SUBTASK 5.3 – WATER AND ENERGY SUSTAINABILITY AND TECHNOLOGY

Final Report

(for the period of October 1, 2008, through September 30, 2010)

Prepared for:

AAD Document Control

U.S. Department of Energy
National Energy Technology Laboratory
626 Cochrans Mill Road
PO Box 10940, MS 921-107
Pittsburgh, PA 15236-0940

Cooperative Agreement No.: DE-FC26-08NT43291
Project Manager: Barbara Carney

Prepared by:

Bruce C. Folkedahl
Christopher L. Martin
David J. Dunham

Energy & Environmental Research Center
University of North Dakota
15 North 23rd Street, Stop 9018
Grand Forks, ND 58202-9018

2010-EERC-09-10

September 2010

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government, nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

This report is available to the public from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161; phone orders accepted at (703) 487-4650.

EERC DISCLAIMER

LEGAL NOTICE This research report was prepared by the Energy & Environmental Research Center (EERC), an agency of the University of North Dakota, as an account of work sponsored by the U.S. Department of Energy National Energy Technology Laboratory. Because of the research nature of the work performed, neither the EERC nor any of its employees makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement or recommendation by the EERC.

SUBTASK 5.3 – WATER AND ENERGY SUSTAINABILITY AND TECHNOLOGY

ABSTRACT

The overall goal of this Energy & Environmental Research Center project was to evaluate water capture technologies in a carbon capture and sequestration system and perform a complete systems analysis of the process to determine potential water minimization opportunities within the entire system. To achieve that goal, a pilot-scale liquid desiccant dehumidification system (LDDS) was fabricated and tested in conjunction with a coal-fired combustion test furnace outfitted with CO_2 mitigation technologies, including the options of oxy-fired operation and postcombustion CO_2 capture using an amine scrubber. The process gas stream for these tests was a coal-derived flue gas that had undergone conventional pollutant control (particulates, SO_2) and CO_2 capture with an amine-based scrubber. The water balance data from the pilot-scale tests show that the packed-bed absorber design was very effective at capturing moisture down to levels that approach equilibrium conditions.

Product water quality was good, which was consistent with previous testing of this concept; however, some contamination was suspected to be caused by trace carryover of amine solution from the upstream CO_2 scrubber. Because of the poor thermal energy recycling within the pilot-scale LDDS, it was not possible to operate the system autothermally: that is, without external heat input. An examination of the system's energy balance shows that the system could benefit from a solution heat exchanger to improve thermal energy recycling. While the LDDS can feasibly recover high percentages of water using low-temperature thermal energy, it is a capital-intense approach for water recovery, and it, therefore, has a relatively high cost for product water. Novel integration strategies are needed to distribute the capital expenses among several power plant functions in order to make the LDDS concept more attractive. Identified strategies include making the absorber multipurpose: for example, moisture absorption and polishing SO_2 control, recovering moisture from multiple process streams using common evaporator and condenser components, and possibly sharing the plant's steam condenser to recover product water.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUBTASK 5.3 – WATER AND ENERGY SUSTAINABILITY AND TECHNOLOGY

EXECUTIVE SUMMARY

The overall goal of this Energy & Environmental Research Center project was to evaluate water capture technologies in a carbon capture and sequestration system and perform a complete systems analysis of the process to determine potential water minimization opportunities within the entire system. To achieve that goal, a pilot-scale liquid desiccant dehumidification system (LDDS) was fabricated and tested in conjunction with a coal-fired combustion test furnace outfitted with CO_2 mitigation technologies including the options of oxy-fired operation and postcombustion CO_2 capture using an amine scrubber. Important factors in the design were the flue gas flow rate entering the absorber as well as the temperature of the gas entering the LDDS.

Shakedown testing with both oxy-fired and CO_2-scrubbing configurations were conducted along with four sets of extended-duration tests using the LDDS to recover moisture following the CO_2 scrubber. The process gas stream for these tests was a coal-derived flue gas that had undergone conventional pollutant control (particulates, SO_2) and CO_2 capture with an amine-based scrubber.

The water balance data from the pilot-scale tests show that the packed-bed absorber design was very effective at capturing moisture down to levels that approach equilibrium conditions. Product water samples from the pilot-scale LDDS were routinely collected during test runs and analyzed for suspected contaminants. Compared to previous studies of moisture recovery from conventional coal flue gas, which were slightly acidic, the product water reclaimed from the CO_2 scrubber exhaust consistently had a high, basic pH. This is most likely a result of trace carryover of amine solution from the upstream CO_2 scrubber.

An energy balance for the pilot-scale LDDS shows that very little preheating of the working fluid was accomplished in the condensing flue gas heat exchanger and, therefore, electric heat input was required for the majority of energy into the system. As a result, it was not possible to operate the system autothermally: that is, without external heat input. Examination of the operating conditions for the flue gas heat exchanger suggest it is unlikely that significant improvements could be made; however, the electric heat input could be reduced by installing a solution heat exchanger. In this heat exchanger, the hot, strong solution leaving the evaporator would be used to preheat the incoming weak solution.

When the LDDS was used to recover moisture from a concentrated CO_2 stream, CO_2 was partially absorbed because it is slightly soluble in aqueous solution. During shakedown tests of the pilot-scale LDDS under oxy-fired conditions, the desiccant solution was neutralized with a bed of $CaCO_3$, and in extreme cases, $Ca(OH)_2$ was added to raise pH.

In terms of the most productive applications for the LDDS, higher-temperature, saturated gas flows offer the most promise. Not only does the maximum capture potential increase for the LDDS with increasing temperature, but the available saturated water content increases dramatically with temperature. For the plant configurations of interest in this work, that is, oxy-

fired or conventional combustion with CO_2 capture, LDDS moisture recovery may be at a disadvantage since the process gas temperatures will be lower to accommodate either downstream CO_2 compression equipment or upstream amine-based scrubbers. Lower temperatures imply lower moisture content for recovery, which would tend to increase the levelized cost of LDDS water production.

The LDDS can feasibly recover a higher percentage of water than ambient-temperature condensation and can use low-temperature recovered heat for input energy, but it is a capital-intense approach. Novel integration strategies are needed to distribute the capital expenses among several power plant functions in order to make the LDDS concept more attractive. Identified strategies include making the absorber multipurpose: for example, moisture absorption and polishing SO_2 control, recovering moisture from multiple process streams using common evaporator and condenser components and, possibly, sharing the plant's steam condenser to recover product water.

SUBTASK 5.3 – WATER AND ENERGY SUSTAINABILITY AND TECHNOLOGY

1.0 INTRODUCTION

The electricity industry is second only to agriculture as the largest domestic user of water, accounting for 39% of all freshwater withdrawals in the nation, of which 71% is used in fossil fuel-based electricity generation. Power plants have to compete with other industrial customers, agricultural interests, and households for this limited commodity. The availability of water for use in electric power generation is limited in many parts of the United States and is an important factor in obtaining site permits for new power plant construction. Difficulty in obtaining necessary water permits can lead to delayed or abandoned projects. Also, it is often the case that additional infrastructure is required to provide a suitable supply, adding cost and environmental impact. In areas that do not have an adequate water source, power plant construction is not even considered, even though these locations are ideal in other respects. Since water is already a contentious issue for conventional coal-fired plants, significant increases in water consumption as a result of the addition of CO_2 capture and sequestration (CCS) will only further complicate the continued operation and construction of these plants. A recent study by the U.S. Department of Energy National Energy Technology Laboratory (NETL) has estimated that the water intensity of a modern supercritical coal power plant using wet recirculating cooling is on the order of 440–580 gallons per MWh of net electricity production (1). The water is primarily used for one of three plant functions: cooling, environmental control (e.g., flue gas desulfurization [FGD], sluicing, etc.), or boiler makeup. Of these uses, cooling is by far the largest and typically represents 85%–90% of a coal plant's water use (1).

Adding CCS to a power plant increases its water requirement by amplifying these existing water needs, primarily cooling. It is estimated that the water demands for a supercritical coal plant will increase by 87% with the addition of an amine-based CO_2 capture system (1). The increase is due to the parasitic power load imposed on the plant by the CCS system and by the additional water needs of the CCS system itself. However, water consumption associated with each of these demands ultimately comes down to an increased need for cooling, which is responsible for 94% of the water increase (1).

For CO_2 capture systems, water will need to be removed to very low levels prior to pipelining the CO_2 to its final destination. This water has significant potential to be utilized in plant operations. However, questions remain as to water quality, the best technology for water removal and collection, and how this can be accomplished in an efficient and economical fashion.

In previous work at the Energy & Environmental Research Center (EERC), a liquid desiccant dehumidification system (LDDS) was investigated in conjunction with Siemens Power Generation (2). The LDDS is an absorption-based system to recover moisture from process gas streams. In the LDDS, a liquid desiccant 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 is desorbed from solution and is condensed to generate liquid water product. The concentrated desiccant, or *strong* solution, is then cooled and is ready to complete the cycle in the absorber.

The LDDS concept has several features that make it potentially attractive to integrate with a coal-fired power plant equipped with CCS:

- The LDDS can lower moisture levels to values lower than those feasible by simple cooling and moisture condensation.

- The desiccant solution separates the process gas and moisture condensation space. In this respect, the LDDS performs a similar function to a water-selective membrane, but it is more robust and can resist fouling in harsh flue gas environments.

- The LDDS produces high-quality product water without additional treatment. Condensed process gas moisture will contain all of the soluble impurities of the process gas.

- The LDDS does not completely cool the process gas stream, which is an important consideration if the gas is to be exhausted to a stack.

2.0 GOALS AND OBJECTIVES

The overall goal of the project was to evaluate water capture technologies in a CCS system and perform a complete systems analysis of the process to determine potential water minimization opportunities within the entire system. Specific objectives were to design and build water capture systems that will remove water from a flue gas stream prior to pipeline preparation of the CO_2 stream. The two water removal technologies included a LDDS and a condensing heat exchanger (HX). Both systems were installed on a pilot-scale CCS system that was built under a complementary project at the EERC.

An additional objective was to evaluate the entire CCS system to identify opportunities to minimize water use. The project was intimately linked to another program at the EERC for demonstration of CO_2 capture technologies, the Partnership for CO_2 Capture.

3.0 EXPERIMENTAL

The LDDS test unit was constructed in the EERC's pilot-scale test facility. The unit is operated on the back end of an existing pulverized coal (pc)-firing system known as the combustion test furnace (CTF). All fabrication and construction of both the CTF and LDDS systems was performed by EERC personnel, and operation was directly overseen by the center's engineers. The next two sections describe the CTF and LDDS systems and components.

3.1 Description of the CTF

Research programs have been under way at the EERC for more than 25 years to study ash fouling of boiler heat-transfer surfaces in coal-fired utility boilers. A 550,000-Btu/hr pc pilot plant test furnace was constructed in 1967 to evaluate the influence of variables, including ash composition, excess air, gas temperature, and tube wall temperatures on ash fouling.

The research capabilities of the CTF have been enhanced and expanded to provide information on a wide range of combustion-related issues. The many research applications of this pilot-scale combustion equipment over the years have included the following:

- Determining ash-fouling rates and the strength, composition, and structure of fouling deposits.
- Applying sophisticated analytical methods to characterize input coal, ash, and deposits and to correlate coal and ash properties with deposit growth rates and strength development.
- Evaluating the effectiveness of ash-fouling additives.
- Studying particulate-size distribution and velocity prior to deposition on convective section heat-transfer surfaces.
- Evaluating combustion characteristics of coal–water fuels.
- Studying high-temperature baghouse operation and performance.
- Evaluating sorbent injection for SO_x control.
- Evaluating sorbent injection for mercury control.
- Assessing integrated particulate and SO_x–NO_x control.
- Studying NO_x control using selective catalytic reduction (SCR) and disposable catalysts.
- Evaluating ash-slagging potential in a simulated wet-bottom firing mode.
- Performing flame stability tests for comparing a particular fuel at full load and under turndown conditions.

In addition to the above capabilities, new equipment and scrubbers (including the LDDS) are being added to allow testing of many of the EERC's and other new environmental reduction technologies.

An isometric drawing of the EERC CTF is shown in Figure 1. The furnace capacity is approximately 60–75 lb/hr (550,000 Btu/hr) of pc. The combustion chamber is 30 inches (76.2 cm) in diameter, 8 feet (2.44 m) high, and refractory-lined.

The furnace diameter may be reduced to 26 inches (66.0 cm) to elevate the temperature entering the convective pass. Furnace exit gas temperatures (FEGT) as high as 2550°F (1399°C) have been achieved during combustion testing in this mode. Most tests are performed using the standard configuration (30-inch inside diameter), with the FEGT maintained at approximately 2000°F (1093°C) for each combustion test.

Coal is pulverized remotely in a hammer mill pulverizer, targeted to a size of 70% less than 200 mesh. The coal is then charged to a microprocessor-controlled weight loss feeder from a transport hopper. Combustion air is preheated by an electric air heater. The pc is screw-fed by the gravimetric feeder into the throat of a venturi section in the primary air line to the burner. Heated secondary air is introduced through an annular section surrounding the burner. An adjustable-swirl burner, which has a distribution of primary and secondary air of approximately 15% and 85%, respectively, is used to fire the coal. Flue gas passes out of the furnace into a 10-inch (25.4-cm)-square duct that is also refractory-lined. Located in the duct is a vertical probe bank designed to simulate superheater surfaces in a commercial boiler.

After leaving the probe duct, the flue gas passes through a series of water-cooled HX before being discharged through either an electrostatic precipitator (ESP) or a baghouse.

In addition to this standard combustion configuration, the CTF is also capable of operating under oxy-fired conditions. Oxygen-firing mode replaces combustion air (approximately

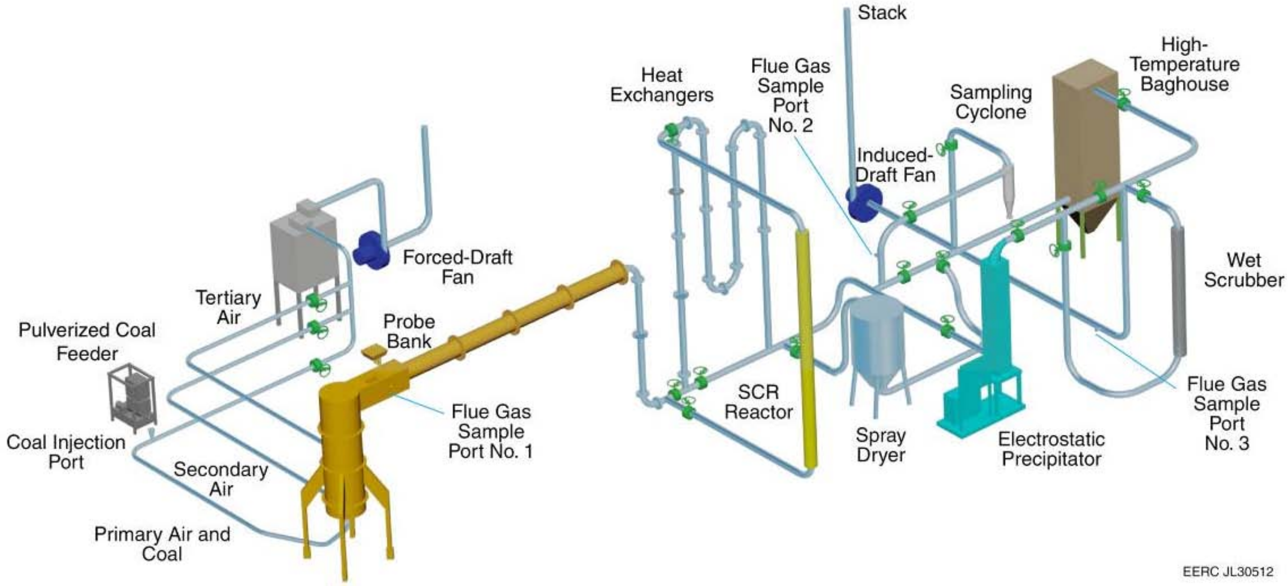


Figure 1. CTF and auxiliary systems.

71% nitrogen and 29% oxygen) with oxygen and recycled flue gas (carbon dioxide and water), eliminating nitrogen from the flue gas stream.

The relative fouling or other tendencies of test coals are determined by burning coal samples under specified conditions. When starting with a cold furnace, the 13.25-hour test program outlined in Table 1 is normally used. This preheating program was followed before all LDDS runs.

The coal feed rate is commonly adjusted to keep the flue gas temperature entering the upper duct to the probe bank at 2000°F (1093°C), with 25% excess air. Coal samples are taken periodically to form a composite sample. Oxygen, carbon dioxide, nitrous oxides, carbon monoxide, and sulfur dioxide in the flue gas are continuously monitored and recorded by a data acquisition system.

The test furnace has numerous ports that permit observation of the probes and the furnace burner zone during the test run. These ports can also be used for installation of additional test probes, auxiliary measurements, photography, or injection of additives.

3.2 Description of the Pilot-Scale LDDS

Important factors in the design were the flue gas flow rate entering the absorber as well as the temperature of the gas entering the LDDS. The LDDS was designed to operate at the flue gas flow rate of the CTF. The system was also designed to address flaws in the previous EERC desiccant-drying unit. Prior to developing the design, all equipment and devices were sized based on mass balance modeling of the process. Complete engineering and process drawings were then prepared by the design team. All fabrication and construction of the system was completed by EERC operations personnel. Figures 2 and 3 below show the LDDS process schematic and a 3-D drawing of the CTF and associated scrubber systems, respectively.

The LDDS system was designed to operate with a solution of $CaCl_2$ and water as the dehumidification agent. $CaCl_2$ was chosen based on an evaluation that was completed during the initial evaluation of this concept (2). In that work, the $CaCl_2$ solution was ultimately selected from a large group of desiccants based on the following characteristics:

- Ability of desiccant to remove water (partial pressure of water)
- Heat-transfer properties (specific heat and thermal conductivity)

Table 1. CTF Standardized Test Program

	Hours
Preheat on Gas	8.00
100% Coal Firing	5.25
Total	13.25

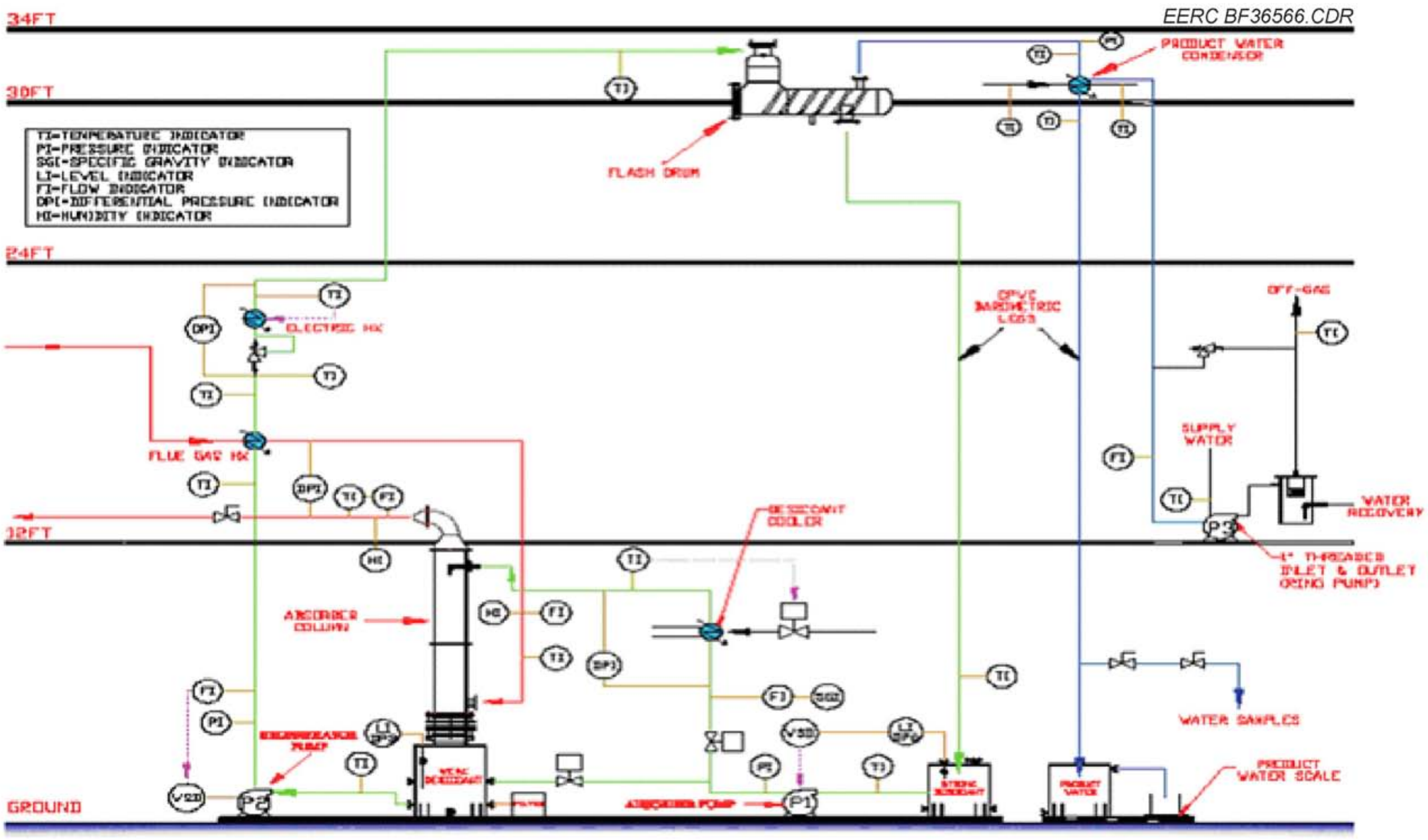
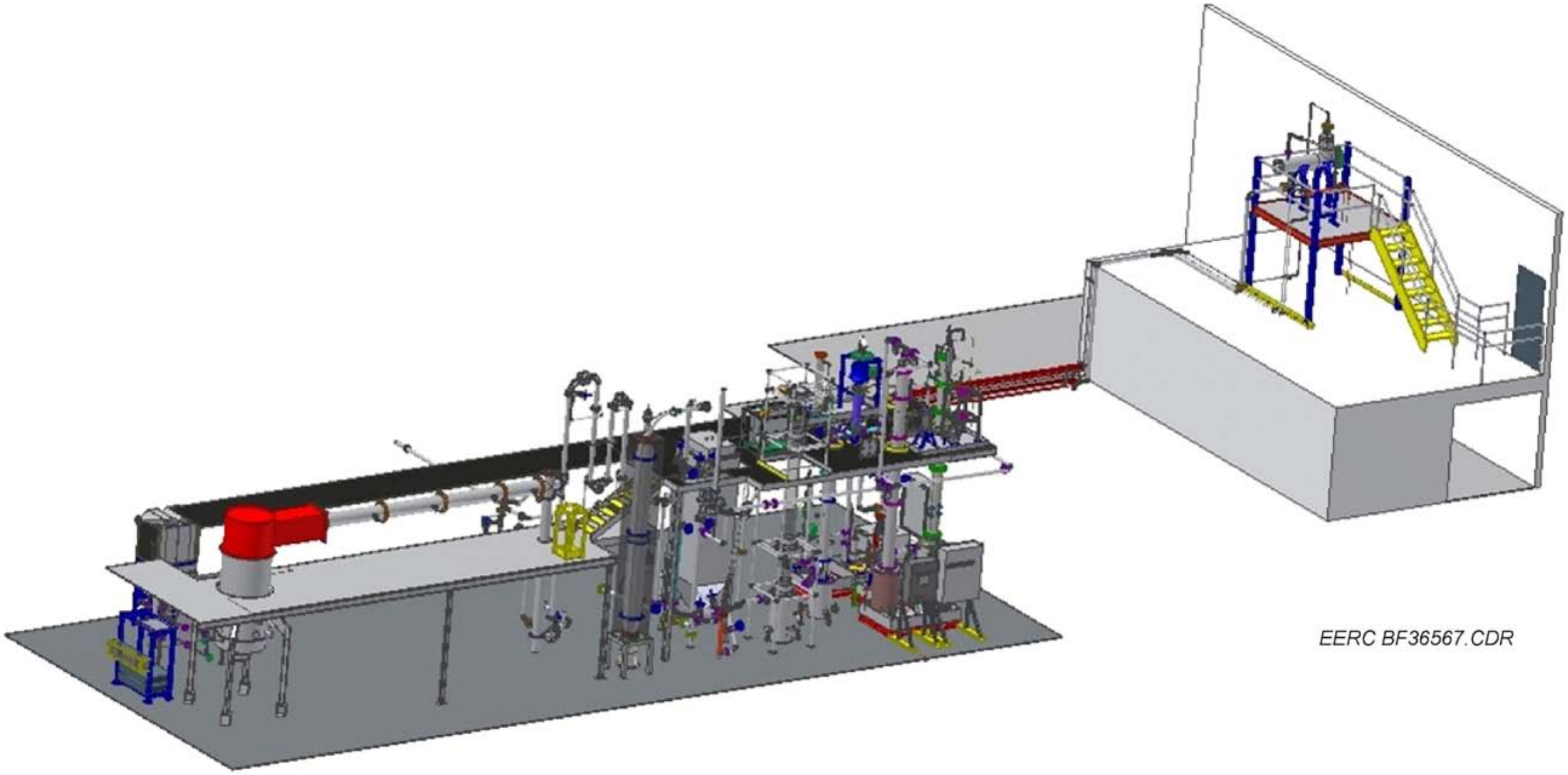


Figure 2. LDDS layout diagram.



EERC BF36567.CDR

Figure 3. Three-dimensional drawing of CTF, scrubbers, and LDDS.

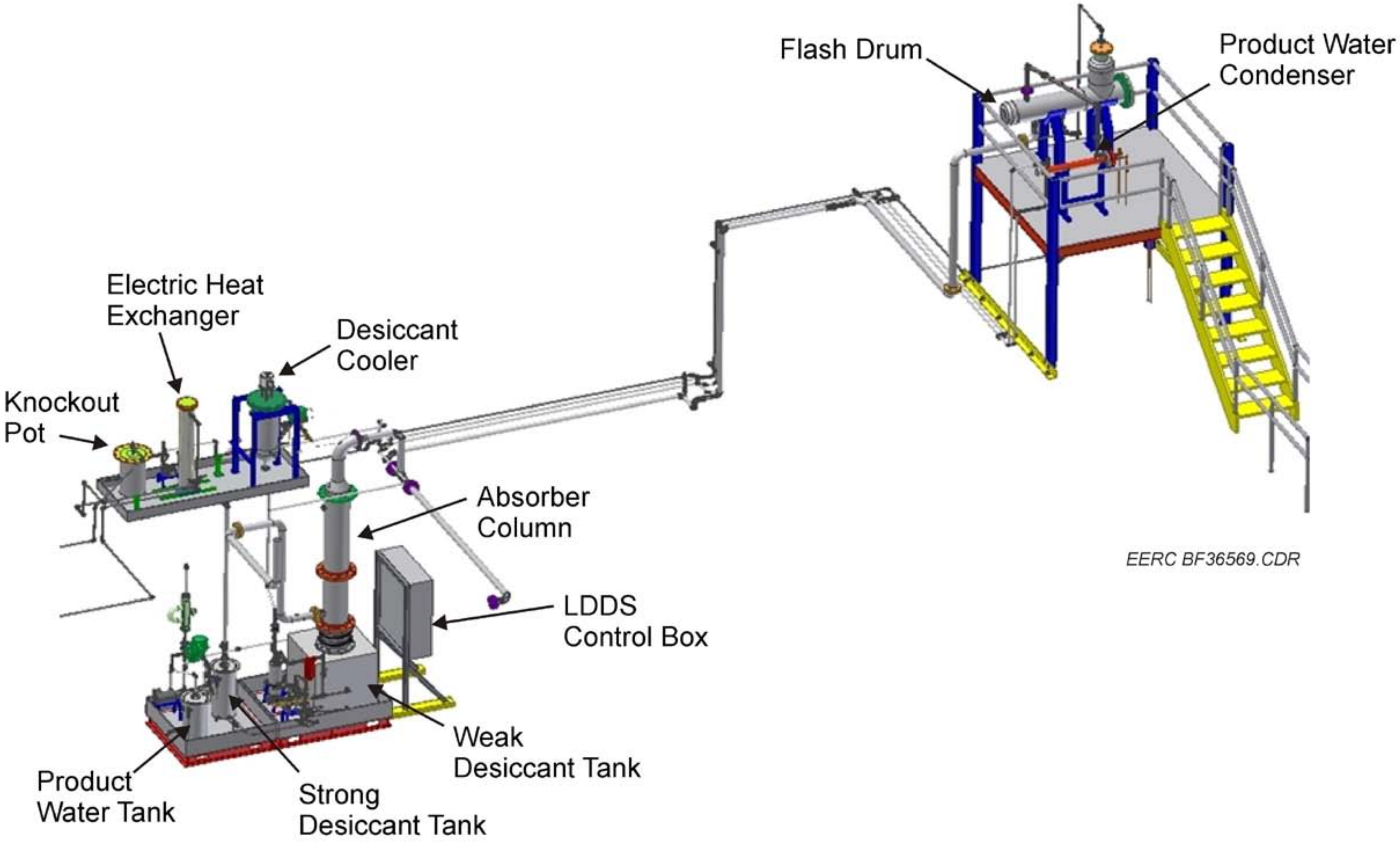
- Desiccant cost (capital and maintenance)
- Equipment corrosion
- Environmental effects of desiccant carryover
- Removal of combustion products other than water
- Flow characteristics when in solution with water (viscosity)
- Impact of desiccant selection on system operation and cost
- Solubility limits (concentration range of desiccant)
- U.S. Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) perception (for permitting purposes)

Thermophysical properties of $CaCl_2$ desiccant mixtures, for example, vapor pressure, saturation concentration, specific heat, and so on, were calculated using property correlations available in the literature (3).

The LDDS operates in two loops. The first is the absorber loop where desiccant dewaters the flue gas after contacting it in the absorber column. The second loop regenerates the desiccant by separating the absorbed water from the desiccant under vacuum and at temperature. The regeneration process is optimized by operating the flash drum (evaporator) under vacuum, which lowers the heat of vaporization of the solution and allows the water to be quickly separated from the $CaCl_2$. After the desiccant is regenerated, it is then ready to be sent back through the absorber. The major components of the LDDS are described in detail in the following sections. All components of the system are made of either 316 stainless steel (SS) or Schedule 80 chlorinated polyvinyl chloride (CPVC) plastic to inhibit the corrosive effects of the $CaCl_2$. Figure 4 shows a three-dimensional drawing of the LDDS with the surrounding infrastructure removed.

3.2.1 Absorber Column

The 3-D drawing of the LDDS system in Figure 4 highlights the absorber column. The column was fabricated from 316 SS, Schedule 10, 12-inch (30.5-cm) pipe. The column is 7 feet (2.13 m) in length and has a rubber expansion joint where the bottom of the column meets the weak desiccant tank to allow for thermal expansion. At the top of the column, a cone reducer is used to transition down to the 3-inch (7.62-cm) pipe that carries flue gas out to the stack. The top of the column holds a 6-inch (15.2-cm) Teflon mist eliminator to prevent entrained desiccant or water droplets from being carried away in the gas stream. The mist eliminator can be rinsed with water jets located above and below during testing if there are indications of desiccant buildup or crystallization in the mesh. The column is filled with 3-inch (7.62-cm) plastic gas/liquid distribution saddles to increase contact area between the moist flue gas and the desiccant. The saddles are held up by expanded metal mesh that is welded across the bottom of the absorber just



EERC BF36569.CDR

Figure 4. Three-dimensional drawing of the LDDS.

above the expansion joint. The column holds approximately 6 feet (1.83 m) of saddles. Moist flue gas enters the bottom of the column through a 3-inch (7.62-cm) pipe, and dry gas exits the top of the column after contacting the desiccant. The CTF can provide anywhere from 100 to 150 standard cubic feet per minute (scfm) (2832 to 4248 lpm) of flue gas to the absorber column. The flue gas velocity through the column is thus limited to less than 5 ft/s (1.52 m/s). The inlet temperature of the flue gas ranged from approximately 80° to 100°F (26.7° to 37.8°C) in shakedown testing. It is expected that this temperature will be somewhat variable depending on the scrubbing systems (SO_2 and CO_2) in use prior to the LDDS.

Strong desiccant is pumped into the top of the absorber column and onto plastic gas/liquid distribution saddles through a 1-inch 316 SS pipe. The design does not incorporate any spray nozzles and relies on the packing saddles for gas–liquid mixing. The absorber column is designed to handle desiccant flow rates from 1 to 10 gallons per minute (gpm) (3.79 to 37.9 lpm).

3.2.2 Tanks

Three tanks are used for the desiccant and product water circulation system. The largest tank, nominally 150 gallons (568 L), is located beneath the absorber column. It functions to collect weak desiccant that has absorbed moisture from the flue gas and supply that solution to the regenerator pump. The tank is sized to handle any upset conditions that might arise where the entire amount of desiccant in the system needed to be stored in one container. The tank also sits inside a stainless steel containment vessel should any leaks develop. The weak desiccant tank was custom-made from 1-inch (2.54-cm) polypropylene and is designed to handle the maximum desiccant operating temperature of 180°F (82.2°C). The tank has plumbing connections for desiccant flow and an opening for solids cleanout. The tank also has a drain port so the desiccant can be pumped out at the conclusion of a test. Desiccant level in the tank is monitored by means of a differential pressure indicator. The tank is also equipped with a sight tube for visual tank-level inspection.

The second tank (strong desiccant) accepts regenerated solution returning from the flash drum and has a 30-gallon (114-L) capacity. This tank is made of polypropylene and has inlet and outlet ports for desiccant flow to the absorber pump and to allow drainage when necessary. The absorber pump has control valves that allow its output to be directed to the column or back to the weak desiccant tank, bypassing the desiccant cooler and absorber. The inlet of the strong desiccant tank is equipped with a dipleg so vacuum is maintained in the flash drum and condenser portion of the system. The level in the strong desiccant tank is measured by a differential pressure indicator. The tank is also equipped with a sight tube for visual tank-level inspection. The plumbing connections of the strong tank are CPVC.

The product water tank is constructed of polypropylene and has a 30-gallon (114-L) capacity. It has an outlet port that feeds into a 5-gallon (18.9-L) bucket that is placed on a scale. The weight of water collected is logged by the data acquisition control (DAC) system. The product water tank has a dipleg through which the barometric leg is drawn. The inlet/outlet ports for the tank are also CPVC.

3.2.3 Desiccant Solution Filtration and pH Control System

A desiccant filtration system was designed to remove insoluble contaminants from the LDDS operating system. The filtration system is used during operation of the unit to ensure the desiccant characteristics remain within test plan guidelines. In addition, the filtration system can be used when loading prior to testing and unloading desiccant at the conclusion of a test. The desiccant is circulated from the weak tank through the pH bed and filtered back to the weak tank. An air-powered polypropylene plastic diaphragm pump is used to pump the desiccant through both the filtration and pH control systems. The filtration system uses a series of hand valves, allowing the desiccant to be pumped across a removable fabric filter cartridge. The replaceable fabric filter cartridge is rated for flows up to 10 gpm (37.9 lpm) and a maximum temperature of 180°F (82.2°C). In the preliminary shakedown testing, a 10-µm-pore-sized filter was used successfully to capture particulates from the desiccant. In addition to this filtration system, particulates are allowed to settle out in the desiccant storage drums between test runs. The desiccant is then drawn off the top of the drums when reloading the LDDS system, leaving the solids on the bottom of the storage drums for easy disposal.

A pH control system was designed to prevent corrosion in the LDDS components as well as to facilitate easier solution disposal upon test run completion. The pH control consists of a bed of coarse-ground 8-mesh calcium carbonate ($CaCO_3$, also known as lime) pellets through which the weak desiccant is passed. After traveling through the lime bed, the desiccant is returned to the weak tank. The pH of the desiccant in the LDDS system is monitored continuously as it leaves the regenerator pump by means of a pH transmitter. A second pH transmitter measures the acidity of the solution after the $CaCO_3$ bed. As the pH begins to drop, the operator turns on the diaphragm pump and circulates desiccant through the $CaCO_3$ bed. During oxy-fired testing, the main cause of pH drop was the high level of CO_2 present in the recirculated flue gas. The lime reduces pH by reacting with water that is saturated with CO_2-yielding calcium bicarbonate, thereby removing the CO_2 from the desiccant stream and driving the desiccant in the basic direction. The reaction is shown in Equation 1:

$$CaCO_3 + CO_2 + H_2O \rightarrow Ca(HCO_3)_2 \qquad \text{[Eq. 1]}$$

However, if acid gas (SO_2, NO_x, and HCl) is present in the flue gas, calcium carbonate can be reduced to CO_2 and water. An example of the reaction with HCl is shown in Equation 2:

$$CaCO_{3(s)} + 2HCl_{(aq)} \rightarrow CaCl_{2(aq)} + CO_{2(g)} + H_2O_{(l)} \qquad \text{[Eq. 2]}$$

If an FGD system and an SCR system are upstream, however, this reaction is expected to be minimal. The $CaCO_3$ can easily be emptied and recharged with fresh product whenever the reactivity of the $CaCO_3$ ceases. In addition to the $CaCO_3$ bed, a $Ca(OH)_2$ slurry injection system is available should the solution require more pH control. A peristaltic pump is used to drip $Ca(OH)_2$ slurry directly into the top of the weak desiccant tank. The pump flow is increased or decreased by the operator according to the acidity of the desiccant solution. Because it forms calcium oxide (CaO), a slimy material, the $Ca(OH)_2$ slurry system only serves as a backup should the $CaCO_3$ bed system fail.

3.2.4 LDDS Evaporator (flash drum)

The evaporator, or flash drum (labeled in Figure 4), is where the desiccant is regenerated. The flash drum is mounted at an elevation of 30 feet (9.14 m) above the floor to facilitate the necessary height for the barometric leg. A drawing of the flash drum can be seen in Figure 5. The flash drum was fabricated from 316 SS 12-inch (30.5-cm) pipe and is 8 feet (2.44 m) in length. The weak desiccant enters from a 1-inch (2.54-cm) pipe at the top of the drum onto packing baffles. The baffles provide surface area for the H_2O to separate from the $CaCl_2$ as vapor. A 12-inch (30.5-cm) blind flange on the inlet end allows the baffles to be removed for cleaning. The flash drum fills with desiccant until it flows over the exit pipe back down to the strong desiccant tank. The water vapor leaves the flash drum through a mist eliminator and 2-inch (5.08-cm) pipe on top of the drum and is drawn over to the condenser by the vacuum pulled from the liquid ring pump. The flash drum was wrapped with an electric cable heater to ensure the flashing process stays isothermal and to decrease warm-up times for faster test start-ups. In addition, the drum was covered in 1.5-inch (3.81-cm) fiberglass pipe insulation. The flash drum also has a 1-inch (2.54-cm) drainage pipe at the bottom, which allows the container to be emptied completely between test runs.

The flash drum operates on the principle of differential pressure. The ring pump keeps the flash drum at a pressure ranging from 1 to 2 psia (2 to 4 inHg). Inlet desiccant temperatures range from 140° to 150°F (60° to 65.6°C). These parameters determine the rate at which H_2O vapor will separate from desiccant. A greater temperature and lower pressure will drive the water off of the desiccant as a vapor, increasing the efficiency of the process. A complete explanation of the entire process is included in a later section of this report.

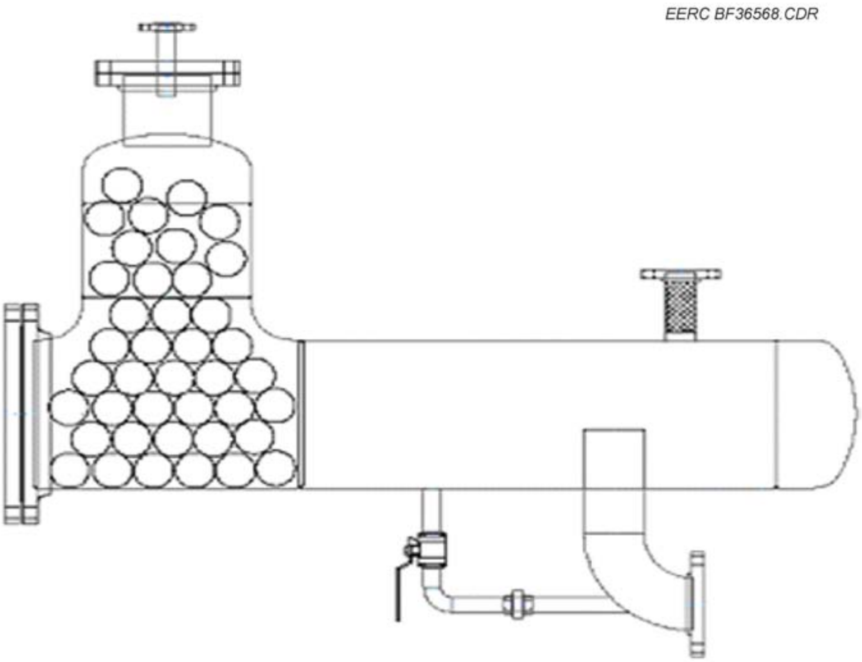


Figure 5. LDDS flash drum.

3.2.5 Heat Exchangers

The LDDS system uses four HXs which are referred to as flue gas HXs, electric HX, product water condenser, and desiccant cooler.

The flue gas HX takes hot flue gas at the outlet of the CTF's ESP and uses that energy to heat the desiccant on its way up to the flash drum. This HX is a two-pass tube-and-shell type with 1-inch (2.54-cm), 18-gauge 316 SS tubes. The unit is single-walled and 4 inches in diameter by 24 inches (61.0 cm) in length. The shell is fabricated from 316 SS. The HX was designed for 1–10 gpm (3.79–37.9 lpm) desiccant flow and up to 175 scfm (4955 lpm) flue gas. The HX is covered with 1.5-inch (3.81-cm) fiberglass pipe insulation to prevent heat loss.

Because the flue gas HX cannot provide enough heat to obtain the needed desiccant temperature for flashing, an electric circulation heater was installed. The electric HX is capable of providing up to 20 kW of heating power to the desiccant flow stream. The desiccant enters the bottom of the electric HX and flows over the heating elements and out the top of the unit. The unit is 5 inches (12.7 cm) in diameter by 5 feet (1.52 m) in length. The nine heating elements are approximately 48 inches (122 cm) in length and are 0.475 Incoloy® alloy-sheathed to resist corrosion. The electric HX is certified to handle a maximum working pressure of 150 psig (356 in. Hg). The walls of the electric circulation heater are insulated to reduce heat loss to the environment. After exiting the electric HX, the solution is pumped to the flash drum, where the water is separated from the desiccant as vapor.

The product water condenser collects water vapor from the flash drum. The cooling medium in the condenser is water and is obtained directly from the city water supply. Because only water vapor enters the condenser, it was constructed from carbon steel and copper for the shell and tubes, respectively. The HX is a two-pass unit with 1-inch (2.54-cm) 20-gauge copper tubes and is 4 inches (10.2 cm) in diameter by 36 inches (91.4 cm) in length. The vapor enters at the top through a 2-inch (5.08-cm) connection and leaves as liquid water through a 2-inch (5.08-cm) fitting in the bottom of the condenser. This connection is then reduced to 1-inch (2.54-cm) Schedule 80 CPVC pipe and is plumbed to the 30-gallon (114-L) product water tank. This HX and piping serve as a barometric leg as well as a delivery path for the condensed water that is removed in the flash drum. In addition, a 1-inch (2.54-in) connection on the top of the condenser is plumbed to the liquid ring pump. The condenser is located at a height of 32 feet (9.75 m) above the product water tank to ensure a barometric seal between the ring pump and flash drum. The condenser is certified for a maximum pressure of 150 psig (356 in. Hg).

The final HX is the desiccant cooler. The purpose of this HX is to cool the desiccant before it enters the absorber column, thus facilitating a more favorable absorption process. The desiccant cooler is located between the absorber column and the strong desiccant tank. The cooler was fabricated by EERC personnel as a tube-and-shell-type HX. The unit was constructed from 18-inch (45.7-cm)-diameter 316 SS pipe and is 24 inches (61.0 cm) long. The top of the HX is flanged and serves as a mount for an electric tank mixer. The cooling medium is circulated through two coils that can each handle up to 5 gpm (18.9 lpm) of water. Cooling water flow through the tubes is regulated by a control valve with a feedback loop from the desiccant exit temperature. The desiccant enters the bottom of the HX and exits the top through 1-inch flanged connections. Should the cooling coils not be able to keep up with the desiccant flow, the mixer can be switched on to increase the heat transfer in the desiccant stream through the HX. A drawing of the side and overhead views of the desiccant cooler is provided in Figure 6.

The unit was designed differently than the other HXs in that the cooling medium, in this case water, flows in the tubes, and the medium to be cooled, the desiccant, is circulated around the tubes. This design was chosen because of $CaCl_2$ icing problems experienced in the previous desiccant testing. The design allows the system to be easily cleaned by eliminating the issue of icing in small-diameter pipes. It also allows a mixer to be incorporated into the design, which adds additional cooling control.

3.2.6 LDDS Pumps

Four pumps are incorporated into the LDDS system. Each is described below.

Absorber Pump – The absorber pump draws regenerated desiccant from the strong tank and pumps the strong desiccant through the desiccant cooler and then to the absorber column. The absorber pump has a magnetic drive and has been sized to handle 1–10 gpm (3.79–37.9 lpm) of desiccant at a maximum working temperature of 155°F (68.3°C). The pump housing and impellor are 316 SS with a Viton® o-ring and ceramic seals. These components are corrosion-resistant and able to handle the working temperature of the desiccant. The three-phase, 240-volt, totally enclosed fan-cooled (TEFC) motor is 1/5 hp and is wired to an electronic variable-speed drive (VSD) controller. The impellor was trimmed to a 2.5-inch (6.35-cm) diameter and is capable of a maximum head of 23 feet (7.00 m), based on the specific gravity of the desiccant.

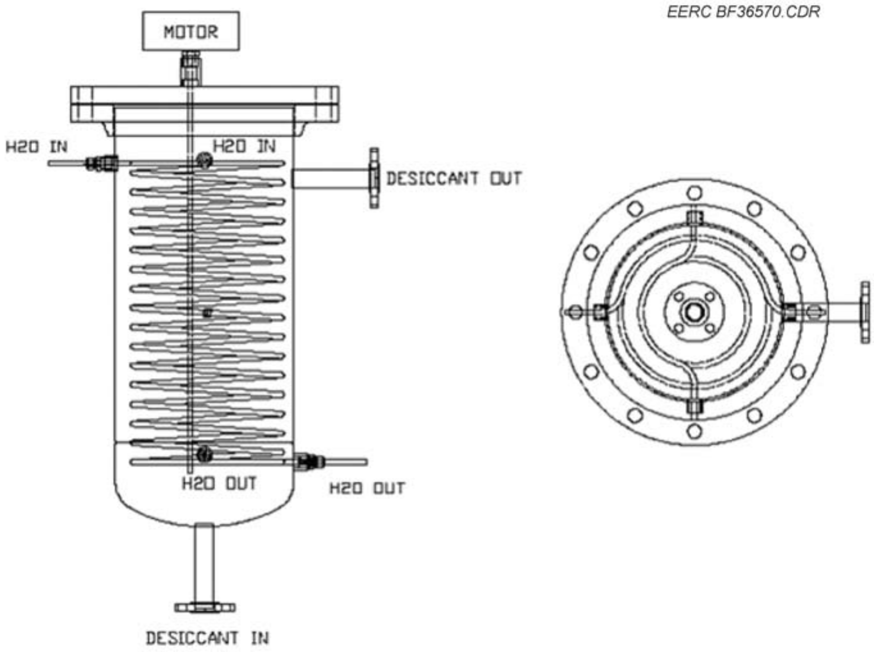


Figure 6. Desiccant cooler.

Regenerator Pump – The regenerator pump draws desiccant from the weak tank and pumps the solution through the heaters to the flash drum. The regenerator pump was sized and made of materials of construction similar to the absorber pump. However, the motor is ⅓-hp, three-phase, 240 volts to provide a maximum head of 35 feet (10.7 m), based on the specific gravity of the desiccant. As was the case with the absorber pump, the regenerator pump is also controlled using a VSD.

Liquid Ring Pump – A liquid ring pump is located downstream of the product water condenser. The ring pump employs a water seal around the impellor to draw noncondensable gases from the flash drum and condenser. It is responsible for maintaining vacuum throughout the product side of the LDDS. The housing and impellor for the ring pump are cast iron. The ring pump is powered by a 1.5-hp, three-phase, direct-drive motor and is capable of 18 acfm (510 L) at 25 in. Hg with 60°F (15.6°C) process water. The pump has 1-inch (2.54-cm) inlet and outlet plumbing connections and typically operates at 1 gpm (3.79 lpm) of water. The noncondensable gases exit the ring pump and are sent to a moisture knockout pot along with the ring pump supply water. The knockout pot separates the supply water from the noncondensable gases, which are passed to a CTF induced-draft fan and then the exit stack. All piping to and from the ring pump is 1 inch (2.54 cm), uninsulated, and fabricated in CPVC and 316 SS where necessary. The ring pump is not controlled by a VSD and thus runs at a set speed. The vacuum in the system is set by means of a relief valve positioned between the pump and knockout pot.

Diaphragm Pump – A diaphragm pump is used to facilitate desiccant loading and unloading as well as the operation of the pH/filtration systems. The diaphragm pump is manually controlled by means of an air regulator and is capable of 23 gpm (87.1 lpm), with particulate matter up to ⅛ inch (0.32 cm) in diameter. All wetted materials on the pump are fabricated from polypropylene, giving it excellent anticorrosion properties.

3.2.7 LDDS Instrumentation

Instrumentation equipment installed to control and monitor the process conditions of the LDDS included temperature, flow, pressure, liquid level, density, humidity, pH, and weight.

Thermocouples were installed at various points (Table 2) throughout the LDDS and are tied into the DAC system, allowing temperature data to be logged.

Thermocouples are Type K with 316 SS sheaths. Thermocouples exposed to desiccant were sheathed with Hastelloy® alloy.

Flowmeters were installed to monitor and control desiccant flow rates at the exit of the absorber and regenerator pumps. Table 3 shows locations and sizes for the LDDS flowmeters. A magnetic flowmeter measures the weak desiccant flow out of the regenerator pump. The magmeter is calibrated to handle desiccant flow rates from 1 to 10 gpm (3.79 to 37.9 lpm), and all wetted measurement parts were constructed using Hastelloy.

To provide highly accurate flow measurements at the outlet of the absorber pump, a coriolis meter was installed. The coriolis meter was sized to accommodate desiccant flow rates

Table 2. LDDS Temperature Measurement Locations

Thermocouple Location	Temperature Measurement
Absorber Inlet	Flue gas
Absorber Outlet	Flue gas
Flue Gas HX Inlet	Flue gas
Flue Gas HX Outlet	Flue gas
Absorber Pump Outlet	Desiccant
Flue Gas HX Inlet	Desiccant
Flue Gas HX Outlet	Desiccant
Electric HX Inlet	Desiccant
Electric HX Outlet	Desiccant
Flash Drum Inlet	Desiccant
Product Water Condenser Inlet	Product water vapor
Product Water Condenser Outlet	Product water
Product Condenser Cooling Water Inlet	Process cooling water
Product Condenser Cooling Water Outlet	Process cooling water
Liquid Ring Pump Vapor Outlet	Noncondensable gases
Product Water Tank	Product water
Strong Desiccant Tank Inlet	Desiccant
Strong Desiccant Tank Outlet	Desiccant
Desiccant Cooler Inlet	Desiccant
Desiccant Cooler Outlet	Desiccant

Table 3. Flow Controls and Instrumentation

Measurement Location	Type	Media	Size
Outlet of Regenerator Pump	Magnetic flowmeter	Desiccant	10 gpm
Outlet of Absorber Pump	Coriolis meter	Desiccant	10 gpm
Inlet to Absorber Column	Pitot	Flue gas	200 scfh
Outlet of Absorber Column	Pitot	Flue gas	200 scfh
Inlet to Ring Pump	Visual flowmeter	Air	13 scfm
Outlet of Absorber Pump	Control valve	Desiccant	0–10 gpm
Absorber Column Bypass	Control valve	Desiccant	0–10 gpm
Inlet to Desiccant Cooler	Control valve	Cooling water	0–5 gpm

of 1–10 gpm (3.79–37.9 lpm). In addition to desiccant flow rate, the meter measures density and temperature. All parts of the coriolis meter that come in contact with desiccant were fabricated from Hastelloy.

To measure the flue gas flow rate at the inlet and outlet of the absorber column, pitot tubes have been installed. Pitot tubes measure differential pressure, which can be used to calculate flow.

A visual flowmeter was installed on the vapor inlet line to the ring pump. When the barometric leg is stable, the flowmeter will show no airflow, ensuring the system is free from leaks.

In addition to flowmeters, several control valves were installed to control flow rates for both the desiccant and HX cooling water. Two 316 SS, 1–10-gpm (3.79–37.9-lpm) control valves are installed in the regenerator loop. The valves are air-actuated and route desiccant either to the desiccant cooler or in a bypass loop back to the weak tank. Another air-actuated control valve is installed on the process water to the desiccant cooler. Based on the temperature of the desiccant out of the cooler, the control valve regulates the flow rate of cooling process water to the coils.

Both differential and static pressure transmitters were installed throughout the LDDS. Table 4 shows pressure measurement devices and locations.

All pressure measurements are logged by the DAC system and recorded on trend charts in the control program.

To monitor flue gas moisture content, two humidity measurement devices were installed at the inlet and outlet of the absorber column. These devices measure and record both absolute humidity and temperature. Knowing the absolute humidity and the flue gas flow rate through the absorber, a moisture weight percentage can be calculated. In this way, the efficiency of the drying process can be monitored. In addition, the total volume of water recovered can be calculated based on moisture readings and total gas flow through the absorber column for a given test period.

Two transmitters were installed to measure the pH of the desiccant at the outlet of the weak desiccant tank and after the $CaCO_3$ bed in the filtration loop. The transmitters have probes that are installed directly into the desiccant flow. The data recovered from the transmitters is logged in the DAC system and is continuously monitored.

To measure the mass of water collected, a floor scale is used. As moisture condenses and fills the product tank, the overflow is collected in a 5-gallon container and is weighed. The output of the scale is also connected to the DAC system and logged.

Table 4. LDDS Pressure Measurement Locations

Measurement Location	Type	Media	Size
Regenerator Pump Outlet	Static pressure transmitter	Desiccant	0–20 psi
Flue Gas HX	Differential pressure indicator	Flue gas	0–10 in. H_2O
Electric HX	Differential pressure transmitter	Desiccant	0–20 psi
Flash Drum Vapor Outlet	Absolute pressure transmitter	Water vapor	0–400 in. Hg
Strong Desiccant Tank Level	Differential pressure transmitter	Desiccant	0–30 in. H_2O
Absorber Pump Outlet	Static pressure transmitter	Desiccant	0–20 psi
Desiccant Cooler	Differential pressure transmitter	Desiccant	0–40 in. H_2O
Absorber Column	Differential pressure transmitter	Flue gas	0–6 in. H_2O

3.2.8 LDDS Control System

A complete control system was implemented to support the LDDS testing. The process outputs from the instrumentation components are used to control all aspects of the LDDS and are monitored and controlled using an industrial-duty laptop computer. The control program was written using National Instruments LabVIEW software. The program communicates with National Instruments hardware modules in the system's control box. The control system and theory are summarized below.

As previously stated, the desiccant flow through the system is divided into two control loops, the regenerative loop and the absorber loop. For the desiccant tank levels to remain constant in steady-state operation, the flows through these two loops must remain equal. The desiccant flow is chosen by the operator and is set based on the output of the magnetic flowmeter. The operator sets a desired flow rate in the program, and the regenerator pump then attempts to reach this set point based on the flow feedback from the magmeter. To do this, desiccant is pumped through the HX up to the flash drum and back to the strong desiccant tank. An independent variable is the strong desiccant tank level, which is entered into the program by the operator. As the solution fills the strong desiccant tank above the set point, the level transmitter sends a signal to the program telling it to turn on the absorber pump. The absorber pump sends strong desiccant up through the cooler and to the absorber column, where it empties into the weak tank, and the control loop is completed. This control theory for the desiccant flow has proved to work well throughout shakedown testing and required no operator interaction after the flow was initially set. To change the desiccant flow rate during testing, the operator simply resets the set point on the interface, and the program readjusts the regenerator pump speed based on the new setting.

The control loop for the electric HX allows the user to enter a desired temperature for the desiccant flowing to the flash drum. The program is linked to the heater's temperature controller, which then ramps the temperature up or down based on the set point. The program has protection written into the logic to prevent the electric heater from overheating and prevents the heater from being turned on without desiccant flow. The logic and controllers have operated well during the shakedown tests.

The flash drum is wrapped with a cable heater to ensure that the flashing process remains isothermal. A controller is used to ramp the heater temperature up or down so that the set point temperature is maintained. The flash drum heater temperature is set by the operator on the computer interface. Because this heater is operated at a relatively low temperature, approximately 175°F (79.4°C), protection logic was not needed.

The desiccant cooler operates on a control loop based on the temperature of the desiccant that is entering the absorber column. The desired temperature of the desiccant into the absorber column is chosen by the operator in the control program. The thermocouple used to indicate this temperature is located at the inlet to the absorber column. If the temperature of the desiccant rises above the set point (135°F [57.2°C] in shakedown testing), the program's logic incrementally opens the cooler's supply water control valve, allowing water to flow through the coils. When the desiccant temperature drops below the set point, the valve is shut until more cooling is again needed. In shakedown testing, the control logic worked as designed, and the system reached a cooling equilibrium after several minutes of operation. The desiccant cooler is also equipped with a mixer that can be engaged to aid in the cooling process. The mixer is manually operated using a switch mounted on the data acquisition box.

The desiccant flow control valves at the outlet of the absorber pump are also controlled by the operator through program logic. The logic necessitates that only one control valve can be open at any given time, ensuring that the absorber pump is not deadheaded. The operator chooses the flow configuration in the control program.

The liquid ring pump responsible for maintaining vacuum in the system is controlled by a switch mounted on the exterior of the DAC box. Although it cannot be turned on or off through the automated system, a warning signal is illuminated on the screen whenever the pump is running. This warning ensures that the pump is not operated without process water, which would damage the pump head and impellor. The process water is turned on manually by means of a block valve on the pump's supply water line.

The vacuum on the flash drum and condenser is set by means of the relief valve on the outlet of the ring pump. This adjustment is made manually and adjusted periodically based on the absolute pressure indicated on the computer interface.

The LDDS control program also includes logic for alarms on many of the process set points. The alarms alert operators when a process parameter is out of range, so changes can be made. A few of the alarmed process set points include desiccant solution levels in the strong and weak tanks, desiccant flow rate, process temperatures, and differential pressures across the HX.

3.3 Measurement and Sampling Procedures

3.3.1 Flue Gas

The only flue gas constituents directly monitored by the LDDS DAC system are the moisture concentrations that are provided by the humidity transmitters. All other flue gas analysis is recorded by the CTF's DAC system. The CTF system has rack mount gas analyzers which monitor the following flue gas constituents:

- SO_2
- CO_2
- NO_x
- CO
- O_2
- Hg
- H_2O

These monitors can be operated at various locations within the system. Typically, the flue gas is analyzed at the outlet of the combustor and after the desired flue gas control systems.

If needed, other flue gas constituents such as particulate and trace elements are measured by EERC personnel using standard procedures.

3.3.2 Desiccant Solution

Desiccant solution samples can be collected online at various points throughout the LDDS. It is expected that both strong and weak desiccant samples will be collected at regular intervals during steady-state operation. A sampling timer is part of the program logic and alerts operators when samples need to be taken. The desiccant samples collected during test campaigns would typically be analyzed for the following:

- Specific gravity
- Density
- Total suspended solids (TSS)
- pH
- Sulfate
- Hg

3.3.3 Product Water

During shakedown testing, product water samples were collected online from a sample port and were analyzed for the following:

- pH
- Total dissolved solids (TDS)
- TSS
- Calcium
- Chlorides
- Sodium
- Sulfate
- Nitrate

These analyses were all done by the EERC's Analytical Research Laboratory.

4.0 RESULTS

4.1 Operating Conditions

Four sets of extended-duration tests took place May 11–14, 2010, and each test ranged from 4 to 10 hours in duration. The process gas stream for these tests was a coal-derived flue gas that had undergone conventional pollutant control (particulates, SO_2) and CO_2 capture upstream of the LDDS. Before reaching the LDDS, particulates were removed in an ESP, SO_2 was removed using a wet FGD system and a polishing scrubber, and finally CO_2 was captured in an amine-based scrubber. A summary of the gas composition entering the LDDS during each test period is provided in Table 5. As the data indicate, by the time the flue gas reached the LDDS, it was primarily N_2, with small fractions of O_2 and CO_2, and it was saturated with moisture.

Table 5. Summary of Gas Composition Entering the LDDS on a Dry Basis

Date	O_2, %	CO_2, %	CO, ppmv	SO_2, ppmv	NO_x, ppmv
May 11, 2010	5.28	1.54	2.65	<1	137.03
May 12, 2010	5.39	1.93	3.21	<1	158.85
May 13, 2010	5.44	1.25	2.29	1.68	2.50
May 14, 2010	5.42	1.27	2.01	<1	7.29

A summary of the May 2010 LDDS operating conditions is provided in Table 6 and includes the average solution concentration, operating liquid-to-gas ratio of the absorber, and key system temperatures.

The targeted absorber inlet strong solution temperature was 52°C and was based on achievable cooling temperatures using an air-cooled heat exchanger. However, the selected operating conditions were such that the cooled strong solution entering the absorber was at a higher temperature than the entering process gas. The maximum heated temperature of the weak solution was 80°C, which was selected because it is low enough to be supplied by a waste heat resource.

A detailed look at all of the strong solution concentration data in Table 6 shows that true steady-state conditions were not reached since the desiccant concentration increased to some extent for each run. This means that more moisture was desorbed in the evaporator than was collected in the absorber, i.e., a net loss of water from the working fluid. The operating conditions within the evaporator determine the equilibrium desiccant concentration. The measured evaporator pressure generally agrees with the calculated saturation pressure based on the strong solution temperature at the evaporator exit, but these values are too high to explain the observed moisture desorption from the desiccant. A slightly better indicator is provided by the

Table 6. Summary of LDDS Operating Conditions During the May 2010 Testing

Test Date	May 11, 2010	May 12, 2010	May 13, 2010	May 14, 2010
Beginning Strong Solution Concentration, mass fraction $CaCl_2$	0.458	0.491	0.506	0.518
Ending Strong Solution Concentration, mass fraction $CaCl_2$	0.475	0.523	0.510	0.523
Absorber Liquid-to-Gas Ratio, gal/kacfm	38.4	38.0	40.1	42.9
Evaporator Pressure, kPa	17.8	15.6	18.0	17.3
Absorber Inlet Gas Temp., °C	42.6	42.5	42.6	42.1
Absorber Outlet Gas Temp., °C	51.0	52.8	51.6	53.5
Evaporator Outlet Strong Solution Temp., °C	67.0	67.3	68.9	70.0
Absorber Inlet Strong Solution Temp., °C	52.2	54.0	52.1	54.7
Absorber Outlet Weak Solution Temp., °C	54.0	55.9	54.4	56.4
Evaporator Inlet Weak Solution Temp., °C	76.9	79.8	78.5	80.2

condensation temperature of the product water, which was typically regulated at 18°C. The corresponding saturation pressure for this temperature does support the observation of increasing desiccant concentration over time, but it is too low in certain cases and suggests that the measured liquid temperature was subcooled to some extent. These conflicting data suggest that the saturation pressure in the evaporator (and, therefore, the equilibrium desiccant concentration) is dependent on dynamic conditions within the flash drum and is difficult to predict using simple equilibrium calculations.

4.2 Water Recovery

The process gas humidity data are summarized in Table 7 along with the corresponding saturation values at the absorber inlet and the calculated minimum equilibrium moisture content at the outlet. Examination of the absorber inlet humidity measurements suggests that the process gas entered the column is not at saturation conditions, which seems contrary to the fact that the gas passed through an amine–water scrubber prior to the absorption column. Based on the configuration of the pilot-scale system and agreement with the system's overall water balance, it seems that the inlet humidity transmitter consistently underestimated the true moisture content. In the absence of substitute instrument data, the assumption was made that the gas entered the absorber saturated.

Data in Table 7 indicate that the outlet humidity values were very close to the values predicted by the equilibrium calculation. This suggests that the packed column resulted in good mass-transfer performance by consistently approaching the equilibrium-based values. However, a curious observation from Table 7 is that the measured humidity level at the column outlet is consistently, and sometimes noticeably, lower than the value predicted from the equilibrium calculation. Measured values within 10% of the equilibrium calculation are generally accepted to signify that the limiting case was reached, but greater discrepancies may suggest other phenomena. One possibility was identified within the absorber where, during a postrun inspection of the packing, solidified desiccant was observed to be coating some of the packing. It could, therefore, be that the exceptional moisture removal performance was enhanced by the fact that a mix of solid and liquid desiccant was present on the packing.

The drop in process gas humidity (assuming a saturated inlet) indicated in Table 8 was used to estimate the moisture capture by the LDDS for the test periods; these values are presented in Table 8. According to the data, 64%–67% of the moisture incoming with the

Table 7. Comparison of Column Inlet and Outlet Values from Steady-State Testing

	Column Inlet		Column Outlet	
Date	Humidity Transmitter Average, g/m^3	Saturated Moisture Content, g/m^3	Humidity Transmitter Average, g/m^3	Equilibrium Moisture Content, g/m^3
May 11, 2010	31.2	58.3	22.5	28.7
May 12, 2010	31.2	58.1	21.9	24.2
May 13, 2010	31.6	58.4	19.9	21.9
May 14, 2010	30.2	57.0	21.1	23.0

Table 8. Flue Gas Inlet Moisture Flow and Absorbed Water Data

Date	LDDS Inlet Gas Flow, m^3/hr (20°C, 1 atm)	Moisture Component of Inlet Gas Flow, kg/hr	Absorbed Moisture by LDDS, kg/hr	Moisture Capture by LDDS, %
May 12, 2010	114	7.2	4.6	64
May 12, 2010	113	7.1	4.5	64
May 12, 2010	111	7.0	4.7	67
May 12, 2010	104	6.4	4.1	64

process gas was absorbed by the desiccant in the absorber. For the size of the pilot-scale system, the magnitude of the captured moisture amounted to between 4.1 and 4.7 kg/hr.

The indicated moisture capture rates from Table 8 are supported by the overall water mass balance, which is summarized in Figure 7 for the four test periods. The outlet harvested water values in Figure 7 were measured directly by weighing the collected condensate from the flash drum. The inlet water streams were computed indirectly, the component of recovered water from the flue gas was determined from the absorber outlet humidity data, and the water lost from the desiccant was based on the long-term trend in strong solution concentration. For all of the May 2010 testing, the system operated in a slight imbalance, because the desiccant working fluid was undergoing a net loss of moisture content that contributed to the collected water totals. The total water loss from the working fluid during each test period was estimated using the nominal working fluid capacity of the pilot-scale LDDS, which was 110 gallons. However, the amount of working fluid was not tracked exactly so the lost water estimates in Figure 7 are only estimates. Furthermore, if any crystallization took place, then additional water would have been released that remains unquantified.

Product water samples from the pilot-scale LDDS were routinely collected during test runs. For the May 11–14, 2010, test series, ten product water samples were collected and analyzed for suspected contaminants. These included standard measures of water quality such as pH, TDS, and TSS; the constituent components of the desiccant, calcium, and chloride; and suspected contaminants from the flue gas or upstream processes, i.e., nitrate, sulfate, and carbon.

The water analyses results are summarized in Table 9 as an average value with key statistics since no discernible trend was observed in the results. Also included in Table 9 are selected analysis results for a deionized (DI) water sample and a city tap water sample analyzed during a previous study (2). In previous studies of the LDDS concept (2), the product water pH was similar to but slightly less acidic than DI water. However, product water from the current tests was consistently basic and is suspected to be caused by carryover of amine solution from the upstream CO_2 scrubber. Trace quantities of amine compounds may have contaminated the product water as indicated by the carbon content values in Table 9.

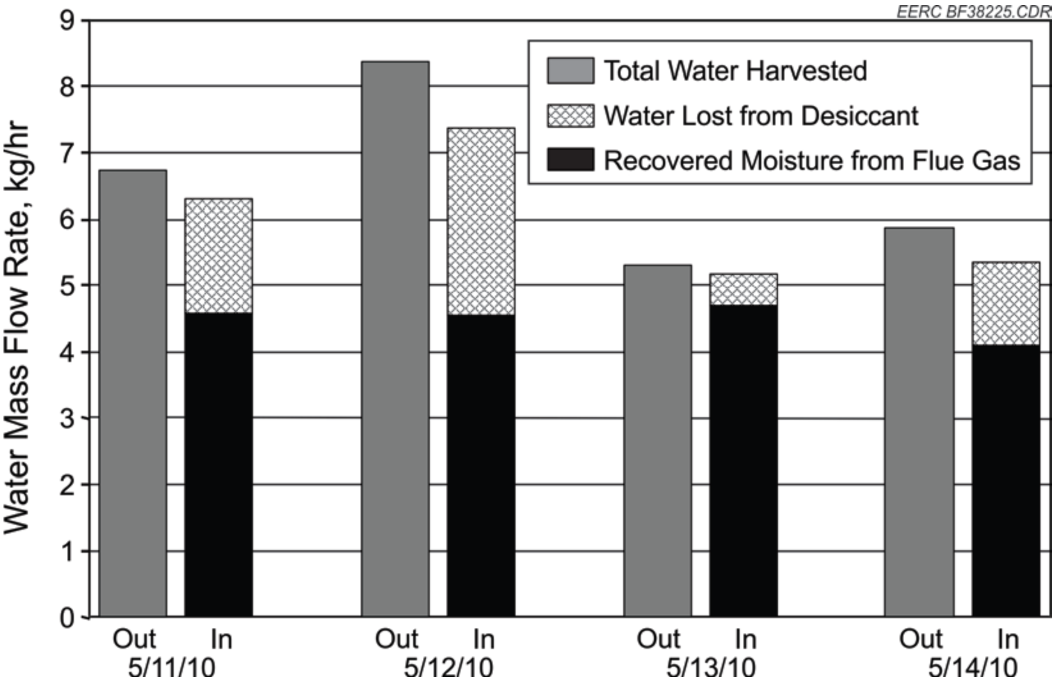


Figure 7. Water mass balance summary.

Table 9. Product Water Analysis Results for May 11–14, 2010, Test Series

	LDDS Product Water (ten samples)				
	Average	Standard Deviation	Maximum Value	DI Water*	City Tap Water*
pH	10.45	(0.22)	10.64	4.31	8.47
TDS, mg/L	49	(25)	105	<1	251
TSS, mg/L	<10	(N/A)	<10	<10	<10
Ca, mg/L	1.6	(2.1)	6.2	<0.09	44.3
Cl, mg/L	4.1	(1.2)	6.8	<1	<1
NO_3, mg/L	<1	(N/A)	<1	<1	2
SO_4, mg/L	8.2	(7.0)	22	<1	93.6
Na, mg/L	2.2	(1.4)	5.2		
Total C, mg/L	101.2	(10.4)	119		
Inorganic C, mg/L	4.9	(1.5)	7.8		
Organic C, mg/L	96.2	(11.2)	114		

* Results are included from a previous study (2).

4.3 Energy Consumption

The corresponding energy balance for the experimental work is shown in Figure 8. Primary sources of thermal energy into the system include electric heating of the weak solution before it enters the evaporator and the weak solution preheating by the flue gas in the flue gas heat exchanger. An additional source of heat input is the heat of absorption that is released in the

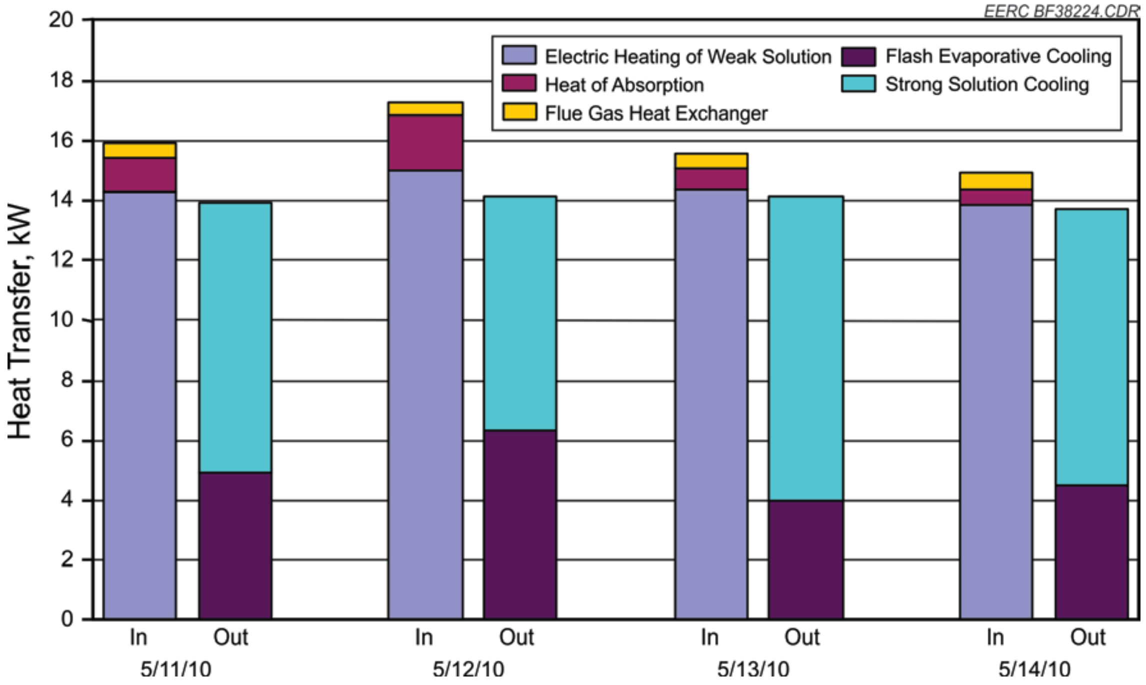


Figure 8. Energy balance summary.

absorber column as moisture is captured. Cooling or heat dissipation from the system occurred in the strong solution cooler prior to the absorber, and the cooling that took place in the evaporator as moisture evaporated from the working fluid. As shown in Figure 9, the heat rejection was consistently lower than the calculated heat input and is due to the unaccounted-for heat losses from the system to the ambient environment.

In an idealized LDDS cycle, the flash evaporative cooling, which is proportional to water production, should be of the same order as the heat of absorption, but it is significantly larger in Figure 8 because of several factors. First, the heat generated by moisture absorption in the column is split between heating the solution and heating the flue gas; furthermore, heat is dissipated to the ambient from the uninsulated absorber. Second, for all of the cases, more water was collected than was absorbed from the flue gas, and the excess water appears to have come from transient evaporation of the working fluid. This component of moisture would not result in a corresponding heat of absorption.

As indicated in Figure 8, the electric heat input makes up the overwhelming majority of energy into the system while the solution cooler is the primary outlet for thermal energy dissipation. The strong solution cooling is required to bring the working fluid down to absorption temperatures. This sensible heating and cooling of the working fluid are unavoidable losses for the system, but they could be minimized by incorporating a solution heat exchanger, like those used in absorption refrigeration cycles. In a solution heat exchanger, the hot strong solution exiting the evaporator would be used to preheat the cooler weak solution exiting the absorber column.

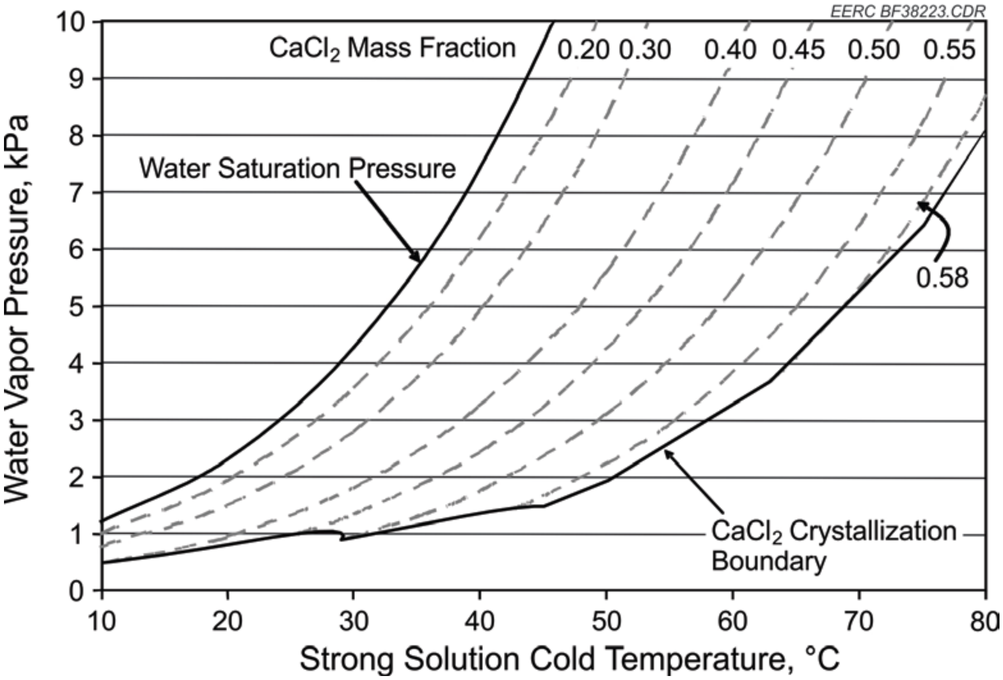


Figure 9. Minimum vapor pressures achievable with $CaCl_2$ LDDS.

The heat-transfer data of Figure 8 also show that very little preheating of the weak solution was accomplished in the flue gas heat exchanger. Ideally, the bulk of the thermal energy needed for water desorption should come from a waste heat source such as quenching the process gas before it enters the LDDS. However, given the relative rates of gas flow and desiccant solution flow, as indicated by the liquid-to-gas ratio of the absorber (approximately 40 gal/kacfm), the mass flow of desiccant for these tests was 6–8 times the mass flow for the process gas stream. Furthermore, the specific heat of the desiccant solution is approximately 2 times that of the process gas. When taken into account, these factors imply that the temperature of the desiccant solution will rise very slowly compared to the temperature drop of the process gas; 1°C of weak solution temperature rise would require ~14°C of process gas temperature drop. These factors lead to inefficient heat-exchange conditions when the goal is preheating the desiccant.

Because of the poor thermal energy recycling within the pilot-scale LDDS, it was not possible to operate the system autothermally, i.e., without external heat input. In cases when the external heat input was turned off, the system was not able to maintain a temperature sufficient for water desorption.

5.0 DISCUSSION

5.1 LDDS Integration

The experimental portion of this project tested and showed equilibrium-level rates of moisture capture and good-quality product water for the extended-duration runs. Further testing with the concept will clearly delineate the optimum operating boundaries of the LDDS. In this section, the operating characteristics of the LDDS are considered for their impact on plant integration.

5.1.1 Moisture Recovery with CO_2 Mitigation

Several plant configurations exist for producing a concentrated CO_2 stream from coal-fired power generation that is ready for sequestration. The two configurations under investigation with the EERC's pilot-scale system include oxycombustion and CO_2 capture using an amine scrubber. Both systems ultimately result in a concentrated stream of CO_2 that is saturated with moisture, but the amine scrubber configuration also generates a high concentration, saturated N_2 stream from which moisture could also be recovered. A comparison of these carbon mitigation system characteristics with respect to LDDS moisture capture is summarized in Table 10.

A technical issue that has an effect on moisture recovery from CO_2 process streams (either the exhaust stream from an oxy-fired system or the CO_2 offgas from an amine regeneration column) is the slight solubility of CO_2 in the LDDS working fluid. Since CO_2 is slightly soluble in aqueous solution, it will be absorbed to some extent in the absorber, where it will cause a drop in weak solution pH. If severe, a neutralization agent may be needed to control pH. During shakedown tests of the pilot-scale LDDS under oxy-fired conditions, the desiccant solution was neutralized with a bed of $CaCO_3$ and, in extreme cases, was dosed with $Ca(OH)_2$ to raise pH.

In addition to pH control, the solubility of CO_2 in aqueous solution may make it possible to transport CO_2 from the process gas to the moisture condenser by transient absorption and desorption to and from the desiccant working fluid. Desorbed CO_2 in the evaporator will add to the noncondensable load in the condenser that must be removed by the vacuum system. If this mechanism occurs to a significant extent, it will increase the parasitic power required to maintain vacuum in the condenser. Furthermore, inspection and analysis of the product water samples suggest slight contamination with amine solution carryover. Obviously, this sort of

Table 10. Comparison of Oxy-Fired and CO_2 Scrubber Configurations for LDDS Moisture Recovery

System	Oxy-Fired	CO_2 Scrubber
Process Gas Stream(s)	Concentrated CO_2 saturated with moisture.	Concentrated CO_2 and N_2 streams, both saturated with moisture.
Gas Contaminants	Stream will have passed through primary particulate and SO_2 control. Contaminant levels probably similar to existing coal-fired stack exhaust.	Very clean process streams due to upstream amine scrubber requirements.
LDDS Integration	Potential to be integrated as a polishing pollution control step for SO_2.	Two absorbers will be needed for each stream. Little opportunity to be integrated for pollution control. The two absorbers could potentially share a common evaporator and condenser.

contamination would only exacerbate CO_2 transport into the condenser since the amine would serve the same function in the LDDS system as it does in the CO_2 scrubber.

5.1.2 Solution Carryover and Crystallization

The absorber of the LDDS is a counterflow liquid–gas contactor, and it has the potential to generate entrained droplets that are carried out of the absorber with the process gas stream. Given the high weight concentration of desiccant in the working fluid, any entrained droplets will ultimately produce solid desiccant particulates that can be corrosive. In the previous investigation of the LDDS (2), particulate measurements were taken in the flue gas downstream of the absorber column. The assessment was that the quantity of particulates was minimal and would not pose problems for LDDS integration. While this was a correct conclusion for cases where the flue gas was exhausted to a stack, it may not be acceptable in a CO_2 stream destined for sequestration. Any desiccant suitable for use with the LDDS will have associated corrosion concerns; therefore, the impact of aerosols generated in the absorber on downstream CO_2 compression stages will need to be evaluated.

The effect of desiccant crystallization within the system will also need to be considered since efficient LDDS operation will be near the desiccant's saturation conditions. The maximum possible capture from a process gas will occur when the gas comes into equilibrium with the cooled strong solution entering the absorber. At this point, the desiccant's vapor pressure is the lowest, and this is the lowest vapor pressure that can be used to absorb moisture. Lowering the desiccant's vapor pressure in order to absorb more moisture requires either cooling of the desiccant and/or increasing its concentration. However, there is a practical limit to concentration that is imposed by crystallization of the desiccant; desiccant concentrations in excess of the saturation concentration for a given temperature will result in solid desiccant separating from solution.

The crystallization versus vapor pressure relationship is shown in Figure 9 for solutions of $CaCl_2$. In Figure 9, the operating conditions for the LDDS lie above the crystallization boundary but below the saturation curve for pure water. The water-absorbing potential is indicated by the water vapor pressure of the cooled strong solution, and the lowest pressure for any strong solution temperature occurs at the crystallization boundary. The slight discontinuity around 29°C is due to the formation of different hydrate phases, but it does not significantly affect the trend of vapor pressure with temperature.

In order to maximize water recovery, the concentration of the strong desiccant solution should approach the crystallization boundary as close as is feasible, but it is almost inevitable that this boundary will be crossed at some point during operation. Ideally, this could become a self-regulating mechanism where saturated conditions always exist to some degree in the cooler and the strong solution enters the absorber at the optimum concentration for a given heat sink temperature.

5.1.3 Common Condenser Option

A further opportunity exists for integration of a LDDS with a power plant by considering that both systems may share key condenser components. In a truly water-constrained environment, any new power infrastructure will most likely not have water available for plant cooling. In these cases, some form of dry cooling will be used, and a frequent option is an air-cooled condenser (ACC) which could potentially condense moisture vapor from the LDDS in addition to its primary role to condense steam from the turbine exhaust. In this case, excess product water could then be withdrawn from the plant's boiler feed pump. Eliminating the ACC and its associated subsystems from the equipment balance for the LDDS would lead to significant capital cost savings and could make the levelized cost of water recovery more competitive with other options. However, development work is needed to determine if the evaporated LDDS moisture is compatible with conventional power plant metallurgy.

5.2 Comparison to Moisture Condensation

Another means for recovering moisture or dehumidifying instead of using a desiccant is to cool the process gas and collect the condensed moisture. This is the process used in most residential and institutional air-conditioning systems to maintain indoor humidity levels.

Equilibrium thermodynamic calculations have been performed to compare the potential water recovery option using a LDDS and by cooling the process gas stream to the local ambient temperature sink. Conditions for the example and the calculation results are summarized in Table 11. The example assumes moisture recovery from a saturated process gas stream at 1 atmosphere and 55°C; these conditions are intended to represent the exhaust flow from either a SO_2 or CO_2 scrubber, depending on the plant configuration. Both systems use the same heat sink, and it is assumed that each can cool its respective working fluids (i.e., strong solution for the LDDS and process gas for the condensation approach) to 40°C. The minimum moisture vapor pressure for each option is the equilibrium vapor pressure that can be achieved either through contact with the desiccant or by reaching saturation conditions at the heat sink temperature. It should be noted that the LDDS vapor pressure corresponds to the inlet gas temperature, rather

Table 11. Water Recovery Comparisons for the LDDS and Process Gas Cooling

Water Recovery Option	LDDS	Cooling with Condensation
Process Gas Stream	Saturated at 55°C	
Minimum Heat Sink Temperature	40°C	
Water Content of Inlet Gas	104 g/m^3	
Minimum Moisture Vapor Pressure at Process Gas Outlet	1.73 kPa* (55°C gas temp.)	7.42 kPa (40°C gas temp.)
Equilibrium Water Content at Outlet	9.8 g/m^3 (inlet gas conditions)	44.6 g/m^3 (inlet gas conditions)
Maximum Moisture Capture	91%	57%

* Assuming a strong solution mass concentration of 0.5 $CaCl_2$.

than the outlet, since cooling of the process gas will not occur across the absorber. Based on the experimental results, the gas will be heated slightly, but it was assumed to maintain temperature for this example.

According to the calculations summarized in Table 11, the LDDS would be able to remove 91% of the moisture in the process gas stream, while cooling the process gas to the same heat sink temperature could theoretically achieve a moisture removal of only 57%. While the process gas conditions presented in Table 11 are representative of typical scrubber outlet conditions, the LDDS has an even greater advantage when lower temperature differentials exist between the process gas stream and the heat sink. To highlight this effect, the calculations of Table 11 have been extended for a wider range of inlet gas temperatures, and the resulting maximum moisture capture values are plotted in Figure 10.

As Figure 10 shows, condensation-based moisture collection cannot harvest water when the inlet gas temperature is below the available heat sink temperature (without power input for subambient cooling), but because of the hygroscopic properties of the desiccant working fluid, it is possible to extract moisture even when the available heat sink is above the process gas temperature. It should be noted that this was the case for the May 2010 pilot-scale test runs.

In addition to the potential for higher moisture capture, the working fluid circuit of the LDDS acts as a barrier to separate the process gas from the product water condenser, thereby preventing contamination of the product water with soluble impurities from the process gas stream. In that way, it functions in a similar manner to a water-selective membrane but is more robust to withstand harsh flue gas environments. Like a membrane-based process, the LDDS

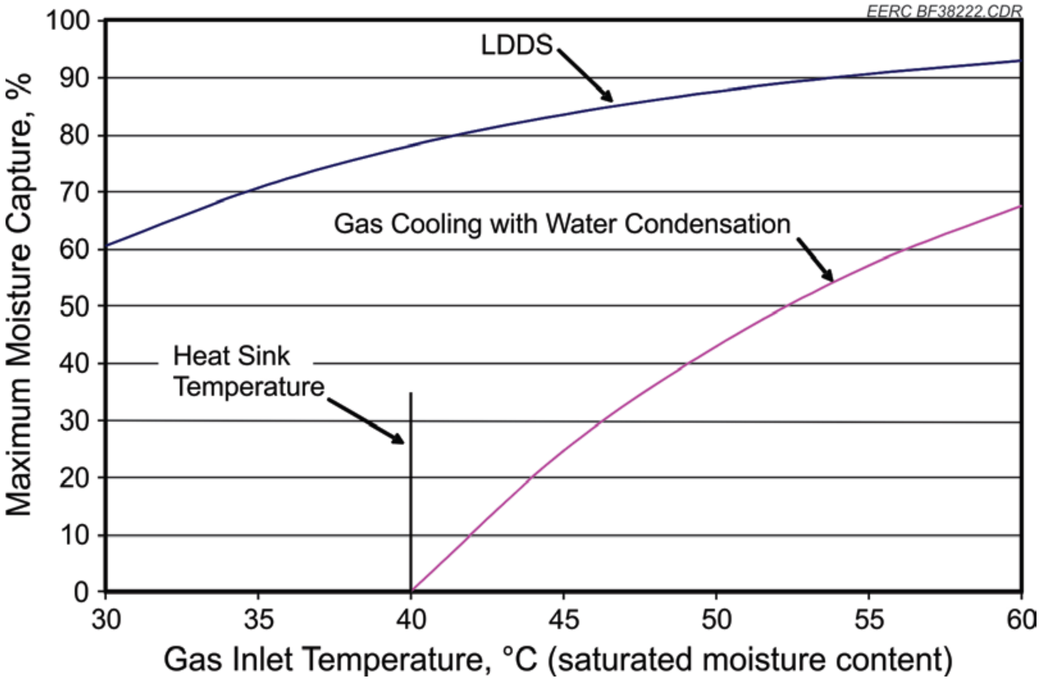


Figure 10. Comparison of maximum moisture capture values.

produces a high-quality product water without additional treatment. Condensed process gas moisture will contain all of the soluble impurities of the process gas. The LDDS does not completely cool the process gas stream which is an important consideration if the gas is to be exhausted to a stack and gas buoyancy needs to be maintained.

5.3 Economic Considerations

The LDDS has a number of advantages for water recovery compared to other options; however, it is a capital-intensive approach and it, therefore, has a relatively high cost for recovered water. Previous economic assessments for the LDDS have estimated the cost of recovered moisture to be in the range of \$0.02 to \$0.04 per gallon (2), which is roughly 10 times the cost of conventionally treated water sources.

In terms of the most productive applications for the LDDS, higher-temperature, saturated gas flows offer the most promise. Not only does the maximum capture potential increase for the LDDS with increasing temperature, as shown in Figure 10, but the available saturated water content increases dramatically with temperature. The net effect on the maximum moisture recovery potential is shown in Figure 11.

Figure 11 presents the maximum water collection possible per unit volume of inlet gas flow; therefore, for a consistent absorber gas-handling capacity, the moisture recovery would depend on the inlet gas conditions. This observation directly affects the levelized cost of water production since it is possible that the absorber's capital cost would remain the same, but its

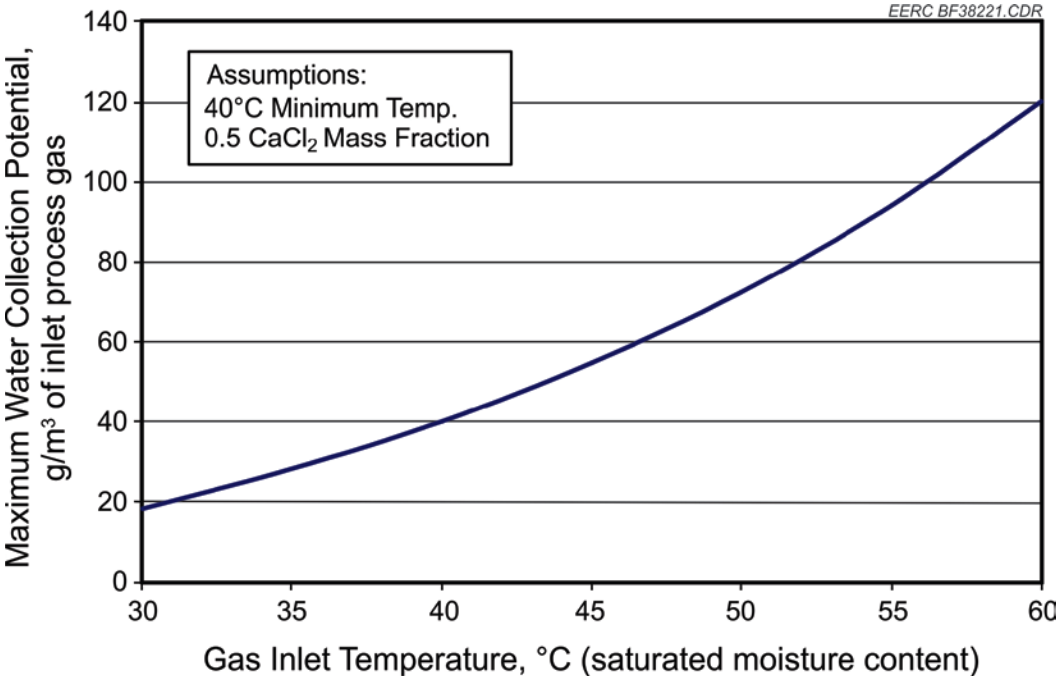


Figure 11. Maximum moisture recovery potential for saturated process gas streams.

potential water recovery could vary by a factor of two or greater depending on the water content of the process gas stream.

For the plant configurations of interest in this work, i.e., oxy-fired or conventional combustion with CO_2 capture, LDDS moisture recovery may be at a disadvantage since the process gas temperatures will be lower to accommodate either downstream CO_2 compression equipment or upstream amine-based scrubbers. According to Figure 11, lower temperatures imply lower moisture content for recovery, which would tend to increase the levelized cost of LDDS water production.

6.0 CONCLUSIONS AND RECOMMENDATIONS

The LDDS can feasibly recover higher percentages of water than with ambient-temperature condensation, and it could use low-temperature recovered heat for input energy, but it is a capital-intensive approach for water recovery; therefore, it has a relatively high cost for product water. Novel integration strategies are needed to distribute the capital expenses among several power plant functions in order to make the LDDS concept more attractive. Identified strategies include making the absorber multipurpose, e.g., moisture absorption and polishing SO_2 control, recovering moisture from multiple process streams using common evaporator and condenser components and, possibly, sharing the plant's steam condenser to recover product water. Based on the analysis of the first phase of experiments with the pilot-scale LDDS and the important economic factors that have been identified, future experimental work should focus on the following:

- Use the absorption column for additional purposes, such as polishing SO_2 removal or oxidizing and removing other flue gas contaminants such as NO_x and mercury.

- Transport CO_2 from the process gas stream to the condenser via absorption and desorption within the LDDS working fluid. The solubility of CO_2 in water may make this a significant transport mechanism in terms of maintaining condenser vacuum.

- Design strong solution circuit for controlled crystallization of desiccant. To maximize water recovery requires the strong solution concentration to approach its saturation concentration. Inevitably, this boundary will be crossed at some point during operation, and the strong solution circuit should be designed to maintain operation under these conditions instead of forcing a shutdown and manual cleaning. Ideally, the situation could become a self-regulating mechanism where saturated conditions always exist to some degree in the cooler and the strong solution enters the absorber at the optimum concentration for a given heat sink temperature.

- Test the integration of a solution heat recovery heat exchanger. In this heat exchanger, the hot strong solution leaving the evaporator would be used to preheat the incoming weak solution. The same concept is used in absorption refrigeration cycles to recycle thermal energy and could enable autothermal operation of the LDDS.

- Quantify desiccant carryover from the absorber column into the dried process gas stream, and determine the impacts on downstream CO_2 compression equipment. Even with a high-efficiency mist collector in the absorber column, it is possible that some aerosols of dried desiccant are emitted. These desiccant salts can be highly corrosive, and their potential effect on downstream systems will need to be considered.

- Evaluate the possibility to use a power plant's existing ACC as the moisture condenser for the LDDS. This integration option could save the capital expense of an ACC for a LDDS installation, thereby lowering the levelized cost of produced water. However, the risk of contaminating the power plant's steam cycle with the LDDS desiccant or other contaminant will need to be addressed.

7.0 REFERENCES

1. U.S. Department of Energy National Energy Technology Laboratory. *Water Requirements for Existing and Emerging Thermoelectric Plant Technologies—April 2009 Revision.* 402/080108; April 2009.

2. Folkedahl, B.C.; Weber, G.F.; Collings, M.E. *Water Extraction from Coal-Fired Power Plant Flue Gas*; Final Report for U.S. Department of Energy Contract No. DE-FC26-03NT41907 and Siemens Power Generation, Inc.; EERC Publication 2006-EERC-12-05; Energy & Environmental Research Center: Grand Forks, ND, Dec 2006.

3. Conde, M.R. Properties of Aqueous Solutions of Lithium and Calcium Chlorides: Formulations for Use in Air Conditioning Equipment Design. *Int. J. Therm. Sci.* **2004**, *43*, 367–382.