Applied Thermal Engineering 136 (2018) 492–503

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Modelling of high temperature furnaces under air-fuel and oxygen enriched conditions

B. Mayr[a], R. Prieler[a,*], M. Demuth[b], C. Hochenauer[a]

[a] Graz University of Technology, Institute of Thermal Engineering, Inffeldgasse 25/b, 8010 Graz, Austria
[b] Messer Austria GmbH - Kompetenzzentrum Metallurgie, Industriestraße 5, 2352 Gumpoldskirchen, Austria

HIGHLIGHTS

- CFD modelling of air-fuel and oxy-fuel combustion in industrial processes.
- Development of a 0/1D model to predict the temperature and heat transfer.
- Comparison of the simplified model with experimental data and CFD.
- Investigation of a lab-scale, melting and a walking hearth reheating furnace.

ARTICLE INFO

Keywords:
Computational Fluid Dynamics
Mathematical model
High temperature furnace
Reheating furnace

ABSTRACT

A zero/one dimensional thermodynamic model was developed that can be used to determine the influence of oxygen enriched combustion (OEC) on the heat transfer, gas, and wall temperatures in a furnace. The model uses simple thermodynamic correlations, which makes it very time efficient (with calculation times of a few seconds), and therefore mean that it can be used in Microsoft Excel. This model was used to calculate the heat flux to a thermal load and the main temperatures (gas and wall) in a lab-scale furnace and industrial scale furnaces. The results were compared with both experimental measurements and the results of CFD calculations. The thermodynamic model showed good agreement with the measurements and the results of the CFD calculations, considering its simplicity. Thus, this model shows high potential for use to quickly determine the effects of OEC on industrial furnaces.

1. Introduction

In many industries, high gas temperatures are required for processes such as annealing, melting, and reheating of metals. The high energy demands of such processes are mainly fulfilled by fossil fuels. Thus the optimisation of processes in this sector are of great interest to achieve the reduction of greenhouse gas emissions. For example in steel plants, reheating furnaces are one of the largest consumers of energy [1,2]. Such reheating furnaces are used to raise the temperature of the steel - mostly introduced in billet or slab form - to a desired level, in order to prepare the steel for subsequent processing, such as through rolling mills. A promising technology for the optimisation of such furnaces is oxygen enriched or oxy-fuel combustion. In oxy-fuel and oxygen enriched combustion, the O_2 concentration in the oxidizer is increased from 21 Vol% up to 100 Vol%. This leads to a higher combustion temperatures due to the smaller amount (or the absence) of N_2. Nitrogen absorbs a high amount of the energy released by the chemical reaction in the flame. In combination with Carbon Capture and Storage (CCS) oxy-fuel or oxygen enriched combustion is a promising technology to reduce the CO_2 emissions of power plants and furnaces [3–5].

In high temperatures processes, it is difficult to perform experiments, and the significance of such experiments is limited. The increase in computational power in recent years means that it is now possible to perform numerical simulations of industrial processes with a reasonable standard of accuracy and in a short period of time. Computational fluid dynamics (CFD) is useful to investigate the heat transfer characteristics, fluid flow, and reaction kinetics inside a furnace operating under high temperature. A number of studies have been performed using CFD to optimise high temperature processes. One of the first investigations of this topic resulted in the models of Zhang et al. [6,7], in which the geometry of the furnace was simplified, and the billets were treated as a single slab placed on the furnace floor. Other simplified models divide

* Corresponding author.
E-mail addresses: bernhard.mayr@tugraz.at (B. Mayr), rene.prieler@tugraz.at (R. Prieler), martin.demuth@messergroup.com (M. Demuth), christoph.hochenauer@tugraz.at (C. Hochenauer).

https://doi.org/10.1016/j.applthermaleng.2018.03.013
Received 28 August 2017; Received in revised form 12 February 2018; Accepted 5 March 2018
Available online 08 March 2018
1359-4311/

Nomenclature

$\dot{Q}_{Air}$	the heat flux of the combustion air
$\dot{Q}_{CH_4}$	the heat flux of the fuel
$\dot{Q}_{O_2}$	the heat flux of the pure oxygen
$\dot{Q}_{LHV}$	the heat of reaction
$\dot{Q}_{Flue\,gas}$	the heat flux of the flue gas
$\dot{Q}_{Wall}$	the heat loses through the walls
$\dot{Q}_{Load}$	the heat flux to the thermal load
$\dot{m}$	mass flow
α_g	the absorptivity of the gas
ϵ_w	the emissivity of the wall
σ	Stefan-Bolzmann constant
M	molar mass
ν_i	molar fraction
T	temperature
H_{LHV}	lower heating value
c_p	specific heat capacity
A	surface
λ	oxidizer-fuel equivalence ratio
$\dot{q}$	heat flux density
l_w	thickness of the wall
ϵ_g	the emissivity of the gas
λ_w	thermal conductivity
ϵ_s	the emissivity of the thermal load
a	convective heat transfer coefficient
$\dot{M}$	molar flow

the furnace into zones with different wall and gas temperatures. In Kim [8], the furnace was modelled as a radiating medium, and the temperature of the billets was calculated using the transient heat conduction equation. More recent work on this topic has been carried out by Han and Chang [1] and Han et al. [9]. In their studies, detailed 3D transient simulations were performed. The movement of the billets was simulated by moving the temperature field in the billets from one position to the next until the end of their residence time in order to reach a periodically transient solution.

The majority of the works described above focus on simplified steady-state simulations with a certain lack of accuracy, but fast calculation times. Other, more complex models solve the reheating process in transient simulations, which provide more accurate results, but also require more calculation time. Recently, new CFD approaches have been proposed which reduce the calculation time necessary. Prieler et al. [10] proposed a new iterative and numerically-efficient solution strategy for reheating furnaces. Combustion in the gas phase was done using a steady-state simulation, while the transient reheating of the billet was performed in a separate, transient simulation. Prieler et al. used the steady flamelet model (SFM) with a skeletal mechanism so as to keep the calculation time to a minimum.

Although using numerical efficient CFD model the calculation times of such numerical investigations are a few days. For design studies or case studies this calculation times are often to long. Also the transient behaviour of a furnace during a load change cannot be calculated by a CFD calculation, unless a fully transient simulation is performed which have calculation times of a few weeks. Therefore, simplified models were developed, such as heat transfer model focusing on single slab. Jang and Kim [11] proposed a slab temperature model using the finite difference method. The model was used to optimise a reheating furnace. Due to this optimisation the residence time for slab was reduced by 13 min, which corresponds to a production increase of 9.72%. Jang and Kim [12] developed a model using the finite element method to calculate the temperature distribution of a billet during the reheating process. The model only considered radiative heat transfer and the convective heat transfer was taken into account by adjusting the emission factor. Jaklič et al. [13] developed a simplified thermodynamic model for the online simulation of a reheating furnace. This model uses a zone method to calculate the temperature field in the furnace. Also the exact geometry of the furnace and the slabs were considered in the model. The exact geometry is used to calculate viewing factors to determine the radiative heat transfer between the slab, the walls and between the different zones. The model also uses measurement values as input parameters for the calculation. The results of the calculation were compared to measurements and showed a reasonable accuracy after tunning the model.

In this paper, a simplified thermodynamic furnace model is presented which is based on the model from Jaklič et al. [13]. In contrast to Jaklič et al. this model do not need any measurement values as input parameter and, is therefore a more general approach. The model is based on simple thermodynamic and heat transfer correlation to keep the calculation time low. Furthermore, the model is cable to calculate beside air-fuel conditions also oxygen enriched and oxy-fuel conditions. The model is used to investigate three furnaces, a lab scale furnace and two industrial scale furnaces which operates under air-fuel condition and different oxygen enriched conditions. The results of the simplified model were compared to results of CFD calculations (which are also partly described in this paper) and to experimental data.

2. Furnace description

2.1. Lab-scale furnace

The natural gas fired lab-scale furnace, has a thermal input of between 28 and 115 kW, depending on the oxygen concentration in the oxidizer. The internal dimensions of the combustion chamber are 0.77 × 0.75 × 0.99 m, and it is surrounded by 0.2 m of ceramic insulation. Fig. 1 shows the lab-scale furnace and the different temperature measurement points (T1, T2, T3, T4). The gas temperature inside the furnace was regulated at measurement point T2. Therefore, the term temperature level is defined as the gas temperature measured at the measurement point T2. Experiments were performed for a temperature level of 1070 °C. A water-cooled plate was placed inside the furnace to simulate a thermal sink. To determine the absorbed thermal power, the water in- and outlet temperatures and the water mass flow were measured. The temperature of the copper plate was measured by thermocouples on different positions. Further information about the lab-scale furnace can be found in [14].

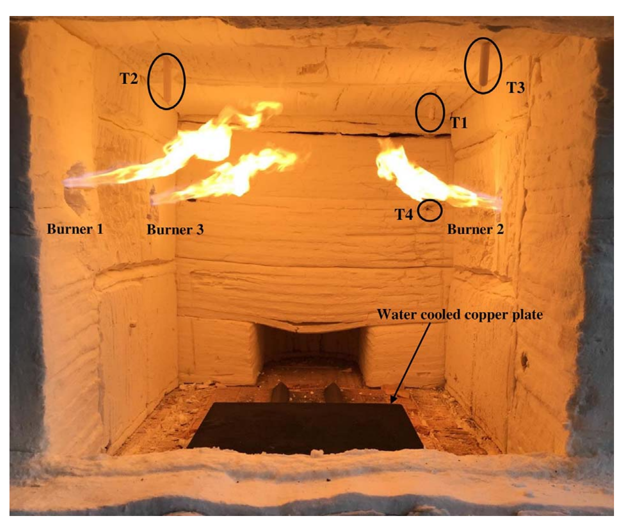

Fig. 1. Experimental-setup lab-scale furnace [14].