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Building the world's largest Chemical Looping Combustion (CLC) unit

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ABSTRACT

The world's largest Chemical Looping Combustion (CLC) demonstration unit is being built close to the city of Chengdu in China. The design and construction of the unit, as well as the coming testing, is done within the CHEERS project, which is a collaborative project between Europe and China. The funding (~25M€) comes from several of the project partners, in addition to EU's Horizon2020 and China's Ministry of Science and Technology (MOST). TotalEnergies has been responsible for the Front-End Engineering Design (FEED) study. The investment decision from December 2021 marks the transition from the R&D studies and design phases to Engineering, Procurement, Construction (EPC) and testing phase. The EPC phase has been led by Dongfang Boiler Co.,Ltd, and the demonstration unit is located at their technology development site in Deyang City, outside Chengdu in China. It is designed for a thermal input of 2–4 MW and includes two different reactor configurations. The first configuration is optimized for conversion of pet-coke, while the second one is tuned towards conversion of lignite. The oxygen carrier (OC) that will be used for the demonstration unit (ilmenite) will be presented, together with an overview of the various OC materials that were tested at various scales (up to 150 kWth) during the first part of the project. In addition, results from testing of a cold mock-up of the unit is presented. Finally, an overview of plans for the rest of the project is given, together with some thoughts related to intercontinental collaboration in highly collaborative projects, such as CHEERS.

1. Introduction

The average concentration of CO_2 in the atmosphere reached the symbolic milestone of 400 ppm in 2015, with current (Dec. 2022) levels standing at 419 ppm. It was at the UN Climate Change Conference (21st yearly Conference Of the Parties) COP21 in 2015 that 196 participating nations consented to make further efforts to limit global warming to 1.5 °C above pre-industrial levels (United Nations Framework Convention on Climate Change 2015). A large share of the necessary global reductions of CO_2 emissions until 2050 are attributed to Carbon Capture and Storage (CCS). The Net-Zero Emissions scenario from the International Energy Agency (IEA) estimates a total CO_2 capture of 7.6 $GtCO_2$ per year by 2050 to be net zero (IEA 2021), whereas the International Panel on Climate Change (IPCC) analyzed many scenarios, showing CO_2 capture by 2050 in the range 5.5 – 18.5 $GtCO_2$ per year (IPCC 2018). In this respect, CCS is seen as a key component and a precondition for low-carbon economies to evolve. Particularly in the energy intensive industries, which have significant process emissions, CCS is the only viable solution for decarbonization. In some areas, where societies are dependent on energy-intensive industry, CCS may also be seen as a matter of survival.

In any case, research to date has shown that while CCS is seen as the

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most capable CO_2 abatement technology at scale, CO_2 capture techniques need further refinement and higher efficiencies. In addition, CO_2 capture needs to be made affordable for a wider adoption. This can be achieved by envisaging and demonstrating the efficacy of CO_2 capture in energy intensive industries, including refineries.

Within this context of mitigating climate change and pursuing the development of CCS in industry, the purpose of the Chinese-European Emission Reducing (CHEERS) project is to reveal emerging opportunities for Chemical Looping Combustion (CLC), as a viable and efficient CO_2 capture technique (see http://cheers-clc.eu/ for more information). It is also to provide for wider deployment of CLC in energy intensive industry, initially via steam generation for auxiliary systems in petroleum refineries in Europe and China.

The CHEERS project will push the technological frontiers beyond the state-of-the-art. With a joint venture between the European and Chinese partners, the CHEERS project offers considerable synergy in terms of dedication, proficiency, and monetary resources. Combined with lower cost and shared public and private co-funding, it allows for a sizeable and comprehensive demonstration to speed up progression with a major impact. Pursuant to this strategy, CHEERS will play a decisive role in accelerated development of CCS for the industry in Europe, in China and globally.

The project has a total of nine partners, of which six are from Europe (SINTEF Energy Research – being the coordinator, SINTEF AS, TotalEnergies, IFP Energies nouvelles, Bellona and Silesian University of Technology) and three are from China (Tsinghua University – being the coordinator of the Chinese part of the project, Dongfang Boiler Co.,Ltd and Zhejiang University). In addition, EU Horizon2020 and the Ministry of Science and Technology in China are involved as funders.

Despite the need to prove the technology at larger scale, only a very limited number of sizable demonstration units for CLC exists today. Already 10 years ago, Alstom tested a 3MW CLC unit in Connecticut, USA (Iqbal et al., 2012; Abdulally et al., 2014), but there has not been more information coming out of this unit for some years now. At the university of Darmstadt, a 1 MW CLC unit (Ströhle et al., 2014) is in regular operation through various research projects. Recently, the unit at Darmstadt was also re-designed for chemical looping gasification (CLG) at 1 MW (Marx et al., 2021). Furthermore, there are currently also two demonstration units of 3 MW under construction elsewhere in the world: the K-CLC project in Ulsan, South Korea (Baek et al., 2022) and the 3 MW CLG unit of Ningxia University, China (Zhao et al., 2020).

The main goal of the CHEERS project is to show that the CLC technology can be scaled up towards industrial scales, even for very difficult solid fuels – such as petcoke. This is done by designing and building the world's largest CLC unit, but we have also made sure that the unit has been designed in a manner such that the FEED can be used directly for the first commercial plant (30–50MW). The most important technical goal is to achieve a carbon capture rate of 96 %.

2. Technology

2.1. Cold flow mock-up

For a CLC reactor system, the solid circulation is very important and affects the mass and heat balance and autothermal operation of the system. It is therefore key to be able to control the solid circulation. A cold flow mock-up equivalent to a 1.5 MW_{th} CLC unit, corresponding to the preliminary reactor design of the full demonstration unit, but at half the power, was therefore constructed and tested, see Fig. 1.

The air reactor consists of a 10 m high riser with a square cross section of 0.25×0.25 m, while the dense section of the fuel reactor is 2.5 m high and has a cross section of 0.6 × 0.6 m. The riser from the dense part of the fuel reactor to the carbon stripper is 3.4 m.

The raw data were analyzed to provide detailed quantitative information of fuel reactor hydrodynamics, solid circulation control between air reactor and fuel reactor, transport of oxygen carrier in air reactor riser and carbon stripper efficiency. The cold flow mock-up is also used to train the operators and provide valuable insights for the design, construction, and operation of the final CHEERS demonstration unit. Important features related to commissioning and operation were also provided. See Chen et al. (Chen et al., 2021b; Li et al., 2022; Chen et al., 2020) for more details of the cold flow experiments.

2.2. Reactor design of the 3 MW unit

The CLC demonstration unit has been constructed at the test site of Dongfang Boiler Co.,Ltd in the city of Deyang, outside Chengdu in China. The original plan for the CHEERS project was to retrofit a circulating fluidized bed (CFB) that already existed on the site as the air reactor of the CLC unit. During the pre-FEED (Front-End Engineering Design), it was realized, however, that the retrofit approach would be both more complex and costly than going for a grassroots approach. For example, the heat exchangers of the existing CFB were not consistent with a thermal power of 3 MW, and the steel structure supporting the CFB was not strong enough to hold the added weight required for the modifications to make it a CLC unit. For the FEED-phase, which was carried out by the engineering company WORLEY, the approach was therefore changed to grassroots.

Since this demonstration unit is a first of a kind, the process design was rather challenging due to lack of references. However, some important lessons could be learned from existing knowledge of FCC (fluid catalytic cracking) and CFBs. Also, since this is a demonstration unit, significantly larger flexibility is required than for a commercial plant. This goes for both plant capacity (2–4 MW), fuel and oxygen carriers. On top of this comes the large number of ports for various sensors, which for example increases the heat loss of the unit, reducing the limit to achieve auto-thermal operation. Regarding the variable feedstocks, it was decided to develop two different reactor configurations, one for pet-coke and the other one for lignite. The two configurations share most components, with the carbon stripper and the dividing fluidized bed (DFB) being the most noticeable exceptions. For the test campaign, the pet-coke configuration will be tested first, before adjustments to the internal reactor piping will be made to convert it into the lignite configuration, which will then be tested. Since the demonstration unit is prepared for both configurations, it will be relatively easy to convert it to the lignite configuration after the testing of the pet-coke configuration has been finalized.

A simplified schematic overview of the reactor system design is shown in Fig. 2, with the pet-coke configuration to the left and the lignite configuration to the right. The fuel reactor has a height of 7.1 m and an internal diameter of 1.51 m. A riser section is leading from the fuel reactor up to the carbon stripper on the top. In the lignite configuration, this is not used as a carbon stripper, and the relatively small amount of particles being entrained up from the fuel reactor are recycled back to the fuel reactor. The total height of the fuel reactor with riser section and carbon stripper is 23.1 m. The air reactor has a height of 32 m and an internal diameter of 0.73 m. It is designed for rather high superficial velocities, in the range 5 – 10 m/s, and operates in the riser mode of fluidization.

In a CLC system, there are two requirements for the circulation rate of oxygen carriers: to satisfy the heat balance and the oxygen required for fuel conversion. For the CHEERS demonstration unit, the circulation rate required for the heat balance is much larger than that for fuel conversion. In this case, the difference in oxidation level between the AR and the FR is small, such that only a small amount of the oxygen carrier capacity is utilized and most of the oxygen carrier is just used as a heat carrier to provide the sensible heat required by the fuel reactor. In general, it can be noted that the higher the solid circulation rate the better the combustion efficiency and the OC lifetime. However, for commercial units, high solid circulation rate is costly as it will increase the size of equipment to circulate the solid and the air flow rate needed in the AR to entrain the solid (impact on air compressor power and then

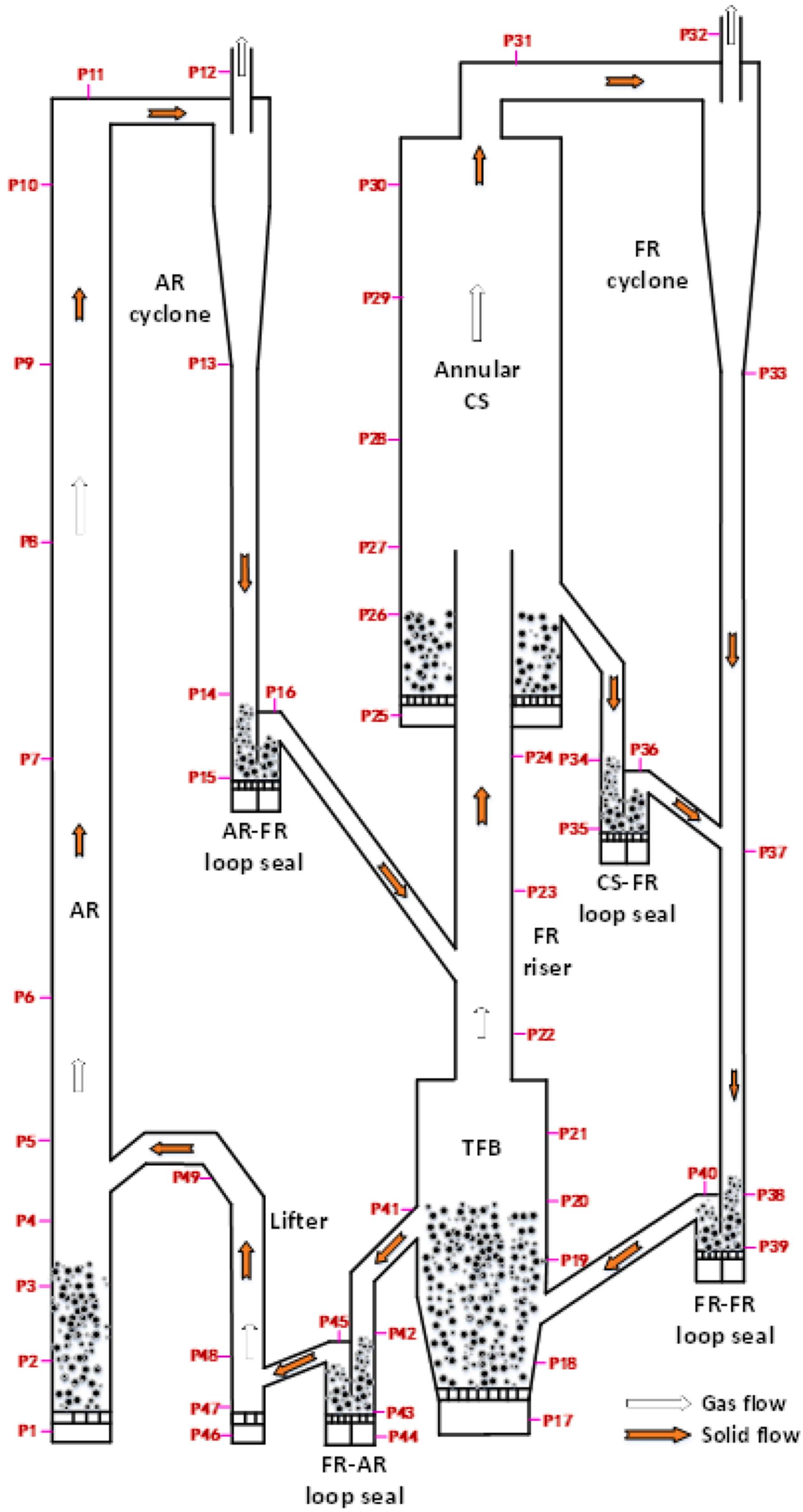


Fig. 1. schematic view of the cold-flow mock-up in Deyang in the lignite configuration.

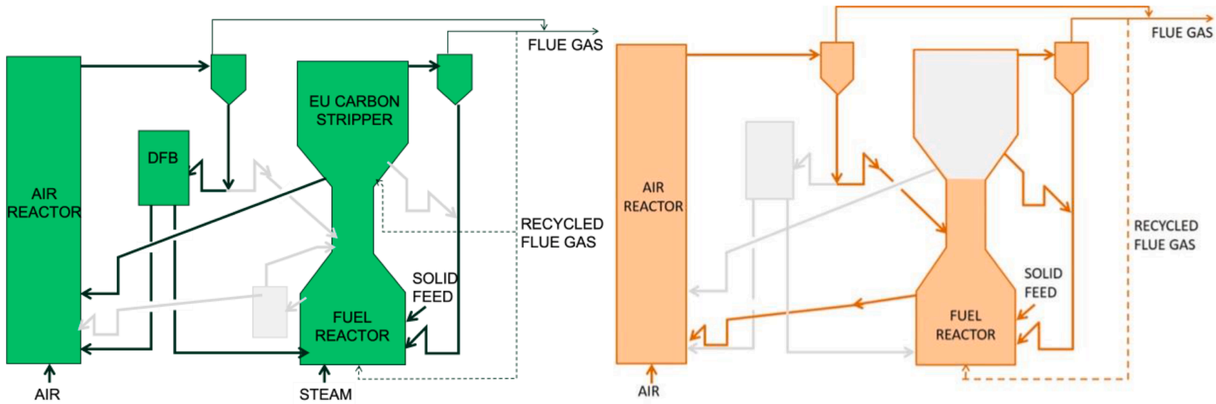


Fig. 2. Schematic design for pet-coke combustion (left panel) and for lignite combustion (right panel). Pipes and equipment in light grey are not active for this configuration.

on CAPEX). Therefore, there is a techno-economic optimum regarding the solid circulation rate. This is why we want to be able to adjust (increase or decrease) the solid circulation rate to assess the impact of this parameter. This adjustment is done by varying the OC recirculation back to the AR using the DFB that is installed in the pet-coke configuration. Having assessed the impact of the solid circulation rate for the demonstration unit, there will be no need for a DFB in commercial units. The decision to use a DFB for the pet-coke configuration is therefore not related to the nature of the feedstock. However, since the recirculation is controlled by L-valves, it means that the pet-coke configuration will have to use larger OC particles to ensure smooth operation of the L-valves.

Despite the fact that the demonstration unit will be the largest dedicated CLC unit in the world, it is still small compared to commercial plants. Furthermore, it will not be operated on a continuous basis. The CO2 that is capture from the process will therefore be vented to the atmosphere. Due to this, and in order to simplify the flue gas cleaning that is required to be in line with local emission regulations in Deyang, the gas stream outlets from the AR and FR are mixed before entering the flue gas cleaning section.

2.2.1. *Pet-coke configuration*

Since pet-coke contains a lot of fixed carbon with very low reactivity (Korus et al., 2021), the pet-coke particles must have very long residence time in the fuel reactor. This is why the lower part of the fuel reactor is constructed as a turbulent fluidized bed (left panel of Fig. 2). To be more specific, the fuel reactor is designed to reach at least 60 % of petcoke conversion in one through at a temperature of 950 °C (Tilland et al., 2020). Considering this kinetic, a residence time of several minutes in the fuel reactor is therefore needed to approach full conversion. When the particles eventually leave the bottom part of the fuel reactor, they are advected upward in a riser section leading to the carbon stripper at the top. In addition to gasifying some more of the char particles, the idea of the carbon stripper is to separate oxygen carrier particles from the un-converted char. The oxygen carriers are then transported back to the air reactor. The remaining particles, which essentially are the smaller char particles, together with the flue gas, leaves the upper part of the carbon stripper before entering the fuel-reactor cyclone, where the char is separated out and fed back to the bottom of the fuel reactor.

From the left-hand panel of Fig. 2 we also see that there is a distributing fluidized bed (DFB) between the air and the fuel reactors. How much of the oxygen carriers that is recycled back to the air reactor, and how much that is fed to the fuel reactor, is controlled by L-valves, with two L-valves leading from the DFB to each of the two main reactors. This is used to control the level of oxidation of the oxygen carriers going to the fuel reactor, while minimizing the air consumption in the air reactor and therefore the air blower power.

2.2.2. *Lignite configuration*

For the other configuration of the demonstration unit, the one that is optimized for lignite, most of the demonstration unit is unchanged (see right hand panel of Fig. 2). There are, however, three main changes. First, the carbon stripper on the top of fuel reactor in the petcoke case is not used for lignite. The carbon stripper for the lignite case is originally designed on the side of the bottom part of the fuel reactor (marked as grey box in Fig. 2 left panel), and details of the carbon stripper can be found in Sun et al. (Sun et al., 2015). It is recognized that the gasification of lignite char is faster than that of pet coke (Li et al., 2019), and the residence time in the fuel reactor is long enough for lignite char conversion, so the carbon stripper for the lignite configuration is not installed in the current demonstration in order to simplify the operation of the system, as depicted in the right hand panel of Fig. 2. A second difference between the configurations is that there is no DFB with associated L-valves for the lignite configuration, while the third major difference is the principle used to control the solid circulation. For the pet-coke configuration, L-valves are used to control the circulation, while in the configuration optimized for lignite, the solid circulation between the fuel and air reactors is controlled by the overflow method, and an overflow port is installed in the fuel reactor (H. Chen et al., 2021). The static bed height in the fuel reactor is higher than the overflow port to prevent it from constraining the solid circulation rate. The operational gas velocity of the fuel reactor is above the threshold required to become a turbulent fluidized bed. This is done to achieve good gas-solid contact and high solid circulation rate (H. Chen et al., 2021). The primary air ratio of the air reactor and the total bed inventory of the entire system are operational parameters to control the solid circulation rate (Li et al., 2022). The oxygen carrier from the air reactor cyclone will return back into the fuel reactor riser and are transported up into the carbon stripper above the fuel reactor. The oxygen carrier inside the fuel reactor riser, as well as oxygen carrier being entrained up into the carbon stripper above the fuel reactor, are also used to convert the unburnt gases released from the fuel reactor. Especially when a material with oxygen uncoupling (CLOU) effect is used as oxygen carrier, such as synthetic perovskite materials (L. Liu et al., 2021), the gas phase oxygen released from the oxygen carrier can be used to effectively convert the unburnt gases inside the riser and carbon stripper. For the oxygen carriers with two-stage oxidation kinetic behavior, the initial fast stage should be fully used, while the slower second stage is not suitable for full oxidation because of very slow kinetics. This is, however, not a problem since the first-stage oxidation kinetics of ilmenite is fast enough such that the ilmenite can reach the level of oxidation needed for oxygen transport required by the lignite combustion (Li et al., 2020). In the configuration for CLC with lignite, increasing the oxygen carrier recirculation ratio was found to reduce the level of oxidation of the oxygen carrier at the air reactor inlet, therefore, the value of the recirculation ratio in this configuration is zero, i.e., all the oxygen carriers from the air reactor are transported to the fuel reactor (H. Chen et al., 2021), see right hand panel of Fig. 2.

2.3. Fuels and operational data

The CLC tests will be conducted with pet-coke and lignite as fuels. In addition, natural gas and lignite will be used during start-up. The ultimate analysis of the two fuels, pet-coke and lignite, are presented in Table 1. Furthermore, fuel consumption rates for various loads are shown in Table 2. The minimum, nominal and maximum consumption rates correspond to thermal fuel feeding rates of 2, 3, and 4 MW, respectively. The carbon capture efficiency is expected to be above 95 % and the amount of captured CO_2 is expected to be between 700 and 1400 kg/h. Since the reactivity of pet-coke char is lower than that of the lignite char, the temperature in the fuel reactor is about 40° higher for the pet-coke configuration. Furthermore, the fuel residence time in the fuel reactor is also longer (up to twice as long ~400 s) for the pet-coke case.

As an example, the gaseous effluents for the nominal case of the pet-coke configuration can be found in Table 3.

Even though only fossil fuels are used in this project, it is known that for example woody biomass is a very suitable fuel for conversion in CLC units. Due to its low, but very reactive, char fraction, the carbon stripper may even be avoided for such fuel. This will lower investment costs and potentially make the performance of CLC even better.

2.4. Oxygen carriers

Given that the oxygen carriers are the "blood" of the CLC-technology, it is crucial to identify the best candidate for use in the demonstration unit. In order to do this, a number of different qualities have to be assessed for various oxygen carrier materials. These include reactivity, mechanical and chemical integrity, lifetime, cost, and agglomeration potential. The procedure used to identify the best material has been to first test the materials at lab scale under different redox conditions in an automated Thermogravimetric Analysis (TGA) set-up, including microstructure characterisation by scanning electron microscopy (SEM) with an attached energy dispersive spectrometer (EDS). Attrition characterisation was done using an accelerated attrition setup following the ASTM E728 standard. The more promising materials are tested further in a laboratory scale batch fluidized bed unit where they were exposed to redox cycling with both methane and pet-coke fuels. Several different materials, including various natural ores, such as ilmenite and manganese ores, in addition to some synthetic materials, have been screened in the lab (see e.g. (L. Liu et al., 2021; L. Liu et al., 2021; Liu et al., 2019; L. Liu et al., 2021) for some examples). Four different ilmenites were tested, of which the ilmenite from Norway showed the best results for oxygen transport capacity (OTC), reactivity, stability, and sulphur tolerance. An Fe-rich ore from China was also tested, but due to low material stability, it was not relevant for further evaluation.

Next, following different recipes, several versions of synthetic perovskite materials based on Ca, Mn, Ti, and Fe were produced by SINTEF. They showed excellent performance for OTC, reactivity, and stability. However, batch fluidized bed tests with petcoke revealed that the sulphur content of the petcoke would deactivate the material and it was considered not relevant for use with petcoke. These perovskite materials can be excellent choices for fuels not containing sulphur, and test production at industrial scale using spray drying have been accomplished in China. Another group of synthetic material that was produced and tested, was variations of Fe-Mn-Ti-(Mg) spinel materials. Since no single-phase materials were obtained, further investigations were stopped.

Finally, three different manganese ores from China were tested, with one showing clearly better material stability than the other two. This ore was chosen for further testing in pilot scale. The Mn-ore is delivered as small stones and needed calcining, crushing, milling, and sieving.

The materials that remain interesting after lab screening and testing in the batch fluidized bed unit have undergone final testing in the 10 kW pilot of IFP-EN (Rifflart et al., 2011) and the 150 kW pilot of SINTEF Energy Research (Langørgen et al., 2017). A total of three different materials have taken part in this final pilot testing: two different ilmenite fractions from Norway in addition to the chosen Mn-ore from China. Much higher attrition rate and fines production were observed for the Mn-ore. Estimated lifetime from the 10 kW tests were just below 500 h, whereas it was about 1400 h for the ilmenite. The Mn-ore will also need more pre-processing steps than ilmenite. The conclusion was that the best compromise, considering reactivity, lifetime, and cost, was a particular product of ilmenite from Titania in Norway (Vin et al., 2021). A total of 250 tons of this ilmenite has therefore been provided for the testing of the two configurations of the demonstration unit.

It should be noted that the reactivity of ilmenite is high only after it has been properly activated. When starting up the unit for the first time with a new fresh batch of oxygen carrier material, enough time will therefore be allocated for a sufficient number of redox cycles to activate the oxygen carriers before full CLC mode is initiated.

Since pet-coke contain sulphur, one of the criteria for the selection of the oxygen carrier material was that it should tolerate significant amounts of sulphur. On top of this, due to the design capacity of the

Table 1
Ultimate analysis of the fuels.

Fuel species	–	Pet-coke	Lignite
Carbon	%	94.24	45.31
Hydrogen	%	1.33	3.35
Oxygen	%	1.02	12.09
Nitrogen	%	1.76	0.27
Sulfur	%	0.86	0.08
Ash	%	0.16	3.61
Moisture	%	0.63	35.29
Volatile	%	8.32	34.60
Fixed carbon	%	90.89	26.50
LHV	kJ/kg	33,565	15,890

Table 2
Fuel feeding rates for various operations.

	Consumption (kg/h)		
	Nominal	Minimum	Maximum
Pet-coke feed	324	216	432
Lignite feed	680	545	909

Table 3
Gaseous effluents from the two reactors in pet-coke configuration.

		AR depleted air	FR flue gas	
T emperature	°C	1002	957	
Flowrate	Nm3/h	3521	2843	
Composition			100 % steam operation	Recycling FG operation
H2	%mol	0.0 %	0.1 %	0.2 %
H2O	%mol	6.2 %	74.1 %	50.0 %
CO	%mol	0.0 %	0.1 %	0.2 %
CO2	%mol	0.5 %	25.4 %	48.9 %
CH4	%mol	0.0 %	0.0 %	0.0 %
O2	%mol	2.2 %	0.0 %	0.0 %
N2	%mol	91.1 %	0.1 %	0.3 %
SOx	ppmv	0	909	1753
NOx	ppmv	0	1276	2460
Solid concentration	g/Nm3	39	39	39

current flue gas treatment system, the test will be performed with a pet-coke containing low amounts of sulphur (<1 %). Based on the above, we are therefore confident that there will be no oxygen carrier related issues with sulphur.

The composition of the ilmenite, which has a particle density of 4250 kg/m^3 when fresh and 2600 kg/m^3 after use, is shown in Table 4. The Sauter average particle size for the ilmenite is 250 μm for the pet-coke configuration and 145 μm for the lignite configuration.

2.5. Numerical simulations

Due to the harsh conditions, with high temperatures and fluidized particles, it is inherently very difficult to make detailed measurements inside a hot CLC unit. This is where numerical simulations can play an essential role. Currently, we are therefore working on full scale CFD simulations of both the 150 kW pilot of SINTEF and the demonstration unit in Deyang. These simulations are based on the N-Euler method and are utilizing the Neptune-CFD code. While these reactive simulations are still in progress, validations of the wall boundary condition and a hydrodynamic investigation has already been performed to validate the fundamental part of the code against the 150 kW pilot (Sun, 2022; Sun et al., 2021). Since the reactivity of pet-coke char is very slow (Korus et al., 2021), conversion of char particles is particularly difficult when OC particles without CLOU (Chemical Looping with Oxygen Uncoupling) effect are used, which is the case for e.g. ilmenite. Within the CHEERS project we have therefore invested a significant amount of work to identify numerical models that accurately account for the char conversion in general (Haugen et al., 2022) and for the heat, mass and momentum transfer between the char particles and the surrounding fluid in particular (Luo et al., 2018; Zhang et al., 2020; Karchniwy et al., 2022; Jayawickrama et al., 2019; Jayawickrama et al., 2021).

3. Further upscaling and techno-economic assessment

Given that the CLC is a very promising, but still immature technology, it is crucial to perform a techno-economic assessment of the technology and compare its performance with that of relevant existing technologies. For pet-coke fuel, a comparison has therefore been made between the CLC-technology and the circulating fluidized bed (CFB) technology (Roussanaly et al., 2023). This has been done both for a refinery application focusing on co-production of power (50 MWe) and steam (100 t/h), and for a case dedicated to power production (200 MWe). In addition, the same two cases have also been compared with the performance of natural gas used in a combined cycle (NGCC). Both for the CFB and the NGCC cases, post-combustion amine scrubbing (MEA) has been used for the carbon capture.

It is assumed that all plants are grassroots plants located in western Europe, with a life-time of 25 years. CAPEX and OPEX costs (fuel, utilities, and raw materials) are based on 2019 prices. Project contingency is set to 30 % while the process contingency of the CLC reaction section is 20 % and that of other mature sections is 5 %. Finally, the discount rate is 8 % and the construction time is set to 3 years with interests.

The main results show that for a solid feedstock like petcoke, CLC is clearly competitive versus CFB with carbon capture. For example, based on the CLC technology tested in the demonstration unit, the levelized cost of electricity with carbon capture is significantly lower than when burning pet-coke in a circulating fluidized bed (CFB) with MEA carbon capture. In particular, for a power production case of 200MWe, the levelized cost of electricity for a CFB with MEA is 130 €/MWhe while it is only 100 €/MWhe for CLC (Roussanaly et al., 2023). This means that the cost of electricity from a CFB with carbon capture from MEA is 30 % higher than for carbon capture with CLC. For the same power production case, the CO2 avoided cost for CLC is estimated to be 19 €/ton CO2 avoided when using CFB without CO2 capture as the basis (Roussanaly et al., 2023). This is less than one-third of the avoidance cost for CFB with MEA, estimated to 64 €/ton CO2 avoided.

By contrast, the benchmark results of CLC burning petcoke against NGCC with CO_2 capture burning natural gas show that the CLC technology is not competitive considering the assumptions made for petcoke and natural gas prices (2019 reference year in the EU market). Given today's high cost of natural gas, however, it is interesting to note that for a natural gas price increase of 45 % compared to 2019, power production with pet-poke in a CLC unit is cost effective compared to NGCC with CO_2 capture (Roussanaly et al., 2023).

Nevertheless, independent on fuel price, CLC is the most cost-efficient technology to burn petcoke, and the same good performances can be expected also for other solid fuels, like coal or biomass.

Table 4
Composition of ilmenite.

Species	Mass frac.	Amount
Fe	wt %	36.9
TiO_2	wt %	45.6
Other	wt %	17.5

4. Current status and further plans

The Engineering, Procurement, Construction (EPC) and testing phase was led by Dongfang Boiler Co.,Ltd (DBC) and the demonstration unit is located in Deyang City, outside Chengdu in China. The time schedule for the EPC was very tight, and only 16 months was originally allocated for this phase of the project. As can be seen from Table 5, in the end, significantly more time was needed. In January 2023, the construction of the demonstration unit and installation of all equipment in Deyang city was finalized. From February to Mai 2023, all sub-systems of the demonstration unit were tested. As of early June 2023, the pre-calcination of ilmenite is on-going. . All operational procedures have been finalized, including procedures for start-up, shutdown, and testing. These procedures will be used for the coming auto-thermal operation. Ilmenite is used as oxygen carrier in the CHEERS project, and 250 tons of ilmenite (size fraction 150–300 μm) is needed for testing the CLC demonstration unit both with pet-coke and lignite. As can be seen from Table 5, testing of the two configurations is scheduled for Q3 2023 to Q2 2024. After the CHEERS projects ends, the demonstration unit may still be used by some of the core partners for testing of their own designs.

5. Conclusion

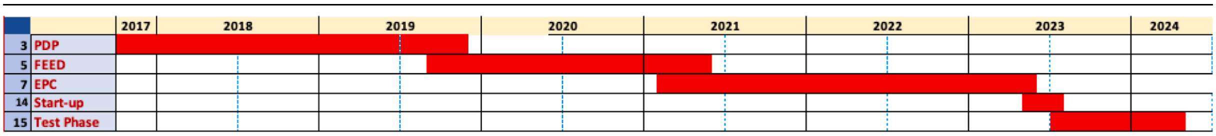
The planned CLC demonstration unit, standing 50 m tall and having a footprint of 270 m^{2}s, will convert a flow of solid fuels of up to 4 MW_{th} measured in thermal energy content while achieving a carbon capture rate of 96 %. The test campaign is planned for 2023 and will form the basis for further upscaling and development of commercial projects.

Technological progress is indeed rarely achieved without cooperation and collaboration between a plethora of stakeholders, including academia, industry, research institutions and civil society. Fruitful results expected from the efforts of the CHEERS project consortium, will offer to both unlock the learning potential curve and allow for wider applications of the CLC—CCS technology. This undoubtedly holds true in today's quest for emission reducing solutions.

The main purpose and goal of the CHEERS project is therefore to reveal emerging opportunities for the CLC—CCS technology and provide a pathway for its wider deployment in the petroleum refining, the generation of steam for industrial purposes and auxiliary power, and eventually in the power industry. In this way, the CHEERS project aims to contribute to the efforts on mitigating climate change and pursuing the development of CCS in industry.

For more information on the project, its work packages, consortium members, and up-to-date news and progress, please visit the project's website: http://cheers-clc.eu/.

Table 5
Critical path for the design, construction and testing of the demonstration unit. PDP: Process design package, FEED: Front End Engineering and Design, EPC: Engineering Procurement and Construction.The test phase include testing of both configurations.



Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors are unable or have chosen not to specify which data has been used.

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