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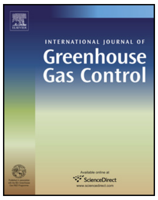

# Application of liquid desiccant dehumidification to amine-based carbon capture systems

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ABSTRACT

Liquid desiccant-based dehumidification with water recovery is an effective and robust method to remove excess moisture from process gas streams and recover relatively high quality product water. A study was undertaken to determine if desiccant-based technology could be applied to the benefit of an amine-based $CO_2$ capture system since the addition of $CO_2$ capture to a coal-fired power plant can significantly increase the plant's consumptive water use. Test data with a pilot flue gas moisture recovery system are presented to illustrate the characteristics of the process, including the water recovery potential, product water quality, and thermal energy consumption. The process is then evaluated theoretically under conditions typical of a monoethanolamine-based $CO_2$ capture process. The analysis indicates that there is less opportunity for moisture recovery compared to a plant without $CO_2$ capture because of the cooler processing temperatures associated with $CO_2$ absorption and stripping. However, a desiccant-based dehumidification system might be useful as a heat-driven moisture management tool since desiccant-based moisture removal is more effective than dew point cooling for a given heat rejection temperature. Dehumidifying the $CO_2$ product stream prior to compression might offer incremental power consumption savings compared to other options of moisture vapor management.

## 1. Introduction

Water consumption is a key concern for all utility-scale power production. Access to sufficient water for cooling can delay permitting, introduce added costs, and even lead to the cancellation of projects. Unfortunately, it seems clear that the water intensity of power production will only increase with the addition of a carbon dioxide recovery (CDR) system. According to baseline studies presented by the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) (2009), pulverized coal plants could experience the most dramatic increase in water consumption, as shown in the trends of Fig. 1. Much of the additional water consumption goes to serve the added cooling load introduced by the amine-based CDR system, as shown in the breakdown of Table 1 (U.S. Department of Energy National Energy Technology Laboratory, 2009). Dry cooling options using air as the heat rejection medium are available, and studies subsequent to the NETL baseline cases evaluated the impact of using dry cooling for at least the power cycle's steam condensation load (Zhai et al., 2011). That study showed that switching to an air-cooled condenser lessened the water consumption for a CDR-equipped pulverized coal plant to roughly match that of a non-CDR plant with wet cooling. However, both of these studies assumed a $CO_2$ capture rate of 90%. Recently, the issue of increased water consumption with CDR was reevaluated with respect to (at the time) proposed U.S. Environmental Protection Agency emission performance standards for new coal-fired electric generation units (Talati et al., 2014). For a regulatory limit of 1100 lb $CO_2$/MWh gross (500 kg $CO_2$/MWh gross), the authors concluded that water consumption would increase by about 31% from the addition of CDR.

The moisture content of flue gas is a potential source of makeup water for power plant operations. While the quantity of recoverable flue gas moisture is far too small to offset cooling tower losses, it can be sufficient to approach the makeup needs for secondary plant processes such as FGD or boiler feedwater. With respect to operation of an amine-based CDR system, situations have been identified where the $CO_2$ absorption and stripping process can operate on a water-neutral basis by cooling the flue gas below its dew point and retaining water in the process (Hetland, 2013). Of course the source of cooling matters since, if evaporative wet cooling is used, water loss is simply transferred to the cooling tower. In the case of using cold seawater, dew point cooling could save the trouble

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**Table 1**
Breakdown of Major Water Uses for a Supercritical pc Plant (U.S. Department of Energy National Energy Technology Laboratory, 2009).

| | Without $CO_2$ Capture | With MEA-Based $CO_2$ Capture |
|---|---|---|
| Cooling Tower Makeup | 88.7% | 91.5% |
| FGD[a] Makeup | 10.0% | 7.5% |
| Boiler Feed Makeup | 1.3% | 1.0% |

[a] Flue gas desulfurization.

of sourcing freshwater makeup (Kvamsdal et al., 2010), but most other locations would need to consider air cooling which is more limiting. Of the coal-fired, amine-based CDR, examples evaluated by Hetland (2013), only the high moisture lignite case appears to result in a water-neutral temperature that could feasibly be met by dry cooling.

## 2. Liquid desiccant dehumidification with moisture recovery

Liquid desiccant dehumidification is a proven and robust method to remove excess moisture from process gas streams. These systems employ a hygroscopic medium that can absorb moisture at vapor pressures below the saturation pressure of pure water. Therefore, they have an expanded range of water-harvesting conditions relative to dew point condensation, albeit at the expense of increased thermal energy needed for regeneration.

The Energy & Environmental Research Center (EERC) has investigated the use of liquid desiccant-based systems for a number of power production applications, including flue gas moisture recovery (Folkedahl et al., 2006), pollutant scrubbing (Martin and Zhuang, 2014), and power plant cooling (Martin and Pavlish, 2013). Liquid desiccant dryers are commonly specified for amine-based CDR to remove moisture from the intercooler stages of the $CO_2$ compression train. However, these systems are designed to dry the $CO_2$ to achieve dew point specifications for pipeline transport and they frequently employ triethylene glycol (TEG) as the liquid desiccant instead of a $CaCl_2$-based solution that is preferred for many of the previously mentioned applications. Compared to $CaCl_2$, TEG has a more limited moisture exchange capacity, which makes it less desirable for bulk moisture recovery, but it is a superior drying agent for removing trace quantities of moisture vapor. For instance, liquid TEG can absorb moisture to achieve a −40 °C pipeline dew point specification, a moisture level that would completely dry out a liquid $CaCl_2$ solution, leaving only a solid hydrate crystal.

Liquid desiccant moisture recovery is similar to conventional gas-drying systems except that desiccant regeneration takes place in a sealed flash evaporator so that product water can be recovered by condensing the vapor in a condenser. A simplified schematic of the process is shown in Fig. 2. According to the figure, a concentrated liquid desiccant solution is used to absorb moisture directly from the process gas in a counterflow absorber; the exiting working fluid that is diluted with absorbed moisture, or weak solution, is then heated and pumped to an evaporator where the moisture flashes from solution and is condensed to generate liquid water product. The concentrated desiccant, or strong solution, exiting the evaporator is then cooled and is ready to complete the cycle by absorbing additional moisture vapor in the absorber.

The liquid desiccant process is primarily heat-driven and is not unlike the fundamental process of amine-based absorption and stripping for $CO_2$ capture. As such, liquid desiccant moisture removal has the potential to remove moisture from a process stream using significantly less mechanical power compared to other options like dew point cooling or compression with condensate separation.

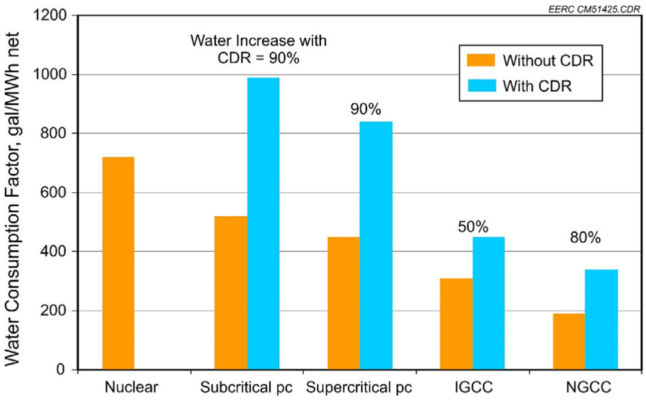

**Fig. 1.** Estimated changes in water intensity by adding monoethanolamine (MEA)-based $CO_2$ capture to various power production cycles (U.S. Department of Energy National Energy Technology Laboratory, 2009) (pc is pulverized coal; IGCC is integrated gasification combined cycle; NGCC is natural gas combined cycle).

## 3. Pilot test experience

A liquid desiccant flue gas moisture recovery system was fabricated and tested in conjunction with one of the EERC's pilot-scale combustion test facilities. The moisture recovery system was fitted to the exhaust stream of a pulverized coal-fired system known as the combustion test furnace (CTF). The EERC's CTF is a 550,000-Btu/h (160 kWth) pulverized coal pilot plant test furnace and was originally constructed in 1967 to evaluate the influence of variables such as ash composition, excess air, gas temperature, and tube wall temperatures on ash fouling. In addition to these original uses, it has also been modified to also allow evaluation of a number of back-end pollution control technologies including postcombustion amine-based $CO_2$ capture and precombustion $CO_2$ separation with oxygen-firing.

For these tests, the liquid desiccant system was designed to treat the flue gas exhaust from the $CO_2$ absorber of a MEA-based CDR system. A solution of $CaCl_2$ and water was used as the dehumidification agent. $CaCl_2$ was chosen based on an evaluation completed during the initial evaluation of this concept (Folkedahl et al., 2006) where it ranked high in key criteria such as low cost, moderate corrosivity, and relatively benign environmental impacts in case of accidental release. Thermophysical properties of $CaCl_2$ desiccant mixtures, including vapor pressure, saturation concentration, specific heat, etc., were calculated using property correlations available in the literature (Conde, 2004).

Fig. 3 shows the as-tested connection schematic for the liquid desiccant system. This schematic is fundamentally identical to the concept presented in Fig. 2, but it includes transducer locations and ancillary equipment such as pumps, storage tanks, valves, etc. The flash evaporator operated at subatmospheric pressure to improve the efficiency of moisture recovery, and this pressure differential was maintained by isolating the evaporator and condenser between two liquid-filled barometric legs, one for the strong desiccant and one for the product water. Noncondensable gases that accumulated in the condenser were evacuated using a liquid ring vacuum pump. The absorption column was fabricated from 12-in. (30.5-cm)-diameter, Schedule 10, 316 stainless steel pipe, and it was filled with 3-in. (7.62-cm) plastic gas/liquid distribution saddles to a depth of approximately 6 ft (1.83 m) to increase contact area between the flue gas and the desiccant. Strong desiccant was pumped into the top of the absorber column and onto plastic gas/liquid distribution saddles through a single 1-in. (2.54-cm) pipe. A Teflon screen mist eliminator was installed at the top of the column to prevent the loss of entrained liquid droplets.

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