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Using an oxygen-carrier as bed material for combustion of biomass in a 12-MW_{th} circulating fluidized-bed boiler

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HIGHLIGHTS

- The investigation was conducted in the Chalmers 12 MW_{th} boiler/gasifier system.
- 40 wt.% of the ordinary used silica-sand bed material was replaced with ilmenite.
- Ilmenite decreased the concentrations of CO and NO by 80% and 30%, respectively.
- The combustion was directed to the furnace, yielding a lower cyclone temperature.

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ABSTRACT

The initial experiences of using an oxygen-carrying metal oxide, ilmenite, in the 12-MW_{th} circulating fluidized bed (CFB) boiler/gasifier system at Chalmers University of Technology are presented. The rationale for the addition of ilmenite to the solids inventory is that ilmenite has the ability to alternately take up and release oxygen, and thereby improve the distribution of oxygen throughout the furnace. As a consequence, less air is needed to maintain low emissions from carbon monoxide (CO) and unreacted hydrocarbons (HC) during the combustion of volatile-rich fuels, such as biomass. One of the conducted experiments involved only the boiler, and the reference case corresponded to operation solely with silica-sand as the bed material, while in an additional three cases, ilmenite in various amounts was added to make up to 40 wt.% of the total bed inventory. During the experiments, the concentrations of CO and nitric oxide (NO) in the convection path of the boiler were measured. The addition of ilmenite to the silica-sand decreased the concentrations of CO and NO by 80% and 30%, respectively. Additional experiments were performed in which a concentrated stream of raw gas produced in the indirect gasifier was injected into the freeboard of the boiler. In one experiment, only silica-sand was used, while 12 wt.% ilmenite was added to the bed material in a separate experiment. The concentrations of CO and HC were measured at three different heights in the boiler and at nine positions over a cross-section of the furnace. The concentrations of CO and total HC in the furnace cross-section during concomitant gasification operation were reduced by the addition of ilmenite.

1. Introduction

In most commercial combustion applications, the most important part is the consumption of gaseous oxygen. Combustion efficiency depends to a large extent on the facilitation of adequate mixing of the fuel and oxygen both spatially and temporally [1]. A commonly applied measure in combustion plants to control the level of oxygen in relation to fuel-specific properties is to adjust the level of excess air. However, increasing the oxygen supply to the furnace usually requires that an excess of air has to be fed into the combustion unit, which results in loss of boiler efficiency. This can also generate a situation in which there is irregular release of heat inside the combustion chamber, owing to the uneven distribution of oxygen and fuel in space and time. The resulting maldistribution can in turn lead to emission-related issues, such as the release of NO_x and SO_x species and the escape of unreacted hydrocarbons (HC) and CO in the flue gases; extensive efforts have been made to resolve this problem. Furthermore, as a consequence of the uneven heat release, high-temperatures zones can be formed within small volumes inside the furnace. These temperature gradients are likely to induce the melting of ash components, which promotes the formation of sticky ash, which may be deposited onto

Abbreviations: CFB, circulating fluidized bed; (T)HC, (total) hydrocarbons; TWC, three-way catalyst; CLC, Chemical-Looping Combustion; FID, Flame Ionization Detector; NDIR, Non-Dispersive Infrared; Me/MeO, metal oxide.

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cooling surfaces. The condensation of ash onto super-heater and heat exchanger surfaces in the convection path may lead to severe fouling and create degraded heat transfer and corrosion problems [2–4].

Currently, measures that can be applied to ameliorate these problems are in two main categories: (1) measures that focus on the preparation and feeding of the fuel; and (2) measures related to the introduction of air together with – in many cases – recirculated flue gases [5]. The first category of measures is essential when solid fuels are to be combusted, as the preparative step aims to yield a fuel that is as homogeneous as possible. Nevertheless, this operation has to have a reasonable energy penalty for the process in terms of affordable equipment and operating cost. For all the different fuel types, and particularly for the solid fuels, optimization of the feeding is a significant challenge [6]. In many cases, this can be seen as the most concealed part of the boiler design from different manufactures of combustion technologies. The feeding system must distribute the fuel to the furnace in an optimal manner while ensuring robust operation of the overall boiler.

The second category of measures is concerned with the implementation of a satisfactory air register. For this, choosing the appropriate number and location of feeding ports for air injection is the key to ensuring complete combustion of the fuel – and possibly limiting combustion to the boiler body itself – and to restricting the levels of harmful emissions. In general, the two categories of measures are combined, and the feeding streams ensure that the fuel and the gaseous oxygen are adequately mixed, i.e., to guarantee that the temperature and stoichiometry are favorable for the specific boiler operation [5]. This also explains why most of the boiler development over the past century has been devoted to furnace design, with a focus on the injection positions for the air and recirculated flue gases. All of these actions reflect the fact that heat release is typically connected to the location of fuel oxidation, which is the general principle for most of the current commercial combustion processes. However, if complete fuel oxidation could be achieved during controlled heat release throughout the furnace volume and at close to stoichiometric combustion, the efficiency and ash-related issues for particularly heterogeneous fuel combustion could be greatly improved. Nevertheless, to overcome mass transfer issues and to make the operation feasible at close to the stoichiometric condition, two crucial conditions need to be fulfilled: (1) the amount of fed oxygen needs to be accessible throughout the whole furnace geometry, to ensure complete combustion of the fuel; and (2) the fed oxygen needs to be retained to benefit the specific reactions coupled to the heterogeneity of the fuel. Taking biomass conversion as an example, the appropriate amounts of oxygen have to be distributed so as to convert the char fraction in the same time as the volatiles fractions are being fully oxidized before entering the convection path.

In the present work, these conditions were considered with the aim of improving the combustion of biomass in a circulating fluidized bed (CFB). The underlying rationale is to replace the totality or a fraction of the usual bed material with an oxygen-carrying metal oxide, as depicted in Fig. 1. This metal oxide, which has the ability to absorb and release oxygen during redox reactions at the temperatures used, will theoretically, owing to its reactions with gaseous HC and the fluid dynamics in the riser furnace, facilitate simultaneous oxygen supply across the entire boiler geometry, thus fulfilling condition (1). When the oxidized metal oxide (MeO) is conveyed upwards through the furnace geometry, the bound oxygen is converted through reactions with the volatiles (C_iH_j) into carbon dioxide and water, and the metal oxide is reduced (to Me). The reduced form (Me) is then separated from the flue gases in the cyclone and recirculated to the bottom bed. The air feed to the furnace can then be balanced from based on the oxygen consumption needed to convert the char fraction (nChar) to CO_2,

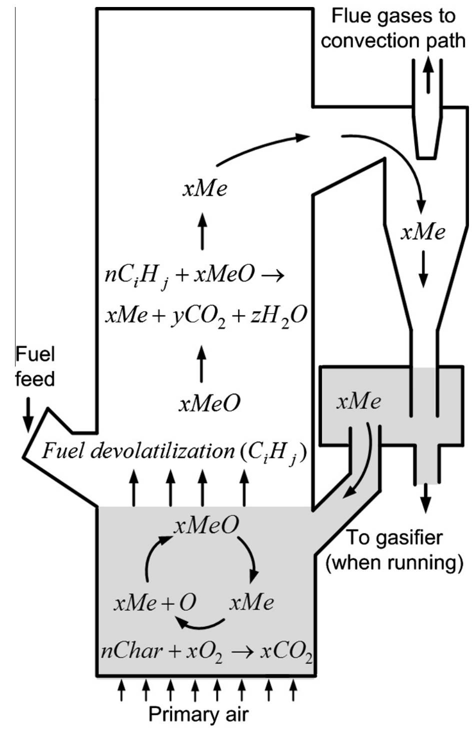

Fig. 1. Reactions involving fuel and oxygen carriers in the boiler.

together with the need for oxygen for re-oxidizing the reduced metal oxide (Me) and thereby completing the redox cycle. This process fulfills condition (2).

In a general sense, the system presented here shares similarities with the oxygen storage device in the universally used three-way catalyst (TWC) for gasoline engines [7], which was developed to reduce simultaneously the emissions of NO_x, CO, and unburned HC under close to stoichiometric conditions. The TWC concept involves a type of downstream gas cleaning and relies on continuous adjustment of the air to fuel ratio to create alternately slightly rich and slightly lean oxygen conditions in the engine, leading to either an excess of oxygen or a lack of oxygen in the exhaust gases. Under conditions of excess oxygen the catalyst absorbs oxygen and under low-oxygen conditions it releases oxygen. This oxygen looping in the TWC is used to finalize the combustion of unburned species, and in this respect it corresponds to the addition of a metal oxide to the boiler. Therefore, the catalyst in the TWC system and the metal oxide in the boiler act as oxygen buffers, to ensure low-level emissions of harmful species, even under the dynamic conditions present in an engine or a boiler.

The concept of applying a metal oxide to a combustion process, exploiting the continuous oxidation and reduction of the metal, is familiar from the principle of Chemical-Looping Combustion (CLC) [8]. However, the CLC system is more complex, as the aim is to combust fuels for heat and power production while at the same time the CO_2 is separated and sent for storage. In the present study, the emissions of CO_2 are of less importance, since biomass is regarded as a CO_2-neutral fuel. Nevertheless, research on CLC has generated much knowledge regarding materials that are suitable for use as oxygen carriers [9,10] and this knowledge is pertinent for a standard CFB boiler.

More specifically, in the present work, the idea of using an oxygen carrier in a CFB boiler was explored through experiments conducted in a commercially operated boiler. The experiments were conducted with biomass as the fuel in the 12-MW boiler/gasifier system at Chalmers University of Technology, where up to