Pilot Test to Capture Water from the Flue Gas of a Coal-Fired Power Station

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ABSTRACT

One of the major challenges of this century is the provision of water for a growing population and the industry. The shortage in water resources in arid areas requires the availability of more efficient and cheaper water production processes. A large source of water is found in the form of evaporated water emitted from different industrial processes. This water vapour can be selectively removed by gas-gas separation membranes. Within the European CapWa project, thirteen partners set out to upscale this technology and pilot test the membranes in a coal-fired power plant. The pilot test was conducted for a period of 3 months at the Rutenberg plant. It can be concluded that a large scale pilot plant produces similar fluxes to lab findings and that the water quality easily fulfils drinking water standards (except for pH). The measured energy consumption values support previously conducted modelling work.

INTRODUCTION

One of the major challenges of this century is the provision of water for a growing population and the industry. The shortage in water resources in arid areas requires the availability of more efficient and cheaper water production processes. In some areas like the Middle East water is even more important than energy production. A large source of water is found in the form of evaporated water emitted from different industrial processes. If, for example, 20 % of the evaporated water from the flue gas stream of a coal-fired power plant were captured, the plant would be self-sufficient from a process water point of view. The objective within the European Integrated Project CapWa is to produce a commercially available membrane-modular system suitable for industrial applications within 3–4 years. The produced demineralized (demin) water from this system should be competitive with existing demin water technologies. The starting point of this project was the water vapour selective composite membranes that were developed in the Proof of Principle project. The Proof of Principle project showed that energy efficiency can also be achieved. The CapWa project (www.watercapture.eu) commenced in 2010 and consists of thirteen partners, of whom nine are from the European Union, two are from the African continent and two are from the Middle East.

One of the goals of the CapWa project was to conduct an industrial-type pilot test at a coal-fired power plant. This pilot test was conducted in the period of June to August 2013 at Rutenberg Power Station in Ashkelon, Israel. This article describes the set-up of the pilot unit, the membrane modules, and the results of the pilot test. Based on this pilot test, recommendations are made and a conclusion is provided that can help describe the future outlook for this technology.

Pilot Plant Siting

To test the pilot installation under real flue gas conditions, a bypass was created at the Rutenberg Power Station of the Israel Electric Corporation (IEC). At Rutenberg Power Station four lines are present, two of which are equipped with a flue gas desulfurization (FGD) unit. These are Units 3 and 4, each producing 550 MW and emitting 1.9 million $m^3 \cdot h^{-1}$.[a] Flue gas was taken from behind the FGD of Unit 4, guided along the stack to the test location and taken back to Unit 3 using polythene (PE) piping. A schematic drawing is shown in Figure 1. Figure 2 shows several detail photos of the pipework connecting Unit 4 to the container and back to Unit 3. According to design calculations, the lower case flue gas temperature entering the pilot test unit would be 46 °C, based on homogeneous flow conditions.

The flue gas at the location of extraction is saturated with water and has a temperature of 50–55 °C. Analyses were

[a] The volume of a gas stated in m^3 refers to standard temperature (0 °C) and pressure (100 kPa).

performed on the flue gas on August 20th, 2013. The composition of the flue gas before (feed) and after (retentate) the pilot system was measured by gas chromatograph (GC) and is shown in Table 1.

The amount of dust particles is higher than what is found in most Western European coal-fired power plants, which have slightly more stringent values of 10 mg · m^{-3}. These particles can result in fouling of the membranes. Also, an amount of water droplets can be expected in the feed flue gas stream of the pilot unit.

Membrane Modules

The membranes were manufactured in an industrial setting (Figure 3) utilizing ultra poly ether sulfon (UltraPES) as a support material, which was coated two times with sulphonated polyether ether ketone (sPEEK). The sPEEK was supplied by a commercial supplier and dissolved in a methanol solution. As part of this project a membrane

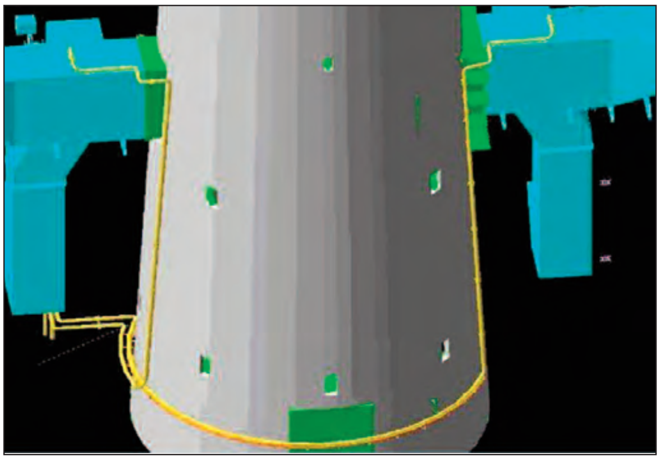

Figure 1:
Schematic drawing of pipework supplying real flue gas to the pilot container.

Figure 2:
Detail photos of extraction of flue gas from Unit 4 (top left), blower and test rig (bottom left), and pipework coming down from Unit 4 and part of return line back to Unit 3 (right).

	Feed*	Retentate*	Average Value in Year 2011–2012**
NO_x ($mg \cdot kg^{-1}$)	232	225	400
SO_2 ($mg \cdot kg^{-1}$)	60	60	140
CO ($mg \cdot kg^{-1}$)	22	12	40
O_2 ($m^3 \cdot m^{-3}$)	0.065	0.063	–
CO_2 ($m^3 \cdot m^{-3}$)	0.122	0.125	–
Particulate matter	–	–	15 $mg \cdot Nm^{-3}$

Table 1:
Flue gas properties during testing on August 20th.
* Corrected for dry conditions
** Corrected for dry conditions and 6% O_2

coating machine was developed. Operating this machine will help provide necessary information to design even larger industrial membrane coating machines. This machine can easily be upgraded to produce membranes on an industrial scale.

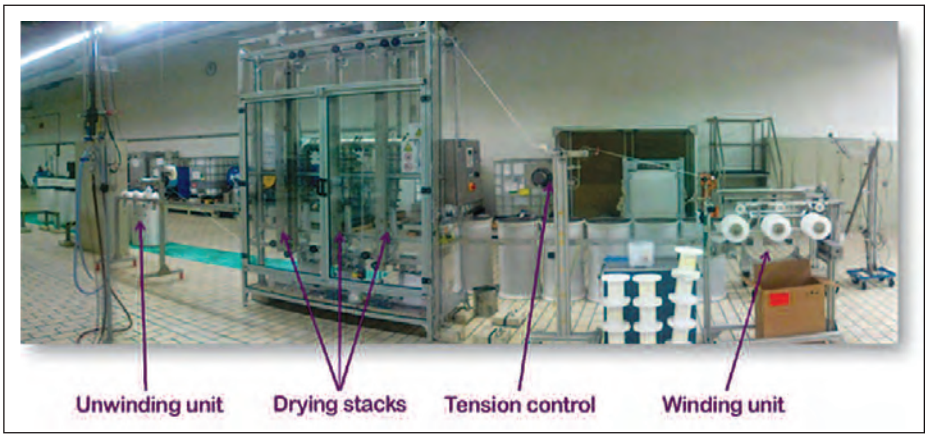

Figure 3:
Semi-industrial coating line at Membrana GmbH.

The support fibre had an outer diameter of 1.2 mm and the coated layer was 5–10 µm thick (Figure 4). More than 20 km of sPEEK membranes were produced during the project and about 8.5 km could be effectively used for the 30 modules intended for the Rutenberg plant (Figure 5), which each had an effective surface area of 1 m^2. Each module forms a "curtain-like" structure through which the flue gas must flow, in that it spans the entire flow area. The construction of this module (with the fibres) was done in a semi-automated way, which also gave information on how a full-scale process would look. The up-scaling factors were:

Up-scaling of membrane manufacturing versus lab method: > 15x

Up-scaling of module manufacturing versus lab method: > 6x

For each individual module a leakage test was conducted and where needed broken fibres were removed and open areas were closed with potting material. For the leakage test a 20 hPa pressure was applied on the inside of a module, a valve was shut and the pressure build-up was recorded after a period of 3 minutes. This increase in pressure gives a good indication of whether modules are leak free. The test results of twenty nine (29) membranes are shown in Figure 6. One membrane module is missing in this graph because it returned to atmospheric pressure

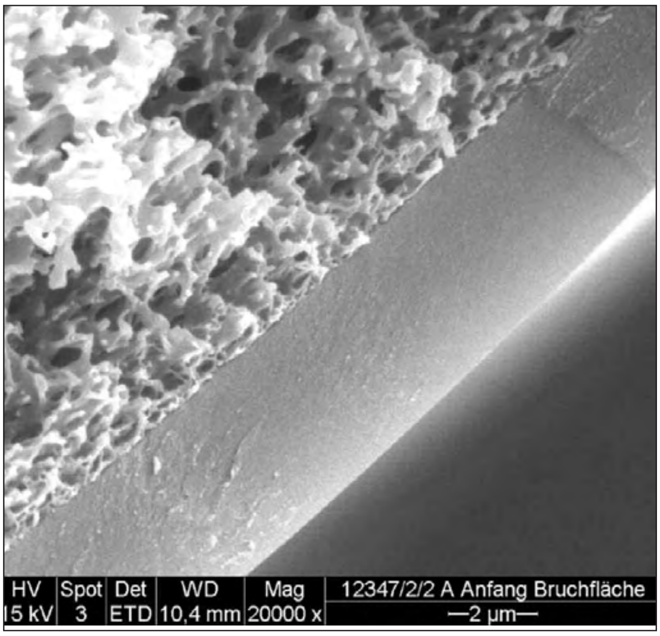

Figure 4:
Support membrane coated with sPEEK.

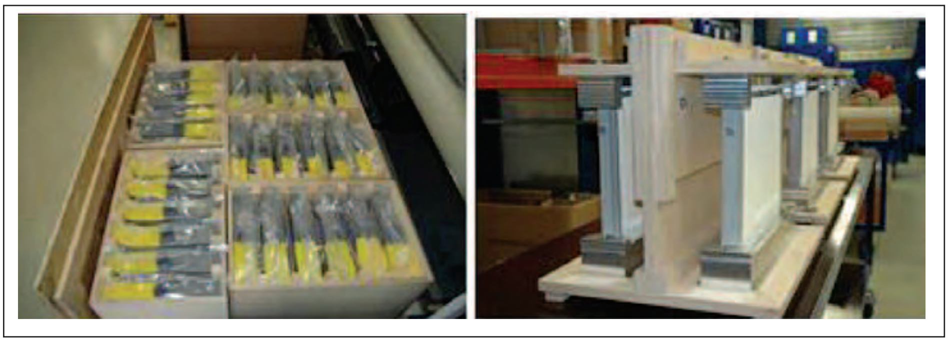

Figure 5:
Modules in potting and 30 modules packaged ready to be shipped.

within the time frame. The difference in leakage test results is likely caused by conditioning of the module with water vapour.

Number of modules with a pressure build-up to atmospheric: 1

Number of modules with a pressure build-up of > 500 hPa: 4

Number of modules with a build-up of 200–500 hPa: 9

Number of repaired modules (48 fibres replaced): 9

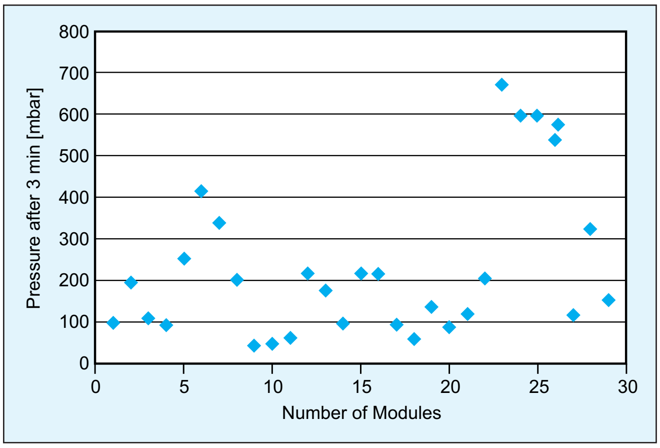

Figure 6:
Overview of leakage test results achieved with the modules produced before shipment to Israel.

Of the above, 1 module is considered to leak, while 4 others are considered poor. Of the 30 modules, 6 were tested under controlled laboratory conditions at DNV GL and thereafter sent to Israel to join the other modules for the pilot test. At DNV GL a gas-fired unit produced the flue gases. The flue gases could be adapted to simulate the water content of a coal-fired plant. This is done using heat exchangers and steam generators. The operation conditions were conducted at a feed temperature of 50 °C, 100 % relative humidity and an operating pressure of 80 hPa permeate. On average a single module produced 2.0 $kg \cdot m^{-2} \cdot h^{-1}$ water and $20 \cdot 10^{-6}$ $m^3 \cdot m^{-2} \cdot h^{-1}$ non-condensables. Based on different relative humidity figures at 50 °C, it was determined that a train of 6 modules would produce 1.55 $kg \cdot m^{-2} \cdot h^{-1}$.

Layout of the Test Installation

In general the layout (Figure 7) of the pilot plant is comparable to that of the laboratory testing facility. The installation contains a feed side, a module holder with the membrane modules, a retentate pipe and a vacuum system. This vacuum system contains a cooler, a water collection unit and a vacuum pump. The main differences from the laboratory experiments are that the size is large, approximately 30 m^2 of membrane surface. Also it's the first time an air-cooled condenser is used instead of a water-cooled condenser. The unit houses 30 modules divided into 5 trains of 6 modules each Figure 8. All trains have two common headers, one for the feed flow and one for the retentate as depicted in Figure 9.

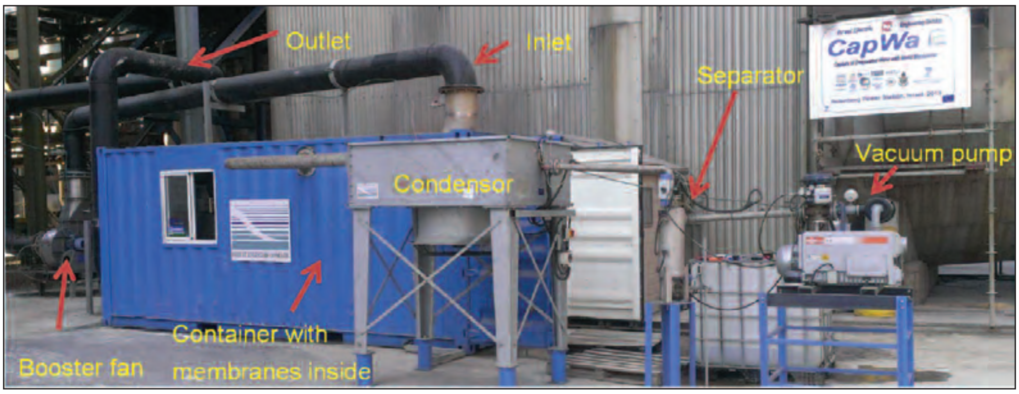

Figure 7:
Layout container.

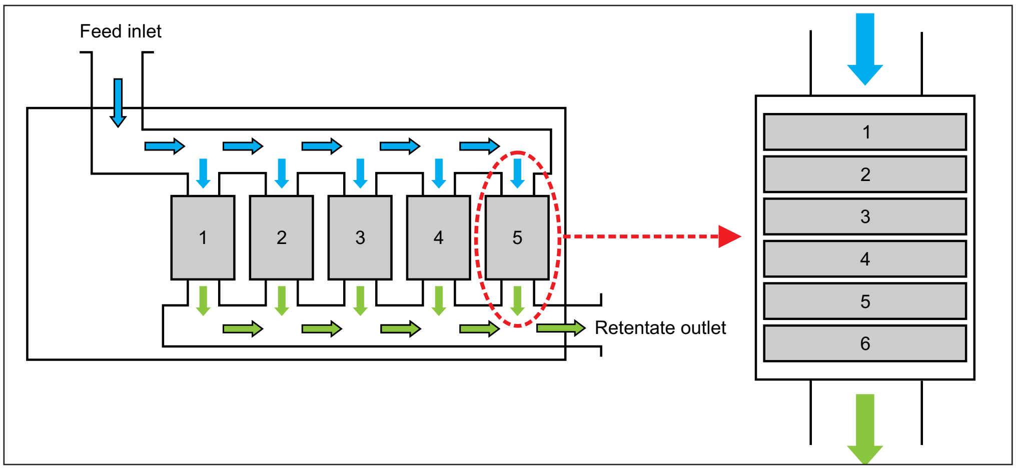

Figure 8:
Module numbering in the train (right), and train position in the pilot system (left).

Figure 9:
Empty trains including headers and one train filled with six modules.

It is assumed that the likeliest market for a technology that provides a new source of water would be in dry regions. This would mean very limited access to water and thus the unit is more likely to have an air-cooled condenser to create the necessary condensation of the water. The air-cooled condenser was a 38.4 kW rotary vane vacuum pump (160 $m^3 \cdot h^{-1}$ at 10 hPa, with gas ballast). The vacuum in the system is fixed by a control valve, which will open or close depending on the amount of gas that needs to be evacuated. The vacuum pump itself has an over-capacity and can easily sustain the set point of 80 hPa.

Leakage Test of Pilot Unit

During the commissioning a leakage test was done to determine if the piping and equipment in the permeate line were free of leakages. This was done by inserting plugs into the 30 permeate ports where each of the 30 modules would connect during normal operation. The feed/retentate side of the system was left open to atmospheric air (no flue gas was fed to the system) during the leakage test. A pressure of 50 hPa was set and maintained after closing the valves. The plugs were replaced with the 30 modules, and without feed flue gas the pressure was brought to 50 hPa. After 2 minutes the pressure reached a value of 100 hPa and after 5 minutes 200 hPa. From previous lab experiments it is known that the coating layer gains air-tightness when conditioned with water vapour.

After 2.5 months of operation an inspection was done and three modules were removed due to broken fibres. Here too a leakage test was conducted on the complete installation with the 27 membrane modules. The 3 ports opened by removal of the modules were sealed with plugs. The 27 modules had been exposed to saturated flue gas, and hence could be considered conditioned. After reaching a pressure of 45 hPa the valves were closed and a pressure of 60 hPa was reached after 5 minutes. This result shows that the installation and the membrane modules were airtight.

PILOT TEST RESULTS

Purpose and Aim of the Test

This test had two purposes. One was to determine whether the results achieved in the laboratory can be repeated on a larger scale. The second one was to determine the performance of the system under real industrial conditions.

Operational Conditions

During the test period several parameters were monitored continuously, like water production, temperature, pressure and relative humidity. All this data was collected and logged every 10 minutes and used for interpretation at a later stage. If required, screen dumps could be made of the logged data which show the recorded values every 10 seconds. Other parameters were measured a few times during the test period, such as water quality and flue gas composition.

In the test period no influence was possible on the flue gas composition and temperature. The only freedom present was the flow, which was set and measured between 3 700 and 4 300 $m^3 \cdot h^{-1}$. The flow was determined using both a handheld pitot tube and a vane anemometer. The online pitot equipment proved to not be suitable for the operational conditions.

The measured temperature at the inlet of the container fluctuated, based on flow and the ambient temperature, between 47 °C and 52 °C. These values were indeed higher than the calculated design (lower case) value of 46 °C. The relative humidity was 100 %.

During operation it was found that the module holders, as shown in Figure 8, are friendlier in use than the ones used in the laboratory. All 30 membrane modules could be easily inspected and checked for broken fibres within half an hour. This was the result of the covers of the housing having an easy closure and release system and the way the modules slid inside the housing. The unit operated at a set pressure of 80 hPa.

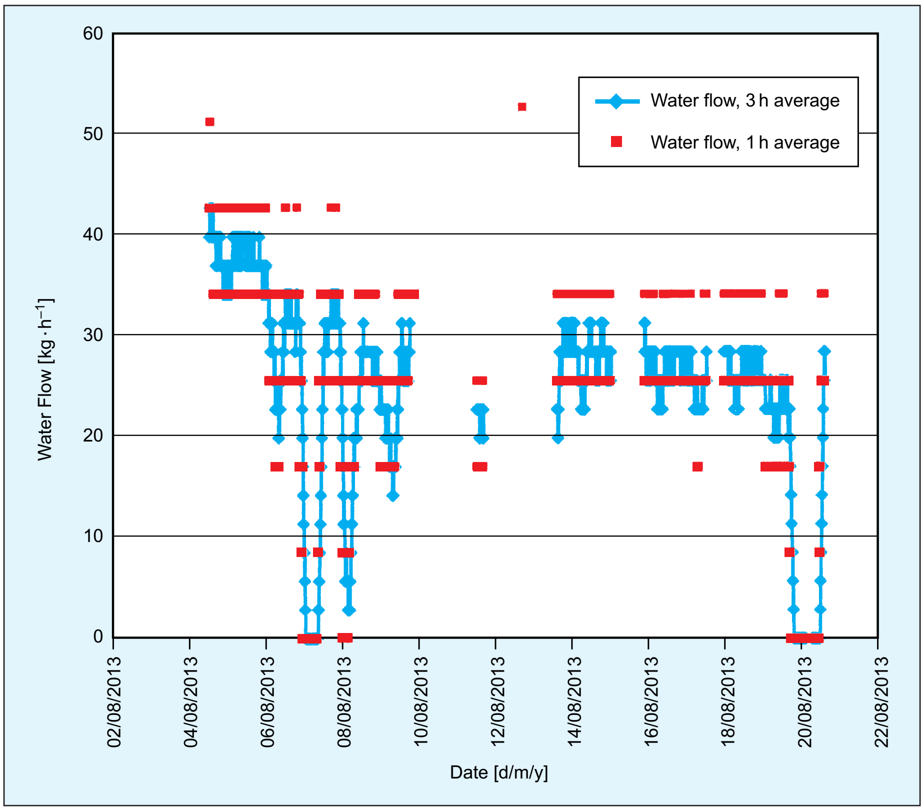

Figure 10:
Flow of water produced at a three-hour average and one-hour average.

Test Results

Water production Since the water production was determined by the number of drainage cycles every hour (a cycle is the time required to fill the separator with 8.5 kg of water), it was decided to use a three-hour average instead of just a one-hour average. A three-hour average shows a more fluent behaviour compared to a one-hour average. This is shown in Figure 10.

The average water production after the 13th of August is 27 kg per hour. In this period there were 27 membrane modules in operation inside the container. Prior to this there was a period where 40 kg of water was produced per hour from 30 membrane modules. This corresponds to a water production of 1.0 to 1.3 $kg \cdot m^{-2} \cdot h^{-1}$. The highest recorded value was 43 kg of water per hour (3-hour average), which corresponds to 1.4 $kg \cdot m^{-2} \cdot h^{-1}$. This was at an operating pressure set point of 50 hPa instead of 80 hPa.

Factors influencing water production Figure 11 shows the data from the 13th of August until the 20th. The left axis has the scale corresponding with the pressure data. The right axis corresponds with the temperature after the condenser in °C and the water production in $kg \cdot h^{-1}$ (three-hour average). Based on the data plotted in Figure 11 it can be seen that there is a correlation between the water production and the temperature behind the air-cooled condenser (ACC). It would be logical to assume that a lower temperature would be related to a higher water production, as more water will be condensed at a lower temperature. However the opposite effect is shown.

In Figure 12 it is clearly shown with the circles that the water production is very much related to the temperature of the feed. This feed temperature corresponds to a partial vapour pressure. As the flue gas is always saturated, the temperature is representative of the amount of water in the feed. The higher the temperature, the higher the amount of water vapour in the flue gas. The temperature recorded inside the feed line in the pilot unit is influenced by the ambient temperature. As this decreases in the evening, and as the permeate pressure is fixed at 80 hPa, the corresponding Δp (difference in partial vapour pressure between feed and permeate) is lower, and hence the water production is lower during the night. As less water is transported to the ACC, the ACC can cool the water to a lower temperature, which is also reflected in Figure 11. That less water vapour is transported is also reflected by the position of the control valve at the vacuum pump, which is more closed during the night.

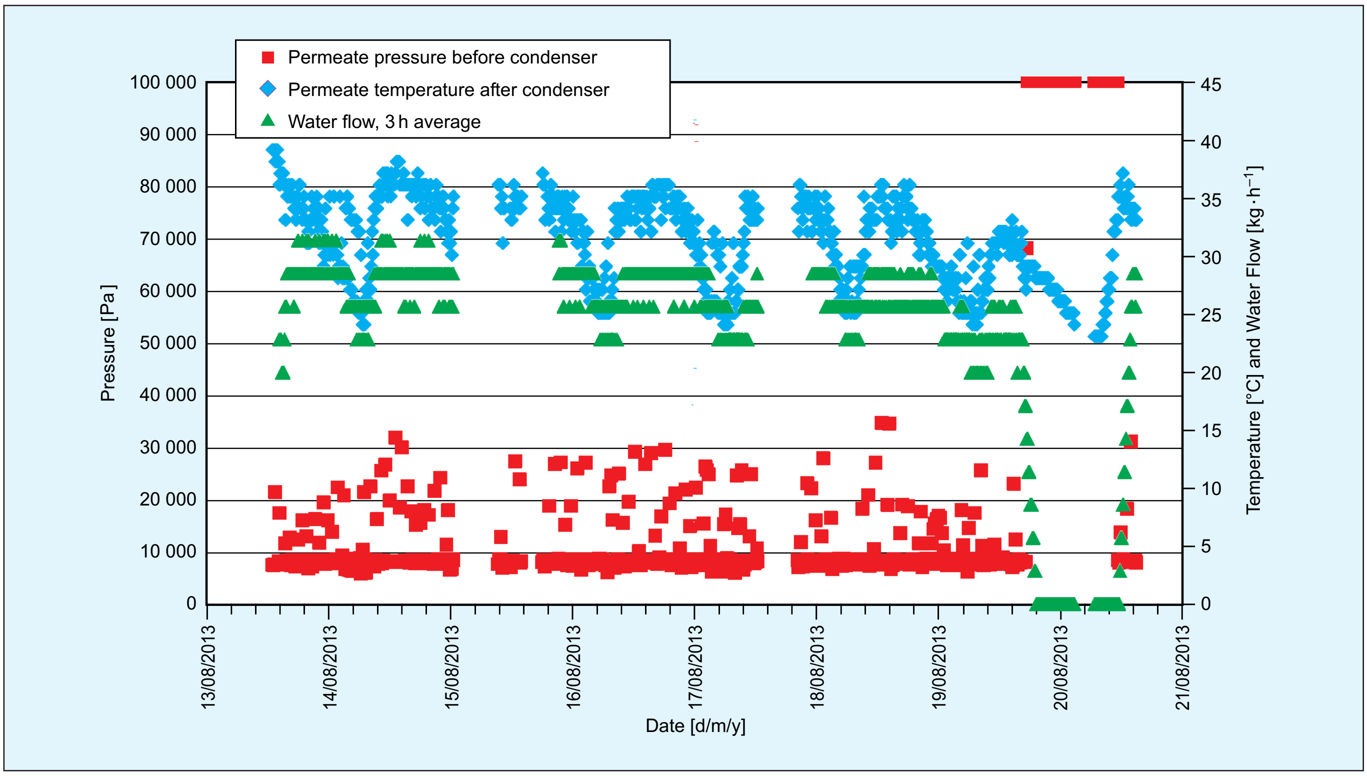

Figure 11:
Flow of water produced vs. temperature after and pressure before condenser.

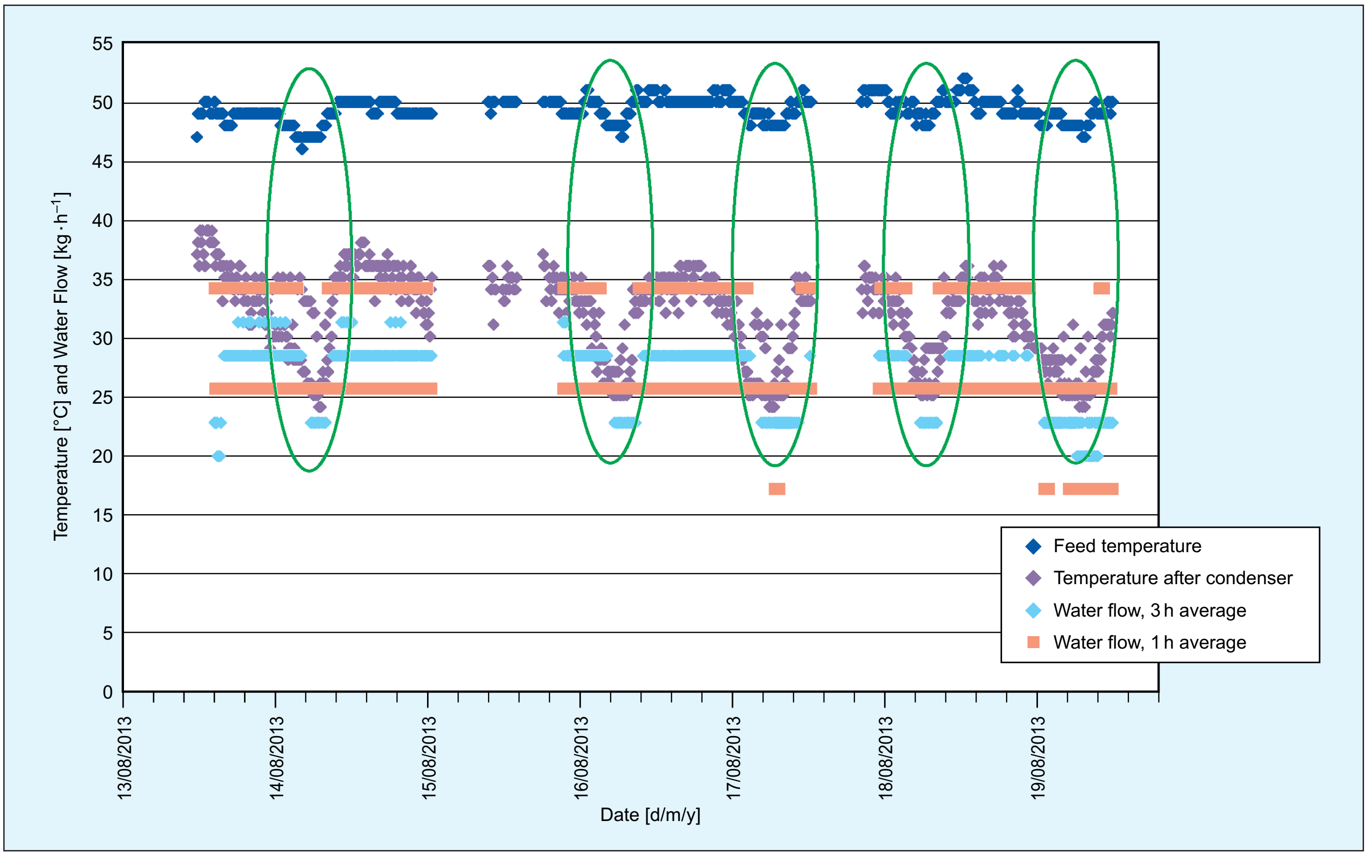

Figure 12:
Influence of partial feed pressure (depicted with feed temperature) on the water production.

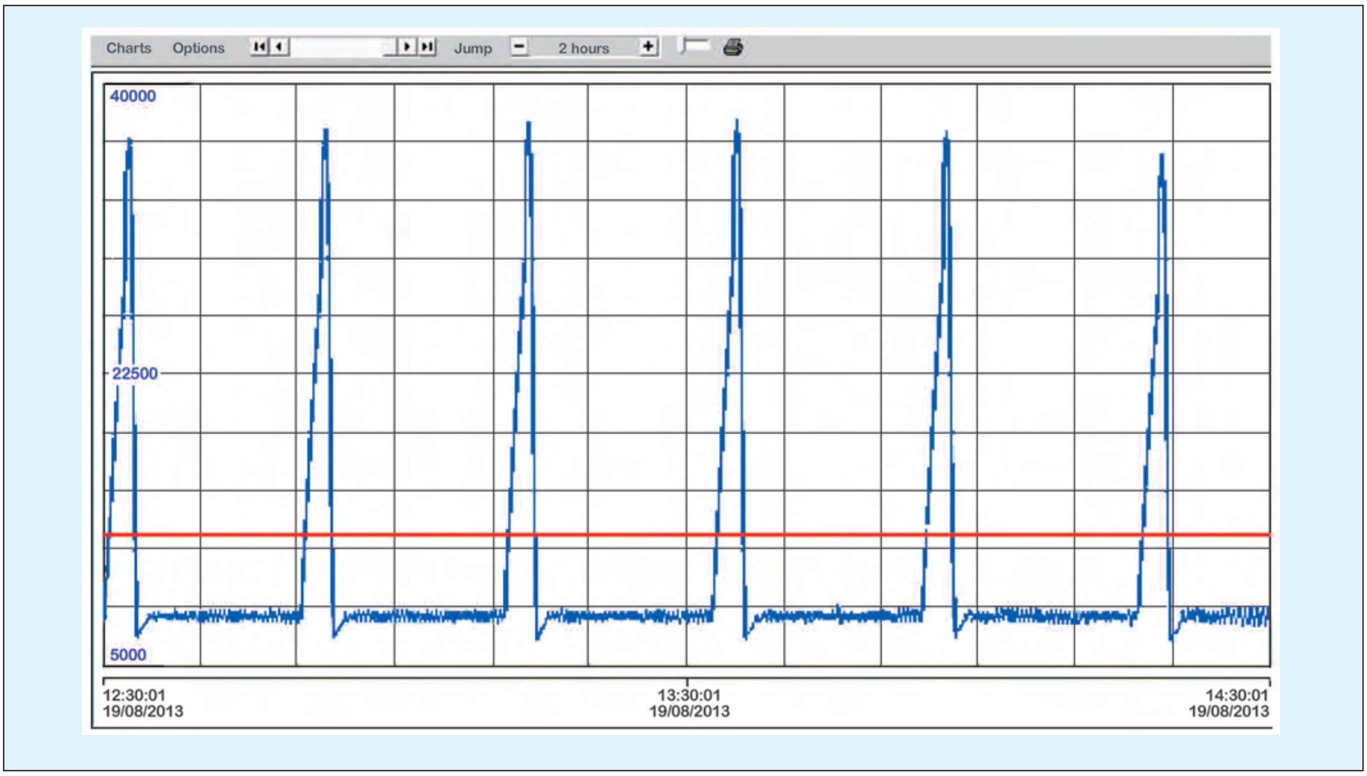

Figure 13:
Screen shot of permeate pressure (red line represents partial vapour pressure at 50 °C).

Figure 11 also shows the permeate pressure (red blocks) in that same period. Clearly there are excursions in pressure above the 80 hPa. This is due to the removal of the produced water. The pressure is measured just before the condenser and the vacuum pump has a set point of 80 hPa. The separator is located just after the condenser. When this separator is filled with approximately 8.5 litres (kg) of water, the level switch is activated, closing the valves to the condenser and vacuum pump and opening the valve to the water collection vessel. After the separator drains, the valve to the collection vessel closes again and the valves to the condenser and vacuum pump open. This releases 20–30 litres of air in the separator into the permeate line, including the condenser, causing a momentary increase in the pressure reading. However the vacuum pump quickly evacuates this air, restoring the pressure to the set point. In Figure 13 there is a screenshot of the process control computer showing the variation in permeate pressure.

This water release step could have a substantial impact on the water production. As shown in Figure 13, the red line represents a partial vapour pressure at 50 °C (123 hPa). When the pressure in the system is higher than the partial vapour pressure of water in the flue gas, no driving force is present, so no water will be produced. This occurs above the red line as shown in Figure 13. This means that for about 3 minutes of every water release cycle no water will be recovered. With an average of 3.3 cycles per hour in this graph this implies that generally every hour for a period of ten minutes no water will be produced. This is about 15 % of the time and corresponds to approximately 5.7 kg of water per hour that is not being captured. More cycles per hour would result in more ineffective water capture. The highest recorded value was 5 cycles in an hour. This implies that an extra 25 % of water could have been captured during this period. This amount of water could easily be captured by using a second separator in parallel. So when one vessel is releasing the water, the other is maintaining the vacuum and collecting the water.

When examining the permeate pressure the following can be concluded:

- The 80 hPa value was maintained throughout this period and fluctuated between 70–90 hPa. If leakage of fibres occurred, it did not influence this value.
- No large excursions or anomalies were seen in the permeate pressure when emptying the separation vessel. In principle these values would go to about 210 and 260 hPa.
- There seems to be a recurring pressure build-up (max. 365 hPa) around 15:00 every day. This could be caused by ambient effects, such as the test unit being exposed to the sun. This permeate pressure value decreases back to about 210 and 260 hPa. That the value drops

back down to about 260 hPa gives an indication that there is no sudden increase in leakage. If there were leakages in the fibres, the pressure would increase gradually or a sudden increase would be experienced, for example at the start of the experiment.

From the measurements of temperature, water production and relative humidity the following can be concluded:

- Both measurements of the relative humidity are constantly at 100 %. For the retentate this was not expected, since water is being removed by the membrane modules. The temperature loss over feed and retentate with the measured flows corresponds to a water loss due to condensation of about 20 kg per hour. It has been hypothesized that as more water is removed the water collected in the retentate header is "wetting" the outgoing flue gas and hence the retentate has a humidity of 100 %. It needs to be mentioned that the retentate header always has some water present due to the design.
- The temperature of the permeate before the condenser and the temperature of the feed are close together, but the first is always higher. This was not expected. A control measurement suggests that the permeate temperature monitor is significantly too high with a deviation of at least 5 °C.
- The temperature of the permeate after the condenser (or condensate temperature) closely follows the ambient temperature. However the ambient temperature is both above and below the temperature of the condensate. For example, in the morning (when the unit is in full sunlight and out of the shade), the ambient temperature is higher than that of the air-cooled condenser.
- As the vacuum system did not become the limiting factor in this test, the exact effect of ambient temperatures on the performance is not yet known. It has been suggested to couple the pressure of the vacuum pump to the condensing temperature. This value is related to the ambient temperature and the pressure set point should be retrieved from the steam table. This would then supply information on the performance of the condenser.
- There are some indications, such as an increase in control valve position, that there is an increase in non-condensables. However these indications are not very strong with respect to the relatively short testing period and the difficulty of measuring the permeate flow continuously.

Vacuum pump and (non)-condensable flow The vacuum system consists of an air-cooled condenser and a rotary vane vacuum pump. The flow of the pump was measured when the system ran at a temperature of 33 °C and a pressure of 80 hPa. From our steam data we know that water has a vapour pressure of 50 hPa at 33 °C and thus 30 hPa is due to non-condensable gases. This would translate into a deviation in volume of 0.625 $m^3 \cdot m^{-3}$ water vapour and 0.375 $m^3 \cdot m^{-3}$ non-condensables.

Indicative measurements at the ambient pressure side of the vacuum pump showed that at 85 °C 14.7 $m^3 \cdot h^{-1}$ of gas was emitted. Corrected for vacuum conditions and using the ideal gas law we can determine the flow that the vacuum pump removes, at the suction side. At 80 hPa 157 $m^3 \cdot h^{-1}$ of gases, of which 98 $m^3 \cdot h^{-1}$ is water vapour and 59 $m^3 \cdot h^{-1}$ is non-condensable gases, would have been removed. These values correspond to 0.624 $m^3 \cdot m^{-3}$ and 0.376 $m^3 \cdot m^{-3}$, respectively. We therefore conclude that the pump ran according to specifications and that the (flow) measurements on the permeate side were accurate.

Inspection and Fouling

On the 12th of August and on the 25th of August inspections were carried out on all membrane modules. Prior to the 12th of August the modules had been exposed to about 2.5 months of flue gas, and also one upset of the FGD unit occurred. During the test period between the 12th and the 25th the modules were exposed to 1 additional week of real flue gas conditions. In Table 2 a summary of the visual inspections is shown as well as other relevant data.

Table 2 shows that a slight majority of the repaired modules did not produce any broken fibres during the pilot test. Also modules with the red stain did not lead to broken fibres. Of the 10 modules with broken fibres, only one module was found in the first three trains (position train 2, 1st row). This module had just one broken fibre. A majority of the fibres, if not all, broke at the contact point with the potting. As all trains experienced similar flue gas composition it is assumed that the flow could be different in the last two trains, causing breakage. The amount of broken fibres amounted to 0.04–0.05 % of the total amount of fibres.

From scanning electron microscopy – energy-dispersive X-ray spectroscopy (SEM-EDS) analysis of the red stain (Figure 14) it seems that this may be a lead-oxide (Pb_3O_4) originating from paint. Elements found in the red stain were: aluminum (Al), calcium (Ca), carbon (C), lead (Pb), oxygen (O), silicon (Si) and sulphur (S). It is unclear where this paint originates from, but it was insufficiently dried and released in the flue gas stream.

In the SEM-EDS pictures it also seems that this material is penetrating through the membrane fibre. A picture of one of the outlets shows (Figure 15) that this material is found here. Another fouling compound found was primarily

Description	Amount	Remarks
Module(s) did not pass leakage test	1	Installed at pilot intallation and removed. Module repaired and tested at DNV GL (not returned).
Modules with poor leakage test report	4	After 3 minutes the vacuum was > 500 mbar. Of these modules only 1 module with 1 broken fibre in test.
Modules repaired prior to testing	9	Approximately 47 fibres removed and replaced with epoxy. All nine modules passed leakage test.
Broken fibres	28	11 fibres were found broken after 2.5 months.
Modules found with broken fibres	10	9 of the 10 modules were found in the last two trains (each train with max. 6 modules).
Repaired modules with broken fibres	4	Nine modules were repaired prior to exposure and passed leakage tests. Four experienced broken fibres during the pilot test.
Modules with red stain	10	Only 3 of these modules had broken fibres.
Fouled modules	25–27	Primarily dust. Cleaner modules were primarily found in the second train.

Table 2:
Overview inspection results of membrane modules.

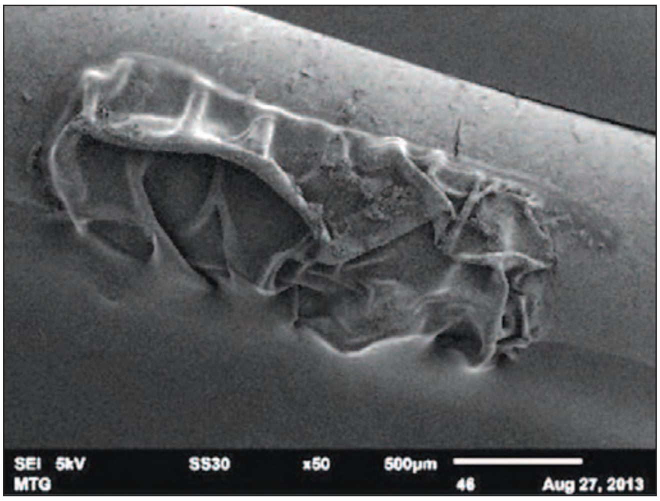

Figure 14:
SEM-EDS of red stain on membrane fibre surface.

Figure 15:
Red stain, probably lead oxide, found on inside of permeate exit as well as on fibre.

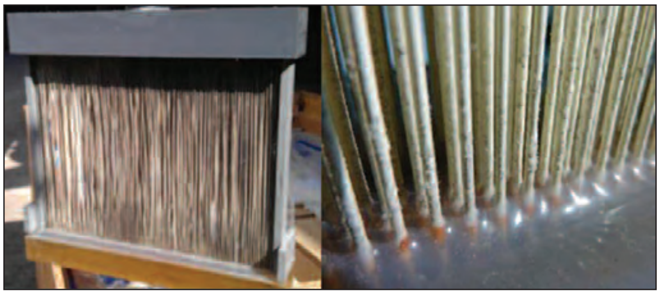

Figure 16:
Fouled membrane module after almost 3 months of exposure.

gypsum (Figure 16). It is known that fouling can cause a decrease in water flux performance as this material covers the surface. Luckily it also covers the end of the broken fibre and might act as a plug (see Figure 17). This can help reduce leakage.

Some membrane modules seemed to have a clean outer surface (2nd train); this is likely due to condensed water that is dripping from the feed header through to the membranes. Some modules in the last two trains were cleaned on the 12th of August using a light water spray from a plant spraying canister. It seemed as if hardly any material was removed, and it is recommended to use a more suitable water flow to clean the fibres.

The occurrence of fibre breakages are a surprise, as previously two modules were placed in an FGD unit of a waste-to-energy plant and over a period of 8 000 hours showed no breakages. A closer inspection of why the majority of the fibres broke mainly near the potting in the last two trains revealed that this was not a sudden (mechanical/tear) breakage but one that may have resulted through resonance. No evidence was found of degradation of the

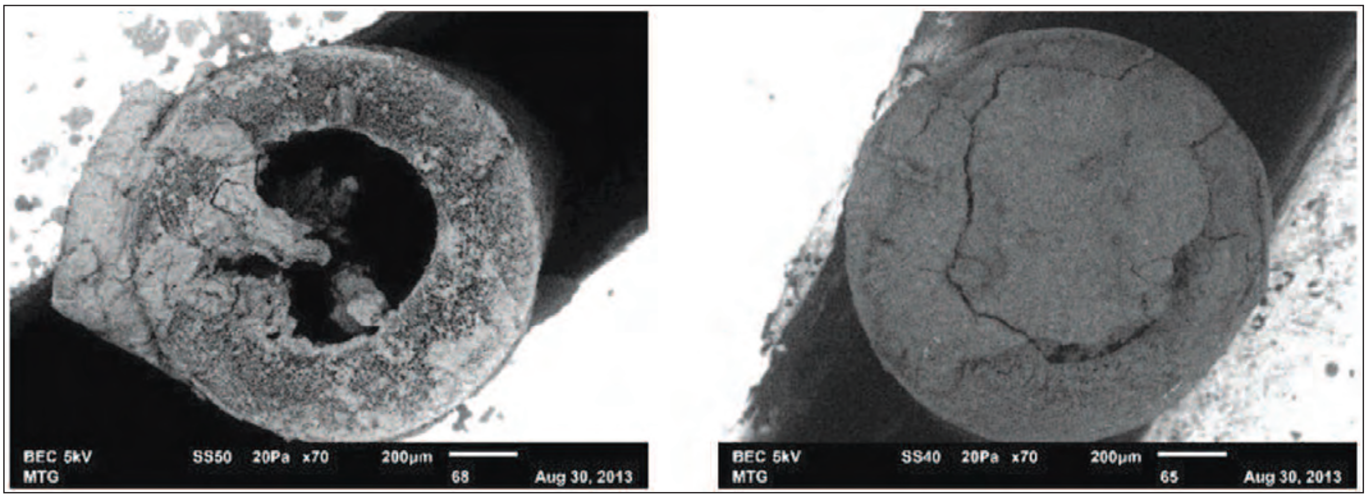

Figure 17:
Cross section of two of the four broken fibres found in one module.

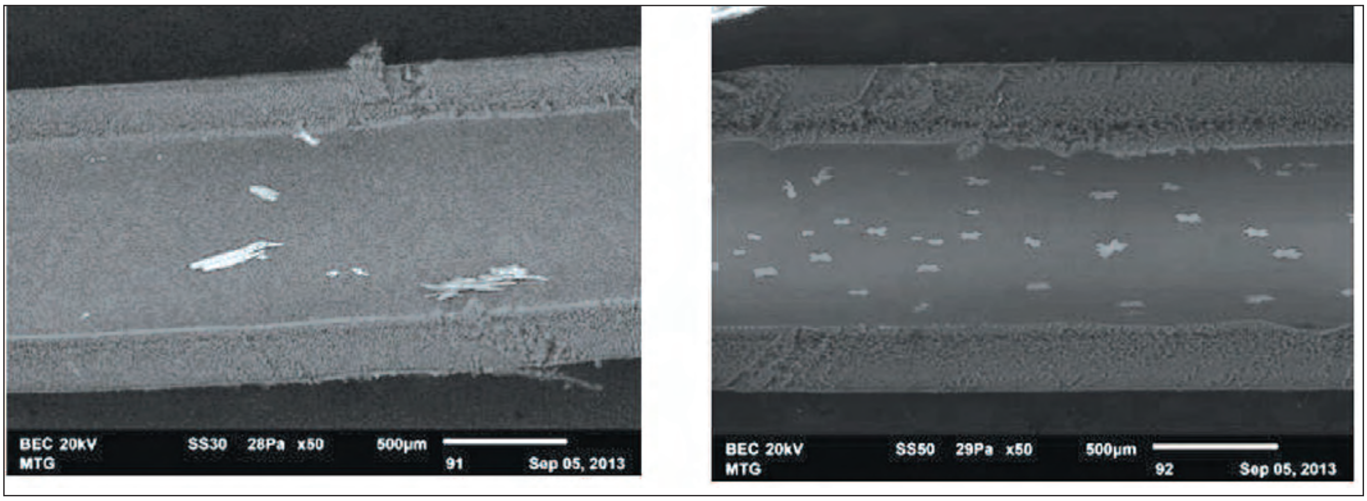

Figure 18:
Crystals found on bore side of fibre. Red stained fibre on the left side, unstained fibre on the right.

silicon material itself, and the silicon covers the fibres at the potting and membrane fibre ends. As the breakages only occurred in the last two trains, it is speculated that the flow of flue gas entering and exiting these trains is suboptimal. Here 90 degree bends are found and experience in the lab with similar flow speeds and bends has shown that the pressure can be locally higher and unwanted turbulences can occur. As this is speculation it is recommended to conduct a visual inspection of the remaining modules from Israel to determine the cause. If it is likely that turbulences are causing the breakages, modelling software tools like computational fluid dynamics (CFD) can be used to determine if higher velocities were achieved locally.

An SEM-EDS investigation of the bore side of the fibres (Figure 18) and permeate head where some scrapings

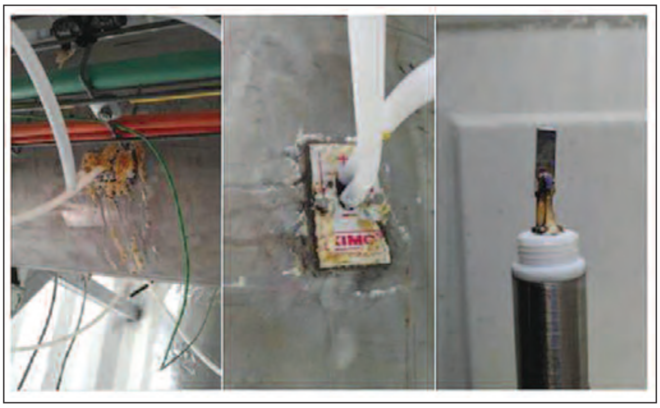

Figure 20:
Corrosion and fouling of monitoring equipment during pilot test.

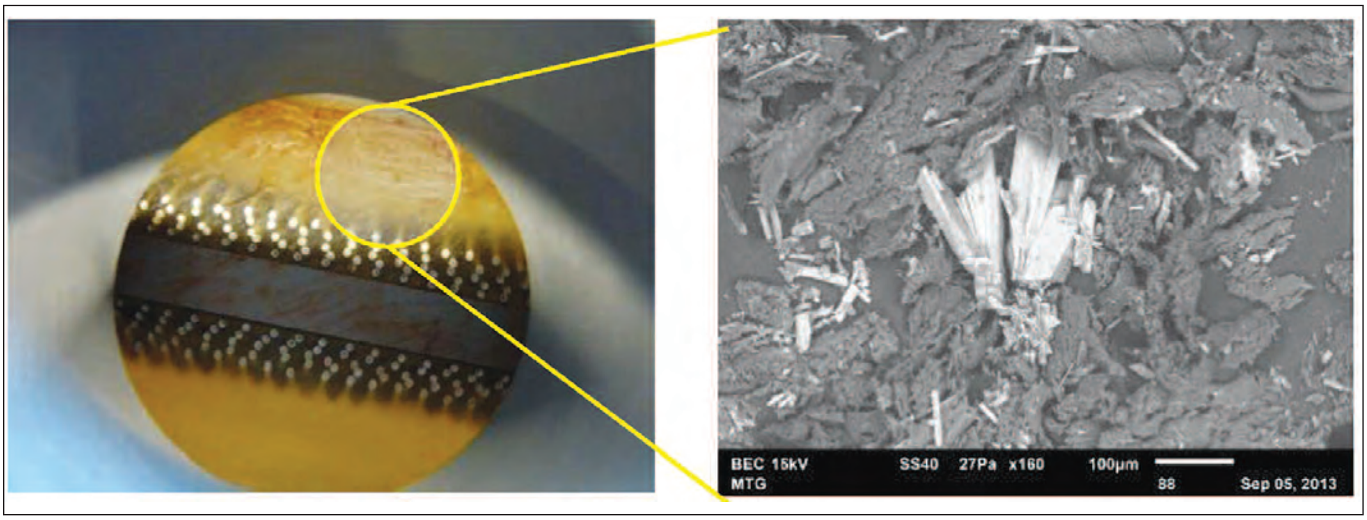

Figure 19:
Inside the module scrapings were taken and analysed by SEM-EDS. The crystals found are likely from gypsum.

were taken off the potting revealed that even the non-broken and stained fibres contained similar contaminants (Figure 19) (paint and gypsum). This material likely originates from the stained and broken fibres. The vacuum on the membrane was returned to atmospheric pressure several times and hence these materials had an opportunity to settle elsewhere. As the inside of the fibre is porous the material can attach itself there.

During the testing it was also experienced that most of the test apparatus could not withstand the fouling (see Figure 20). The majority of the thermocouples, the relative humidity meters and the pitot probe in the flue gas streams malfunctioned completely. This is likely caused by acidic water droplets with particles and gypsum. The Pt100 temperature sensors had no problems.

Prior to the pilot test, one membrane module did not pass the leakage test (see above). This module was removed after 2.5 months of flue gas exposure, cleaned and repaired. After the repair, the performance of the module was determined in the controlled laboratory environment of DNV GL. The water flux returned to $2.0 \cdot 10^{-6}$ $m^3 \cdot m^{-2} \cdot h^{-1}$ and the non-condensable flux was around $200–300 \cdot 10^{-6}$ $m^3 \cdot m^{-2} \cdot h^{-1}$. The increase in non-condensable flux could be attributed to some leakage.

Water Production and Quality

An overview of the water quality and membrane performance is given in Tables 3 and 4. Included are the test results of another pilot test conducted at a paper mill and the energy consumption values. At this paper mill the

Description	Large Pilot in Coal-Fired Power Plant Rutenberg	Small Pilot in Sappi Paper Mill	Measured Values at DNV GL
Amount of membrane area	27–30 m^2	1 m^2	1–2 m^2
Average water production	1.0–1.5 $kg \cdot m^{-2} \cdot h^{-1}$	1.8 $kg \cdot m^{-2} \cdot h^{-1}$	2.0 $kg \cdot m^{-2} \cdot h^{-1}$ for 1 m^2 module 1.55 $kg \cdot m^{-2} \cdot h^{-1}$ for > 6 m^2 modules
Water production in one day	0.7–1.0 m^3	0.050 m^3	–
Water conductivity*	80–130 $\mu S \cdot cm^{-1}$	8.2 $\mu S \cdot cm^{-1}$	15–20 $\mu S \cdot cm^{-1}$
pH of water*	3.6–4.9	–	–
Energy consumption**	Condenser: 37 $kWh \cdot m^{-3}$ Vacuum pump: 58 $kWh \cdot m^{-3}$ Total: 95 $kWh \cdot m^{-3}$	–	Condenser: 27 $kWh \cdot m^{-3}$ Vacuum pump: 81 $kWh \cdot m^{-3}$ Total: 108 $kWh \cdot m^{-3}$

Table 3:
General results of pilot tests.
* Drinking water pH 6.5–8.5 and conductivity is 100–1 000 $\mu S \cdot cm^{-1}$
** Energy consumption values at Rutenberg are measured. Energy consumption from DNV GL were obtained through modelling [1]

Chemical	Concentration [$\mu g \cdot L^{-1}$]	EPA Drinking Water Limits [$\mu g \cdot L^{-1}$]	Dutch Drinking Water Limits [$\mu g \cdot L^{-1}$]
Chloride	30 600	250 000	150 000
Fluoride	780	2 000	1 000
Nitrate	12 200	–	50 000
Sulfate	32 300	250 000	150 000

Table 4:
Water quality of the large pilot installation in a coal-fired plant versus drinking water limits.

exhaust gas of the hood was taken as feed gas. The results show that the industrial-made membrane modules are performing in line with expectations. Even though the water quality easily fulfils drinking water standards (except for pH), a better water quality was expected for the pilot test at the Rutenberg plant. This is likely caused by the breakage of some fibres.

DISCUSSION AND LESSON LEARNED

General

In general it can be stated that the test was successful. The unit performed as expected based on laboratory tests and managed to run and remain running in harsh conditions. The test unit was user friendly with easy access to the membrane modules. Also broken fibres in a module could be easily identified and the module could be repaired. The likely cause of the broken fibres was turbulence of the flue gas flow in the last two trains. The turbulence could have caused the membranes to vibrate. While vibrating they broke. It is hence recommended to simulate the vibration behaviour and find out through CFD whether it is necessary to redesign the intake of the modules and how to do this. Another issue regarding plant layout was solved during the pilot test. During testing it was determined that water vapour in the returned flue gas (retentate side) condensed due to a temperature drop. This condensation was expected, only the construction was such that the water got trapped in the pipe work. An additional drain was installed to release the water, as shown in Figure 21.

Mass Balance – Retentate Saturated

As the results of the vacuum pump characteristics give confidence regarding the flow measurements, a mass balance over the entire unit could not be determined. The water removed would be approximately 19–22 $kg \cdot h^{-1}$. The water vapour loss for permeate (about 3 $kg \cdot h^{-1}$) and the water captured (about 30 $kg \cdot h^{-1}$) amount to 33 kg per hour. This does not include any water condensation due to the temperature drop between feed and retentate, which is about 1–3 degrees. The mass balance cannot be determined due to the presence of water droplets. As this latter factor cannot be determined, more water may be present. Also water droplets and condensation can lead to a lower read-out of the flow meter.

Supporting the previous hypothesis, "liquid water is being evaporated and transported from the retentate header", are the difference in water quality measured of the condensate found in the feed and on the retentate side. Here

Figure 21:
Drain at return pipe.

conductivity measurements show that feed condensate is typically 2 000–3 000 $\mu S \cdot cm^{-1}$ while that of the retentate increases over time and goes up to 14 000 $\mu S \cdot cm^{-1}$. Here too the pH of the retentate is lower than that of the feed. The pH of the feed ranges between 2.2 and 3.8 while the pH of the retentate ranges between 1.6 and 3.4. A condensate water sample from the retentate near the pilot unit and one sample from farther down the retentate line going back to the unit show a similar trend. Only when the feed blower is turned off are the conductivity and pH values of the retentate close to those of the feed. This is due to condensate being transported back to the retentate header, which is the lowest point of the installation.

Optimizing Vacuum Design

The present water removal system causes pressure variations in the collection vessel and in the condenser. This happens during emptying and return to service. It is recommended to apply a second separator to avoid this issue. Also, the valve operation should be changed. At the end of a drain cycle, the separator is first reconnected to the vacuum pump to evacuate the air from the separator, and the valve between the separator and condenser should only be opened after this air is removed.

The effects of ambient temperature on the performance of the air-cooled condenser and also the membrane performance were not simulated here, as the pressure was fixed at 80 hPa. Lower vacuum condensing pressures can be expected on cooler nights. It is recommended to have the vacuum pump's set point lower to correspond to this condensing temperature and pressure. This can be done by software changes and using an ambient temperature measurement. This should lead to an increase in water production and likely a decrease in total energy consumption as more water is produced with similar energy consumption.

Another finding is that once the vacuum pump was shut down and the permeate pressure brought to atmospheric, there was a residual driving force to produce water. This driving force was lost over time and after about 40 hours there was hardly any water production.

Membrane Performance

Generally the performance of the membranes was in line with what was measured in the laboratory. The optimization of the vacuum pump led to higher values measured in the pilot unit by approximately 15 %. Also a lower condensation temperature was established in the laboratory, reducing the amount of vapour exiting the vacuum pump by an extra 10 %. This corresponds to a 15 to 25 % increase in the measured value of 1.3 $kg \cdot m^{-2} \cdot h^{-1}$, which leads to a value of 1.5 to 1.6 $kg \cdot m^{-2} \cdot h^{-1}$. This corresponds nicely with the 1.55 $kg \cdot m^{-2} \cdot h^{-1}$ value determined from lab work and extrapolations. Based on different findings in the field the module design can further improve this water extraction by 50 %. It is recommended to further optimize the thickness of the coating layer either by coating optimization procedures or further improvement of the support material. This can lead to improvement by several factors.

It is unclear what caused the factor-ten increase in non-condensable flux for both a repaired module and the 27 installed modules. During the pilot test the non-condensable flux stayed stable. Prior to the field test a $20 \cdot 10^{-6}$ $m^3 \cdot m^{-2} \cdot h^{-1}$ non-condensable flux per module was expected (total flow of 0.6 $m^3 \cdot h^{-1}$). During the pilot test it seemed that a factor-ten increase was measured, namely 5–6 $m^3 \cdot h^{-1}$ non-condensable flow for the 27–30 modules and 200–300 $\cdot 10^{-6}$ $m^3 \cdot m^{-2} \cdot h^{-1}$ for the single repaired unit. It is not likely that this was only caused by damaged fibres. Prolonged water vapour conditioning of the membrane fibres is recommended. Also during transport and commissioning care was taken to keep the membranes wet at all times.

From measurements in the feed and retentate (Table 1), there are indications that the membranes remove part of the CO. This could be due to the dipole momentum of CO and the interaction with the charged groups on the membrane. However this is highly speculative and it is recommended to investigate this further.

Fouling of the membrane modules did occur during the experiment, but as the duration of the experiment was limited it hardly affected the performance (compared to laboratory results). It is recommended to use cleaning in place units that spray a suitable water flow to clean the fibres.

Energy Aspect

The energy consumption of the installation was about 10 % lower than what was estimated by modelling; see also Table 3. This difference was likely caused by the use of a different vacuum pump and different ambient temperature. The results give confidence in the modelling results. Hence the modelled optimized vacuum system in the modelling results can give us an indication of the energy consumption. The model and the outcome of the results have been published [1]. In this article the determined energy consumption depends on the manner of cooling. If cooling water is available, the energy consumption can be around 7 $kWh \cdot m^{-3}$ water. For air cooling this is about 35–40 $kWh \cdot m^{-3}$ based on a fixed high operating condensing temperature of the ACC. It is recommended to determine the effects of changing ambient temperatures (night and day) on the energy consumption both in the field and by modelling.

When applying this technology energy savings can be achieved by preheating the condensate and removing any flue gas reheating. To do this a minimum removal of 12 % of the water vapour in the feed flue gas is required. The temperature of the permeate is suitable for the first preheater, which typically goes from 30 to 43 °C for plants with low condenser pressures (water cooled). The energy savings for a 600 MW coal plant would amount to 27.5 kWh · m^{-3} at 20 % water recovery (924 kW total).

At plants located in hot areas where air cooling is used the condensate preheater temperature is higher, namely 60–100 °C. Here the condensing pressure is designed at 45 °C. For these plants permeate (or flue gases) of > 100 °C would be necessary in order to achieve energy savings. This is likely the case for coal plants without FGD units or with dry FGD unit operation. It is recommended to investigate this further with SPENCE® energy modelling. The modelling should take into account dispatch patterns and (cool) night operation, since excess steam still needs to be condensed by the ACC.

As for the flue gas reheating, the test results show that the decrease in temperature over the membrane modules (and the rest of the stainless steel installation) was very low, which confirms that a dehydrated flue gas stream at near feed temperature can be possible. That desaturated flue gas was not measured during the pilot test is likely caused by the evaporation of the water located at the retentate header. This is due to the layout of the pilot unit. Hence the assumptions made regarding energy savings that can be achieved when flue gas reheating is no longer necessary are still valid. For a 600 MW coal plant more than 30 % of the water vapour needs to be captured and this would amount to a 1 200 kW savings or 23.8 kWh · m^{-3}.

An overview of the energy and consumption savings is given in Table 5. A negative value in the last column represents energy consumption while a positive value shows an energy savings achieved when applying the technology. Although promising, these figures need to be verified in practice on a full-scale basis. Also it should be noted that the ability to achieve the energy savings needs to be determined on a site to site basis.

CONCLUSION AND RECOMMENDATIONS

The pilot test at the Rutenburg power plant had two main purposes:

1. To determine whether the results achieved in the laboratory can be repeated on a larger scale.
2. To determine the effects of industrial conditions on the performance of the pilot system.

It can be concluded that a large-scale pilot unit with 30 m^2 of semi-industrially made membrane modules coupled together with an industrial vacuum pump and air-cooled condenser is feasible. An important achievement is that the performance of the membrane modules in water production is similar to that of the lab findings, namely 1.5–1.6 kg · m^{-2} · h^{-1}.

Under real conditions it was shown that the system was well designed and that both the ACC and vacuum pump were able to fulfil the task required. Operational changes caused by the power plant or by ambient conditions were easily absorbed by the pilot unit. The main parameter influencing the water production was the feed temperature, which was affected by ambient conditions.

The test unit was user friendly with easy access to the membrane modules. Also, broken fibres in a module can be easily identified and the module can be repaired. The amount of broken fibres, 0.04–0.05 % of all fibres, was not expected but also did not pose a threat to the operation of the unit. These findings give confidence for future operational use. A possible cause of the breakage could be turbulence in two of the five trains, and it is recommended to investigate this further.

The water quality easily fulfils drinking water standards (except for pH), however a better water quality can be expected if breakage of the fibres can be prevented. Nevertheless, for the IEC this water quality is acceptable and it is also better than their current raw water source (drinking water).

As the membranes can be improved by several factors, further improvement of membrane coating and support material are recommended. Also recommended is to further investigate the conditioning of the membranes and (development of) the non-condensable flux.

Description	Consumption	Max. Savings Achievable	Net Energy
Water-cooled	7	51	+ 44
Air-cooled	35 to 40	24	– 11 to – 16

Table 5:
Net energy savings in kWh · m^{-3} when applying the technology in a coal-fired plant based on modelling results.

The measured energy consumption values support previously conducted modelling work. This gives confidence in the determined consumption values and energy saving values. Also the pilot test results support the energy savings opportunities such as no-reheating of flue gas and preheating of the condensate. The savings can lead to a net energy savings for coal plants that have access to cooling water. For coal plants in dry areas, the recommendations are to determine the effects of cold night cooling on the energy consumption and to investigate whether preheating the condensate for coal plants without FGD or with dry FGD is feasible.

The system can be further improved if the pressure of the vacuum pump is coupled to the condensing temperature. This value is related to the ambient temperature and the pressure set point from the steam table. In layman terms, the effects of night cooling should be investigated.

In the near future a pilot test will be conducted at a gas-fired power plant in Madrid. This unit will have a different flue gas composition and also the pilot installation will have a different selective membrane material. The occurrence of droplets and dust is unlikely and the acidity of the flue gas will be lower compared to the coal-fired plant in the present study. The focus in this pilot test will be on determining the effects of night and day operation as well as the durability coupled to the performance of the membrane at higher temperatures and low relative humidities.

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