A novel two-bed reactor for a chemical looping combustion system with a moving bed

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Abstract:
This work presents a novel concept of reactor design in CLC technology. This is the second concept in a series of patents on the construction of air and fuel reactors. The first patent ”The combustion chamber design of a duo-fluidized bed reactor with circulating solid oxygen carriers of the CLOU type” was presented at the 6th International Conference on Chemical Looping in Zaragoza, Spain in September 2022.
The purpose of the presented solution according to the invention was to develop a simple reactor structure for the optimization of the chemical looping combustion process. According to the invention, the presented reactor dedicated to solid fuels combustion in the CLC system has two chambers of identical conical-cylindrical shapes, which are symmetrically and permanently attached with their upper conical parts to rotatably fixed transport pipes located on a common axis.
The simple and compact design of the reactor makes it economic & easy to manufacture and takes up significantly less space than a classical unit designed for the chemical looping combustion process. The proposed design enables uncomplicated process control due to fewer auxiliary devices as compared to the previous designs used for process control. Moreover, the reactor according to the invention has a lower energy expenditure because it uses lower gas velocities for effective operation than in a traditional CLC unit.

Keywords:
Chemical looping combustion, fuel reactor, oxygen carrier, moving bed.

1. Introduction

The currently visible climate changes encourage the reduction of pollutant emissions and the search for low-emission combustion technologies. There are many ways to mitigate climate change, but two are the most common. The first method includes all means that reduce CO_2 emissions into the atmosphere while increasing energy efficiency or using zero or low-carbon fuel sources. Another, also effective method is the use of negative emissions (NET) to reduce carbon dioxide from the atmosphere using sequestration techniques [1]. Commonly known and used CO_2 capture methods are: pre-combustion, oxy-fuel combustion, and post-combustion separation [2]. Another method of reducing carbon dioxide emissions into the atmosphere is oxy-fuel combustion. In this method, the combustion process takes place in a mixture of oxygen and CO_2 [3].

All of the above methods are effective, but at the same time energy-intensive, resulting in a significant decrease in overall combustion efficiency and consequently leading to higher energy prices [4].

1.1. CLC technology a brief characteristics

The Chemical Looping Combustion (CLC) technology is one of the methods of reducing CO_2 emissions. In the combustion process, fossil fuels release pollutants responsible for the greenhouse effect into the

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atmosphere. Fossil fuels are estimated to be responsible for as much as one-third of global CO_2 emissions [5–7]. This undoubtedly has a significant impact on climate change. CLC allows to obtain a high concentration of CO_2 in flue gases, therefore it eliminates the need to use Carbon Capture and Storage (CCS) methods. This type of combustion can be classified under the category of oxy-combustion techniques, it has the advantage of producing nitrogen-free flue gases from the combustion air. It is an environmentally friendly method that reduces costs and time while reducing CO_2 emissions into the atmosphere [8–10].

A typical CLC unit consists of two separate reactors: an air reactor and a fuel reactor, which form two separate circulation contours (Figure. 1). In the literature, a system for chemical looping combustion of fuels is known, which was designed by Chalmers University of Technology (Sweden). A conventional unit consists of fuel and air reactors, a cyclone and two loop seals connecting the reactors. Each of the reactors has a different structure and dynamics of the fluidized bed, characteristic for a given chamber: a circulating fluidized bed in an air reactor and a bubble fluidized bed in a fuel reactor. The reactors are located parallel to each other, and the entire unit has a stationary structure [9,11].

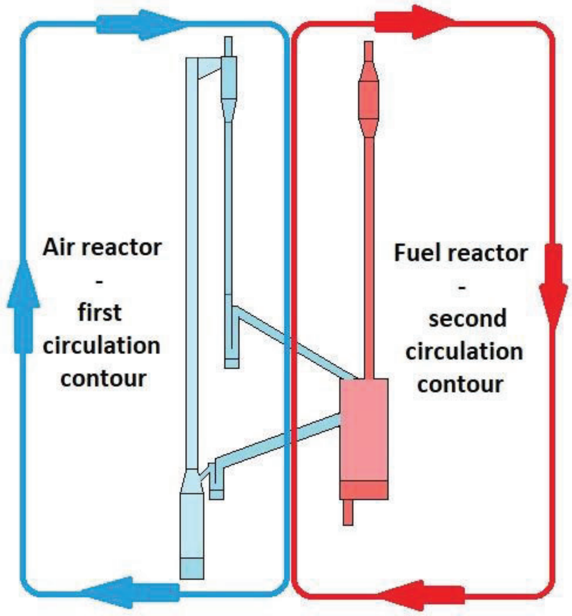

Figure. 1. Typical scheme of a CLC unit divided into circulation contours.

CLC technology applies solid oxygen carriers in the fuel combustion process, which are metals or metal oxides that carry oxygen between the air reactor and fuel reactor. Oxygen carriers play a vital role in the overall process because their oxygen-carrying capacity eliminates direct contact between air and fuel [12].

The selection of the appropriate oxygen carrier is a very important issue in the design of CLC combustion, as its properties affect the entire process. Therefore, the oxygen carrier should be: environmentally friendly, economically viable, resistant to abrasion and agglomeration. Additionally, the oxygen carrier should be characterized by the following features: high oxygen carrying capacity, reactivity, both during the oxidation and reduction stages, high melting point, ease of fluidization and mechanical resistance [13–16].

1.2. CLC pilot facilities

One of the largest pilot CLC installations with a capacity of 1MW is located at Darmstadt University of Technology. The air reactor and fuel reactor are designed as two separate circulating fluidized bed reactors. The inner diameter of the fuel reactor is 0.40 m, while the air reactor is 0.59 m. The height of the fuel reactor structure is 11.35 m, while that of the air reactor is 8.66 m. In addition, the entire system has been covered with insulating material to minimize heat losses. The use of insulation of the entire system is crucial because the reactors are not additionally heated with electric heaters. Tests studies were carried out on the pilot plant in Darmstadt using coal as fuel and Fe, Cu, Mn and ilmenite as oxygen carriers [17–19].

Another example is CLC pilot plant which is located at the Vienna University of Technology. The 120 kW test stand is dedicated to burn gaseous fuels [20]. The structure of the fuel reactor is designed to operate in a turbulent fluidization regime. This ensures better mixing of the gaseous fuel with the oxygen carriers in the

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fluidized bed. In studies conducted on this pilot unit used nickel and ilmenite as oxygen carriers, while the fuel was natural gas and a gas mixture of CH_4, CO, H_2 and C_3H_8 [8,20,21].

Another well-known CLC pilot unit is located at Chalmers University in Sweden. The designed 100 kW system is dedicated to burn solid fuels. The pilot plant was developed as part of the European ÉCLAIR project coordinated by the ALSTOM concern. Tests were conducted using hard coal and ilmenite as oxygen carriers. During the test studies, a temperature of 1000°C was maintained in the fuel reactor and 970°C in the air reactor. A good CO_2 capture rate of 98 – 99% was achieved [17].

There are two CLC units in Poland. The first one is located at the Institute for Chemical Processing of Coal in Zabrze (IChPW). The second one is located at the Czestochowa University of Technology. The CLC unit located in the IChPW is dedicated for the combustion of gaseous fuels. The following gases are supplied to the installation: nitrogen, methane and process gases. The CLC plant operates at atmospheric pressure, at temperatures 800°C - 1000°C. The maximum feed rates for fuel, air and oxygen carrier are 1 m^3/h, 15 m^3/h and 40 kg/h, respectively. The height of fluidized bed reactors are 1 m high and 0.133 m in diameter [16].

The second unit for Chemical looping combustion of solid fuels is located at the Institute of Advanced Energy Technologies, Czestochowa University of Technology [5].

The CLC system for solid fuels consists of two main circulating contours [11]:

(1) an air reactor with a circulating fluidized bed, an ascending section and a return system comprising a cyclone and a precipitation section,

(2) a bubbling fluidized bed fuel reactor and a particulate collector.

The air reactor is constructed as a cylinder, which transitions into a cone at the top. In contrast, building a fuel reactor is more complex (Figure 2), as the structure is a cuboid with incomplete internal baffles. These baffles are designed to improve mixing processes and increase the residence time of the gas and material grains. The CLC stand is equipped with electric heaters with a total output of 72 kW. The heating system is located at full height on both sides of the stand [5,11,22,23].

a) b)

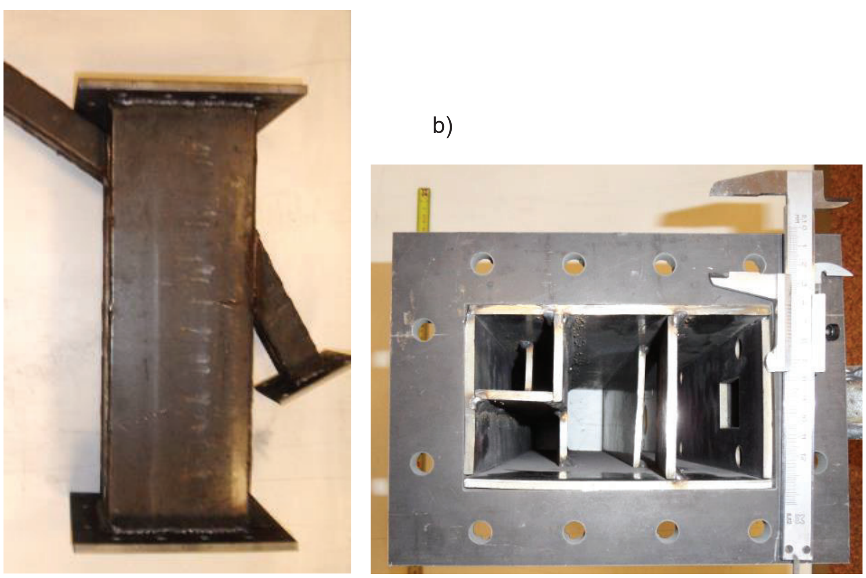

Figure. 2. Photo of the fuel reactor: a) side view; b) cross-section of the fuel reactor.

1.3. Motivation and scope of research

The proposed idea concerns the new design of the fuel reactor with a moving bed and is dedicated to solid fuels. It can be used in power plants and research laboratories. This reactor design allows for the implementation of subsequent processes of solid fuel combustion and regeneration of the oxygen carrier. In addition, this reactor design increases the efficiency of the system.

The reactor for solid fuels in a chemical looping combustion system, according to the invention has chambers of identical conical-cylindrical shapes, which are symmetrically and permanently fixed with their upper, conical parts to rotatably fixed transport pipes located on a common axis. In the channel narrowing between the conical parts of the chambers there is a material flow control valve, and in the conical part of the air chamber there are air supply nozzles. In the conical part of the combustion chamber there are gas

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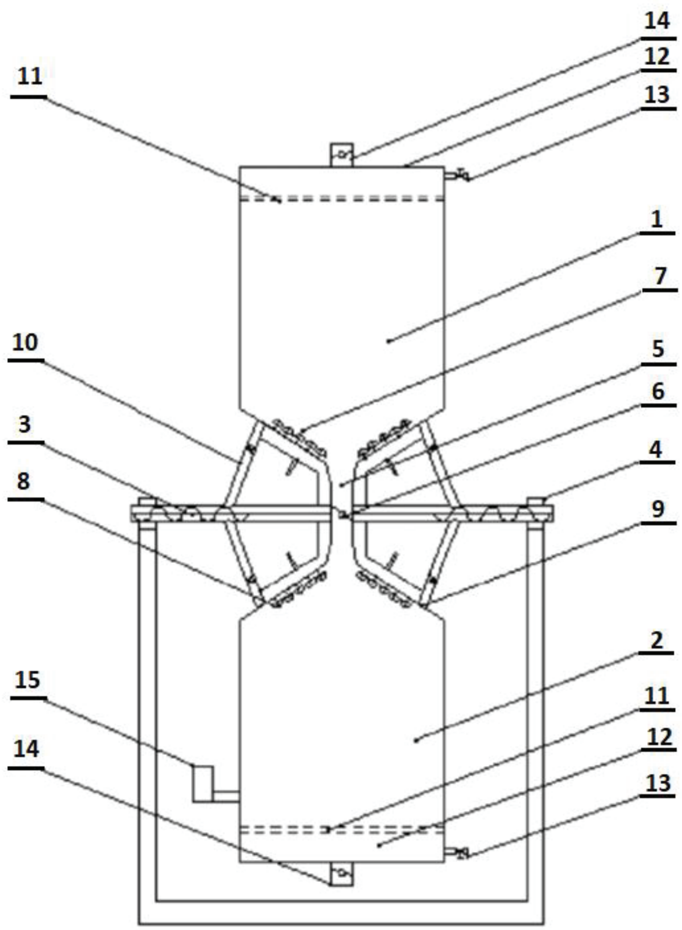
nozzles, while the outlets of the chute channels are located in both chambers in their conical parts from the side of the cylindrical parts.

2. Results and discussion

2.1. Two-bed reactor design

A novel two-bed reactor for a chemical looping combustion system with a moving bed is presented in this paper. The invention is the subject of patent No. PL 234783 (Czakiert et al., 2017). The novel fuel reactor is designed to ensure the more efficient performance of the CLC process in general. The idea of the construction is shown in Figure 3, and the details are provided below [24].



1 – air chamber
2 – combustion chamber
3 – transport pipes
4 – the supports of the frame structure
5 – channelled constriction
6 – control valve
7 – air nozzles
8 – gas nozzles
9 – outlets
10 – ash chute channels
11 – grate
12 – air box
13 – gas inlet port
14 – gas outlet stack
15 – fuel feeder

Figure. 3. Schematic of two-bed reactor for a chemical looping combustion system with a moving bed.

The chemical looping combustion reactor for solid fuels has two chambers (1) and (2) of identical conical-cylindrical shapes, with one chamber being air chamber (1) and the other combustion chamber (2).

Chambers (1) and (2) are symmetrically and permanently fixed with their upper conical parts to pivotally fixed transport tubes 3, for removing ash from the reactor, situated on a common axis. The transport tubes (3) are connected by bearings to the supports of the frame structure (4). The mobile connection of transport pipes (3) ensures that the entire reactor can rotate around the horizontal axis. Between the conical parts of chambers (1) and (2), which are connected to each other, there is a channelled constriction (5) in which a control valve (6) for the flow of material during the combustion process is fitted. In the conical part of the air chamber (1), nozzles (7) are fixed to supply air to the inside of the air chamber (1) and in the conical part of the combustion chamber (2) there are gas nozzles (8). Gas nozzles (8) in the combustion chamber allow air to be supplied when combustion chamber (2) is above air chamber (1), while, after the rotation of chambers (1) and (2), when combustion chamber (2) is below air chamber (1), gas nozzles (8) allow exhaust gases to exit combustion chamber (2). Both chambers (1) and (2) are equipped with outlets (9) of chute channels of ash (10) connected to transport pipes (3). The outlets (9) of chute channels (10) in chambers (1) and (2) are located in their conical parts on the side of the cylindrical parts. The positioning of the outlets (9) of the ash chute channels (10) close to the vertical walls of the cylindrical section allows efficient ash removal during reactor operation.

In the lower cylindrical part in each chamber (1) and (2), above the bottom, there is a grate (11) with an air box (12) equipped with a gas inlet port (13) and a gas outlet stack (14). Above the grate (11) in combustion chamber (2) there is a fuel feeder (15).

The reactor according to the invention, shown in Figure 3, allows pendulum movements during which, in an alternating cycle, once the air chamber (1) and once the combustion chamber (2) are in the upper position, while the other chamber is in its lower position. Depending on the position of chambers (1) and (2) in relation to each other, their functions change. The chamber in the lower position becomes combustion chamber (2), while the chamber at the top of the reactor becomes air chamber (1).

When the upper air chamber (1) of the reactor is emptied, chambers (1) and (2) rotate 180 degrees around the horizontal axis - the transport pipe (3). The lower chamber (2), which acted as the combustion chamber (2) and was fluidized with an inert gas in the form of carbon dioxide, henceforth becomes air chamber (1) and is fluidized with air. A channelled constriction (5) connecting chambers (1) and (2) equipped with a control valve (6) allows the flow of material between chambers (1) and (2). The gas in the lower chamber of the reactor constituting combustion chamber (2) is fed through a gas inlet port (13) via an air box (12) and grate (11), while in the upper chamber of the reactor constituting air chamber (2) it is fed through nozzles (7). Gas is discharged from air chamber (1) through a gas outlet stack (14) and from combustion chamber (2) through gas nozzles (8).

The solution according to the invention allows for the implementation of subsequent processes of solid fuel combustion and regeneration of the oxygen carrier.

To summarise the novel design concept of the CLC unit, the innovative reactor is characterised by:

1. The fuel and air reactors are made in the form of identical cylindrical-conical chambers connected by a flow channel.
2. The flow channel connecting the tops of the reactors is equipped with a valve to regulate the flow of material between the reactors.
3. The rigidly connected reactors, after emptying the upper chamber, perform a pendulum motion - a rotation of 180 degrees around the horizontal axis.
4. Nozzles are used in the reactors, which in the air reactor supply air to the chamber, while in the fuel reactor they are used to exhaust the flue gases.

The fuel combustion reactor design is simple and compact, so it is cheap to produce and takes up much less space than a classical unit designed for a chemical looping combustion process. The developed design allows for easier process control due to the smaller number of auxiliary devices previously used to control the process. In addition, the reactor according to the invention is characterised by lower energy expenditure because lower gas velocities are used in the reactor than in a traditional CLC unit to lift the fluidised layer. In addition, the reactor during operation is characterised by a lower consumption of the media and gases necessary for the fluidisation process needed for the chemical looping combustion process. The advantages mentioned above will affect the faster dissemination of ecological CLC technology in various industrial applications.

3. Conclusions

The CLC concept generally offers a highly concentrated CO_2 stream at the outlet of the power unit without any additional energy-consuming systems for gas separation (oxygen fractionations from atmospheric air or carbon dioxide capture from conventional flue gases), which makes this technology competitive with other

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pro-CCSU (Carbon Capture, Storage and Utilization) technologies. However, the presented novel fluidized-bed fuel reactor, which is tailored to the use of solid oxygen carriers and the utilization of solid fuels, provides further reduction of operating costs with even higher inherent CO_2 capture efficiency.

The new fuel reactor concept was designed for solid oxygen carriers. Solid fuels, such as coal, and biomass, can be used as fuel. The proposed idea is characterised by an innovative reactor design that makes it economic and easy to manufacture. In addition, such a design takes up significantly less space than a classical unit designed for the chemical looping combustion process. These are undoubtedly the most significant advantages of the presented idea. As a result, the new fuel reactor concept ensures more efficient operation of the CLC processes.

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