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SUMMARY

VDZ, IKN and HeidelbergCement (HC) have designed, constructed and operated the world's first oxyfuel clinker cooler prototype ever tested in an industrial environment. The experiment was performed within the Horizon 2020 CEMCAP project, which aims to promote the readiness of technologies for CO_2 capture in cement plants. The focus of this paper lies on the design and operation of the prototype. The main technical specifications of the prototype are described and experimental challenges are discussed. A comprehensive list of lessons learned during the trials is presented to give guidance for the future design of prototype or industrial-scale oxyfuel clinker coolers. The control of moisture and dust load of the recirculated cooling gas as well as of false air ingress may play a relevant role in the design of future oxyfuel clinker coolers and the application of CO_2 capture in cement plants. An exact determination of the heat transfer rates in a CO_2-rich atmosphere by clinker cooling curves will require further investigation with full industrial-scale equipment. Clinker samples were taken during the trials for subsequent analysis and determination of the influence of the cooling gas composition on clinker chemistry. The experimental results of the effects of the oxyfuel cooling medium on clinker quality will be presented and discussed in a second article which will be published soon in this journal. ◂

ZUSAMMENFASSUNG

Die Projektpartner VDZ, IKN und HeidelbergCement (HC) haben den ersten Prototyp eines Oxyfuel-Klinkerkühlers entwickelt, gebaut und in industrieller Umgebung getestet. Der Versuch wurde im Rahmen des Forschungsprojekts CEMCAP durchgeführt. CEMCAP wird durch das Forschungs- und Innovationsprogramm Horizon 2020 der Europäischen Union gefördert. Das Projekt soll die Voraussetzungen für einen großflächigen Einsatz von CO_2-Capture-Technologien in Zementwerken schaffen. Der Schwerpunkt dieses Artikels liegt auf dem Design und dem Betrieb des Prototyps. Die wichtigsten technischen Anforderungen des Prototyps werden beschrieben und die experimentellen Herausforderungen diskutiert. Enthalten ist auch eine umfassende Liste der während des Versuchs gewonnenen Erkenntnisse, die als Leitfaden für das zukünftige Design eines Oxyfuel-Klinkerkühlers im industriellen oder experimentellen Maßstab dienen soll. Die Kontrolle der Feuchte- und Staubbelastung des rezirkulierten Kühlungsmediums sowie des Falschlufteintrags können eine wichtige Rolle bei der Entwicklung zukünftiger Oxyfuel-Klinkerkühler und bei der Umsetzung der CO_2-Abscheidung in Zementwerken spielen. Eine genaue Bestimmung der Wärmeübertragungsraten in einem CO_2-reichen Medium mithilfe von Klinkerkühlungskurven erfordert weitere Untersuchungen mit einer vollständigen Ausrüstung in industriellem Maßstab. Klinkerproben wurden während des Versuchs genommen, um den Einfluss der Gaszusammensetzung des Kühlungsmediums auf die Klinkerqualität zu untersuchen. Die Versuchsergebnisse zur Klinkerqualität werden in einem zweiten Artikel in dieser Zeitschrift veröffentlichen und diskutiert. ◂

PROCESSING

(English text supplied by the authors)

First oxyfuel clinker cooler tested in an industrial environment

Erster Oxyfuel-Klinkerkühler in industrieller Umgebung getestet

1 Introduction

The world is aiming to reduce the emission of greenhouse gases (GHG) and thus keep the increase in global average temperature below 2 °C. Climate protection has therefore become one of the most important and challenging future issues for our society. CO_2 emissions from the cement industry constitute around 7 % of global anthropogenic CO_2 emissions [1]. The cement industry has responded to the need to reduce CO_2 emissions by increasing thermal efficiency, the use of alternative fuels in the substitution of primary fossil fuels, and reducing the clinker content in cement. These measures can contribute to a substantial reduction of CO_2 emissions from cement production. However, they are still insufficient to achieve CO_2 mitigations in the cement industry which significantly contribute to stabilising the greenhouse gas concentration in the atmosphere and not exceeding the 2 °C target. Cement will continue to be a key material for building society's infrastructures in the future and thus one of the driving forces for development and economic growth around the world. Significant demand reduction and/or substitution are not realistic scenarios given world economic growth, the migration of people to cities and the consequent increase of urbanisation, the need for new infrastructures to minimise the effects of climate change, etc. Carbon capture for further storage (CCS) or utilisation (CCU) has been identified as one of the key CO_2 reduction levers for the cement industry. Two different CO_2 capturing technologies to be applied in the cement industry [7, 11, 12, 13] have been under assessment over the past few years: post-combustion technology and oxyfuel technology. Given the relevance of the cement industry regarding global CO_2 emissions, ECRA has undertaken a research project which focuses on the deployment of oxyfuel technology in the cement industry. The ECRA Oxyfuel Project served as the basis for the construction and testing of an oxyfuel clinker cooler on a pilot scale within CEMCAP. The participation of VDZ, IKN and HC in both research projects proved to be a fruitful synergy for the successful testing of the oxyfuel clinker cooler prototype.

In oxyfuel combustion a mixture of oxygen and recirculated exhaust gas is used instead of air for the combustion process [4, 7, 8]. This results in a CO_2-rich flue gas flow, which, after further processing, can be transferred to a storage site or utilised in other manufacturing processes. With oxyfuel technology, not only the CO_2 arising from the combustion of fuels (a share of around 40 %), but also from the calcination of raw materials (calcium carbonate, with a share of around 60 %) can be captured. Being a process-integrated CO_2 capture technology, oxyfuel technology introduces some changes in the clinker manufacturing process and has not yet been implemented or tested in existing cement plants so far. Some issues concerning the oxyfuel process integration, plant operation, retrofitability and operation costs, among others, require thorough assessment before the demonstration of oxyfuel technology at industrial scale. One of the most important questions is if clinker quality can be maintained with oxyfuel operation [10, 12]. The major concern

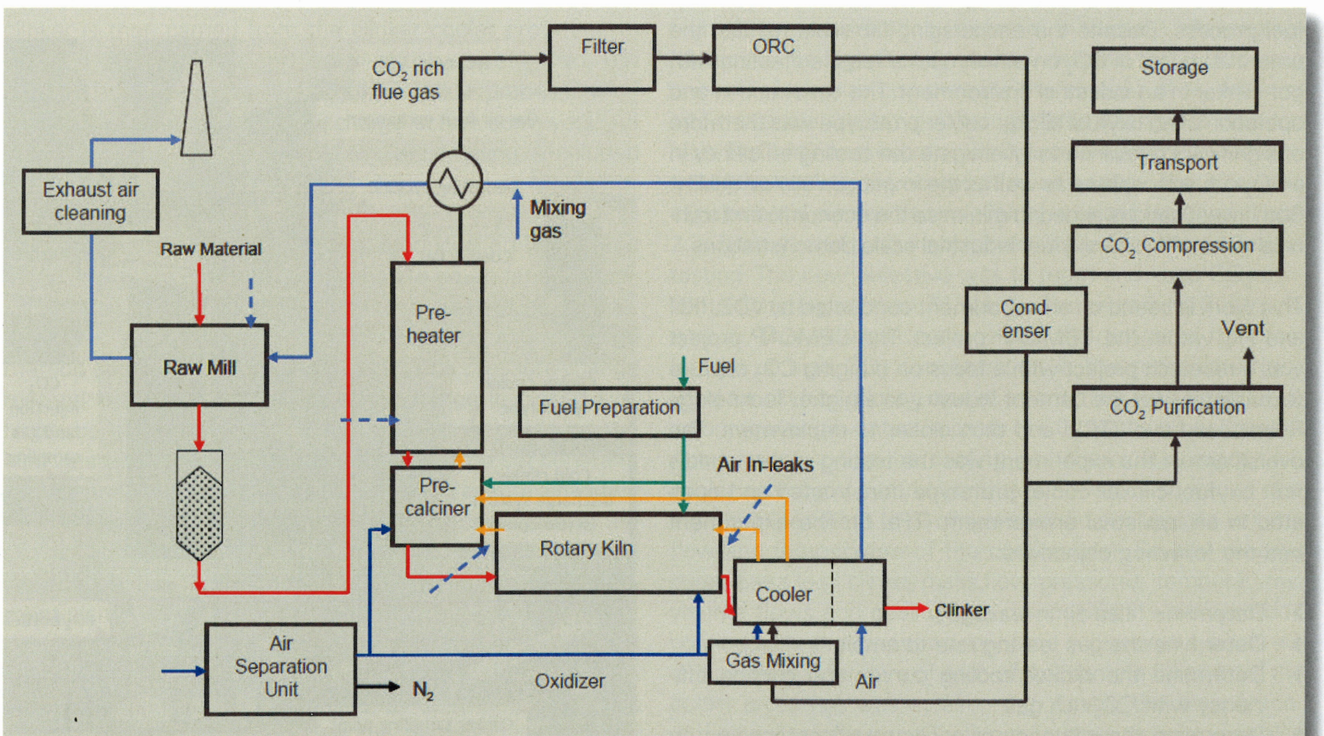

Figure 1: Oxyfuel cement plant flow sheet developed in the ECRA's Oxyfuel project [5, 7]

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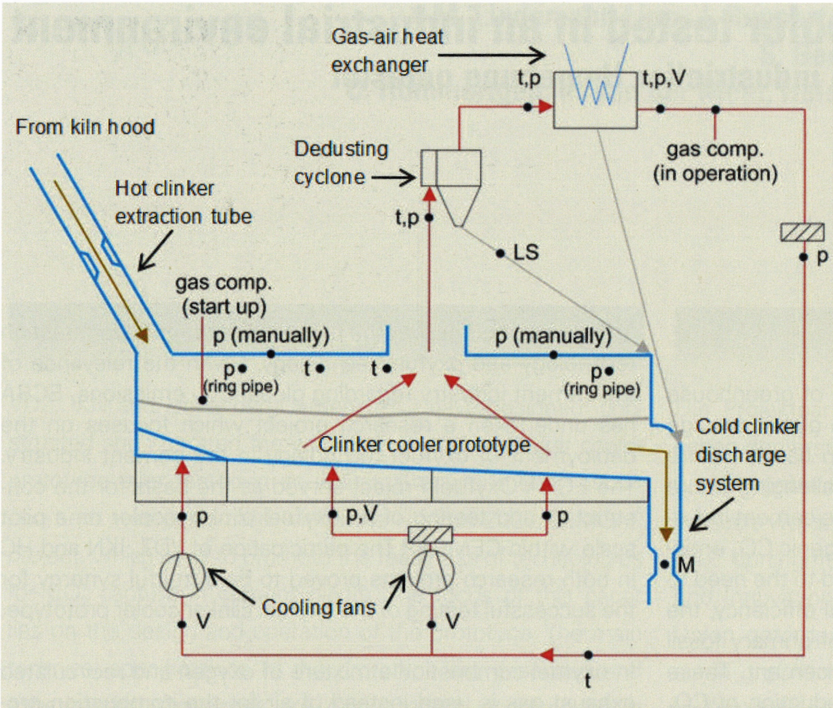

Figure 2: General concept of the cooler prototype with measurement points for temperature (t), pressure (p); volume flow (V); mass flow (M) and gas composition

lies in the potential reaction of CaO contained in the alite and belite clinker phases (C_3S and C_2S respectively) with CO_2 in the cooling medium and a consequent loss of clinker quality. Lab-scale experiments revealed that the impact of high CO_2-concentration in the cooling medium on the clinker quality and the resulting cement properties were negligible and that the required clinker quality could be met [5, 9].

Clinker quality is strongly influenced by the clinker cooler operation and cooling rate [9]. In addition, the clinker cooler operation impacts the thermal energy consumption of the cement plant, and thus indirectly the CO_2 emissions. Both effects are also valid for a clinker cooler operated in an oxyfuel process. Despite the encouraging lab-scale results, the potential impact of CO_2 on clinker quality required testing with hot clinker in an industrial environment. The construction and operation of an oxyfuel clinker cooler prototype was therefore of significant relevance to investigate the cooling efficiency in a CO_2-rich atmosphere as well as the impact on clinker quality. Both investigations aimed to minimise the economic and technical risks of future oxyfuel industrial-scale demonstrations.

This work is based on an experiment conducted by VDZ, IKN and HC within the CEMCAP project. The CEMCAP project was a research project with a focus on bringing CO_2 capture technologies for the cement industry to a higher Technology Readiness Level (TRL) and thus closer to deployment. The overall aim of the experiment was the testing of the world's first oxyfuel clinker cooler prototype constructed and operated in an industrial environment (TRL 6). The experiment had the following objectives:

- Determine false air in-leakage
- Determine the gas leaking rate to ambient
- Determine the clinker cooling curves and cooling efficiency with CO_2-rich gas
- Determine the influence of cooling gas composition on clinker chemistry

The focus of this paper is on the design, construction and operation of the oxyfuel clinker cooler prototype, which is in accordance with objectives 1 to 3. The experimental results with respect to the influence of cooling gas composition on clinker quality (objective 4) will be presented later in a second paper in this journal. Nevertheless, the results confirm that CO_2-rich cooling gas has neither a significant impact on clinker quality nor on cement strength development.

2 Methodology

The design of the oxyfuel clinker cooler prototype was based on existing designs for single-stage and two-stage gas-tight clinker coolers which had been developed for application in an oxyfuel process in ECRA's Oxyfuel Project phase III (➧ Fig. 1).

Furthermore, the design took into account the potential for up-scaling, as well as the technical feasibility to be operated in a prototype scale in a cement plant. A continuous bed with full gas recirculation was the layout option selected for further construction and testing. The use of hot clinker and the correct sizing of the prototype were essential for a proper up-scale of the experimental results. Therefore, the option of feeding hot clinker from a running rotary kiln into the prototype was chosen. The prototype was installed at the HeidelbergCement plant in Hanover, Germany. It was designed with a capacity to cool up to 3 % of the usual clinker production of the kiln line. This percentage was considered adequate to run the tests without interfering with the normal operation of the cement plant. The hot clinker bed was cooled with air or CO_2-rich gas. CO_2 was available from a filling station equipped with CO_2 bottles and could be mixed with ambient air. In order to minimise

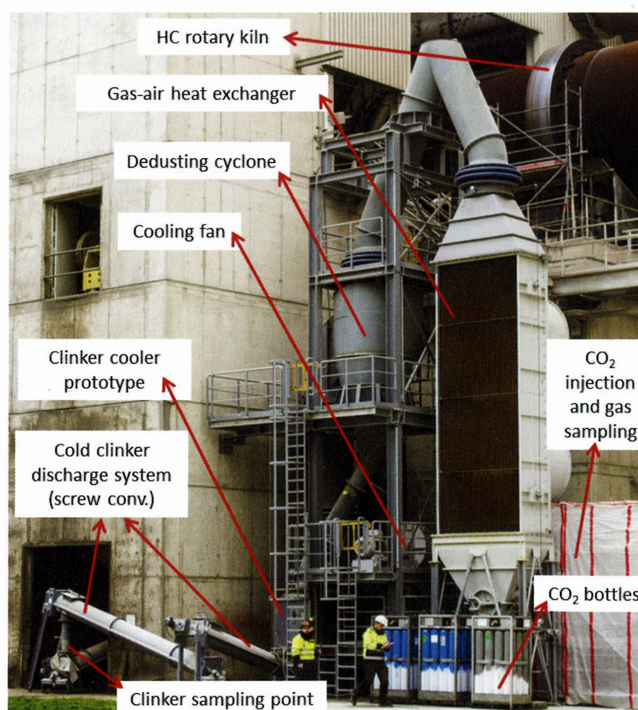

Figure 3: On-site construction of the oxyfuel clinker cooler prototype

Table 1: Cooling gas chemical composition: references and test settings

Cooling gas composition setting	Cooling media	CO_2 [Vol. %]	O_2 [Vol. %]	N_2 [Vol. %]
–	Oxyfuel (ECRA reference)	67	21	9
–	Oxyfuel (base case)	70	18	12
1	Ambient air	0	21	79
2	Oxyfuel tests with CO_2-rich gas	> 70	< 6.3*)	< 23.7*)

*) Only CO_2 was injected. Air was the single source of O_2 and N_2. Therefore, O_2 and N_2 volume percentage are related to each other and their relative volume proportion remained constant.

CO_2 consumption, the cooling gas was recirculated. The general concept of the oxyfuel clinker cooler prototype is shown in ❱ Figs. 2 and 3. Hot clinker is extracted from the kiln hood of the pyro line by a rotating extraction tube and then charged into the cooler prototype. As the hot clinker drops onto the static clinker inlet, the hot clinker forms a clinker bed. The hot clinker bed is cooled with the CO_2-rich gas (or ambient air) which is taken from the suction line behind a gas/air heat exchanger and is transported by two cooling fans to the pressurized compartments underneath the cooler. From the cooler compartments the cooling gas is distributed to the bottom of the clinker bed by passing through the grate surface of the oxyfuel cooler. After passing the clinker bed (cross-flow) the cooling gas leaves the cooler prototype through an exhaust duct located at the cooler roof. The cooling gas is afterwards de-dusted in a cyclone and cooled by a gas/air heat exchanger. At the heat exchanger outlet, the gas is routed again to the cooling fans of the cooler prototype to close the recirculation loop. Besides the production capacity of 2.6 % compared to a full-scale plant, the main difference is that no recuperation gas is routed to the kiln and the heat coming from the cooler is not utilised. The material inside the clinker cooler prototype is transported by the moving grate and discharged at the end of the cooler via a clinker hopper. With the help of four discharge screw conveyors the clinker is then carried from the clinker cooler prototype to the cold clinker extraction system of the cement plant. The clinker mass flow is measured by a mass flow probe installed on a chute connecting two discharge screw conveyors. An extraction point for manual cold clinker sampling is included in the same chute.

As the CO_2-rich cooling gas was produced artificially and recirculated, the cooler prototype had to be, as far as technically possible, gas-tight. Gas tightness was tested on-site. Tightness tests were performed with the pressure change method described in DIN EN 13184 [2]. The pressure change method is used to determine mass change in closed systems, here as gas leakages. This method is based on the ideal gas law. If most of the parameters can be set constant, the change in mass is deducible from pressure changes. As the clinker cooler prototype was an open system, the clinker inlet and outlet were shut. Afterwards the system was connected to the compressed air system of the cement plant and pressurized. The pressure could not be kept constant after stopping the injection of compressed air. This indicated the presence of leakages. To locate the leakages a tracer testing method was used, as described in DIN EN 13185 [3]. This method enables the detection of gas flow through leakages from the inside to the outside. A pressure difference is produced, a tracer is injected and a leakage proof is given, resulting in a local change of colour where the leakages occur. This method was performed three times and all the main leakages in the gas recirculation circuit were detected and sealed. The length of the hot clinker extraction tube, the permanent material flow through the tube as well as similar static pressure in the plant's kiln hood and in the oxyfuel clinker cooler prototype led to the assumption during the engineering phase that the gas exchange between both systems would be very small and negligible during operation.

The aim of testing the oxyfuel clinker cooler prototype in an industrial environment was to collect relevant information regarding the cooler operation and clinker chemistry at different gas compositions. The performance of the test and its integration into the industrial clinker production process was documented in a video shot on-site [14]. The main chemical gas components, which were varied during the testing phase, were nitrogen, oxygen and CO_2. The influence of argon was neglected because of its low quantity. In the case of dry recirculation the humidity was expected to be low and was therefore neglected during the design of the experimental plan. Results from the oxyfuel process simulation performed by ECRA [4] were used as a reference to set the oxyfuel cooling gas composition base case during the tests (❱ Table 1). In addition to the CO_2 supply, a separate oxygen supply was installed in the cooler prototype to enable the simulation of oxyfuel flue gas composition. This was required because O_2 Vol. % is higher than N2 Vol. % in the oxyfuel cooling gas as shown in Table 1.

During the experiment, the cold clinker discharge system was revealed to be a relevant source of false air ingress, which hindered the production of oxyfuel cooling gas with a chemical composition defined as base case. The control of the CO_2 injection to keep the cooling gas with the desired high CO_2 concentration became extremely challenging. Moreover, the high O_2 volume flow demand that would have been necessary to compensate the amount of N_2 entering into the cooler prototype through false air ingress was too high. The additional injection of O_2 would have made the control of the cooling gas composition unfeasible. Therefore, the experimental plan had to be slightly adapted (settings 1 and 2 in Table 1) and a new objective was set for the prototype testing. The new objective was to reach and keep CO_2 concentrations higher than 70 Vol. %. The remaining 30 Vol. % was air. This new gas composition still replicated the main feature of high CO_2 concentration in the recirculated gas used for oxyfuel cooling operation and thus was a good indicator regarding eventual impacts of CO_2 on the clinker quality. Apart from varying the cooling gas chemical composition, cooler prototype control parameters were also varied during the experiment (e.g. clinker-specific cooling gas volume flow and temperature of the cooling gas). Several process parameters (e.g. clinker mass flow, pressures, temperatures, volume flows and cooling gas composition) were recorded continuously at different points of the cooler prototype. In addition, the temperature of each clinker sample taken from the cooler prototype was measured to enable the assessment of the cooling efficiency. Testing innovative technologies also requires checking the need for the implementation of new health and safety measures. As CO_2 has a higher density

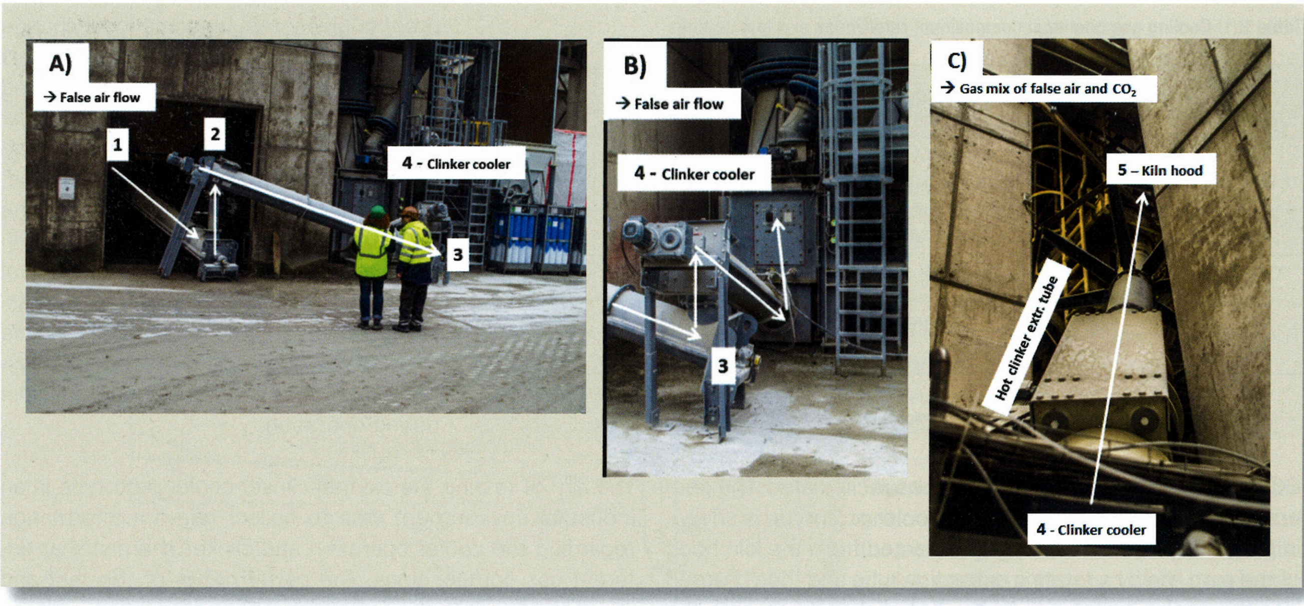

Figure 4: False air ingress circuit

compared to air and thus the risk of accumulation in sub-level areas, special safety measures had to be implemented on-site. A static CO_2 warning system installed at ground level, as well as the mandatory usage of individual mobile CO_2 detectors by each member of the team were the main measures implemented to minimise the risk of CO_2 inhalation in case of leakage. The CO_2 detection systems had been calibrated and tested before on-site installation and usage.

3 Experimental results

3.1 False air ingress

A considerable amount of false air ingress established an unexpected experimental challenge. False air was pulled continuously through the cold clinker extraction system (screw conveyors) into the pilot plant, mixing with recirculated cooling gas and leaving the system through the hot clinker extraction tube (➧ Fig. 4).

The false air ingress volume flow was measured with an anemometer. The measuring point used for this measurement was the opening used for cold clinker sampling (s. ➧ Fig. 3). The measurements with the anemometer (➧ Table 2) could only be performed when clinker was not being fed to the clinker cooler prototype.

Table 2: False air measurement results (performed with an anemometer); $T_{amb.}$ = 8 °C; kiln hood pressure = -0.9 mbar; chute inner diameter = 200 mm

Fans load	Air speed [m/s]	Volume flow [Am³/h]
Fans off	2.7	305
Fans @ partial load (33 to 45 % of maximum rpm)	2.7	305
Fans @ full capacity (maximum rpm)	3.3	373

Table 3: Experimental data: cooling media and clinker temperature

Setting	Cooling media	CO_2 (dry) [Vol. %]	O_2 (dry) [Vol. %]	Cooling medium temperature [°C]	Cold clinker temperature [°C]
1	Air	0	~ 21	91	51
2	Air	0	~ 21	57	30
3	CO_2-rich gas	84	3.0	71	25
4	CO_2-rich gas	67	6.6	55	n/a
5	CO_2-rich gas	75	4.8	66	45
6	CO_2-rich gas	75	4.9	65	45
7	CO_2-rich gas	76	4.6	53	67
8	Air	0	21	63	131
9	Air	0	21	60	83
10	Air	0	21	57	92

3.2 Gas leakage rate to ambient

Gas leakage to ambient may only take place in the pressurized areas of the pilot plant (pressure higher than the atmospheric pressure). The static and the mobile CO_2 warning systems did not detect any leakages of CO_2-rich gas during the experiment.

3.3 Cooling media and clinker temperature

In order to assess the cooling performance of the cooler prototype during oxyfuel operation the chemical composition, temperature and volume flow of the cooling medium were measured continuously. In addition, clinker samples were taken downstream from the cooler prototype and the temperature was measured (➧ Tables 3 and 4).

3.4 Moisture content of the recirculated gas

Without any relevant sources of water in the recirculation circuit (e.g. injection of water in the cooler), the absolute moisture content of the clinker cooling gas (air or CO_2-rich gas) should not change over time. The absolute moisture content of the clinker cooling air is normally below 1 Vol. % (taking European climate as a reference). Therefore, no higher moisture content was expected in the cooling gas

Table 4: Experimental data: cooling media and clinker mass flow

Setting	Cooling media	Cooling medium volume flow [m³/h] (stp., wet)	Clinker mass flow [t/d]	Clinker specific cooling gas volume flow [m³/kgclinker] (stp., wet)
1	Air	7914	30*)	6.3
2	Air	2747	23**)	2.9
3	CO_2-rich gas	6205	20**)	7.4
4	CO_2-rich gas	5856	19**)	7.4
5	CO_2-rich gas	2774	47*)	1.4
6	CO_2-rich gas	2257		1.2
7	CO_2-rich gas	1114		0.6
8	Air	1781		0.9
9	Air	1120		0.6
10	Air	1005		0.5

*) Measured by clinker extraction from the pilot plant and weighing. Clinker weighing was performed only once for the whole set of measures from 5 to 10 due to the impossibility of running the experiment and weighing the clinker simultaneously

**) Measured by contactless mass flow sensor

Table 5: Cooling medium moisture content

Cooling media	CO_2 [Vol. %] (dry)	Measured moisture [Vol. %]
Air	0	8
CO_2-rich gas	74	13

of the pilot plant. Nevertheless, a single measurement of moisture content for each cooling medium (air and CO_2-rich gas) was performed during the experiment (❱ Table 5). The moisture measurement was performed by controlled cooler gas extraction and measurement of the weight difference in silica gel, which absorbs the gas moisture.

4 Discussion

4.1 False air ingress

False air ingress is a very relevant issue in oxyfuel operation with regard to the CO_2 capture rate and efficiency. It can increase the power consumption of the CPU (CO_2 Purification Unit, s. Fig. 1) significantly. In the prototype testing, false air ingress had a significant impact on performing the experiment. The oxyfuel cooling gas chemical composition had to be adapted according to the continuous loss of CO_2 and the ingress of false air (s. Table 1). CO_2 had to be continuously injected in the pilot plant in order to maintain the desired high CO_2 concentration levels for test settings 3 to 7. In addition, the clinker temperature at the cooler prototype inlet and at the cold clinker sampling point was affected. Cold clinker was cooled down in the screw conveyors by false air ingress before clinker sampling and temperature measurement. A CO_2-rich gas (a gas mix of recirculated cooling gas, injected CO_2 and false air) partially cooled down the hot clinker in the extraction tube before reaching the cooler inlet.

The measurements shown in Table 2 confirm that the kiln hood pressure level was the driving force of false air ingress during the experiment. The impact of the load of the cooling fans on total false air ingress was very limited. A maximum false air volume flow of about 370 Am³/h was measured in the worst-case scenario (lowest kiln hood pressure level and cooling fans running at full capacity). False air ingress was assessed to be lower during the tests (up to about 300 Am³/h maximum), as the fans were operating with partial load, and kiln hood relative pressure had been increased to about -0.2 mbar. The false air volume flow measured in the pilot plant can only be used to estimate up-scaling effects very roughly, as the scale and the cold clinker discharge system are different in the prototype cooler system compared to an industrial-scale cooler. The cold clinker discharge system in an industrial-scale oxyfuel clinker cooler will consist of a clinker crusher and pan conveyor rather than screw conveyors. The amount of false air ingress through the clinker crusher installed at the clinker cooler outlet in the normal full-scale clinker manufacturing process is currently unknown and no measurements are available. Nevertheless, the minimisation of false air ingress in oxyfuel operation should always be pursued. How relevant false air ingress through the clinker crusher is and, if relevant, how air tightness could be improved are questions that remain for the design of oxyfuel coolers at industrial scale.

4.2 Gas leaking rate to ambient and seals

The absence of CO_2 leakages proves that the seals installed in the pressurized zones of the pilot plant (from cooling fans to clinker cooler under-grate area) performed properly. However, the use of similar sealing technology in industrial-scale oxyfuel coolers should be treated with some caution. Operating conditions are more demanding at industrial scale and the seals' performance over a long time period could not be assessed during the limited duration of the tests.

4.3 Clinker cooling curves and cooler efficiency with CO_2-rich gas

The assessment of the cooling efficiency of the oxyfuel clinker cooler prototype with CO_2-rich gas and of the clinker cooling curves was partially compromised by false air ingress. Some process data relevant to closing the energy and mass balances of the oxyfuel clinker cooler prototype were not measured during the experiment. The hot clinker temperature at the cooler prototype inlet is an important parameter to close the energy and mass balance but cannot be measured accurately. For the purpose of calculating hot clinker energy, a temperature of about 1400 °C is assumed for industrial clinker grate coolers [6]. The significant amount of false air ingress in the pilot plant did not allow the application of this simple assumption. The cooling gas escaping through the hot clinker extraction tube promoted a fast cooling of the clinker which already started in the extraction tube and before reaching the cooler (counter-flow heat exchange). Therefore, a hot clinker temperature much lower than 1400 °C was expected at the cooler inlet for the prototype tests. As expected, some impacts on clinker mineralogy and microstructure were observed due to such fast cooling conditions.

Clinker temperatures below the cooling medium temperature were observed due to some additional cooling promoted by false air ingress in the clinker extraction system before sampling. The measurement of the clinker mass flow by a contactless mass flow sensor showed limited reliability (strong fluctuation and inaccuracy). This led to cooling down the clinker with much higher clinker-specific cooling gas volume flows in some tests (up to 7.4 m^3/kg clinker, stp.) than is common practice in industrial-scale coolers (1.6 to 2.3 m^3/kg clinker, stp.). As the clinker-specific cooling gas volume flow from settings 1, 3 and 4 are out of the desired range, one may assume that they are not representative of normal industrial cooler operation. The use of these settings for the assessment of the prototype cooler performance is very limited.

In summary, the calculation of the cooling curves and cooler efficiency with oxyfuel operation was subject to significant uncertainty due to false air ingress and inaccuracy of the clinker mass flow sensor. Therefore, it was not possible to draw final conclusions about the clinker cooling curves for future oxyfuel industrial application. For the purpose of optimisation of the cooler designs further research is therefore recommended. Nevertheless, the lack of precise information about the oxyfuel clinker cooling curves does not put at stake the construction of an oxyfuel clinker cooler for the demonstration of the oxyfuel process at full-scale in cement plants. For demonstration purposes the oxyfuel clinker cooler should be designed with generous safety margins to minimise operational risks. Operational data collected during the demonstration project can then be used for cooler design optimisation. Also, the effects of the cooling gas temperature, volume flow and chemical composition (CO_2 concentration and moisture content of the recirculated kiln gases) on the clinker cooling rate should be assessed further in a full-scale demonstration project.

4.4 Moisture content of the recirculated gas

The measurements indicated a surprisingly high cooling gas moisture content well above 1 Vol. % (s. Table 5). The reason for such high moisture content in the cooling medium remains unclear. The accuracy of the measurements and the indicated absolute values remain questionable. One plausible explanation is that moisture had its origin in the refractory lining of the pilot plant. Despite its general plausibility, it is impossible to prove this explanation with the available experimental data. Moreover, silica gel may also be prone to absorbing CO_2 to a certain extent. Such an occurrence would distort the moisture measurements performed on site. Nevertheless, one may affirm that the moisture content in the recirculating gas was higher than expected. One obvious effect was the blockage of the grate plates due to the presence of fine dust particles combined with moisture in the recirculating gas (Figs. 5 and 6).

Figure 5: Dust clogging the lamellas of the cooler grate plates

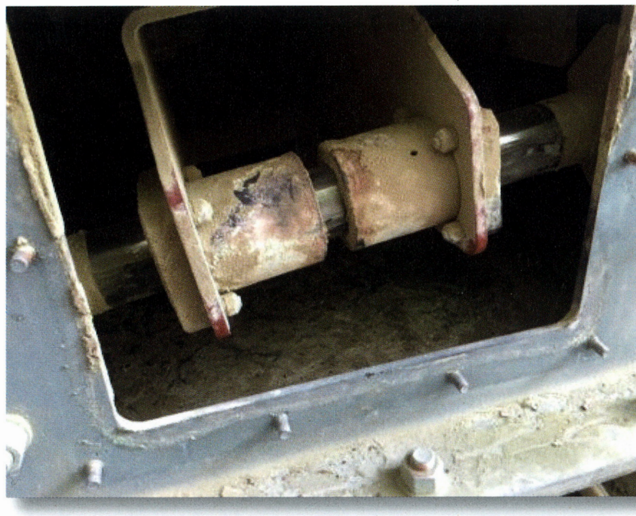

Figure 6: Dust clogging the linear unit of the grate suspension

4.5 Other design and experimental challenges

The immersion of a refractory-lined steel tube in the kiln hood to route hot clinker to the cooler prototype poses several technical and operational challenges. The tube's refractory tip was completely destroyed three times during the tests by large clinker lumps falling from the kiln. In addition, the mechanical impacts in combination with high thermal stress slightly bent the extraction tube over time, which made the control of the hot clinker extraction tube more difficult. Partial-load operation led to the reduction of the overall recirculation gas flow, which in turn decreased the separation efficiency of the de-dusting cyclone. Recirculated clinker dust in combination with moisture in the recirculated gas slowly narrowed the ventilation slots and clogged the cooler grate plates several times. Therefore, the maximum acceptable moisture and dust content in the recirculated cooling gas should be investigated in order to guarantee a reliable and trouble-free operation of the cooler. The reduction of the overall recirculation gas flow also affected the control of the heat exchanger gas outlet temperature. With very low ambient air temperatures in January 2017 and even without the operation of the two axial fans of the heat exchanger (switched off) the gas outlet temperatures remained in a range of 53 to 71 °C, except for test setting 1 (s. Table 3).

5 Conclusions

The recovery of heat from burnt cement clinker plays a key role in the total energy consumption and CO_2 emissions of the clinker burning process. Thus, the successful testing of the world's first oxyfuel clinker cooler prototype in an industrial environment was an important step forward for the development of future industrial-scale oxyfuel cement plants.

The focus of this paper is purely on the operation of the oxyfuel clinker cooler prototype. Clinker samples were also collected during the experiment and analysed afterwards in VDZ's laboratories. The analyses confirmed that CO_2-rich cooling gas has neither a significant impact on clinker quality nor on cement strength development. Detailed information will be presented in a second paper.

PROCESSING

The operation of the oxyfuel clinker cooler prototype confirmed that the design of the cold clinker discharge system requires special attention concerning the minimisation of false air ingress. This conclusion is relevant for prototypes as well as for industrial-scale oxyfuel clinker coolers.

The clinker cooling rates in a CO_2-rich atmosphere could not be determined and, thus, further investigation with full industrial-scale equipment is required.

Moisture in combination with dust from the recirculated gas increases the risk of blocking the cooler grate plates. The maximum acceptable moisture and dust content in the recirculated cooling gas of an oxyfuel cement plant should be investigated in order to guarantee a reliable and trouble-free operation of the clinker cooler.

No CO_2 leakages were detected during the experiment, which is a good indicator of the reliability of the seals for future use in industrial-scale coolers. Despite the promising results, the performance of the seals still needs to be assessed over a long time period and under real industrial operating conditions.

Acknowledgements

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