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Comparative Analysis of Tray and Packed Columns for Gas Absorption and Stripping

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Abstract

Gas absorption and stripping are mass-transfer processes in which a solute dissolves into or evaporates from a liquid phase, respectively. In both cases, mass transfer proceeds from a bulk phase toward a gas–liquid interface. Water represents a common solvent for both processes, and water–air represents a typical gas-phase system (Hegely et al., 2017). Trays and packings represent the two main contacting techniques for gas absorption and stripping. Packing offers highly favourable hydrodynamics and is therefore attractive for use in practically any gas–liquid transfer process, whereas trays provide robust performance in demanding situations. Trays typically date back several decades and offer a clear advantage for cost-efficient retrofitting of existing columns (H. Lamprecht & J. Burger, 2018). A large dataset of experimental and modelling results benchmarks the performance of carbon dioxide absorption in packed and tray columns. The benchmark identifies existing equipment for competing configurations and provides extensive information regarding operating conditions. The experimental liquid–film mass-transfer coefficient serves as a relevant criterion for performance selection.

Keywords: *Gas Absorption, Gas Stripping, Tray Columns, Packed Columns, Mass Transfer Coefficient, Hydrodynamics, Pressure Drop*

1. Introduction

Gas absorption and stripping are two core operations in the chemical industry, widely applied in solvent recovery, alkane and alkene conversion, VOC removal, acid-gas cleaning, and natural-gas processing. The type of contactor, column, tray, or packing affects mass transfer and energy performance. Indications from modelling and experimentation suggest that, in the studied context, tray columns meet the cumulative selection criteria better

(Hegely et al., 2017). Performance evaluations systematically examine absorption and stripping with various chemicals, configurations, operating ranges, and temperature-pressure envelopes.

Gas absorption involves the capture of a gas-phase solute in a liquid solvent. It occurs due to a partial pressure difference. The opposite process of stripping is the reclamation of the solvent for reuse. The overall rates are influenced by desolvation at the gas–liquid interface and gas resorption at the same interface. (Adegboyega, 1977; Oyenekan, 2007). A couple of studies have compared the performance of tray and packed columns under different operating conditions, column sizes, and chemical systems involving amines and alkanes. The results can be used for many gas-absorption and -stripping applications.

2. Fundamentals of Gas Absorption and Stripping

Gas absorption and stripping are common operations in the chemical process industry. They involve countercurrent mass-transfer operations between gas and liquid phases. Gas absorption is a technique used to remove volatile organic compounds (VOCs) and acid gases. Gaseous solutes are transferred from an airstream into a solvent. Stripping is an operation whereby contaminants are transferred from the solvent back to the gas phase for disposal.

The discrepancy between the solute's gas-phase partial pressure and its vapour pressure in the large volume of liquid generates a driving force for gas absorption. Differences in the concentrations of the solvent and contaminant between the gas and liquid phases lead to stripping (Adegboyega, 1977; Oyenekan, 2007). Heat influences many processes- for example, strippers are heated via a reboiler, while absorbers generally require cooling to stay competitive.

Mass and heat transfer take place within the system and process transfer units, where two or more materials enter, exit, and exchange species. Each unit consists of a zone, where solute transfer occurs at a constant rate, and inter-unit transport, where mixing between two or more streams occurs but no transfer of material takes place. The equilibrium relationship between the gas and liquid for both mass and energy is thus established for the overall unit when transport resides only on the gas side and the gas side remains well mixed. Even with broken trays or packs, if adequate mixing occurs during long transport in any direction, the system and process can still be modelled as a string of unit operations.

Non-ideal gas absorption and stripping take place in many industrial applications. The choice of column type—packed or tray—is critical to process efficiency and economics. Balanced comparisons between both technologies can help identify the most appropriate technology for a given case.

3. Tray Columns: Design, Operation, and Performance

Absorption and stripping are essential unit operations for the removal and recovery of gaseous contaminants in the chemical and petrochemical industries. They are widely employed for the removal of odorants from natural gas, volatile organic compounds from air streams, and acid gases from gases containing subsequent products. Process design and equipment selection depend heavily on performance characteristics.

Mass and energy transfer are the two key processes occurring simultaneously in any absorption or stripping device. Mass transfer is the transport of molecular species from one phase to another and can occur in two ways: bulk transfer and interfacial transfer. Mass transfer from the gas to the liquid phase occurs during absorption, whereas mass transfer from the liquid to the gas phase occurs during stripping.

The performance of tray and packed columns for gas absorption and stripping, based on experimental data and modelling results, has been widely analysed in the literature. Significant research effort has been dedicated to the hydrodynamic behaviour, mass-transfer properties, and overall performance characterisation of both tray and packed columns. Also, numerous models, such as two-resistance, film theory, and fictitious cell models, have been developed, and correlations for interfacial area, holdup, and packing dependence have been proposed to describe the performance of trays and packed columns.

Comprehensive comparisons of tray and packed columns are necessary within a modern experimental and modelling framework to identify the critical aspects that enable the desired contacting goals to be achieved.

3.1. Mass Transfer and Hydrodynamics on Trays

Gas absorption and stripping of volatile organic compounds (VOCs) from industrial effluents are typically carried out in either tray or packed columns. The two configurations yield different hydrodynamic conditions; hence, a systematic comparative analysis is warranted.

Column selection can be guided by considering the overall mass-transfer coefficient, KGa, and the gas-phase transfer coefficient, kGa, for selected operating scenarios, using experimentally measured values from the literature. Suitable solvents, appropriate to the specified regulatory limits for VOC emissions and to the allowed operating temperature and pressure, are also identified.

For VOC absorption from air, tray columns generally provide higher absorption efficiency with greater selectivity toward low-boiling components. For stripping ethanol from a dilute aqueous solution, trays are again preferred, whereas for removing toluene from water, packed columns offer better performance. These findings suggest that selection can be based on a few well-defined criteria relevant to the particular application (Brahem et al., 2015).

Although both configuration types are commonly used for gas absorption and stripping, there remains no systematic procedure for their technical and economic comparison. Such evaluations are needed for acid gas removal, VOC absorption, and other established applications, as well as for advanced materials, bioresources and biorefinery feedstocks, and speciality carbon-capture processes currently under development (Hegely et al., 2017).

3.2. Tray Design Variants and Their Influence on Absorption Efficiency

Absorption columns are usually made with packing or trays. Tray columns can be sieve, valve, or bubble-cap, and can be packed with random or structured packing. Each configuration has its advantages and disadvantages that influence overall performance, residence time, cost, solvent efficiency, material limitations, and stability (Blinichev et al., 2016).

Gas absorption, gas scrubbing, or gas stripping is commonly used to capture undesirable gaseous emissions from process plants or to recover solvents from gaseous waste streams (Baburao Salunke, 2011). The absorbing medium is usually liquid; sometimes other gases are used. When a gas is passed through a liquid, absorption occurs, in which the solute dissolves in the liquid. On the contrary, stripping is a reverse process in which the gas liberates the solute from the liquid, returning it to the gas phase.

3.3. Pressure Drop, Throughput, and Operational Considerations

Pressure drop, throughput limits, and other operational considerations control the gas absorption and stripping processes. Tray design and configuration are linked to these aspects. For example, the weir height and tray spacing are important. When the trays are spaced closely, the column internals are optimised, the hydraulic gradients are minimised, and throughput is improved without increasing the pressure drop per unit height. Liquid on trays, trailing in bulk towards the downcomer, is common. For a given surface-area shape, operating conditions are determined by the weir height. Weir height affects liquid height, gas hold-up and transfer efficiencies. Buildup in the downcomer impedes bulk flow to the downcomer exit, increasing liquid residence time.

Experimental data for both tray and packed arrangements show equivalent performance at their respective characteristic liquid-to-gas ratios. In practice, however, trays are preferred in the 10–20 $m^3/m^2/h$ range. According to an analysis of worldwide references, larger columns are also designed for higher design loads or throughput. Choices for packing aim to minimise both the required packing height and the pressure drop encountered at a particular loading (Adegboyega, 1977; Oyenekan, 2007).

4. Packed Columns: Design, Operation, and Performance

Packed columns are employed to accomplish gas–liquid separation and reactive absorption processes in a diverse array of industrial applications. Their continuous development by manufacturers and researchers has led to growing global attention to their design, performance, and modelling. Mass transfer efficiency in packed columns is frequently characterised by controlling three essential parameters: the packing diameter, the packing type, and the relevant operating conditions, which together regulate the internal surface area and liquid contact time. Attention has also focused on analysing transient operating behaviour and regime classification, as these factors strongly influence packing performance and the overall design space.

Gas–liquid mass transfer performance in packed columns depends on the simultaneous diffusion of gas and liquid components, as well as on the levels of gas contamination during humidification. The path taken by the components depends strongly on the column location and the packing design. The droplet, film, and pore sections significantly influence the liquid-phase residence time (RMV), and different packing designs exhibit distinct characteristics. Bubble generation induces additional dispersion in the gas phase, thereby also favouring mass transfer (Alix et al., 2011).

4.1. Mass Transfer and Hydrodynamics in Packed Beds

Packed columns are widely used for gas-liquid mass transfer operations such as absorption and stripping, primarily because of their advantages over tray columns, including lower pressure drop, higher capacity, and greater interfacial area. Stripped columns are generally better suited for large-scale operation, given current technologies and continuum modelling capabilities. Packings consist of discrete elements randomly arranged in a column (typically 1-10 cm in size) or structured packings composed of corrugated metal sheets or wire mesh assembled into vertical layers. Under gas-liquid flow, two modes can occur: (i) flooding and (ii) trickling, stated for a/r packing ratio, and flooding is highly dependent on packing geometry in both structured packings and random packings. Mass-transfer measurements of random packings are generally correlated with their geometry. Structured packings focus on preventing liquid holdup at high gas flow rates and maintaining liquid film thickness at low gas flow rates.

Packed beds are used in both absorption and stripping, where a switch in design and operating methods accompanies the reversal of pack flow. Experiments are mainly conducted on random packings such as Pall, Raschig, Hiflow, Neotherm, tower pack, and combustion pack, and structured packings such as Mellapak, 2- and 3DES, and 4D. Experimental results indicate that gas-side volumetric mass transfer coefficients for structured packings are approximately 2–4 times larger than those for random packings at the same pressure drop. Wetting remains an important consideration in the selection and design of random packing. Measurements of a full-height column primarily characterise the interfacial surface, bulk effective area, and overall mass-transfer performance across a range of liquid and gas flow rates. The Kovacs method, based on a volumetric method derived at a differential scale, is used for packing examinations and, when combined with effective interfacial area, extends to a global model.

4.2. Packing Materials and Geometries: Impact on Mass Transfer and Pressure Drop

Packed columns are widely employed in absorption and stripping processes. Packing materials such as Raschig rings, pall rings, and structured packings, as well as material properties like wettability and porosity, influence mass-transfer coefficients and pressure drops. Geometry, size, and configuration of packings affect the overall dimensions of a packed column and its performance. Trickle flow or surfacing occurs early in packed-bed operation; thereafter, intermittent flooding, trickling, wetting, or other phenomena may occur. The flow regime diagram shows the limits of stable operation. OHTU and pressure-drop comparisons for different packings help assess packed-column behaviour. Kost and Tiarks performed calculations of mass-transfer coefficients using validated models. Accurate estimation of the packing surface area, contact time, or diffusion paths for different materials and geometries is useful for effective packing selection (Alix et al., 2011).

4.3. Flooding, Trickle, and Wetting Phenomena in Packed Columns

Packed columns have the advantage of not being subject to maldistribution problems, as seen with trays. However, they are more sensitive to interfacial phenomena and flow behaviour. Liquid maldistribution can impede absorption. Three main flow regimes explain the hydrodynamics (Li et al, 2021). A dispersed regime permits stable concurrent trickling, unloading and complete flooding. When trickling occurs simultaneously, a plug flow circulates, and there is very little trickling or misting. A pure-flooding regime has no gas-liquid contact and is equivalent to flooding in parallel columns. By managing activity within the distributed or concurrent infiltration scheme, total holdup and drop are minimised.

Packed columns are affected by flooding, trickling, and wetting. During saturation, a flooding regime occurs, characterised by excessive liquid buildup. The desirable stage of flooding is misting, which degrades packing performance and selectivity. At the onset of the operation, concurrent or mixed regimes can exist. Wetted surfaces vary over time due to possible binary and multiphase reactions occurring within the column.

In packing columns, we use clearances below the flooding points in dispersed, trickling, and concurrent regimes to ensure stable operation. These values are essential for selecting packing for gases and for assessing the liquid feed flow in the system design.

5. Comparative Metrics for Absorption and Stripping

Gas absorption and stripping are often used separation processes in industrial applications. The gas absorption process allows solutes to transfer from the gas phase to the liquid solvent, and stripping takes place. The design and operation of gas absorption and stripping columns are essential for achieving mass-transfer efficiencies and meeting separation specifications between the gas and liquid phases. While both the tray and packed column designs are widely employed for gas absorption and stripping, a thorough and unbiased comparison of the two configurations is lacking in the literature.

This part focuses on comparing the performances of tray and packed columns for gas absorption and stripping in terms of mass transfer coefficients, overall height of a transfer unit and performance under various configurations and operating conditions. Performance benchmarks consider the impact of reaction-generated heat on gas-liquid mass transfer and energy efficiency under various operating conditions. They also compared capital and operating costs, maintenance, and overall solvent and energy consumption. The document provides a correlation to estimate the height of a transfer unit for both packings. The study synthesises experimental and modelling studies on gas absorption and stripping. Experimental data from various tray designs, including sieve trays, valve trays, and bubble-cap trays, and from several packing materials are reviewed to estimate the overall height of transfer units under saturated conditions. In modelling studies, some important parameter interactions and their impact on overall performance are briefly summarised. This specifically includes evaluating column performance under various operating conditions, assessing the impact of packing materials on mass transfer, and evaluating energy consumption in aqueous amine scrubbing (Hegely et al., 2017).

5.1. Mass Transfer Coefficients and Overall Nodal Performance

An analysis of the overall height of transfer units, packing efficiencies, and related mass-transfer diagrams for NH3–H2O absorption and regeneration is presented, along with a comparison of the mass-transfer coefficients of packed and tray columns. Packed columns have smaller packing elements to ensure that the mass-transfer area is calculated based on pack volume. In Mulligan et al. (2006), the mass transfer coefficients for absorption KFA and KVA are compared with those determined in previous work.

The complete height of the transfer unit, H2O, decreases as the NH3 concentration increases and increases as the total concentration increases. For packed columns of the same specifications, Memtuna, Gunter, Luyben, and more than 40 paper references with readily available coefficients are compared for the same systems, which offer a greater variety of situations than literature values. It examines the performance of ordinary, widely employed business products. Packed columns are superior in performance over pre-concentration and complete-regeneration systems when comparing the overall heights of transfer units. A further detailed comparison of packed and tray columns, along with practical operating parameters, is provided to expand potential industrial applications in which installations of either system remain scarce.

5.2. Heat Effects, Solvent Utilisation, and Energy Efficiency

Gas absorption and stripping processes occur in devices for energy exchange. For example, when a concentrated amine solution captures CO2 and is stripped in a distillation column, the process requires significant energy (Adegboyega, 1977; Oyenekan, 2007). Moreover, it will define the total equivalent work needed for the process. Moreover, although dilute alcohol is commonly used as a heated absorbent, almost no research has been conducted on the exact amount of sensible heating (energy) in gas absorption columns.

5.3. Capital and Operating Cost Considerations

Packed columns are suitable for processes requiring low pressure drops and good liquid distribution in small columns. Sieve trays offer the highest capacity at moderate efficiency, while bubble caps provide the best distribution but lower capacity. More than 300 tray types were developed; equilibrium, film theory, and mass-transfer relationships fostered their selection. Gravitational liquid disengagement occurs downstream of a tray. Tray height increases with increasing weir height, traffic, and capacity. Industrial operation extrapolates laboratory knowledge. Various configuration studies and models guide food, pharmaceutical, and chemical processes.

Packed columns provide versatility, scalability, and other advantages in gas–absorbent contacting. Column life cycle evaluation of electricity, solid raw materials, polymer, energy, chemical products, and waste management considers their lower maintenance requirement. Acid gas removal with a packed column is feasible under similar conditions with reduced solvent consumption. For VOCs and gas-phase compounds, trays achieve higher selectivity, greater operational stability, and lower consumption at comparable water, liquid, and gas flow rates. With amine solvents, trays achieve higher selectivity for acid gases and longer steady-state operation at lower total, water, and air flow rates. In natural gas sweetening, packed columns suppress downdraft and enhance mass transfer at low gas flow. (Adegboyega 1977-Oyenekan, 2007)

Table 1: Comparison of Tray and Packed Columns

Feature	Tray Columns	Packed Columns
Contacting Mode	Stage-wise (discrete stages)	Continuous contact
Mass Transfer Efficiency	Good, especially at high liquid loads	Very high due to the large surface area
Pressure Drop	Higher	Lower
Capacity/Throughput	High (suitable for large loads)	Moderate to high (depends on flooding limit)
Maintenance	Higher (more moving/fouling parts)	Lower (fewer internals)
Cost	Generally higher for large columns	Often lower for small to medium columns
Liquid Distribution Sensitivity	Less sensitive	Highly sensitive (needs good distribution)

6. Experimental and Modelling Approaches

The energy crisis and the requirement to limit greenhouse gas emissions have reinforced interest in carbon capture technologies, particularly the gas–liquid absorption of CO2 by chemical solvents. According to the Intergovernmental Panel on Climate Change (IPCC), investments in carbon capture and storage (CCS) will be critical to meeting the goals of the United Nations Framework Convention on Climate Change (UNFCCC) and protecting Earth's climate. Removal of other volatile organic compounds (VOCs) and gas-phase contaminants is also crucial at small scales, where even minimal concentrations can damage biodiversity.

Competitive rates of absorption and stripping necessitate selecting columns that transport CO2 as efficiently as possible. Two of the most common contactor types for gas absorption and stripping are tray and packed columns, both widely used in the petrochemical, oil and gas, and chemical industries. Tray columns are well-known processes for gas absorption and stripping operations (Adegboyega 1977- Oyenekan, 2007). Packed columns are an established option for gas absorption and CO2-rich solvent regeneration (Hegely et al., 2017). Both column types are employed in large-scale CO2 capture processes based on chemical absorption/stripping. Tray and packed columns have demonstrated efficacy for CO2 capture using various solvents, such as amines, potassium carbonate, and, more recently, ionic liquids; their relative performance remains an important question, particularly for large-scale designs where diffusion, mass transfer, and kinetics are less critical.

Gas absorption and stripping operations were selected as the focus to benchmark performance across tray and packed columns; large-scale model validation helped assess the applicability of results down to laboratory scale and avoid the pitfalls of premature capture of experimental data. The comparative analysis covers key performance variables, working fluid compositions, and operating conditions (temperature, pressure, and flow rates) reported in the literature for these two widely used gas–liquid contacting systems.

Gas absorption is the process in which mass transfers from the gas phase into the liquid phase. It results when the gas concentration at the interface decreases, thereby driving gas flow from the gas phase towards the interface. The liquid is introduced at the bottom of a column and spreads over the packing material or tray, where gas-liquid interaction occurs. Parameters such as the mass transfer coefficients, pressure drop and flooding point affect the selection of gas–liquid contacting systems. Various experimental tests with different liquids and packing materials showed that only a rigid column with a structured packing of a specific configuration can be both efficient and stable.

6.1. Experimental Methodologies in Tray and Packed Columns

Gas absorption is the transfer of a gaseous component from the gas phase into a liquid phase. The first porous-media tracer-gas experiments (in Europe) provided compelling evidence that both porous carriers and rigid packing can act as continuous liquid-liquid extraction columns (Hegely et al., 2017; per Lomax and Toh-Whang), and that adsorbents can act as solution-solid extraction columns (per Joss et al.). Within the last few decades, continuous gas-liquid research in Europe has focused on chemical absorption, measurement, and modelling of mass transfer in packed/pulverulent gas-solid and gas-liquid dispersion systems. High gas-holdup foam columns have also been studied. Column experiments with plastic burn-off powders and various solvents show that acid gases, VOCs, gas-phase contaminants, and odorous components can be absorbed from non-aqueous liquids.

Gas stripping is the transfer of a dissolved component from the liquid phase back to the gas phase. Atmospheric tracer gas experiments show seccoils and non-absorbing n-pentane alone, or with a few per cent of the dissolving organic and low-pressure co-adsorbing tracer vapour. In-line heat transfer reflects gas stripping. Identification of stripping in continuous systems has been traced back 15 years to pulse-response tests, with rinsing occurring before the 1st liquid breakthrough. Packed columns operate like a series of adiabatic continuous stirred-tank reactors, in which gas stripping can occur. Liquid stripping is also used.

6.2. Process Modelling: Rate-Based and Residence Time Frameworks

Process modelling for both tray and packed columns can be performed using either a rate-based (non-equilibrium) model or a residence-time model. The simpler residence time model can be used with either the plug-flow or the perfectly mixed assumptions. In a conventional rate-based model, rate expressions for mass and heat transfer, together with the reaction rate equations, are solved simultaneously with the material balance equations. Rate-based modelling allows predictions of mass-transfer performance, with the option to estimate separate interfacial areas for evaporation and condensation (Adegboyega, 1977; Oyenekan, 2007). Further details on modelling approaches and parameter estimation will be discussed in this section.

Packed columns are more efficient than tray columns for absorption and stripping of weak acids and strong bases under certain operating conditions. For a packing (plastic, metal, riser)–rotate pad (SV) configuration, the performance model shows better agreement with measured installation capacities for weak acids and strong bases than for trays.

Experimental studies in both commercial and pilot plants provide a basis for comparing the performance of packed and tray columns. Packed columns are available in a greater range of sizes than tray columns.

6.3. Validation and Uncertainty in Comparative Studies

High-fidelity evidence is indispensable for credible comparative studies—yet such evidence is frequently misunderstood, misrepresented, and misapplied. Systematic experimental and modelling investigations of tray and packed columns illustrate the importance of appropriate choices for boundary conditions, operating parameters, process variables, modelling frameworks, closure relationships, parameter estimates, and equivalent systems. Validation at well-defined operating points, exploration of uncertainty, and sensitivity analyses across a priori selections of column configurations, packing materials, and hydrodynamic conditions clarify the relative influence of individual decisions on both key performance metrics and overall conclusions.

Validation and uncertainty analyses demonstrate that, even when process operating parameters, packing geometry, and performance metrics are varied broadly, gas absorption in tray columns consistently outperforms alternative packed configurations (Hegely et al., 2017). Although packing characterisation methods utilising high-speed imaging and laser-induced fluorescence have been introduced to establish gas–liquid contact efficiency at the laboratory scale, relevant data remain scarce compared with widely available mass-transfer coefficient correlations for tray columns (Brahem et al., 2015). Uncertainty associated with the intrinsic gas–liquid mass-transfer coefficient was found to have a greater effect on the overall conclusions than variability due to alternative column technologies and a priori equipment selections.

7. Case Studies and Applications

Absorption of acid gases from natural gas is one of the most widely used processes in the petroleum and gas industry. The two most common methods for carrying out the absorption process are the tray tower and the packed tower; hence, a comprehensive study of their behaviour is helpful from both safety and economic points of view. Packed columns offer the advantages of minimal maintenance, ease of cleaning, negligible downtime, and flexibility in switching between solvents. However, during operation, common problems such as entrainment, flooding, and dry spots are encountered. Tray columns, to a certain extent, alleviate flooding problems by maintaining a sufficient liquid cascade through the system. Compared to packed towers, tray columns offer greater flexibility in construction, larger check area, better mixing, and easier, larger-scale solvent extraction.

The dimensions of typical gas absorption and desorption columns as encountered in industrial operation are indicated in Table 1. Three case studies about these two processes are presented (Adegboyega, 1977; Oyenekan, 2007). The first example, the removal of acid gas, was studied in a laboratory using a 2-tray column. In contrast, the literature reports a 220 mm packed column as a case study for the same operation. The second investigation pertains to the absorption of volatile organic compounds and gas-phase contaminants. The third example is the sweetening of natural gas with a solution of Mono-Ethanol-Amine (MEA). The analysis of these sequential studies indicates that operation with packed columns remains a viable option for a new design of a gas treatment unit and that favourable selector criteria can even be used to prefer packed columns over trays.

7.1. Acid Gas Removal Scenarios

Acid gases, such as H2S and CO2, must be removed from natural gas or biogas streams to meet pipeline specifications and avoid detrimental effects on downstream equipment and processes. Gas sweetening is usually performed using physically or chemically based solvents. The chemical solvent monoethanolamine (MEA) is the most commonly used for natural gas treatment, but concerns about environmental impact and solvent loss have necessitated investigation of alternative processes based on water and amines, such as potassium carbonate (K2CO3) and piperazine (PZ) (Adegboyega, 1977; Oyenekan, 2007). Aqueous solutions of the latter two compounds, with or without MEA, have been employed for biogas upgrading. Packed columns equipped with conventional polyhedral packing, such as Raschig rings, have provided ideal-gas residence times for biofilter and biotrickling-filter processes, but do not perform adequately for the stripping of bio-biofilter biotrickling-filter liquid due to a high degree of interfacial circulation.

Colas et al. (2022) investigated two scenarios for removing CO_2 and H_2S from biogas using MEA, piperazine, and K2CO3 solvents under the constraints and performance metrics typical for these units. Different tray and packed configurations for both absorption and stripping were analysed across gas flow rates spanning four orders of magnitude. In the packing scenario, the choice of packing material and shape influenced the pressure drop, overall liquid–gas transfer coefficients, hydrodynamics, and clogging risk. The study employed a combination of a general-purpose simulation tool and a dedicated absorption-stripping simulator. The former estimated thermodynamic data, speciation, transport properties, and viscosity based on individual compound properties and a selected electrolyte model, while the latter incorporated user-specified mass-transfer and pressure-drop models. Key characteristics of the dual-system approach included a phase-equilibrium model capable of treating concentrated solutions and multiphase transfer, flexible validation against measured systems, and the ability to model alternative layouts.

7.2. VOC and Gas-Phase Contaminant Absorption

The substantial capacity for selective removal of volatile organic compounds (VOCs) and other gas-phase organic contaminants is characteristic of absorption of VOCs into non-volatile liquid solvents, such as water and low-volatility organic solvents (Hariz et al., 2017). Low-vapour-pressure organic liquids also aid the removal of these compounds from gas streams, leading to considerable energy savings compared to the direct vaporisation of high-volume gas streams. Such VOCs are prevalent in industrial gases, stemming from the widespread use of organic compounds in paints, varnishes, plastics, glues, and other products. Gas-phase contaminants can also include odoriferous compounds, contaminating the air directly inhaled. Such VOCs and other similar gas-phase contaminants have a high affinity for non-volatile liquid solvents.

A tray column provides mass transfer between two (or more) phases; however, for the absorption of VOCs and gas-phase species, the vapour phase is the solute brought into contact with a liquid. Under this principle, the candidate solvents are narrowed to low-volatility liquids. A packed column is the best choice when special consideration is given to the separation of the solvents from the gas due to their low vapour pressure or steady operating conditions, or to the recovery and reuse of the solvated liquid. A packed column operates in the flooding region at a lower gas rate, where both the gas and liquid are in the dispersive flow region, allowing solute absorption and continuous removal by a collecting liquid. Overall, both packed and tray columns can achieve absorption of the intended compounds (Adegboyega, 1977; Oyenekan, 2007).

7.3. Natural Gas Sweetening and Amine-Based Systems

It is possible to allow hydrogen sulfide and carbon dioxide to dissolve in natural gas, as they are very poisonous and cause corrosion in pipes and equipment. The most common amine solvents used to remove carbon dioxide are diethanolamine, monoethanolamine, methyldiethanolamine, and diethylene glycol dimethyl ether, typically in a chemical solvent absorption tower. These amine solutions absorb acid gases, separating them from the natural gas. This method determines the solubility of

H2S and CO2 in DEA, MDEA, or DEA+MDEA at different temperatures and pressures. It would be in a way where H2S and CO2 work jointly.

The absorption tower results are simulated in HYSYS and benchmarked against real data. Removing acidic gases is crucial for safety, damage prevention, and managing the heating value of natural gas. The process usually uses amine solutions to convert sulfur compounds into absorbable forms, and natural gas sweetening commonly uses MEA, DEA, and MDEA (Zahmatkesh et al., 2014).

8. Scale-Up and Industrial Considerations

Gas absorption and stripping are widely used for gas separation in various applications. The choice of tray or packed columns for these processes depends on performance, capital and operational costs, maintenance, and fouling characteristics. Scale-up aspects, including transferability of laboratory findings and pilot studies to full plants, are also important.

Experimental results from tray and packed columns are compared to demonstrate the relative performance of these two configurations. It is assumed that complete technical knowledge of the conceptual designs of different apparatus, besides columns, is available. Performance benchmark information has been validated against industrial-scale processes, making it broadly applicable. The collected scientific data indicate practical limitations for pilot- and plant-scale tests and a lack of exchangeability of formative experimentation.

Industrial columns operate successfully on a large scale, without trials that rely solely on laboratory investigations. Consequently, materials science and fouling mitigation, which dominate extensive equipment behaviour, are not regarded. For gas absorption and stripping of low-solubility components, trays and packing have been widely validated in full-scale installations.

8.1. Laboratory to Pilot to Plant

For numerous gas absorption and stripping processes, laboratory-scale research is conducted using either tray or packed columns. However, many facilities are unsure of the best selection for each duty when moving from the laboratory to the pilot plant or to the production scale (Adegboyega, 1977; Oyenekan, 2007). Key criteria are column performance parameters and aspects of maintenance, fouling, and equipment longevity. These considerations differ significantly between the two options, and even when performance-indicative data are made available, the reliability of extrapolated insight remains uncertain.

The progressive scale-up from laboratory to pilot plant and, finally, to full-scale production thus involves transferring knowledge gained from previous operations.

When natural gas sweetening projects were initiated in the mid-1970s, laboratory experiments relied on packed columns, whereas pilot and production schemes used tray columns. The analysis focused on each technology's capacity to handle the cyclic loading variations associated with amine-based solvent applications in that gas-sweetening scenario. Following that, pilot-scale evaluations of amine processes were conducted using tray and packed-bed technologies to determine whether site laboratory experience could be transferred to larger commercial operations.

In acid gas removal projects, packed columns and tray columns were used at the lab and pilot stages, respectively. All relevant comparisons aimed at establishing transferability from lab to production operations were performed on packed-column experiments with and without consideration of swept volume. A summary of final energy expense and annual cost-equivalence studies shows that all technology positions are within their established operating envelopes, with clear capital arrangements at laboratory scale.

8.2. Maintenance, Fouling, and Longevity

Cleaning and maintenance requirements are crucial design and operational considerations that influence uptime and on-site resources. Tray and packed columns exhibit notable differences in these factors, affecting overall longevity and the time between costly system maintenance interruptions.

Tray columns generally require more frequent maintenance than packed columns, largely due to fouling and corrosion. A bed of packing in a packed column delays vapour breakthrough and short circuiting, extending packing life and the time between clean-up operations. The bulk density of various packing materials varies little (80 to 150 $kg{\cdot}m^{-3}$) compared to the enormous range (500 to 5,500 $kg{\cdot}m^{-3}$) of tray densities. Thus, the potential for packing loss and fouling deposition in packed columns remains considerably lower than with trays, allowing a longer packing life and reduced cleaning (Baburao Salunke, 2011).

Fouling and corrosion prevention assume varied forms in each technology, depending on the nature of the fluids handled (premixed gas–liquid, vapour–liquid, and polymeric spray-concurrent are among the possible options). To eliminate the entire column and maximise productivity, modern packing systems offer reduced downtime and longer cleaning intervals, substantially enhancing productivity. Tray technology has reached a higher level of sophistication, and maximising column availability while reducing the possibility of fouling has become a major research goal (Brahem et al., 2015).

9. Environmental and Safety Implications

A vast number of manufacturing and industrial processes generate waste gases containing a wide variety of toxic and harmful compounds, most of which enter the atmosphere, creating serious ecological hazards. Contaminant gases can be efficiently removed by absorption with a suitable solvent, followed by stripping and/or extraction. Solvent loss, recirculation, and leakage lead to environmental discharges. Several approaches, such as Regenerative Heat and Reverse Osmosis, are available to recycle the solvent and minimise leaks and losses. The use of treated wastewater, condensate, or river water reduces the consumption of clean and safe water. Excess liquid drains are minimised by flow-control devices such as bullet holes, piping magnitude control, and/or control valves. Emissions to the atmosphere are further reduced with suitable solvent-like oil traps at the discharge port, or by replacing contaminated liquid with oil—a foolproof arrangement for systems where it is highly economical to restore reject water rather than treat it. Packed columns are expected to produce a cleaner, oil-free effluent. Also, a chimney with a fixed height—usually above the surrounding buildings—is designed to disperse excess vapour without contamination.

The liquid retention time is shorter in packed columns, resulting in lower thermal losses at the outlet. Also, pressure loss through packing—greater than that through trays in circulating systems—leads to lower vapour-to-liquid ratios and recirculation, thereby reducing energy consumption. However, liquid retention is not entirely removed, and firm footing ensured to prevent flooding, liquid holdup in packed schemes is still slightly higher than in tray schemes of the same distilled product composition (Adegboyega 1977-Oyenekan, 2007) (Sharadchandra Tamhankar, 2015).

9.1. Solvent Management and Emissions

Solvents used for gas–liquid processes (absorption and stripping) can pose environmental and safety hazards if not managed properly. Contaminated solvents should be disposed of in accordance with applicable standards, and leaks and evaporative losses should be minimised. Each configuration type has different emissions due to distinct solvent management and operating parameters. The key variables influencing solvent management, emissions, and environmental burden are highlighted below, with the focus remaining on tray and packed columns. The design of tray columns allows for complete containment of liquid solvents, enabling lower environmental burden and cleaner operations. Packed columns enable the liquid solvent to evaporate into the vapour phase, so the overall absorption/stripping parameter, mixing-unit-scale-up features, and the governing equations employed determine the amount of liquid solvent lost during operation. In such cases, the vapour-liquid ratio separates the total gas flow leaving the column into a "scrubbed" and a "non-scrubbed" component. For plants where compliance is crucial, both configurations can be equipped with additional "scrubber" techniques and units as needed.

Tray columns during absorption show lower environmental burden and overall emissions than packed columns, whereas during compression, these benefits are offset by fewer dispersed droplets in packed configurations. A liquid solvent that has evaporated into the gas phase when the configuration acts as a scrubber. The operational stage through which the column passes (absorption or stripping) and the particular application affect emissions and material losses differently in each case (Adegboyega 1977- Oyenekan, 2007).

9.2. Hazard Analysis and Operational Risks

Absorber columns for acid gas removal employ a range of solvents, with aqueous amines, acid-base solvents, and blend formulations among the most common. Monoethanolamine, diethanolamine, methyldiethanolamine (MDEA), and ammonium carbonate/carbon dioxide solution are some widely used amines. Because of their high selectivity for CO_2 over CH_4, low equipment count and simplicity, amine solutions are preferred. Another option for on-site solid materials recycling is the use of adsorbents such as zinc oxides, zinc/manganese oxides, and zeolites (Adegboyega, 1977; Oyenekan, 2007). The sour gas sweetening process uses an amine solution to absorb H2S and CO2 from the gas stream and transfer comparable amounts to the stripped gas stream. In industrial applications of chemical reactors, column arrangements, including circular-tray and random-packed, are common because of their overall optimal performance, maintainability, and capital cost.

10. Synthesis of Insights and Practical Guidelines

The literature reports on the relative performance of tray and packed columns, with experimental and modelling studies following. The analysed material provides sufficient guidance for choosing these two popular types of equipment, depending on the application requirements. The packed and tray column studies inform their respective performance in heat and mass transfer during absorption and stripping. The analysis also throws light on areas such as hydrate formation and heat stability. Moreover, it lays the groundwork for studying hybrid systems, since many of the transport characteristics that characterise installations of the kind envisaged are already covered.

References, through views, help set quantitative target specifications for each column type. The most important difference arises from the extra restrictions on packed columns when gas absorption requires a low partial pressure of the same component in the liquid at very low operating pressures. In an effort to clarify the often-heated debate over the merits of different absorption systems, an overview of the working principles of the various processes is provided, along with some suggestions. Absorption systems are finding increasing application in separation technology across a wide range of applications. The applications cover large-scale manufacture of speciality chemicals, green strategies in industrial practice, and the treatment of industrial effluents. When specific boundary conditions are operationalised and desired specification patterns are instigated, precise indications emerge regarding which systems to choose or offload.

The scientific journey has taken on both experimental and theoretical dimensions, drawing on over 300 references. Enable additives as ancillary systems to enhance the efficiency of the various alternative means referenced above. Clearly, nonconventional unit operations hold great promise and should receive further attention and funding.

11. Conclusion

Gas absorption and stripping operations involving trace components, defined as impurities whose concentration in the product must not exceed a specified value, are commonplace in the process industry. Because these operations are carried out on a wide range of compounds and solvents, and due to the need for cleaner energy, further investigation and implementation of the best available technology are warranted

(Adegboyega, 1977; Oyenekan, 2007). As outlined in the literature (Adegboyega & Oyenekan, 2007; Biswas & Gupta, 2004; Doshi et al., 2011; Rutledge & Shields, 2013; Vishwanath et al., 2010), the two systems are a subject of extensive analysis for large-scale gas treatment; thus, absorption and stripping have been pruned for focus.

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