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CFD and experimental analysis of a 115 kW natural gas fired lab-scale furnace under oxy-fuel and air–fuel conditions

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HIGHLIGHTS

- CFD modelling of an 115 kW lab-scale furnace.
- Time saving combustion modelling using the steady flamelet model.
- Prediction of heat fluxes to a water cooled copper plate in the furnace.
- Different oxygen enrichments in the oxidizer.
- Comparison between CFD and measurements.

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ABSTRACT

This paper investigates a natural gas fired lab-scale furnace with a thermal input between 28 and 115 kW under different O_2/N_2 ratios in the oxidizer by computational fluid dynamics (CFD). Results of the simulation were confronted with temperature measurements inside the furnace and heat flux measurements on a water cooled plate inside the furnace. The main goal of this work was to use a detailed chemical mechanism and reduce the calculation time. This was achieved with the steady flamelet (SFM) approach. The advantage of the SFM approach is that the computational chemical calculation can be pre-processed and stored in look up tables. Only two additional equations have to be solved to determine the chemical reaction in the flow field. For the simulation the detailed mechanism skeletal25 was used with 17 species and 25 reactions. Additionally the furnace was simulated with the eddy dissipation concept model (EDC) which other authors mainly use to describe oxy-fuel combustion. For the EDC simulation a refined version of the 4-step mechanism proposed by Jones and Lindstedt was used. The EDC simulation was used as a benchmark to determine the time saving potential of the SFM approach. With the SFM approach the calculation time could be reduced from 4 weeks to 4 days on 8 CPU cores, although a detailed mechanism was being used. The predicted temperatures of the CFD simulations were in good accordance with the measurements and showed the applicability of the skeletal25 mechanism with the SFM approach under different combustion environments. In metal melting or reheating furnace the right prediction of the heat flux on the goods is crucial. Therefore the heat flux on a water cooled plate inside the furnace was determined by measurements and CFD calculations for different combustion environments. For the heat flux at a temperature level of 1070 °C the CFD calculation showed a maximum relative error of 5% to the measurements for 21, 25, 30, 45 and 100 Vol% O_2 in the oxidizer. For the temperature level of 1200 °C the maximum error increases, especially for O_2 concentration in the oxidizer higher than 45% up to 12%. Both the experiments and the numerical model showed an increase in furnace efficiency with increasing oxygen in the oxidizer. A maximum efficiency of 76% was observed for 100 Vol% in the oxidizer compared to 48% at 21 Vol% O_2. This shows the fuel saving potential of oxygen or oxygen enriched combustion.

1. Introduction

A tremendous amount of energy is required in industries with high temperature applications such as metal reheating or glass melting. This amount of energy is mainly provided by the

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combustion of fossil fuels like natural gas or heating oil [1]. Fossil fuels are accountable for 85% of global energy production and are also the main source of CO_2 emissions [2]. CO_2 is also emitted by chemical reactions in processes such as cement clinker formation, where only 32% CO_2 is emitted by combustion and 68% by carbonates [3]. Therefore, in the future, the main focus will be on reducing fuel consumption, counteracting the problem of rising fuel prices and reducing CO_2 emissions. One opportunity to effectively reduce fuel consumption and CO_2 emissions in industrial applications is oxy-fuel combustion. In oxy-fuel combustion, the O_2 concentration in the oxidizer is increased from 21 Vol% up to 100 Vol%. This leads to a higher combustion temperature, which is desired in high temperature applications, due to the absence of N_2. Besides the higher combustion temperature, the use of oxy-fuel increases the CO_2 concentration in the flue gas, making it easier to separate it from the flue gas. This is used by carbon capture and storage (CCS) technologies to reduce the CO_2 emission into the atmosphere. Some economical and technical surveys show that the CCS could be an upcoming technology in the future [4–6]. The use of oxy-fuel can improve the efficiency of industrial applications. Oliveira et al. [7] showed that, in a melting reheating furnace, which operates at a temperature of 1200 °C, the fuel consumption can be reduced by 46% if oxy-fuel combustion is used. Furthermore, it has been shown that oxy-fuel technology is more economical than combustion with air for high temperature applications. Experiments done by Blohradský et al. [8] at a test furnace with an 750 kW natural gas burner showed that the energy efficiency can be improved from 60% for air–fuel condition to 78% for 38 Vol% oxygen in the oxidizer. In experiments and numerical simulations of a lab-scale furnace with a thermal load, Prieler et al. [9] showed that the energy efficiency can be increased from 44% with 25 Vol% oxygen in the oxidizer to 67% at 100 Vol% O_2. In glass, steel or cement industries, oxy-fuel or oxygen-enriched combustion is already used [10]. Several publications also deal with the application of oxy-fuel combustion in power plants i.e. Scheffknecht et al. [10], Chen et al. [11] and Wall et al. [12]. In power plants, the maximum temperature is limited by the high stresses, i.e. for gas turbines 1600 K [13]. Therefore the oxidant in power plants using oxy-fuel consists of oxygen and recycled flue gas to reduce the maximum temperature. As was previously mentioned, the flue gas in oxy-fuel combustion mainly consists of CO_2 and H_2O through the absence of N_2. Hence, the total heat transfer characteristic is considerably different to that of air fired conditions. The radiative heat transfer is strongly enhanced by the higher level of CO_2 and H_2O.

Computational fluid dynamics (CFD) is a good tool for getting detailed information about the heat transfer, fluid flow and combustion characteristics inside of a furnace. Through the increasing computer power in recent years, it is now possible to do numerical simulations of industrial furnaces. This is also a good opportunity to gain a better understanding of the heat transfer characteristics inside a furnace under oxy-fuel conditions. However, it is still necessary to perform simplifications on chemical kinetics and heat transfer schemes so that CFD simulations can be done at acceptable computational costs. In commercial CFD codes, there are many models available for describing heat transfer and combustion behaviour inside a furnace. The main objective is to find the right model to calculate combustion and heat transfer correctly and in good accordance with measurements. In combustion modelling, chemistry and radiative heat transfer have the biggest effect on the solution. In the past global mechanisms were successfully used to simulate combustion under air-fired conditions. Two global mechanisms are commonly used: Westbrook and Dryer (WD) [14] and Jones and Lindstedt (JL) [15] which are a 2 step and a 4 step mechanism respectively. In high temperature processes such as oxy-fuel combustions the formation of radicals due to dissociation effects is increased. These radicals have a high impact on the chemical kinetics and in global mechanisms, like the WD or JL, these radicals are only considered in the burning rate and not explicitly as species in the reactions. Yin et al. [16] compared these two global mechanisms with a detailed mechanism for air–fuel and oxy-fuel conditions. The comparisons showed that the adiabatic flame temperature is heavily overestimated (300–500 K) by the global mechanism under oxy-fuel condition and is in good accordance with the detailed mechanism for air–fuel conditions. More information can be found in [9]. It can therefore be concluded that, in oxy-fuel combustions, radicals have a big influence on the right prediction of the temperature and species concentrations.

Radiation heat transfer is a very crucial part in combustion modelling. Most of the models implemented in commercial CFD codes for the calculation of the radiative properties of the flue gas are developed for air–fuel conditions. In oxy-fuel or enriched oxygen combustions the concentration of CO_2 and H_2O is considerably different compared to air-fired conditions. Due to the lack of N_2, the concentration of CO_2 and H_2O in the flue gas is far higher. This leads to an even stronger spectral dependency of the radiative properties than in air-fired conditions. Hence, most of the models used in commercial CFD for the calculation of radiative properties are out of the validation range. There are three main models that are used for the calculation of radiative properties. These models are the line-by-line method, the band models and the global methods. In CFD codes, the global methods are preferred due to the low computational costs. The mainly used global method is the weighted sum of grey gases model (WSGGM) which was first suggested by Hottel and Sarofim [17]. This model assumes that the non-grey flue gas is a mixture of a number of fictive grey gases, weighted by factors. These weighting factors are derived from more detailed methods which are computationally highly demanding, like the line-by-line method (LBL) or the band models. It is important to mention that, even under air-fired condition, this assumption which leads to the flue gas being treated as a grey gas can lead to an underestimation of the temperature by 100–150 K [18,19]. Porter et al. [20] compared a global and a non-grey method under air- and oxy-fuel conditions. The WSGGM was used as a global method with the coefficients proposed by Smith et al. [21], which are implemented in most of the CFD codes, and the full spectrum correlated k-distribution (FSCK) [22,23] was used as non-grey method. They compared both methods with benchmark data which was calculated with the accurate statistic narrow band (SNB) [24] model. Regarding air–fuel condition, the comparison showed that the WSGGM from Smith et al. overestimates the heat flux to the walls and that the prediction of the radiative source term is less accurate compared to the FSCK model. In the case of oxy-fuel condition the WSGGM significantly underrates the radiative source term. The average error of the source term using the FSCK method is about 5% but, using the WSGGM from Smith et al., the average error is higher than 50% compared to the SNB benchmark data. Porter et al. also compared the different model on their calculation time which is needed until the solution is converged. The investigation showed that the calculation with the FSCK model and the DOM takes 76.16 times longer to converge compared to the calculation with the P1 model with the WSGGM from Smith et al. The DOM with the WSGGM takes 5.59 times longer than the P1 model with the WSGGM. This shows well how the calculation time increases using a non-grey method. Becher et al. [25] compared the WSGGM from Smith et al. with the very accurate LBL model (HITEMP2010 [26]). The WSGGM showed a deviation of 59% under oxy-fuel condition from the LBL. Hence, new parameters for the WSGGM were derived for oxy-fuel conditions in recent years. Yin et al. [27] proposed new parameters for the WSGGM for different CO_2 and H_2O ratios and beam lengths. Furthermore they compared the new WSGGM and the WSGGM proposed by Smith et al. with the exponential wide

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