

The EU-FP7 Project SUCCESS – Scale-up of Oxygen Carrier for Chemical Looping Combustion using Environmentally Sustainable Materials

Stefan Penthor, Tobias Mattisson, Juan Adánez, Stéphane Bertolin, Enrica Masi, Yngve Larring, Øyvind Langørgen, Jochen Ströhle, Frans Snijkers, Lieve Geerts, et al.

► **To cite this version:**

Stefan Penthor, Tobias Mattisson, Juan Adánez, Stéphane Bertolin, Enrica Masi, et al.. The EU-FP7 Project SUCCESS – Scale-up of Oxygen Carrier for Chemical Looping Combustion using Environmentally Sustainable Materials. Energy Procedia, Elsevier, 2017, 114, pp.395 - 406. 10.1016/j.egypro.2017.03.1181 . hal-01740328

HAL Id: hal-01740328

<https://hal-ifp.archives-ouvertes.fr/hal-01740328>

Submitted on 4 Jan 2019

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.





13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18
November 2016, Lausanne, Switzerland

The EU-FP7 project SUCCESS – Scale-up of oxygen carrier for chemical looping combustion using environmentally sustainable materials

Stefan Penthor^{a*}, Tobias Mattisson^b, Juan Adánez^c, Stéphane Bertolin^d, Enrica Masi^e,
Yngve Larring^f, Øyvind Langørgen^g, Jochen Ströhle^h, Frans Snijkersⁱ, Lieve Geertsⁱ,
Knuth Albertsen^j, Gareth Williams^k, Otmar Bertsch^l, Olivier Authier^m, Ytalo Dávilaⁿ,
Mahdi Yazdanpanah^o, Tobias Pröll^p, Anders Lyngfelt^b, Hermann Hofbauer^a

^aInstitute of Chemical Engineering, Vienna University of Technology, Getreidemarkt 9/166, A-1060 Vienna, Austria

^bDepartment of Energy and Environment, Chalmers University of Technology, S-412 96 Gothenburg, Sweden

^cInstituto de Carboquímica (CSIC), Miguel Luesma Castán 4, 50018 Zaragoza, Spain

^dIFP Energies Nouvelles, Etablissement de Lyon - Rond-point de l'échangeur de Solaize, BP 3, FR-69360 Solaize, France

^eInstitute National Polytechnique de Toulouse, Allée du Professeur Camille Soula, FR-31400 Toulouse, France

^fSINTEF, Forskningsveien 1, NO-0314, Norway

^gSINTEF Energi, Sem Saelandsveg 11, NO-7465 Trondheim, Norway

^hInstitute for Energy Systems and Technology, Technische Universität Darmstadt, Petersenstraße 30, D-64287 Darmstadt, Germany

ⁱFlemish Institute of Technological Research (VITO), Unit Sustainable Materials Management, Boeretang 200, B-2400 Mol, Belgium

^jEuro Support Advanced Materials BV, Liessentstraat 9F, NL-5405 AH Uden, Netherlands

^kJohnson Matthey, Blount's Court, Sonning Common, Reading RG4 9NH, United Kingdom

^lBertsch Energy GmbH & Co KG, Herrengasse 23 – Postfach 61, A-6700 Bludenz, Austria

^mEDF R&D Lab Chatou, 6 Quai Watier, 78400 Chatou, France

ⁿShell Global Solutions International B.V., P.O. Box 38000, 1030 BN Badhuisweg 3, 1031 CM Amsterdam, Netherlands

^oTOTAL, Research & Technology Gonfreville (TRTG), 76700 Harfleur, France

^pInstitute of Chemical and Energy Engineering, University of Natural Resources and Life Sciences Vienna, Peter-Jordan-Straße 82, A-1190 Vienna, Austria

* Corresponding author. Tel.: +43-1-58801-166367; fax: +43-1-58801-16699.
E-mail address: stefan.penthor@tuwien.ac.at

Abstract

The paper gives a high level overview of the work performed in the EU-FP7 funded project SUCCESS (Scale-up of oxygen carrier for chemical looping combustion using environmentally sustainable materials). The project is the most recent one in a series of successful EU-funded research projects on the chemical looping combustion (CLC) technology. Its main objective is to perform the necessary research in order to demonstrate the CLC technology in the range of 10 MW fuel power input. The main focus is on scale-up of production of two different oxygen carrier materials using large scale equipment and industrially available raw materials. This will guarantee availability of oxygen carrier material at tonne scale. The scale-up of the two materials, a Cu and a Mn based, was successful and first tests with the Cu material have already been performed in four different pilot units up to 150 kW where the material showed excellent performance regarding fuel conversion. In addition to technology scale-up, extensive end-user evaluation is performed. This evaluation includes investigations on health, security and environmental impacts (HSE), a life cycle analysis and a techno-economic analysis to compare the CLC technology for steam generation against the current state-of-the-art technologies.

© 2017 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of the organizing committee of GHGT-13.

Keywords: Chemical looping combustion, carbon capture, carbon capture and storage, oxygen carrier, fluidized bed, natural gas

1. Introduction

1.1. Chemical looping combustion

Chemical looping combustion (CLC) is an innovative combustion technology with inherent CO₂ capture and nearly no energy penalty [1]. This is achieved by avoiding the energy intense gas-separation step typical for CO₂ capture technologies. Chemical looping combustion is thus seen as a potential break-through CO₂ capture technology [2].

To avoid gas-separation, the combustion process is separated into two different reaction zones, air reactor (AR) and fuel reactor (FR) in a way that fuel and combustion air are never mixed. A solid oxygen carrier (OC), a metal oxide, is circulating between AR and FR and transporting oxygen from combustion air to fuel (see Fig. 1). The oxygen carrier is oxidized in the AR by combustion air and reduced in the fuel reactor by the fuel. The process yields two different exhaust gas streams. AR exhaust gas contains N₂ and excess O₂, exhaust gas from the FR contains the combustion products CO₂ and H₂O. After condensation, a highly concentrated CO₂ stream can be obtained. The total heat release in the two reactors is exactly the same as in normal combustion processes.

Nomenclature

AR	Air reactor
CFB	Circulating fluidized bed
CLC	Chemical looping combustion
EU	European Union
FR	Fuel reactor
LCO _E	Levelized costs of energy
OC	Oxygen carrier
TLV	Occupational exposure limit values
X _{CH₄}	Methane conversion
γ _{CO₂}	CO ₂ -yield

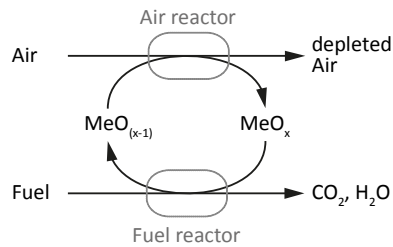


Fig. 1. Concept of chemical looping combustion.

AR and FR are designed as interconnected circulating fluidized bed reactors and the oxygen carrier is the bed material circulating between these reactors. The process temperature for CLC is comparable to conventional combustion processes, i.e. 800-1 000 °C depending on fuel and oxygen carrier material. Thus, a CLC reactor system can be used in the same way as a conventional circulating fluidized bed reactor (CFB) in a steam cycle process (heat recovery steam generator plus steam turbine) to produce power, heat and/or process steam [3].

Early deployment is seen in natural gas steam generation, where gas-to-steam efficiency penalty with CLC is below 1%-point compared to 15%-points with amine scrubbing and 8%-points with oxyfuel combustion, all for 95% capture rate. Reduction of the CO₂ avoidance cost of 60% compared to amine scrubbing post combustion capture results from higher efficiency.

Research in CLC has to focus on two different aspects of the technology: the oxygen carrier material and the reactor system. However, it is of great importance that the reactor system meets the demands of the oxygen carrier and vice versa. For successful up-scaling of the technology both need to be accomplished in parallel. CLC of gaseous fuels is well understood being demonstrated at pilot scale 140 kW and in long term experiments (1 000 hours at 10 kW) using a nickel based oxygen carrier [4, 5]. Further, several promising nickel free oxygen carriers have been identified reaching full fuel conversion and being economic and environmentally attractive [6]. From a technology point of view, chemical looping combustion of gaseous fuels can be seen close to demonstration at next scale (10 MW).

1.2. Project objectives and concept

The main objective of the EU-FP7 funded project SUCCESS (Logo in Fig. 2) is to perform the necessary research to close the last gap between the state-of-the-art and demonstration of the CLC technology for gaseous fuels at the 10 MW scale. This will include scale-up of OC production to the 100 tonne scale, as well as demonstration of the technology at 1 MW fuel power input. Industrially available raw materials are used to produce environmentally sound oxygen carriers based on two highly successful materials developed in previous EU funded projects [6]. This can be translated into the following project objectives:

1. Production of two large batches (≥ 500 kg) of scale-up ready material using industrially available raw materials and large scale production techniques.
2. Proof of performance of these materials in pilot plants up to 150 kW fuel power input
3. Demonstration of the CLC technology for gaseous fuels at 1 MW.
4. Presentation of an optimized system design for next scale (10 MW).
5. Quantification of the techno-economic potential of the CLC technology for gaseous fuels.



Fig. 2. Logo of the SUCCESS project

To reach these goals, the following work is performed within the project:

1. Applying oxygen carrier production methods at industrially required scale and assuring the adequate performance.
2. Development of a standard for determination of mechanical stability of OC particles.
3. Operation in four smaller pilots up to 150 kW of significantly different design.
4. Operation with gaseous fuels in a 1 MW pilot plant, representing a scale up of the state of art by one order of magnitude.
5. Detailed studies of reaction mechanisms and fluid-dynamics.
6. Use of results in optimization of a previous design for a 10 MW demonstration plant and techno-economic study of full-scale plant.
7. Assessment of health, safety and environmental issues associated with OC handling including life cycle analysis.
8. Overall techno-economic evaluation of the CLC steam generation technology.

The project is structured in eight technical work packages, where six (WP1-WP6) are related to technology scale-up and testing of OC material up to 1 MW and two (WP7 and WP8) are related to end-user evaluation of the technology. The structure is summarized in Fig. 3.

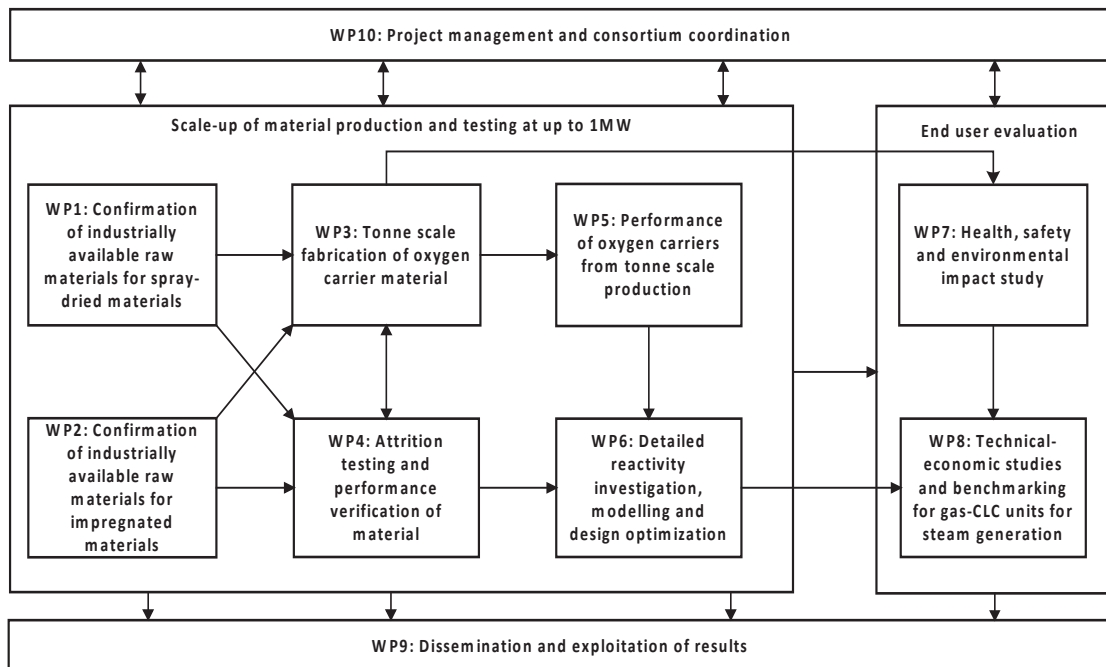


Fig. 3. Project structure

1.3. Project consortium

Combined efforts of key European developers of the CLC technology assure the continued European leadership in this development and bring the technology a major step towards commercialization. The SUCCESS consortium consists of 16 partners from 9 countries including research institutions, technology providers and end-users. The project partners and their activities are summarized in Table 1.

Table 1. The SUCCESS project partners.

Partner name	Country	Type	Activities
Vienna University Technology	Austria	University	Project coordination, pilot plant OC testing, 10 MW system design
Chalmers University of Technology	Sweden	University	OC development, pilot plant OC testing, attrition testing
CSIC	Spain	Research Institute	OC development, OC testing, attrition testing, reactivity investigations, modelling, OC recycling investigation
IFP Energies Nouvelles	France	Research Institute	Pilot plant OC testing, attrition testing, reactivity investigations
Institut National Polytechnique de Toulouse	France	University	3D-Modelling
SINTEF Materials	Norway	Research Institute	Reactivity investigations, attrition testing
SINTEF Energy	Norway	Research Institute	Pilot plant OC testing
Darmstadt University of Technology	Germany	University	Pilot plant OC testing (1 MW)
VITO	Belgium	Research Institute	OC development, life cycle analysis, health safety and environmental impact evaluation
Euro Support Advanced Materials	Netherlands	Material producer	Large scale production of OC material
Johnson Matthey	United Kingdom	Material producer	Large scale production of OC material
Bertsch Energy	Austria	Boiler manufacturer	Sizing and design of equipment for economic evaluation
Électricité de France (EDF)	France	Power	Techno-economic evaluation
Shell Global Solutions	Netherlands	Oil&Gas	Health safety and environmental impact evaluation
TOTAL Raffinage Chimie	France	Oil&Gas	Pilot plant OC testing, attrition testing, techno-economic evaluation
University of Natural Resources and Life Sciences	Austria	University	Mass and energy balance calculations for techno-economic evaluation

2. Oxygen carrier development

Production of two different OC materials will scaled-up to multi tonne scale in SUCCESS. This scale-up does not only include scale-up of production equipment but also use of raw materials available in large quantities. The two materials have different active metal oxides (Mn and Cu) and are made by two different production methods, spray-drying and impregnation where the recipes were developed in earlier research projects.

2.1. Spray-dried CaMn particles

The spray-dried CaMn perovskite materials were developed within the EU-FP7 funded project INNOCUOUS [6-8]. The material is a so-called CLOU material (Chemical Looping with Oxygen Uncoupling [9]) and able to release gaseous oxygen in the fuel reactor to improve fuel conversion. For the scale-up of material production, different Mn sources in the form of Mn ores and Mn oxides were examined and investigated. The key question here is, how the impurities (see Table 2) and the different parameters of the spray-drying process affect the final particle properties like reactivity and lifetime. In order to find the best raw materials and production methods, 24 small batches of materials have been spray-dried and evaluated in small batch reactors. More detailed information about the scale-up process and influence of raw materials can be found in Jacobs et al. [10]. A summary of the used Mn sources is listed in Table 2.

Table 2. Overview of different Mn sources (data from [10]).

Material	Supplier	Mn oxide	Mn content	Main impurities	BET [m ² /g]
Hausmannite LM type	Erachem-Comilog	Mn ₃ O ₄	68%	1-2% Fe, <1% Al	2.7
Elkem Colormax P	Elkem, Norway	Mn ₃ O ₄	69	1% Al, 1% Fe	1.4
BassTech	BassTech	MnO	>76-78	-	23.3
CDMA	Erachem-Comilog	MnO ₂	51	2-3% Fe, 1-2% Si, 4% Al	28.3
Battery grade N60	Autlan	MnO ₂	45	5-6% Fe, 5-6% Si, 2-3% Al, 2-3% Ca	33.3

Based on the investigations, the best candidate was selected for production of up to 2 tons of material by Euro Support Advanced Materials using large scale equipment. This material will be tested in four different pilot units up to 150 kW fuel power input and also in the 1 MW unit at Darmstadt University of Technology.

2.2. Impregnated CuO particles

The recipe for the impregnated material, CuO on Al₂O₃, has also been developed before the start of the project by CSIC and was already tested before in different pilot units up to 120 kW [11-16]. The OC material has an active Cu content of 14 wt% and is impregnated on a γ -Al₂O₃ support material. The main task in scale-up of this material was identification of an industrially available support material and keep the excellent properties of the original benchmark material. Several smaller batches have been produced and tested in a continuous 500 W unit. The best and scaled-up OC material using industrially available support materials and relevant protocols was manufactured by Johnson Matthey using the incipient wet impregnation method. It is here referred to as *Cu14 γ Al Commercial*.

The properties of fresh and used particles and the comparison to the original benchmark material are shown in Table 3.

Table 3. Properties of scaled up material (fresh and used) in comparison with benchmark material (data from [17, 18]).

Oxygen Carrier	Cu14γAl_Commercial		Benchmark Material
	Fresh	Used	Fresh
Total CuO content [wt%]	13.8	10.1	69
Particle size [μm]	153	151	
Porosity [%]	53.0	49.1	
Mechanical strength [N]	1.2	1.2	
AJI	3.1	2.6	
XRD phases	CuO, CuAl ₂ O ₄ , δ -Al ₂ O ₃	CuO, CuAl ₂ O ₄ , CuAlO ₂ , δ -Al ₂ O ₃ , α -Al ₂ O ₃	CuO, CuAl ₂ O ₄ , δ -Al ₂ O ₃

The material has been extensively tested in a 500 W continuously operation unit (information about unit in [17]) where fuel conversion above 95% has been reached.

3. Oxygen carrier testing

The oxygen carrier material produced using large scale equipment is tested in four different pilot units up to 150 kW fuel power input with different designs to allow an unprecedented characterisation of the oxygen carrier material. Further, each unit has special features for very detailed investigation of parameters like solids circulation, solids inventory, long-term stability and sulphur tolerance.

Furthermore, the spray-dried perovskite material will be used to demonstrate the CLC technology at 1 MW fuel power input. The mechanical stability of the oxygen carrier materials is tested under hot and cold conditions in three different units.

3.1. Available pilot plants

Continuous pilot unit testing is performed in five pilot units up to 1 MW fuel power input. Each of these units shows specific advantages and potential disadvantages regarding specific inventories, solid circulation rates and possible range of operating parameters. However, the differences in designs give great opportunity for extensive material testing and identification of important fuel conversion mechanisms. A summary of the different pilot units and their special features is shown in Table 4. Sketches and flow sheets of the pilot units are shown in Fig. 4- Fig. 6.

Table 4. Pilot units up to 1 MW used in SUCCESS.

Operator	Fuel power	Fuel	Special feature
Chalmers University of Technology	10 kW	Natural gas	<ul style="list-style-type: none"> Overnight operation High gas velocities for attrition testing
IFP Energies Nouvelles	10 kW	CH ₄ , CO, H ₂	<ul style="list-style-type: none"> L-valves for control of solid flow rate Control of gas and solids residence time 3 reactors (2xAR, 1xFR)
Vienna University of Technology	120 kW	Natural gas, CO, H ₂ , Hydrocarbons, H ₂ S	<ul style="list-style-type: none"> High solids circulation rates Operation with higher hydrocarbons and sulphur
SINTEF Energy	150 kW	Natural gas	<ul style="list-style-type: none"> Routing of particle flow Internal recirculation of particles
Darmstadt University of Technology	1 MW	Natural gas	<ul style="list-style-type: none"> Fully refractory lined reactors Post combustion chamber using pure oxygen

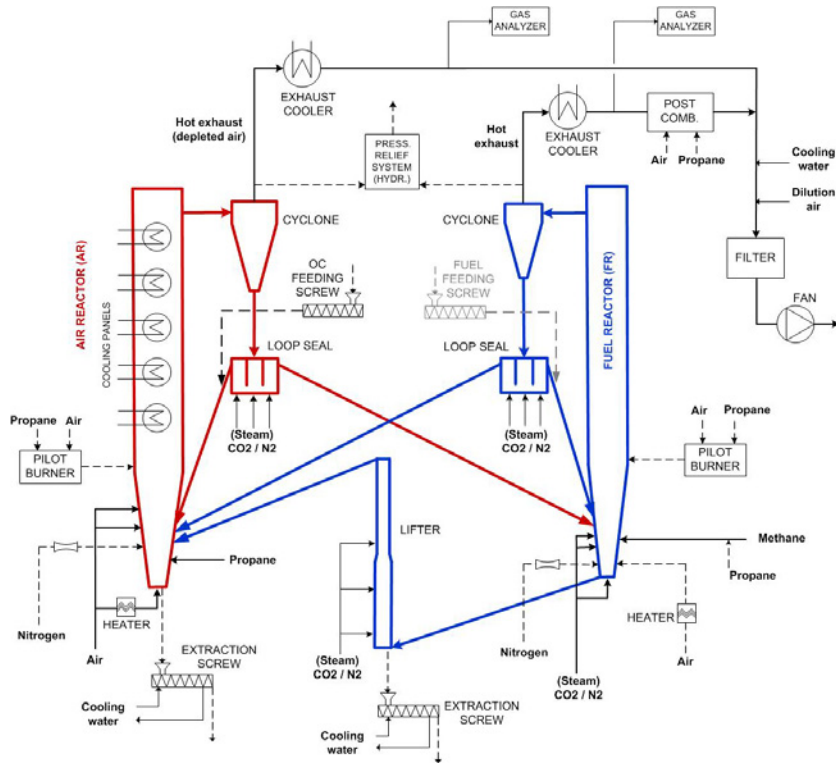


Fig. 5. SINTEF 150 kW unit.

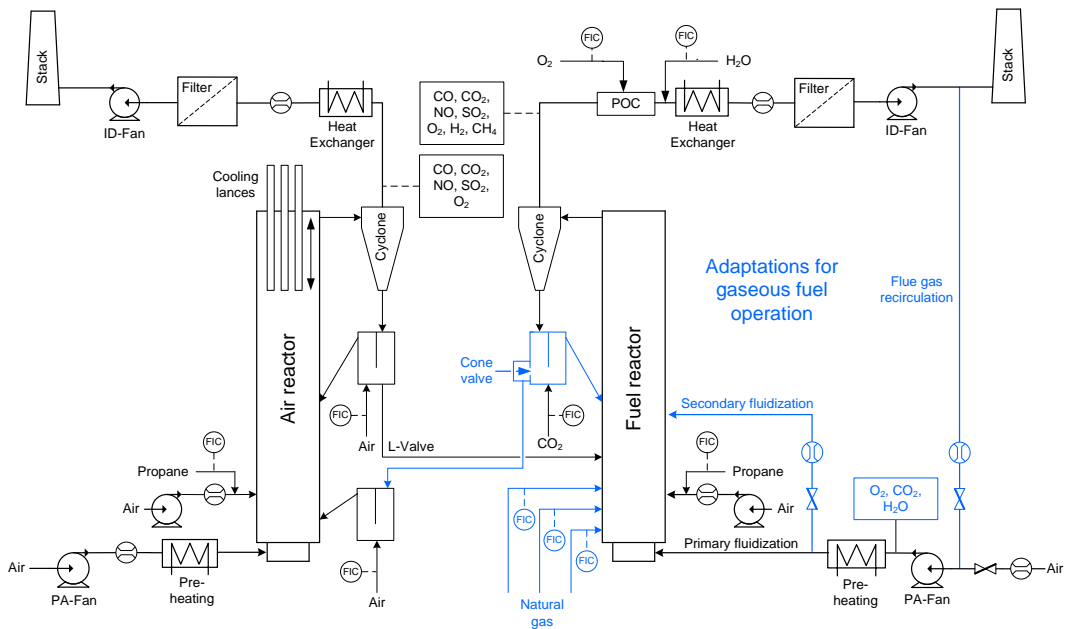


Fig. 6. Darmstadt 1 MW unit. Blue lines show adaptations for natural gas operations.

3.2. First results from material testing

So far, the impregnated *Cu14γAl_Commercial* OC has been tested in pilot units up to 150 kW where it showed very good performance. The two most important performance parameters for comparison of different operating conditions are the methane conversion written as

$$X_{CH_4} = 1 - \frac{y_{CH_4,FR}}{y_{CH_4,FR} + y_{CO_2,FR} + y_{CO,FR}} \quad (1)$$

and the CO₂-yield written as

$$\gamma_{CO_2} = \frac{y_{CO_2,FR}}{y_{CH_4,FR} + y_{CO_2,FR} + y_{CO,FR}} \quad (2)$$

The material performed outstanding in all units reaching methane conversions $X_{CH_4} > 90\%$ (for more detailed information see [19, 20]). When comparing these numbers, it has to be taken into account that the investigated particles were not the design particles for these pilot units. Detailed results for the pilot units are shown in Fig. 7-Fig. 9.

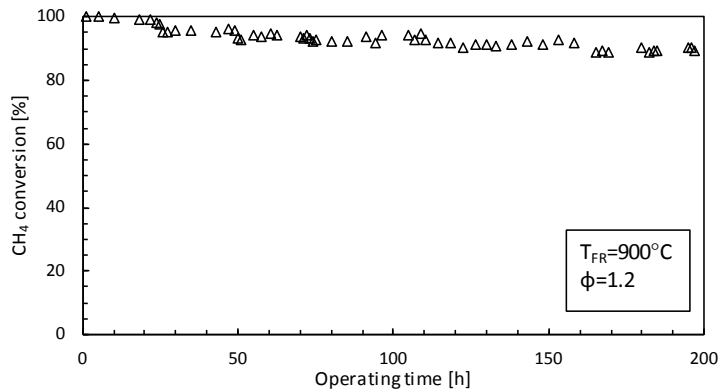


Fig. 7. Results from testing in 10 kW IFP unit. CH₄-conversion over operating time (data from [19]).

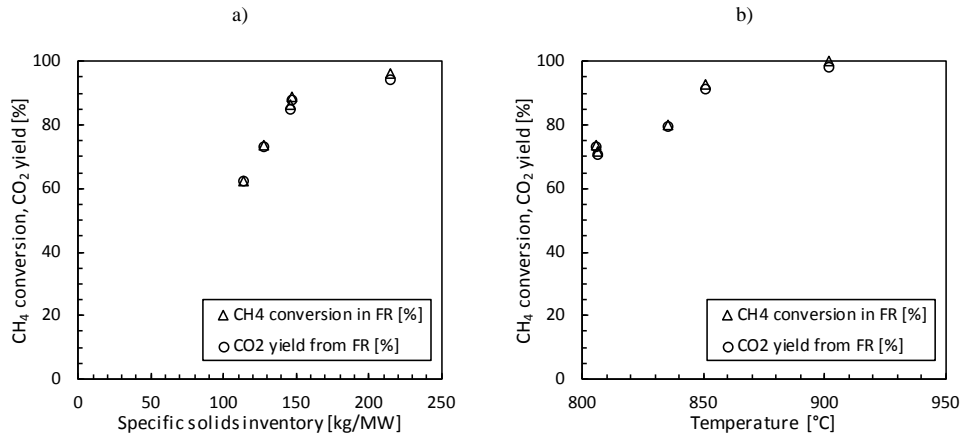


Fig. 4. Results from testing in Vienna 120 kW unit. a) Influence of solids inventory, b) influence of temperature.

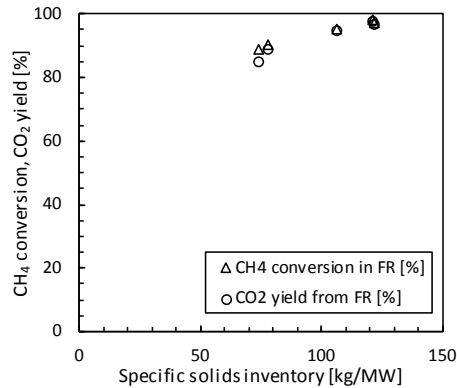


Fig. 9. Results from testing in 150 kW SINTEF unit. Influence of solids inventory (data from [20]).

4. End-user technology potential evaluation

In addition to experimental process investigations and development, a lot of effort is put into end-user evaluation of the CLC technology for industrial steam generation. These investigations include extensive health, security and environmental impact assessment of the two scaled-up oxygen carrier materials, a life cycle analysis and techno-economic evaluation of different application scenarios.

The environmental impact assessment investigated potential risks related to humans and the environment in a three tier approach. Based on the results, detailed recommendations for required safety equipment and material handling can be made. Acute and chronic toxicity tests were performed on algae, waterflea, and zebrafish embryo to assess the human and environmental hazard of fresh and spent oxygen carriers. Acute risk on aquatic ecosystem is low except Al poisoning of algae is possible using the Cu-based OC material. For the exposure assessment a realistic exposure level for workers was established. The potential human exposure has been evaluated by simulation experiments (generating dust under controlled conditions). The risk evaluation is based on measured data (during dust generation, as worst case proxy for OC handling) and occupational exposure limit values (TLVs). It showed a potential risk for Mn exposure.

Techno-economic evaluations were performed based on methods from the European Benchmarking Task Force (EBTF). To allow the comparison of CLC with other CO₂ capture technologies, a techno-economic study will be performed. As basis for this study, a natural gas reference case with and without post combustion CO₂ capture via mono-ethanol-amines was established for several capacities and steam parameters. In total, two different cases, one with high grade steam and one with low grade steam will be evaluated. The first case is preferable for power (high grade steam) whereas the second case is for oil and gas industry (low grade process steam). All necessary plant equipment is considered in both cases, state-of-the-art penalty demonstrated in real conditions as well as up-to-date thermal integration options are integrated for CO₂ capture. In both cases the levelized cost of energy (LCOE_E) increases.

5. Conclusions and outlook

The objective of the EU-FP7 funded project SUCCESS is to close the gap between the state-of-the-art of chemical looping combustion for gaseous fuel and next scale demonstration in the size of 10 MW fuel power input. To achieve the goal, necessary research is performed in the fields of oxygen carrier production at large scale, extensive material testing in pilot units up to 1 MW and end-user evaluation regarding techno-economic and life-cycle performance. The production methods of two different oxygen carrier materials based on Mn and Cu have been successfully scaled-up to the tonne scale using industrially available raw materials. First tests of these materials in pilot units up to 150 kW show very good results regarding fuel conversion performance and particle lifetime.

Intensive investigations regarding health, safety and environmental impact assessment of the oxygen carrier materials give detailed instructions for material handling and necessary safety equipment. To evaluate the techno-economic potential of the CLC technology for industrial steam generation, comparison between the new technology and a reference case is performed based on methods from the European Benchmarking Task Force. Here, two different cases, high grade and low grade steam, are investigated.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 608571. Financial support is gratefully acknowledged.

References

- [1] W.K. Lewis, E.R. Gilliland, W.P. Sweeney, Gasification of carbon: Metal oxides in a fluidized powder bed, *Chem. Eng. Prog.*, 47 (1951) 251-256.
- [2] O. Bolland, Fundamental thermodynamic approach for analyzing gas separation energy requirement for CO₂-capture processes, in: *Proceedings of the 8th International Conference on Greenhouse Gas Control Technologies (GHGT-8)*, Trondheim, Norway, 2006.
- [3] A. Lyngfelt, B. Leckner, A 1000MWh boiler for chemical-looping combustion of solid fuels – Discussion of design and costs, *Applied Energy*, 157 (2015) 475-487.
- [4] A. Lyngfelt, Oxygen Carriers for Chemical Looping Combustion - 4 000 h of Operational Experience, *Oil & Gas Science and Technology - Revue d'IFP Energies nouvelles*, 66 (2011) 161-172.
- [5] J. Adánez, A. Abad, F. García-Labiano, P. Gayán, L.F. de Diego, Progress in Chemical-Looping Combustion and Reforming technologies, *Prog. Energy Combust. Sci.*, 38 (2012) 215-282.
- [6] T. Mattisson, J. Adánez, K. Mayer, F. Snijkers, G. Williams, E. Wesker, O. Bertsch, A. Lyngfelt, Innovative Oxygen Carriers Uplifting Chemical-looping Combustion, *Energy Procedia*, 63 (2014) 113-130.
- [7] D. Jing, T. Mattisson, H. Leion, M. Rydén, A. Lyngfelt, Examination of Perovskite Structure CaMnO_{3-δ} with MgO Addition as Oxygen Carrier for Chemical Looping with Oxygen Uncoupling Using Methane and Syngas, *International Journal of Chemical Engineering*, 2013 (2013) 1-16.
- [8] D. Jing, T. Mattisson, M. Ryden, P. Hallberg, A. Hedayati, J. Van Noyen, F. Snijkers, A. Lyngfelt, Innovative Oxygen Carrier Materials for Chemical-Looping Combustion, *Energy Procedia*, 37 (2013) 645-653.
- [9] H. Leion, T. Mattisson, A. Lyngfelt, Using chemical-looping with oxygen uncoupling (CLOU) for combustion of six different solid fuels, *Energy Procedia*, 1 (2009) 447-453.
- [10] M. Jacobs, P. Weltens, Y. de Vos, D. Jing, T. Mattisson, F. Snijkers, Development of Mechanically Strong Manganese-based Oxygen Carriers by Spray Drying method, in: *4th International Conference on Chemical Looping*, Nanjing, China, 2016.

- [11] J. Adánez, P. Gayán, J. Celaya, L.F.d. Diego, F. García-Labiano, A. Abad, Chemical Looping Combustion in a 10 kW th Prototype Using a CuO/Al₂O₃ Oxygen Carrier: Effect of Operating Conditions on Methane Combustion, *Industrial & Engineering Chemistry Research*, 45 (2006) 6075–6080.
- [12] L.F. de Diego, F. García-Labiano, P. Gayán, J. Celaya, J.M. Palacios, J. Adánez, Operation of a 10kWth chemical-looping combustor during 200h with a CuO-Al₂O₃ oxygen carrier, *Fuel*, 86 (2007) 1036-1045.
- [13] C.R. Forero, P. Gayán, L.F. de Diego, A. Abad, F. García-Labiano, J. Adánez, Syngas combustion in a 500 Wth Chemical-Looping Combustion system using an impregnated Cu-based oxygen carrier, *Fuel Process. Technol.*, 90 (2009) 1471–1479.
- [14] C.R. Forero, P. Gayán, F. García-Labiano, L.F. de Diego, A. Abad, J. Adánez, High temperature behaviour of a CuO/γAl₂O₃ oxygen carrier for chemical-looping combustion, *International Journal of Greenhouse Gas Control*, 5 (2011) 659–667.
- [15] P. Gayán, C.R. Forero, L.F. de Diego, A. Abad, F. García-Labiano, J. Adánez, Effect of gas composition in Chemical-Looping Combustion with copper-based oxygen carriers: Fate of light hydrocarbons, *International Journal of Greenhouse Gas Control*, 4 (2010) 13–22.
- [16] S. Penthor, F. Zerobin, K. Mayer, T. Pröll, H. Hofbauer, Investigation of the performance of a copper based oxygen carrier for chemical looping combustion in a 120kW pilot plant for gaseous fuels, *Applied Energy*, 145 (2015) 52-59.
- [17] A. Cabello, P. Gayán, A. Abad, L.F. de Diego, F. García-Labiano, M.T. Izquierdo, A. Scullard, G. Williams, J. Adánez, Long-lasting Cu-based oxygen carrier material for industrial scale in Chemical Looping Combustion, *International Journal of Greenhouse Gas Control*, 52 (2016) 120-129.
- [18] A. Cabello, P. Gayán, A. Abad, L.F. de Diego, F. García-Labiano, M.T. Izquierdo, A. Scullard, G. Williams, J. Adánez, Evaluation of a promising Cu-based oxygen carrier for its use at industrial scale in CLC of CH₄, in: 4th International Conference on Chemical Looping, Nanjing, China, 2016.
- [19] A. Lambert, A. Tilland, W. Pelletant, S. Bertholin, F. Moreau, I. Clemencon, M. Yazdanpanah, Performance and degradation mechanisms of CLC particles produced by industrial methods, in: 4th International Conference on Chemical Looping, Nanjing, China, 2016.
- [20] O. Langorgen, I. Saanum, N.E. Haugen, Performance of a 150 kW chemical looping combustion reactor system for gaseous fuels using a copper-based oxygen carrier, in: 4th International Conference on Chemical Looping, Nanjing, China, 2016.