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Feeding a gas turbine with aluminum plant exhaust for increased CO₂ concentration in capture plant

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Abstract

Aluminum production contributes to global CO₂ emissions both due to the production process itself and due to the generation of electric power required for aluminum production. A concept is presented for increasing the CO₂ concentration in the aluminum exhaust from ~1% to ~5% through the feeding of aluminum plant exhaust gas to a natural gas combined cycle (NGCC). The specific energy demand for CO₂ capture is therewith reduced for both the aluminum plant and the NGCC. An evaluation was made of the impact the aluminum exhaust gas may have on the gas turbine and it is estimated that the most critical issues are corrosion due to SO₂ in the aluminum plant exhaust gas and gas turbine inlet filter saturation, since the exhaust gas is saturated with seawater after the wet scrubber. A gas turbine inlet filter was tested for a period of five weeks, but a longer filter test period would be required for verifying filter integrity over time. In order to proceed, the viability of the concept should be evaluated by a gas turbine manufacturer. An alternative concept to evaluate for concentration of CO₂ emissions could be to feed the aluminum plant exhaust gas to a boiler in a steam power plant.

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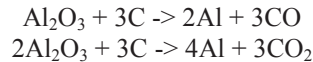
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1. Introduction

CO₂ emissions from the aluminum industry occur from the aluminum-production process itself and often also from the generation of the electric power that is required in the production process. CO₂ emissions from electric power could be avoided or reduced through the use of hydropower or other renewable energy sources, or through the application of CO₂ capture from fossil-fuelled power generation. However, reduction of CO₂ emissions from the aluminum production process itself is perceived as more difficult and energy demanding due to the low CO₂ concentration in the aluminum plant exhaust. This paper presents a concept that may enable a reduction of the energy demand for capturing CO₂ from the aluminum production process, and simultaneously provide on-site power production with CO₂ capture.

During the aluminum production, using the Hall-Héroult process, alumina (Al₂O₃) is reduced to aluminum according to the two reactions in parallel:



The second reaction is dominating due to reaction kinetics. The carbon required is supplied by carbon anodes, and as can be seen, the CO₂ emissions from the process are an inherent part of the aluminum production. CO₂ emissions from Al₂O₃ reduction amounts to approximately 1.6 tonne of CO₂ per tonne of aluminum produced. However, the CO₂ concentration in the exhaust is very low, typically below 1%, since large quantities of air are employed for cooling of the electrolytic cells and for cooling of the raw gas before gas treatment. Feeding exhaust gas with very low CO₂ concentration to a post-combustion capture plant would be very energy-demanding. Simulations with the SINTEF/NTNU in-house simulator CO₂SIM [1] predict an energy demand of 6.1 MJ/kg CO₂ captured, for a CO₂ concentration of 0.95%, when using MonoEthanolAmine (MEA) in the capture process.

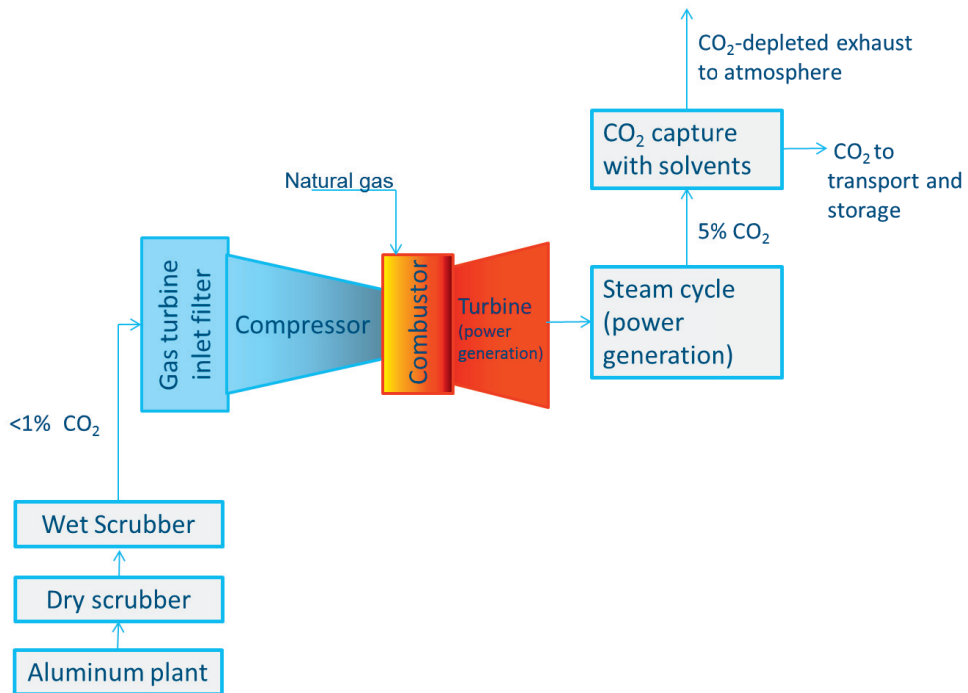


Figure. 1. Concept for feeding the gas turbine with aluminum plant exhaust and increase CO₂ concentration prior to capture.

An alternative solution, envisaged in order to increase the CO₂ concentration of the aluminum plant exhaust, could be to use the aluminum plant exhaust as the working fluid in a gas turbine that operates in a natural gas fired combined cycle (NGCC), as illustrated in Figure 1. The aluminum plant exhaust gas is rich in oxygen, and should from that point of view be possible to use for combustion purposes in a gas turbine combustion chamber. The resulting CO₂ concentration in the exhaust gas would then typically be 5%. A calculation with CO2SIM shows that this corresponds to a capture penalty of 3.5 MJ/kgCO₂ captured. Moreover, an NGCC with an exhaust gas CO₂ concentration of 4% has a CO₂ capture penalty of around 3.9 MJ/kg CO₂ captured [2]. As illustrated in [4], the energy demand for CO₂ capture with MEA decreases with increasing CO₂ concentration up till a concentration around 12%. Hence, when combining the aluminum plant exhaust and the NGCC, and thus increasing the CO₂ exhaust concentration to 5%, the energy demand for capturing CO₂ from the NGCC will also be reduced. This reduction in energy demand would result in an efficiency increase of around 0.6 %-points for the NGCC in stand-alone operation, from 49.8 to 50.4%. However, the calculated overall efficiency for an NGCC when fed with a gas composition of the type listed in Table 1, instead of with air, is 49.0%. The resulting reduction in overall efficiency is the energy penalty for capturing and compressing the additional CO₂ from the aluminum plant.

Hence, from an energy consumption point of view, the concept illustrated in Figure 1 appears attractive, in particular for an aluminum producer that would prefer on-site power generation with low CO₂ emissions. However, the aluminum plant exhaust gas will always contain minor fractions of gaseous impurities that are not naturally present in air. Although these impurities should be below permissible levels regulated by national authorities, it is not obvious without conducting further investigations that it is possible to operate a gas turbine engine with the aluminum plant exhaust gas as working fluid. Therefore a first qualitative assessment is presented in this paper as a part of the work with assessing whether this concept is feasible or could have potential showstoppers. Thereafter test results from the feeding of a slip-stream of the aluminum plant exhaust to a gas turbine filter are presented.

2. The aluminum plant exhaust composition

The final process step before emitting the exhaust gas to the ambient from a typical aluminum plant is the sea water scrubber, where SO₂ is dissolved in sea water, so that that the SO₂ emitted to the atmosphere is reduced to permissible levels. A typical composition of the aluminum plant exhaust after the wet scrubber is shown in Table 1. In addition, the exhaust gas may also contain fine dust particles with traces of metals such as V, Ni, Pb, Zn, K, Ca, Na.

Using a sea water scrubber leads to saturation of the aluminum plant exhaust with sea water. This can potentially be problematic if feeding this gas as inlet air to a gas turbine, as described further on. Any NaCl contents in the water would come from the sea water. From an emissions point of view, content is regarded as insignificant and consequently smelters are not required to analyse and report NaCl.

Table 1. Major constituents of a typical aluminum plant exhaust stream after sea water scrubber.

Component	Concentration
CO ₂	0.90-0.95% (v)
O ₂	20.7-20.8% (v)
H ₂ O*	1.2% (v)
HF	20-28 ppb (v)
SO ₂	1.4-3.5 ppm (v)
NO _x	0.8-1.3 ppm (v)
CO	640-720 ppm (v)
N ₂	Balance

3. Qualitative analysis on possible impact on the gas turbine from aluminum plant exhaust

3.1. Inlet filtration system

The air entering any stationary gas turbine must pass through an air filtration system, which is typically of the HEPA (High Efficiency Particulate Air) type. The filtration efficiency is very high when operating under normal conditions, meaning that fouling and erosion rates are quite low for the gas turbine. However, filters operating at 100% relative humidity may experience "filter saturation", where the filter ultimately releases the entire amount of filter pollutants (in solution with water) into the engine in a very short time period, with resulting costly engine failures. A remedy to filter saturation is to install an inlet heating system, at the expense of reduced gas turbine performance and increased energy consumption. Since the aluminum plant exhaust is saturated with sea water after the wet scrubber outlet, avoiding filter saturation appears to be one of the key issues with the concept illustrated in Figure 1.

It should be noted that commercial gas turbine inlet filters designed for marine applications exist today. Also, manufacturers have begun to offer inlet filters claimed to be able to operate at 100% relative humidity in air.

3.2. Compressor

Modern gas turbine compressors have precision-made highly loaded blades that are sensitive to geometry changes caused by fouling or erosion, both of which can occur if particles enter the compressor. Compressor fouling (impurities attach to the compressor blading, which temporarily changes the aerodynamics) is usually concentrated to the first stages, and the remedy is washing, which is a standard procedure that should be possible to apply also in the aluminum case. Compressor erosion (impurities hit the blading and change its surface) alters the aerodynamic performance permanently, which reduces the compressor efficiency and reduces the surge margin. The cure to avoid compressor erosion, that could be necessary in the present case, is to introduce an aluminum slurry blade coating with a ceramic top layer for maximum erosion resistance. Such compressor coatings have been developed for aeroengines, where filtration is impractical. It is also common practice today to use various types of coatings even for land- and marine based units. The latter type of engines is especially susceptible to compressor corrosion due to the harsh environment. As mentioned above, fouling and erosion are rather low for a gas turbine compressor when using a HEPA filter, but it cannot be said with certainty without further experimental investigations, if the situation will remain the same in the case where the inlet air is replaced by the aluminum plant exhaust.

Compressor corrosion is mainly due to moisture that contains acids and salts. The high working fluid velocities will cause the temperature to drop in the first stages of the compressor and droplets will form in the air and also water will condense on the compressor surfaces. Pollutants will be effectively scrubbed from the air and make the droplets and surfaces acidic. Very low levels of pollutants may have very high acidic effects on the compressor surfaces, which could cause corrosion. It is claimed in [3] that a level of 100 ppb of SO₂ in air would result in a pH of 4.5 on the blading, and 1 ppm would result in a pH of 4.0. The corrosion mechanism is usually pitting corrosion, and the primary damage mechanism is crack initiation.

3.3. Cooling flow channels/secondary air system

The compressor surfaces can probably be coated to withstand erosion and corrosion, but, approximately 19-25% of the flow entering the compressor in a modern gas turbine engine is extracted from the main compressor flow and ducted through narrow passages to the combustion chamber and turbine blades. These passages are difficult to protect through coating, which may prove to be troublesome for the gas turbine integrity and operation over time. The passages are also very narrow, and thereby sensitive to particles that may cause fouling or even blocking of the passages. This would be detrimental to the hot part of the gas turbine expander, which relies on continuous cooling to remain its integrity.

3.4. Gas turbine burner section

The complete gas turbine burner section includes the liner, burner and transition piece. For modern F- G- and H-class frame engines, the combustor outlet temperature may exceed 1500°C, while the actual flame-zone temperature is even higher. The hot parts are typically protected with thermal barrier coatings and also cooled with cooling air, in order to get the required lifetime of the burner section. There is also a concern that HF cause corrosion, and it must be further evaluated whether present thermal barrier coatings can withstand this type of corrosion. As can be seen in Table 1, however, the concentration of HF is typically very low in the aluminum plant exhaust, since most of this component is removed in the dry scrubber.

3.5. Expander

The gas turbine expander consists of highly stressed rotating blades, attachments and discs. There are also non-rotating parts that are exposed to the hot, pressurized working fluid. The reaction $2\text{Na} + \text{SO}_2 + \text{O}_2 \rightarrow \text{Na}_2\text{SO}_4$ is very energy demanding, but it cannot be excluded that it could occur in the gas turbine combustion chamber in the present case. Na_2SO_4 is a molten sulfate that will cause hot corrosion, which is an extremely rapid process. The main damage mechanism is that the protective layers of the turbine (Al_2O_3 and CrO_3) are depleted or destroyed. If these protective layers are destroyed, there will be a reduced material thickness and reduced load carrying capacity in the expander, which probably can lead to fatigue failures. The situation gets even worse if metallic salts containing V, Pb, Ca, K, Li, or Mg are present as either fuel- or air-borne pollutants. This type of corrosion is usually referred to as type I hot corrosion, and is typically kinetically restricted to temperatures above 900°C.

In addition, the combination of NaCl (from the inlet gas saturated with seawater) and Na_2SO_4 produces a molten salt mixture that condensates at temperatures already below 600°C (type II corrosion). The outlet temperature of a large modern stationary gas turbine is roughly around 600°C or somewhat below, which means that there is a risk that the last stage of the gas turbine expander could be exposed to type II corrosion.

Altogether, the combination of high turbine stress levels and elevated temperatures results in a sensitive system. Most catastrophic failures from corrosion damages, like a blade-off scenario, should be contained (i.e. only cause damage inside the turbine) with severe secondary/collateral damage. A full disk burst would be catastrophic, and certainly not contained, i.e. parts would penetrate the engine casing with associated serious safety, fire and health issues.

3.6. Conclusions from qualitative evaluation

The following key issues that may be of concern arise from this first qualitative evaluation:

- Filter saturation
- Compressor corrosion (pitting corrosion, causing crack initiation)
- Cooling flow channel injury (fouling, corrosion, blocking due to particles)
- Risk of corrosion in combustion chamber due to presence of HF
- Expander corrosion, type I and II

Based on this first evaluation it was concluded that the first priority would be to test the filtration capacity of a standard gas turbine inlet filter when exposed to the aluminum plant exhaust gas, in order to quantify the amounts of SO_2 , Cl, and metals (Na, K, Ca, V, Ni, Pb, Zn) that pass through the filter. It was also clear already at this stage that in order to proceed much further with the investigation, a gas turbine engine manufacturer should be consulted in order to clarify the main obstacles to the concept, and possible remedies.

4. Experimental setup for gas turbine filter testing and sampling

An experimental test facility (Fig. 2) was designed to place a standard gas turbine HEPA filter (class E12) in a slip stream of the Hydro aluminum plant at Sunndalsøra in Norway. This filter is designed to be able to operate at 100% relative humidity. Based on knowledge of the aluminum production process and subsequent dry scrubbing and wet scrubbing processes, the following components could be expected in the exhaust gas:

- V, Ni, Pb, Zn, K, Ca, Na
- SO₂
- Cl⁻

HF was not included in this first measurement series since the levels of HF are measured regularly in the exhaust of the plant, and the concentration of HF is stable and significantly lower than the typical values given in Table 1.

The filter test fixture dimensions did not allow for isokinetic sampling. After a HEPA filter class E12 (> 99.5 % retention), the particle loading of the filtered gas (upstream particle concentration < 0.1 mg Nm⁻³ for a filter with > 99.9 % retention) is nevertheless expected to be very low. Aerosols of size less than 0.3 microns may pass the filter, facilitating transport of adsorbed or dissolved species. As isokinetic sampling is less critical for particles < 1 microns, the sampling is expected to be fairly representative for the evaluation of filter efficiency. The use of impingers or fritted absorbers also counteracts further losses of aerosols not being absorbed into the gas washer absorbent solution. The sampling train is illustrated in a general way in Figure 2.

Sampling of metals was done according to the EN 14385:2004 standard, sampling of sulphur was done according to the EN 14791:2006 standard and sampling of chloride ions was performed in accordance with EN 1911:2010 standard. No sampling of Cl₂ was done, since there are no sources of chlorine gas in aluminum production. The source of the chloride ions is the seawater in the wet scrubber that enters in direct contact with the aluminum plant exhaust. The subsequent analysis of the samples was performed with Inductively Coupled Plasma – Mass Spectrometry (ICP-MS). In addition, the pressure drop over the filter and the difference in pressure upstream of the filter and the atmosphere were measured. One of the main purposes with this measurement was to be able to locate in time a possible filter breakdown, which would have been detected as a sudden decrease in pressure drop between the two transducers. The main reason for filter breakdown was anticipated to be the minor fractions of HF present in the aluminum plant exhaust gas.

Three series of measurements were conducted:

- Background measurements, filtering ambient air (as shown in Figure 3)
- Filtering of aluminum exhaust gas, new filter
- Filtering of aluminum exhaust gas after five weeks of operation

A gas turbine filter is normally operated for three years of operation, the short test period of five weeks was judged to be reasonable for a very first evaluation of the filter capability and of the experimental facility in itself.

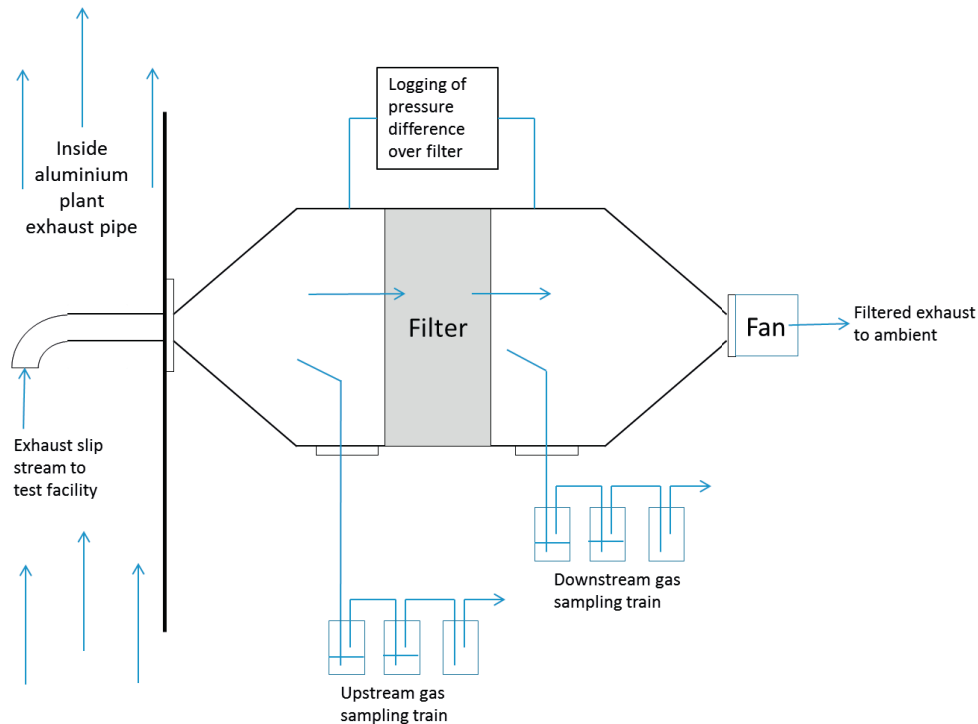


Figure 2. Schematic illustration of experimental facility with gas sampling.

5. Key results from measurement campaign

The main constituents in the collected gas samples were S, Cl, K, Ca, Na and Al. The measured concentrations can be seen in Table 2.

Table 2. Samples collected and ICP-MS results of significant constituents in gas samples. All results are of unit ppm (w). Results for samples S4S5 and S6S7 show averaged values.

Sample/ Location	Description	Time	Absorbent	Gas volume (Nm ³)	SO ₂	Cl	K	Ca	Na	Al
S1/AF	Background	BOT	HNO ₃ /H ₂ O ₂	7.894	0.007	0.004	0.003	0.003	0.019	0.094
S2/AF	Metal sampling	BOT	HNO ₃ /H ₂ O ₂	8.529	2.951	0.003	0.001	0.000	0.004	0.001
S3/AF	SO ₂ /Cl sampling	BOT	H ₂ O ₂	6.823	3.287	0.001	0.001	0.001	0.002	0.000
S4S5/AF	Metal and SO ₂ /Cl sampling	EOT	HNO ₃ /H ₂ O ₂	4.511	0.589	0.022	0.003	0.003	0.003	0.002
S6S7/BF	Metal and SO ₂ /Cl sampling	EOT	HNO ₃ /H ₂ O ₂	6.000	1.163	0.014	0.002	0.002	0.003	0.003

AF = After Filter, BF= Before Filter, BOT = Beginning of test, EOT = End of test

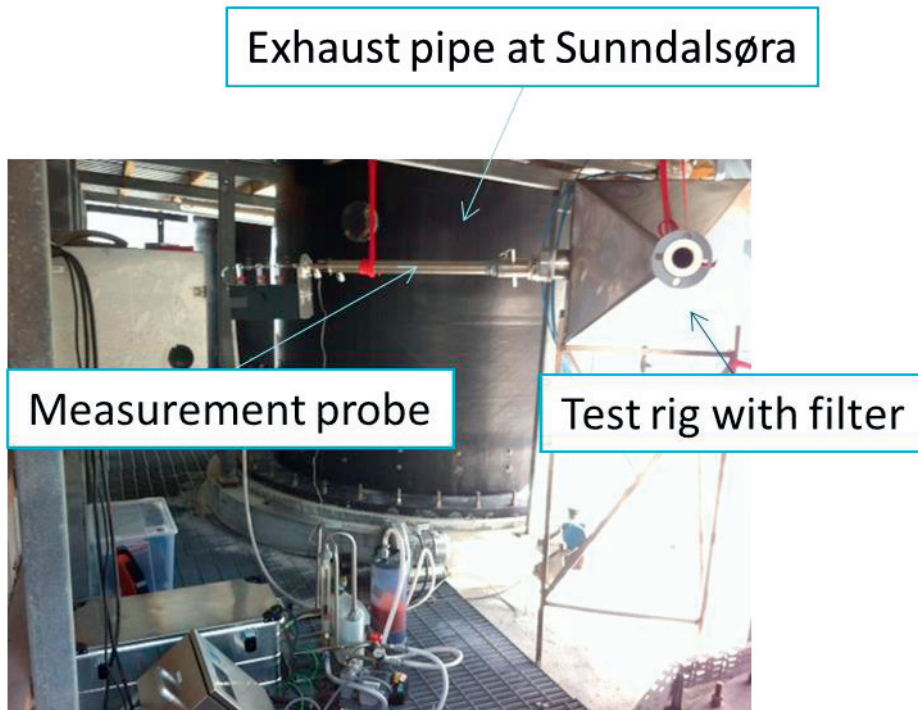


Figure 3. Test rig operating with air (background measurements) at Sunndalsøra.

Draining of the experimental facility illustrated in Figure 2 was insufficient, and approximately 3 centimeters of the filter was soaked in water at the end of the test period. Apart from this, there was no visible indication of filter deterioration after the testing, and no sudden decrease in pressure drop over the filter during the test period, meaning that the fractions of HF (typically at ppb level at Sunndalsøra) did not destroy the filter during the test period. There were signs of corrosion inside the experimental facility, upstream of the gas turbine filter, due to carbon steel being employed in one of the flanges joining the experimental facility to the aluminum plant exhaust pipe. Samples were taken from the condensed water at the end of the test period. Elements sourcing from steel and seawater were quantified in the ppm concentration range.

The level of SO_2 was measured to be approximately halved over the filter and is well below Norwegian permissible emission levels already upstream of the filter. However, SO_2 is at the order of magnitude of 1 ppm, and it has been calculated by Haskell [3], that 1 ppm of SO_2 in gaseous phase can result in a pH of 4.0 when condensation occurs on the compressor blading, and potentially acidic droplets can be present also in the cooling channel system. It should also be mentioned that the SO_2 concentration in the Sunndalsøra plant exhaust varies slowly over time. For example, one year before the measurements, it was one order of magnitude less. As mentioned in section 3.2, 100 ppb of SO_2 in the gas turbine inlet air should correspond to a pH of 4.5 in condensed droplets in the compressor.

The sum of Na and K amounts to up till roughly 6 ppb downstream of the filter which is less than what was detected in the background measurements. Most engine manufacturers have limits for how much alkali can enter the engine, typically in the order of a few or one ppm of Na+K. The fuel flow is typically 1.5-2% of the air flow through the gas turbine, which means that the permissible concentrations of alkali in the incoming air or from the aluminum plant exhaust should be two order of magnitudes lower. But there are indeed gas turbines operating in

coastal areas, and altogether, since the alkali level was higher in the background measurements, this should not be an alarming issue, compared to the measured levels of SO₂.

It should be noted that there is both Na and SO₂ present in the gas downstream of the gas turbine filter, meaning that the risk of Na₂SO₄ formation, and hence of hot corrosion in the gas turbine, cannot be excluded at this point in the concept evaluation. It should be noted that the measured levels of K, Ca and Cl are higher downstream of the filter than upstream at the end of test and they may have been influenced by the fact that the filter was soaked – this would have to be one of the topics to investigate further in new measurements.

6. Overall conclusions and thoughts on further work

6.1. Gas turbine concept conclusions and further investigations

Based on the work conducted so far it is not (yet) possible to draw the desired conclusion that a gas turbine can be fed with the exhaust gas from an aluminum plant. The qualitative investigation pointed out several potentially problematic topics, where corrosion in different parts of the engine is seen as the most critical, followed by the risk of filter saturation. The conducted testing of the HEPA filter of class E12 revealed an approximate halving of SO₂ concentration removed with standard filter technology. However, the SO₂ level is probably still significantly above what could be allowed if a gas turbine manufacturer should give guarantees for a long gas turbine life. Therefore, in order to proceed with this concept, a gas turbine manufacturer should evaluate the viability of the concept and quantify the permissible levels of SO₂, as well as Na, K and HF and other potentially harmful substances that may enter the gas turbine. Possible replacement of materials in critical sections of the gas turbine may be evaluated, as well as the necessity to derate the engine (i.e. reduce the firing temperature, and hence the process overall efficiency), and the necessity of more frequent inspection intervals and washing intervals than for conventional industrial gas turbines. There are indeed aeroengines flying in coastal polluted areas, which are exposed to both NaCl and SO₂, but routines for O&M may be significantly different for these engines than for industrial gas turbines operating at base load.

In addition, there are several other potential areas for further investigations:

- Alternative ways of removal (deep cleansing) of SO₂ and other impurities from the aluminum plant exhaust could be evaluated, in order to avoid saturation with seawater and obtain further reduction of SO₂ levels. This would also mean that the Na and Cl occurring from seawater could be avoided.
- The normal lifetime of a gas turbine inlet filter is approximately three years. An accelerated filter test over a test period of several months should be of interest to conduct, in order to evaluate any impact over long term from the aluminum exhaust gas. In particular, it is of interest to measure HF levels after the filter and try to verify whether the presence of the very low HF concentrations in the exhaust gas may damage the filter.
- An evaluation of chemical reactions that may occur in the gas turbine combustion chamber, such as formation of Na₂SO₄, should be of interest to investigate. The risks associated to a possible presence of minor fractions of HF in the gas turbine should probably be given particular attention. HF is corrosive and potentially also has the capacity of destroying the protective scales on hot super-alloys.
- Once it has been assessed what happens in the combustion process, i.e. what components are present in the gas entering the expander, the influence on the CO₂ capture system (e.g. amines) must be investigated, in order to identify problems that may need to be resolved. For instance, chlorides may lead to corrosion in the capture plant, and increased corrosion will usually increase the degradation rate of the solvent. There may also be other issues to address, like degradation of the solvent due to the presence of SO₂.

6.2. Alternative concept: feeding a steam boiler with aluminum plant exhaust gas

Using the aluminum plant exhaust gas in a gas turbine is likely to be the most efficient solution for on-site power production and co-capture of CO₂ from power and aluminum production. However, the alternative illustrated in Figure 4, with burning e.g. coal or biomass in a boiler and produce power in a steam power plant could be an interesting alternative to investigate. A boiler fired with coal or biomass would enable further increase of the CO₂ concentration at the power plant outlet and further reduce the energy demand for CO₂ capture. The disadvantage would be the reduction in power generation efficiency, compared to the gas turbine combined cycle. However, a boiler is presumably less sensitive to the aluminum exhaust impurities, and biomass boilers are designed and operated for an alkali-containing environment. Also, the availability and reliability of such a concept would probably be better than for the gas turbine combined cycle, in view of e.g. the potential hazards with corrosion and possible additional inspection intervals that could be required for the gas turbine.

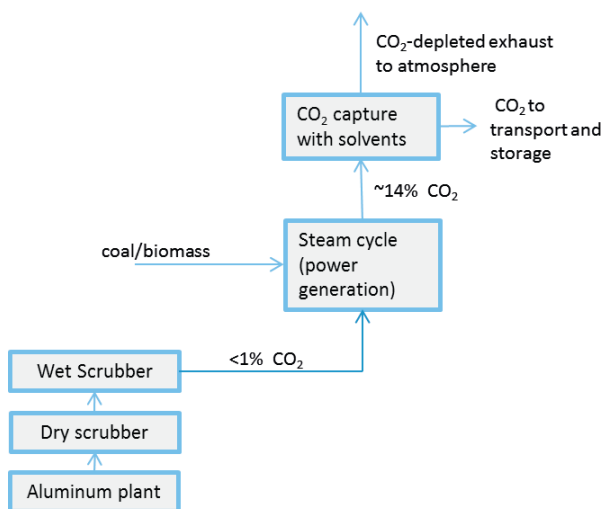


Figure 4. Concept for feeding a steam power plant with aluminum exhaust gas for increased CO₂ concentration prior to capture.

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