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Outdoor prototype results for direct atmospheric capture of carbon dioxide

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Abstract

At Carbon Engineering, we have built a prototype air contactor with 10 m^3 of packing volume, and have absorbed carbon dioxide from ambient air for over 1000 hours of outdoor operation. Our prototype was built to: a) test our cross-flow, pulsed-liquid, PVC packing-based contactor design in an operational environment; b) to evaluate fan and liquid pumping energy requirements of our design; c) to assess technical and safety risks involved with liquid solution loss through entrained "drift" droplets, and; d) to examine for packing or solution fouling by atmospheric particulates. In this paper we present our results on the liquid pumping and fan energy requirements of our prototype, and show preliminary analyses we have conducted on liquid loss through "drift" droplets and NPE fouling.
Our operation with pulsed liquid flow allows us to fully wet the surface of our structured packing with a brief period of full flow, then to cut flow for a duration of several minutes to let the liquid slowly react away as CO_2 is absorbed. Using this technique we have cut average liquid flow to 10% of full manufacturer's specifications while retaining an average of over 80% of the capture rate observed at full flow. This method, under patent application, has allowed us to reduce our *mgh* fluid pumping energy requirement for the contactor to <40 MJ/ton-CO_2 (<11 kWh/ton-CO_2). Here we report this energy requirement without accounting for pump efficiency, which we nominally assume to be η_{pump}=90%.

Our prototype contactor has utilized high-performance XF12560 structured packing from Brentwood Industries (Reading, PA), manufactured from PVC rather than a stainless-steel. This choice has given us several advantages, chiefly that it costs far less on a per-surface-area basis, and that is provides a much lower pressure drop on a per-surface-area basis. We have previously shown data that suggests these plastic packings absorb CO_2 with equal performance to traditional stainless-steel designs once wetted properly [1]. The high-performance and low pressure drop characteristics of our XF12560 product have allowed us to achieve *PV* work requirements of <350 MJ/ton-CO_2 (<100 kWh/ton-CO_2). Again, this value does not reflect fan efficiency, which we commonly use as η_{fan}=55% in our analyses. This current value for PV work requirement is higher than we had previously reported, due to a specific cause of under-performance in our prototype which is discussed in this paper. Despite this, we are in fact very encouraged by the results of our first attempt at long-duration outdoor contacting, and we have numerous design

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improvements stemming from our prototype operation that will be included in the next iteration of our full-scale contactor design.

Extensive air sampling was carried out during our contactor operation to measure the loss of liquid solution via "drift" droplets. During normal pulsed-flow contactor operation, 6 hour air samples taken from the contact outflow and measured for our K^+ ion tracer, showed OH concentrations to be <5% of the OHSA regulated indoor respiratory requirement. After our 1000 hours of integrated CO_2 absorption time, we have as of yet been unable to observe any significant performance decrease in the absorptive properties of our working solution or in the efficiency of our structured packing product.

Direct air capture, CO_2 capture, prototype results.

1. Introduction

Carbon Engineering is an independent company located in Calgary, Canada, and was formed to develop and commercialize cost-effective, industrial-scale direct air capture (DAC) technology. Carbon Engineering was formed in 2009, by Dr. David Keith to build upon the DAC research that was carried out by his groups at the University of Calgary, and previously, Carnegie Mellon University. Carbon Engineering has focused on commercializing DAC by designing a process that uses existing industrial-scale technologies wherever possible to minimize technical and scale-up risks; these technologies are integrated together with CE's own internal IP. For these reasons, we at Carbon Engineering have focussed on a wet-scrubbing air contactor design that that is rooted in the gas scrubbing and cooling tower industries, coupled with a "Pelletized" variant of the Kraft Recovery Process to regenerate our capture chemical and produce purified pipeline-quality CO_2. The result is a system that takes in roughly 10 GJ of natural gas to supply all heat and electrical energy needs, that captures nearly all of the natural gas combustion CO_2, and that supplies the combined air-captured and combustion CO_2 streams at pipeline-purity and 150 bar. The system also requires a water input, and small chemical make-up streams to compensate for losses.

Our internal cost estimates – which we do not discuss in this paper, but were covered in previous work [2] – suggest that we can commercialize our technology by using DAC to produce and market low life-cycle carbon intensity fuels into carbon-constrained markets, such as that which exists currently under California's LCFS regulation. Carbon Engineering's longer term vision is to help enable direct fuel synthesis from air captured CO_2 and hydrogen produced by carbon-neutral electricity.

2. CE's "Outdoor Contactor" Prototype

CE's wet scrubbing air contactor design represents a departure from traditional gas scrubbing techniques. It couples elements of gas scrubbing and cooling tower technologies, upon which we have innovated our own IP. The result is a slab-geometry air contactor, filled with structured packing material over which is supplied a strong hydroxide solution. This solution forms a film on the packing, and its natural affinity for CO_2 removes the CO_2 from the air which passes through the packing channels. Fans are used to drive air flow, and the contactor operates in "cross-flow" mode where air passes through horizontally and the liquid solution is pumped to the top and distributed throughout the structured packing by gravity (see Figure 1). In our end-to-end direct air capture process, a stream of the hydroxide solution,

which also embodies the captured CO_2 as a carbonate ion, is processed to liberate pure CO_2, and remake the original hydroxide. This process is detailed in previous work [3][4].

Our slab contactor is designed to minimized total overall cost of CO_2 capture, in $/ton-$CO_2$, rather than maximize capture fraction, as is common in CCS applications. The slab design minimizes base footprint area and allows use of prevailing winds to partially drive air flow and manage recirculation. Our contactor uses inexpensive and low-resistance PVC packing (an order of magnitude less costly than traditional stainless-steel products used in scrubber columns) to minimize fan energy requirements while retaining high performance of CO_2 capture. And we also use our own intermittent liquid flow concept, discussed later in this paper, which allows us to reduce the pumping energy requirement. We filed a patent application in 2009 [5] for this intermittent flow, slab contactor design.

Internal engineering and analysis showed this design to be very cost effective, but ambient CO_2 absorption with a cross-flow design using PVC packing and intermittent liquid flow had never been proven and quantitatively validated at a size relevant to full-scale designs, nor tested in a fully operational environment. This validation was the chief goal of our "Outdoor Contactor" (OC) prototype.

Beginning in 2010, and with Flint Energy Services as a fabricator, CE designed, engineered, and constructed the OC prototype. The OC was built as the smallest representative module of our full-scale air contactor design, with the goal of replicating the air and liquid flow properties that would be present at full-scale. Originally, our goal was only to test the air contactor performance itself, but to minimize the disposal costs of waste solution and to properly examine the accumulation of non-process-elements (NPE's, which generally includes ingested atmospheric contaminants, and any inerts that form in the system), we also built several steps of our regeneration process. Our OC prototype featured the air contactor, which used a hydroxide solution on structured packing to capture CO_2 and produce carbonate, then a "causticizer" to react this solution with lime (CaO) to precipitate calcium carbonate and re-generate the hydroxide for further capture, and finally a filter to separate out the calcium carbonate as a wet cake. In our full system design, the calcium carbonate would be heated in an oxy-fired calciner to liberate CO_2 for subsequent clean-up and compression. The calciner also re-forms the lime required by the causticizer, thus closing the chemical loop. This is a commonly used chemical cycle in the pulp and paper industry, known there at the "Kraft Process", and its use for air capture has been detailed in other work [3]. We did not build the high-temperature calciner into our pilot due to cost restrictions, so the pilot required a lime feed to run, and produced $CaCO_3$ for disposal.

Fig. 1: Rendering of CE's full-scale slab contactor design. This module would capture 100 kt-CO_2/yr.

2.1. Specifications

The OC was designed to examine the core packing wetting, mass transfer, and potential particulate fouling phenomena that underpin the performance of CE's air contactor design. A quantitative understanding of these phenomena is critical for our scale-up efforts and for continual revision and improvement of the design itself. The core components of the OC are outlined in details as follows, and an illustrative design of the air contactor is given as Figure 2.
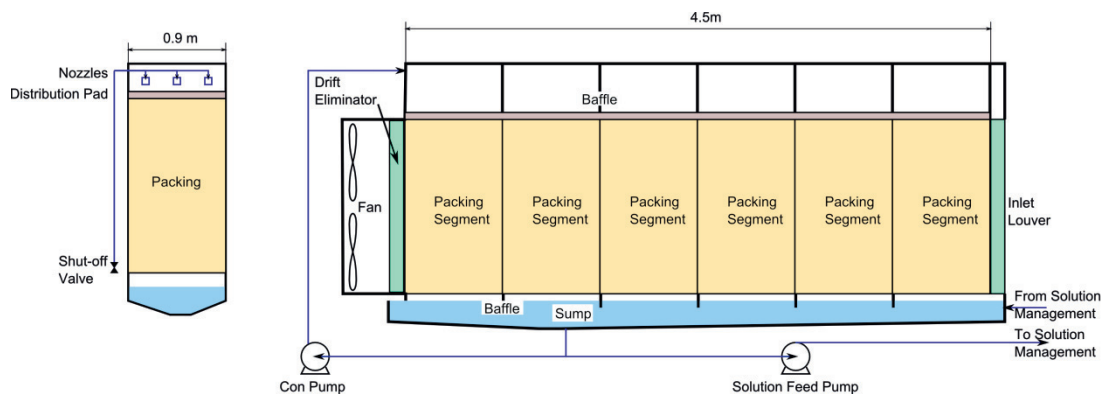

Fig. 2: Simple schematic of CE's OC air contactor.

The OC contains 10 m^3 of Brentwood Industries XF12560 structured PVC packing. CE's previous testing with a bench-top scale apparatus evaluated the CO_2 absorption performance and pressure drop characteristics of several packing products, both stainless-steel and PVC based. XF12560 emerged as the

most optimal design for our ambient CO_2 capture and design configurations, and as such, was used in our OC prototype. The packed volume was 1.8 m tall, 0.9m wide, and could be set up with an air travel distance of 4.5-6.0 m. Air travel distance is the distance which air travels through wetted packing.

The 1.8 m height of the packing was chosen to allow uniform liquid flow conditions to develop as the solution passed down through the packing. This was important, as proper flow conditions ensure that the surface wetting in the packed volume represents what would be achieved in a larger-scale system. At least 20 cm of height was required to achieve uniform liquid distribution, then the rest of the height served to mimic the realistic wetting conditions of a full scale contactor. Packing wetting phenomena is a key driver of overall contactor performance, and was hence one of our key aspects of study with the OC. Our ATD of 4.5 m was chosen to strike a middle ground between a small, transportable structure and a full representation of the 6-8 m ATD values predicted to optimize overall contactor cost [2].

Directly above the structured packing volume is a set of spray nozzles used to distribute the hydroxide solution over the packing. Each module, covering a top area of packing of 1 m^2, had 9 nozzles for liquid distribution, which immediately fell on what is termed a "distribution pad" – a device commonly used in the cooling tower industry – to push the solution laterally before it fell into the actual packing volume. After flowing down through the packing volume, the liquid fell through a grated floor back into the main sump. A combination of pumps and flow control valves allowed us to supply this liquid over the packing at a wide range of flow rates. It was also from this sump, that a small stream of liquid was removed for processing by our solution management system, which removed some of the constituent CO_2 in order to re-form the OH to allow continued capture. When run in steady state operation, the removal rate of CO_2 from solution matches our capture rate of CO_2 from the air, allowing us to maintain steady OH and CO_3^{2-} concentrations in the sump.

In addition to the packed volume in the air contactor, there were also two further commercial components from Brentwood Industries, to prevent ingestion of large particulates at the front, and to manage loss of small liquid particles at the back. At the inlet of the contactor, an "inlet louver" was used to catch debris in the air before it passes into the packing volume, where it could cause clogging or increased pressure drop. The inlet louver is a very simple PVC mesh which strains out large debris – such as leaves - in the intake air flow, and prevents splash-out of liquid droplets by passing the air through a downward sloping chevron path.   At down-stream end of the contactor, we installed a product called a "drift eliminator", again supplied by Brentwood Industries, that passes the air through a tortuous path that strains out any small, entrained hydroxide droplets. Quantifying the loss rates of drift droplets (as they are termed in the cooling tower industry) was also of chief importance in our prototype operation, as loss of drift represents and environmental and safety risk. Many commercial drift eliminators are available from the cooling tower industry, with manufacturer specifications that control drift to levels way below safety regulations, but none had been validated and quantified with our contactor configuration and operating parameters. Our drift measurement results from 2012 operation were very encouraging and are detailed in this paper. Several illustrative images of our OC prototype are shown in Figure 3.

Fig. 3: CE Outdoor Contactor Prototype fabrication and worksite.

2.2. Main OC Goals

CE's main goal in building the OC prototype was to quantitatively validate the performance of our cross-flow, PVC packing-based, intermittent liquid flow contactor design. We aimed to achieve this by demonstrating several months of run-time without significant performance degradations, and also in conjunction with the results from our subsidiary goals on energy use, drift, and particulate ingestion.

Our subsidiary goals involved studying long term trends in our CO_2 absorption performance in an operational outdoor environment, and to study the response of the absorption performance to a wide range of environmental conditions. Further, we designed our prototype with instrumentation to take measurements of fan energy requirement (by measuring pressure drop and air flow rate to calculate *PV* work), and liquid pumping energy (by measuring liquid flow rate and calculating *mgh* work) to quantify the energy demands of our larger scale design. Note that in this paper, we report these energy requirements before taking pump and fan in-efficiencies into account, for clarity of communication.

An additional goal of our outdoor contactor was to allow thorough measurement of the quantities and loss rates of hydroxide droplets in the contactor outflow air. As described briefly above, the cooling tower industry defines drift as the percentage of total re-circulating liquid lost as fine droplets. Since the hydroxide solutions we use for CO_2 capture are non-volatile, they do not suffer any evaporative losses, and drift droplets represent the only real loss stream, and thus health and safety risk, out of the contactor. Commercial "drift eliminator" products are common in the cooling tower industry, with well-established and certified efficiency ratings, that when applied to our air contactor design, should control drift levels to

values far lower than common Occupational Health and Safety standards require [6][7]. We used a thorough vacuum sampling program to measure drift concentrations in contactor outflow air, under a wide variety of operating conditions and over multiple months of operations. The results are given in Section 3.5.

Finally, we also had a goal of using the OC prototype to examine the impacts of slow, long-term physical and chemical fouling issues. We wished to examine for the presence of slow physical fouling of the packing due to scale formation or atmospheric particulate ingestion and trapping. We also wished to examine for "chemical fouling", in the form of ingested NPE's (non-process elements) or contaminants slowly decreasing the chemical ability of our capture solution to absorb CO_2. Our OC was designed to replicate these physical and chemical fouling issues for a larger-scale system.

2.3. Methods

Our primary method of operation for the OC, was to pick a set of operating parameters – solution concentrations, air velocity, liquid on/off duty cycle – and then to run at steady state for several days at a time to let the environmental variables – primarily inlet temperature and relative humidity – fluctuate underneath. During all runtime, the OC would log a full suite of sensor readings including CO_2 concentration at the inlet and outlet, temperature and relative humidity at the inlet and outlet, pressure drop across the packing, air velocity, liquid flow rate, and a large set of system diagnostics to validate the proper operation of all OC sub-systems. From these raw measurements, our data analysis program calculates the secondary metrics of interest, such as CO_2 capture rate (in g/s), "effective" mass transfer coefficient (in m/s), fan and pumping energy work rates (in J/s), and others.

In addition to this, we also used a system of manual sampling to augment our dataset from our sensors and instrumentation. Chiefly, the capture solution from the sump – which is what re-circulates over the packing to absorb CO_2 – was sampled and titrated to determine $[OH^-]$ and $[CO_3^{2-}]$ in (mol/L). These results were entered into our data logging program at the time of titration for integration with our recorded dataset. It is then with all this data in place that we can start to separate out the response of CO_2 absorption performance to different variables, such as temperature, solution $[OH^-]$, or liquid flow rate. The ability to understand CO_2 absorption as a function of our different variables is key to giving us greater predictability of how a large system will perform in fluctuating environmental conditions, greater ability to identify effects which can be used to improve contactor performance, and finally, the ability to separate out these effects from long-term performance trends and examine for any evidence of slow degradation.

We targeted several different combinations of $[OH^-]$ and $[CO_3^{2-}]$ for the steady state run method described above, and we planned them so that ideally, each combination would be run while outside temperature varied through a significant range. This was our strategy to obtain data at as wide of a span of operating conditions as possible, so that we could study the correlations and trends as described above.

In addition to these steady-state runs, we also ran numerous experiments that were shorter duration and more targeted in nature. We would routinely run the device to take a pressure drop curve – which maps out the response of total pressure drop across the packing to several different air velocity set-points – and we examined these PDC's for any small change over time. We ran tests to isolate the impact of liquid flow rate on CO_2 absorption. And as one of our primary techniques of contactor operation is our on/off liquid flow rate cycle, we ran a large variety of on/off cycle times and intensities. We also studied

causticization performance – the ability of our mixed tank to precipitate $CaCO_3$ as a function of inlet stream conditions, temperature, and residence time – but we will not discuss these efforts in this paper.

In addition to the operational methods described above, we also implemented a thorough plan of physical sampling and investigation. As already discussed, liquid samples from the sump were taken regularly (multiple times per day) for titration, and further to this sampling of our filter solids and regular investigation of the packing material and drift eliminator were conducted.

Our primary physical sampling effort was focused on measuring the concentration of drift droplets – fine, entrained liquid particles of our capture solution – in the contactor outflow. For this effort, we used a standard industrial air quality vacuum sampler to pull a known flow-rate of air through a filter cartridge. By deploying these cartridges in the contactor outflow air, and sampling for several hours, the fine liquid solution particles entrained in the flow would be trapped in the filter paper with their constituent K^+, OH^- and CO_3^{2-} ions. These ions were recovered off the filter papers into aqueous solution and analyzed at Access Analytical Laboratories (Calgary, Ab) by mass spectrometer for K^+ ion quantity. By comparing filter measurements that were taken at several times while the contactor was not running, and measurements taken directly in the outflow air at different times, dates, and durations, we were able to calculate the concentration of drift particles in the contactor outflow. Air sampling tests were conducted at several different combinations of air velocity, liquid flow rates, positions and orientation, and certain measurements were conducted many times over several weeks to establish the repeatability of our method.

2.4. Operations

CE began design and engineering of the OC in late-2010, fabrication progressed through early-2011, and the OC prototype was delivered to our work site in July 2011. We were able to achieve CO_2 absorption with the OC in September and October 2011, after which time we shut down the device through winter, since this particular prototype and our worksite did not easily facilitate winter operation. We resumed operations in June 2012, and were able to achieve mostly continuous runtime for the device from July-September 2012.

One of the first phases of operation of the prototype air contactor in 2011 was a start-up phase to prepare the prototype to begin automated conditioning of the structured packing in the air contactor. This start-up phase entailed sensor and equipment diagnostics, water runs, and slowly built up to autonomous automated operation. In the subsequent packing conditioning phase, we flushed the packing with mineralised water and then slowly dried it out, and repeated this cycle numerous times. When our PVC packing product arrives from the manufacturer, the plastic surface is relatively hydrophobic, due to the nature of the plastic itself and due to residual oils from the manufacturing process. This wet/dry conditioning phase both serves to remove any of these trace oils, and to slowly build up a mineral scale on the plastic surface. This scale is then what facilitates the formation of a liquid film – rather than "rivering" or beading – once our hydroxide capture solution is applied. This conditioning process is very well known and widely used in the cooling tower industry. If our packing was not conditioned, it would provide a much smaller interfacial area to the passing air and this would substantially decrease CO_2 absorption performance.

After our start-up and conditioning phases, we charged the system with NaOH in September 2011 and began actual CO_2 absorption. Our standard methods of operation were described in the previous section.

One of our key outcomes from the Fall 2011 operation was the validation of our intermittent liquid flow operating mode. Since CO_2 in ambient air is very dilute, and the hydroxide solutions we use for absorption are relatively strong, we do not need to continually flow hydroxide over the packing to ensure continued CO_2 capture. We have developed, and filed a patent application on, a method to supply full specified liquid flow for a short period of time to properly wet the packing with capture solution, then to turn off solution flow and let the residual liquid film continue absorption of CO_2 for some duration. This method was developed with a previous generation of prototype that our team had run in 2008, and this OC operation in 2011 finally quantified the benefits of using this operating mode. By varying the on-time, off-time, and flush intensity of the liquid supply duty cycles, we were able to study different duty cycles and their merit at minimizing pumping work while retaining as high a fraction of maximum capture as possible. An illustrative plot showing some of these duty cycle variations is given as Figure 4.

In Figure 4, the red data-set is the solution flow rate supplied to the packing in the air contactor; the blue data-set is total pressure drop through the packing; and the green data-set is the effective mass transfer coefficient. This effective mass transfer coefficient (in units of mm/s), is our standard metric for indicating CO_2 capture performance [2]. As can be seen in the figure, each time the packing is wetted (small pulses or long duration flushes), the mass transfer coefficient (indicating CO_2 absorption) spikes noticeably and gradually decreases as the packing wetting decreases and reactant (sodium hydroxide) is consumed. It can also be noted that the pressure drop spikes briefly as the liquid is supplied and the packing channels are partially constricted by the flowing liquid.

After a winter hiatus, OC operation began again in summer 2012. The system was stocked with KOH, due to its faster kinetics with CO_2 than NaOH, and to validate its suitability for long-duration operation. The main goal for the Outdoor Contactor in 2012 was to obtain as much long duration run time as possible. A key constraint to high uptime was the filter press that we purchased and installed on our prototype to filter out the produced $CaCO_3$. This was an economical option for $CaCO_3$ handling, but did necessitate that we bring the system off-line for 1-2 hours per day to clean the filter, and was an acceptable design trade-off within our goals outlined above. We pursued long-duration operation through July, August, and part of September 2012, during which time we built up a significant data-set from which to mine our performance trends. In September we began to focus more on specific, targeted experiments to test effects of liquid wetting and different operational modes. Also, throughout July-September 2012 we executed our air sampling program to measure and quantify drift concentrations.
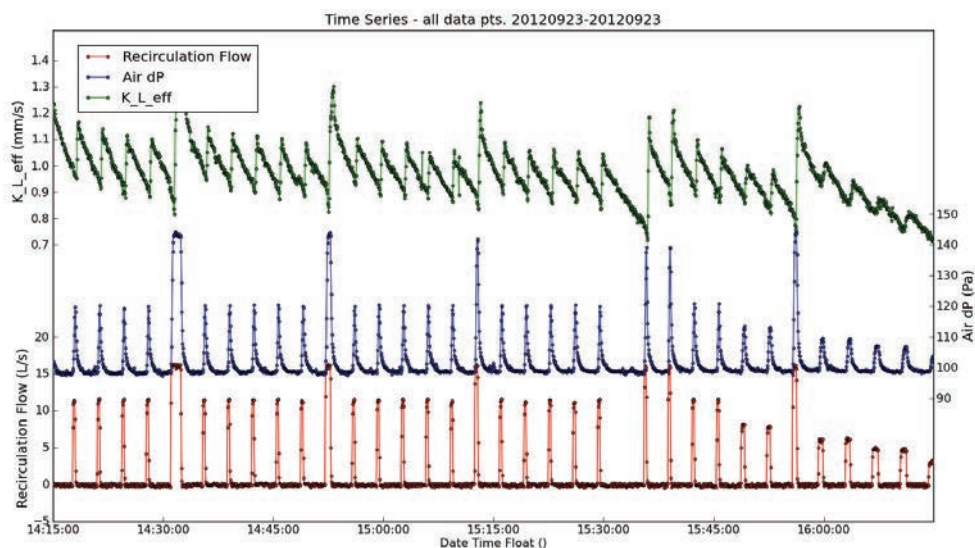
Fig. 4: Pulsed flow operation, and duty cycle manipulation.

3. Results

Over fall 2011 and summer 2012, we accumulated over 1000 hours of CO_2 absorption. We were highly encouraged to achieve this result, to see the system perform largely within predictions, and also to gather a wealth of new data to refine our trends and augment our understanding of the key performance phenomena. We were able to obtain critical CO_2 absorption performance data that will now be used for contactor scale-up and design, we were able to effectively measure drift concentrations with our required accuracy and well below the OHSA limits as predicted, and finally, over our 1000 hours of operation, we were not able to measure long-duration performance degradation, giving us an upper bound on costs required to limit long-term degradation in future larger-scale systems.

Over our 2012 operation, we ran roughly 2200 duty cycles with our packing, and captured a total of roughly 2 tons of CO_2. Though we spent much of the summer operating with sub-optimal solution concentrations for CO_2 capture rate in order to focus on maximizing our uptime and long-duration goals, we did do several experiments with high-performance solutions. These notably stand out as the one area of under-performance for our OC, where capture rate was ~30% lower than we had previously expected. As will be detailed below, this lower than expected capture rate led to an updated fan energy requirement that is higher than our previously reported values. Our estimate for liquid pumping energy requirements has remained unchanged from our previously reported value because we were able to achieve a similar, corresponding reduction in liquid flow requirement. We currently think that this under-performance stems from a specific design characteristic of our air contactor which impeded liquid distribution, and upon which we are currently re-working our design.

3.1. Long duration operation

Figure 5 shows an abridged dataset from our summer 2012 operations. Areas without data points show times where the system was either down for maintenance, or in a few cases, simply due to scheduling requirements of certain tests. This figure shows the average air velocity through the contactor (red), the effective mass transfer coefficient which indicates CO_2 capture performance (blue), and the ambient temperature (green). This outdoor contactor, and its successful run over these months, validated our design that differed in several respects from previous designs speculated at in the air capture field and from industrial precedent. The OC has cross-flow geometry rather than counter-flow as is common in traditional packed gas scrubber columns, it uses PVC based packing from the cooling tower industry rather than stain-less steel packing, it operates in the pulsed liquid-flow mode that we have described rather than continuous flow, and it uses all of these components with a strong hydroxide solution rather than with water as is done in cooling towers. These differences from previously existing designs and component uses – especially when taken together - represented a technical risk in our contactor design that we have now driven down through our prototyping efforts. We view this as one of the chief successes of this project.
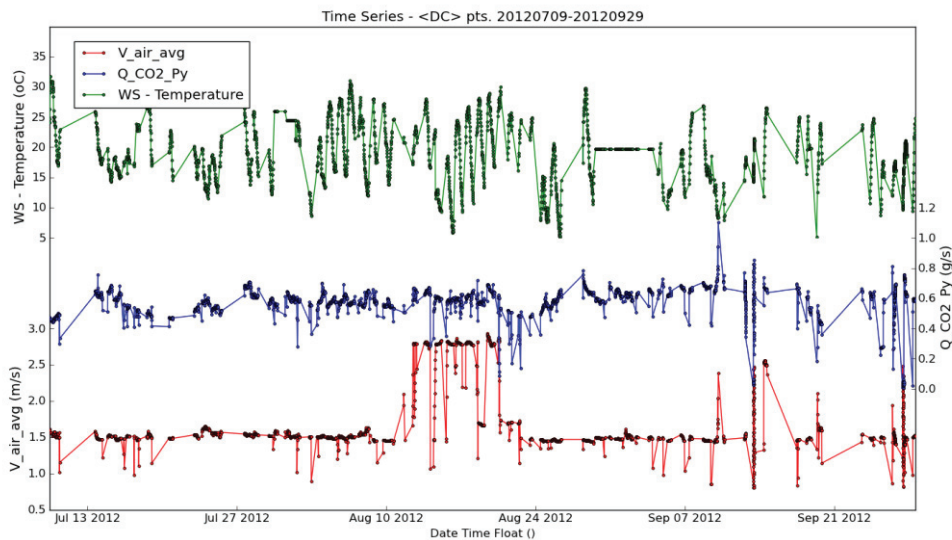

Fig. 5: 2012 summer OC data.

3.2. Intermittent liquid flow

Gas scrubbing columns and cooling towers, the two fields from which we form our design basis, operate in continuous flow mode, with both liquid and gas entering at steady, uniform flow rates. As we have outlined in previous sections, the dilute nature of CO_2 in air and the relatively strong concentration of OH in our capture solution, allows us additional freedom with which to manage our liquid flow rate. Manufacturer's specifications for the type of packing products we use define a minimum flow rate that is sufficient to cascade through the packing with enough force to wet all (or nearly all) of the packing surface area and form a liquid film. For example, the standard solution flow for uniform wetting of our XF12560 packing product is 4.1 $L/s \cdot m^2$ (L/s per top area in m^2) according to manufacturer's specs. However, our internal analysis and previous prototyping efforts [1] suggested that continually supplying

this flow rate of strong hydroxide to the packing would deliver far more OH^- into the contactor than required to react with incoming CO_2 at any reasonable air feed rate.

CE adopted a strategy to take advantage of these facts, and reduce pumping energy requirements – which would form a significant portion of air contactor cost if run at continuous full flow [1] – by operating liquid distribution in pulsed-flow mode. This method meets the flow rate required to form a liquid film over a large fraction of the packing surface area, but once averaged over multiple duty cycles, gives an average flow rate that is roughly 1/10th of the full continuous flow. Since CO_2 absorption continues into the hanging liquid film even after liquid flow rate has been throttled, the averaged CO_2 absorption rate can be kept at upwards of 85% the maximal absorption rate obtained with full, continuous flow. This operation method serves to significantly reduce the liquid pumping energy on a per-ton-CO_2 basis [2]. This "duty cycling" operation technique was shown in Figure 4.

Figure 6 illustrates the difference in average CO_2 capture rate (<Q_CO$_2$>, as a percent of capture rate at full, continuous flow) and average liquid flow (<Q_liquid>, as a percent of full manufacturer specified flow) that we can obtain in the Outdoor Contactor. The calculated mgh work for liquid pumping, once converted to a per-ton-CO_2 captured basis, from our OC prototype, is <40 MJ/ton-CO_2 (<11 kWh/ton-CO_2).
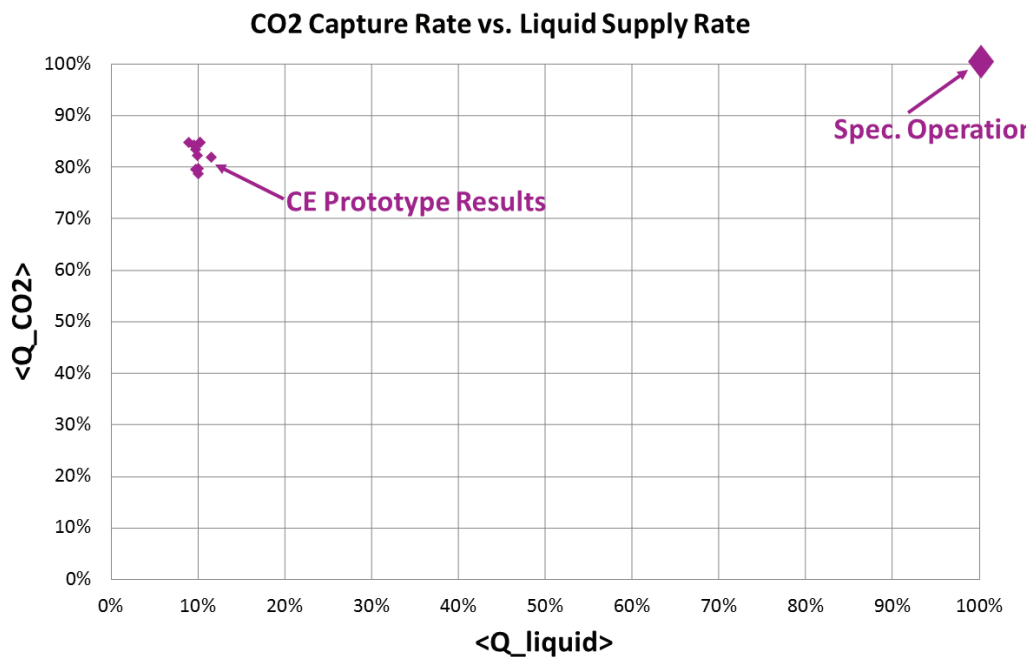

Fig. 6: Duty cycling performance.

3.3. Pressure drop and fan energy

PV work (fan energy) requirements can also be a significant portion of the air contactor costs. On average, the total differential pressure through all media (including inlet louvers, packing and drift eliminators) is approximately 100 Pa at 1.4 m/s. From this, and our CO_2 capture rate measured in the OC, our current estimate of fan energy is roughly <350 MJ/ton-CO_2 (<100 kWh/ton-CO_2). This is higher than

our previously stated value, because our OC capture rate during high absorption-performance experiments was lower than our previous analysis and preliminary results had indicated. We have a candidate cause for this absorption under-performance, which may have stemmed from a liquid distribution artifact introduced by our specific prototype design. We are aiming to test this hypothesis, and remedy the effect in our next air contactor design.

The air velocity at which we choose to run our contactor represents a classic trade-off between cap-ex and op-ex. Air contactor designs that rely solely on natural passive air movement, or wind driven air movement have been suggested. Our internal cost optimizations have shown us that these concepts suffer from intermittency, which limits the overall average CO_2 capture rate, which in turn increases the contribution from capital expenditure on total cost per ton CO_2 captured. Alternately, using fans to drive air very quickly through the contactor will produce an increased CO_2 capture rate, but this increased air velocity results in greater pressure drop and hence greater op-ex for the fan energy required. Our internal cost optimization, using manufacturer specified pressure drop data, has suggested that optimal air velocities for our system are in the range of 1.4-1.6 m/s.

With our OC prototype, we wanted to validate that we could achieve the same pressure drop performance as given by the manufacturer, and also that we could avoid severe scaling or clogging issues that would drive the pressure drop up over time. Figure 7 illustrates several Pressure Drop Curves (PDC's), which plot the total pressure drop across our packing (in Pa) versus the average air velocity through the packing (in m/s). The green trend is the manufacturer specified PDC for our depth of XF12560 packing. Both of our measured pressure drop curves are slightly higher than this since we measured pressure drop across the XF12560 packing itself, and also across the inlet louver and drift eliminator components, which add slightly to the total pressure drop. To quantify the effect of slow pressure drop increase over time – due to fouling or clogging – we took multiple PDC's over the duration of our OC operation. Shown here are a PDC from start of operations (red) compared with one from end of operations (black). These two curves do not differ beyond experimental uncertainty, and thus do not show evidence of physical performance degradation. Post-operation examination of packing is on-going.

The packing used in our air contactor was plastic packing from Brentwood Industries known as XF12560. This packing design has lower pressure drop than common Sulzer stainless steel varieties, which are more expensive and greater much greater pressure drop due to the turbulent gas mixing that is often needed to drive gas scrubbing operations to full conversion. For our application, since we operate at ambient temperatures within the tolerance of PVC materials, and since we need less turbulence in our gas phase, we are able to use this cost-effective, efficient XF12560 packing product.

Pressure Drop Curve
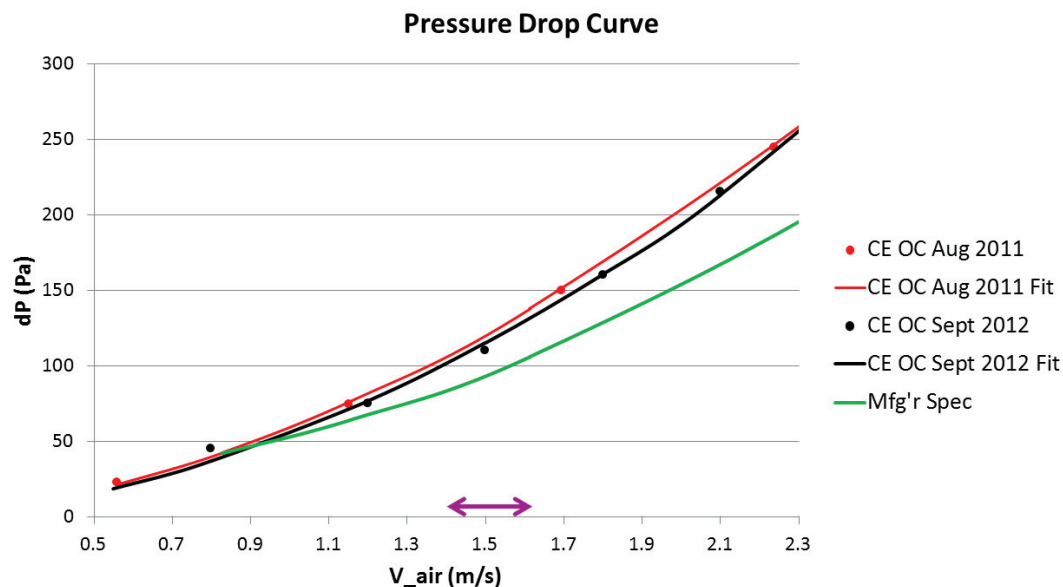
*Total pressure drop shown, including inlet louver and drift eliminator.
**Liquid flow at ~1.5 L/m^{2}s.

Fig. 7: Pressure drop curves, measured (red, black) and modeled (green) with liquid flow at 1.5 L/m^2·s.

3.4. CO$_2$ capture rate

One of the goals for the OC prototype, was to measure CO$_2$ capture rate –expressed as either capture rate itself (in g/s) or in terms of our mass transfer coefficient K_L (in m/s) – at all possible combinations of operating conditions (which we control) and environmental conditions (which we do not). This meant spending significant amounts of runtime at operating conditions that we knew to be sub-optimal in terms of producing maximum CO$_2$ capture rate, but were essential to creating a data-set from which we could mine accurate sensitivities of CO$_2$ capture rate to the various parameters.

During our operation at "high-performance" conditions, which unfortunately we cannot disclose, we observed capture rates that were roughly 30-40% lower than what we had expected based on theoretical predictions, beaker-scale laboratory data, and previous smaller-scale experiments with structured packing. We currently think this was due to the particulars of liquid distribution at our small-scale design and may be remedied at larger scale. In relative context, this was our first serious attempt at outdoor cross-flow contacting, and it would have been surprising to see performance meet or exceed our expectations. Our efforts will focus on understanding this discrepancy and addressing the cause as we move to the next iteration of our design. When running with optimal solution, we saw duty cycle-averaged mass transfer coefficient values of ~1.1 mm/s, rather than 1.5 mm/s that our previous experiences predicted, and as we have reported in some of our previous work. Once contactor depth and operational air velocity are re-optimized to account for this lower mass transfer performance, this current under-performance effect would represent an additional contactor cost of $10/ton-CO$_2$ to our total contacting cost if left unaddressed. We are working both to counter this effect, which we are confident can be achieved, and through other projects at CE, to further reduce contacting cost via cheaper structural materials and construction methods.

3.5. Drift measurements

A chief health and safety concern about wet scrubbing contactors for direct air capture has been that they would emit "drift" – small liquid droplets entrained in the contactor outflow – to the surrounding environment. As our working fluid is a strong hydroxide solution, rather than water as in a cooling tower, we take this risk very seriously, and are determined to control drift to below all industrial health and safety regulations.

According to OHSA, the maximum 8-hour-average permissible exposure limit for hydroxide droplets is 2 mg/m^3-air. Anything below this limit is considered safe to work in without wearing a respirator, and anything above require that proper PPE be worn. Both the cooling tower and gas scrubber industries make commercial drift eliminator products, that strain out entrained droplets by passing the air through a tortuous, chevron flow path which causes droplets to impact on the flow channel walls and drain back into the system. Modern designs for drift eliminators are very effective, and we have used a Brentwood Industries XF80MAx product which is specified to control drift loss rate to less than 0.0005% of the total recirculating flow rate inside the contactor. XF80MAx products are used on industrial cross-flow cooling towers with high efficacy and we wanted to validate that they could be used for our hydroxide-based air contactor system.

To measure the concentration of hydroxide drift droplets in our outflow air, we undertook an intensive air sampling program, utilizing industrial air quality equipment. Air was sampled for through a filter cassette at a specified flow rate, commonly for 6 hours, and subsequently any K^+ ion trapped in the filter membrane was recovered into aqueous solution and analyzed at Access Analytical Laboratories (Calgary, Ab). We determined early on that the K^+ ion has a very low background concentration in ambient air, and that the K^+ present in our hydroxide contactor solution could be used as a tracer from which to calculate quantity, and ultimately concentration, of drift. Unopened filter cassettes, and filter cassettes which had passed only ambient air before the contactor was run were analyzed to establish the baseline K^+ concentration produced by our method. Then, 6 hour air samples were taken repeatedly in our contactor outflow air, at various operating conditions of air velocity and liquid flow rate. Further, air samples were taken over a wide time range at the same operating conditions to establish the repeatability and uncertainty of our measurement technique. From the measured K^+ concentration in the recovered aqueous sample, we were able to use the flow rate of air through the filter cassette and the sample time to back-calculate the concentration of hydroxide droplets (which contain both K^+ and OH^-) in the contactor outflow air stream that the filter was sampling.

Figure 8 shows the calculated hydroxide concentration in air from a number of our drift measurement tests. These results are in agreement with our previous drift measurement results from 2011, and are highly encouraging. Once back-calculated, and accounted for imperfect recovery of our tracer from the filter paper itself, each of the drift tests that we took during normal operation came back with an OH^- concentration in air of less than 5% of the OSHA permissible exposure limit. We continue to treat drift as the important safety issue that it is, and our next generation of pilot will continue this drift measurement program and we also aim to include independent 3rd party validation of our measurements.
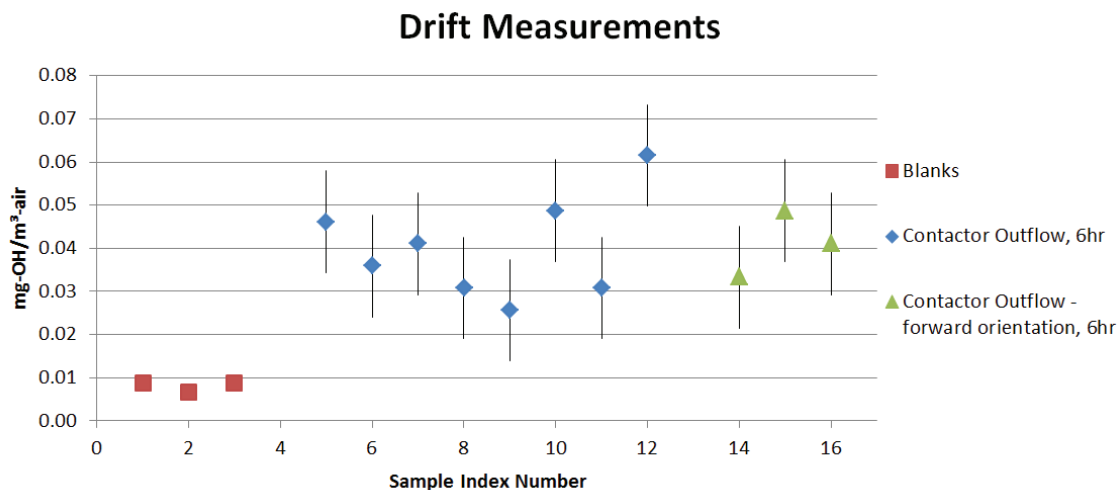
Drift Measurements

Fig. 8: Drift measurements summary.

4. Conclusion

We have presented the design characteristics, and several examples of operational methods, measurements, and results from our Outdoor Contactor prototype. Carbon Engineering plans to built industrial scale direct air capture facilities, and this prototype was engineered to be a smallest representative unit of the air contactor in our full-scale design. The successful operation of this OC prototype with over 1000 hours of CO_2 capture, has validated our novel and cost-effective "slab" contactor geometry, our use of efficient PVC packing, and our own pulsed liquid flow operation mode. The measurements obtained with this prototype have increased our understanding of the core phenomena that dictate contactor performance, and have given us a valuable empirical data-set on which to base our scale-up engineering efforts. We have also used this prototype to update our quantitative estimates of fan and liquid pumping energy requirements, to measure the concentration of "drift" droplets in our outflow stream and confirm that they are well below OHSA permissible exposure levels, and to examine for evidence of slow, long-duration performance degradation.

At Carbon Engineering, we are now closing a second funding round that will allow us to build an end-to-end commercial pilot of our direct air capture process. This pilot will capture of order 1 kt-CO_2/yr, and will deliver that CO_2 at pipeline purity. The pilot is designed to have appropriately-sized unit operation components, such that a successful run will secure us the support of our main process equipment vendors to then build at full industrial scale.

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