Extension of the limitations of use of flameless oxidation for small burner capacities

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Abstract

Flameless combustion has been successfully used for burners with a capacity range from 10 kW to 300 kW. An important issue in the development of the flameless technology is the down-scaling to the smallest possible burner capacity. Experimental results show that in a direct comparison of the measurements by OH*-chemiluminescence visualization with thermocouple measurements of temperature profiles carried out in an experimental small scale reactor, a good correlation of the results with respect to the position of the reaction zone was observed.

Introduction

The flameless technology has been successfully used for burners with a capacity range from 10 kW to 300 kW. It is characterized by the fact that low NO_x levels can be realized despite high air preheating and thus both targets, on the one hand increasing the combustion-efficiency and on the other hand the reduction of environmental pollution through the emission of NO_x, can be satisfied simultaneously.

Two important issues in the development of the flameless technology are the downscaling to the smallest possible burner capacity at which a stable process can still be achieved, and an up-scaling to the MW range of burner capacity. These issues are investigated using two different experimental setups consisting of a big scale and a small scale reactor. At the same time the combustion process at these different scales is investigated by means of numerical tools based on a simplified approach (free jet CFD) with the aim of reproducing the experimental observations and providing general designing rules for the up- and down-scaling of flameless oxidation. In this paper a feasibility study and first results of OH*-chemiluminescense visualization of small scale flameless oxidation (Micro-FLOX®) is presented.

Experimental Setup

For the realization of experimental investigations a small scale reactor has been built at the IOB (Department for Industrial Furnaces and Heat Engineering). The chosen geometry is a cylindrical chamber with a diameter of $D_{reactor}$ = 550 mm and a height of $H_{reactor}$ = 790 mm. The burner is positioned upright in the base plate, the burner exit is located in its center at R = 0 mm and H = 0 mm. The exhaust gas escapes near the reactor wall trough a narrow annular gap and is drawn off on one side by an exhaust pipe below the base plate. By the use of an annular gap, a symmetrical flow can be ensured in the interior of the reactor despite a one-sided escape for the burnt off-gas. An overview of the entire test facility is provided in figure 1.

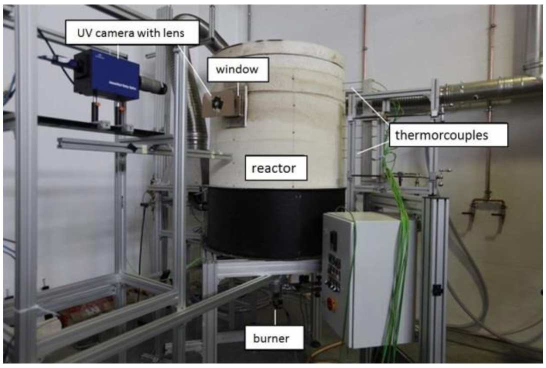

Fig. 1: Experimental Setup

Due to the relatively small capacity of the test burner and the requirement of reaching high temperatures allowing flameless oxidation, the reactor is provided with a thick insulating layer. The thickness of the insulation is 210 mm in the cladding region and 170 mm on the cover. The burner used for the investigation was built by the company WS Wärmeprozesstechnik GmbH. It allows to be operated both in flame (for reaching the required minimum FLOX®-temperature) and in the FLOX®-mode. While in flame mode the fuel is injected radially into the combustion chamber, where mixing with the combustion air takes place and leads to the formation of a stable flame. If the burner is operated in FLOX®-mode, the fuel enters the reactor through the FLOX®-lance in the center of the burner. Fuel and combustion air are separated all the way through the burner and mixing takes place inside the reactor.

Measurement Equipment

The visualization of OH*-chemiluminescence is carried out with a measuring-system consisting of a magnifying lens, a UV-bandpass-filter (peak transmission at 308 nm), an UV lens and a CCD-camera with a signal amplifier (IRO). The complete equipment is shown in figure 2. The pictures are taken through a window of 80x80 mm² inside the wall of the reactor which is located at a height of 530 mm. With the use of a plano-concave condenser lens a picture size of 175x175 mm² at the median plane of the reactor can be realized. The

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sample area the camera is focused on, is located on the burner axis and starts at a distance of 485 mm from the base plate. The images that are recorded show not only OH*-chemiluminescence in this plane but in the complete projected volume through the reactor. The use of the UV-bandpass-filter minimizes the influence of background radiation from the reactor walls and leads to a better image quality.

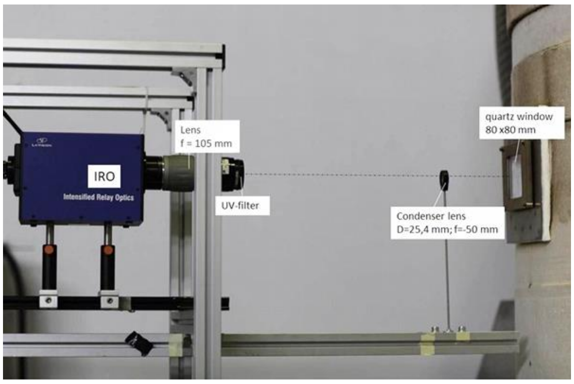

Fig. 2: Equipment for OH*-chemiluminescence

OH*-chemiluminescence and temperature measurements

First the feasibility of visualizing OH*-chemiluminescence when operating the experimental burner in FLOX®-mode had to be investigated. To this end, the camera measurement system shown in figure 2 was used. The reactor was preheated with a burner capacity of 10 kW in the flame mode to a temperature of 750 °C, and then it was switched to flameless oxidation mode. Starting at a reactor temperature of 850 °C the OH*-chemiluminescence visualization images were recorded. In order to receive reliable results, in each state that was investigated, over 300 single pictures were taken (capturing rate: 10 Hz) and averaged into one. The analysis of the heating up experiments that were carried out subsequently shows that at low reactor temperatures the reaction zone is formed in the upper region of the reactor near the top. With increasing temperatures the reaction zone moves in accordance with the theory downward on the burner axis towards the burner.

As an example it will be briefly discussed how the extension and location of the reaction zone varies at two tested burner capacities (10 kW and 8 kW). The measurement of the reaction zone when operating the burner at 10 kW is in both dimensions (axial and radial) larger than during the 8 kW measurements, as shown in figures 3 and 4. This is directly related to the higher burner capacity. The flow of combustion air and gas is increased by 25 % and therefore the reaction extends over a larger volume. Simultaneously the signal count increases slightly, which is also driven by the increased fuel consumption. Since the fact that at the higher burner capacity more heat is released, the combustion reaction runs faster or at a slightly higher temperature, when operating the burner at 10 kW instead of 8 kW. The number of counts depends on the intensity of the signal amplification and is not representative for other measurements. It has been set to a constant value to ensure comparability of both measurements.

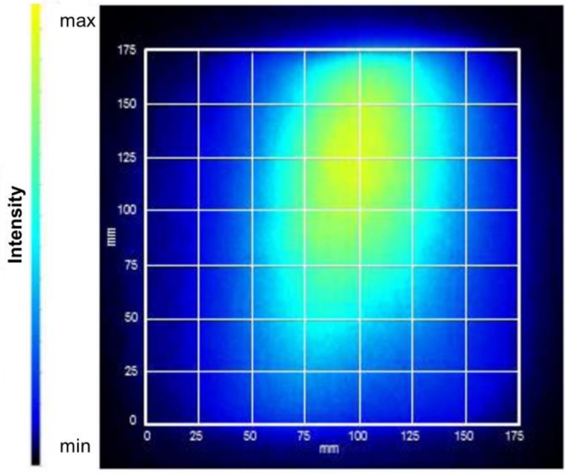

Fig.3 : OH*-chemiluminescence at 10 kW ($T_{Reactor}$ = 850 °C)

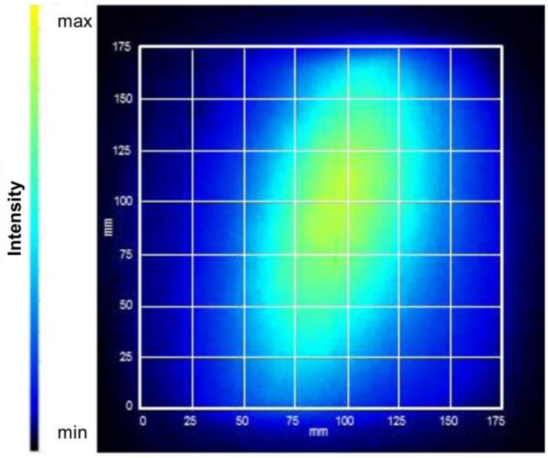

Fig.4 : OH*-chemiluminescence at 8 kW ($T_{Reactor}$ = 850 °C)

There is a large number of parameters that have influence on the dimension and position of the reaction zone. While recording temperature profiles it is necessary to keep all of them at constant values to ensure a steady-state inside the reactor. If other parameters are varied the influence on the dimensions and position of the reaction zone of the investigated parameter cannot be described precisely. The parameters which are subject to the complete investigation are burner capacity, reactor temperature, equivalence ratio and air-preheating temperature. The reactor temperature is measured in the annular gap surrounding the base plate. At this point only the influence of the reactor temperature on the location of the reaction-zone will be discussed.

For the measurement of the temperature profiles in steady-state conditions nine thermocouples are installed at different heights of the reactor. These can be moved with a displacement device simultaneously in radial direction. The 17 measuring points have the following distances from the burner axis: 0, 10, 20, 30, 40, 50, 60, 70, 80, 100, 120, 140, 180, 220, 250, 260, 270 mm. Thus, an area of 710 mm in height and 270 mm radially can be covered with a total of 153 measuring points. This corresponds to 87.6% of the observed symmetry plane of the reactor. For each measuring point a time of 60 seconds has to be waited for adjustment of the thermocouple to the new temperature. Afterwards the recorded temperature is averaged over a time of 60 seconds. To determine the position of the reaction zone, the focus of the temperature measurement is only on the areas of high temperature changes which are consistent with the OH*-chemiluminescence visualization images. The end of the reaction zone cannot be determined by temperature measurements, because the hot exhaust gas is still present afterwards.

One example provided in figure 5 is the combined presentation of the temperature distribution and the OH*-chemiluminescence visualization at a reactor temperature of 850 °C and 10 kW burner capacity with an air ratio of $\lambda = 1.2$ ($\phi = 0.83$). The beginning of the reaction zone was determined using the temperature measurement to about 560 mm height, since in this region the strongest temperature rise is observed. A more precise definition is not possible on the basis of the recorded temperature profile, since there is already an increase in temperature in the free jet due to recirculation of hot exhaust gas. Furthermore the temperatures between the measured values have been interpolated for the plot, so that the display of the temperature profile does not reflect the actual resolution of the measurement. Due to the resolution of 9 points in axial direction an accurate determination of the reaction zone is not possible using the temperature measurements.

When viewing the recorded image of the OH*-chemiluminescence visualization the first presence of signals (‘counts’) can be defined for a height of about 530 mm. The starting point of higher intensities, represented by a higher number of counts, begins at 560 mm. This height is consistent with the value derived from the temperature measurement which proves, that the beginning of the reaction zone of a flameless combustion can be determined by using temperature profiles recorded with thermocouples. Furthermore the overall radial and axial dimension of the reaction zone can be determined by means of OH*-chemiluminescence visualization, as shown in figures 3 and 4, if necessary.

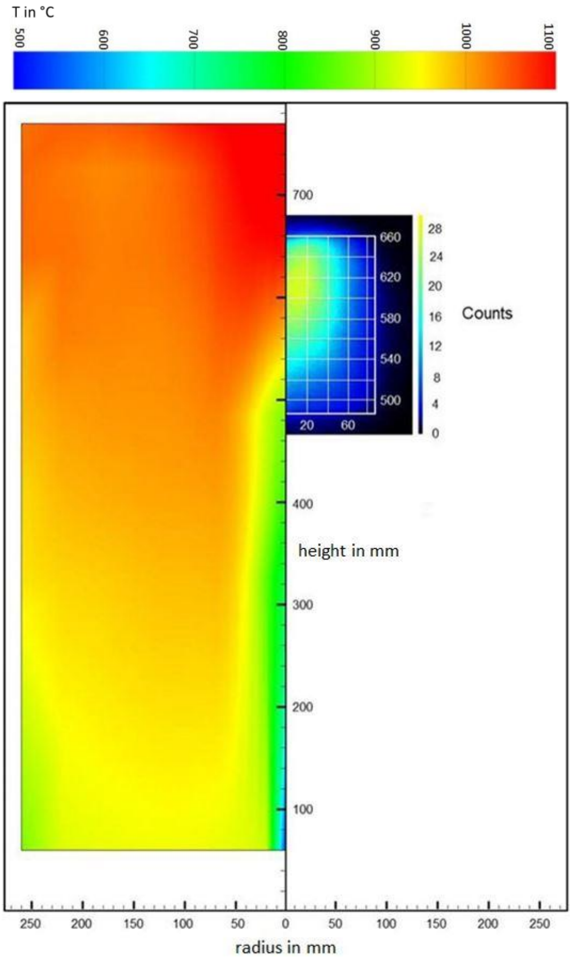

Fig. 5: measured Temperature distribution (153 measurement points, interpolated) vs. OH*-chemiluminescence visualization

The movement of the reaction zone towards the burner outlet with rising reactor temperatures, which was observed when testing the OH* chemiluminescence visualization, can be reproduced by the stationary temperature measurements with thermocouples.

The temperature measurements were performed for burner capacities between 8 kW and 10 kW, the air ratio ($\lambda = 1.2$) was maintained constant. Figure 6 shows the comparison of the measured stationary temperature distributions for five reactor temperatures between 800 °C and 900 °C at a burner capacity of 8 kW. The shift of the reaction zone towards the burner outlet with increasing reactor temperatures is evident. A determination of the beginning of the reaction zone is therefore possible on the basis of the recorded temperature profiles.

The comparison of the recorded temperature profiles and the OH*-chemiluminescence shows a good correlation concerning the beginning of the reaction zone. It is located at the point of the highest increase in temperature. The OH*-chemiluminescence furthermore provides information on the dimensions of the reaction zone. The temperature profiles were recorded using ordinary thermocouples that are not shielded against the influence of radiation. Therefor they are much more uniform because they lack the extreme minimum and maximum temperatures noticed in the results of the numerical simulation.

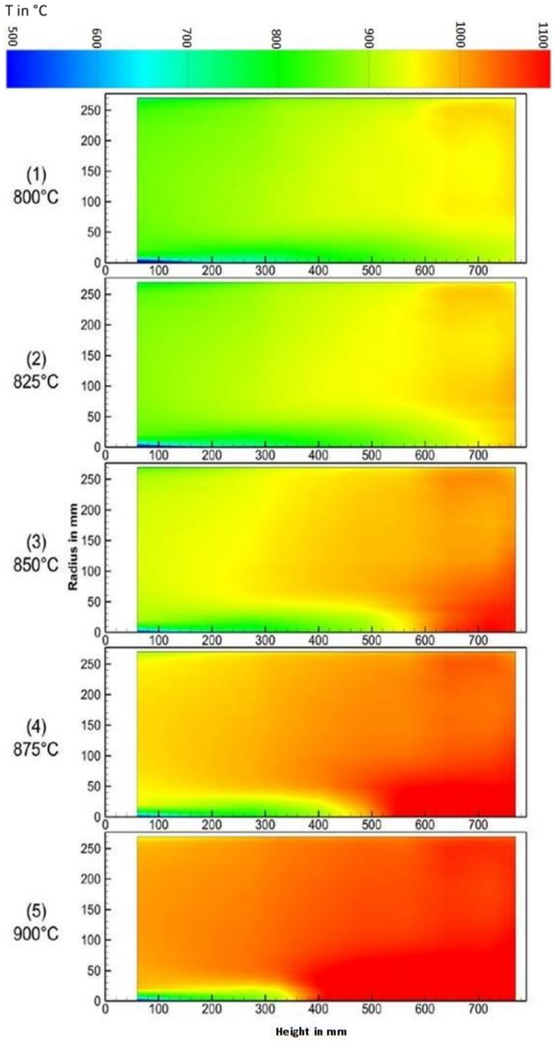

Fig. 6: Temperature distribution (153 measurement point, interpolated) at P = 8 kW

Summary and Outlook

Increasing the efficiency and simultaneously reducing the emission of pollutants are a focus of present research in combustion technology. Especially through the use of air preheating the off-gas losses are reduced at high temperature processes. However, this is at the expense of increased thermal NO_x formation. By using flameless oxidation the formation of thermal NO_x can be reduced while using high temperature air preheating by avoiding peak temperatures in the flame front. Currently at the Department for Industrial Furnaces and Heat Engineering (IOB) research is being conducted for the extension of the application limits for FLOX®-burners at lower burner capacities.

In a direct comparison of the measurements by OH*-chemiluminescence visualization with measurements of temperature profiles, a good correlation of the results with respect to the beginning of the reaction zone was observed. The OH*-chemiluminescence visualization provides precise information on the extent and position of the reaction zone. With the results of the temperature measurements only the beginning of the reaction zone can be measured reliably. As for the OH*-chemiluminescence visualization recordings visual access must be available, the area of application for this technique is restricted in comparison to the temperature measurements. Therefore the result that the beginning of the reaction zone can be determined based on temperature measurements is of great importance.

Further studies on the influence of other parameters (e.g. composition of fuel gas, air preheating temperature) on the position of the reaction zone when using flameless oxidation will be performed in the course of the research project. The capability of identifying the reaction region and its characteristics (e.g. its location and extension inside the reactor and the related temperature distribution) by means of the measuring techniques used on the current experimental setup is an important accomplishment for the following steps of the project as the capacity of the burner will be further reduced to a few kW.

Acknowledgements

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