# The Technologies in H<sub>2</sub>S Removal from Gas Streams

Subjects: Chemistry, Applied

Contributor: Francisco Jose Alguacil

Hydrogen sulfide is a toxic and corrosive gas; thus, in order to mitigate its environmental impact, its capture and removal from various emitting sources, natural and anthropogenic, is of a necessity.

absorption adsorption hydrogen sulfide membranes

## **1.** Absorption Processes to Remove Hazardous H<sub>2</sub>S from Gas Streams

This technology uses both chemical and physical solvents and is one of the most preferred to remove  $H_2S$  from these gas streams. The use of chemical solvents mitigates the presence of  $H_2S$  in the corresponding phase.

Among these chemicals, alkanolamine solutions know a wide usefulness because, together with toxic  $H_2S$ , the solvent removes  $CO_2$  <sup>[1]</sup>.

One step ahead the use of conventional solvents, ionic liquids are considered as their reliable alternatives. The well-known singularities or properties that these chemicals make are gaining positions on  $H_2S$  removal <sup>[2]</sup>. The use of mixtures (AAILs) of tertiary amines and ionic liquids (amino acid) to remove  $H_2S$  was investigated in <sup>[3]</sup>. Among these compounds, tetramethylammonium arginine and tetramethylammonium glycine, [N111][Arg] and [N1111] [Gly], respectively, presented  $H_2S$  removal rates of 100%. The rate of gas removal is increased when transferring protons between the ionic liquid and the tertiary amine. Larger-scale applications of the method seemed to be unpractical due to the costs and complex synthesis of the ionic liquids.

In term of costs, deep eutectic solvents (DESs) are an option to ionic liquids. Interaction between  $H_2S$  and DES (basic) does not imply chemical reaction. Functionalizing these deep eutectic solvents with some chemicals, including amines, and oxidizing reagents produced an increase in the absorptive and regenerative properties of the compounds <sup>[4]</sup>. The addition of polyethyleneimine to deep eutectic solvents was investigated <sup>[5]</sup>, the mixture having 90%  $H_2S$  removal efficiencies after four consecutive absorption–regeneration cycles.

Nanofluids also emerged as potential absorbents for  $H_2S$ . These absorbents are formed by dispersion of several inorganic compounds (SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>) in the form of nanoparticles or graphene oxide and carbon nanotubes into organic solvents (monoethanolamine, diethanolamine, etc.) <sup>[6]</sup>. Removal of  $H_2S$  via the use of Fe-

Monoethanolamine-BmimCl solution with inert nanoparticles (SiO<sub>2</sub>) presented good perspectives, though H<sub>2</sub>S removal efficiency decreased after continuous use (cycles)  $\boxed{Z}$ .

Some of the difficulties presented by conventional solvents appeared to be resolved with the use of these ionic liquids and deep eutectic solvents; however, some of the properties of these compounds, i.e., high viscosity, can be considered a drawback since it reduces mass transfer coefficients and thus causes an increase in energy demand <sup>[8]</sup>. The use of mixtures of these compounds can improve the removal of the toxic gas; however, the greatest negative impact of these mixtures is the lack of maintaining the removal properties after continuous use <sup>[9]</sup>. A new perspective has been raised in terms of improving the regeneration step to avoid this being lost in the absorption properties.

Various triethylenetetramine functionalized ionic liquids (TETAH-ILs) are mixed with ethylene glycol (EG) to investigate their performance on H<sub>2</sub>S absorption <sup>[10]</sup>. The results showed that the mixture 10% [TETAH][BF4]-EG presented the best absorption capacities (1.128 mol H<sub>2</sub>S/mol IL) at 30 °C and 100 mL/min. Removal of H<sub>2</sub>S is attributed to the formation of H<sub>2</sub>S-IL compounds via hydrogen bonds.

A bubble absorption column is used to investigate hydrodynamics of  $CO_2$  and  $H_2S$  removal from pure water and water containing nanofluids dispersed with neat and OH- and NH<sub>2</sub>-functionalized multiwalled carbon nanotubes <sup>[11]</sup>. Sodium dodecyl sulfate is used as surfactant and stabilizer. Maximum  $CO_2$  removal and  $H_2S$  removal are found to be 0.0038 mmol/m<sup>2</sup>·s and 0.056 mmol/m<sup>2</sup>·s using NH<sub>2</sub>-MWCNTs/nanofluid, respectively.

The improvement in the absorption properties of diethanolamine with respect to the removal of  $H_2S$  from sour industrial off gas was investigated in <sup>[12]</sup>. The influence of lean amine  $H_2S$  impurity (LAHI), lean amine temperature (LAT), and column pressure (CP) on  $H_2S$  removal was studied. The increase of LAHI and LAT is detrimental for  $H_2S$  removal from the gas stream and LAT, LAHI (83%) being the key factor on  $H_2S$  removal, whereas LAT (15%) and CP (2%) have a minor impact on this efficiency.

The next investigation used machine-learning operations to study the solubility of  $H_2S$  in fifteen ionic liquids <sup>[13]</sup>. No less than six machine-learning operations were used, and the respective results were compared. The conclusions showed that the least-squares support vector machine predicted  $H_2S$  solubility into the ionic liquids well with  $R^2$  (0.99798), RMSE (0.01079), MSE (0.00012), RRSE (6.35%), RAE (4.35%), MAE (0.0060), and AARD (4.03). It was found that  $H_2S$  solubility decreased with temperature and has a direct dependence with the pressure. Ionic liquids such as [OMIM][Tf2N] are the best choice for  $H_2S$  capture.

The next investigation <sup>[14]</sup> explored various aspects of the processing and technologies used in acid gas removal (AGR). The work summarized processing by chemical absorption and mechanisms involved in the removal process; it also showed the main amine-based solvents currently used in such tasks. Absorption by physical methods is also discussed, summarizing pros and cons of the most used absorbents. Industrial applications of AGR processes were considered.

The removal of  $H_2S$  from industrial gas streams using an iron/copper bimetallic catalytic oxidation desulfurization system was investigated in <sup>[15]</sup>. The absorbent is formed by adding N-methyl pyrrolidone (NMP) and CuCl<sub>2</sub> aqueous solution to an iron-based ionic liquid (Fe-IL). The acidity and viscosity of the system are greatly reduced by addition of NMP and water, improving gas–liquid mass transfer efficiency. The presence of the copper(II) salt increased the oxidative properties of the solution, allowing for the improvement of the Fe<sup>3+</sup> catalytic influence on the oxidation of H<sub>2</sub>S to the monomer form of sulfur.

### 2. Adsorption Processes to Remove Hazardous $\rm H_2S$ from Gas Streams

Various materials: metal oxides, zeolites, activated carbon, metal organic frameworks (MOFs), biochar, mesoporous silica, ash, and composite materials have been investigated in the removal of  $H_2S$  from gas streams. Selection of these materials is based in some of their properties, such as elevated uptake capacity, selectivity, and thermal and mechanical stability with respect to the removal of this toxic gas <sup>[16]</sup>.

A mixture of biosolid (sewage) and surfactant (pluronic surfactant F127, heated at 950 °C) was used for the adsorption of H<sub>2</sub>S in <sup>[17]</sup>. It was shown that the presence of the surfactant increased the mesopore volume and carbon content of the biosolid, whereas the treatment at 950 °C developed the micropores, leading to the dispersal of the catalytic sites (Ca and Fe oxides) responsible for the gas adsorption, and increased the nitrogen atoms of pyrrolitic nature. Besides adsorption, the catalytic sites provide an environment to promote the oxidation of H<sub>2</sub>S to elemental sulfur. As a consequence, the breakthrough capacity is greatly improved (250% better than that presented by the biosolid alone); moreover, this capacity (221.2 mg/g) is better than those derived from other adsorbents such as STIX<sup>®</sup> (North Tonawanda, NY, USA) (201 mg/g), S-208 (36 mg/g), or Centaur<sup>®</sup> (Mumbai, India) (176 mg/g).

Metal oxides presented have good properties for adsorbing  $H_2S$ ; however, there is a continuous effort to improve their characteristics in this important field. Adsorption of  $H_2S$  by molybdenum(IV) oxide nanoparticles is described in the literature <sup>[18]</sup>. The best results are achieved at 0.081 and 0.074 g  $H_2S/g$ , at a temperature of 85 °C, pressure of 16 bar, and superficial velocity of 0.018 m/s. The above capacities are obtained when the adsorbent presents non-spherical and spherical shapes and using an initial  $H_2S$  concentration of 43 ppm in the feed gas stream. MnO<sub>2</sub> is the most effective adsorbent compared with other composite nano-sized metal oxides such as NiO/TiO<sub>2</sub>, CoO/TiO<sub>2</sub>, graphite oxide/ZnO, and CuO/TiO<sub>2</sub>.

Zeolites are other group of adsorbent materials of a wide use in several fields; some of the properties of these materials, i.e., elevated porosity and surface areas and porosities, are responsible for the wide use of these materials, including the removal of  $H_2S$ . Y and ZSM-5 zeolites' properties (including surface and pore structure) have been modified by the use of magnetite nanoparticles <sup>[19]</sup>, being the performance, with respect to the  $H_2S$  removal, of both adsorbents at the temperatures in the 100–300 °C range at a pilot scale.

Activated carbons and biochars are other types of adsorbents with active adsorption sites. Jute thread waste (a cellulosic biomass) activated with KOH served to yield a N–S-rich nanoporous carbon <sup>[20]</sup>. The carbon has a pore volume of up to 1.50 cm<sup>3</sup>/g and a surface area of up to 2580 m<sup>2</sup>/g. Within this material, increasing the pressure increased the H<sub>2</sub>S adsorption capacity by 1 bar (19.1 mmol/g), 10 bar (32.6 mmol/g), and 35 bar (45.0 mmol/g). Again, the presence of pyrrolic-N atoms in the material helps with H<sub>2</sub>S uptake onto it, this being attributable to hydrogen bonds; at the same time, negatively charged sulfur atoms around the pyrrolic-N atoms are responsible for a physisorption process. This material presented an 84% of adsorption regeneration after five cycles.

Using a peanut shell as precursor, impregnated with copper and activated by KOH, an activated carbon was formed and used to investigate the removal of  $H_2S$  <sup>[20]</sup>. The best sample of the activated carbon has 1523.2 m<sup>2</sup>/g of surface area, with 97.6 mg/g of gas uptake. The non-linear Langmuir isotherm model best fits the experimental results:

$$[H_2S]_{e,a} = \frac{[H_2S]_{m,a}K_L[H_2S]_e}{1 + K_L[H_2S]_e}$$
(1)

where  $[H_2S]_{e,a}$  is the gas uptake at an elapsed time,  $[H_2S]_{m,a}$  is the maximum monolayer uptake capacity,  $K_L$  is Langmuir constant, which is related to the affinity, and  $[H_2S]_e$  is the gas uptake at the equilibrium. The kinetic displayed pseudo-first-order trend:

$$[H_2S]_t = [H_2S]_e(1 - \exp(k_1 t))$$
 (2)

In the above equation,  $[H_2S]_t$  is the uptake at an elapsed time,  $[H_2S]_e$  is the gas uptake at the equilibrium, and  $k_1$  is the rate constant of the pseudo-first-order model. Both film diffusion and intraparticle models are responsible for  $H_2S$  uptake onto the adsorbent. After five cycles, the adsorbent maintains a gas removal rate of 90%.

Biochar, biomass ashes, and sewage sludge (incinerated) are used to compare their performance on  $H_2S$  from a biogas <sup>[21]</sup>. Sewage sludge is discarded due to its surface characteristics and low porosity. Biochar exhibited the highest adsorption capacity of 171.8 mg/g, its low density translated into low volumetric adsorption capacity, limiting its scale-up. Biomass ashes have the highest volumetric adsorption uptakes, 22.2–38.3 mg/cm<sup>3</sup> (35.6–78.2 mg/g), attributable to their porosity properties and the presence of mineral oxides responsible for the catalytic  $H_2S$  oxidation. Biochar has the highest adsorption uptake (171.8 mg/g), but its use at a greater scale is limited by its low density.

It is known that activated carbons incorporating metal or metal oxides have enhanced their H<sub>2</sub>S removal efficiencies <sup>[22]</sup>. Several investigations <sup>[23][24]</sup> have surveyed the life-cycle cost and the environmental footprints/impact of these hybrid materials. Biochars derived from banana peel, rice hull, and sawdust by pyrolysis

are used as adsorbents of  $H_2S$  from municipal solid waste <sup>[25]</sup>. The order for removal efficiency of  $H_2S$  (>94%) was banana peel > saw dust > rice hull.

The use of a goethite-based material to adsorb  $H_2S$  from a mimic biogas mixture ( $H_2S$  and  $N_2$ ) was described in [26]. In the process, crystalline FeS was formed.

With respect to pristine s-C3N6 (-0.33 eV to -0.45 eV), Fe-, Pt-, and Ti-modified s-C3N6 structures (-1.06 eV to -2.66 eV) presented larger adsorption energies for the removal of H<sub>2</sub>S on their surfaces <sup>[27]</sup>. s-C3N6-Fe has semiconducting properties after adsorbing this harmful gas. Pristine s-C3N6 and its modified derivatives represented a series of smart adsorbents and sensing media for toxic gases.

The defective GaSe monolayer material having selenium vacancies and being doped with oxygen and nitrogen is another material to be considered in the removal of toxic gases from gaseous streams <sup>[28]</sup>. After gas adsorption, the distance between the defective GaSe monolayer and four toxic molecules is reduced.

An activated carbon-fiber mat containing both metal chlorides and metal oxides is used to investigate  $H_2S$  (and ammonia) removal <sup>[29]</sup>. The adsorbent, containing NiCl<sub>2</sub> and MgO, has a hierarchical porous structure, large surface area, and a good dispersion of bimetallic active sites. Metal oxides promote the chemical adsorption of  $H_2S$ . The use of these ternary hybrid materials increases gas uptake with breakthrough capacities up to 209.2 mg/g.

Adsorbent materials from banana empty fruit bunch biochar (BEFBB) and banana peel biochar (BPB) wastes are used to remove  $H_2S$  from biogas <sup>[30]</sup>. Both types of adsorbents have good characteristics to remove  $H_2S$  (low performance in the case of CO<sub>2</sub> and methane), with breakthrough capacities of 7.65 mg/g and 5.85 mg/g, respectively. Pellet-sized adsorbent (0.5 cm) has a better gas removal efficiency than larger pellets (1.5 cm), this being attributable to its larger surface area. Both hydroxide and carboxylic groups present in the BEFBB material are responsible for the removal of  $H_2S$  from the gas stream.

#### 3. Membranes and Membrane Contactors to Remove Hazardous H<sub>2</sub>S from Gas Streams

The membranes as a separation technology are widely used in a variety of industries, and this wide usefulness is attributable to the properties or characteristics of the technology: modular aspects, easiness of operation, low environmental impact, etc., that in many aspects surpassed the offer presented by other separation technologies, this being specially noted when the operation, i.e.,  $H_2S$  removal, is accomplished in areas or locations where communications are not easy <sup>[31]</sup>.

There are some recent publications reviewing the use of these membrane technologies on the treatment of gases [32][33][34][35], but surprisingly, they are dedicated to industrial gases instead of H<sub>2</sub>S; some of the gases mentioned in these reviews are: nitrogen, hydrogen, oxygen, CO<sub>2</sub>, etc. In the case of H<sub>2</sub>S, polymeric membranes are the

candidates to resolve this important industrial issue. The permeation of gas across these types of membranes is ruled by diffusion, and a series of investigations [36][37] have mentioned that plasticization of the membrane performs well in the removal of H<sub>2</sub>S when the gas in the stream is present at high concentrations; moreover, this plasticization improves the selective separation of H<sub>2</sub>S over methane. This selective separation is attributed to the transport mechanism, which in the case of H<sub>2</sub>S is of sorptive in nature, and this separation is negatively influenced by diffusion.

The transport ruled by solubility is particularly important in the case of rubbery polymers, and this is a key rule in the separation of  $H_2S$  from methane. It is reported <sup>[38]</sup> that the variation of the cross-linking density tuned the usefulness of polyethylene glycol-based membranes. This change in the membrane properties significantly improves the selectivity in the pairs  $H_2S$ /methane and  $CO_2$ /methane.

Computational methods have developed a series of tools to improve the knowledge and optimize the use of these membrane technologies in the capture of gases <sup>[39]</sup>. Another implication of membrane technologies on the removal of gases is their use to act as an interface between the different streams, liquid and gases, feeding the removal process. These membranes, preferably with high porosity, increased the gas flow through the membrane structure. In practice, hollow fiber modules are the most used devices; under operation, the gas flowing in the shell side diffuses across the membrane's pores to the tube side; here, the gas is conveniently absorbed by a solution, whereas these modules can be operated in co-current and counter-current form, and the latter is usually preferred since it gives a better contact between both operating phases. This counter-current configuration is shown in **Figure 1**.



Figure 1. Hollow fiber membrane module for gas removal in counter-current operational mode.

In these membrane modules, the gas flux is controlled by its concentration gradient <sup>[40]</sup>. Mass transfer in the module is conveniently represented in **Figure 2**. Some parameters to be controlled in these hollow fiber operations are pore size and its distribution <sup>[41]</sup>, and these assured the best transfer across the module fibers. Some improvements in the technology are described in the literature <sup>[42]</sup>.



Figure 2. Mass transfer in the hollow fiber module. Multiple curve black lines represented membrane micropores.

#### References

- Lee, W.Y.; Park, S.Y.; Lee, K.B.; Nam, S.C. Simultaneous removal of CO2 and H2S from biogas by blending amine adsorbents: A performance comparison study. Energy Fuel. 2020, 34, 1992– 2000.
- Chan, Y.H.; Loh, S.K.; Chin, B.L.F.; Yiin, C.L.; How, B.S.; Cheah, K.W.; Wong, M.K.; Loy, A.C.M.; Gwee, Y.L.; Lo, S.L.Y.; et al. Fractionation and extraction of bio-oil for production of greener fuel and value-added chemicals: Recent advances and future prospects. Chem. Eng. J. 2020, 397, 125406.
- 3. Tian, X.F.; Wang, L.M.; Zhang, P.; Fu, D.; Wang, Z.Y. A high efficient absorbent for the separation of H2S from low partial pressure coke oven gas. Environ. Sci. Pollut. Control Ser. 2021, 28, 5822–5832.
- Wibowo, H.; Susanto, H.; Grisdanurak, N.; Hantoko, D.; Yoshikawa, K.; Qun, H.; Yan, M. Recent development of deep eutectic solvent as absorbent for CO2 removal from syngas produced from gasification: Current status, challenges, and further research. J. Environ. Chem. Eng. 2021, 9, 105439.
- 5. Wang, B.; Cheng, J.; Wang, D.; Li, X.; Meng, Q.; Zhang, Z.; An, J.; Liu, X.; Li, M. Study on the desulfurization and regeneration performance of functional deep eutectic solvents. ACS Omega 2020, 5, 15353–15361.
- Liu, X.; Wang, B.; Dong, X.; Qiu, Y.; Meng, Q. Enhancement effect of nanofluids on the desulfurization and regeneration performance of ionic liquid-based system. J. Hazard Mater. 2021, 419, 126394.

- Liu, X.; Wang, B.; Lv, X.; Meng, Q.; Li, M. Enhanced removal of hydrogen sulfide using novel nanofluid system composed of deep eutectic solvent and Cu nanoparticles. J. Hazard Mater. 2021, 405, 124271.
- Alkhatib, I.I.I.; Ferreira, M.L.; Alba, C.G.; Bahamon, D.; Llovell, F.; Pereiro, A.B.; Araújo, J.M.M.; Abu-Zahra, M.R.M.; Vega, L.F. Screening of ionic liquids and deep eutectic solvents for physical CO2 absorption by Soft-SAFT using key performance indicators. J. Chem. Eng. Data 2020, 65, 5844–5861.
- Liu, X.; Wang, B.; Qiu, Y.; Dong, X.; Song, Y.; Meng, Q.; Li, M. Study on the desulfurization performance of iron/ethanolamine/deep eutectic solvent system. Environ. Sci. Pollut. Control Ser. 2021, 28, 38026–38033.
- 10. Zhang, M.; Dong, B.; Wu, Y.; Hu, H.; Huang, H. Mechanism study on H2S capture of ionic liquids based on triethylenetetramine blended with ethylene glycol. J. Molec. Liq. 2022, 368, 120704.
- 11. Jafari, F.D.; Ameri, E. Effect of sodium dodecyl sulfate on CO2 and H2S absorption enhancement of functionalized multiwall carbon nanotubes in water: Experimental study and empirical model. Arabian J. Chem. 2022, 15, 104314.
- Askari, M.; Salehi, E.; Baluchi, A. Intensification of hydrogen sulfide absorption by diethanolamine in industrial scale via combined simulation and data-based optimization strategies. Chem. Eng. Res. Design 2022, 188, 545–554.
- Abdi, J.; Hadipoor, M.; Esmaeili-Faraj, S.H.; Vaferi, B. A modeling approach for estimating hydrogen sulfide solubility in fifteen different imidazole-based ionic liquids. Sci. Rep. 2022, 12, 4415.
- Abotaleb, A.; Gladich, I.; Alkhateeb, A.; Mardini, N.; Bicer, Y.; Sinopoli, A. Chemical and physical systems for sour gas removal: An overview from reaction mechanisms to industrial implications. J. Nat. Gas Sci. Eng. 2022, 10, 104755.
- 15. Qiu, K.; Liu, Z.; Dong, Y.; Liu, L.; Li, W.; Niu, S.; Jin, Z. FeCl4 efficient catalytic oxidative removal of H2S by Cu2+ synergistic reinforcement. Chem. Eng. Technol. 2022, 45, 1867–1875.
- 16. Georgiadis, A.G.; Charisiou, N.D.; Goula, M.A. Removal of hydrogen sulfide from various industrial gases: A review of the most promising adsorbing materials. Catalysts 2020, 10, 521.
- 17. Florent, M.; Bandosz, T.J. Surfactant-modified biosolid-derived materials as efficient H2S removal media: Synergistic effects of carbon phase properties and inorganic phase chemistry on reactive adsorption. Chem. Eng. J. 2020, 401, 125986.
- Hassankiadeh, M.N.; Hallajisani, A. Application of molybdenum oxide nanoparticles in H2S removal from natural gas under different operational and geometrical conditions. J. Petrol. Sci. Eng. 2020, 190, 107131.

- Jafari, M.J.; Zendehdel, R.; Rafieepour, A.; Pour, M.N.; Irvani, H.; Khodakarim, S. Comparison of Y and ZSM-5 zeolite modified with magnetite nanoparticles in removal of hydrogen sulfide from air. Int. J. Environ. Sci. Technol. 2020, 17, 187–194.
- Wang, S.; Nam, H.; Nam, H. Preparation of activated carbon from peanut shell with KOH activation and its application for H2S adsorption in confined space. J. Environ. Chem. Eng. 2020, 8, 103683.
- 21. Gasquet, V.; Kim, B.; Sigot, L.; Benbelkacem, H. H2S adsorption from biogas with thermal treatment residues. Waste Biomass Valorization. 2020, 11, 5363–5373.
- Zhao, C.; Wang, B.; Theng, B.K.G.; Wu, P.; Liu, F.; Wang, S.; Lee, X.; Chen, M.; Li, L.; Zhang, X. Formation and mechanisms of nano-metal oxide-biochar composites for pollutants removal: A review. Sci. Total Environ. 2021, 767, 145305.
- Kozyatnyk, I.; Yacout, D.M.M.; Caneghem, J.V.; Jansson, S. Comparative environmental assessment of end-of-life carbonaceous water treatment adsorbents. Bioresour. Technol. 2020, 302, 122866.
- 24. Nowrouzi, M.; Abyar, H.; Younesi, H.; Khaki, E. Life cycle environmental and economic assessment of highly efficient carbon-based CO2 adsorbents: A comparative study. J. CO2 Util. 2021, 47, 101491.
- Izhar, T.N.T.; Kee, G.Z.; Saad, F.N.M.; Rahim, S.Z.A.; Zakarya, I.A.; Besom, M.R.C.; Ib, M.; Syafiuddin, A. Adsorption of hydrogen sulfide (H2S) from municipal solid waste by using biochars. Bioint. Res. Appl. Chem. 2022, 12, 8057–8069.
- 26. Alguacil, F.J.; Alonso, M.A.; Lopez, F.A.; Robla, J.I. Dynamic adsorption of H2S onto a goethitebased material. Molecules 2022, 27, 7983.
- 27. Cai, X.; Yang, Q.; Tong, Y.; Wang, M.; Zhang, S. Metal-modified s-C3N6 as a potential superior sensing medium for effective capture of toxic waste gases CO, H2S and SO2 in the iron and steel industry based on first-principles investigations. Appl. Surf. Sc. 2022, 606, 154947.
- 28. Cheng, W.-Y.; Chang, C.-R.; Fuh, H.-R. First principles study of NH3, H2S, Cl2, and C2H2 gases adsorption on defective GaSe monolayer. Appl. Surf. Sci. 2022, 606, 154722.
- 29. Xu, Y.; Chen, Y.; Ma, C.; Qiao, W.; Wang, J.; Ling, L. Functionalization of activated carbon fiber mat with bimetallic active sites for NH3 and H2S adsorption at room temperature. Sep. Purif. Technol. 2022, 303, 122335.
- 30. Juntarachat, N.; Onthong, U. Removal of hydrogen sulfide from biogas using banana peel and banana empty fruit bunch biochars as alternative adsorbents. Biomass Convers. Biorefin. 2022.
- 31. He, X.; Kumakiri, I.; Hillestad, M. Conceptual process design and simulation of membrane systems for integrated natural gas dehydration and sweetening. Sep. Purif. Technol. 2020, 247,

116993.

- 32. Shi, Y.; Liang, B.; Lin, R.-B.; Zhang, C.; Chen, B. Gas separation via hybrid metalorganic framework/polymer membranes. Trends Chem. 2020, 2, 254–269.
- 33. Han, Y.; Ho, W.S.W. Polymeric membranes for CO2 separation and capture. J. Membr. Sci. 2021, 628, 119244.
- Valappil, R.S.K.; Ghasem, N.; Al-Marzouqi, M. Current and future trends in polymer membranebased gas separation technology: A comprehensive review. J. Ind. Eng. Chem. 2021, 98, 103– 129.
- 35. Yong, W.F.; Zhang, H. Recent advances in polymer blend membranes for gas separation and pervaporation. Prog. Mater. Sci. 2021, 116, 100713.
- Liu, Y.; Liu, Z.; Morisato, A.; Bhuwania, N.; Chinn, D.; Koros, W.J. Natural gas sweetening using a cellulose triacetate hollow fiber membrane illustrating controlled plasticization benefits. J. Membr. Sci. 2020, 601, 117910.
- 37. Liu, Y.; Liu, Z.; Liu, G.; Qiu, W.; Bhuwania, N.; Chinn, D.; Koros, W.J. Surprising plasticization benefits in natural gas upgrading using polyimide membranes. J. Membr. Sci. 2020, 593, 117430.
- Harrigan, D.J.; Lawrence, J.A.; Reid, H.W.; Rivers, J.B.; O'Brien, J.T.; Sharber, S.A.; Sundell, B.J. Tunable sour gas separations: Simultaneous H2S and CO2 removal from natural gas via crosslinked telechelic poly(ethylene glycol) membranes. J. Membr. Sci. 2020, 602, 117947.
- 39. Shamsabadi, A.A.; Rezakazemi, M.; Seidi, F.; Riazi, H.; Aminabhavi, T.; Soroush, M. Next generation polymers of intrinsic microporosity with tunable moieties for ultrahigh permeation and precise molecular CO2 separation. Prog. Energy Combust. Sci. 2021, 84, 100903.
- 40. Chuah, C.Y.; Kim, K.; Lee, J.; Koh, D.-Y.; Bae, T.-H. CO2 absorption using membrane contactors: Recent progress and future perspective. Ind. Eng. Chem. Res. 2020, 59, 6773–6794.
- 41. Pang, H.; Chen, Z.; Gong, H.; Du, M. Fabrication of a super hydrophobic polyvinylidene fluoridehexadecyltrimethoxysilane hybrid membrane for carbon dioxide absorption in a membrane contactor. J. Membr. Sci. 2020, 595, 117536.
- 42. Zhang, H.; Xue, K.; Cheng, C.; Gao, D.; Chen, H. Study on the performance of CO2 capture from flue gas with ceramic membrane contactor. Sep. Purif. Technol. 2021, 265, 118521.

Retrieved from https://encyclopedia.pub/entry/history/show/95003