Chemical-looping: the answer to the cost and energy penalties of CCS?

With the first generation of CO2 capture now being well established, and with the pressure to decarbonize the economy building up, the time may have come to look for the 2nd generation of CO2 capture.

By Professor Anders Lyngfelt, Chalmers University of Technology, Sweden

The key obstacle for CCS is well known; the large cost and energy penalty of CO2 capture. For every tonne of fuel burned, infinitely small CO2 molecules must be removed from 10,000 cubic meter, or 350,000 cubic feet, of flue gas. This is not even in theory possible without energy and equipment for capture.

However, there is a way around this problem. In normal combustion you mix air and fuel, and therefore your combustion products inevitably become diluted in nitrogen, the major constituent of air. But, if you could transfer the oxygen needed for the combustion from the air to the fuel without mixing air and fuel, the problem would be solved. And this is exactly what Chemical-Looping Combustion (CLC) does.

CLC is a novel principle of combustion, where the combustion air is kept separate from the fuel. Instead, the oxygen is transferred from air to fuel by means of the oxygen carrier, i.e. metal oxide particles which circulate between two fluidized beds, the air reactor and the fuel reactor, Fig. 1. The gas leaving the fuel reactor is ideally pure CO2 and H2O, the latter easily removed by condensation.

A key question is of course if this process really works in practice, but more than 11,000 h of operation in 45 pilots with more than 100 different oxygen carrier materials gives a clear answer.[1] In particular the results for solid fuels, including more than 3000 h of operation in more than 20 pilots, are important because of the potentially very low costs for CO2 capture.

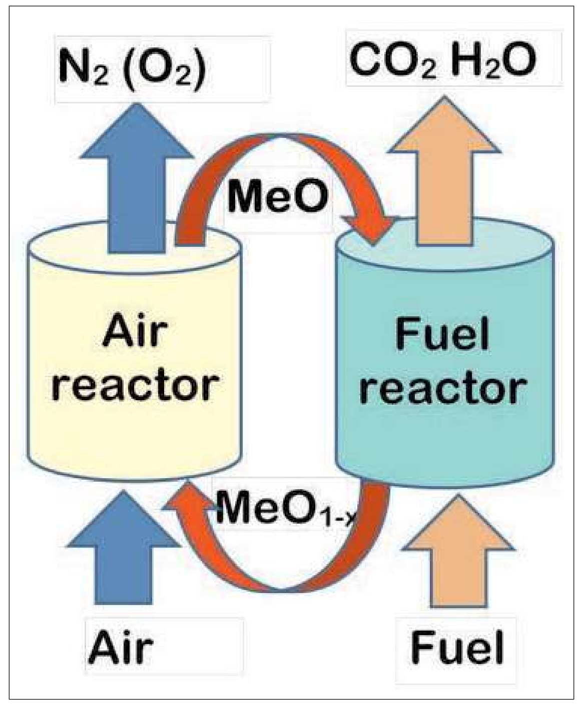

Figure 1. CLC principle. MeO is the metal oxide circulated

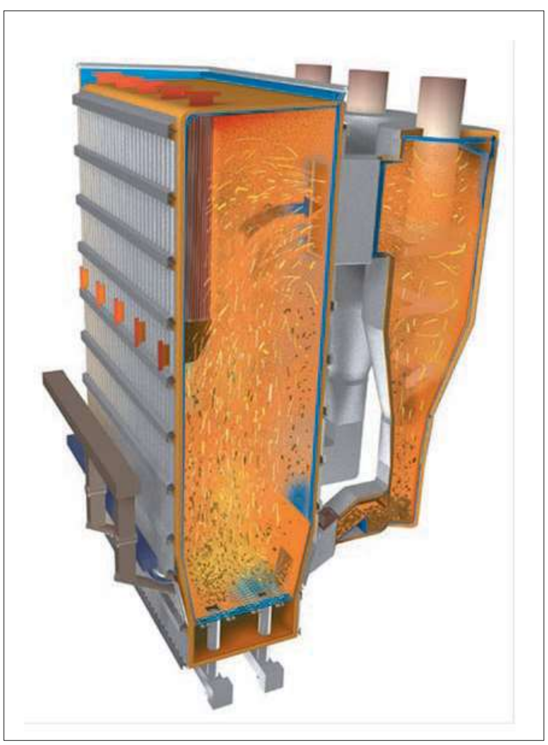

Figure 2. Circulating fluidized-bed boiler

The reactor system used involves two interconnected fluidised beds, a fuel reactor where the fuel reacts with the oxygen-carrier to form CO2 and steam, and an air reactor where the oxygen carrier is regenerated. The oxygen carrier is used as bed material. After condensation of the steam a flow of essentially pure CO2 is obtained – without any active gas separation.

The CLC process has important similarities to combustion of solid fuels in Circulating Fluidized Bed (CFB) boilers, cf. Figs. 2 and 3.

Thus, CFB combustion is an integral part of the state of art for CLC. A techno-economical comparison between a 1000 MWth CFB boiler and a 1000 MWth CLC boiler highlights important differences and similarities.

The two boilers are outlined in Fig. 4. The most important differences and similarities are:

i) The horizontal cross-section area is similar, because of similar gas flows and gas velocities.

ii) In the case of CLC the combustion chamber is divided in three parts, with one fuel reactor in the middle surrounded by two air reactors.

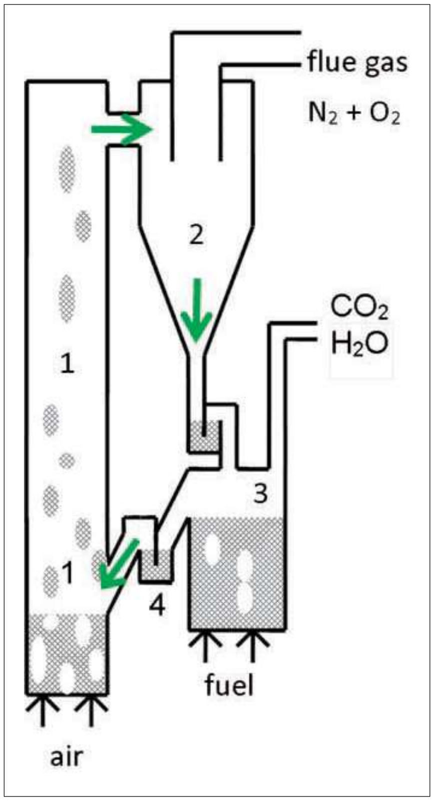

Figure 3. CLC reactor system for gas, 1) air reactor, 2) cyclone, 3) fuel reactor 4) loop seals

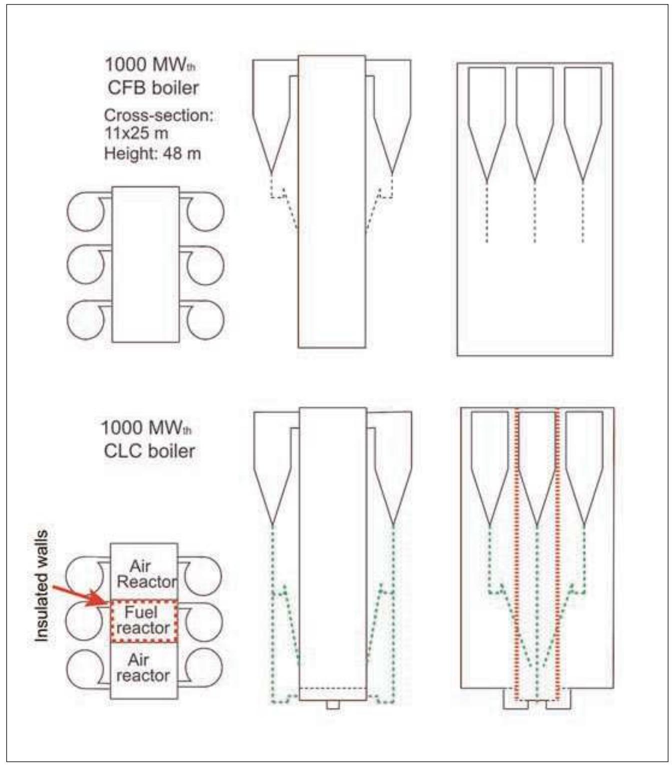

Figure 4. Top: layout of 1000 MWth FBC boiler, Bottom: Layout of 1000 MWth CLC boiler

iii) Because no heat is generated in the fuel reactor, it is adiabatic, i.e. not cooled. iv) There are ducts for transferring material from air reactor cyclones, to fuel reactor, as well as a fluidized connection below the reactors for returning the material.

The important cost of a boiler is related to the large heat-transfer surfaces needed to take the combustion heat to the steam generated. Because CLC operates at higher temperatures, this area is expected to decrease. However, the adiabatic fuel reactor will give added costs for insulated walls that are not used for steam generation.

Based on the cost of insulated boiler wall, 1500 €/m2, and the total wall needed, 2500 m2, the added investment cost of the fuel reactor should be around 4 M€. If this corresponds to a yearly cost of 0.4 M€, and 2 million ton CO2 is captured yearly the corresponding CO2 capture cost is only 0.2 €/ton.[2]

The major added costs of CLC are not associated with the boiler. The largest cost is CO2 compression, around 10 €/ton, which is inevitable and common to all CO2 capture technologies. The second largest cost, 4-9 €/ton, is air separation for production of oxygen. This assumes a gas conversion of 85-95% meaning that the need for oxygen is in the range 5-15% of that of oxyfuel CO2 capture. Other added costs are related to oxygen carrier, steam fluidization of fuel reactor and fuel grinding. The total cost of CO2 capture for CLC with coal is estimated to be 20 €/tonne CO2 and within the range of 16-26 €/tonne.[2]

Operation with coal in a 100 kW pilot clearly demonstrates that the process works well, although a full conversion of the gas is not attained leading to the need of adding oxygen to the exhaust stream.

Pilot experiences indicate that gas conversion typically ranges from 75-95% depending on fuel and operating conditions. This is when using low-cost oxygen-carrier materials such as natural ores.

Further, pilot operation shows that essentially complete CO2 capture, >99, can be reached. However, the pilot operation shows a loss of unburned fuel char, corresponding to 10% of total carbon. Significant improvement of this number is expected in the full scale, where a 10 times higher riser and an efficient cyclone will add important residence time for char conversion.

In addition to a radical reduction of CO2 capture cost, CLC also has potential to eliminate SO2 and NOx emissions, as these are concentrated in the small CO2 stream and may addressed there at reduced cost. A critical feature is also the potential of 100% CO2 capture – in a world now starting to aim for carbon neutrality, is 90% CO2 capture enough?

So why is not everyone building CLC boilers? Today, no-one is prepared to take the cost and risk of scaling up this technology, when there is known and proven technology available, albeit at high cost and energy penalty. But this should change when the CO2 capture market takes off.

References

1. Lyngfelt, A.; Brink, A.; Langørgen, Ø.; Mattisson, T.; Rydén, M.; Linderholm, C., 11,000 h of Chemical-Looping Combustion Operation – Where Are We and Where Do We Want to Go? International Journal of Greenhouse Gas Control 2019, 88, 38-56.

2. Lyngfelt, A.; Leckner, B., A 1000 MWth Boiler for Chemical-Looping Combustion of Solid Fuels – Discussion of Design and Costs. Applied Energy 2015, 157, 475-487.

More information

Anders Lyngfelt, Dept. of Space, Earth and Environment, Chalmers University of Technology

www.entek.chalmers.se/lyngfelt