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Numerical and experimental investigation of pollutant formation and emissions in a full-scale cylindrical heating unit of a condensing gas boiler

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HIGHLIGHTS

- Detailed numerical and experimental study of a full-scale condensing gas boiler.
- Identified high emission regions due to locally varying burnt temperature levels.
- CO emissions are caused by a freeze of CO oxidation due to a steep cooling gradient.
- Majority of NO is formed within the flame front and not in post flame region.

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ABSTRACT

The condensing gas boiler technology has received increasing attention due to its very high efficiency of more than 90%, which is an increase of more than 15% compared to non-condensing boiler devices. With this, condensing gas boilers offer the chance to decrease the energy consumption and CO_2 emissions for domestic hot water and heating. While further increasing the energy efficiency of condensing boiler devices, pollutant emissions have to be considered as well since they are a threat to human health and therefore subject to continuously intensified governmental restrictions. In this study, a comprehensive investigation of the full-scale heating unit of a commercial condensing gas boiler was performed. Local measurements at different axial positions revealed an inhomogeneous distribution of CO and NO emissions due to varying temperature levels in the burnt region. Resolved simulations with finite rate chemistry identified a quenching of the CO oxidation reactions due to a fast depletion of OH radicals. Consequently, the CO concentration in the cooled exhaust gas is significantly higher than expected from chemical equilibrium calculations. Regarding NO formation, the majority of NO is found to be produced within the flame front, while only a small part is formed in the postflame region. A detailed pathway analysis pointed out that besides the well known thermal NO pathway, the NNH pathway has the highest contribution to the overall NO emissions. These insights open up possibilities to develop new condensing boiler generations where emission levels below the permitted limits can be achieved.

1. Introduction

Providing energy for domestic hot water and heating accounts for one third of the total energy consumption in Europe [1]. Here, natural gas represents the main energy source with a share of roughly 80% [1]. To generate heat from natural gas, condensing gas boilers are state of the art and their market share is continuously increasing in Europe, China, and the United States [2–4]. This boiler generation is more efficient than previous non-condensing heating devices, because the latent heat of the water vapor in the flue gas is exploited by condensation [2]. With this, energy efficiency levels of up to 115% with respect to the lower heating value can be obtained [5]. Such high efficiency levels enable noteworthy gas fuel consumption savings along with a massive reduction of CO_2 emissions, which possess a significant global warming potential [1]. Despite these achievements, further steps are planned to decrease CO_2 emission levels in condensing gas boiler devices. By adding hydrogen to the natural gas network, the carbon content of the fuel and consequently the CO_2 concentration in the flue gas can be decreased significantly [6]. The condensing gas boiler technology can also support the energy transition towards renewable energy sources,

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because power-to-gas processes represent a method to store the intermittent solar and wind energy sources by producing gaseous fuels like hydrogen or methane, which are then fed into the natural gas network [7].

While developing new condensing gas boiler generations, emission levels of carbon monoxide (CO) and nitrogen oxides (NO_x) have to be considered as well. These species contribute to the ozone depletion and in higher concentrations are highly dangerous to human health [8,9]. On this account, legal regulations, such as the European norm DIN EN 15502-1 [10,11], were established and emission limits have become continuously stricter since then. To achieve such low-emission characteristics, different types of condensing gas boiler devices exist, mainly characterized by the burner geometry that stabilizes the laminar premixed flame.

Porous media burners, such as ceramic foam or metal fiber burners, received much attention recently [12–17] in an attempt to effectively decrease NO and CO emissions by employing a radiant mode [13]. Malico et al. [14] studied the effect of high flame heat losses to a porous media burner and its reducing effect on the course of CO and NO emissions. They compared numerical results to experiments of Trimis et al. [12] and found their model to underpredict CO and overpredict NO emission levels. The drawback of increasing heat losses to the burner is the simultaneously increasing thermal load of the burner material, which reduces the lifetime and increases the material costs of the boiler.

Besides porous media burners, perforated burner plates have been investigated. Here, focus was on stabilization and blowoff limits [18], burner velocity profiles [19], and the effect of varying pressure levels on the flame surface area [20]. Only a few investigations on cylindrical multi-hole burner plates have been carried out, mainly discussing geometry optimization in order to improve the system efficiency [21,22].

Regarding the formation of carbon monoxide and nitrogen oxide, Bouma et al. [13] pointed out that reducing the flame temperature by using leaner mixtures decreases CO and NO concentration in the exhaust gas simultaneously. However, this measure is limited to flammability and blowoff limits and commercial boiler devices are already operated under lean conditions.

Lee et al. [23] studied numerically the effect of different burner-to-coil distances on the CO and NO_x emissions. In their optimized model, one coil package was positioned relatively close behind the flame front to cool the flue gas below the NO critical temperature. A second cooling stage was positioned further downstream to improve the CO oxidation.

These studies focused on selected or idealized aspects of condensing boiler devices. They provide knowledge on how effective various measures are in reducing emissions. However, the reasons on a mechanistic level, which are important for reduction of such pollutants, have not been discussed. Consequently, the aim of this study is to analyze a full-scale condensing boiler system with detailed experimental and numerical methods. With this, the important processes leading to emissions of CO and NO should be identified and suggestions to further decreasing emission levels will be derived.

In condensing gas boilers, the hot flue gas is rapidly cooled down by the heat exchanger. This causes a fast depletion of OH radicals and consequently a freezing of the CO oxidation reaction, which has been investigated more fundamentally in a simplified setup by Creighton [24]. This CO oxidation freezing can be expected to be the dominating cause for CO emissions in condensing gas boilers. However, this effect has never been analyzed in detail in a full-scale system. With regard to the NO emissions of condensing gas boiler devices, the nowadays standard operation under lean conditions has already decreased burnt gas temperatures and NO emission levels simultaneously. However, lower temperatures in the postflame region reduce the importance of the thermal NO formation pathway [25]. Consequently, other NO formation pathways like the NNH-, the N_2O, or the prompt NO mechanism become more relevant.This is a crucial aspect, since the strategies for avoiding NO from these sources are not as straightforward as for thermal NO.

In this study, radial profiles of the interesting quantities CO, NO, and temperature along the pathway from the cylindrical multi-hole burner surface through the cylindrical cooling coils were extracted. Temperature was measured using a thermocouple, while species measurements were performed utilizing probe sampling coupled to a gas chromatograph (GC) and a chemiluminescence detector (CLD). To study the homogeneity of the full-scale heating unit, these radial measurements were repeated at several axial positions. To gain further understanding of the CO and NO formation, resolved simulations utilizing detailed chemical kinetics were performed and numerical results were compared to the experimental data. The availability of radical concentrations in the simulation allowed a deeper analysis of the CO oxidation freezing at flue gas cooling and a detailed NO formation pathway analysis according to the method of Trisjono et al. [26].

This paper is organized as follows: in Section 2, the setup of the cylindrical heating unit and the applied measurement techniques are explained. The numerical framework of the resolved simulations is summarized in Section 3. Section 4 outlines the experimental results of the temperature and species measurements, before in Section 5, numerical and experimental results are compared and discussed. Finally, conclusions are drawn and steps for future work are suggested in Section 6.

2. Experimental methods

2.1. Burner setup

The investigated cylindrical heating unit is shown in Fig. 1. It was taken from a commercial, condensing boiler, which was modified to enable radial profile measurements of temperature as well as CO and NO concentrations. The heating unit – consisting of burner and cooling coils – was separated from the burner housing to make it accessible for

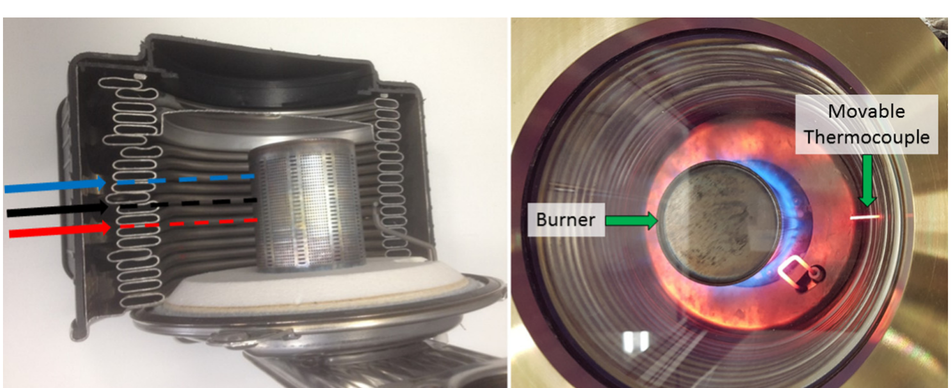

Fig. 1. Photos of the utilized cylindrical heating unit. Left: Cross-sectional view of the standard serial produced device consisting of burner, combustion area, cooling coils, gas mixing arm, and housing along with the upper (blue), center (black) and lower (red) axial measurement position. Right: Modified heating unit applied in the present study. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)