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Cross-Flow Absorber (XFA) Performance for Engine-based CO_2 Capture: Design, Optimization and Testing

Alexander K. Voice[1]*, Karl Kiebel[1], Austin Keller[1], and Ted Parsons[2]

[1]Aramco Americas – Detroit R&D Center, Novi MI 48377. [2]Brentwood Industries, Reading, PA 19610
**alexander.voice@aramcoamericas.com*

Abstract

A cross-flow absorber (XFA) system was designed, built and tested for capturing CO_2 from a diesel engine. The system is the largest of its kind known to have been tested as part of a post-combustion CO_2 capture plant—significantly reducing potential end-effects and facilitating accurate scale-up. Although performance of the system was initially poor, improvements in the packing design, gas distribution and bypass, and liquid collection and distribution, collectively improved the CO_2 absorption rate by ~2.5x. All-in-all the system was able to reduce emissions from the diesel engine by around 35-40%--well beyond what is possible using current engine efficiency and waste heat recovery technology alone[1]. This work shows the potential for compact, wieldy, XFAs to enable cost-competitive deployment of small-scale carbon capture technology and significantly reduce CO_2 emissions from some of the hardest to abate sources.

Introduction

Modular carbon capture systems are expected to be necessary for deep-decarbonization of many small-scale or engine-based CO_2 sources – including in the transport and power-generation sectors. These applications—which include vessels and marine installations, on- and off-road machines, natural gas and diesel gensets for remote, temporary or backup power generation, and building heating systems—may be unsuitable to electrification due to insufficient energy availability when and where it is needed. Renewable fuels can store large amounts of energy and reduce the carbon intensity of some sectors, but lack the scale, economics, infrastructure, and carbon intensity to meet carbon abatement goals across all sectors. Small-scale carbon capture systems can allow hard-to-abate sectors to further reduce emissions beyond what is achievable with renewables alone [2-5].

Although smaller-scale CO_2-capture systems (in the range of around 500 kW to 30 MW) lack the economies of scale of large, stationary CO_2 sources, they come with other advantages. Engine-based systems reject 50-70% of the chemical potential energy consumed as waste heat [6]. Use of this waste engine heat for CO_2 capture solvent regeneration can reduce net CO_2 emissions by nearly 10x the amount that can be achieved using conventional waste heat recovery systems to generate additional power[5]. Specifically, modest capture rates of around 25 to 80%, which are thermodynamically achievable using available waste heat in engine exhaust and coolant systems[7], far outweigh the 3-5% additional power which can be produced from organic rankine cycle systems. Such capture rates can allow engine and transport systems to meet proposed emissions regulations, while contributing to meaningful reductions in greenhouse gas emissions.

Modular systems which use compact, standardized designs, are factory-built, operate fully autonomously, and are assembled in large numbers can significantly reduce costs compared with large bespoke installations which are custom designed, built on site, use one-off equipment and instrumentation, and require a team of skilled operators. Some engines produce relatively clean feed

exhaust for the capture system, due to the need to meet strict criteria-pollutant emissions limits for many mobile sources. This exhaust may contain only trace levels of NO_x, SO_x, hydrocarbons, and particulate matter owing to the use of low-sulfur fuel, and complex engine and aftertreatment systems (high pressure fuel injection, exhaust gas recirculation, oxidation catalyst, selective catalytic reduction, and a particulate filter). Clean exhaust can extend the solvent and equipment life, minimize process upsets, and minimize the potential for emissions of hazardous air pollutants.

On the other hand, a major challenge for small-scale applications is space availability. The absorber and gas cooling equipment are usually the largest pieces of process equipment in an amine-based capture system[8]. Small-scale systems, including those onboard vessels and vehicles, may also have packaging constraints which may preclude the use of large, unwieldy, vertical columns[9, 10]. The performance of such columns used in amine scrubbing systems are also likely to be negatively affected by tilting [11] which could cause mal-distribution of liquid in the absorption tower. In this work an elegant solution to this challenge is proposed, which is the use of cross-flow absorber (XFA) technology to produce a compact, wieldy, higher performance absorber for small-scale and space/height-constrained applications. Commonly used in cooling towers and deployed more recently for direct air capture applications (due to their low pressure drop), XFA have not been well studied for post-combustion capture systems, with most previous work focused on modelling, design, or small bench-top experiments [9, 12-14].

By comparison, counter-current absorbers (CCA) have typically been preferred for point-source post-combustion capture systems due to their well-characterized performance and larger average driving force than XFAs. XFAs require either more packing, higher liquid rate, or lower lean loading to achieve the same performance as a CCA. However, the performance penalty associated with XFA may be modest due to the rate-based nature of CO_2 absorption, and especially when considering lower capture rates acceptable for small, mobile, and harder to abate sources. XFAs also have several advantages compared with CCAs. Long, short absorbers may require less structural support and be easier to construct than tall vertical columns. They may require less manifolding if the gas does not have to turn when entering the vessel, increasing the ratio of the packing volume to the total absorber volume[13]. Furthermore, cuboidal (and other irregularly-shaped cross-flow absorbers) have an extra degree of freedom compared with counter-flow columns. This allows the gas and liquid velocities to be varied independently of one another—increasing liquid flux and mass transfer while reducing gas velocity and pressure drop.

Methods

In this work, an XFA was designed, fabricated, and tested as part of an engine-based carbon capture system using amine scrubbing with thermal swing solvent regeneration. The engine was operated at around 165 kW and produced around 520 kg/hr of exhaust containing around 8% CO_2 (wet basis). Between 50 to 100% of the exhaust was sent to the absorber, allowing for variation of the gas residence time and lean loading. The liquid rate was variable from around 20 LPM to 45 LPM. The solvent was regenerated in a flash tank using heat from the engine exhaust streams (exhaust and EGR). Pressure was controlled on the regenerator, but not heat duty or temperature; thus the lean loading fluctuated with changes in rich loading or liquid rate. The solvent was 7 m monoethanolamine (MEA).

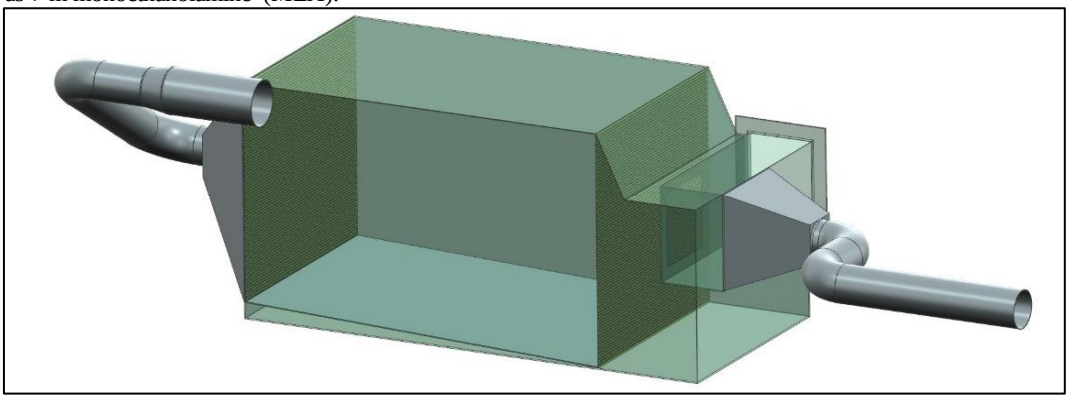

Figure 1: Schematic of the XFA

The XFA built was 1156mm L x 775mm D x 775mm H, where the length was defined as the gas flow direction and the height was defined as the liquid flow direction (Figure 1). Various packings were tested including a random packing (Rashig Super Ring #0.1), a corrugated-sheet stainless steel and a poly-propylene structured packing (both with the same 250X nominal geometry), a high-density (750m^2/m^3) metal gauze Y-type structured packing, and a less dense (500 m^2/m^3) X-type structured gauze packing--all of which were sourced from Brentwood Engineering (Table 1). Packing modules were constructed from corrugated packing sheets or metal gauze into cubes approximately 10” D x 12” L x 15” H and installed through the top of the absorber. All structured packing was rotated 90 degrees in the HxL plane so that the gas flow path remained the same as in the

vertical counter-flow column configuration. The false bottom was sloped at a 2-3° angle to allow liquid to drain towards the drain located at the gas outlet. Packing was cut according to the height as a function of length; variation in packing height once installed was around 1/4".

Table 1: Summary of packings tested in the XFA

Packing	**Material**	**Specific Area (m^2/m^3)**
Rashig super ring #0.1	stainless stainless	453
MASSdek 250S	stainless steel sheet	250
MASSdek 250 HTC	polypropylene sheet	250
MASSdek 500SGX	stainless steel gauze	500
MASSdek 750SGY	stainless steel gauze	750

Results

Preliminary results showed that performance of the XFA was very poor, reaching only around 10-15% CO_2 removal at various liquid rate and stripper pressure. It was hypothesized that the poor performance may have been related to poor gas and liquid distribution, poor packing irrigation, and a low liquid side mass transfer coefficient due to the large liquid flow area and low liquid velocity. The low liquid flux is expected to have a deleterious effect on both the wetted area and mass transfer coefficient[15, 16]. Although low liquid flux can reduce performance for any height-constrained system (XFA or CCA), proper design of internals and packing aspect ratios can help to maximize performance.

To this end, a second generation XFA was designed using the same outer dimensions as the first, but with changes to the gas and liquid distribution systems, packing type, and arrangement. These changes improved fluid uniformity and reduced bypass of gas outside of the packing. The Gen 2 design resulted in a dramatic improvement in performance to around 30-40% capture rate – an increase in around ~2.5x in the CO_2 absorption rate (Figure 2).

The effect of process conditions and equipment sizing was explored by varying the liquid flow rate, stripper pressure, lean loading, gas flow rate, and packing volume (Figure 3). Of these variables, lean loading was by far the most important factor--resulting in around a ~60% improvement in the CO_2 absorption rate, however as expected, this also resulted in an increase in the specific reboiler duty. Reducing the gas rate by around 1/3 increased the capture rate by a similar amount – in part due to the higher L/G. Varying stripper pressure from around 1.7 to around 4 bar (at constant liquid rate and heat rate) did not have a significant effect on the CO_2 capture rate. This may be due to simultaneous changes in stripper temperature which occur when pressure is adjusted while heat rate remains constant, resulting in an overall similar lean loading.

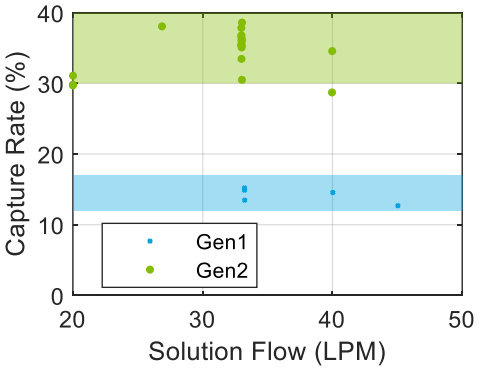

Figure 2: Capture rate comparison for the Gen 1 and Gen 2 cross-flow absorber (520 kg/hr gas at 8% CO_2)

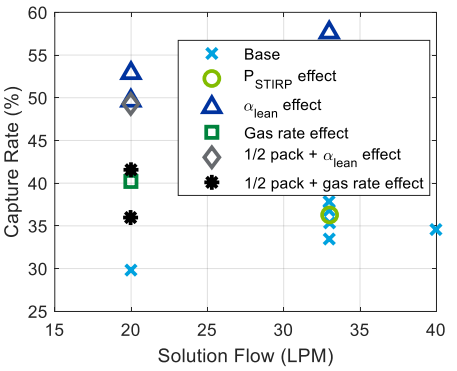

Figure 3: Effect of various process conditions and equipment sizing on cross-flow absorber performance

Simulation of the XFA in ASPEN Plus suggested that much of the packing was under-utilized and that the unit, consequently, was significantly oversized. This prompted testing of the XFA with either ½ or ¾ of the packing removed, which showed that performance of the half-sized XFA (containing around $0.35m^3$ of packing) was not significantly different than the full-sized absorber. The simulation showed that at a given lean loading and liquid rate, reduction in the available packing area was largely cancelled out by an improvement in the mass transfer performance of the remaining packing, due to higher liquid velocity, increased wettability, and increased liquid-side mass transfer coefficient.

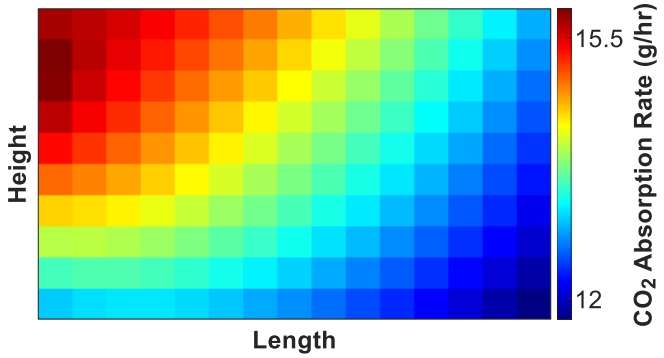

Figure 4: Heat map of CO_2 absorption rate vs. XFA length and height

Conclusions

This work provides initial performance results for a pilot scale cross-flow absorber, which is the largest of its kind known to the authors to have been built and tested for a post-combustion CO_2 capture application. Future work will report on detailed features of the internals, as well as performance results of various packings, and findings from a CFD analysis-led design process used to optimize the XFA internals.

Keywords:cross-flow absorber (XFA); marine carbon capture; engine; small-scale; modular; CO_2 absorption; packing; absorber

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