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Modeling, Design, and Testing of a Novel Biphasic Solvent-Enabled Absorption System for Post-Combustion Carbon Capture

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Abstract

A novel absorption process enabled by a new class of biphasic solvents for post-combustion carbon capture (BiCAP) is presently being developed at the University of Illinois at Urbana-Champaign. The new biphasic solvents are water-lean solvent blends that develop dual liquid phases with the absorbed CO₂ highly enriched in one of the phases. These solvents are superior in CO₂ capacity and have high thermal and oxidative stability. The BiCAP technology features a unique process configuration of multi-stage CO₂ absorption and liquid-liquid phase separation during CO₂ absorption, allowing continual separation and removal of the CO₂-enriched liquid phase for maintaining low solvent viscosity and a fast absorption rate. Only the CO₂-enriched liquid phase (i.e., heavy phase) with a reduced mass is required for regeneration, allowing for high pressure stripping and a reduced heat duty requirement.

A rigorous rate-based Aspen Plus® simulation model for a selected biphasic solvent (BiCAP-1 solvent) was developed and validated based on experimentally measured property (e.g., viscosity, specific heat capacity and density), phase equilibria, and kinetic data. The developed model was used to assess four different CO₂ stripping configurations of the BiCAP system for capturing 90% of the CO₂ in the flue gas from a 550-MWe (net) supercritical pulverized coal-fired power plant (**Fig. 1**):

- Simple Stripper configuration: only a single stripping column is used for CO₂ desorption;
- Flash + Stripper configuration: sequential use of a flash and a stripping column for CO₂ desorption;
- Cold Feed Bypass configuration: a portion of cold feed stream bypasses the cross-heat exchanger and enters the single stripping column without being heated; and
- Cold Feed Bypass and Flash + Stripper configuration: a combination of the Cold Feed Bypass and Flash + Stripper configuration.

For all configurations, the stripper reboiler temperature was maintained at ~150 °C and the pressure at ~5.1 bar. The heat consumed in the flash (if used) and stripper reboiler was supplied by using the same intermediate pressure (IP) exit steam at 9.3 bar and 364 °C. The cross-heat exchanger log-mean temperature difference was fixed at 10 °C. Results of process simulation revealed that among the four stripping configurations, the Simple Stripper was the least energy efficient and the Cold Feed Bypass the most energy efficient. The Cold Feed Bypass configuration could

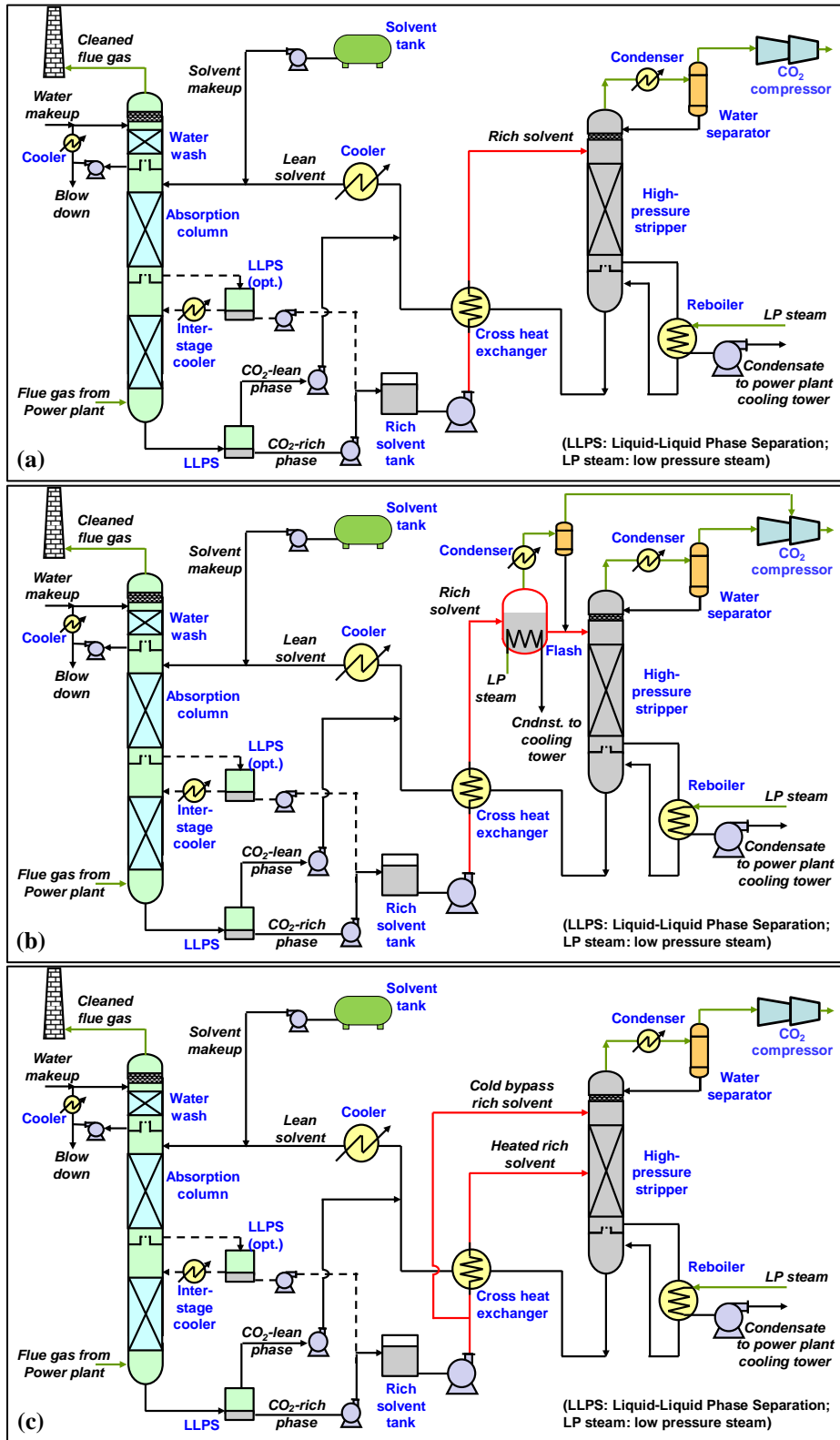
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achieve a total energy requirement of 0.209 kWh/kg of CO₂ captured (**Table 1**). The energy performance may be further lowered by using more advanced biphasic solvents (e.g., BiCAP-2 solvent).

The Cold Feed Bypass process was thus selected for design, fabrication, and testing of a 40 kWe bench-scale system using BiCAP-1 solvent. The Aspen Plus model was used to optimize the bench-scale capture unit design in order to minimize overall energy use while avoiding excessive packing height requirements for the absorber and stripper columns. Stripper optimization was performed by determining reboiler heat duty as a function of regenerated lean loading of the heavy-phase solvent (**Fig. 2**). Absorber packing height required to achieve 90% CO₂ removal was determined as a function of the lean CO₂ loading (**Fig. 3**). Under the optimal design, the absorber is two 8-inch internal diameter (ID) by 13.5-feet-height packed-bed columns with an intercooler, and the stripper is one 4-inch ID by 15-feet-height packed-bed column operating at 6.0 bar and 150 °C with 35% cold solvent bypass to the top of the stripper. The absorber is separated to two packed-bed columns in sequence solely in order to reduce the height of the bench-scale equipment. The optimal design can achieve a reboiler heat duty of 2,210 kJ/kg CO₂ captured at 90% overall removal.

Equipment engineering and design work of the 40 kWe bench-scale system has been completed, and skid fabrication is underway. The bench-scale system will be sited at University of Illinois' Abbott power plant for slipstream tests. **Fig. 4** displays the layout of major equipment. Major equipment, including the columns (i.e., absorber, stripper, and water wash), liquid-liquid phase separation vessels, reboiler, and most heat exchangers, will be mounted to a 6-feet by 6-feet by 60-feet high multilevel tower structure (**Fig. 5**). The tallest column, the stripper, will reach an elevation of 34 feet, with the condenser mounted next to it up to the same elevation. Pumps and the cross exchanger surrounding the structure on the east and south sides. The Direct Contact Cooler (DCC) and blower will be mounted on the northwest corner of the skid, with the solvent surge tank directly south. The Programmable Logic Control (PLC) and Motor Driver Control (MDC) panels will be mounted on the southeast corner. The bench-scale capture system is planned to be installed and then commissioned by the summer of 2020.

Keywords: biphasic solvent; absorption; process simulation; design optimization



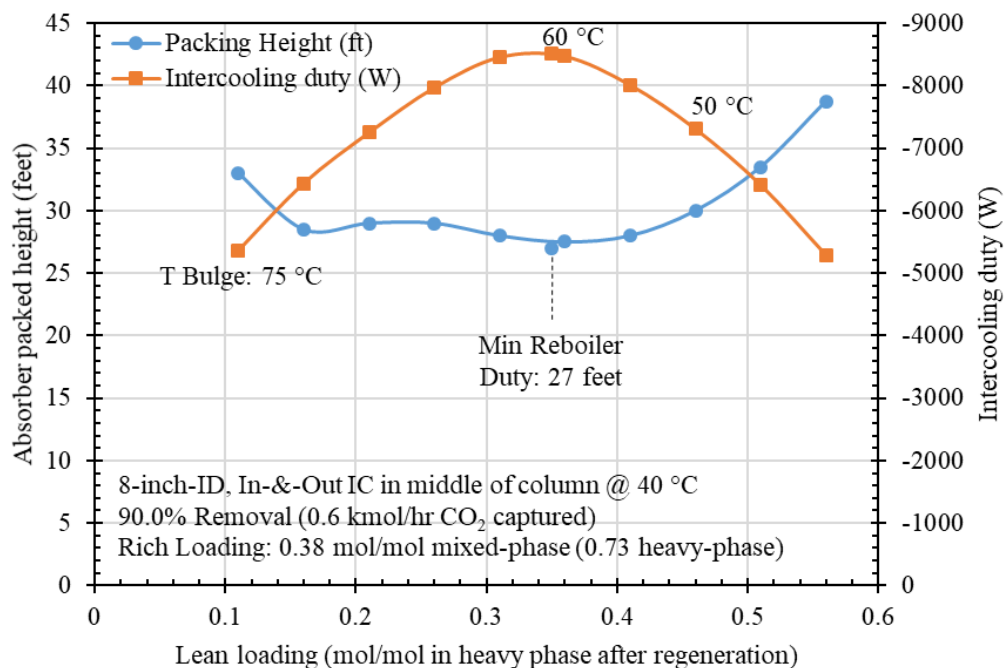


Fig. 3: Absorber packing height and intercooling duty required for 90% CO₂ removal in an 8-inch ID column [Mellapak 250X packing, fixed rich loading of 0.38 mol CO₂/mol amines in mixed phase of BiCAP-1 solvent (corresponding to rich loading of 0.73 mol/mol in heavy phase), intercooled to 40 °C].

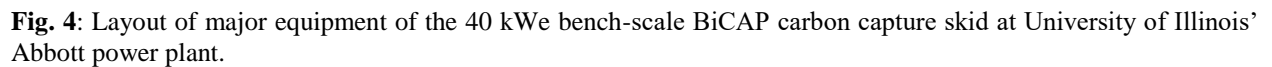


Fig. 4: Layout of major equipment of the 40 kW_e bench-scale BiCAP carbon capture skid at University of Illinois' Abbott power plant.

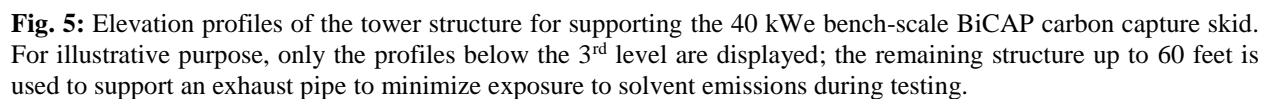


Table 1. Energy consumption estimated for different BiCAP stripping configurations with BiCAP-1 solvent.

	Simple Stripper	Flash + Stripper	Cold Feed Bypass	Cold Bypass & Flash + Stripper
Flash pressure, bar	n/a	9.7	n/a	9.7
Flash temperature, °C	n/a	140	n/a	144.5
Stripper pressure, bar	5.1	5.0	5.1	5.1
Reboiler temperature, °C	150	150	~150	~150
CO ₂ release from flash, %	0%	34.50%	0%	28.75%
CO ₂ release from stripper, %	100%	65.50%	100%	71.25%
Intermediate / low pressure steam use				
Total heat duty, kJ/kg CO ₂	2,613	2,649	2,132	2,441
Parasitic power loss, kWh/kg CO ₂	0.186	0.188	0.152	0.174
Compression work, kWh/kg CO ₂	0.058	0.053	0.058	0.054
Total energy use, kWh/kg CO₂	0.244	0.242	0.209	0.227