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Carbon Dioxide Adsorption by Variation in Operating Parameters of Sound Assisted Fluidization Using Coal Based Fine Activated Carbon

A. P. Ganorkar† and A. M. Langde
Department of Mechanical Engineering, Anjuman College of Engineering and Technology, Nagpur-440001, Maharashtra, India
†Corresponding author: A.P. Ganorkar; apganorkar@rediffmail.com

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ABSTRACT

This research delves into the promising domain of CO_2 capture through fine solid activated carbon adsorbent, offering a more energy-efficient alternative to traditional adsorption methods. The central challenge addressed here is the utility of cheaper CO_2 adsorbent, fine powder materials whose properties can be precisely tailored via molecular-level fictionalization. Equally vital is selecting an optimal fluidizing column configuration that maximizes CO_2 interaction with adsorption particles and enhances adsorption efficiency. The proposed solution is a fluidized bed column uniquely equipped with integrated acoustic vibrations to counteract interparticle forces common in fine powders. For adsorption evaluations, sound-assisted fluidized-bed experimentation on a laboratory size was set up. Adsorbent material activated carbon made up of coal underwent rigorous testing between a range of 20 Hz-200 Hz and 20 dB-135 dB. Results reveal the beneficial effects of acoustic enhancement of fluidization quality and adsorption efficiency, increased adsorption capacity, enhanced bed utilization, and accelerated adsorption rates. Extensive research has been conducted on the detailed effects of major operational variables on adsorption performance, notably frequency, sound intensity, and minimum fluidization velocity. The findings highlight the pivotal role of particle size with mean size 75 microns range as a determinant of adsorption capacity at 100 Hz and 125 dB. At the end of experimentation, the adsorbent considered for the experiment is compared to the study adsorption capacity at operating conditions. The research concludes with a discussion on the effects of influencing parameters for adsorption on employing sound vibrations using fluidization technique adsorption for CO_2 capture.

INTRODUCTION

During the 20th century, there was a surge in energy consumption and global population growth, accompanied by rapid technological progress and material expansion. This transformation resulted in a significant dependence on hydrocarbon fuels and carbon-based electricity production. EPA (Environment Protection Agency) report states that the main source of CO_2 is the use of fossil fuels. Indirect human-caused effects on forestry and other land uses, such as deforestation, clearing land for agriculture, and soil degradation, can also release carbon dioxide into the atmosphere. Similarly, land can absorb carbon dioxide from the atmosphere by improving soil, planting new trees, and engaging in other activities. Fossil fuels presently meet more than 80% of the world's energy demands. Still, their combustion generates CO_2 emissions, which are responsible for about 75% of human-caused CO_2 emissions and have a substantial impact on climate change (Ganorkar & Langde 2023).

The International Energy Agency (IEA) estimates global CO_2 emissions from various sources, with power generation responsible for 45% of these emissions (IEA 2022). To address this, carbon capture and storage (CCS) technologies aim to capture CO_2 from industrial sources, transport it to storage, and isolate it from the atmosphere for thousands of years. Applications for carbon capture and storage (CCS) have been developed to lower these emissions. Therefore, up to 80% of the global warming potentials released by conventional electricity generation can be avoided by sequestering 96% of the CO_2 produced by burning fuels in power plants (Kon & Caner 2024). Successful wide-scale deployment of CCS requires substantial research and development to ensure economic and environmental viability. In light of the information provided, it is evident that post-combustion capture stands out as the most suitable carbon capture and storage (CCS) technology for application in existing power plants. The substantial expense associated with the capture phase, constituting approximately two-thirds

of CCS costs, poses a significant barrier to widespread implementation (Feron & Hendriks 2005). Therefore, the creation of an effective and financially sustainable CO_2 adsorption technique is the primary goal. Fighting the anthropogenic emissions of greenhouse gases (GHGs) that cause climate change has become an urgent priority in recent decades (Masson-Delmotte 2021). Chemical absorption using amines, membranes, cryogenic distillation, and selective adsorption on solids is the most developed and most suited technology for removing CO_2 from flue gas currently in use (Mathieu 2003). Fluidization is usually difficult with fine powders, which are categorized under Geldart group C because of their small size of particles (<30 μm) and high material density. Fluidization is challenging due to cohesive forces between particles, such as electrostatic, moisture-induced tension on the surface forces, and van der Waals, leading to issues such as plug formation, channeling, and agglomeration (Hakim et al. 2005). Recent tests, however, cast doubt on the predictability of fluidization behavior based on initial particle size and density by indicating that nanoparticles can be fluidized efficiently over a broad range of gas velocities. Because it requires less energy, solid adsorbent-based adsorption is a desirable choice for CO_2 capture (Sumida et al. 2012). Regeneration energy and equipment costs are major contributors to capture expenses. Enhancing separation efficiency in capture materials offers significant cost-saving potential. It is crucial to create CO_2-specific adsorbents with molecularly tunable physical and chemical characteristics.

A comprehensive 3-D transient heat and mass transfer analysis has been performed to study the adsorption characteristics of carbon dioxide onto highly microporous activated carbon (MaxsorbIII) (Sahoo 2019). A fixed-bed column adsorption system was used to study the adsorption of CO_2. This study showed that thermally treated alum sludge at 800°C has a lot of potential as a CO_2 adsorbent (Yusuff et al. 2019). Micron-size materials, especially ultra-fine particles, are versatile for customization, allowing improvements in adsorption efficiency. Investigation was carried out of two adsorbates, methanol and acetone, and their adsorption on AC35 activated carbon (Foued & Jemni 2014). When used as an adsorbent for the removal of CO_2 and NO_2, activated carbon was found to be highly effective at removing CO_2(Madiraju et al .2020). Effective modification can involve increasing the surface's CO_2 affinity and high adsorption capacity. A variety of raw materials, including coconut shell, wood, peat, and coal, can be used to create activated carbon (AC), which is widely used as an industrial adsorbent and support. Carbon can be chemically modified on the surface to create materials with specific uses (Thakare & Jayaram 2018). Material development must align with practical CO_2 separation processes to ensure successful implementation. To achieve efficient fluidization, it is crucial to minimize aggregate size by breaking them apart and overcoming cohesive forces. Externally assisted fluidization, involving forces like acoustics, electricity, magnetism, or mechanical vibrations, can enhance powder dynamics in a fluidized bed. Among these techniques, sound-assisted fluidization is considered a promising option for smoothly fluidizing fine and ultra-fine powders (Raganati et al. 2015). It offers several advantages, including non-intrusiveness, no specific powder requirements, reduction in fine particle elutriation, and cost-effectiveness using readily available equipment like signal generators, audio amplifiers, and loudspeakers.

MATERIALS AND METHODS

Experimental Setup

In the pursuit of understanding the intricacies of fluidization behavior and CO_2 adsorption capacity, an experimental apparatus on a laboratory scale was employed, illustrated schematically in Fig. 1. The setup features a fluidized bed, a substantial component of which is a transparent PVC column, measuring 50 mm in inner diameter and extending to a height of 800 mm. Situated at the base of this column is a gas distributor with a porous jeans cloth. This apparatus served as the experimental platform, allowing for a detailed exploration of the fluidization phenomena and the adsorption capabilities of CO_2 within the bed. The patent office registers this experimental setup design in the name of the authors of this paper (Design No. 366537-001). Through systematic experimentation within this column, crucial insights were gained into the fluid dynamics and adsorption potential of the system, shedding light on its performance and characteristics.

Apparatus

The experimental setup involved a function generator, amplifier, speaker, sound level meter (RionMake, Japan), and gas analyzer (AVL make). CO_2 mass flow controller (Line Take make, Korea). Bed pressure was expertly measured by a U U-tube manometer, whose tapping is situated just 5mm below the gas distributor. To precisely assess the composition of the outlet and inlet gas stream, a gas analyzer was employed. The sonic prowess for enhancing fluidization was achieved via a sound-generation system, a sophisticated arrangement comprising a digital function generator, a sound amplifier for signal amplification, and a capable loudspeaker. The audio system involves a digital function generator producing a specified frequency electric sine wave, amplified by a 40 W audio amplifier and delivered through an 8 W woofer loudspeaker kept above the column in a closed chamber, particularly for high-intensity acoustic fields.

Physical Characteristics of Coal-Based Activated Carbon

Coal-based Activated carbon purchased from supplier space black adsorbents (Gujarat, India) is used as adsorption material. Morphological characterization of the powder was conducted through SEM analysis, as shown in Fig. 2, in the metallurgy lab of Visvesvaraya National Institute of Technology, Nagpuremploying a Philips XL30 SEM instrument. The resulting powder properties have been meticulously documented and are presented in Table 1, offering a comprehensive overview of their pertinent characteristics.

Table 1: Physical characteristics of coal-based activated carbon.

Appearance	Black, Granular
Bulk density	442 $kg.m^{-3}$
Wt. of material loaded in column	87 g
Particle size, MESH(ASTM)	4%+200 Mesh

Conducting Fluidization Experiment

Using CO_2 and N_2 gas of 99.99% purity, all fluidization tests were conducted under ambient conditions of temperature and pressure. In the trials, the activated carbon materials underwent a meticulous preparation process involving a preheating step, ensuring the complete removal of any residual moisture. Before its utilization for adsorption tests, the activated carbon underwent an extensive fluidization process to evaluate its fluidization behavior under both conventional and sound-assisted conditions. Design Expert Software was used for selecting sound parameters for experimentation, and these conditions encompassed a range of sound intensities (125, 130, 135, and 140 dB) and frequencies (20, 50, 80, 120, and 300 Hz). These sound parameters were in agreement with previously done research

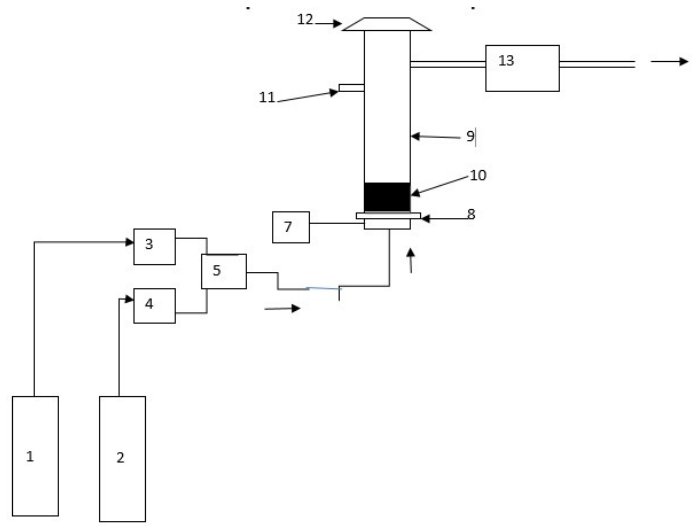

Fig. 1: Experimental setup: (1) CO_2 gas cylinder, (2) N_2 gas cylinder, (3) CO_2 gas mass flow controller, (4) N_2 gas rotameter, (5) Gas mixing chamber, (7) Pressure measuring device(U tube manometer), (8) Distributor plate (Jeans cloth), (9) Fluidization column (10) Adsorbent material(Activated carbon powder), (11) Sound level meter,(12) Loudspeaker, (13) Gas analyzer. (14) Microphone

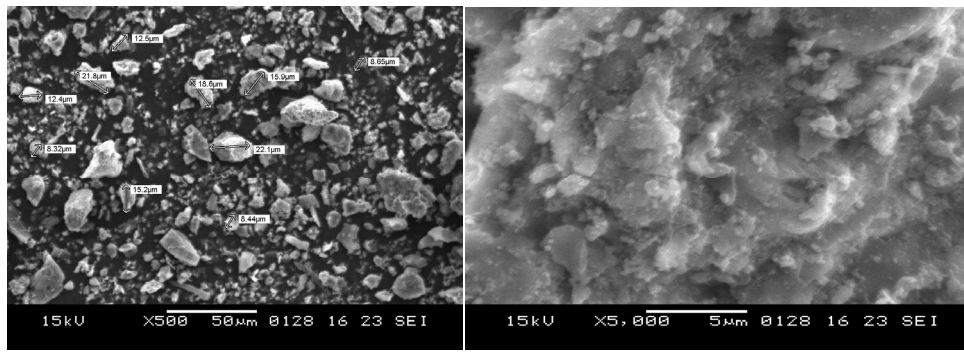

Fig. 2: SEM analysis of coal-based activated carbon.

work (Raganati et al. 2015). It is essential to note that all experiments were meticulously conducted at standard surrounding temperature and pressure, with nitrogen (N_2) serving as the fluidizing gas. This choice was made to mitigate the potential increase in powder cohesiveness that can occur due to air moisture. In each experimental run, a precisely measured 87 g (10 cm bed height) of activated carbon was loaded into the fluidization column, ensuring a consistent bed height of approximately 10 cm. Comprehensive data on bed expansion and pressure drop were gathered for each test, including measurements of the superficial gas velocity made both when the N_2 flow rate was increasing (UP) and decreasing (DOWN). A graphical process was then used to infer the minimal fluidization velocity (μ_{mf}), as depicted in Fig. 3, from the resulting pressure drop curves (Raganati et al. 2015, Diamantis et al. 2012). Detailed information about the chosen operating conditions and corresponding results for the determining minimum fluidization velocity experiments is discussed in the result section.

Adsorption Test Procedure

The adsorption tests were executed in standard environmental conditions, and before each test, the activated carbon underwent meticulous heating to eliminate any residual moisture (Raganati & Ammendola 2021). In a typical experiment, precisely 87 g of the activated carbon was loaded into the column, resulting in a consistent bed height of 10 cm. Following this, a pre-conditioning phase lasting approximately 3 min involved the introduction of nitrogen (N_2) at a flow rate (around 2.11 pm) that comes from the bottom of the column and corresponds to the minimal fluidization velocity at set values of 100 Hz and 125 dB, ensuring the establishment of stable fluidization conditions. These are the ideal sound parameter values to increase the efficiency of the gas-solid contact and fluidization quality, as concluded from experimentation, which in turn improves the fine-solid materials' capacity to adsorb CO_2 without sound characteristics. Subsequently, the core adsorption phase was initiated, introducing controlled flow using a mass flow controller (line tech make, Korea) of a gas mixture of fixed CO_2 concentration (15% of CO_2 in N_2) into the column. The continuous monitoring of CO_2 concentration in the outlet gas stream, creating a CO_2 outlet concentration profile, was sustained till the gas composition closely matched the initial inlet gas composition (about 90%), indicating that the bed had reached saturation.

Time (t) was noted to establish CO_2 concentration profiles, starting from the point at which the gas mixture started to flow through the fluidized column to the gas analyzer. The transit time was accurately recorded from AVL software for a set gas flow rate, a process typically taking around 23 min to reach saturation of activated carbon. This procedure was repeated for 2 test runs using a fresh sample of activated carbon each time for both using sound and without sound parameters. Each adsorption test was performed under both conventional and sound-assisted fluidization conditions, allowing for a comprehensive exploration of the impacts of sound parameters (SPL and frequency), and fluidization velocity, adsorption efficiency.

RESULTS AND DISCUSSION

Physical Characteristics

SEM analysis reveals that the powder presents itself in the form of aggregates rather than individual micron-sized particles. On average, the particles have a mean size of approximately 75 microns, following the analysis report provided by the supplier of activated carbon.

Fluidization Test

The data related to bed expansion were subjected to analysis, facilitating the fluidizing velocity estimation, a process explained in greater detail elsewhere (Raganati et al. 2014, Rashidi & Yusup 2016, Garcia et al. 2011).

In Fig. 4, the provided data illustrates unitless pressure drop and bed expansion curves in standard operating conditions (without sound). To obtain dimensionless pressure drop values, the actual pressure drop (P) was divided by the pressure drop corresponding to the weight of particles per unit area (P_0). Likewise, unitless bed expansion values were calculated by dividing the actual bed height (H) by the static bed value (H_0), which was set at 10 cm.

It is important to note that under these typical conditions, where no acoustic field is applied, the fluidization quality is notably inadequate and often characterized by channeling (Xu et al. 2022). This is shown by the fact that the approaching pressure ratio value is less than 1. Thus, the introduction of sound is indispensable to establish an appropriate fluidization quality. This transition is closely associated with effectively breaking up the large aggregates formed due to cohesive forces, resulting in smaller, more manageable structures that enhance the fluidization process. A comprehensive examination was conducted, specifically aimed at assessing the most efficient acoustic conditions. This study sought to determine whether it was feasible to identify optimal values for Sound Pressure Level (SPL) and frequency. Results shown in Table 2 indicate that there is no significant effect on fluidization quality over 100 Hz and 125dB operating parameters of sound.

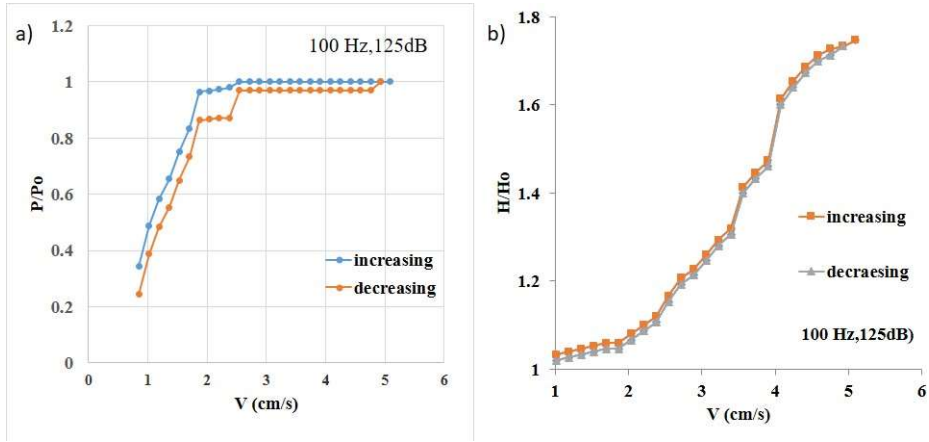

Fig. 3: a) Pressure drop curve Vs velocity of feed gas. b) Bed expansion curve Vs velocity of feed gas at operating sound parameters (100 Hz and 125 dB).

Table 2: Experimental results of minimum fluidization velocities (cm/s) based on the above parameters.

Frequency	Sound level							
	20dB	50 dB	80 dB	100 dB	120 dB	125 dB	130 Db	135 dB
50Hz	3.9054	3.9054	3.7356	3.7356	3.396	3.396	3.2262	3.2262
80 Hz	3.7356	3.7356	3.5658	3.396	3.0564	3.0564	2.8866	2.7168
100 Hz	3.5658	3.396	3.0564	2.7168	2.547	2.2074	2.2074	2.2074
120 Hz	3.396	3.396	3..0564	2.7168	2.547	2.2074	2.2074	2.2074
125 Hz	3.396	3.396	3..0564	2.7168	2.547	2.2074	2.2074	2.2074
150 Hz	2.3772	2.3772	2.3772	2.3772	2.3772	2.2074	2.2074	2.2074
200 Hz	2.3772	2.3772	2.3772	2.3772	2.3772	2.2074	2.2074	2.2074

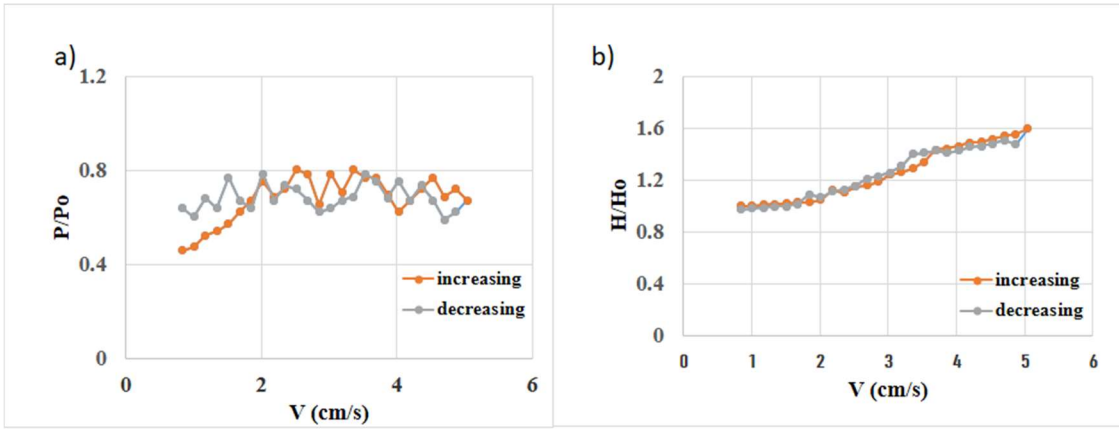

Fig. 4: (a) Pressure drop curves and (b)bed expansion curves acquired during standard tests (without sound).

Adsorption Capabilities

Every test was run at least twice, and each time, the difference was less than 5% or mostly within the experimental error margin. The typical CO_2 outlet concentration curves were found for adsorbent material. After computing these curves, a few more operating parameters were assessed to compare the material's adsorption performance like a. transient time(t_t), i.e., the time in seconds to reach 90% of inlet CO_2 concentration for set sound parameters (100 Hz,125 dB) as shown in Fig. 5

Adsorption time comparison between adsorption capabilities at frequencies lower and higher than 100 Hz at set sound levels of 125 dB and 20 dB (Fig. 6).

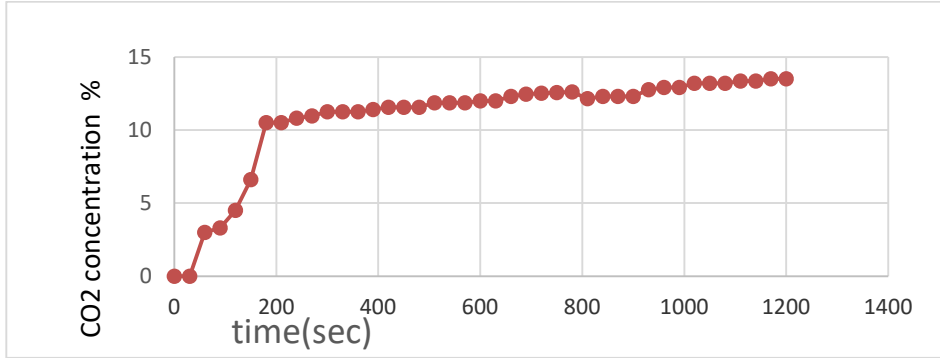

Fig. 5: CO_2 Concentration at outlet curve against time (t_t) at set sound parameters (100 Hz, 125dB).

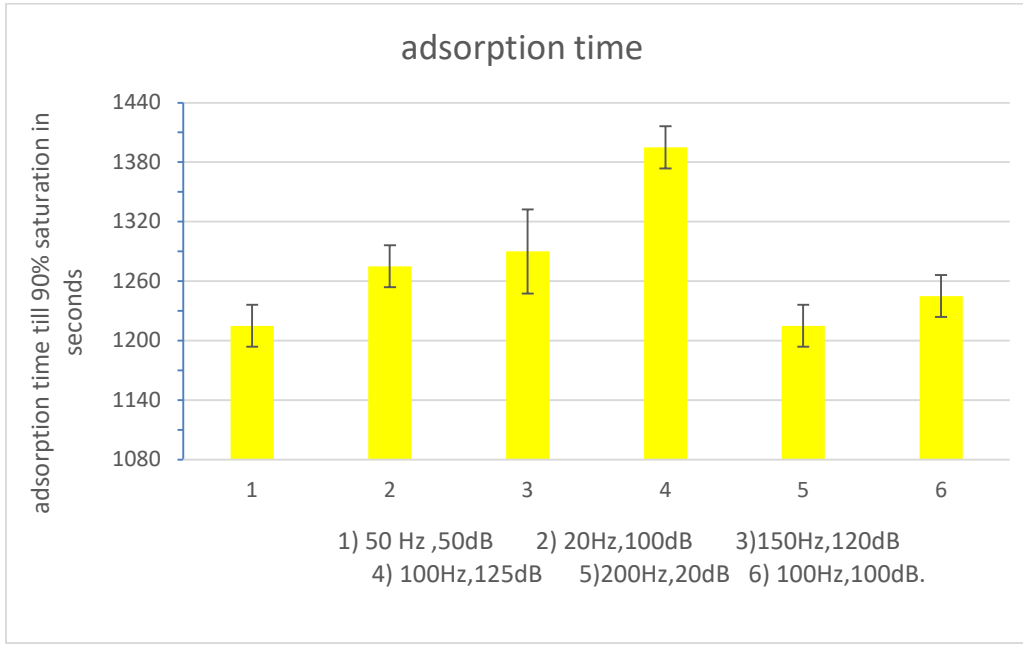

Fig. 6: Comparative analysis of CO_2 adsorption time(t) at setsound parameters.

CONCLUSION

This study compared the CO_2 capture capabilities at optimum minimum fluidization velocity of micron-size coal-based activated carbon material. Specifically, audio-assisted fluidization was employed to reduce the limitations on the samples' intrinsic adsorption capacity and boost the gas-solid interaction efficiency. Every adsorption test was carried out using measured CO_2 concentrations in a mixture of CO_2 and N_2 gas at room temperature and pressure. Based on the results, it can be concluded that there is no significant effect on fluidization quality over 100 Hz and 125 dB operating parameters of sound. Moreover, the best CO_2 adsorption is found at 100 Hz and 125 dB of sound level parameters in terms of time taken for adsorption. In essence, there is great potential for developing sound-assisted fluidization techniques for CO2 capture to overcome global warming to a greater extent.

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ORCID DETAILS OF THE AUTHORS

A. P. Ganorkar : https://orcid.org/0000-0003-1811-9352