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A Novel Test Rig for the Evaluation of Auxiliary Reducing Agents (ARAs)

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ABSTRACT

Injecting auxiliary reducing agents (ARAs) in the raceway zone of a blast furnace increases the efficiency and reduces CO2 emissions in case using bio-based sources. Reliable conversion rates are crucial to identify new ARAs or their mixtures and to optimize the ARA injection process, but they are hardly available in literature. The harsh reaction conditions in blast furnaces require suitable experimental equipment to determine reliable conversion rates. In this work a novel entrained flow reactor for evaluating ARAs will be presented and compared to the reaction conditions in a blast furnace. Furthermore, first experimental results will be presented

Keywords: auxiliary reducing agents (ARAs), blast furnace, raceway zone, test rig, reaction kinetics, coal combustion

INTRODUCTION

Injecting auxiliary reducing agents (ARAs) directly into the raceway zone of a blast furnace is a widely used approach to increase efficiency and reduce greenhouse gas emissions and metallurgic coke consumption. ARAs therefore serve as alternative carbon carriers. A large spectrum of ARAs, such as natural gas, oil, waste plastic, pulverized coal, and biomass, can be used in the blast furnace process.[1] To identify suitable ARAs, sufficient knowledge about their conversion rates in the raceway zone is crucial to estimate the impact on the blast furnace operation. ARAs undergo following thermochemical conversion steps in the blast furnace:

- Drying
- Devolatilization
- Gasification and burnout

The conversion should be completed before the ARAs leave the raceway zone, which forms in the vicinity of the tuyeres.[2] Computation Fluid Dynamics (CFD) can help determining the conversion time, but it relies on kinetic parameters and hence experimental data. The harsh reaction conditions in the blast furnace limit the feasibility of in-situ measurements. Optical access to the raceway zone allows for determining particle sizes and temperature distribution and provides essential information while using ARAs.[3] However, it cannot contribute to extracting kinetic parameters and hence there is additional data needed to specify whether using a specific carbon carrier is beneficial for operating the blast furnace. To obtain reliable kinetic parameters for potential ARAs, experimental equipment must recreate realistic temperature, pressure, velocity, and species profiles. Table 1 gives typical operation conditions of the raceway zone.

Table 1. Raceway Reference Conditions[4–7]

Temperature	Heating rate	Pressure	Gas velocity	Particle velocity	Residence time	O_2 content
1200 – 2500 °C	104 – 105 K/s	200 – 500 kPa	~200 m/s	~20 m/s	20-100 ms	~27 vol%

Different methods for testing ARAs are used, e.g., thermo-gravimetric analysis, drop-tube furnaces, flow reactors, injection rigs, or combustion chambers. [8] Some drop-tube furnaces and flow reactors can recreate similar reaction conditions as in the raceway zone, but the testing capacity is limited. Therefore, a new reactor concept for testing pulverized solid fuels under blast furnace conditions was developed. The subsequently presented reactor design aims to enable high temperature, high heating rates, and elevated pressure while providing short residence times for the particles. Furthermore, the measurement equipment and methods for extracting the kinetic parameters are discussed. Finally, the experimental and the blast furnace conditions are compared.

REACTOR DESIGN

The key parameters for the reactor are temperature, heating rate, pressure, residence time, and gas species concentration. Previous investigations showed that an entrained flow reactor could meet the necessary parameters[8]. The design process focused on recreating the raceway conditions as closely as economical and technically possible, while providing experimental conditions as flexible as possible. The main emphasis is placed on the extraction of kinetic parameters of ARAs under blast furnace conditions. However, other combustion processes as well as pyrolysis processes and further gas-solid reaction with high temperature and elevated pressures can be investigated.

Figure 1 shows a schematic drawing of the reactor. The main reaction zone is a 0.9 m long ceramic tube (aluminium oxide) with an inner diameter of 50 mm (RE) inside a pressure vessel (dotted line), which holds up to 11°bar. The ceramic tube is closed above by a hydrogen burner (BR), surrounded by electrical heating elements (HE), and ends with a water and nitrogen-cooled quench (QU). The co-flow, ensuring the right gas atmosphere and residence time, is heated by a gas heater (FH). The fuel sample is inserted through the lance in the center of the burner. The dosing unit (DO), which is in a separate pressure vessel, ensures constant solid flow. The solid residuals are separated in a cyclone (CY) after the quench, while a filter (FI) removes the fines. An orifice measures the volume flow of the offgas stream, and a gas analyzer and gas chromatograph determine the species concentrations.

Sixteen sample ports for optical access or extract probes out of the reaction zone are available. These sample ports are on four different levels along the ceramic tube. They will be used to obtain further and more detailed information about the reaction behavior of the injected particles.

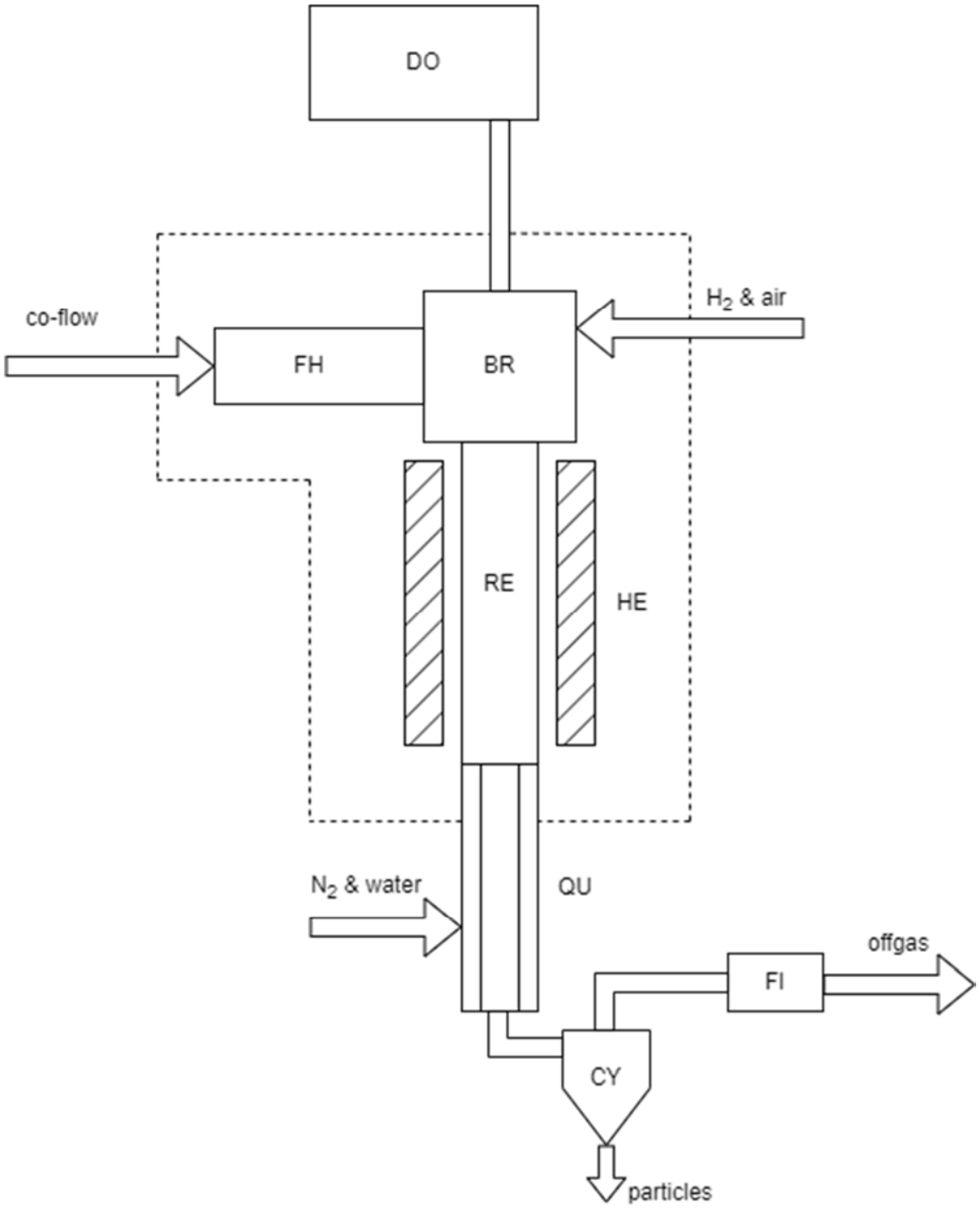

Figure 1. Reactor schematic drawing.

Electrical Heating

The heating system consists of two components: the gas heater and eight heating elements. The gas heater enables gas co-flow temperatures up to 1100 °C and maximal volume flows of 100 Nm^3/h, while using 40 kW of electrical power. The co-flow composition can be varied to attain the desired gas atmosphere in the reaction zone. Currently the following gases can be used: compressed air, nitrogen, and carbon dioxide in different mixtures. Since the flow heater is not pressure-tight, it must be placed inside the pressure vessel in a sidearm.

Eight half-cylindrical heating modules surround the ceramic tube on four levels. The heating elements have a maximum operating temperature of 1550 °C and power consumption of 1.4 kW each. A ceramic plate separates the levels to reduce convection and stabilize the ceramic tube. All four heating zones can be controlled separately to ensure a uniform temperature distribution along the ceramic tube.

Hydrogen Burner

The burner at the top of the ceramic tube serves multiple purposes. It provides a high-temperature zone around the entry of the particles into the reaction zone, directs the pre-heated co-flow into the ceramic tube, and allows the injection of ARAs into the

reaction zone. One of the main design challenges was to operate the burner inside a pressure vessel and keep the flame at different pressures always at the right spot to ensure high heating rates for the particles. Therefore, a new burner was designed for the test rig. Figure 2 shows a cross-section of the burner. The burner lance consists of three coaxial pipes. The central pipe is for the particles and carrier gas, the middle pipe is for the fuel gas, and the outermost is for combustion air. The gas co-flow enters the burner from the side and is directed by flow straighteners to the ceramic tube. A CFD study analyzed the exact inner design of the burner to ensure the proper flow conditions at the particle entry. The flame temperature and power output can be regulated by changing the air-fuel ratio and fuel gas flow, respectively. In the current design, hydrogen is used as fuel to avoid affecting the carbon balance, achieving more accurate information about the burnouts of the injected ARAs.

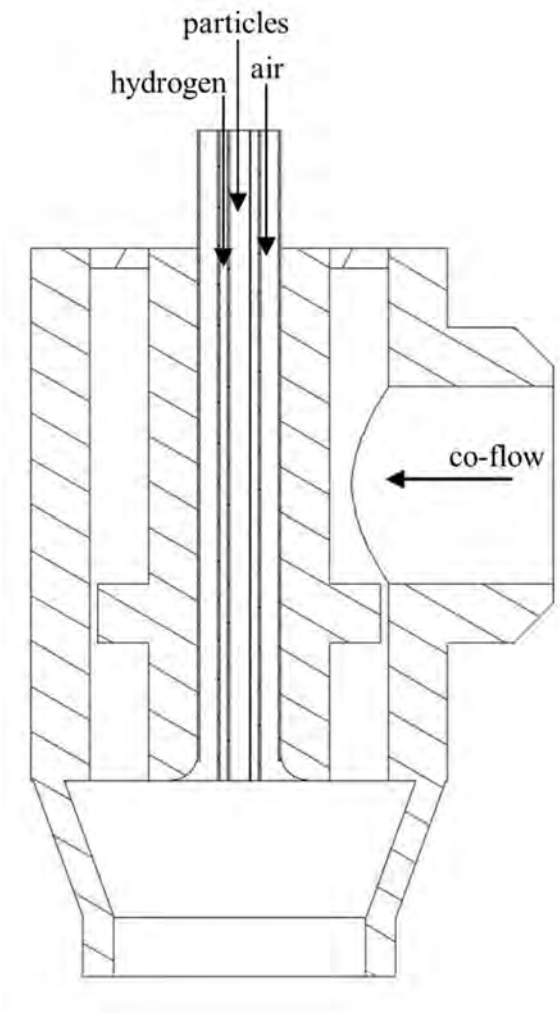

Figure 2. Cross-section hydrogen burner.

Dosing Unit

A precisely controllable and constant mass flux of the ARAs must be ensured to extract reliable kinetic parameters. The dosing unit has to sustain the desired mass flux for at least 20 minutes. It should be suitable for a large spectrum of different particle sizes. The necessary gas flux has to be minimized to avoid a cool down of the reaction zone. The probe chamber must be easy to clean and change while the rest of the reactor is running. A particle mass flux of about 1-2 g/s is considered to be suitable to enable investigating the injected particles properly and derive suitable data.

Different dosing unit designs were considered[9]: a vessel doser, a venturi doser, a mechanical screw doser, and a revolver doser. A literature study and prototyping identified the revolver doser design as the most promising. The revolver doser (Figure 3) consists of a rotating disc with small holes on edge[10]. The disc can be changed to meet the requirements for different particle sizes. The particles are fluidized from below and can flow into the holes of the disc. The carrier gas stream picks up the particles on top of the dosing unit. The whole dosing unit is placed into a separate pressure vessel to enable changing the probe without depressurizing the big pressure vessel with the reaction zone.

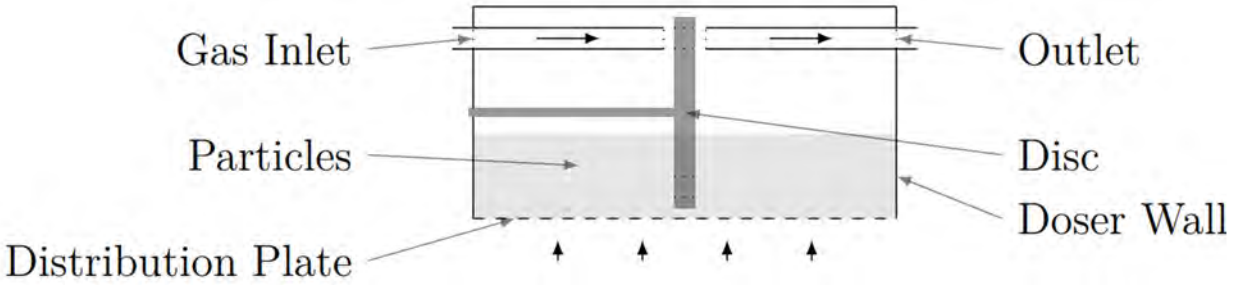

Figure 3. Revolver doser design.[9]

Offgas Treatment

The quench at the end of the reaction zone is water-cooled, and nitrogen is injected at its beginning. The cooling of gas and particles and dilution with nitrogen leads to an immediate stop of the reaction. As a result, the conversion process of the particles is limited to the ceramic tube. The quench is 1 m long and has an inner diameter of 20 mm.

The gas enters a cyclone to separate the remaining particles till 1 µm from the offgas after the quench. The particles can be extracted from the cyclone via valves during the reactor operation. A filter behind the cyclone removes the remaining particles before the offgas passes an orifice to determine the volume flow. The sampling point for the gas analytics is located after the pressure retention valve.

Gas and Residual Analytics

An online gas analyzer monitors the CO, CO_2, and O_2 concentrations in the offgas. As soon as the reactor reaches the desired steady-state operation point, a gas chromatograph analyses the offgas and gives more detailed information about the exhaust gas composition.The offgas temperature can vary significantly depending on the exact experimental conditions. Operating the reactor at low temperatures or gas flows, might lead to condensation in the offgas stream. Thus, the offgas' composition might alter through selective absorption of some components in the condensate. Therefore, additional isolation or heating might have to be applied to the offgas stream.

Burnout, structure, and composition of the solid residues will be analyzed and compared to the virgin coal sample. This comparison will reveal additional information about the conversion behavior of the ARAs.

EXPERIMENTAL CONDITIONS

The reactor is designed to enable gas residence times of about 100 ms at 800 kPa, while assuming plug flow in the reaction zone. Prior CFD studies of the reactor suggest, that the particle residence time is underestimated by about 50% through neglecting vortices and other flow phenomena[11]. Without further investigation and CFD studies, the residence time cannot be exactly determined. The gas heater enables co-flow rates of up to 100 Nm^3/h. Lowering the operational pressure allows higher operational volume flows and shorter residence times to recreate the blast furnace conditions more accurately. At 500 kPa and 1600°C at the end of the reaction zone, the gas residence time can be reduced to approximately 50 ms.

The co-flow can consist of pure nitrogen or air and arbitrary mixtures of these components. Moreover, up to 60 Nm^3/h carbon dioxide can be added the co-flow stream.

According to the CFD study, the hydrogen burner provides heating rates up to 10^5 K/s and a maximum particle temperature of about 1800 °C. Table 2 compares the conditions of the raceway zone and the test rig.

Table 2. Comparison of Raceway Conditions to Operation Conditions of the New Test Rig

	Temperature	**Heating rate**	**Pressure**	**Gas velocity**	**Particle velocity**	**Residence time**	**O_2 content**
raceway	1200 – 2300 °C	10^4 – 10^5 K/s	200 – 500 kPa	200 m/s	20 m/s	20 – 100 ms	~ 27 vol%
Test rig	< 1800 °C	10^4 – 10^5 K/s	100 – 800 kPa	4 – 30 m/s	1 – 2 m/s	~50 – 200 ms	< 25 vol%

The test rig's temperature is limited by the maximal operational temperature of the electrical heating and the maximal service temperature of the burner's ceramic lining. Although the maximum temperatures in the raceway zone are higher than in the test rig, the co-flow temperature provided by the flow heater closely matches the hot blast temperature in the blast furnace of 1100 – 1200 °C. In combination with the radiative heat fluxes from the burner and ceramic tube, the particles experience similar conditions when entering the reaction zone in both applications. The high heating rate and elevated pressure can be recreated precisely by the new test rig.

The absolute gas and particle velocities are lower in the test rig than in the blast furnace, due to the smaller scale. The small coal particles will closely follow the gas flow because the Stokes Number is << 1. Therefore, the difference between the absolute velocities can be neglected for extracting kinetic parameters.

The various values for the particle residence time in the raceway zone have been reported in literature.[4,5,7] The estimates range from 20 – 30 ms for the whole raceway to over 100 ms derived from CFD studies. The test rig focus on smaller particles, which tend to stay longer in the raceway zone.

The experimental particle mass flux is around 2 g/min, but the design of the dosing unit allows a wide particle mass flux range. However, the particle velocity in the burner lance is limited by the minimum volume flows required for fluidization and pneumatic transport. Calibration experiments for the dosing unit suggest a gas and particle velocity of about 1 – 2 m/s at the entrance in the reaction zone.

During the reactor commissioning phase, first tests of the heating elements and the flow heater were conducted. The ceramic tube and co-flow were heated to approximately 1100 °C., The thermocouple at the end of the reaction zone to supervise the gas temperature measured a maximum gas temperature of 950 °C. The discrepancy between the gas and surface temperatures is pretty sure caused by radiation losses towards the quench. The radiation losses need to be compensated to obtain the correct gas temperatures.

CONCLUSIONS AND OUTLOOK

The data from the start-up of the test rig will be further compared with the results of CFD studies to gain a more thorough understanding of the reaction conditions inside the ceramic tube. As next step, the burner will be tested and the influence on the gas temperature investigated. After successfully commissioning the burner, the first experiments at ambient and elevated pressure will be carried out.

For the evaluation of the first experimental results a simple first order extraction algorithm[11], supported by the insights of the CFD study, will be used. Additionally, the surface structure of the particle before and after the experiment will be investigated. A large spectrum of ARAs will be investigated at high temperatures, high heating rates, elevated pressure, and different gas atmospheres.

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