the gas tube. All investigated primary air ratios $\lambda_{Primary}$ show a similar temperature distribution. In the inlet area the temperatures are lower, although the air is continuously switched. This may be because the cooling air is supplied only from the left side. The temperatures in the inlet area are around 930 °C and 950 °C in the outlet area, which results in a temperature variance of $\Delta T = 20$ K over the entire tube length. Investigations with a gas tube with 36 holes and a primary air ratio of $\lambda_{Primary} = 0$ show a temperature variance of $\Delta T = 30$ K [3]. The deviation in the range between x = 1300 mm and x = 1800 mm may be caused by thermocouples located near slight hot spots at primary air ratio $\lambda_{Primary} > 0.2$.

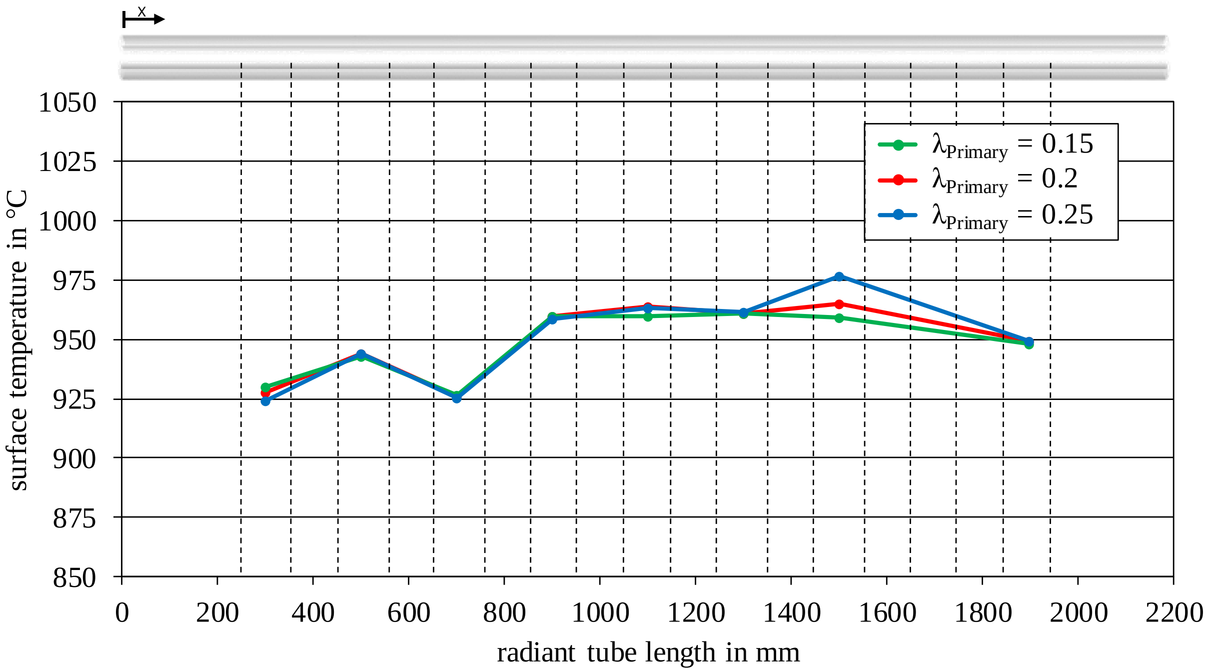

Figure 5: temperature distribution on the radiant tube surface for variable $\lambda_{Primary}$ and 20 kW burner capacity

The NO_x and CO concentrations in ppm (at 5 vol. % O_2 in the off-gas) as a function of the primary air ratio $\lambda_{Primary}$ for both sides of the tube are shown in Figure 6. A primary air ratio of $\lambda_{Primary} = 0.15$ results in a NO_x concentration of about 145 ppm for the left side and around 235 ppm for the right side. With increasing air injection, the NO_x concentration decreases to about 70 ppm (left) and 90 ppm (right). The reason therefor is the reduced formation of thermal NO_x due to flame cooling caused by the increasing injection of cold primary air.

The CO concentration also shows a decreasing trend. At a primary air ratio $\lambda_{Primary} = 0.15$, 18 ppm CO are measured for the left side and 10 ppm for the right side. With increasing injection, the CO concentration is reduced to 10 ppm (left) and 9 ppm (right). The increasing air injection leads to an enhancement in local turbulence in the area of the gas outlet openings. This favors the mixing of natural gas and air and thus lowers the CO concentration. At the same time, the decreasing secondary air volume reduces the total turbulence in the tube. With decreasing oxygen content in the off-gas, the CO and NO_x concentrations on both sides increase.

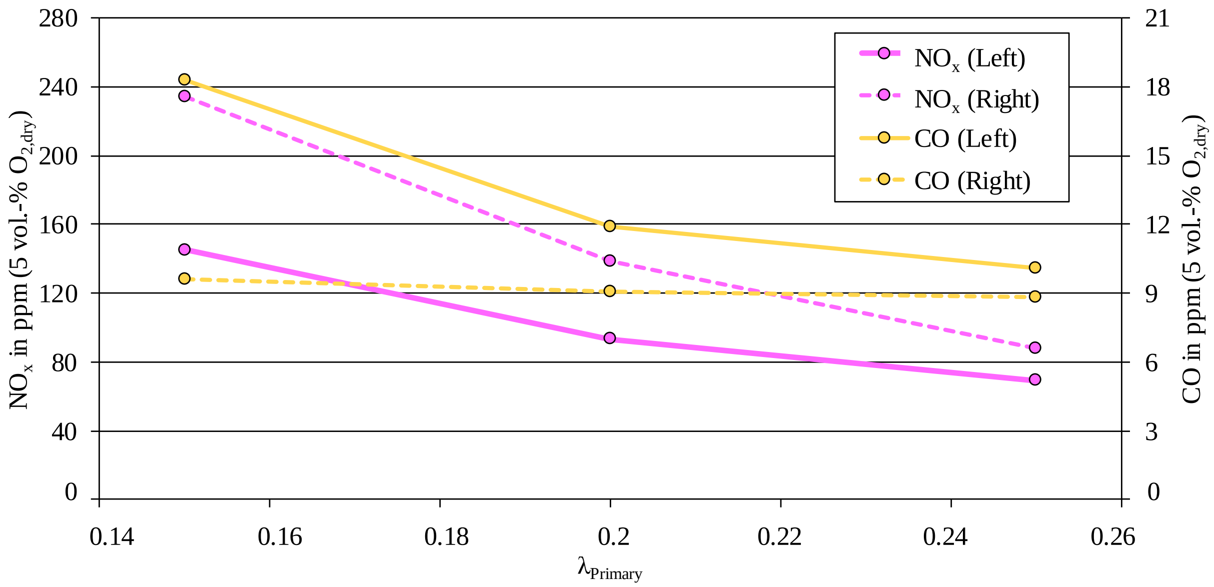

Figure 6: NO_x and CO as a function of air injection for 20 kW burner capacity

5. Further Investigations and implementation in prototype

Previous tests have shown that the one-sided supply of natural gas results in different burnout characteristics depending on the side of air supply. When natural gas and air is supplied from the same side, the NO_x concentration is higher compared to the counterflow of natural gas and air. One reason for this is the high static pressure in the gas tube on the supply side and the resulting uneven outflow of gas. On the right side, lower temperatures are reached due to the reduced gas volume caused by the pressure loss in the tube which leads to lower NOx concentrations. Further experiments will be carried out with a gas tube with the diameter of the holes increasing over the length in order to optimize the flow uniformity at both cycles. Furthermore, the burner capacity is to be increased to 30 kW.

The experiments with the test model show that staged combustion in a compact radiant tube and safe operation are possible. A requirement for the prototype is that the gas and air connections are on one side. For this reason, the prototype is designed as a metallic U-tube. The tube has two legs in which the gas tubes are located and the intended burner capacity is 40 kW.

6. Summary

Investigations were carried out on a test model with a modified gas tube and 20 kW burner capacity. To avoid hot spots on the radiant tube surface, a gas tube with 72 holes with a diameter of Ø = 1.2 mm was selected. The steady-state numerical investigations show that a homogeneous temperature distribution without hot spots may be achieved. The experimental investigations have shown that the formation of hot spots up to a primary air ratio of $\lambda_{Primary} = 0.2$ can be avoided. With a primary air ratio $\lambda_{Primary} > 0.2$, the formation of slight hot spots is observed. The concentrations of NO_x and CO decrease with higher primary air injection. The reason for this is the reduction of flame temperature and the increased local turbulence. Different burnout characteristics depending on the cycle and therefore on the direction of the air flow were discovered. Increased concentrations of NO_x and CO were found when gas and air were supplied from the same direction. A further optimization of the gas tube is carried out by enlarging the hole diameter over the length. Investigations with the modified gas tube will be done with regard to a homogeneous temperature distribution on the surface of the radiant tube and a uniform burnout characteristic.

The construction of a prototype based on the results of the numerical and experimental experiments takes place. The prototype will be a metallic U-tube with a gas supply by gas tubes in both legs. Investigations regarding temperature uniformity and burnout characteristics will be performed.

Acknowledgements

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