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Carbon capture from pulverized coal power plant (PCPP): Solvent performance comparison at an industrial scale

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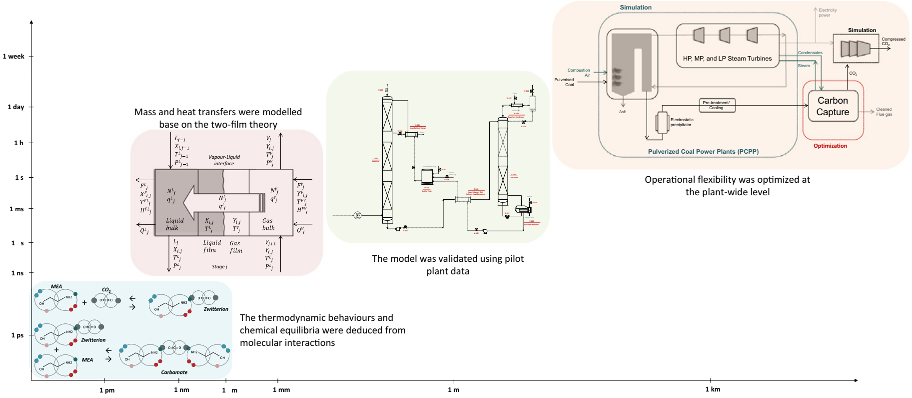
HIGHLIGHTS

- A multiscale model is constructed using SAFT theory and rate-based gas–liquid absorption/desorption columns.
- The detailed model was validated using pilot plant data.
- A systematic method for integrated design and control of capture process is presented and applied.
- The propose methodology provides an efficient method for solvent comparison at the industrial scale.

GRAPHICAL ABSTRACT



Mass and heat transfers were modelled base on the two-film theory

The model was validated using pilot plant data

Operational flexibility was optimized at the plant-wide level

The thermodynamic behaviours and chemical equilibria were deduced from molecular interactions

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ABSTRACT

Coal is the most abundant fossil fuel on the planet. However, power generation from coal results in large amounts of greenhouse gas emissions. Solvent-based carbon capture is a relatively mature technology which can potentially mitigate these emissions. Although, much research has been done on this topic, single-point performance analysis of capture plant and ignoring operational characteristics of the upstream power plant may result in unrealistic performance assessments. This paper introduces a new methodology to assess the performance of CO_2 capture solvents. The problem is posed as retrofitting an existing pulverized coal power plant with post-combustion carbon capture using two solvents: CDRMax, a recently developed amine-promoted buffer salt (APBS) solvent by Carbon Clean Solutions Limited (CCSL) and the monoethanolamine (MEA) baseline solvent. The features of interest include model development and validation using pilot plant data, as well as integrated design and control of the capture process. The emphasis is on design and operation of the capture plant, when integrated with the upstream coal-fired power plant, subject to variations in the electricity load. The results suggest that optimal design and operation of capture plant can significantly mitigate the energetic penalties associated with carbon capture form the flue gas, while providing effective measures for comparing solvent performances under various scenarios.

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1. Introduction

The International Energy Agency (IEA) asserts that fossil fuels will remain the dominant sources of energy for a foreseeable future [1]. While coal is the most abundant source of fossil fuel on the planet, its exploitation for power generations results in large amount of greenhouse gas emissions.

Post-combustion solvent-based carbon capture is an end-of-pipe technology which can be integrated with the power plants and reduce CO_2 emissions. This technology is already well-established for natural gas sweetening [2] (with differences in operating conditions) and compared to other capture technologies, requires minimal process modifications. Therefore, retrofitting the existing power generation stations with post-combustion solvent-based carbon capture has been the focus of academic and industrial researchers. Recently a team of European researchers studied post-combustion from advanced supercritical pulverized coal power plants [3]. They reported a 12% reduction in the overall energy conversion efficiency, when 86.3% of the produced CO_2 is captured. Similarly, the National Energy Technology Laboratory (NETL) in the US conducted a study [4] on carbon capture from pulverized coal Rankine cycle power plants. About 10.9% reduction in the overall energy conversion efficiency was reported when 90% of CO_2 was separated from the flue gas. In addition, a significant increase in the required cooling water was observed. Desideri and Antonelli [5] proposed a simplified method for evaluation of the performance of coal-fired power plants when integrated with a CO_2 capture plant. They observed that depending on the coal type, the flue gas composition and CO_2 flowrate can change by up to 9% and 12%, respectively. They concluded that the overall conversion efficiency decreases with the solvent specific heat of regeneration, percentage of the carbon in the coal and the percentage of the CO_2 removal from the flue gas. The costs of 90% CO_2 removal was estimated to lie between 64 $/tonne CO_2 and 44 $/tonne CO_2 resulting in almost 100% increase in the cost of electricity (COE). Recently, Manzolini et al. [6] investigated the economic performance of a supercritical coal power plant and a natural gas combined cycle power plant. Their economic analysis methods were based on (1) historical data from similar projects, and (2) detailed costing analysis based on process flowsheeting, mass and energy balances. The significant difference between the results of two methodology (Table 7 of that publication), illustrated the challenges associated with economic analyses. Goto et al. [7] studied post-combustion carbon capture from various co-fired power plants. They concluded that the efficiency losses associated with CO_2 capture were around 10% and do not depend on the type (e.g., sub-critical, supercritical and ultrasupercritical) of steam cycle system. Hammond and Spargo [8] discussed carbon capture from coal-fired power plants in the UK, where they reported the value 35.3 $/tonne for the undiscounted cost of avoided CO_2. They suggested that the introduction of a “floor price” for carbon can potentially make carbon capture technologies economic. Wang and Du [9], studied the economic viability of carbon capture and storage (CCS) from coal-fired power plants in China using the real options approach. They concluded that between various sources of uncertainties such as the carbon price, fossil fuel price, investment cost and government subsidies, the latter has the most significant effect in economic. Recently, Damartzis et al. [10] applied a module-based generalized design framework for synthesizing the configuration of CO_2 capture process. The optimization decisions included the stream topologies, the heat redistribution and the cascades of desorption columns for several commercially available solvents. They reported significant potential for economic improvement (15–35%) and reductions in the reboiler duty (up to 55%).

Furthermore, researchers in the field have focused on power plant efficiency and the method of process integration from a thermodynamic point of view. Efficient operation of power plants can significantly reduce the CO_2 emissions. Fu et al. [11] identified combustion reactions, heat transfer between flue gas and water/steam, low temperature heat losses, and the steam cycle as the causes of irreversibilities in coal-fired power plants. By including these irreversibilities in their exergy analyses, they quantified the theoretical maximum as well as practical values for energy efficiency of the power plant. They concluded that solvent-based CO_2 capture is the second most important cause of efficiency loss after combustion irreversibilities. Oexmann et al. [12] analysed post-combustion carbon capture from coal-fired power plants. They argued that the operational setting which minimizes the solvent regeneration energy may not be necessarily optimal with respect to the overall energy efficiency.

The method of integrating the capture process into the power plant affects the overall energy efficiency. Using heat integration and pinch analysis, Hanak et al. [13] suggested that 78.4% of the steam between the intermediate and low pressure steam turbines is needed for solvent regeneration. They conducted pinch analysis in order to analyse five heat integration schemes. Heat recovery from the fuel gas was identified as the most important energy-saving opportunity. Olaleye et al. [14] studied the implication of various processing units for exergy destruction. They compared process configurations including absorber with intercooler, split-flow to desorber, and a combination of both. The last scenario showed the most significant potential for reducing the exergy destruction.

The heat integration schemes investigated in the literature include the method of steam extraction and condensate recycling [15], integrating compressor inter-coolers to the low pressure section of the steam cycle [16] or stripper reboiler [17], preheating combustion air using waste heat from the capture plant [18], and application of pressurized hot water instead of steam for solvent regeneration [19,20]. Furthermore, the CO_2 concentration of the flue gas can be increased by recirculation of the exhaust gases [19,21,22] or using a supplementary burner placed in the duct connecting the turbine exhaust and heat recovery steam generation (HRSG) system [21–23]. Other researchers have explored the implications of the process configuration on the capital investment and energy costs. It was shown that depending on the solvent heat of desorption, either a multi-pressure or vacuum desorber could be the optimal configuration [24]. Other configurations include the absorber with intercooling, condensate heating, evacuation using water ejector, stripper overhead compression, lean amine flash, split-amine flow to absorber and desorber, and their combinations. Le Moullec et al. [25] classified these configurations into three categories of (1) absorption enhancement, (2) heat integration and (3) heat pump applications. They enumerated twenty process configurations from the open literature and patents. In general, up to 37% energy saving in terms of the required reboiler steam was reported [26]. Recently, Wang et al. [27] reviewed the methods for process intensification. They concluded that a rotating packed bed (RPB) absorber/stripper can result in energy-saving due to enhanced transport phenomena. Karimi et al. [28], argued that a high degree of energy integration may result in poor dynamic behaviour, because in energy integrated processes, disturbances propagate in several paths. Therefore, a trade-off between energy saving and process controllability should be established [29].

Nevertheless, integrated operation of carbon capture processes may not be realizable without considering the main operational characteristics of the upstream power plants. Power plants are subject to drastic variations in the electricity demand. Examples of such variations include regular daily and hourly variations in